PROCEEDINGS OF THE
2016 EVIAN WORKSHOP
ON LHC BEAM OPERATION

Evian, 13th to 15th December 2016

Edited by
S. Dubourg, B. Goddard, G. Trad
The principal aims of the workshop are to:

- review 2016 performance, availability, operational efficiency and identify possible areas for improvement;
- examine beam related issues and establish a strategy for the rest of Run 2;
- perform a critical review of system performance;
- review control system performance and examine possible future developments;
- develop an outline of the operational scenario for 2017 and 2018 for input to Chamonix 2017

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The outgoing Workshop organisers would like to thank all participants, speakers, enablers and unsung heroes who have made the Evian Workshops such a successful forum for LHC commissioning and operation since January 2010. To the new organisers, *iuventuti nil arduum.*
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‡No written contribution
SETTING THE SCENE

M. Lamont, CERN, Geneva, Switzerland

OVERVIEW OF 2016

After four full years of LHC operations, sophisticated tools and experience mean that preparatory phases are executed without too much fuss. Hardware commissioning for 6.5 TeV operation, although intense in terms of a testing schedule, proceeded calmly. There was the usual high level of interest for first circulating beam on 23rd March. This was followed by 4 weeks of relatively smooth commissioning with beam with the machine fully validated for $\beta^*$ = 40 cm in this period. This led to first Stable Beams being declared on the 19th April.

The effect of improved tools, experience, diagnostics and well-developed understanding of the key hardware systems was clearly apparent during commissioning. Two points of note: the reduced availability of key personnel for critical commissioning steps; and the need for iteration and the passage of time to resolve issues, particularly those relating to machine protection. The time freed up as a result during this period allowed the team to push forward operational development, preparation for special physics runs, and more exotic system development.

The first part of the operating period was hit by a number of serious problems in both the LHC and the injectors.

- 26th April: The development of a vacuum leak on the high energy internal dump (TIDVG) of the SPS. Caution subsequently limited the beam intensity injected from the SPS for the rest of the year.

- 27th April: Severe damage to a capacitor container of the PS POPS system. The rotating machine subsequently failed bringing the PS down for around 6 days.

- 29th April: Damage to the bushings of a 66 to 18 kV transformer initiated by curious beech marten.

After the POPS recovery, however, things progressed very well. The number of bunches was ramped up to 2040 per beam – the maximum with 72 bunches per injection. A bunch population of $1.1 \times 10^{11}$ gave a peak luminosity of $\approx 8 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$. Already at this stage this was coupled with excellent availability and the week Mon 30th May – Sunday 5th June saw:

- Record luminosity in a fill: 380 pb$^{-1}$
- Record luminosity per day: 390 pb$^{-1}$
- Record luminosity per week: 1.98 fb$^{-1}$

Design luminosity was reached on the 26th June thanks to the reduced $\beta^*$ and lower transverse beam sizes from the injectors compensating the lower number of bunches. The excellent job in injectors to optimize beam brightness via continuous optimization, the change of PSB working point, and the deployment of BCMS should be acknowledged. Indeed in July, the PS started to deliver BCMS beam to LHC. A peak luminosity of around $+20\%$ and a new record of $\approx 1.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ was obtained as a result.

The smaller emittances allow the reduction of the crossing angle from 370 $\mu\text{rad}$ to 280 $\mu\text{rad}$ and a concomitant increase in the geometrical reduction factor from around 0.59 to 0.7. This measure was deployed following the autumn technical stop. Performance was also helped by the use of a reduced bunch length in Stable Beams.

Thus, despite the limit in number of bunches and limit in bunch intensity from injection kicker vacuum issues the peak performance of 40 – 50% over nominal was obtained – see table 1.

<table>
<thead>
<tr>
<th>Table 1: 2016 peak performance parameters</th>
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<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Protons per bunch</td>
</tr>
<tr>
<td>Number of bunches</td>
</tr>
<tr>
<td>Normalized emittance</td>
</tr>
<tr>
<td>$\beta^*$</td>
</tr>
<tr>
<td>Crossing angle</td>
</tr>
<tr>
<td>Bunch length</td>
</tr>
<tr>
<td>Peak luminosity (CMS)</td>
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<td>Peak mean pile-up</td>
</tr>
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</table>

2016 was also blessed by unprecedented machine availability: the machine was available for operation 72% of the time scheduled for physics. Overall Stable Beam efficiency was of order 49% (to be compared to 36% in 2012, and 30% for the short production period in 2015). This is the result of a sustained, target effort across the board by all teams. Beam related issues such as radiation to electronics, UFOs, beam induced heating have all been relentlessly addressed. Effective fault tracking has been put in place. The result is a revelation and is something that the community can be proud of.

CONCLUSIONS

In a full operational year at 6.5 TeV the LHC has enjoyed the following.

- Good peak luminosity via full exploitation of all available parameters ($\beta^*$, bunch length, crossing angle, emittance from injectors). Bunch number and bunch intensity were limited in 2016 but the full range remains to be exploited in 2017.
• Excellent luminosity lifetime in general with only moderate emittance blow-up in Stable Beams and minimal non-luminosity beam loss after the first hour or so.

• Stunning availability following sustained effort from hardware groups accompanied by effective fault tracking.

• Few premature dumps allowing long fills: the UFO rate is down and radiation to electronics effects have been largely mitigated, again after a sustained and successful campaigns.

• Excellent and improved system performance across the board, for example, the new developments of the transverse damper system (OBSbox etc.); collimator alignment software, injection kicker performance.

• The magnets, circuits and associated systems are behaving well at 6.5 TeV.

• Good beam lifetime through the cycle

• Operationally things are very well under control

• Magnetically reproducible as ever

• Optically good, corrected to excellent by the OMC team

• Aperture is fine and compatible with the collimation hierarchy.

• Collimation system is demonstrating excellent performance and impressive robustness

• Machine protection regime assuring safe exploitation

After the trials of 2015, 2016 was really the first year when it all came together: injectors; operational efficiency; system performance; understanding and control; and availability. Remarkable operational flexibility was demonstrated, in particular, during the exceptional proton-lead run during the last running period. Flexibility also allow the team to handle the slower than expected electron cloud conditioning, the implications of which remain a worry for the HIL-LHC era to be understood fully. It should also be noted that it was fortunate that UFO rates have conditioned down, accompanied, as elsewhere, by excellent diagnostics, well thought through mitigation actions and understanding through simulation.

The LHC has moved from commissioning to exploitation, and is enjoying the benefits of the decades long international design, construction, installation effort – it’s clear that the foundations are good. It’s present performance is worthy reflection of this effort and the huge amount of experience and understanding gained and fed-forward over the last years. Progress represents a phenomenal ongoing effort by all the teams involved.
SUMMARY OF SESSION 1: “OPERATIONS”

C. Bracco, M. Solfaroli Camillocci

INTRODUCTION

The operational performance of the LHC in 2016 was reviewed and compared with respect to the past years. Key aspects, limitations and improvements were analysed; further developments to push the machine performance beyond present achievements were proposed.

E. BRAVIN - “OPERATION OF A 6 BCHF COLLIDER: DO WE FIT THE EXPECTATIONS?”

LHC performance and luminosity reach in 2016 confirmed that all the systems, including operation, fulfilled the expectations. Further improvements can nevertheless be envisaged for what concerns tools, communication, written procedures and documentation. The main goals should be facilitate the integration of new comers, reduce the number of operational mistakes and fasten the diagnose of recurrent problems to minimise the turnaround time.

Discussion:

J. Wenninger commented that things quickly evolve in operations and keeping the procedures updated is not evident. He also asked what E. Bravin means with “intelligent” softwares as an example of improved tools. E. Bravin replied that there are several well established procedures for activities which are regularly performed in operations but no documentation exists. Written guidelines should be available and would simplify the learning process of new EIC and operators, especially in view of the future turnaround of people. He then explained that an intelligent software is capable of performing some data analysis and can provide a guidance in the diagnose of a problem or a system fault reducing the investigation time (see also K. Fuchsberger’s talk). For example, in case of unsuccessful injections, a tool that checks all the active interlocks (in the SPS, TL and LHC) and identifies the problem would drastically improve the operation efficiency. He added that all information is available but it has to be adequately organised. J. Wenninger asserted that written procedures are important but the EICs should maintain a level of knowledge which allows them to operate differently still insuring the safety of the machine. This is particularly important during MDs when unconventional activities are performed.

M. Lamont underlined that fiftytwo faults were imputed to operational mistakes in 2016 and asked if a 6 BCHF machine can afford that. E. Bravin answered that these faults mainly occurred during commissioning or MD time and they had only a very little impact on the physics production. He commented that this kind of mistakes can hardly be reduced. M. Lamont insisted that operation should aim to a failure rate as low as in the aerospace science environment.

W. BARTMANN - “LHC INJECTION”

During Run 1 injection losses were dominated by showers from the transfer lines while longitudinal losses gave the main contribution in Run 2. A clear improvement was observed in the transfer line stability after the reduction of the MSE current ripples and no limitation is expected for injections of up to 288 bunches. The longitudinal losses are strongly dependent on the beam configuration and could be reduced by one order of magnitude when using the second 40 MHz PS cavity. Batch spacing of 200 ns and 500 ns (MKP and MKI rise time) in the SPS and LHC respectively can be reached. Improvements are being implemented in the IQC (revised thresholds and color code) and diamond BLMs will be added. Automatic preparation of the LHC beam in the injectors is proposed.

Discussion:

J. Wenninger reaffirmed that IQC thresholds should be more consistent with respect to BLM dump thresholds. They should unambiguously indicate when injections have to be stopped and the beam quality from the injectors or the transfer line steering have to be checked and improved. R. Schmidt asked clarifications about the follow up of the diamonds installation, operation and also the control part. W. Bartmann explained that the diamonds are under the full responsibility of BI people who have also to coordinate the different activities with the other involved teams (ABT, MPE and collimation). He explained that works are already on going to standardise the system and make the data available for operation and not only for experts. He added that diamonds are already used for online loss monitoring at the SPS extraction. R. Jones confirmed that the system will soon be like any other BI system.

V. Kain commented that an automated preparation of the beam in the injectors during the LHC ramp down should be possible and would indeed reduce the turnaround time. Still a non negligible effort is needed to put that in place for all the different machines and the OP manpower is principally busy with shift work. D. Jacquet underlined that an efficient communication between the different CCC islands is a key requirement to optimise the operational time. She also reminded that in 2016 the problem with the SPS dump prevented the preparation of the high intensity beams far in advance. B. Mikulec added that the time for LHC beam setup should not cause a loss of physics for the other users.
K. FUCHSBERGER - “TURNAROUND: ANALYSIS AND POSSIBLE IMPROVEMENTS”

For the presented analysis, the turnaround was defined as the time between two consecutive “stable beam” declarations and faults inducing stops longer than 24 hours were discarded. The time needed to perform each operational step (e.g., end of “stable beam” to dump, ramp down, injection, ramp up, etc.) was carefully evaluated and the injection process was identified as the dominant contributor to turnaround. New diagnostics will be available after the EYETS that should allow a faster detection of the problems preventing successful injections into the LHC. A median turnaround time of 5.2 hours was estimated for 13-17 hours long fills. Stopping the precycle at 3.5 TeV instead of 6.5 TeV allowed to gain 21 hours, not further significant gain is expected.

Discussion:
J. Boyd asked what the difference in average turnaround time was between programmed and emergency dumps. A. Apollonio answered that the difference was of the order of 0.5 hours.
M. Lamont asked if removing every stop longer than 24 hours could have cut off important information. A. Apollonio and L. Ponce answered that this was of course an arbitrary choice but it allowed discarding exceptional events (e.g., weasel induced damages, cryo recovery and MK3 failures) which would have faked the operational turnaround time evaluation.
B. Goddard asked if an analysis over the different years was done and if any change or improvement was visible. D. Nisbet answered that this was not done and it would require a considerable effort (one man month work). M. Soffaroli added that the data were not treated in the same way in the past so that a direct comparison is not possible.
L. Ponce reminded that many faults were transparent since they occurred and could be solved before the end of the ramp down. K. Fuchsberger confirmed that including those failures would have doubled the number of recorded faults.
M. Zerlauth commented that several circuit trips happened during the ramp down and one should check if any optimisation is needed to avoid these failures.

D. NISBET - “CYCLE WITH BEAM: ANALYSIS AND IMPROVEMENTS”

The analysis was based only on proton physics fills which reached “stable beams”. Performance in 2016 was excellent, the machine was extremely reproducible and improvements could be observed through the whole beam cycle. The most significant improvement was given by the use of the combined ramp and squeeze while the injection process was still the biggest limitation. Further gains can be envisaged, in particular at injection, but will generally tend to be less and less effective. Parallelisation and optimisation of some sequencer tasks could help in pushing the performance beyond the present achievements.

Discussion:
J. Wenninger commented that combined ramp and squeeze could be pushed toward 1 m β* (now 3 m). Optimising the “adjust” phase is complicated because of the totem bump while the collision process in IP1 and IP5 could be revised.
W. Höfle asked why the mean and the average time at injection differed more than for the rest of the machine cycle. D. Nisbet D. Nisbet explained that the injection phase is where most unexpected events can occur, and also gave an example where in some cases the fill number was not updated if a dump occurred at injection and the fill had to be restarted (thus the fill time is much longer). R. Tomas Garcia asked if the change of the tune from injection to collision could be incorporated in the squeeze process to gain some time. D. Nisbet commented that this could be done however the gain is not significant (20 s of beam process, 3 min if all settings overhead are included).

J. WENNINGER - “MACHINE REPRODUCIBILITY AND EVOLUTION OF KEY PARAMETERS”

LHC reproducibility in terms of tune, chromaticity, coupling, orbit and IP offsets was revised. The machine proved to be extremely reproducible, especially at top energy, with the only exception of the decay and snapback effects. Coupling could be improved by moving the tune change to the end of the squeeze as it was done for the ATS optics MDs. All these observations could endorse the option of limiting the number of test cycles when reusing a previously tested set of settings even after a long interruption. The triplets caused the largest orbit perturbation and affected mainly stable beams at low β*.
This behaviour became clearer in 2016, partially also for the more systematic usage of the WPS system. Common correctors in the OPB could improve the orbit control, provided the reproducibility of BPMs is adequate. Periodic fast orbit oscillations at the mm level were observed on the levelled luminosities and on DOROS BPMs but no explanation could be found.

Discussion:
G. Iadarola commented that the chromaticity is the only parameter which is not stored in any repository; having it available on TIMBER would simplify the data analysis and the correlation with other observables. J. Wenninger answered that chromaticity could be indeed logged in TIMBER anytime its value is modified.
J. Boyd asked if the shown reproducibility could allow to reduce the validation and setup time. J. Wenninger answered that it should be possible to go faster to stable fills but main revalidation will still be needed.
SUMMARY OF SESSION 2: “AVAILABILITY”

L. Ponce, B. Todd

INTRODUCTION

AVAILABILITY - A. APOLLONIO

The scope of the presentation is the Proton Run 2016. Data has been prepared by the AWG and fault review experts using the AFT. This presentation is a summary of three individual reports that were written for three periods: Restart - TS1, TS1 - TS2 and TS2 - TS3 When combining all of these, 782 faults were recorded and analysed, 65 parent / child relationships were identified and two new categories were added: access management and ventilation doors. 213 days were considered, 153 days of which were dedicated to physics and special physics. The time distribution for the considered period is the following:

- Restart - TS1: 45% downtime, 30% stable beams, 22% operations, 2% pre-cycle
- TS1 - TS2: 20% downtime, 58% stable beams, 21% operations, 1% pre-cycle
- TS2 - TS3: 16% downtime, 54% stable beams, 29% operations, 1% pre-cycle.
- Overall: 26% downtime, 49% stable beams, 23% operations, 2% pre-cycle

Availability ranged from a minimum of 30% to high of around 90%, which was stable over several weeks. The best weeks achieve around 3 fb⁻¹.

Over the 175 + 4 = 179 fills reaching stable beams, 47% reached end of fill, 48% were aborted, 5% were aborted due to suspected radiation effects. The main categories of premature aborts are UFO and FMCM. Short duration stable beams are due to intensity ramp up. Before MD1 and BCMS the machine was left to run for very long fill as luminosity lifetime was very good. The average fill duration for the three periods is the following:

<table>
<thead>
<tr>
<th>Periods</th>
<th>End Of Fill</th>
<th>Aborted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Restart - TS1</td>
<td>6.9 h</td>
<td>8.0 h</td>
</tr>
<tr>
<td>TS1 - TS2</td>
<td>16.2 h</td>
<td>7.7 h</td>
</tr>
<tr>
<td>TS2 - TS3</td>
<td>11.5 h</td>
<td>7.8 h</td>
</tr>
</tbody>
</table>

In the period of physics production there were 779 faults, representing 1620 hours (integrated fault time duration) with 77 pre-cycles due to faults. The distribution by systems is presented ordered by “Integrated Fault Duration”, “Machine downtime” (corrected for parallelism of faults) and by “Root Cause” (re-assigned for root cause dependencies). The Top 5 are:

- The period was dominated by high-impact faults. The big improvors versus 2015 are QPS which was almost invisible to OP. Radiation effects to electronics which presented significantly fewer events than predicted and Cryogenic system as impact of ecloud stayed under control, and recurring sources of faults were solved. In conclusions, 2016 was an excellent year. Several weeks with 90%, 3 fb⁻¹ luminosity produced, and very re-produceable operating conditions. The un-Availability is due to typically long isolated issues and 2017 should be the same, unless we move from the zone in which we are now.

Discussion

J. Wenninger asked what is the operation section of the pie-chart and if it can be separated. A. Apollonio answered that we can quantify it, but not automatically and L. Ponce added that the column for operation mode can be extracted, but we need an automated means to correlate this.

M. Lamont noted that the operational conditions of the machine being stable appears to influence the stability of the LHC availability and asked if keeping the operational conditions stable mean that systems will keep (or have kept) the same availability. A. Apollonio answered that we will see next year. The comparison of 2015 to 2016 is difficult, as the things like BCMS and bunch spacing has changed the operational conditions of the machine. L. Ponce commented that 2015 was dominated by cryogenic recovery and stability, 2016 has not had the same issues. The sources of aborted fills, which are immediately repaired, are a factor which needs to be considered, for example, a fault which leads to a beam abort, which requires no repair, but the machine to be re-filled.

S. Redaelli reminded that this year was one of the years where we lost the most number of operational days due to long faults and asked once this is corrected out, what the characteristic of the fault data is. A. Apollonio added that 2016 began with poor availability, with isolated faults, having a long duration, since then it appears that "random faults" have been the driving factor.

S. Redaelli asked if it is understood why we observed so few failures related to R2E. S. Danzea mentioned that the TCL settings are one of the main contributors of R2E failures.

G. Rakness asked how come that at the end of the year there is high availability and yet not much physics produced. L. Ponce reminded that at the end of the year there were several areas of machine exploitation that meant the machine...
was not producing physics, for example there were several MDs. It was noted that on 24th October in three consecutive days, there was the highest luminosity delivery of the year.

TECHNICAL SERVICES - J. NIELSEN

The five systems which are monitored by TIOC are: Cooling and Ventilation, Electricity, Safety Systems, Access System and IT network. These categories are distributed across several elements of the AFT tree. The events which occur are classified by groups, in the future this could be done by mapping systems and equipment instead of by group, matching the approach from the AFT. This will help classify events more clearly. For example, some systems are groups of systems, the classification could be improved and AFT should show groups of systems. To achieve this the definition of a “system” should be improved.

TIOC meets every Wednesday to analyse the events that have occurred during the week, then recommendations are made to mitigate root causes. TIOC coordinates the larger technical interventions. If an accelerator is stopped, then a major event is created. The data for such an event is taken once, and is not subsequently synchronised, this could be improved. The major events are presented in the weekly TIOC meeting. The machine or service operator fills in the first part of the information, then the user and/or group then fills in more information.

The fault information for 2016 shows 3 major groups: ENEL for 40% (largely due to the weasel), EN-CV for 32% and BE-ICS for 17%. To be noted that this does not include the cryogenics. The Breakdown by fault count (with duration) is the following:

- Controls and instrumentation = 12% (15%)
- Equipment = 31% (36%)
- Electrical perturbations are 46% of the faults (45%)

For “Controls and Instrumentation” category, the faults are mostly PLC failures. For “Equipment Faults”, faults are usually due to common-mode power supply faults, for example a failure which trips the power supply to several element (selectivity tripping at a higher level). Certain events are due to equipment not suitable for use (old installations being re-tasked), general equipment failure, or calibration problems. Downtime attributed to this category is higher than 2015, but if you remove the weasel, it is lower (-30%). Concerning Electrical Perturbations, in 2015 we had 3 hours of downtime representing around 15 faults, whereas in 2016, we accumulated 23 hours of downtime for around 45 faults. A general report from the mains supply services shows that 2016 has had -19% thunderstorms than a typical year.

In conclusions, TIOC is effective, and the follow-up has been good. Several things are being worked on and followed up. The next goals are to try and exploit the AFT in a better way, to align and synchronise the information.

Discussion

M. Lamont asked if the weasel event showed that there were some spares issues. J. Nielsen answered that there were spares, but not in good condition.

D. Nisbet asked how we close the loop with equipment groups and how we can see improvements. J. Nielsen mentioned that next year we hope the duration of fault assigned to the technical services will be lower as this year suffered from long effect faults. For the follow up it is the equipment groups and users. An event is not closed in the TIOC unless it is not going to be mitigated, or that it has been mitigated.

L. Ponce remarked that the TIOC is doing much more follow up on a regular basis than the machines do for the AFT.

INJECTOR COMPLEX - B. MIKULEC

Injectors were the number one cause of 2016 LHC downtime, although it should be taken into account that there are four injectors before LHC. If this was split, then the LHC "injector" would be a shorter bar per machine. It is not easy to find which accelerator is the source of LHC downtime, AFT is being discussed to be added to assist in this work. 138 faults were attributed to the injectors, with 15 days downtime. This analysis was very time consuming, as the connection from LHC to the Injectors logsheets is not automatic.

LINAC2 accumulated 6 h 20 m downtime as seen by LHC, mainly due to 3 faults, including the replacement of an ignitron. Booster accumulated 11 h 45 m as seen by LHC due to several faults, mainly electro-valves with the longest individual fault of 4 hours. PS accumulated 9 days 10 hours of downtime as seen by LHC, due to power converters, MPS and POS, vacuum and radio frequency. Power converter is over 6 days of this, vacuum over 1 day, and RF over 15 hours. Finally SSPS is 4 days 19 hours as seen by LHC due to power converters (no real systematic over 1 day and 8 hours, targets and dumps (23 hours), and radio frequency (over 18 hours). A lot of systematic issues have been reported affecting beam quality, but which should be considered as degraded mode, not an actual fault.

If you contrast the overall performance of the injectors, as LHC only needs beam during filling, considering each machine as a continuous operation, availability numbers are the following.

LINAC2 has a bad year with 97.3% uptime, 166 h downtime. Source problems are 44.1% (a new source being tested in EYHTS), RF system is 34.6% (analysis is ongoing) and External is 14.7% - power glitches and cooling water.

Booster showed 93.9% uptime, 384 h downtime. LINAC2 is 33.6%, RF system is 17.5% (was in a degraded mode, but incorrectly actioned), Beam Transfer is 15.8% (septa and electro valves issues - will be replaced next year) and Power converters for 14.3% (random faults).

PS had 88% uptime, 727 h downtime. Power Converters is 38.3% (POPS capacitors will be replaced), Injectors is 26.6% (detailed in the previous category), RF is 10.7% and
Beam Transfer is 6.9%. The availability per user varies from 79-94%.

SPS accumulated 74.8% uptime, 1366 h downtime. Faults are mainly due to injectors and targets problems, looks random failures.

Several issues are reported with fault tracking in the injectors: Not everything is captured in the injectors, perhaps automated tools can be added, the concept of a destination and user is tricky to add, SPS cannot distinguish between no request, or request but fault, faults attributed to a timing user currently, but rather has to be LSA context. Root fault cause is not correctly identified and a question is still opened on how to account for degraded modes. Injector AFT will address some of these issues. Categories are organised, LSA contexts will be used, so statistics by context or group of context can be done, an elogbook interface context dependent will be done and it is planned to separate warnings from faults. Injector downtime appears to be correlated by a few longer uncorrelated breakdowns.

**Discussion**

J. Jowett commented that the consideration of only the proton run has hidden some issues which were observed during the P-Pb run. Although there were other injectors used for the PbPb injection.

M. Lamont asked how come that the LHC was not adversely affected by poor LINAC availability. B. Mikulec answered that the LHC never asked for beam during these problems, and therefore no fault was logged.

M. Lamont wondered if the breakdowns are really uncorrelated if it could be correlated with maintenance activities needing some improvement. B. Goddard noted that sometimes the maintenance has led to lower availability (e.g. water valves).

L. Ponce commented that the tracking of degraded modes was abandoned in the LHC. AFT was not adapted to track, and so was not done, but following 2016 experience with the limitation on bunch numbers imposed by injectors, the question can be asked on how to track degraded modes.

R. Steerenberg added that having this degraded information for the whole period would make things clearer, at the moment the reality is obscured due to the incomplete capture of the degraded mode. L. Ponce agrees, in addition, injector "downtime" can be flagged in AFT, for example, "prevents injection". Following MKI problem this was added, this was not used in 2016. For example the 35h fill, for example, was kept so long to avoid injector issues.

**CRYOGENICS - K. BRODZINSKI**

There are four cryogenic islands, 8 cryogenic plants (A = Low Load, B = High Load). During run 1 two cryogenic plants could be stopped. In 2015 all plants were activated to compensate electron cloud heat load, there was still some operations margin. In 2016 a new configuration was used, switching off one cold compressor unit, moving capacity between A and B systems. This can be safely done as LHC is running below ultimate values. During LS2 some valves will be replaced to allow even further sharing of load between A and B systems. Cold boxes were tuned, achieving 175 W per half cell capacity on the worst performing sectors (around point 8). In sectors 2-3 the beam screen heat load cooling capacity can reach 195 W. The general limit is 160W.

In 2016, cryogenics system reached 94.4% availability. If you exclude users (Quench) and supply (mains), it achieves 98.6%. In 2016, the total downtime was 79 hours, to be compared with 273 hours in 2015. This improvement comes from four effect: feed-forward logic for beam screen heating, points 2 and 8 optimisation, point 8 cold box repairs and DFB level adjustment. Overall around 60% of downtime was due to PLC failures, this is a known issue for some time. During YETS 2015/16, an anti crash program was added, it has still some issues, then during EYETS 2016/17, a further upgrade will be applied by BE/ICS on 50% of the equipment. The faults on the 4.5 K are due to 1 human factor and 2 PLC problems. For the 1.8 K, 1 mechanical failure and 1 AMB CC.

The Helium Losses have been reduced to 17 tons (9 operational) to be compared with 40 tons (29 operational) in 2010. The Beam Screen Heat Load was on average 120W per half cell, 160 W is the general limit.

The plans for 2017 are in the EYETS, update 50% of the PLCs to attempt to deal with code crashing issues, some operational scenario as 2016, the limit is still 160W per half cell, the inner triplet cooling will be OK provided the load is <250 W per inner triplet. In 2016 200 W per inner triplet was seen, at 6.5 TeV and 1.5e34 peak luminosity, so a maximum possible is 1.7e34.

**Discussion**

J. Wenninger insisted on the limit on peak lumi and asked if the triplet limit is 2.0e34 or 1.7e34. K. Brodzinski clarified that the limit is really 1.7e34. After the tests carried out, a baseline of 300W heat load on triplet was expected, but once the re-calibration correcting factor was added, the actual load managed was only 240-250W. There is still room for improvement. 1.75e34 is something that is known, and can be done. To reach 2.0e34 tuning is needed.

**SOURCES OF PREMATURE BEAM ABORTS - I. ROMERA / M. ZELAUTH**

In 2016, 86 fills were aborted, a Pareto of these has three large contributors: Technical Services (27 events), Power Converter (15 events) and Beam Losses/UFO (14 events). Premature dumps attributed to Technical Services are comprised of 23 electrical network perturbations (22 FMCM, 1 QPS XL5, XRS), 3 water pumps and flows and 1 water infiltration (cooling and ventilation). 12 FMCMs are installed in LHC, designed to interlock on current change as 250 mA change at RD1 changes the orbit 1.5 sigma. 9 of the FMCM events were global, big enough to effect other parts of the complex, FMCM on the 18 kV network observe more glitches, being closer to the 400 kV line. After the EYETS,
four SATURN supplies will replace the four converters on the 18kV.

The 15 events due to Power converters are comprised of 6 SEU candidate events, 4 internal/external converter failures, 2 communications issues, 2 orbit dipole corrector issues and 1 interlock interface, which has not been solved in 2015. No significant correlation between events.

The 14 Beam Losses / Unidentified Falling Objects (UFOs) are distributed as 6 in the IRs, 3 in sector 12 since threshold changes in August and the rest in the arcs. No magnet quenches due to UFO have been observed since July 2016 but we have low statistics.

The remaining premature dumps have small counts, the interesting cases are: Collimation - LVDT measurement (3 events), QPS - $I_{DCCT}$ current measurement likely screen grounding issue (3 events), Training Quench of MQ.22L8 (2 events at the beginning of the year) and Cryogenic - Cry Maintain lost (2 events). There is no correlation obvious. In conclusions, everything looks random, bottom of the bathtub curve!

**Discussion**

G. Arduini noted that for the power converters which have a possible radiation effect, five out of six are in point 5 RRs. M. Zerlauth confirmed that this is the case, these are planned to be changed, first by replacing the controller (FGClite) and then the converter power part. S. Danzeca added that the events in RR53/57, happen when the TCL settings are "closed", when the TCL are opened there are no events.

A. Lechner mentioned that concerning the UFO for the IR, thresholds have already been increased for the year.

B. Goddard commented putting the last presentations together, it's remarkable that there was only one dump from the dump kickers, and the dilution systems. This is due to the reliability run, which has shown to be clearly beneficial.
SUMMARY OF SESSION 3: “PERFORMANCE - PART 1”
G. Iadarola* and A. Mereghetti†

OPTICS CONTROL IN 2016
Speaker: Tobias Persson

The LHC optics was successfully commissioned down to $\beta^*=0.4$ m at 6.5 TeV, beyond the design value of 0.55 m at 7 TeV. In these challenging conditions, it was possible to achieve corrections to $\beta$-beating below 1% at the high luminosity IPs and below 2% RMS around the ring, marking an unprecedented level of control of linear optics corrections for any high-energy proton collider. These results were made possible by the recent improvements in the measurement of $\beta$-functions, namely: the usage of the K-modulation method, the incorporation of the obtained results in local and global corrections, the use of appropriate weights on the different optics parameters, a longer AC-dipole plateau, the N-BPM method, the reduction of the orbit drifts from quadrupole movements. Moreover, a correction of the linear coupling down to the per-mil level was demonstrated in MD using the AC-dipole, achieving the lowest levels ever measured in the LHC. For 2017 it is proposed to correct the effect deriving from the sextupolar errors in the IPs in combination with crossing angles. This should help to further reduce the $\beta$-beating.

Discussion
J. Wenninger remarked that the ramp and squeeze allowed to save a significant amount of commissioning time. He then asked whether the stability of the linear coupling in the triplet area is known. T. Persson replied that this was relatively stable throughout the year.

NON LINEAR CORRECTIONS
Speaker: Ewen Hamish Maclean

The effect of non-linearities in the Insertion Regions (IRs) becomes more and more relevant when decreasing $\beta^*$. In particular the amplitude detuning introduced by normal octupole errors in the IRs can significantly perturb the tune spread introduced by the “Landau octupoles” installed in the arcs. This can have a detrimental effect on the performance of beam instrumentation (e.g. linear coupling measurement) and on beam stability.

In 2016 octupolar errors from the IRs could be measured using feed-down and amplitude detuning methods and could be successfully corrected. The positive effects of the correction have been verified through direct observation of octupole resonances and beam-lifetime, also with ATS optics. It is therefore possible to incorporate this correction operationally in 2017.

Sextupole errors in experimental IRs also become a concern at small $\beta^*$, as feed-down from these errors can generate significant linear optics perturbations. This is not critical for LHC operation in Run 2 but it will become relevant for HL-LHC. It is therefore important to acquire experience with the correction of this kind of errors.

Chromatic coupling effects can be corrected with negligible commissioning overhead when applying the linear coupling correction. Beam-based compensation of octupole and decapole errors has been applied operationally since the start of Run 2.

Non-linear optics commissioning in 2017 is expected to require two shifts of eight hours.

Discussion
G. Iadarola asked whether it is understood why correction based on magnetic measurements do not work. E. Maclean replied that this is most likely due to misalignments.

W. Kozanecki asked whether the mentioned 1-2% imbalance in $\beta^*$ between ATLAS and CMS is before or after correction. E. Maclean answered that this is after correction.

EXPERIENCE WITH THE ATS OPTICS
Speaker: Rogelio Tomas (on behalf of S. Fartoukh)

The 2016 MD program allowed to gain significant experience with ATS (Achromatic Telescopic Squeeze) optics. Optics solutions were developed in order to have a “close to optimal” phase advance between the extraction kickers in Point 6 (MKD) and the tertiary collimators in Point 1 and Point 5 (TCT). Optics and coupling could be corrected for $\beta^*$ values as low as 21 cm and the telescopic squeeze could be pushed down to $\beta^*=10$ cm with probe beams.

Tests with a few nominal bunches were performed with ATS “pre-squeezed” optics to $\beta^*=40$ cm and with a moderately telescopic squeeze to $\beta^*=33$ cm. In particular collisions could be established in all experiments and the performance of the collimation settings could be positively assessed. This was an important milestone for the validation of the ATS scheme in view of the HL-LHC upgrade as well as in view of a possible use of the ATS for operation in 2017.

The operational cycle could be further optimized by combining the squeeze down to $\beta^*=90$ cm with the energy ramp and reducing the time of the final squeeze at flat-top energy to about 4 min. With ATS optics the mass acceptance for the CT-PPS experiment is lower than for the nominal optics.

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This could be partially mitigated with an optics change operating the Q6 at lower current with a consequent increase of the squeeze time.

The ATS MD program in 2017/2018 foresees the validation of the flat optics (e.g. 60/15 cm), possibly in synergy with tests on long-range beam-beam compensation using electromagnetic wires. Long-range beam-beam compensation with octupoles and the HL-LHC running scenario with negative octupole polarity will also be studied.

**Discussion**

M. Deile stressed that the figure of merit used to compare options for CT-PPS should take into account that at least three roman pots need to be used for their measurements.

M. Lamont asked whether the reason for which the expected loss peak in IR8 was not observed is understood.

S. Redaelli answered that this is not yet understood and could be investigated with further tests in the future. Nevertheless it is good that the model was found to be pessimistic.

M. Lamont asked whether any showstopper has been identified that would prevent the deployment of the ATS optics in 2017. R. Tomas answered that the only real concern is the performance for CT-PPS physics. G. Arduini underlined that the problem identified in 2015 consisting in an unfavorable MKD-ICT phase advance is now mitigated.

R. Bruce commented that still the phase advance is more favorable in the nominal optics compared to ATS. G. Arduini replied that the ATS satisfies the specifications defined for machine protection. R. Bruce stressed that for operation in 2017, the $\beta$-beating in the collimation area should be further corrected w.r.t. 2016 MDs.

M. Solfaroli reminded that at the moment we have one missing sextupole spool piece circuit and we need to compensate with those of the other arcs. He asked whether losing a second of these circuits is expected to be an issue. R. Tomas replied that detailed studies would be required to have an answer but he does not expect serious issues.

**COLLIMATION EXPERIENCE AND PERFORMANCE**

**Speaker: Daniele Mirarchi**

The performance of the LHC collimation system in 2016 was summarized. The system proved to be very reliable and effective, with no magnet quench due to losses from circulating beams and an excellent local cleaning inefficiency steadily at about $10^{-4}$ at 6.5 TeV. A big effort was put in place to minimize the setup time during commissioning. An optimized procedure was developed to obtain off-momentum loss maps without incurring into beam dumps. A record-time of about five hours was needed to align the entire system. Daniele also gave a brief overview of the setup and performance of the system during the ion run, for which the same short set-up times and steady performance were underlined. Highlights from collimation MD activities, both in view of the the choice of settings for 2017 and of interest for the HL-LHC project, were presented.

**Discussion**

Referring to one of the MD activities reported in the presentation, F. Roncarolo asked whether the losses observed with TCPs set at 4.5 $\sigma$ indicate that this is an ultimate limit.

D. Mirarchi and R. Bruce replied that the poor lifetime in the MD was observed also before applying the tight collimator settings. Therefore they would like to repeat the test before drawing firm conclusions.

R. Schmidt finally pointed out that the observed losses were comparable to those happening when going in collisions; hence, they would not represent a problem for machine protection.

**ANALYSIS OF BEAM LOSSES**

**Speaker: Stefano Redaelli**

S. Redaelli gave an overview of levels of beam losses throughout the year. The performed analysis relies on tools of loss decomposition in the three phase planes and beam lifetime estimations. Lifetimes during Run II were very good, showing a remarkable improvement with respect to performance in 2012. The handling of $\sim$250 MJ beams at the LHC was excellent, running steadily with nominal gaps at primary collimators, regular 25 ns beams, and values of $\beta^*$ at the high luminosity IP 30% smaller than the nominal value. A small decrease of the beam lifetime was observed when the crossing angle was reduced.

**Discussion**

B. Goddard asked whether the same type of analysis could be run on the cycle from injection to collisions.

S. Redaelli replied that transmission is not in the plots and the analysis should be added. Nevertheless, the ramp was always very clean.

G. Arduini reminded that a better control of beam stability was a key factor to reduce the losses with respect to Run 1.

J. Wenninger also underlined that orbit control in Run 1 was poorer due to temperature fluctuations of the BPM system and less smooth orbit corrections. He also remarked that the point at $\beta^*$ equal to 1.3 m had problems especially with BCMS beams, but they were cured by coupling corrections.
SUMMARY OF SESSION 4: “PERFORMANCE 2”

R. Bruce, K. Li

M. HOSTETTLER: HOW WELL DO WE KNOW OUR BEAMS?

An overview was given of various key parameters of the beam, how they are measured, and how reliable the measurements are estimated to be. FBCT measurements of bunch-by-bunch intensities over the year were presented, with an estimated uncertainty of 1–2%, given by the discrepancy with the reference measurements of the total intensity by the DBCT. For the transverse emittance, results from wire scanners and the BSRT were shown. The estimated systematic error is around 10–20%. Bunch length measurements were shown from the BQM, the BSRL, and the RF 40 GS/s scope, for which uncertainties arise from making Gaussian fits to non-Gaussian bunches. The most important changes of the measured parameters over the year were given by the change from nominal to BCMs beams, resulting in a significant reduction of the transverse emittance from about 3.5 μm to about 2 μm, and a decrease in bunch length target from 1.25 ns to 1.1 ns. It was also observed that the beams were not round during a large part of the year, which is compatible with the observed luminosity difference between ATLAS and CMS. However, in the last part of the run, more round beams were observed, but the luminosity imbalance was still present. The reason is still to be understood.

Discussion:

E. Shaposhnikova had a remark on the longitudinal profile measurements on slide 13, where she mentioned that what is always measured is the FWHM. She explained that one multiplies this value with a constant in order to obtain the 4π equivalent to a Gaussian profile. The measured value itself, however, is independent of the distribution i.e., it not being Gaussian does not render it meaningless.

W. Höfle asked referring to slide 7 and the cross calibration between BCTs, how satellite bunches were treated. E. Bravin explained that everything was included and that the FBCTs measures these as well.

M. Lamont asked about the beam roundness towards the end of the year, and whether it was clear how these evolved during a fill. M. Hostetttler replied that this was difficult to assess since there were no independent measurements. He explained they had only about 1–2 scans and that, with this, the comparison becomes very hard due to the lack of reference. J. Boyd added that they had done the crossing angle reduction scan and that this revealed that the crossing angle was causing a significant difference, hence, the beams may have not been round. However, he added that this was done with special beams. W. Kozanecki agreed that this was puzzling and that he believed that there may be an issue with the scale. He remarked that there were a couple of subtleties but that the emittance estimates by ATLAS and CMS agree very well. There have been very small differences in H and V which, finally, are very hard to interpret.

F. ANTONIOU: CAN WE PREDICT LUMINOSITY?

A luminosity model was presented, including burnoff, IBS, synchrotron radiation, and elastic scattering. All parameters can evolve according to the underlying physics, or some variables can instead be taken from data. The model was used to simulate the emittance along the cycle, where an unexplained blowup was observed in the ramp. The calculated peak luminosity agrees fairly well with measurements, although some discrepancies are observed, especially towards the end of the year. Along the fills, the model overestimates the measured luminosity, unless both the emittance and bunch length are taken from the data instead of the model. An additional emittance blowup of about 0.1 μm²/h is observed, on top of what is predicted. Significant losses, not explained by burnoff, are observed in the first few hours in stable beams. The impact on integrated luminosity for each effect is estimated at a few percent for most fills. Finally, losses per bunch in stable beams were presented, and higher losses were observed on bunches with full long-range encounters after the reduction of crossing angle.

Discussion:

E. Bravin asked about quoting peak luminosity, whether this meant the peak value of the average over all bunches? F. Anoniou replied that this values is taken bunch-by-bunch.

O. Brüning asked whether the additional emittance blow-up was intensity dependent. F. Anoniou explained that she had looked at the high intensity fills but still needed to check the low intensity ones in order to make this correlation.

W. Kozanecki asked with respect to the impact of the LHCb polarity whether there was any correlation with the beam loss monitors and whether there was any information in the sensitivity to crossing angles. Y. Papaphiliopou pointed out that they had made global observations which show clear correlations, however, so far no checks were made in detail to see what is going on close to LHCb. Simulations do show some long-range effects but, more importantly, differing head-on effects. The dynamic aperture can be worse from one case to another. There are ongoing efforts trying to interpret the simulation results. He remarked that optimizing the tune can solve this problem in any case. T. Pieloni
with respect to this remarked, that in the long-range beam-beam MDs they had also observed a tune shift despite the passive compensation in IP1 and IP5. These tune shifts are comparable to what can be expected from the change of polarity and the corresponding head-on effects in IP8. She pointed out that B. Salvachua had optimized the working point according to the values found in the MD which had brought a significant improvement.

G. Trad: made a remark on the discrepancies between predictions and measurements of, that he would not expect any changes from the machine, in principle. F. Antoniou clarified that, in the plots, the dependence is not on the pile-up but on the crossing angle.

X. BUFFAT: LONG-RANGE AND HEAD-ON BEAM-BEAM: WHAT ARE THE LIMITS?

The observations and experience with long-range beam-beam effects during 2016 were recalled. The limitations were probed in MDs, which showed an onset of losses below 8.6 \( \sigma \). In August, the half crossing angle in physics operation was reduced from 185 \( \mu \)rad to 140 \( \mu \)rad, corresponding to a reduction of normalized beam-beam separation from 10 \( \sigma \) for a 3.75 \( \mu \)m emittance to 9.3 \( \sigma \) for a 2.5 \( \mu \)m emittance. After this reduction, a smaller luminosity lifetime and larger losses were observed, which could be mitigated by a tune optimization. Furthermore, asymmetries were observed in the long-range tune shift in IR1 and IR5, which are yet to be understood. Other tests were carried out to investigate the feasibility of luminosity leveling using the parallel separation, and no detrimental effect was observed on the beam quality. Finally, the limitations from head-on beam-beam were discussed, and it was concluded that this is not a limitation with the present machine and beam parameters. The presence of noise together with head-on beam-beam might, however, fully or partly explain the observed emittance growth in physics that was not predicted by the luminosity model in the previous talk. A further optimization of the ADT might be a possible way to mitigate the issue.

Discussion:

O. Brüning asked whether, during the studies with changing crossing angle, the losses were predominantly halo or core particles. X. Buffat replied that this could be seen well when looking at the luminosity data which indicated that losses occur in both the tail and core.

O. Brüning asked in view of HiLumi LHC, how much the presented tests with large beam-beam parameter would be impacted when adding the long-range beam-beam. X. Buffat replied that the efforts are currently focused towards understanding the impact of the head-on collisions and that they will move to adding also the long-range interactions only later. He added that when doing leveling, if only one experiment decided to start leveling, he would recommend to go for leveling in both planes right away, even if this meant some extra work.

H. Burkhardt remarked that the head-on beam-beam tune shifts had rather high values in the high-beta run without long-range interactions and that limitations were encountered there. He concluded that losses were then present even in absence of long-range interactions. X. Buffat replied that this was difficult to analyze due to the collimator scrapings. H. Burkhardt replied that they had data also without scraping so that one could check this in more detail.

M. Lamont asked whether one should say that a separation of 9.3\( \sigma \) is actually pushing the limits. X. Buffat explained that this was not the case. One can observe some losses during the first hour only. He pointed out that one does lose some margin in this case, however.

S. Redaelli added that from the global losses there is no worry for the machine and pointed out that one could not speak of a detrimental effect from these losses for the machine. X. Buffat explained that indeed one starts to see losses when there are set-up problems but these do disappear once the machine has been optimized.

Y. Papaphilipou pointed out that the strategy of first going with larger crossing angle and moving to low emittances allowed them to gain some freedom in order to first explore margins and optimize setups and then to start tightening these margins stepwise.

F. Zimmermann: asked for a confirmation about the impact of the 9 nm noise at the IP to explain the emittance growth. X. Buffat explained that this is true if this noise occurs at the level of the bunch spectrum and reminded that this is indeed in agreement with the expectations from the LHC design.

L. CARVER: INSTABILITIES AND RF HEATING: ARE WE STABLE AND COOL?

The performance in terms of collective effects in 2016 was found to be very good, with beams reaching 1.4 times the LHC design brightness used routinely. Some parameters, such as octupoles, chromaticity and coupling, had to be further adjusted during the year to suppress emittance blowup at various phases in the cycle, and the important role of linear coupling was further explored. The role of \( Q'' \) as a further knob affecting beam stability has been tested at flat top. Some instabilities were observed, however, some did not significantly impact performance, and the ones that did could be cured. Furthermore, measurements of impedance over the year were shown, as well as tests of beam stability for various settings during the cycle. The results are well understood except at the end of the
squeezed, where more studies are needed to clarify the required octupole current. Extrapolations to 2017 were performed and it was concluded that the collimators could be further tightened without stability issues, e.g. inserting the primary collimators to 5 \( \sigma \) and the secondaries to 6.5 \( \sigma \). For beam-induced heating, no limitations were encountered in 2016 and it is not expected that further limitations arise in 2017. However, any unknown non-conformities might change this.

Discussion:

O. Brüning asked why we needed LIU if we are already able now to inject beyond HL-LHC brightness bunches. L. Carver replied that LIU was required for high brightness bunch trains.

L. Mether: Electron Cloud in 2016: Cloudy or Clear?

The electron cloud effects gave in 2016 the main contribution to the heat load in the arc. This was not limiting the performance, since the limit from the SPS beam dump was more constraining. A weak conditioning was observed, with a total decrease of the heat load by about 20% over the year. The accumulated electron dose on the beam screens in 2016 is estimated to have been four times larger than in 2015, which, based on lab measurements, should suffice to fully suppress the electron cloud effects, which is however not observed. The unexplained difference in observed heat load between sectors stayed similar to 2015. Experimental tests showed that a hybrid injection scheme of 8\( \times \)4e and BCMS could suppress the heat load significantly, which might be needed in Run 3 and for HL-LHC. For 2017, if BCMS beams are used, it is not expected that the performance will be limited by the heat load. Several open points remain for further studies, such as the difference between sectors, the evolution of scrubbing, the disentangling of heat load contributions from different elements, and further improvements in the simulations.

Discussion:

G. Trad asked whether scrubbing with doublets was planned. L. Mether said this question would be addressed in detail in the talk by G. Iadarola later in the workshop.
INTRODUCTION
This session focused on different aspects of the control system, reviewing past experiences, current state and bringing ideas for possible improvements in a short and long term.

List of presentations
1. Using the LHC Control System – retrospective on 2016 and short term plans by Guy Crockford
2. Evolving expert tools into operational software by Delphine Jacquet
3. How to improve interactions with the Control System? by Stephane Deghaye
4. Testing and deployment strategies and their impact on accelerator performance by Jean-Christophe Garnier
5. Thinking outside the box – paradigm changes ahead? by Mike Lamont

USING THE LHC CONTROL SYSTEM – RETROSPECTIVE ON 2016 AND SHORT TERM PLANS
G. Crockford

R. Schmidt commented that when it comes to human errors, one cannot blame individuals but instead a systematic approach is needed. He added that improving the situation requires looking at the managerial and organizational aspects.

S. Readelli asked about plans for the EYETS concerning luminosity and crossing angle leveling.

K. Fuchsberger answered that the goal is to be able to do leveling of ATLAS and CMS; the plan is to use for that a new server and remove the old application. The exact scope has not been decided yet.

B. Goddard made a remark that the operational paradigm should be challenged, adding, that the expertise of the OP crew should not be used to protect against operational errors. He also commented that the LHC is operated in a similar way as LEP was and he wondered whether starting with a fresh approach would lead to the same practices.

E. Bravin pointed out that during MDs it is hard to avoid all errors, as one cannot test everything in advance.

V. Kain commented on software development within OP, saying that it is not enough to put an OP software team in place. It would be necessary to change the structure to liberate time for the OP developers.

EVOLING EXPERT TOOLS INTO OPERATIONAL SOFTWARE
D. Jacquet

E. Hatziangeli referred to the collaborative development between CO and OP. She stated that a very good collaboration already existed on the LSA project and that CO is open to support such collaborations.

J. Wenninger commented that working together is a good model as, among other advantages, it addresses the maintenance problem. However, there are two issues related to that. The first is that today the team is mainly organized around the LHC OP. In addition OP developers have only 2-3 months per year to work together. The second is that at the moment even within LHC it is not easy to find an agreement on priorities and milestones. He concluded that finding a common agreement with other groups and sections might be even more difficult.

K. Fuchsberger confirmed that there is a commitment from CO to work together during EYETS and if that works well, the collaboration will be continued.

R. Steerenberg added that there are some duplications of efforts and there would be a clear gain working together.

H. Timko mentioned that in RF there are examples of duplicated software development. She explained also that expert tools are based on LabView and Matlab scripts that are difficult to maintain. These are being progressively migrated to Inspector. She also expressed concerns about PyJAPC library for which there is no long-term support from CO.

V. Baggiolini confirmed that CO is committed to collaborating, but agreeing with the statement of J. Wenninger, he reminded that it is important to define common priorities within OP, as they are often not clear for CO.

Q. King asked why OP develops software and whether CO should not get the necessary resources to develop all necessary tools using their expertise, especially in the situation when OP does not have enough time.

V. Kain responded that it would be difficult for CO to have all the necessary domain knowledge and insight. OP knows best what tools they need. She added that the optimal approach would be to have a collaborative development, involving OP and CO developers.

J. Wenninger commented that OP used to collaborate also with other groups but with progressively extended run periods such collaborations are disappearing.

S. Redaelli asked whether there is a clear list of requirements, allowing to better understand those systems, which OP considers as high priority. He underlined that discussions and agreement on that is very important.
Referring to the comment of H. Timko, A. Masi commented that he does not see LabView as a problem as there is a team ready to provide long-term support. He also would like to have discussions with all stakeholders to avoid duplications of efforts.

**HOW TO IMPROVE INTERACTIONS WITH THE CONTROL SYSTEM**

S. Deghaye

E. Bravin pointed out that documentation of libraries and tools provided by CO is often not sufficient or not easy to find, compared to tools provided by external companies. As an example, he gave the migration to RDA3 that would have been much simpler with a set of simple examples.

S. Deghaye responded that after LS1, CO has put in place an entry point on CO wikis, leading to the documentation of different products. Since then, there is an ongoing effort to improve the documentation and make it easier to find the necessary information.

V. Kain added that CO experts are always ready to help or point the appropriate documentation.

R. De Maria stated that until now CO did not collaborate on Python libraries used to access the control system. He asked if CO would join now the collaboration and participate in development. He remarked that non-CO developers are much less efficient writing bindings to CO libraries than CO experts would have been.

S. Deghaye answered that CO’s intention is to collaborate but it all boils down to finding resources. The exact form of collaboration is being discussed now.

R. Steerenberg asked if CO has already a concrete strategy to hide different islands of the control system and make interfaces more coherent.

S. Deghaye responded that at the moment various ideas of achieving that are being discussed.

V. Kain suggested that collaboration between OP and ABP on Python development would facilitate implementation of algorithms that are used operationally, and not only during MDs.

R. Steerenberg agreed, adding that thanks to G. Sterbini, in PS, they have Jupiter that allows quick switching between MD and Operational context.

**TESTING AND DEPLOYMENT STRATEGIES AND THEIR IMPACT ON ACCELERATOR PERFORMANCE**

J.C. Garnier

M. Zerlauth asked about testability of controls software outside of the Technical Network, whether the technical obstacles to expose all controls services outside of the TN could be overcome.

S. Deghaye commented that instead of the TN we could have an accelerator network i.e. all laboratory computers would be inside, having access to all services.

K. Fuchsberger asked whether it means that all developments would be inside TN, questioning whether this is a good idea.

E. Hatziangeli answered that this was a proposal from the security team and the CNIC working group. The WG is now at the stage of quantifying the costs.

V. Kain commented that testing is the key and we are not doing enough in this area. She asked if there are plans to test the vertical slice as a part of the startup sequence.

J. Wenninger remarked that typically development and testing should not be done within the TN, to not access accidentally the operational devices. He underlined that he would rather move the development outside of the TN. He also reminded that RBAC rules are already very complex and basing safety of operational devices only on RBAC might not be the best way to go.

**THINKING OUTSIDE THE BOX – PARADIGM CHANGES AHEAD?**

M. Lamont

E. Bravin asked whether going to seven Beta* in one or several steps is actually possible.

B. Goddard pointed out that to achieve such goals it is not enough to have real-time tasks adjusting and driving settings. Many other components of the machine would have to be taken into account. He summarized that such ideas would have to be discussed and applied across the whole accelerator complex.

J. Wenninger asked whether CO is part of huge projects such as LIU and whether CO ideas, requirements and constraints are taken there into account.

E. Hatziangeli assured him that CO is part of the LIU and other big projects.

J. Wenninger replied that CO participates in discussions on sub-packages, but this might be not sufficient to change paradigms.

V. Kain pointed out that making big steps in all machines is possible but high-level controls must be taken into account at all stages.

L. Arduini commented that Beta* leveling is a revolutionary idea and he asked whether this could be done incrementally.

M. Lamont answered that these are proposals and ideas to be explored.
SUMMARY OF SESSION 6: “SYSTEMS”
R. Alemany-Fernandez, W. Bartmann

Abstract
Session number six focused on a set of accelerator sub-systems to address the limitations observed in 2016 and provide with possible solutions. The session also aimed at summarising the equipment performance and present new possible upgrades for 2017. This paper reports on the discussions held during the session.

FAILURE SCENARIOS AT BEAM TRANSFER
C. Bracco

During the presentation Chiara discussed possible failure scenarios when transferring the beams from SPS to LHC. In particular slide 18 discusses the possibility to hit the LHC aperture in case the TCDIs are at 5 sigmas. Beam impacts with large impact parameters are the worst-case scenario. G. Arduini asked if there is a significant difference in the response of the TCDI if they are moved by half a sigma. Chiara answered that there is no difference because the large impact parameters are the problem. If the beam impacts the collimator with a large impact parameter the beam will not be fully diluted and it could come out performing quite big oscillations of up to 12 sigma. If this beam impacts in a low beta element the energy density left in the beam could be beyond the damage threshold.

During the talk Chiara highlighted that local orbit bumps in LHC should not be neglected when addressing failure scenarios. G. Arduini commented that ULO-like bumps are meant to be consistent with the available aperture. Chiara answered that the problem is that local orbit bumps reduce nevertheless the aperture margins and bring the beams closer to the aperture limit making more likely to hit the aperture and produce damage. G. Arduini asked what is the safe aperture such if the beam is intercepted we are still below the damage limit. Chiara answered that if the attenuation provided by the TCDIs is not sufficient it is not possible to identify a safe aperture.

S. Redaelli asked if the aperture in the transfer line could be hit in case of a MKE failure. Chiara answered that in bad cases yes, however, measurements performed in 2016 revealed 15 sigmas aperture, thus there is quite some margin.

R. Bruce commented that large impact parameter could be a risk for the aperture, but then the beam goes through the whole aperture of the collimators and gets dilute, how can the emittance matters? Chiara answered that the problem is the beta function value at the level of the hit, which defines the beam size, and therefore, if enough energy is left in the beam, the energy density at the impact position can be an issue. V. Kain commented that the additional angular spread does not matter, and on top of this, the line is a single pass so the emittance is not blown up.

MKI
M. Barnes

M. Lamont asked if the “dynamic pressure rise” referred to is due to electron cloud and how this can be mitigated. Mike Barnes answered that yes the “dynamic pressure rise” is due to electron cloud - because the naked alumina has a secondary electron yield (SEY) of 10. With Cr2O3 coating, however, the maximum SEY goes down to 2.25 and therefore the expectations are that the electron cloud, and hence pressure rise, will be considerably reduced. In addition lab measurements show that the SEY of the Cr2O3 coating conditions down to ~1.3. A set of Cr2O3 coated liners will be installed in the SPS, during the SYETS, for tests with beam. The plan, if the tests in the SPS go according to plan, is to get a ceramic tube coated by June next year and install it in an MKI to see if this is a viable solution.

ADT, OBS BOX
D. Valuch

M. Lamont recalled that the loss in integrated luminosity as computed by F. Antoniou due to noise is a few %, he wonders if it is worth investing the effort in solving this issue. Daniel answered that in any case they will be working to fix other problems and the noise will be part of the package. Y. Papaphilippou reminded that there is still an unknown and considerable emittance blow up from injection to stable beams that could be coming from there. W. Hofle explained that he calculated the loss of luminosity and seems to be compatible with the 2 um shown in Daniel’s.

B. Goddard asked if now that the ADT can provide with the same functionality as the AC dipole, both systems need to be maintained or we could shut down the AC dipole. R. Tomas answered that from optics measurements point of view it is important to have both systems since they cover different regimes in strength and frequency.

R. Tomas made the remark that he has the impression that the ADT is noisier than the AC dipole. Daniel answered that this is not possible because it is a digital processing and therefore free of noise by itself.
BEAM INSTRUMENTATION
G. Trad

J. Jowett asked if it is possible to re-calibrate BSTR data from the pPb run at 6.5 TeV for the fills where the wrong calibration was used. Georges answered that unfortunately it is not possible because a proper calibration with beam was not done. 6.5 TeV PbP is the only available data where a proper calibration with beam was carried out. However, relative differences can be used in any case.

M. Lamont asked if it is possible to reprocess the already existing data with new calibration values. Georges answered that yes, in fact the emittance plots shown by M. Hostettler where different measurements are compared over 2016 contained the re-processed data after fixing the calibration factors.

R. De Maria asked how it is possible to make compatible the changing crossing angle in case of luminosity levelling with this technique, with the DOROS feedback system. Georges answered that this needs to be assessed.

W. Kozanecki asked if the emittance plot shown by George contain the emittance reconstructed by the LHCb beam-gas vertex imaging or by the BGV. Georges commented that these are the online data as we get in the control room via DIP, but the off-line data also exist and it should be more precise.

RF
H. Timko

E. B. Holzer asked where the two events not caused by luminosity debris come from? Salvatore answered that may be they come from an orbit bump because the two events are much localised, but the source is not really known.

S. Redaelli commented that the TCL settings increases the losses but nevertheless they should remain in the shadow. We should understand, however, if something else has changed concerning failures in these regions. Salvatore answered that nothing has changed, the observed cross-sections match the expected ones in the RRs.

M. Lamont asked why the TCL are moving. S. Redaelli answered that TCLs go closer to the beam when the ROMAN POTs go in beam to protect them.

J. Jowett asked if it has been investigated why in the proton-lead run the losses in cell 8R1 and 8R5 where the reasons for the QPS failure. Salvatore answered that they have checked cell 9 not cell 8, but can be checked afterwards.

R. Schmidt asked why only the FGC-lites in the arcs would be installed during EYETS and not the ones giving problems in the RRs. D. Nisbet answered that the baseline is to exchange the RRs in LS2, but everything will be ready to do it in YETS 17/18 if needed. The exchanged of FGCs to FGC-lites in the RRs is more cumbersome than the ones in the arcs. Nevertheless, installing already the ones in the arcs will allow us to test the FGC-lite in operation. The reason why the FGC-lites are ready to be installed in the arcs and not in the RRs is that originally it was anticipated to have more problems in the arcs.

R. Alemany pointed out that the observation done during the talk concerning the possible improvement of the vacuum during 2016 is confirmed by the fact that in 2016 the beam-gas background is a factor two better than in 2015.

RADIATION TO ELECTRONICS
S. Danzeca

E. Jensen pointed out that the RF team wishes to have the full detuning option operational in 2016 to demonstrate its feasibility in view of HL-LHC where this is absolutely needed due to klystron power limitations.

S. Redaelli asked where the two events not caused by luminosity debris come from? Salvatore answered that may be they come from an orbit bump because the two events are much localised, but the source is not really known.

S. Redaelli commented that the TCL settings increases the losses but nevertheless they should remain in the shadow. We should understand, however, if something else has changed concerning failures in these regions. Salvatore answered that nothing has changed, the observed cross-sections match the expected ones in the RRs.

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R. Alemany pointed out that the observation done during the talk concerning the possible improvement of the vacuum during 2016 is confirmed by the fact that in 2016 the beam-gas background is a factor two better than in 2015.
SUMMARY OF SESSION 7: “MACHINE PROTECTION”

A. Apollonio, D. Valuch

Abstract
This session reviewed the relevant aspects related to machine protection during 2016 LHC operation, focusing on improvements with respect to previous runs and aspects/issues to be followed up in the future.

Machine protection during 2016 run and review of machine protection strategy (D. Wollmann)

- The 2016 intensity ramp-up was very efficient, requiring only two weeks to reach 1700 bunches. Two standard ramp-up scenarios have been identified and performed: one following minor hardware interventions, requiring 2 fills for intensity ramp-up, and one following major interventions, requiring instead 3-4 fills.
- Additional gain could obtained by redefining minimal scenarios for asynchronous dumps and loss maps. A clear distinction should be made between performance studies and machine protection tests.
- For MDs, the approach followed in 2016 was very efficient: a detailed procedure was developed and approved for each MD. Three classes defined the risk related to MDs, from A to C, C being the one with highest risk. Class C MDs require approval by rMPP.
- Any change in machine protection settings or systems require approval by MPP.

Discussion
- J. Wenninger pointed out that the MD procedures used to be written by the MD users together with the EIC who was foreseen to be on shift during the MD. This implied too many complications in the follow-up and the practice was dropped. G. Papotti added that it is nevertheless important to continue the preparation of the MDs with EICs, as it allows more efficient preparation of settings and filling schemes.
- J. Wenninger stated that the machine was so reproducible during the p-Pb run that he took the decision, after consulting a small number of people, not to go for any special validation before switching back to 4 Z TeV at the end of the Pb-p run. D. Wollmann agreed with the excellent reproducibility of the machine, but commented that as some collimator settings were changed, this decision might have been reviewed.

BLM thresholds and UFOs: summary of 2016 and outlook for 2017 (A. Lechner)

- In 2016 about 2000 BLM thresholds were changed for proton operation, 50 for ion operation.
- Applied thresholds are defined based on a master threshold (shared for all BLMs of the same family) and a monitor factor (can change individually for each BLM).
- Most changes were applied to avoid unnecessary dumps due to UFOs in the arcs and DSs.
- The conditioning observed on the UFO rate continued in 2016.
- 22 UFO-induced dumps were registered in 2015, over 700 h of stable beams; 21 events were registered in 2016 over 1800 h of stable beams, demonstrating the effectiveness of the applied strategy for BLM thresholds. In both years 3 UFO-induced quenches were observed, but the statistics are too low to make any extrapolation for future operation.
- If we would have applied a quench preventing strategy, we would have observed 71 UFO-induced dumps and still one quench (too fast to be prevented).
- In 5 cases in the LSS the beams were dumped by the Beam Condition Monitors. An optimization of the related thresholds should be studied.
- In 5 cases beams were dumped by a UFO in cell 5L1, which could be mitigated with a local adjustment of the thresholds.
- It was proposed to keep the same strategy as 2016, namely keeping arc thresholds a factor 3 above the quench levels.

Discussion
- J. Uythoven asked what would have been the gain (if any), of setting the BLM thresholds at 5x the quench levels, as at the moment they are at 3x the quench levels. A. Lechner answered that there would not have been any significant gain with a factor 5, a factor 3 seems to be the optimum.
- O. Bruning mentioned that there was a spike in the UFO rate after beam screen warm-up. A. Lechner confirmed this effect was observed, but already in the next fill the rate was in line with the usual values in the arcs.

LBDS (E. Carlier)

- All dump requests were properly executed by the LBDS in 2016, with no asynchronous beam dump.
- Operation in 2016 was more demanding for LBDS than for the 2015 run, due to the longer time operating at 6.5TeV. Despite this, the total LBDS downtime was lower in 2016 as compared to 2015.
Two MKBH self-triggers were observed, leading to synchronous dumps. The recovery from these events requires a generator exchange and a system revalidation (total of about 15 h). These issues will be addressed during the EYETS 2016-17.

The problem related to the MKBH retrigger line coupling, potentially leading to a simultaneous misfiring of three MKB kickers, has been solved during EYETS.

A local reliability run at 7 TeV will be performed during the EYETS 2016-2017 to re-assess the LBDS availability for 6.5 TeV operation and to re-evaluate the ability to go to 7 TeV.

A remote reliability run with local BIS loops is needed to revalidate the system at the end of the EYETS (featuring upgrades on MKBH generators, TSDS and CIBDS).

Standard Cold Checkout / Recommissioning with beam will be performed at the end of the EYETS.

**Discussion**

- P. Baudrenghien stated that due to the foreseen cavity phase modulation and full detuning running mode, the minimal length of the abort gap (or in general the beam gap) should be defined. What will be the longest gap in the filling scheme? E. Carlier answered that the abort gap itself should not be longer than 3us as from design. W. Hofle added that the last injected train should be as close to the abort gap as possible, in order to keep the beam gap short.

- R. Bruce asked what is the main reason for the very low rate of asynchronous beam dumps. E. Carlier answered that the abort gap itself should not be longer than 3us as from design. W. Hofle added that the last injected train should be as close to the abort gap as possible, in order to keep the beam gap short.

- J. Wenninger pointed out that alignment times are now at the level of ~6 hours. Now we spend much more time testing out functions than actually aligning collimators, so this calls for taking these parts into account for further optimisation. S. Redaelli confirmed that indeed, the setup is not driven anymore by the alignment time.

**QPS (J. Steckert)**

- The QPS system has reached its nominal configuration in 2016
- All quenches were detected correctly and the system exhibited more than 99 % average availability
- The QPS showed an excellent performance with respect to radiation-induced failures: during the proton run no faults were registered, two unconfirmed events were observed during the ion run
- Faults induced by massive upgrades of QPS in LS1 have decayed (cables & connectors, cards not properly inserted, etc.)

- YETS 2015-16 interventions significantly improved system availability
- No major changes to the QPS are foreseen prior to LS2, the challenge is shifted towards keeping and improving the excellent performance of 2016 in the future

**Discussion**

- M. Lamont asked about the zero crossing spikes – do they come with beam? J. Steckert answered that the spikes are not correlated with the beam, but occur during the ramp-down of the circuit and pre-cycles. M. Lamont asked if it is needed to have the zero crossing. D. Nisbet answered that it is needed, it is an inductive circuit.

- A. Apollonio commented that as we have reached the maturity of the system (i.e. a constant failure rate), more rare events are probably going to show-up and these will be driving the downtime. J. Steckert confirmed this is the case, the piquets will have to deal with more and more exotic failure scenarios.

**Collimation (A. Mereghetti)**

- A limited number of hardware and software upgrades of the collimation system was performed during the YETS 2015-16. Nevertheless, these were relevant for speeding up commissioning and set-up activities (e.g. RF trim for off-momentum loss maps and BPMs for fast alignment)
- The collimation system exhibited excellent reliability and reproducibility in operation
- Given the good orbit stability, a SIS interlock on BPM readouts at TCTs (and IR6 TCSP) can be proposed
- The installation of new hardware during the EYETS 2016-17 is especially relevant for MD activities in view of HL-LHC (e.g. low-impedance collimator prototype and two collimators with long-range beam-beam wire compensator).

**Discussion**

- J. Wenninger pointed out that alignment times are now at the level of ~6 hours. Now we spend much more time testing out functions than actually aligning collimators, so this calls for taking these parts into account for further optimisation. S. Redaelli confirmed that indeed, the setup is not driven anymore by the alignment time.
SUMMARY OF SESSION 8: “INCOMING”
M. Pojer and R. Tomas Garcia

EXPERIMENTS - EXPERIENCE AND FUTURE – JAMIE BOYD

Jamie congratulated the accelerator community for the great run in 2016.
In 2017 at pile-up up to 60 events per crossing will be acceptable. The preference is to run with BCMS for performance. There is a request from CT-PPS to improve their physics acceptance with an orbit bump, but this depends on the IP5 re-alignment strategy. In terms of special running conditions in Run-2, the experiments have requested an intermediate beta* run (likely to be scheduled in 2018) and a 5 TeV pp reference run (likely to be scheduled at the end of 2017).
For 2017 there are collection of wishes and requests:
- explore bunch lengths of 0.9ns
- a dedicated fill with higher pile-up by at least about 10% more than nominal
- measurements with zero crossing angle
The hypothesis to explain the luminosity imbalance is via the different horizontal and vertical emittances.
In 2017 one should define crossing angles with the actual beam emittances. This has the complication on how to determine emittance.
Jorg commented that the CTPPS bump with crossing angle leveling will require changing the bump and realigning the pots.
Enrico highlighted that the luminosity imbalance does not go to zero for zero crossing angle. ATLAS is going to recalibrate so the residual might become more important.
Witold confirms that indeed new analysis shows that the previous luminosity was overestimated by 3%.
Mike commented that there are 3 different emittance measurement methods that say beams got more round.
Jamie added that Z counting supports the luminosity imbalance. Gianluigi replied that hence the Z counting should be used on-line but Jamie argued that this is very hard.
Jamie added that with a crossing angle reduction early in the run experiments could improve luminosity calibration.

BEAMS FROM INJECTORS – HANNES BARTOSIK

The BCMS horizontal emittance is limited by blow-up at injection in the PS, probably due to a dispersion mismatch. The vertical emittance is blown-up in the PS cycle and this was cured in an MD via working point optimization.
The 200 ns MKP kicker gap was tested with 25 ns beam during LHC MDs.

Emittance and intensities of the different beams for 2017 are presented together with highest possible brilliance to be demonstrated in MDs.
Jamie asked about the roundness of the beams in the injectors. Hannes answered that the emittance measurement in the injectors probably has worse resolution than in the LHC. Emphasis could be put on this in 2017.
Mike asked Simone about dump status. Simone advised to wait until March since delivery of copper blocks is underway.
Elias proposed to test emittance exchange in the injectors via coupling and tune crossings.

FILLING SCHEMES AND E-CLOUD CONSTRAINTS – GIOVANNI IADAROLA

Giovanni presented an overview of the e-cloud experience and observations in 2015-2016. The normalized heat-load has reached a flat bottom with a very slow conditioning. Measurements during MDs show a steep dependence of heat-load versus bunch intensity. BCMS holds the best promise for operation in 2017.
He requests 7 days in 2017 for scrubbing.
Doublet beams will need machine developments plus longer period for scrubbing if successful.
Mirko asked whether we are opening the worst arc concerning e-cloud heat-load. Giovanni answered that it looks so, but, since we do not know the source of the heat-load arc-to-arc variation, we cannot predict the effect of opening the arc.

BETA* REACH FOR THE DIFFERENT SCENARIOS – RODERIK BRUCE

Roderik presented the beta* reach for nominal and ATS optics, based on 2016 MDs. Both optics can achieve the same beta* for 2017 in the range between 30-33 cm for a TCP gap of 5 sigmas.
Brennan asked for the loss in ATS beta* reach if we kept the same margins as in nominal. This would imply a beta* = 37 cm. On the other hand, using interlocks in the collimator BPMs, the beta* would recover the 30-33 cm range in ATS.
Jorg asked on the required setting, which is 1σ in the TCTs.
Stefano clarified that this setting would have generated zero dumps in 2016.
Jamie asked about the impact of having a horizontal CTTPS bump. Riccardo answered that the Totem bump does not impact the aperture in the triplet, but that we need to look at the combination of all bumps.
SCENARIOS FOR 2017 AND 2018 – YANNIS PAPAPHILIPPOU

Yannis presented the possible scenarios for 2017. The main assumptions are a target beta* = 31 cm, a crossing angle of 10 sigmas (eventually pushed to 9 sigmas) and the use of BCMS beams. ATS is the favored optics choice regarding the LHC and HL-LHC long-term performance. A flat optics could be operational in 2018.

Chiara mentioned that the heat load is very different between 288 and 144 bunches. Do we know that this is a limitation without testing it? For robustness 192 would be preferred. Giovanni clarified that for BCMS we are not so far from the limit and that with the BCMS there is hope, maybe, with a bit of conditioning.

Gianluigi explains that these are considerations for the start of operation in 2017. Additional conditioning is expected during the year. Triplet cryogenics will limit luminosity to 1.75e34/s/cm2.

Yannis was asked about the preference for ATS. He replied that ATS is the optics that will enhance machine performance in the near and long-term future, like HL-LHC. Brennan expressed disagreement and mentioned that there are two problems: CTPPS and margins in the asynchronous dump.

Jorg mentioned that another option would be to use ATS only in the pre-squeeze.

Jamie supported the importance of building experience for the future but asked to consider implementing ATS in 2018. Yannis replied that this could be a compromise approach.

EYETS RECOVERY – MATTEO SOLFAROLI

Matteo presented the training campaign which was carried out in sector 34 and 45 to try and reach 7 TeV. 20 quenches were done in S45 and 7 in S34, before stopping due to the appearance of a short to ground (solved by a capacitive discharge). The equivalent of 6.82 TeV were reached in S45.

He spoke then about the main interventions to be done during the EYETS and the strategy for the restart.

Oliver asked whether periodic radiographies of the metallic debris are done. Matteo confirmed that they were taken afterwards, but they are complicated because of no easy access.

Mike stressed on the fact that the two faulty points (the present one and the one of 2015) are close: is there any correlation? Mirko reminded that the first fault appeared in 2007, and it was in S45.

Enrico asked whether the 2 faults appeared in magnets belonging to the same producer. Mirko replied negatively.

RUN 3 AND HL-LHC – RICCARDO DE MARIA

Riccardo recalled the objective of Run III and HL-LHC (300 and 3000 fb⁻¹, in summary) and presented the transition parameters between Run II and HL-LHC.

Important tests could be done in the coming years to estimate the limits for the future: pile-up, e-cloud, beam-beam effects. It will be important to find the minimum crossing angle with a good lifetime and investigate the potential of flat telescopic optics, by pushing the performance of the ATS in MD. Other important areas to be studied are the improvement of stability of the orbit (also related to the instrumentation), the crab cavities potential and the possibility of pushing the RF to 16 MV in full detuning mode.

John stressed on the need for MDs for the ions, in particular to prove the feasibility of the 2ns-spaced ion bunches.

MACHINE DEVELOPMENT – JAN UYTHOVEN

The planning for the MDs in 2016 was presented by Jan, which foresaw 22 days in 4 blocks. In this amount of time, with an average availability of 84%, 56 MDs could be executed: the most relevant of them were highlighted by Jan.

An inventory of 85 MDs has been for the moment prepared for 2017, which would require 44 days (assuming the same efficiency as in 2016), plus 72 hours of end of fill studies. Unfortunately, only 15 days are presently allocated for MDs, which will require a prioritization, but also improved procedures for recovery and settings clean up.

Enrico stressed on the fact that the procedures should be improved in terms of preparation, since at the beginning of each MD there are a lot of things that are not working: filling scheme, beam not ready, etc.

Jamie suggested to try and limit the number of MDs at the beginning and possibly give more time at the end, according to the progression of data collection. If things go well, in fact, people from the experiments will be more available to free time for the MDs.
OPERATION OF A 6 BCHF COLLIDER: DO WE FIT THE EXPECTATIONS?
E. Bravin, CERN, Geneva, Switzerland

Abstract

The way a complex machinery is operated has a direct impact on the production efficiency. In the case of the Large Hadron Collider (LHC), which required huge efforts to design and build, it is of the utmost importance to assure an adequate operation quality. The exceptional results obtained in 2016 prove that all LHC systems and all teams, including the operation (OP), have reached an excellent maturity level. This presentation will review the present status of the operation, by highlighting areas where further improvements could be investigated.

INTRODUCTION

Operation constitutes a very important factor in particle accelerators. In fact, the efficiency at which a large complex like the LHC is exploited depends in large part on the quality of its operation.

Looking back at 2016 a number of facts has to be acknowledged. The end of YETS on March 4 marked the start of the powering tests that lasted till March 23. The first beam was injected on March 25 and two days later we already reached the end of squeeze.

On March 29 we started operating with nominal bunches and by April 23, that is less than a month later, we declared the first stable beams with 3 bunches per beam. On May 18 we were well advanced with the intensity ramp-up operating regularly with more than 1000 bunches per beam in physics production as it can be seen in Fig. 1.

Figure 1: Commissioning milestones for 2016.

Figure 2 shows how during the year we managed to deliver something of the order of 40 inverse femto barns, much more than the target of 25. Also the peak luminosity, shown in Fig. 3, reached the value of $1.4 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, that is 40% above design value, despite the various limitations like the SPS internal dump.

Figure 2: Production of p-p physics in 2016.

On the top of that we also had an intensive programme of proton-nucleus, with Pb-p and p-Pb collisions at different energies. We should also not forget the special forward physics Run, the LHC-i Run and the more than 60 MDs.

All this could be achieved thanks to the excellent availability of the LHC, in the order of 75%, and the direct consequence of spending about 50% of the available time in stable beams[1].

Figure 3: Peak luminosity in CMS and ATLAS vs. time for p-p physics in 2016.

From this we can already take a first conclusion. In 2016 the LHC surpassed the most optimistic expectations. If you now take into consideration the assioma that in any complex system the result can only be as good as the weakest link allows, we have to conclude that all systems, including operations, fulfilled the expectations.
But this immediately triggers the question: "how high should we set the bar for the future?"

POSSIBLE IMPROVEMENTS

Looking at the professional sports world, we can see how athletes after achieving great results do not sleep on their success. They keep on improving and over the years they surpass what seemed extraordinary results. With the LHC we should do the same as there are still margins for improvement.

And this triggers the next question: "how can we improve the operation even further?"

First of all, we need to clarify what operation is and what responsibilities it has.

The main tasks of operation are:

- To operate the various systems for a safe and efficient exploitation of the LHC.
- To document what is being done.
- To inform people outside the control room of what is going on.

OPERATION IN DETAIL

Operation is made of: people, tools, procedures, documentation and communication.

People

At the moment we have a competent and experienced operation crew. The engineer in charge and operators have often different backgrounds. This has positive sides as it helps cover all aspects of the machine, but it also has the downside that response to a given situation may be quite different, going against the common quality assurance criteria. Also, at the moment, there is a very steep learning curve for the new arrivals in the operation team as learning is done exclusively by shadowing and try and error. In 2008, at the start of the LHC, there was a lot of time to coach and learn, now there is much less as the pressure to produce physics is very strong. In addition, certain key knowledge is concentrated in few people introducing single point failure possibilities.

Tools

There is an impressive code base used to operate the LHC. We have a lot of specific tools, that is tools created with one particular purpose in mind, and we lack homogeneity between the different tools. The consequence is that the operators have to learn how to do similar things in several different ways. There are also a few generic tools. These are very powerful tools enabling many possibilities, but they also open the doors to mistakes. Take the FESA navigator as example, a must have tool for development, but to be avoided at all costs in operation, or EquipState another very dangerous tool. Sometimes unfortunately the generic tools are all that there is available for certain actions.

Another point to highlight is that the operation of the LHC could profit from having more intelligent tools, meaning tools in which the experts knowledge is fixed into the coding. This would be particularly useful for all the cases where an analysis is required, being it the decoding of a measurement or the deciphering of a failure.

Extending the documentation of the existing and future tools would also be of great benefit to operation.

What tools can we add? There are many time consuming cases for which human analysis is the only available tool in the moment, an example for all diagnosing injection problems. For this example a tool that could help the operators understand in a few seconds if the problem comes from losses in the transfer lines, from excessive/insufficient scraping in the SPS or from longitudinal losses would be very useful, as it would allow the concerned people to act on the relevant parameters.

A tool that diagnoses the injection mechanisms would also be very useful. We have many interlocking signals from different machines, we also have a complex timing and control infrastructure that synchronises the different rings during the injection phase. Having a self-diagnosing system that responds fast and indicates immediately what the problem is would be of great help.

One could extend this principle to most systems. Ad-hoc self-diagnostic tools would allow a faster response in case of problems or failures. They could help reducing the time needed to identify the right expert to call; with some failures this is not at all obvious.

Procedures

The operation team has well established procedures for all operation scenarios. Large part of these procedures are coded into the sequencer and the state machine. This part covers nearly 100% of the physics production tasks. On the other hand, for commissioning operations and MDs the procedures are mostly only embedded into the BiC and operators knowledge. This situation leads to frequent recurrent problems (ever heard of the safe beam flag forced false by mistake?) and introduces an additional human effect based on who is in shift, another clear problem of quality assurance.

Written procedures could help improving the situation and would have several benefits. First, it would preserve the present knowledge; secondly, it would share and consolidate the knowledge among the different people in the operation team, and lastly, it would act as the "LHC user manual" for the new arrivals.

Human mistakes

Mistakes are part of any human activity. In the operation of an accelerator we can have direct human mistakes, bugs inside the tool, new situations never seen before etc. Mistakes can happen and there is no way we can remove them entirely.
For 2016 there are 52 records of operational mistakes in the LHC fault tracking tool[2], documenting only the human errors. Most of these events are at injection, meaning that the time lost is relatively small, nevertheless they testify how relying on personal knowledge and experience is not sufficient.

A few examples to illustrate the situation: during the ion run at the end of 2016 there are 4 events where the operator turned on accidentally the injection cleaning, leading to a beam dump, where the operational procedure was clearly to leave it off, or other cases where the tune or orbit were trimmed with the feedbacks on. More severe are the cases where the safe beam flag was forced to false during MDs, deactivating all the masks on the interlocks leading to beam dumps later in the cycle, often compromising the whole MD or commissioning cycle. Similarly, there are cases where it was forgotten to mask certain interlocks leading again to major loss of time.

Communication

Communication is a key aspect of operation. The tools and structure for an effective documentation and communication are in place but not always optimised or properly used. We should improve the communication between the machines coordinators and the operation crew, by having clear written instructions on the programme of the day with an outlook on the following days. We can also improve the communication between shifts: the shift handover is often not complete, based only on the short-term memories of the outgoing crew. After a long shift people are tired and may forget to pass over important information. There should be a systematic preparation for the shift handover, with written notes, during the dead times in operations, "consignes" should be entered in the logbook in the corresponding area.

The use of the logbook can also be improved. There are lot of screenshots in the logbook but these often lack the comment that would make them much more useful. A systematic reediting of the logbook entries during the dead time would improve the situation. To complicate even more the situation of the logbook we have dozens of automatic entries, making the reading unnecessarily complicated by diluting the important information inside a lot of non-relevant information. One option would be to store the automatic entries into a separate logbook or allow to disable them in the normal logbook viewers. We can also improve the use of the vistors by updating them regularly, making sure that people outside the control room understand what is going on and what is the programme for the coming hours. It is indeed not uncommon to still read on page one "preparing for injection" many hours after stable beams have been declared.

Parallel activities

All engineers in charge and operators have other activities beside the operation shifts, what is often referred to as the second job, with some not only having a second job but also a third, fourth or fifth job. However, it is important to ensure that during a shift operation is the main activity. All other activities done in parallel during a shift can only be accepted if these do not have negative impact on the operation. It is of course very difficult to draw a line on what is allowed and what should be avoided. The limit should however come as part of the professionalism and conscience of the people in shift.

THE CONTROL ROOM

Another important point in the operation of the accelerators is the control room (CCC). The control room and the people that occupy it constitutes a complex ecosystem. The main purpose of the control room is to provide a place to operate the accelerators together with the relative infrastructure. the CCC is, however, also used as: office space, meeting place, visitor centre and also as chatting place.

The frequent and varied frequentations of the CCC help the communication between people and help keeping everyone better informed of the situation, but this also dilutes the concentration of the shift crews leading to more mistakes or misunderstandings.

CONCLUSIONS

The 2016 results indicate that the operation of the LHC fulfills expectations at least as well as any other system of the LHC, but there are still margins for improvement and it is of particular importance to consolidate the high point that has been reached.

Fixing the present knowledge and expertise into documents and procedures is of paramount importance, in particular because of the continuous turnover of people and the need for faster and more effective learning tools than the shadowing method presently used.

Additionally, the communication inside the control room, between islands and between crews, and outside of the control room, between OP and other groups and experiments, can and has to be improved.

REFERENCES

LHC availability and outlook
LHC INJECTION


Abstract

Losses at injection will be distinguished between the two main loss causes, transverse loss shower from the transfer line collimators and longitudinal loss shower due to satellites which are placed on the kicker field rise and thus improperly kicked into the machine. The dependence of these losses on the different beam types, TL stability and injector performance will be reviewed. A status and potential improvements of the injection quality diagnostics and new values for the SPS and LHC injection kicker rise times will be suggested.

INJECTION LOSSES

Injection losses during run 1 were dominated by showers from the transfer lines T1 2 and T1 8 onto the ring beam loss monitors (BLM) of the matching regions in P2 and P8, Fig. 1. These showers were originating from the transfer line collimators (TCDI) and impacting the ionization chambers in the tunnel area common to ring and transfer lines from the outside, without attenuation from the cryostat. This loss scenario was mitigated by installation of additional shielding, opening the TCDI from 4.5 to 5 σ and by stabilising the transfer line trajectory with filters on the SPS extraction septa power converters. In addition, a temporary inhibit of the interlock input from the BLM system was developed. This inhibit possibility is implemented but remains to be fully validated with trains of 288 bunches, which were never injected in Run 2.

Since Long Shutdown 1 (LS1), the injection losses were dominated by particles which were outside the nominal filling pattern and therefore filling the gaps used for the SPS extraction and LHC injection kickers to rise and fall their magnetic fields. The particles in these gaps were sprayed on protection devices at SPS extraction (TPSG), in the transfer line (TCDI), onto the injection dump (TDI), and onto the collimators in P7. These losses can be well distinguished with the help of diamond detectors, Fig. 2.

Injection losses in 2016

The high intensity proton operation in 2016 can be separated in two periods. The first period until September is characterized by swapping between different beam types or machine configurations of which both have significant impact on injection loss levels. In the second period from September until the ion run a stable period of luminosity production with low injection loss levels was observed which allows to estimate loss levels for 2017. Transverse injection losses do not vary significantly during 2016 and the median loss level over the injection region is below 2% of the dump threshold. Also the maximum loss levels which are a factor 2-3 above the median provided a comfortable loss level to inject the beam. This was mainly due to the improved line stability and a trajectory reference which allowed for straightforward steering by the operators. The transverse

Figure 1: Injection losses in 2012 (top) were dominated by transverse showers, the losses in 2016 (bottom) by longitudinal losses on the TDI.

Figure 2: Injection losses as measured by the diamond detectors and kicker waveforms schematically.
losses scale linearly with the total injected beam intensity, thus there are no issues expected with injection of 288 bunch trains from the SPS.

The longitudinal losses were much more sensitive to changes in beam types or machine configuration. Figure 4 shows the high loss level of up to 50-60% of dump threshold for the median for the period when changing from standard to BCMS beam and again after reducing the MKI flatop length. Such a high median level resulted in several beam dumps at injection when the beam quality was only slightly deteriorating. In order to maintain a high availability at injection, the loss levels should be below 20% of the dump threshold. A significant improvement of these loss levels was reached by improving the transfer from the PS to the SPS where a bunch rotation at PS extraction is required to reduce the bunch length from about 11 ns to 4 ns to fit into the 200 MHz rf structure of the SPS. Deployment of a second 40 MHz cavity during the bunch rotation improved the PS to SPS transfer such that losses at LHC injection were reduced by a factor 10.

The second period of the year from September until the end of the Run showed a remarkable stability at low loss levels during injection, see Fig. 5. Only the ion Run has strikingly high losses given the low intensity during the transfer of 28 bunches. The ion Run setup suffered from several machine problems and therefore setup time was reduced which explains the poor injection performance compared to the high intensity proton Run. While the absolute loss levels during the ion Run were acceptable with median loss levels below 5%, the spread in loss levels between good and bad injections was much higher than for the late proton Run. While the maximum losses for protons were a factor 2-3 above the median, the ion losses even caused several dumps at injection. Both, the proton and ion Run show that it requires a phase of several fills until beam parameters at LHC injection are tuned and stable.

*Injection quality check*

The injection quality check tool IQC has become an orphan in the control room and was rarely used by the operators. Most likely this is caused by two problems. First, the tool is not maintained since LS1 and therefore adapting of internal
is not the cause because the orbit position at SPS extraction is very stable over several hours, Fig. 6. So in order to minimize the waiting time for beam while LHC is ready, it is suggested to automatize the preparation of the LHC in the injectors as soon as LHC starts its ramp down. In the injectors there could be an automatic fall-back to a prepared supercycle for LHC filling. A disadvantage is that several supercycle templates have to be maintained in parallel. The automatization should have almost no impact on non-LHC physics program compared to a dedicated LHC filling cycle. There is most likely some impact on MD programs in the injectors in case LHC is not ready for injection as expected. Daily tuning of the LHC beams is very valuable and lead to impressive beam quality at SPS extraction. This daily tuning is supported by a continuous improvement of beam quality monitoring in the injectors which should help for automatizing the LHC beam preparation process.

**SPS AND LHC BATCH SPACINGS**

![Figure 7: Intensity along the batch for 200 ns batch spacing without damper (top) and with damper (bottom).](image)

**INJECTION PROCESS**

Time spent at injection energy of LHC is a significant contributor to the turn-around-time. Stability of the injectors thresholds to beam types did not happen. This caused the monitoring tool to be on red alert for too many cases and it got ignored. The second problem is that too much information is displayed.

As improvement it was suggested to simplify the internal thresholds and raise the level for red alert to become meaningful again. Transverse loss scaling can remain as it is, longitudinal thresholds should be adapted at the TDI to show green for losses less than 30% of dump threshold, orange between 30% and 50%, and red above 50%. If the loss level is above 50%, operation should be focused to solve the cause of this loss level. The triplet magnets in the shower of the TDI should have colour limits of 10% between green and orange, and 25% between orange and red. Also, an overall reduction of the displayed information is suggested. These improvements are pending implementation by the operations group.

The above mentioned diamond loss monitors showed to be very useful in detecting where losses are caused, Fig. 2. During the development phase of these devices, their maintenance became very diverse over different groups. At this stage their functionality is mature enough to be added into online monitoring tools as already done in the SPS. It is suggested to also add a diamond tab in the IQC.
The batch spacings for the SPS and LHC injection kickers have both been reduced for the ion Run after performance measurements. The SPS batch spacing was first increased from the nominal 225 ns to 250 ns after load balancing between the different units of the injection kicker hardware which lead to a possible increase of the rise time. Tuning the timing of each unit allowed finally to reduce the batch spacing to 200 ns with an acceptable effect on the beam quality.

In Fig. 7, the intensity loss of the first and last bunch of a batch is shown. Without damper this lead to an intensity loss of 25% while this effect is barely visible with the transverse damper working. The drawback of a 200 ns batch spacing is the higher sensitivity to synchronisation drifts of the injection kicker switches. This might require regular tuning in the SPS, which is however transparent to LHC beam time. The minimum required batch spacing in the LHC was measured with low intensity bunches and bunch trains, observing injection oscillations and emittance growth.

By reducing the batch spacing from the nominal 900 ns to 800 ns increased injection oscillations for the last and first bunches of a train can be measured, Fig. 8. The growth of the emittance of these bunches is however well within the variation along a batch.

**CONCLUSIONS**

During Run 2 injection losses were dominated by satellites being kicked onto the injection dump. These loss levels were reduced by a factor 10 by improving the PS to SPS transfer. After this improvement, the proton operation showed a very good loss performance at injection. There are no issues expected with injection of 288 bunches. Ion Run losses were high compared to the proton Run given the low intensities injected. This is mostly due to the limited time spent during setup.

The injection quality check identified the various loss scenarios but requires updates on its thresholds to be less sensitive and also to reduce its visual over-stimulation. Diamond loss detectors are ready to migrate from being only available for experts to be included in the injection quality check application.

In order to reduce the idle time at injection it is suggested to fully automatize the LHC beam preparation in the injectors.

Batch spacings of 200ns for the SPS and 800 ns for the LHC injection kickers have been fully validated and should be deployed in 2017.
Turnaround - Analysis and possible Improvements

K. Fuchsberger

Abstract

This paper will present data of turnaround times during the previous run, give some insights in the distribution and try to spot different bottlenecks. The impact of the turnaround time on the optimal fill length will be shown and different contributing factors to the turnaround itself will be discussed. The final goal is to identify areas of improvements and give concrete proposals, based on data presented.

INTRODUCTION

When talking about the turnaround in the Large Hadron Collider (LHC), then we usually define this as the period between the end of stable beams of one fill until the start of stable beams of the subsequent fill. This is illustrated in Fig. 1.

![Figure 1: Definition of the turnaround during an LHC Cycle: Time between end of stable beams of one fill and start of stable beams of the subsequent fill.](image)

Since the turnaround is the only time (during standard operational periods) which is lost for physics production, there is a high motivation to keep it as short as possible. Unfortunately, at the same time, the turnaround is the least reproducible period of operation, because of many manual steps to be done by the operators and the strong dependence on external systems (injector chain).

In the attempt to gain more detailed insights, the following sources of information were used for this paper:

- Full dataset of faults, extracted from the Accelerator Fault Tracking System (AFT),
- Excel sheet, compiled and manually filtered and compiled from the full AFT dataset by A. Apollonio,
- Timing events extracted from the CERN Accelerator Logging Service (CALS),
- All Shift data extracted from the LHC Logbook.

After having these datasets available, the temptation was high to combine all of it. It turned out to be a challenge to get speaking results out of it, as described in the following sections.

A FIRST GLANCE

As a starting point, Fig. 2 shows the turnaround durations throughout the year 2016. Already from this it is visible that some of the turnarounds show very high numbers. This comes from different special periods with no stable beams (e.g., technical stops, MDs, etc.). In the plot these periods are shown with a white background, while the physics periods are marked with a green background.

![Figure 2: A first glance on the turnaround durations throughout the year 2016. The numbers indicate the fill numbers of notably long turnaround durations. Green background indicates physics production periods, white background indicates other periods.](image)

To make more sense out of this data, we apply the same strategy as applied in [1, 2] and exclude the following datasets:

- Faults longer than 24 hours.
- Fills following accelerator mode changes, which therefore have no associated turnaround:
  - Following the Restart (#4851, #4874)
  - Following Technical Stops (#5005, #5330)
  - Following Special Physics Commissioning (#5024, #5068, #5251, #5287)
  - Following Ion Cycle Commissioning (#5437)
TURNAROUND PHASES

This section summarizes some more detailed analysis of individual phases of the turnaround, highlighting potential problems.

Dump vs. End of Stable Beams

As the turnaround is defined as the time from end of stable beams to start of the next stable beams and some of the following analysis is based on beam mode changes, the first aspect to look at is the relation between the actual dump time and the first beam mode change in the turnaround (STABLE BEAMS $\rightarrow$ BEAM DUMP). Since this time in some sense (at least in the case of protection dumps) corresponds to a reaction time of the operations crew to the dump event, we will in the following denote it as such.

Figure 5 shows the distribution of these reaction times in the case of protection dumps and Table 2 shows the corresponding statistics results.

![Figure 5: Reaction times (times between dump and beam mode change) for protection dumps.](image)

<table>
<thead>
<tr>
<th>Min</th>
<th>Median</th>
<th>Mean</th>
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<tr>
<td>0.7 min</td>
<td>2.2 min</td>
<td>3.6 min</td>
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</table>

Table 2: Statistic results of the reaction times for protection dumps.

In an attempt to identify potential impacts of daytime on such reaction times, those times are plotted against the time of the day in Fig. 6. However no evident trend could be deduced from this analysis. The same analysis was done for the reaction times for dumps which were not protection dumps, but programmed dumps. Despite there is no strong technical reason to have delays in this case, there can be some observed. These delays are due to the current operational practice which is used in this situation, were some sequences have to be run after the actual dump event to

![Figure 3: Turnaroud durations after filtering out faults longer than 24 hours and turnaround after accelerator mode changes.](image)

Figure 3: Turnaround durations after filtering out faults longer than 24 hours and turnaround after accelerator mode changes.

![Figure 4: Histogram of turnaround times after filtering. The green line indicates the median, the red line shows the mean.](image)

Figure 4: Histogram of turnaround times after filtering. The green line indicates the median, the red line shows the mean.
switch the beam mode from Stable Beams to Beam Dump. Nevertheless, the delays are clearly smaller than in the protection case, as expected. This is illustrated in Fig. 7 and Fig. 8 and summarized in Table 3.

<table>
<thead>
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<th>Min</th>
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<tr>
<td>0.1 min</td>
<td>0.7 min</td>
<td>0.9 min</td>
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Table 3: Reaction times for programmed dumps.

**Dump to Start of Rampdown**

The next phase to consider is the time between the actual dump and the start of the rampdown. The main factor of this delay is again that some sequences have to be executed in between. Amongst others, the currents of the power converters are driven to the start of the rampdown cycle. This process also dominates the minimal time required. The corresponding distribution is shown in Fig. 9 and the statistical results are shown in Table 4.

<table>
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<th>Min</th>
<th>Median</th>
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<tr>
<td>5.6 min</td>
<td>8.8 min</td>
<td>10 min</td>
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Table 4: Statistical Results for times between dump time and start of rampdown.
Start of Rampdown to End of Rampdown

This phase has always the same length: Exactly 21 minutes. This is simply due to the fact that there is no manual action to do in between. The rampdown is started with a timing event and then executed by the power converters.

Pre-Injection phase

As this phase, we consider the time between the end of the rampdown and the time of the first injection. The first part of it is taken up by several individual magnets, (e.g. the triplet magnets) which do not do a function-driven rampdown like e.g. the main magnets, but are switched to openloop at the start of the rampdown and take longer to reach their standby current. This is illustrated in Fig 10: The first vertical marker indicates the time when the main bends reach their standby current and the second one the time when the triplets reach it. The amount of time the

Figure 10: The triplets reach their standby current slower than the main magnets.

slowest magnet takes longer than the main bends, is about 11 min.

The rest of the preinjection phase is completely fault dominated (which is natural, because this is the phase at which the operations crew usually waits until all problems (e.g. in the injectors) are sorted out. This way the risk of required precycles is minimized).

Clean Turnarounds

Despite several tries to subtract recorded fault times from the preinjection phase and deduce meaningful statistics, none of them proved to provide reliable results. Therefore, the only means to determine potential operational margins for time reduction, was to fall back to restricting the following analysis to “clean turnarounds”. By “clean turnarounds” we denote turnarounds with the following properties:

- No gap in fill-numbers
- No faults during the full turnaround
- No precycle between the fills
- No end of fill MDs

Applying these criteria, 14 turnarounds fall into this category. All of them intrinsically follow a programmed dump, because any protection dump is considered automatically as fault by the fault tracking tool. The distribution of the length of such turnarounds is shown in Fig. 11 and the statistical results are given in Table 5.

Figure 11: Distribution of durations of clean turnarounds.

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<tr>
<th>Min</th>
<th>Median</th>
<th>Mean</th>
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<tr>
<td>2.5 h</td>
<td>2.67 h</td>
<td>2.74 h</td>
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Table 5: Statistical Results for durations of clean turnarounds.

Taking into account only these clean turnarounds, then a more representative figure for the pre-injection durations can be given, as illustrated in Fig. 12 and Table 6. So the currently minimal achievable duration for this phase is about 15 minutes, out of which about 11 minutes can be accounted to the abovementioned end of the rampdown of some power converters.

<table>
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<th>Min</th>
<th>Median</th>
<th>Mean</th>
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<tbody>
<tr>
<td>15 min</td>
<td>19 min</td>
<td>21 min</td>
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Table 6: Statistical Results for preinjection durations, taking into account only clean turnarounds.

Injection

Also the injection phase is very fault dominated. Therefore it also makes sense in this case to look only at clean turnarounds. Since more details and durations of phases with beam are covered in [3], we will focus here only on a simple estimation of the efficiency of the filling phase of the LHC. Each time before filling, pilot beams are injected into the LHC. To keep the following simple, we consider
the filling phase as the time between the third injection and the last injection, which is mostly correct, especially in the considered cases (of clean turnarounds).

Figure 13 shows a comparison (for clean turnarounds) of the required number of injections (blue dots), the received injection events (green crosses) and the number of injections which could have been done more in the time spent (red crosses) - denoted as "missed injections" in the following. The statistical values for those missed injections, are summarized in Table 7.

Comparing these numbers to the 50 injections required for a standard physics fill in 2016, it turns out that about every 3rd injection was missed. In other words, we spent about 50% more time while filling than necessary.

Table 7: Statistical Results for "Number of missed injections".

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<th>Min</th>
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<th>Mean</th>
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<tr>
<td>5</td>
<td>17</td>
<td>25</td>
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The reasons why injections are missed can vary a lot. Examples are:

- The injection request is rejected by the CBCM,
- an interlock appeared,
- or the injection was blocked by the SPS BQM (Beam Quality Monitor).

Unfortunately, the root causes are currently not tracked in enough detail. Therefore, more detailed conclusions are practically impossible for the moment.

To improve this situation, a new diagnostics tool [4] is under development and is hoped to record more detailed information, starting after the coming EYETS (End of Year Technical Stop). It is based on a simple Domain Specific Language to describe different conditions. Both, the input values of these conditions and their result will be logged, so that it can be postprocessed for analysis in detail. Figure 14 shows a screenshot of the online GUI of this new filling diagnostics tool. Each line presents one assertion (condition).

Figure 14: Screenshot of the newly developed system for filling diagnostics, which is supposed to provide more detailed insights in 2017.

**PRECYCLE**

Another relevant part of the turnaround is the magnetic precycle. It is executed each time something goes wrong in a cycle which would have a relevant impact on the quality of the magnetic field. The precycle guarantees reproducible initial condition at the start of a cycle.

The precycling strategy was changed in June 2016 (fill 5000 onwards) from cycling the whole machine to a current in the main bends equivalent of 6.5 TeV to a current
equivalent to 3.5 TeV only. This way, the duration could be reduced from 1 h down to 35 min.

![Figure 15: Time spent for precycling, grouped by fill.](image)

Figure 15 shows all the executed precycles in 2016 and their length. In total 64 precycles were executed, 53 of them being short ones. This corresponds to a gain of 21 hours compared to a situation if the original strategy would have been kept. The cost of the change was estimated to about 8 hours of commissioning.

**Can we do better?**

The main constraining components which prevent the precycle from being shortened more, are several independently powered quadrupoles (IPQs). Currently, the slowest one (RQ4.R2) takes about 5 minutes longer to reach its standby current than the main bends, as illustrated in Fig. 16. If this could be shortened, about 5 hours of cycling time could be gained for the next run (assuming a similar number of precycles than in 2016). Such a change could be implemented without significant commissioning time, as the tune decay could be measured parasitically.

![Figure 16: End of precycle. The plot shows the current for the main bends (yellow) and the current for the currently slowest magnet in the precycle, RQ4.R2 (blue), which takes about 5 min more to reach standby than the main bends.](image)

Shortening the precycle even further, would require changes in the cycle of the main bending magnets (RBs). From the field quality point of view, the lowest meaningful flat-top value would be a current equivalent to 2 TeV of beam energy. This would safe about 8.5 min per cycle, which corresponds to about 9 h over the full year. However, this option would require further discussions before being implemented, because it comes with a significant commissioning cost to re-quality the field quality and e.g. re-measure chromaticity along the cycle. The required time is estimated to about 2 shifts (16 h).

**SUMMARY**

Summing up the mean values of the phases discussed in the previous sections and taken from [3], results in 3.0 h, while the sum of the minimal values gives 2.2 h. The fastest turnaround in 2016 (2.5 h) is quite close to this number, which basically represents the absolute minimal operationally achievable time at the moment (without significant changes in the process). The average values of the individual phases of the turnaround, together with the corresponding minimal values (in brackets) are summarized in Fig. 17 (with some numbers quoted from [3]).

From this, the biggest potential gains and possible improvements can be identified as:

- **Injection Probe** (potential gain of 15 min): During this phase, the parameters of the machine are corrected. Common principles could help here to correct just enough but not more: E.g. Which coupling to correct and which better to leave?

- **Injection Physics** (potential gain of 11 min): Faster diagnostic tools could help to identify problems quicker when the beam does not come; Also common principles could help again: E.g. When to correct the Transferlines, when not?

- **Adjust** (potential gain of 8 min): Do we need to optimize before stable beams?

Using the numbers derived in the previous sections (Median 5.2 h; Average 7.1 h) and relating them to the optimal fill-length, using the same approach as in [5], then an optimal fill length of about 13 to 17 hours can be expected. This is illustrated in Fig. 18.

For the precycle, two potential options are available, both with a moderate gain which have to be weighted against the required commissioning times.

**ACKNOWLEDGEMENTS**

The author would like to thank A. Apollonio, L. Ponce and B. Todd for all their continuous work they do within the availability working group, including digging into all the data, cleaning it and discussing issues with all the equipment groups. A special thanks to all the people from the AFB group who worked on compiling a very useful set of python analysis scripts (including pytimber), as well as M. Hostettler who helped me a lot to get started (again) with python data analysis. Finally, I would like to thank D. Nisbeth, M. Sofaroli and all colleagues from the OP-LHC section for all the discussions and their input.
Figure 17: Average lengths of the individual phases of the turnarounds and the corresponding minimal values (in brackets) for 2016. Numbers for phases with beam taken from [3].

Figure 18: Turnaround times between 5 and 7 hours result in an optimal fill length between 13 and 17 hours.

REFERENCES


Abstract

The LHC 2016 proton beam cycles will be analysed, and proposals for improvements will be made based on the results. Some other suggestions are proposed for reducing the beam cycle time, for example modifying the combined ramp and squeeze, and their effects quantified. The objective is to present a synthesis of quantified potential improvements as a basis for further discussion.

INTRODUCTION

This paper looks only at the modes where beam is present. As such this excludes the determination of turnaround time, which is treated separately [1,2,3]. In 2016 a total of 178 fills reached Stable Beams.

Method

The analysis presented in this paper references only proton fills used for physics (containing Stable Beams mode). In 2016 this was almost exclusively with 25 ns fills. The determination of the moment when moving from one phase to the next is obtained by analysing when the beam mode is changed, according to the timestamps stored in the logging database. Beam modes are set by the LHC sequencer and thus this allows a good method reproducibility.

Further notes on the choice of beam modes are referenced in [4], explaining why some modes are not considered.

For each phase of the cycle the average time was calculated. In order to reduce the dependency on the tail of the distributions, which is mostly representative of problems and special fills rather than standard operation; the median value was also computed. By removing the tails, the median tends to remove the effect of the exceptional events to give a value which is representative of typical day-to-day operation.

THE 2016 LHC NOMINAL CYCLE

2016 v 2015

Several changes were introduced to the nominal cycle in 2016 compared to 2015. In particular the squeeze beam process, where the Beta* is changed to the physics value, was partly moved into the ramp, thus the ramp is now a ‘Combined Ramp and Squeeze’ (CRS). Previously the Beta* at IP1 and 5 was set to 10m until the start of the squeeze, however with the CRS the Beta* at the end of the ramp is 3m.

Although the CRS saved a significant fraction of the squeeze time, the Beta* in 2016 was chosen to be 40cm, whereas a value of 80cm was used in 2015. The luminosity

potential thus benefitted significantly, however the total squeeze beam process time to achieve the new Beta* target had to be increased to a similar length as used in 2015.

Finally during the Adjust beam mode, an additional beam process was necessary to implement an orbit bump close to the TOTEM roman pots, to meet the experiment request for adequate dispersion.

Table 1: Average time of beam modes in 2015 and 2016

<table>
<thead>
<tr>
<th>Mode</th>
<th>Average 2015</th>
<th>Average 2016</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection</td>
<td>72 min</td>
<td>65.6 min</td>
<td>-6.4 min</td>
</tr>
<tr>
<td>Prepare</td>
<td>10 min</td>
<td>4.9 min</td>
<td>-5.1 min</td>
</tr>
<tr>
<td>Ramp</td>
<td>20 min</td>
<td>20.5 min</td>
<td>+0.5 min</td>
</tr>
<tr>
<td>Flattop</td>
<td>5.9 min</td>
<td>5.6 min</td>
<td>-0.3 min</td>
</tr>
<tr>
<td>Squeeze</td>
<td>15.7 min</td>
<td>18.1 min</td>
<td>+2.4 min</td>
</tr>
<tr>
<td>Adjust</td>
<td>13.7 min</td>
<td>16.1 min</td>
<td>+2.4 min</td>
</tr>
<tr>
<td>Stable</td>
<td>5.7 hrs</td>
<td>10.0 hrs</td>
<td>+4.3 hrs</td>
</tr>
<tr>
<td>Total</td>
<td>137.3 min</td>
<td>129.0 min</td>
<td>-6.5 min</td>
</tr>
</tbody>
</table>

Injection

The injection phase is the most intensive phase of the LHC cycle, with several manual actions performed and many factors that may have an impact on its length.

The injection phase is divided into two distinct phases: the setup of the machine with pilot beam intensity, and the setup and injection of the physics beam.

The pilot phase should be reproducible as the same actions are performed each time. Typically the correction of the orbit, RF phase, tune, chromaticity and coupling. However the total time is heavily influenced by machine availability, as demonstrated by the difference between the mean time of 23.5 min and the median time of 14.6 min.

The physics phase is prone to more variability, depending on whether the transfer line trajectory requires correction (necessitating additional 12b trains, followed by dumping and starting to fill again), and also the number and length of trains being injected. The availability of beam from the injectors, and intensity of the circulating beam, also has a significant influence. By considering all fills reaching stable beams, a mean time of 39.2 min is achieved, and a median of 37.0 min. However this included many fills during the intensity ramp up which have fewer injections. By considering fills of more than 2000 bunches, the mean increases to 42.1min, for a median of 37.8 min.

Two important situations present throughout most of 2016 influence the injection time: the status of the injection kicker vacuum (MKI8) [5], and the limitations of the SPS dump [6]. The Injection Kicker had a direct influence on the peak intensity permitted in B2, as injecting a proton current of more than ~2.4e14 would cause a pressure rise to exceed the interlock level, preventing further injections.
The SPS dump limitation limited the maximum length of the trains to 96 bunches (compared to the theoretical maximum of 288b), thus imposing an increase in the number of injections to reach a given total bunch count.

Considering injection of both the pilot and physics beams of more than 2000b, the average time in 2016 was 65.6 min, with a median of 52.4 min. Further details are discussed in [7].

Prepare Ramp

This beam mode is declared when the injection process is completed and some operations, such as change of feedback reference, settings incorporation and loading are done to prepare for the energy ramp. This phase is well reproducible and the distribution is quite narrow with an average of 4.9 min and a median of 4.2 min. In seven cases the beam mode lasted more than 10 minutes, and all can be attributed to problem solving, with no particular pattern identifiable.

Ramp

The beam mode Ramp is declared right before the timing event is launched and terminates once arrived at flattop. For this reason the time distribution is extremely sharp and the average (20.5 min) and the median (20.4 min) are very close to each other and to the settings length (1210 s).

Flattop

Once the energy ramp is completed the Flattop beam mode is declared for performing some actions (feedback reference change, settings incorporation and loading) to prepare for the squeeze; the tune change into collision tunes is also performed. The distribution has an average of 5.6 min with a median of 4.2 min. In six cases the beam mode lasted more than 15 min, all attributed to planned studies and measurements.

Squeeze

The distribution of Squeeze reflects the settings length, as this beam mode is set just for their execution. The average is 18.1 min while the median is 18.0 min.

Adjust

The Adjust beam mode is the phase when the beams are brought into collisions. This phase consists of two parts as the high and low luminosity regions are treated separately. Once the collisions are established, the luminosity is optimized and the orbit feedback with reduced gain is switched on. The following beam mode (Stable Beams) is declared sometime during the last manual actions (so ending this beam mode), with an average time of 16.1 min and a median of 14.1 min. The increased time compared to 2015 reflects the addition of a beam process to insert a bump to the right of CMS, increasing the dispersion for the TOTEM Roman Pot experiment.

Figure 1: Histogram of time in injection physics beam mode (where more than 2000b are injected)

Figure 2: Histogram of time in prepare ramp beam mode

Figure 3: Histogram of time in the flattop beam mode

Figure 4: Histogram of time in the adjust beam mode (with 15 end of fill machine studies removed)
The computed values are found after removing 15 End of Fill Machine Development periods, where the beam mode was put back to Adjust following a physics run to allow some specific measurements to be made.

A total of seven instances of the beam mode lasted more than 30 min. No particular pattern can be identified as to the source of the delays. The longest times are attributed to resolving a BPM issue and also to finding collisions in CMS (due to triplet movement).

**Stable Beams**

The time in Stable Beams is found to be 10.0 hours on average, with a median of 8.2 hours.

The termination of a period in stable beams is either by a deliberate operator action (programmed dump) or by an unforeseen event inducing a beam dump (typically resulting in an early termination of the fill).

The reason for a programmed dump in the early weeks is due to the desired machine protection objective being achieved and thus the desire to move to higher intensities. As intensities stabilised in the machine, the reason for a programmed dump is to obtain optimum luminosity production. Taking into consideration the average turnaround times, for standard emittance beams the optimum time for luminosity production was ~24 hours. This time reduced to ~18 hours when the beam production mode moved to Bunch Compression Merging and Splitting (BCMS) beams in July.

The average and mean figures include all data, independent of the reason for terminating the stable beam mode. A significant improvement on 2015 can be seen, principally due to the primary objective of luminosity production in 2016, whereas in 2015 the objective was to explore the machine operating envelope.

Another aspect to be explored further is the collision of all IPs simultaneously. Currently the high luminosity IPs are brought into collision before the levelled IPs to allow additional degrees of freedom, however this could be optimised. Should the orbit bump be again required for the TO-TEM experiment, it may be of interest to also include this beam process as an additional step in the squeeze, and not as a separate task.

Incremental time gains are also possible by focusing on the many small steps to bring the beams from injection to collision. As an example, some sequencer tasks could be made more in parallel, such as loading settings to different equipment groups (perhaps requiring some additional development).

**CONCLUSION**

When comparing performance in 2016 with 2015, on average the total time required to inject, accelerate and collide the LHC beams has been reduced by 6.5 min. This is an excellent performance considering the additional challenges such as lower Beta*, and the limited length of trains that could be injected (thus requiring additional injections). The results show efficiency improvements during each beam mode. The data also indicates a high consistency between fills, with the tails in the distributions generally attributed to special studies or problem solving.

Further, no strong pattern could be observed in the cause of the problems encountered.

In light of the good performance of the beam modes in 2016, in general only marginal gains in efficiency are possible. The challenge may in fact be to conserve the same performance. There are however some significant potential gains available by changing the playing field. For example injection of longer trains will reduce the total time at injection, and pushing the CRS to 1m Beta*, and colliding all IPs simultaneously will all contribute time savings. With the beams modes before stable beams representing on average 129 min in 2016, there is a realistic possibility of achieving less than 100 min in 2017.

**ACKNOWLEDGEMENT**

The author wishes to thank the many contributors who assisted with the preparation of this paper. In particular M. Solfaroli for his assisting with the analysis methods and the many discussions on optimising the beam processes, K. Fuchsberger for the many discussions (and for taking on the turnaround work!), L. Ponce on the availability and sequencer insights, J. Wenninger for the discussions on all aspects. Thanks also to the LHC operations team for their many discussions on all aspects, and for their dedication - a non-negligible contribution to the excellent performance in 2016.

**REFERENCES**


LHC PARAMETER REPRODUCIBILITY

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Abstract

This document reviews the stability of the main LHC operational parameters, namely orbit, tune, coupling and chromaticity. The analysis will be based on the LSA settings, measured parameters and real-time trims. The focus will be set on ramp and high energy reproducibility as they are more difficult to assess and correct on a daily basis for certain parameters like chromaticity and coupling. The reproducibility of the machine in collision will be analysed in detail, in particular the beam offsets at the IPs since the ever decreasing beam sizes at the IPs make beam steering at the IP more and mode delicate.

INTRODUCTION

The analysis presented in this document covers the tune, chromaticity, coupling and orbit stability of the LHC during the 2016 pp run. Depending on the case either all data is presented, or data limited to the high intensity proton fills.

TUNE

The tune is corrected automatically at injection for b2 decay by the FIDEL server and for intensity effects by a dedicated application [1]. Quality and limitations of those corrections were discussed in details at the 2015 Evian Workshop [1]. As soon as the probe bunches are injected, the tunes are measured and if necessary also corrected manually by the shift crews. The corrections correspond to un-modelled (or non reproducible) cycle to cycle tune changes. The range of trims is similar for both beams and both planes, ΔQ ≈ 0.015. The spread is clearly visible in Fig. 1 that presents the superposition of all tune functions that were used throughout 2016 for beam 1 in the vertical plane. Those manual trims are still incorporated linearly into the ramp although they should be incorporated in snapback style since the tune changes seem to follow the decay / snapback model [1]. The later point could be improved for the 2017 run.

Figure 1: Superposition of all vertical B1 tune trims for the ramp.

The real-time (RT) trims applied by the tune feedback (QFB) during the ramp are presented for beam 1 high intensity fills in Fig. 2. Beyond ≈ 500 seconds the tune in the ramp is extremely stable, reproducible to better than ±0.002.

In the first half of the ramp there are some systematic (Laslett tune trim incorporation) and some non-reproducible RT corrections. Possible improvements to reduce the amplitude of the RT corrections and to lower the dependence on the QFB include:

- modification of the incorporation of the Laslett tune trims to follow an inverse energy rule (1/E),
- incorporation of the manual tune trims at injection with the correct snapback-type rule by the FIDEL server.

Figure 2: Evolution of the beam 1 tune RT trims during the ramp for the horizontal (top) and the vertical plane (bottom). The data is based on all high intensity cycle with beams having 25 ns bunch spacing (>1000 bunches).

The tune is extremely stable and reproducible during the squeeze, consistent with the second half of the ramp. The RT trims are stable to ±0.002 as can be seen in Fig. 3. After feed-forward the residual trims are very small, consequently the squeeze can be operated without QFB, as had to be done in certain periods when the tune quality was not sufficient.

CHROMATICITY

The b3 decay at injection is in principle compensated by the FIDEL server. Manual Q’ trims are however performed following measurements with the probe bunches at the beginning of the injection process. The magnitude of those manual trims reflect the quality of the b3 decay modelling:
trims with a range of up to $\pm 7$ units are applied based on $Q'$ measurements with the probes, see Fig. 4. It is very likely that the incorporation into the ramp should follow the usual snapshot shape instead of the linear decay as applied up to now. The solution would be similar to the case of the tune. The reproducibility of $Q'$ after $\approx 200$ s of ramp is estimated to be around $\pm 2$ units based on the few available $Q'$ measurements during the ramp.

Figure 5: Superposition of all vertical chromaticity trims for B1 in the squeeze. The initial function of 2016 had strange jumps of around 5 units that were mostly likely due to inconsistent $Q'$ targets during the setup. After correction the functions were rather reproducible along the year within the limited measurement statistics.

COUPLING

In 2016 the coupling was measured and corrected systematically at injection for the first time since the LHC startup. From those measurements it was possible to confirm a clear decay of the coupling. The decay was observed online in the CCC with the BBQ when probe bunches were measured during longer time intervals. A dedicated MD in MD period 4 provided direct coupling measurements over a few hours [2]. Figure 6 presents the coupling knob trims performed at injection for both beams along the year. It is clear that for all cases the values remain within a well defined band, there are apparently no drifts over long time scales. Figure 7 presents the same trims as a function of the time at injection: no clear decay-like signature is visible. This may be due to the fact that pre-cycle and 6.5 TeV cycles do not generate the same coupling decay (similar to tune and chromaticity): the data should in that case be separated for the two cases. Another explanation may be simply a fill to fill non-reproducibility.

The ramp functions of the coupling knobs converged slowly over a few weeks as it took some time to take measurements of coupling on the fly using the AC-dipole, see Fig. 8. The correction of $C_{\gamma}$ was generally not much better that 0.01 for most of the 2016 ramps (low, medium and high $\beta^*$). This did not harm since all ramps were operated with injection tunes (0.28/0.31).

Only few coupling measurements were performed along the squeeze. Most measurements were consistent with each other within $\pm 0.002$ (knob units). The endpoint is consistent for B1 between April and October. After TS2 however a trim on the endpoint, due to poor quality BBQ derived coupling correction, is suspected to have generated instabilities at the end of the squeeze. Some days later it was confirmed that towards the end of the squeeze (below 80 cm), the increased tune spread and degradation of the tune peak sharpness led to incorrect coupling measurements by the BBQ. The lesson
is that the BBQ only provides realizable coupling results when they are clean and unique Q peaks.

ORB\textit{T}

Since the beginning of the 2016 run, a very flexible and powerful new software is in place to generate the reference orbits along the cycle [3]. With this system a unique flat reference orbit was used for all machine configurations and cycles in 2016. All bumps (separation, crossing angles, TOTEM bump, luminosity scan knobs, ULO bump) were added to the base orbit using their LSA function settings. For the ion run the typical difference between the probe bunch and the nominal bunch orbit was added as additional 'bump' to this collection. This new system ensured for example that in IR7 the reference orbit was identical at every moment in the year, for every fill and every configuration.

The Orbit Feedback (OFB) was used throughout the run with the same configuration, manual orbit corrections were only applied during the initial setup of the cycles, and very rarely to follow triplet movements. Every one or two months, a feed-forward of the orbit corrector RT trims was applied to maintain the OFB trims as small as possible.
Global orbit

The general orbit data quality improved significantly after LS1 with the BPM rack cooling. Some remaining systematic shifts are still observed, but they are smaller by factor roughly 5 to 10 as compared to Run 1. This improvement allowed to run the OFB in stable beams since 2015 (but only with gentle correction strategy).

The orbit quality throughout the cycle evolved very little over the year. There were small degradations around the four experimental IRs (triplet region). They are most likely driven by triplet movements that are not perfectly compensated by the OFB due to the absence of the MCBX correctors in the OFB corrector set.

The orbit reproducibility (excluding the experimental IRs) in stable beams is presented in Fig. 10. The stability is excellent over the entire run, with a short term reproducibility of around 20 μm and a long term reproducibility of around 40-60 μm. An independent confirmation is the quality and stability comes from the IR7 collimator re-alignment that was performed in September for the ATS MD. The alignment results were consistent within 20 μm rms with the initial alignment performed in April 2016 (courtesy A. Mereghetti). In Fig. 10 the period when the wrong BPM calibrations were applied is clearly visible with a degradation to around 80 μm rms. During that period a BI server could not correctly set the calibration to be used, as a consequence the high sensitivity calibrations were used instead of the low sensitivity values.

Figure 10: Evolution of the orbit rms in stable beams for 25 ns beams in 2016. The reference corresponds to a fill on July 14th. The period between days 100 and 125 was affected by an incorrect calibration (high sensitivity instead of low sensitivity). Isolated outliers are also due to incorrect calibrations, usually due to the wrong beam type selection.

Figure 11 presents the orbit rms with respect to the reference orbit along the cycle from the start of the ramp to the end of adjust for two fills. The first fill (4979) is one of the first high intensity 25 ns beam fill. The second fill (5448) corresponds to one of the last high intensity 25 ns beam fills. The difference between the two fills is very small, which highlights the excellent reproducibility of the orbit during the run which is a key ingredient of the very stable cleaning efficiency of the LHC collimation system.

The evolution of the 60 A MCB arc orbit corrector strength can be used to estimate the machine movements during the run. The rms kick change of around 1.2 μrad over half a year corresponds to a rms misalignment of the machine quadrupoles of around 55 μm. Scaled to an entire year the misalignment corresponds to around 100 μm. This value is consistent with survey observation (already from LEP times). The misalignment is small enough to be able to bootstrap a run with the orbit corrector settings of the previous one, and obtain immediately a circulating beam without the need of threading.

Figure 11: Evolution of the orbit rms with respect to the reference orbit through the cycle from the start of the ramp to the end of adjust. The upper figure corresponds to an early 25 ns beam fill while the lower figure corresponds to one of the last fills.

Figure 12: Evolution of the arc orbit corrector (60 A MCB circuits) kick rms in stable beams during the 2016 run.

Beam offsets at the IPs

The beam separation corrections that are applied during the run to bring beams back to head-on collisions are presented in Fig. 13 for ATLAS and CMS for the low β⁺ configuration (40 cm). The beam size is indicated by the small
Figure 13: Evolution of the beam separation corrections at IP1 and IP5 for the horizontal (top row) and vertical (bottom row) planes. Each point corresponds to a luminosity optimization during stable beams or in adjust.

Figure 14: Distributions of the fill to fill beam separation changes at IP1 and IP5 for the horizontal (top row) and vertical (bottom row) planes.
The corrections are very large, exceeding 10 rms beam sizes over the year. In general the vertical plane is slightly quieter than the horizontal plane that is affected by support issues. The main effects that drive beam separation changes are movements of the triplet quadrupole magnets. Those movements are induced by:

- triplet magnet quenches that lead to sudden position jumps,
- cryogenic transients with large pressure transients (for example the weasel event in May 2016 affecting point 8),
- triplet thermal screen temperature changes [4],
- and sudden unexplained movements as was observed for the IP5 triplet in October and November 2016 [5], see top right plot of Fig. 13.

The beam offset corrections that must be applied to bring the beams head-on are rather reproducible with optics and energy as can be observed in Fig. 15 where the typical offsets are compared for the various optics configurations used in 2016. A positive side effect is that once the corrections are known for one optics, they can be used to efficiently bootstrap other configurations. This is another positive side effect of the orbit reference system based on a unique base orbit for all configurations.

If the resolution and long term accuracy would be sufficient, the Q1 BPM position measurements performed with the DOROS acquisition system could be used to steer the beams deterministically into collision. Unfortunately this is not possible because the fill to fill reproducibility of the DOROS readings, interpolated to the IP, is much worse than the fill to fill machine reproducibility as can be seen in Fig. 16. The DOROS IP position fill to fill accuracy is around 20 μm in the separation plane and over 100 μm in the crossing plane. This difference is explained by the ≈ 3 mm beam offset in the Q1 for the crossing plane. The short term accuracy (time scale of 15-60 minutes) of the DOROS readings is however excellent, at the level of 1 μm.

**Triplet wire position system**

The Wire Position Sensors (WPS) installed for each triplet monitors the position of the cryostat outside shell with respect to a wire stretched from the IP side of Q1 to the end of the D1 separation dipole as shown in Fig. 17. Provided the cryostat movement reflects the movement of the cold mass, it should be possible to estimate the beam separation at the IP from the WPS readings by reconstructing the total effective kicks for each triplet and by taking into account the action of the OFB. This was done with good success for the the slow movement of the triplet on the right side of IP5 in 2015 [6].

The prediction of the IP shift from WPS data at the end of adjust with a simple effective kick and scale factor (≈ 36 μm/μrad) agrees with the observed beam separation only for the horizontal plane of IP5, see Fig. 18. For the
other cases the correlation is not very good. This may be an indication that the cold mass and cryostat movement are not (always) identical, for example during sudden changed following quenches or other violent events. For smooth and slow movements on the other hand, the correlation is more satisfactory.

**Orbit feedback improvements**

It is very likely that the dominant contribution to the beam separation changes (Fig. 13) observed in stable beams is due to an imperfect correction of the local orbit by the OFB. Triplet movements cannot be corrected locally because the common MCBX correctors are not included in the set of correctors used by the OFB. The reason is the presence of the Quench Protection System (QPS) that is very sensitive to acceleration changes of the circuit current. The other LHC orbit correctors are self-protected and operate without QPS. If the MCBX were included in the OFB corrector set, the situation could improve significantly provided the BPM fill to fill reproducibility is at the level of 10 \( \mu \text{m} \) or better (exact value to be confirmed). If the BPM fill to fill reproducibility is too poor, the OFB could even degrade the situation with the MCBX by propagating BPM errors to the IP [6]. An MD that tested the MCBX in the OFB in 2016 highlighted again that to use the MCBX the OFB will have to control (limit) the acceleration rates that it is using to steer the beams. Limiting the acceleration will effectively apply a low pass filter to the OFB RT trims, fast corrections will be slowed down and high frequency noise will be suppressed. An analysis should be made on past orbit corrector data of the 2016 run to understand what the impact of an OFB acceleration limiter would be. It may be possible to prepare an implementation in the OFB with a switch to enable/disable the acceleration limits that could be tested in 2017 during MDs.

**FAST ORBIT OSCILLATIONS**

The levelled experiment’s luminosities clearly exhibit the signatures of different types of small amplitude (\( \mu \text{m} \)) periodic orbit oscillations visible in Fig. 19 [7]. Two main oscillation patterns can be observed. A first pattern lasts typically 30-40 minutes with periodic orbit changes every 15 seconds. This pattern repeats roughly every 4 hours. A second pattern is more erratic, with sudden jumps roughly every 6 minutes. This also affects mainly beam 2 in the horizontal plane. For both cases the orbit change is clearly visible on the DOROS Q1 readings.

**CONCLUSIONS**

With the exception of decay and snapback effects, the LHC reproducibility proves to be remarkable, in particular
at 6.5 TeV with a tune stability of ±0.002, a chromaticity stability of ±2 and probably a coupling stability of ±0.002. With the OFB acting on the beam, the arc orbit stability is 20 – 50 µm.

The potential impact of poor(er) coupling could be reduced by moving the tune change (from injection to collision tunes) to the end of the squeeze as was done during the ATS MDs.

The reproducibility of the machine is so good that there is no real need for extensive test cycles when settings for special configurations are reused after a longer interruption (for example medium or high β*). The impact of triplet movements during a period where settings were not used can be assessed and even corrected.

The triplets are the most notable source of orbit perturbation, and their impact affects mainly the beam separation for stable beams at low β*. The overall behavior and the impact of triplet movements has been clarified in 2016, in part due to the systematic monitoring of the WPS data in the CCC. Including common correctors in the OFB may be the only qualitative jump that one could envisage for the orbit control, provided the BPM reproducibility is adequate.

The origin of the periodic fast orbit oscillations with µm amplitudes, clearly visible on levelled luminosities and on the DOROS BPMs, remains a mystery.

REFERENCES


2016 AVAILABILITY SUMMARY


Abstract

The LHC exhibited unprecedented availability during the 2016 proton Run, producing more than 40 fb\(^{-1}\) of integrated luminosity, significantly above the original target of 25 fb\(^{-1}\). This was achieved while running steadily with a peak luminosity above the design target of 1\(\times\)10\(^{34}\) cm\(^{-2}\)s\(^{-1}\). Individual system performance and an increased experience with the machine were fundamental to achieve these goals, following the consolidations and improvements deployed during the Long Shutdown 1 and the Year End Technical Stop in 2015 (YETS 15-16). In this presentation, the 2016 LHC availability statistics for the proton Run are presented and discussed, with a focus on the main contributors to downtime.

INTRODUCTION

The Accelerator Fault Tracker (AFT) was released at the beginning of the 2015 LHC Run, allowing systematic and consistent LHC fault tracking in 2015 and 2016. The fault review procedure was further streamlined in 2016 to allow for a direct interface of system experts with the AFT. As a result, system experts actively participated in the fault review throughout the year, validating entries created by the LHC operations team and the core members of the availability working group. Before each of the three technical stops, the data collected was validated in a meeting of the Availability Working Group and the results published in dedicated technical notes [1][2][3][4]. Results presented in this paper summarize the results of these analyses for the proton Run.

Table 1: 2016 LHC exploitation [days].

<table>
<thead>
<tr>
<th></th>
<th></th>
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<tr>
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OVERVIEW: 2016 AVAILABILITY

The 2016 proton Run began on the 25\(^{th}\) March and ended on the 31\(^{st}\) October. Table 1 shows the breakdown of the time allocated for different machine activities during this period. Out of the 213 days, 146 were devoted to integrated luminosity production, plus 7 dedicated to the ‘special physics’ run with 2.5 km β\(^{*}\). Beam commissioning and scrubbing took 33 and two days respectively. Machine Developments (MDs) were carried out in five blocks, for a total of 20 days. Twenty-five hours were dedicated to ion cycle commissioning, over two days.

In the reference period, 779 faults were registered and analysed in the fault tracker, with 65 relevant parent/child relationships. In such cases, the occurrence of a primary failure/event (parent) affects the performance of a number of secondary systems (children). It is important to account for these dependencies to correctly prioritize consolidation actions and identify the most effective failure mitigation strategies.

Two new fault/downtime categories were introduced in 2016: ‘ventilation doors’ and ‘access management’.

Figures 1-2-3 show the evolution of the LHC performance in the three reference periods introduced in Table 1.
‘Operations’ includes the nominal cycle, measurements, injection tuning and planned accesses for machine interventions.

In the period between the restart of operation with beam to the first Technical Stop (TS1), the LHC experienced 45% fault / downtime – two long periods of unavailability within this were due to the failure of a 66 kV transformer in Point 8 (about 6 days) and the mains power supply of the PS (about 5 days). The availability increased significantly in the period from TS1 to TS2, reaching the record of physics efficiency for the LHC (58% of time in stable beams). This was achieved despite another long stop (about 3 days) due to a flood in Point 3, which affected in particular the control systems of the collimators. In the last period of the proton run from Technical Stop 2 to 3, the performance was still excellent (achieving 54% physics efficiency).

Combining these figures for the whole proton Run yields the results shown in Fig. 4 (49% average physics efficiency over the year), for a total of more than 1800 h in stable beams. For comparison, the 25 ns proton Run in 2015 yielded 33% physics efficiency, which implies a gain in 2016 of more than 15%. Also of note was the fraction of time dedicated to pre-cycles; this was reduced by 50%, thanks to the reduced number of failures requiring pre-cycles and to the shorter pre-cycle duration [5].

The increased machine availability in 2016 is related also to the significant reduction of the number of premature dumps with respect to previous runs. Figure 6 shows the ratio of fills reaching stable beams which are prematurely dumped due to failures or intentionally by LHC operators. In total, 53% of the fills were dumped due to failures (5% due to radiation effects) and 47% by operators. In 2015 about 70% of the fills were dumped by failures, highlighting an improvement also in this respect of 15-20%. Many factors contribute to this achievement, the main ones being:

- The optimization of BLM thresholds in the LHC arcs, which allowed limiting the number of unnecessary dumps due to UFOs
- The low number of radiation-induced failures, thanks to lower radiation levels in the arcs than expected and the mitigation measures deployed in L1 and the YETS 15-16

Figure 5 shows the evolution of the availability by week and relates it to the physics production. ‘Incomplete weeks’ indicate that the corresponding week was not entirely devoted to luminosity production (e.g. for technical stops or MDs). Several weeks exhibited more than 90% availability with more than 3 fb⁻¹ produced. Weeks 17 and 21 are characterised by a low availability (about 30%) and correspond to the occurrence of the aforementioned 66 kV transformer failure in Point 8 and the failure of the PS main power supply, respectively.

Figure 4: LHC Mode breakdown during the 2016 proton Run (all).

Figure 5: Availability (blue) and luminosity production (purple) by week in 2016.

Figure 6: Physics beam aborts in 2016: due to failures (purple), due to radiation effects (blue) or triggered intentionally by operators (green).
ANALYSIS OF FILLS TO STABLE BEAMS

A detailed analysis of the 179 fills that reached stable beams was carried out (4 during the special physics run, where collisions were performed in ‘adjust’). In the period up to TS1 the intensity ramp-up was carried out, requiring relatively short fills to stable beams (20 h integrated time for each intensity step). In this period a record fill was kept in the machine for 35 h. In the period from TS1 to TS2, the best period in terms of physics efficiency (58 %), many fills lasted up to 24 h. After the introduction of BCMS beams, which imply a higher peak luminosity and a shorter luminosity lifetime, the optimal fill length was set to 15 h. In the last part of the year, the physics efficiency was reduced to 54 %. This is the result of the shorter optimal fill length, which requires performing more cycles for the same total time in stable beams. Furthermore, in this period additional time was dedicated to measurements and tests even outside MDs (e.g. end-of-fill studies). Table 2 summarizes the average fill durations in the three reference periods.

Table 2: Average stable beams duration in 2016.

<table>
<thead>
<tr>
<th>Restart - TS1</th>
<th>TS1 – TS2</th>
<th>TS2 – TS3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aborted</td>
<td>8.0 h</td>
<td>7.7 h</td>
</tr>
<tr>
<td>End of Fill</td>
<td>6.9 h</td>
<td>16.2 h</td>
</tr>
</tbody>
</table>

The average duration of fills dumped due to failures was remarkably stable during the year, indicating a very reproducible operation and a well-established machine reliability. Short fills (few hours) dumped by operators are either relative to the intensity ramp-up (e.g. following TSs or MDs) or were triggered to anticipate the loss of cryogenic conditions.

DOWNTIME ANALYSIS

A total of 779 faults were registered in the AFT for the proton run, with 77 pre-cycles due to faults. Table 3 shows the statistics related to faults in terms of occurrence and downtime. Three different classes of downtime are presented:

1. ‘Fault duration’: integrated downtime logged for the faults
2. ‘Machine downtime’: real impact on machine operation, accounting for possible parallelism of faults
3. ‘Root cause duration’: real impact on machine operation, accounting for possible parallelism of faults and parent/child relationships

Figures 8-9-10 visually show the contributions of the different systems to LHC downtime. Figure 10 is used as a basis for the assessment of the top contributors to the unavailability in 2016.
Table 3: 2016 LHC downtime.

<table>
<thead>
<tr>
<th>Root Cause Class</th>
<th>Root Cause System</th>
<th>Faults [#]</th>
<th>Fault Duration [h]</th>
<th>Machine Downtime Duration [h]</th>
<th>Root Cause Duration [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>Injector Complex</td>
<td>138</td>
<td>360.38</td>
<td>317.82</td>
<td>313.21</td>
</tr>
<tr>
<td></td>
<td>Technical Services</td>
<td>67</td>
<td>221.68</td>
<td>210.73</td>
<td>278.35</td>
</tr>
<tr>
<td></td>
<td>Power Converters</td>
<td>66</td>
<td>106.62</td>
<td>87.84</td>
<td>75.05</td>
</tr>
<tr>
<td></td>
<td>Experiments</td>
<td>52</td>
<td>59.86</td>
<td>50.27</td>
<td>50.27</td>
</tr>
<tr>
<td></td>
<td>Quench Protection</td>
<td>45</td>
<td>36.97</td>
<td>31.02</td>
<td>25.93</td>
</tr>
<tr>
<td></td>
<td>Cryogenics</td>
<td>42</td>
<td>361.08</td>
<td>133.15</td>
<td>90.32</td>
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<tr>
<td></td>
<td>Beam Instrumentation</td>
<td>40</td>
<td>47.08</td>
<td>37.91</td>
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<tr>
<td></td>
<td>Radio Frequency</td>
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<td>40.20</td>
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<td>10.72</td>
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<td>9.63</td>
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<td>12.77</td>
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<tr>
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<td>Access System</td>
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<td>24.50</td>
<td>9.99</td>
<td>13.88</td>
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<tr>
<td></td>
<td>Transverse Damper</td>
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<td>13.84</td>
<td>10.60</td>
<td>10.60</td>
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<td>Ventilation Door</td>
<td>10</td>
<td>21.12</td>
<td>9.30</td>
<td>9.16</td>
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<td>Machine Interlocks</td>
<td>8</td>
<td>5.96</td>
<td>4.39</td>
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<td>IT Services</td>
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<td>0.13</td>
<td>0.13</td>
<td>9.15</td>
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<tr>
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<td>1.37</td>
<td>1.20</td>
<td>1.20</td>
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<td>0.04</td>
<td>0.04</td>
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<tr>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td></td>
<td>Losses</td>
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<td>0.75</td>
<td>0.72</td>
<td>45.24</td>
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<td>Induced Quench</td>
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<td>0.34</td>
<td>0.00</td>
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<td>11.36</td>
<td>11.31</td>
<td>11.05</td>
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<td></td>
<td>Access Management</td>
<td>8</td>
<td>21.48</td>
<td>19.00</td>
<td>15.11</td>
</tr>
</tbody>
</table>

Σ 779 1620.5 1231.4 1232.4

Figure 8: 2016 LHC fault duration
Figure 9: 2016 LHC machine downtime.

Figure 10: 2016 LHC root cause duration.
The top contributors to downtime are the injector complex and technical services, both having caused over ten days of downtime. The downtime is in both cases dominated by isolated, high-impact faults. The technical services suffered from the occurrence of the 66 kV transformer failure in Point 8 and the flood in Point 3, with a combined downtime of about ten days. In addition, 22 premature dumps were triggered by perturbations in the electrical network (see [6], [7]). The downtime of the injector complex was dominated in 2016 by the PS, which experienced several problems including main power supply issues and a vacuum leak [8].

The cryogenic system is still among the top contributors to downtime, but has significantly improved its availability in 2016 [9]. This is due to the optimization of the cryogenic configuration (only four cold-compressor units supply the eight arcs) which led to a reduced failure rate and the implementation of the feed-forward system for the dynamic of compensation of transient heat-loads on the beam screen. Also, the issues observed for DFB level adjustments in 2015 were solved. These factors resulted in a major reduction of the losses of cryo-maintain and therefore reduced the number of premature beam dumps.

The QPS operated very reliably throughout the year, with an average availability above 99 % [10]. This is a result of the efforts invested in the improvements of the system over the past years. In particular, mitigations deployed in the YETS 2015-2016 on 600 A quench detection systems have proven to be very effective against radiation induced failures.

A few more events are of note; for magnet circuits, a long stop (about 40 h) was required for the investigation of the suspected inter-turn short in RB.A12. Concerning the Beam Dumping System [11], two MKB erratics occurred in 2016, leading to synchronous beam dumps. These required the replacement of two generators and a system revalidation (10 + 5 h for each of the two events). In addition, one more generator was preventively replaced (10 h).

CONCLUSIONS

The LHC exhibited unprecedented availability in 2016, which resulted in the production of 40 fb⁻¹ of integrated luminosity, well beyond the target set at the beginning of the year. Several factors contributed to this success, certainly the profound understanding of the machine and the improved system reliability. In this respect, all mitigation measures deployed in LS1 and the YETS 2015-2016 have proven to be very effective in operation. Furthermore, the changes of critical settings/configurations (BLM thresholds, cryogenic feed-forward, etc.) were a key factor for the improved performance.

In 2017 the machine should profit from the lessons learned in 2016 and from the continued machine conditioning. Similar equipment availability should be observed in 2017, as that which was experienced in 2017. Nevertheless, it is important to consistently monitor the performance of the different systems to identify recurring effects and the first signs of component ageing and end of life. Changes in accelerator operating conditions could impact on the availability; for example, time might be required to optimize the injection of trains of 288 bunches. In addition, the possible deconditioning of sector 1-2 following the dipole magnet replacement will have to be assessed in terms of e-cloud and UFO rate.

ACKNOWLEDGMENTS

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REFERENCES

Abstract
CERN’s technical infrastructure is a common root cause source of unavailability impacting the accelerators, injectors, experiments and the computer center.

The Technical Infrastructure Operation Committee (TIOC) monitors, analyses and coordinates the technical infrastructure operation in order to increase the overall availability of the LHC. All events impacting or potentially affecting directly or indirectly the LHC runs are analyzed and recommendations are made for immediate intervention or long term actions. Tools and performance indicators are progressively being implemented considering a more structured approach to system breakdown identification and fault tree analysis.

The unavailability caused by the technical infrastructure during 2016 has been analyzed and compared with previous years together with the impact of electrical power glitches. Tools and strategies to perform availability analysis across all systems and equipment are proposed and the tracking of the root cause analysis and dependences assessed to explain past and future performances.

SYSTEMS MONITORED BY TI

The Technical Infrastructure control room in the CCC is mandated to monitor the technical infrastructure needed to run the accelerators complex. The main systems monitored are:

- Electrical distribution network covering everything from the 400 kV / 130 kV supply from EDF / RTE and SIG / EOS to the 66 kV and 18 kV distribution internally at CERN to the 400 V / 3.3 kV for end users.
- Ventilation for the accelerators and experiments as well as machine buildings
- Cooling for accelerators, experiment and machine buildings including primary water, demineralized water, chilled water, reject water, tap water and more.
- Safety systems including fire detection, gas detection, evacuation systems, emergency stops. All technical parameters are monitored by TI while level 3 alarms are monitored by the fire brigade.
- Access system to the experiments and accelerators as well as access to buildings and sites
- IT network interventions and break downs are coordinated with the 513 operators. TI also monitors part of the industrial controls.

Systems monitored by TI are not under the category of Technical Services in AFT, this inevitably causes inconsistencies between the TI logbook and AFT. The proposal is to make a joint effort to make the categories in AFT aligned with the ones used in the TI logbook.

SYSTEM BREAKDOWN STRUCTURE

For many years, major events are recorded and ordered using the group “responsible” for the fault. This has shown to be imprecise because of two main reasons:

- The groups change from time to time at CERN, and sometimes groups expand and change responsibilities which makes it difficult to compare from one year to another.
- A cooling fault can be under EN-CV responsibility, but also TE-EPC when the fault is on a power converter or BE-RF if it is inside a BE-RF rack.
- There is more technical interest in knowing what type of equipment the failure belongs to than the actual owner.

After thorough analysis of previous major faults at CERN a new system breakdown structure has been developed and will be proposed to be implemented in AFT for all technical infrastructure faults. This new structure consists of 2 parts: The first part defines the faulty system breakdown structure, as shown in Fig. 2.

![Figure 1: System breakdown structure](image)

The second part of the system breakdown structure is the type of fault that can occur to the system chosen as shown in Fig. 3.
Figure 2: Faults breakdown structure

Using the combination of the faulty system, the type of the fault and the group responsible for the fault it is straightforward to extract statistics and perform analysis based on equipment, fault typology and owners, e.g. all PLC faults regardless the system, faults on the electrical distribution network other than EN-EL.

The committee consists of members from all groups concerning the technical infrastructure, the LHC coordination, LHC experiments technical coordinators and the technical infrastructure.

When a major event is created by the TI operator, the next step is to analyse it at the TIOC meeting. To help clarifying the event all equipment groups and users of the systems can add comments to the report, in form of group reports. The actions to be taken and consolidations necessary are discussed during the meeting, and once all actions are completed the report is closed and validated for the statistics.

2016 FAULTS BY GROUPS, SYSTEMS AND FAULT TYPES

In 2016 the faults were distributed using the groups and calculated on downtime. The distribution is seen in Fig. 5. Figure 6 presents the same data set, but using the new system breakdown structure.

Figure 3: TIOC committee workflow

The mandate of the TIOC is:

- monitor, record and analyze events related to the infrastructure systems serving the accelerator complex, the experiments and the computer centre.
- Recommend consolidations paths which would correct situations originating from the reduced maintenance, non-conformities or weaknesses of the technical infrastructure.
- Coordinate bigger technical interventions and incidents.

Figure 4: Fault distribution calculated on downtime

Figure 5: Fault distribution calculated on downtime using the new system breakdown structure
The sharing of all major events, based on the downtime and not the number of events highlight 3 categories of fault stand: Equipment faults, controls and instrumentation faults and electrical perturbations. The distribution is shown in Fig. 7.

Figure 6: Fault types calculated on downtime

In 2016 we recorded 48 perturbations compared to 16 in 2015. There are 2 ways a recording of a perturbation can be triggered in TI: Either the perturbation is big enough to be detected on the electrical network and therefore causes alarms to be raised, which will be seen by the operator, or 1 or more of CERN’s accelerators stop due to the perturbation. In the case of a stop of an accelerator EDF is contacted and can normally correlate with some action on the network or some recording of a minor perturbation. It is worth noting that if EDF would have not been contacted, we would not necessarily have recorded the perturbation.

Several reasons why we saw more in 2016 can be considered:
- We saw more time in stable beams in 2016, which obviously makes the complex more vulnerable to electrical perturbations.
- A fair amount of the perturbations recorded were relatively small in amplitude and were only stopping the LHC on a trip of the FMCM. The exchange of some of the older power converters in the YETS will solve this problem and could potentially bring down the number of perturbations by 30%
- 2016 was generally a very bad year for thunderstorms in France, whereas 2015 was noted as the most stable year in the last 30 years.

The comparisons can be seen in figure 7 where the bars represent the downtime and the lines correspond to the number of perturbations.

Figure 7: Electrical perturbations

All of the electrical perturbations recorded in 2016 were due to external perturbations coming from either EDF / RTE or SIG / EOS distribution network. 50% of the perturbations recorded were causing less than 10% of voltage dip.

These events are based on meteorological conditions and are outside the control of CERN. Nevertheless, the sensitivity of equipment to perturbations can and shall be reviewed in order to guarantee the lowest downtime while still considering their safe operation.

The faults on controls and instrumentation can be further split in to 4 categories as seen in figure 8. 75% of the faults can be considered as PLC faults. PLC faults have gone down by a remarkable 67% since 2015.

Figure 8: Breakdown of controls and communication faults

The equipment faults can be further split in to 6 categories as seen in figure 9. 28% are due to equipment in short circuit. The faults can sometimes be hard to detect because the breaker that trips is usually not the faulty
element. Another 34% can be classified as equipment faults.

**Figure 9: Breakdown of equipment faults**

**DOWNTIME 2016 COMPARED TO 2015**

In 2016 a long downtime was recorded due to a long cut of the 66kV network by an external event. By removing this external event and statistically not significant, the total downtime went down and was 30% below what accumulated in 2015.

**CONCLUSION AND OUTLOOK**

In 2016 the coordination of events by the TIOC committee has proven very effective, and minimized downtime during the intervention of EDF on the 400kV network.

It has been proposed to put in service a “best effort” service for the TIOC committee, with a list of persons available to coordinate emergencies on the technical infrastructure.

The organization and structure of the major faults can be improved to simplify and improve the analysis. This is being implemented now with the new system breakdown structure. The work will now be focused on harmonizing this structure with the AFT, which will allow everyone to compare systems on the same level in AFT.

The electrical perturbations are hard to avoid, but we can definitely make equipment less sensible. A lot of work has gone in to this by the TIOC and in particular all the equipment groups. 2017 will be a very interesting year to prove the efforts put in place during the YETS and the preparations done in 2016 allow to maintain the high level of availability reached in 2016.

Last but not least, even though the LHC saw a remarkable time in stable beams and therefore higher sensitivity to perturbations, the technical infrastructure recorded less downtime than in 2015 or 2012. Part of the success in the 2016 Run is to be attributed to the TIOC follow up, monitoring and proposal for consolidations as well as the efforts done by all the equipment groups on consolidating the equipment.

**Figure 10: Downtimes compared 2016 to 2105**
INJECTORS: UNAVAILABILITY BY MACHINE, ROOT CAUSES, STRATEGY AND LIMITATIONS

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Abstract
During the 2016 LHC proton Run the main contributor to LHC downtime turns out to be the LHC injector chain. In this paper the corresponding LHC downtime will be assigned to either Linac2, the Proton Synchrotron Booster (PSB), the Proton Synchrotron (PS) or the Super Proton Synchrotron (SPS). The main root causes for the injector faults will be explained and a strategy outlined for the future to increase the injector availability. Ideas how to improve the injector fault tracking will also be given.

2016 INJECTOR FAULT ANALYSIS
As presented by the LHC Availability Working Group (AWG) and based on the LHC Accelerator Fault Tracking (AFT), the injector complex accounted for >25% of the total LHC root cause duration (corrected for parent/children faults and fault parallelism) during the 2016 LHC proton Run [1]; see Fig. 1.

Figure 1: Root cause duration for the various LHC fault categories [1]. The injector complex is the main root cause for LHC downtime during the 2016 proton Run, followed by the Technical Services and Cryogenics.

During the last years, a lot of effort has been made by the various equipment groups to minimise downtime for the LHC with visible success. The injector complex has not yet been in the focus, but this has changed this year, also due to a few long-lasting incidents. The next paragraphs will analyse the 2016 injector faults and propose a few improvements and strategies to reduce the fault duration for the next years.

It should nevertheless be mentioned that the LHC proton chain consists of four individual accelerators (Linac2, PSB, PS and SPS) that have to work in series to produce the LHC beam, while they are all serving in parallel various other physics facilities at CERN. Each of these four accelerators has their own equipment fault catalogue and should perhaps be treated as separate fault category entry for the LHC fault analysis.

For the 2016 LHC proton Run, 138 faults were recorded in the LHC elogbook for the injectors; their total (uncorrected) downtime amounted to 360.38 h (15d, 23 min), of which 9.8% happened during ‘beam in set-up’. These faults were extracted with their occurrence in time from AFT, but a big fraction of the faults was not yet attributed to a specific machine of the injectors. Therefore the description of each single injector complex fault had to first be checked in the LHC elogbook, then identified in one of the four injector elogbooks and the root cause of the fault understood from there to able to obtain its final categorisation of accelerator plus fault class observations could be made in this context: Firstly the fault duration is of course different between the LHC and injector elogbooks (the LHC only notes the time of the fault when it was affected, i.e. during injection preparation and execution, but the fault in the injectors could have lasted much longer), and secondly quite often no fault was noted in the injector elogbooks (in particular for beam quality issues, seen as beam setup and not as fault and in case of the SPS also because there is no more automatic fault insertion when it runs under LHC mastership).

2016 INJECTOR DOWNTIME FOR LHC OPERATION
After manual analysis of all the 138 injector faults registered by the LHC operations team, only less than 6 min of downtime could not be assigned to any of the injectors (not traceable anymore). The remainder was attributed to the different accelerators and fault categories.

As a remark, these statistics do not reflect ‘degraded’ beam operation, where there might be limits to the total intensity in the ring or extracted, in the maximum number of bunches, in beam quality or setting up efficiency. Examples for this might be that certain RF cavities are not working, one PSB ring is out of operation, beam dump issues, kicker limitations, noise problems with certain equipment, issues with the proton source current/stability or electron cloud limitations. It might be interesting to define for the future a way to account for degraded operational modes as well.

1 2016 was the first year members of the injector complex were nominated to join the AWG; they started since ~mid of the year to attribute LHC Injector Complex faults to their specific machines.
Linac2 Faults for LHC Run

Linac2 had an unusually bad year in 2016, accumulating a few longer-lasting interventions around the source and radio frequency (RF) issues. Nevertheless it appears with only three faults in the LHC fault statistics, amounting to a total of **6h 20m downtime for the LHC** (see Fig. 2). The main fault concerned the replacement of the ignitron for RFQ and tank 1 (RF) of more than 3h duration on 29/10, followed by Linac2 source parameter tuning after intensity fluctuations and a problem with a PLC of the cooling station.

Figure 2: 2016 Linac2 faults for LHC running. Total registered downtime: 6h 20m.

This low fault duration despite a few additional serious Linac2 problems during 2016 can be explained by the fact that either the Linac2 interventions could be scheduled to happen in the period when the LHC was in ‘Stable Beams’ or the LHC stopped requesting the beam (and noting the faults), adapting their program and waiting for the fault to be resolved.

PSB Faults for LHC Run

The PSB accumulated **11h 45m of downtime** during the period when the LHC prepared for beam injection (see Fig. 3). The top fault category was Beam Transfer due to an issue with septa electrovalves throughout the year, which required access into the machine (plus radiation cool-down time) for repair. The longest individual PSB fault for the LHC (>4h) was due to a problem with a controller of a power supply in the PSB recombination line.

Figure 3: 2016 PSB faults for LHC running. Total registered downtime: 11h 45m.

PS Faults for LHC Run

The total fault duration noted by the LHC operations team during the 2016 proton Run that was attributed later to the PS was **9d 10h 34min** (see Fig. 4). The PS suffered during the 2016 run from faults related to their main power supply (‘new’ POPS and ‘old’ MPS). This is reflected in the downtime of 6d 10h 17min under the category ‘Power Converters’ with POPS faults (short circuit of DC1 capacitor bank in April and replacement of the motor of a POPS cooling pump in October) and the longest fault of 5d 19min concerning the MPS (start of fire of the 6 kV high-power switch in May). The second-largest contributor to the downtime was vacuum with a single fault of 1d 5h 5min when a leak on a vacuum flange downstream of the dump nearby the PS injection septum had to be repaired (long radiation cool-down time involved). Contributor number three was Radio Frequency with several un-correlated faults (mainly cavity trips); there it has to be taken into account that the PS uses a large number of cavities tuned at different frequencies and complex control loops to allow the required complex longitudinal beam manipulations (splittings, bunch merging, bunch rotations etc.).

Figure 4: 2016 PS faults for LHC running. Total registered downtime: 9d 10h 34m.

SPS Faults for LHC Run

2016 was also a difficult year for the SPS. Intensity limitations were imposed throughout the year after a vacuum leak had developed on the SPS internal dump (TIDVG). After analysis, the SPS downtime for LHC operation amounted to **~4d 19h 38min**. The longest integrated fault duration per category was attributed to Power Converters (1d 8h 47min) with the following main interventions: 18 kV cable head fault on MBE2103 (8h 33min), a fault with the current measurement for the Beam Energy Tracking System (7h 36min) and the removal of a busbar for the septum MSE2183 after a water leak. Power Converter downtime was followed by the one for Targets and Dumps (several TIDVG issues with the longest individual fault duration of 16h 52min) and Radio Frequency (uncorrelated high and low level RF faults).

Figure 5: 2016 SPS faults for LHC running. Total registered downtime: 4d 19h 38min.
Although not in the top three most important SPS fault categories, it is interesting that Operation is in fourth place with >7h of downtime. The main reason for this is that the LHC beam was still being set up in the SPS or checked while the LHC was preparing or was ready to inject. The LHC beams are not constantly played in all injectors; parameters are drifting and require re-adjustments before LHC injection.

2016 INJECTOR UNAVAILABILITY

As mentioned before, the injector complex faults ‘seen’ by the LHC represent only a subset of all the faults that actually occurred in the injector chain. In order to draw some valid conclusions on the most important faults or to identify recurring faults for each of the injectors during 2016 and to evaluate appropriate mitigations and predictions for the 2017 run, the comprehensive injector fault overview should be used instead.

Linac2 Total Faults during 2016 Proton Run

Figure 6 summarises the total registered downtime in hours for Linac2 during the 2016 proton run, split into the different fault categories. Data was extracted from the Linac2 elogbook for the period from 02/03/2016 – 14/11/2016. The total downtime amounted to 6d 22h 22m, which has to be put into contrast with the 6h 20m of Linac2 faults registered for LHC running.

The source had many problems throughout the year and was responsible for >44% of all the Linac2 faults. There were two vacuum leaks at the source, whose detection was quite time-consuming. The source cathode had to be exchanged twice, and in addition quite some time was spent during the run to investigate problems with decreased source current or current fluctuations along the Linac2 pulse. The degraded Linac2 source performance had some repercussions on high-intensity users like the ISOLDE experiments, but for LHC beams there was no important brightness reduction, also because the LHC was running for the major part of the year with BCMS beams that require only low intensities injected into the PSB.

The second-most important fault category concerned Radio Frequency (34.6% of all faults). The following main faults occurred: Problems with the high voltage (HV) system (ignitron, RF amplitude jitter due to a broken HV cable connector), a broken RFQ tuner1 (worn out thread) and issues with the reference amplifier.

In summary, the total uptime of Linac2 was 97.3%, which is slightly less than the 98.3% average over the last 15 years [2].

The following actions will be taken to improve the Linac2 availability and performance for the 2017 run:

- **Spare Linac2 source:** During the extended year-end technical stop (EYETS) 2016/17 a spare source with a ~10% larger anode aperture will be extensively tested; this source will be put into operation for the 2017 run if successful. In parallel the source used during the 2016 run will undergo its annual maintenance.
- **BE-ABP and BE-RF** will make a full inventory of the Linac2 RF equipment and its state during the EYETS; they will also investigate the spare situation and produce new parts if necessary.

PSB Total Faults during 2016 Proton Run

The 2016 PSB proton run (from 08/03/2016 – 14/11/2016) did not contain any serious long-lasting faults. The total downtime was 16d 24m, of which 6d 22h 22m were Linac2 downtime. The availability reached 93.9%, which is an improvement compared to the 2015 run (92.5% uptime).

The source had many problems throughout the year and was responsible for >44% of all the PSB faults. After the contribution of Linac2 faults (36.6% of PSB downtime - see previous section), radio frequency is next (17.5%), followed by beam transfer (15.8%) and power converters (14.3%). The total list of faults (and warnings) during the 2016 proton run is illustrated in Fig. 7.

After the contribution of Linac2 faults (36.6% of PSB downtime - see previous section), radio frequency is next (17.5%), followed by beam transfer (15.8%) and power converters (14.3%). The total list of faults (and warnings) during the 2016 proton run is illustrated in Fig. 7.

Taking the PSB as example, one can illustrate the problem this year that warnings could not be separated from faults in the 2016 statistics. There were two periods of >1d in October during which the C16 cavities of the PSB (used for longitudinal blow-up and also intensity control through longitudinal shaving for certain beams) were not working due to a water leak of the

Figure 7: PSB total faults (and warnings) during the 2016 proton run. Total downtime: 16d 24m.

After the contribution of Linac2 faults (36.6% of PSB downtime - see previous section), radio frequency is next (17.5%), followed by beam transfer (15.8%) and power converters (14.3%). The total list of faults (and warnings) during the 2016 proton run is illustrated in Fig. 7.

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2 BCMS: Batch Compression, Merging and Splitting scheme.
prototype Finemet cavity that sprayed water on the cavities. Nevertheless, most of the beams could still be provided to the users after some operational adjustments (except during the required machine accesses); therefore the machine was operating in degraded mode (no real fault). Correcting for these particular two periods, the PSB statistics look different (see Fig. 8). The radio frequency fault category has moved to the fourth place (10.3% of total faults), and after Linac2 (39.8%) we now find beam transfer (17.2%) and power converters (15.5%).

As previously mentioned, the main reason for the beam transfer downtime were electrovalve failures of the septa; for their repair machine access was needed, and because of the relatively high dose rate around the septa corresponding radiation cool-down times. The electrovalve failures were unexpected, as this equipment had been renewed before 2016. Unfortunately, the new type of valve deployed seems to be less radiation tolerant. During the 2016/17 stop these valves will be exchanged with yet another type for the septa that showed the highest failure occurrence and if successful, all valves will be replaced. It is therefore hoped that the downtime for the PSB Beam Transfer category will decrease for the 2017 Run.

**PS Total Faults during 2016 Proton Run**

Concerning the faults, the year 2016 for the PS was characterised by several long-lasting issues with the PS main power converters – the ‘new’ Power supply for the PS (POPS) system and the previous Main Power Supply (MPS), still used as backup during longer POPS breakdowns.

The considered period for the PS fault statistics was from 14/03/2016 - 14/11/2016. During this period 30d 07h of downtime were registered, which includes 8d 01h of downtime from the PS injectors.

As mentioned, the main fault contributor were the power converters (38.3% of total downtime); towards the beginning of 2016 the DC1 converter of POPS developed a short circuit that forced major reparation of the system. Shortly before the start of the 2016 Run, the system was repaired and ready to restart, when an additional short circuit developed on one of the capacitors in the DSP1 container of POPS. This short circuit led to the explosion and collateral damage of the container and of all the 126 capacitors installed there. During the repair time the rotating machine (MPS) was brought back into operation, but on 20th of May one of the two MPS generator output switches broke due to an incorrect closing position and developed an arc with important smoke generation. This fault led to the longest fault registered for the PS in 2016 of >150h.

Not taking into account the downtime from the PS injectors already covered earlier (26.6%), radio frequency systems follow (10.7%) and beam transfer (6.9%). For RF, no systematic faults were observed.

Like for the other machines, corrective actions have already been taken in particular for the most important fault category to improve the situation for the 2017 Run [3]. Concerning POPS, two newly designed containers are under construction, one to replace the damaged DSP1 plus a spare. The capacitor banks in these containers were rearranged to divide the total capacitance into four groups, each group protected by an individual fusing element. This will reduce the amount of energy and peak discharge current in the event of an internal fault. A new capacitor design has been deployed and tested at CERN to mitigate the weaknesses of the older version. Non-negligible downtime for POPS was also due to failures of non-reliable cooling water pump motors; a new model was purchased and tested during more than three years. All old water pump motors will be replaced with the new ones during the EYETS 2016/17. For the MPS, the damaged high-power switch has been repaired; the MPS has been successfully tested at the end of the run and can continue to serve as POPS backup.

The PS is a good example to illustrate that the availability can vary significantly from user to user.
For the various PS proton beam users, this number has a span between ~79% and ~94%. This is due to several reasons:

1. Different start dates per user
2. Users can switch on and off their beam request depending on the situation of their experiment
3. Certain users are not permanently programmed in the supercycle
4. Some equipment is beam-specific (e.g. certain cavity combinations or extraction elements), leading to different availabilities in case of faults of this equipment.

For a future machine availability analysis of the injectors it will therefore be necessary to separate the data for different users/beams, contrary to the LHC situation.

**SPS Total Faults during 2016 Proton Run**

The SPS fault analysis is based on the period from 18/04/2016 until 14/11/2016. For the Fixed Target (FT) physics the 2016 uptime was 74.8% (compared to 85.5% in 2015). The total time the SPS was unavailable to deliver the FT beams was 56d 22h, including 20d 11h from the injectors.

Like Linac2 and PS, the SPS was also suffering in 2016 from major breakdowns; in the SPS case the main problem concerned the vacuum leak of the internal dump (TIDVG), leading to long downtimes and a serious operational limitations throughout the year to avoid dumping too much beam on the TIDVG, as no operational spare was available for replacement.

![SPS Total Faults+Warnings 2016 proton Run](image)

Figure 10: SPS total faults (and warnings) during the 2016 proton Run.

Figure 10 shows the distribution of the 2016 faults for the SPS. Neglecting the number one fault contributor, the PS Complex (35.9%; see previous subsections), targets and dumps follow with 26.5%, technical services and power converters amount to 9.8% and 9.5%, respectively. The main contributor to the downtime for the technical services was the BA3 overheating incident; for the power converters the principal fault lasted 49h 14m and was due to an insulation fault of an 18 kV cable head in the auto-transformer of MBE2103.

Concerning the TIDVG fault, a newly designed dump is under construction and will hopefully replace the damaged TIDVG before the 2017 restart. This would allow lifting the operational limitations that affected LHC operation, but even more North Area physics delivery. It should be pointed out that this degraded operation is not visible from the fault statistics (apart from the investigation time).

**INJECTOR AVAILABILITY**

It is not at all straightforward to provide availability data for the injectors. There are several issues with the injector availability statistics that are summarised here:

1. **Manual insertion of faults in the injector logbooks** → not everything is captured. In the SPS a system called 'Big Sister' is used that automatically inserts an elogbook entry if there are three consecutive cycles without beam for a user, for which 'Big Sister' is enabled. It could be discussed whether a modified implementation for Linac2, PS and PSB would make sense, but the faster the machines cycle, the more care has to be taken that the elogbook will not be submerged with entries.

2. **Availability for a given destination** (e.g. LHC):
   a. Statistics are reliable if a user is permanently played in the supercycle, but breaks down for beams on request (e.g. LHC, AWAKE, ISOLDE, nTOF...). For those users the request is often removed when beam production is not possible due to a fault, thus the faults are not any longer accounted for in the specific user availability statistics. There is no obvious solution for this issue, and at the same time it has to be mentioned that this leads to the high flexibility and optimum beam usage for the physics experiments served by the injector chain.
   b. The SPS does not automatically note any fault when the LHC beam is in the supercycle and under LHC mastership; it cannot distinguish between 'no request' and 'request, but fault'.
   c. Currently faults are attributed to 'timing users' (slots that can be used for various types of beams); this will be modified for 2017, when faults will be assigned to LSA contexts (non-ambiguous cycles).
   d. There exists no automatic link between LHC faults for the injectors and the injector elogbook entries. Since June 2016 selected persons from each injector are at least
attributing the faults noted by the LHC to the correct injector.

c. Beam setup: Sometimes the LHC is waiting for beam from the injectors, when the beam is still being set up or checked/optimised. This leads to a fault entry in the LHC eLogbook, but not for the injectors. This time should of course be minimised by in-time announcement of the LHC intention to inject, and the current situation is judged acceptable for the moment.

3. The root fault cause is sometimes not correctly identified → we propose to assign this task on a weekly basis to the team of the weekly machine supervisors.

4. Degraded mode – how should it be accounted for?
   a. Degraded machine operation (warnings) will be separated in 2017 from the machine faults.
   b. A solution should be identified to mark also long-term degraded operation (like in the SPS after the T1DVG fault).

Plans for 2017 Injector Statistics - AFT

A working group has been put in place in 2016 to evaluate the possibility of extending the LHC Accelerator Fault Tracking (AFT) to the injectors. The outcome of this work is that a modified version will be implemented to allow at least the correct data capture from the start of the 2017 Run, followed by the full functionality including visualisation throughout the year. This will address several of the above-mentioned problems through the following points:

- Harmonisation of the injector fault categories with the LHC categories; these categories have already been defined per injector and will be implemented in the 2017 injector eLogbook version.
- Use LSA contexts instead of timing users: Statistics will be produced by LSA context or groups of LSA contexts (e.g. all LHC cycles)
- Implementation of the interface eLogbook/AFT similar to the LHC, but context-dependent
- Separation of warnings and faults in the statistics
- Weekly review of root causes in the injectors.

Still there are outstanding issues that will not yet be solved by the 2017 injector AFT version, and it is proposed that discussions should continue on these subjects.

**SUMMARY**

The injector complex accounted for >25% of the total LHC root cause duration (corrected for parent/children faults and fault parallelism) during the 2016 LHC proton Run. LHC and injector eLogbook data has been analysed for the 2016 proton run, and the resulting downtimes per injector are summarised in table 1.

Table 1: Summary of injector downtimes during the 2016 proton Run. The percentage values in the downtime for the LHC have been rounded. In the last row the downtimes of the upstream machines have been subtracted to provide the individual machine downtime durations.

<table>
<thead>
<tr>
<th></th>
<th>Linac2</th>
<th>PSB</th>
<th>PS</th>
<th>SPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downtime</td>
<td>6h 20m</td>
<td>11h 45m</td>
<td>9d 10h</td>
<td>4d 19h</td>
</tr>
<tr>
<td>for LHC</td>
<td>(1.8%)</td>
<td>(3.3%)</td>
<td>(62.9%)</td>
<td>(32.1%)</td>
</tr>
<tr>
<td>Total downtime per machine</td>
<td>6d 22h</td>
<td>16d</td>
<td>30d 7h</td>
<td>56d 22h</td>
</tr>
<tr>
<td>Total individual machine downtime</td>
<td>6d 22h</td>
<td>9d 2h</td>
<td>22d 6h</td>
<td>36d 11h</td>
</tr>
</tbody>
</table>

The injector downtime in 2016 has been marked by a few uncorrelated major faults, and mitigation measures have been laid out that should allow increased injector availability for the 2017 Run.

A first version of the injector AFT will be put in place for the 2017 Run, and efforts should continue to improve the fault and availability statistics for the injectors.

Despite a quite bad year 2016 for the injectors, their flexibility has been a big contributor to the success of the 2016 LHC Run and the physics runs of the many experiments served by the different injectors.

**REFERENCES**

Abstract

Run2 (2016) is considered as very successful year. The cryogenic availability indicated by Cryo Maintain (CM) interlock reached the level of 98.6%. Such a good result comes from multiple factors, where operation scenario is a strategic key point for the cryogenic production plants configuration. New operation scenario, with optimization on P18/P2 cryogenic plants, was validated and set as production configuration from 25th March 2016. Helium yearly consumption was on the level of 14% of total inventory. Consolidations and repairs applied during YETS 2015 were effective and resulted directly in improvement of cryogenic stability and availability. Beam screen (BS) heat load was handled without particular problems thanks to optimized feed-forward logic and also by fact that beam parameters were limited by other factors than cryogenics. However, in some cases related heat load deposition was ~50% higher than values assumed for the LHC design. Last year operation period was affected with one major failure of a helium compressor. The system reconfiguration and applied strategy for the cryogenic spare parts allowed for continuous operation of the plant and replacement of defective part during dedicated technical stop.

INTRODUCTION

The cryogenic infrastructure built around LHC ring is composed of 8 cryogenic plants supplying 8 related LHC sectors. Thanks to different intersection piping, various operation scenarios can be set for operation depending on availability of the cryogenic equipment (e.g. because of failure reasons) or optimizing for energy consumption and availability [1, 2]. Each operation scenario is validated with several tests before admittance for operation with physics. Figure 1 presents three operation scenarios applied for Run1, Run2 (2015) and Run2 (2016).

The LHC Run1, with beam parameters lower than nominal, allowed for LHC operation with disabled cryoplants A at P6 and P8 (see Fig.1). The cooling power for both related sectors was provided by plant B. This configuration allowed for electrical power savings over 3 years of operation between 10% and 20% with relation to the installed power.

Run2 (2015) operation scenario was put in place in order to optimize for availability of rotating machines. Thanks to lower than assumed for design heat load at 1.9 K combined with built-in capacity margin on cold compressors, three 1.8 K pumping units could be stopped and kept as hot spares in case of failures.

Run2 (2016) operation scenario was put in production from 25th March after dedicated validation test. This operation scenario completes assumed approach to run one cold pumping unit over two sectors with 4 pumping units off.
GLOBAL CAPACITY OPTIMIZATION FOR SECTORS 2-3 AND 7-8

Sectors 2-3 and 7-8 are equipped with the same type of cryogenic plant upgraded from LEP. Experience of 2015 run shown that global capacity of these two plants shall be investigated and optimized (valid especially for sector 2-3 which is one of the most heat loaded sectors from electron cloud effect). In March 2016 two mentioned plants were tested and optimized reaching capacity limit for BS heat load compensation at the level of 10.3 kW and 9.3 kW for sectors 2-3 and 7-8 respectively (195 W/hc for s2-3 and 175 W/hc for s7-8). The limits are valid for steady state operation with reserved ~50-60 g/s of cold flow for 1.9 K refrigeration.

Adaptability of the cold boxes capacity for the heat load transients was tested with rapid increase and decrease of the heat load delivered by electrical heaters (-/+5 kW for s7-8 and -/+6 kW for s2-3 without losses of CM signal). The corresponding curves are presented in Figures 2 and 3.

Considering real dynamic behaviour of the system with beam, value of 160 W/hc is assumed as guaranteed operation limit applicable for all cryogenic plants of the LHC for next operation year.

POST 2015 REPAIRS, MAIN FAILURES AND OPERATIONAL DIFFICULTIES

During YETS 2015 main cryogenic refrigerator supplying sector 8-1 (QSRB at P8) was repaired for two internal leaks. First leak concerned turbines circuits (mentioned in Evian 2015) and second one concerned Aluminium/Stainless steel transition which was repaired temporarily with special vacuum varnish (related spare part was ordered and is planned to be installed during EYETS). The performed repairs allowed for smooth operation of the cold box during whole 2016 year significantly reducing number of CM signal losses.

Main failures during 2016 concerned two warm compressors (P8 and P4) and two electrical motors for warm compressor station at P2. Additionally two PLCs controlling production plants had to be replaced because of failures.

Five RFL valves, controlling AL turbines operation were replaced. First prototypes of new technical solution to replace the RFL valves are planned to be installed for testing during EYETS.

CRYOGENIC AVAILABILITY

Similarly to LHC Run1, presented cryogenic availability is based on signal from cryo-maintain (CM) interlock and was equal to 98.6 % including only losses generated by cryogenics and to 94.4% including losses generated by users and supply. The analysed operation time window for 2016 started on 25th March and ended on 5th December (TSs were excluded for the analysis). The layout and main contributors for downtime are presented in Fig. 4. Comparison with results from Run1 is provided in Fig. 5.
**Downtime analysis**

The total time of unavailability for Run 2016 was 79h25min caused by 19 losses of CM signal. About 60% of the down time was caused by two main contributors: production plants PLC failures and 1.8 K production plant process failures.

Figure 6 presents a layout of all contributors to the cryogenic down time in 2016.

![Figure 6: Cryogenic down time – contributors](image)

The most frequent losses are attributed to DFBs liquid helium level perturbations caused by non-optimized process. However the number of CM losses was significantly reduced w.r.t. 2015 Run mainly by fact of QSRB P8 repairs and optimization of control system on related DFBs. The global view of number of CM losses is presented in Fig. 7.

![Figure 7: Number of CM losses – contributors.](image)

The cryogenic team focuses to analyse origin and minimize both, most time consuming and most frequent losses.

**Production plants availability**

As shown in Fig. 6, the main contributors to the unavailability are the failures causing stops of the cryogenic production plants (4.5 K main refrigerators and 1.8 K pumping units). Such failures are very unlike because of long time constant for recovery of operation conditions. Thanks to collaboration between the cryogenic group and BE-ICS new improvements to the control system could be introduced over las years. Optimization in operation scenario which allows for stop of 4 over 8 cold pumping units resulted in statistical low down of the number of failures. Figures 8 and 9 show evolution of failures of 4.5 K refrigerators and 1.8 K pumping units respectively. Such operation scenario should be kept as long as it could compensate effectively for heat load coming from the tunnel equipment.

![Figure 8: Statistics of 4.5 K refrigerator failures.](image)

![Figure 9: Statistics of 1.8 K pumping units.](image)

**Helium losses**

Thanks to collective effort in the cryogenic team during Run1, LS1 and Run2 the helium loses were significantly reduced reaching level of 14% of total inventory for 2016 run. The increase of the YETS losses in 2016 relates to the fact that the machine was emptied from helium and some helium was lost during the transients and warm storage on the surface (while in 2015 YETS the helium stayed in the magnets). Additionally, significant contribution (~2.3 t) to the losses comes also from two incidents classified as an operational issues during YETS. Figure 10 presents evolution of the helium losses for Run1 and Run2.

![Figure 10: Helium losses evolution.](image)
BEAM SCREEN HEAT LOAD VS COOLING CAPACITY

The handling of BS heat load during operation year of 2016 was fully under control. The distribution of the heat load in 2016 was similar to one form 2015 with four high loaded sectors and four low loaded sectors. In the first phase of operation, just after restart on the beginning of the year, the maximum loaded sector (s1-2) raised with the heat load to nearly 160 W hc. Then cleaning effect allowed for decrease of the load and operate second half of the year at the level of 90-120 W hc for high loaded sectors and at 40-60 W hc for low loaded sectors. The overview on the heat load distribution over the sectors in 2016 is presented in Fig. 11.

It is important to mention that stable operation of the BS cooling loops during 2016 was a result of multiple parameters. The main improvement applied on local control system was feed-forward logic, which could be tuned and adapted for smooth operation. The second improvement was mentioned in above section optimization of global capacity of the cryogenic plants supplying sectors 2-3 and 7-8. However, stable operation was achieved also due to the fact that beam injection scheme was limited to 72 bunches/train and injections with 144 or 288 bunches/train did not took place in 2016. Fact of non homogenous distribution of the heat load over the sectors is still not understood. Complete warm up of sector 1-2 can give more information on the phenomenon.

EYETS PREPARATION AND MAIN ACTIVITIES

All LHC LSSs and arcs will be emptied from liquid helium and conditioned at about 30 K except of sector 1-2 which will be completely warmed up and conditioned for 31L2 dipole replacement. During extended year end technical stop (EYETS) the following main activities will be performed on the cryogenic system:

- P8 cold box repairs – replacement of AL/SS transition
- P4 and P6 exLEP plants – installation of additional coalescers for oil separation
- PLCs upgrade – up to ~50% of all PLCs
- Replacement of charcoal in 14 adsorbers
- Installation of RFL prototype valves controlling the turbines operation parameters
- Other planned updates of software, maintenance and repairs standard activities.

CONCLUSIONS

The LHC Run2 (2016) is considered as a very successful year for cryogenics with availability at 98.6 % including only losses generated by cryogenics and to 94.4% including losses generated by users and supply. New applied configuration with 4 cold pumping units stopped was a good choice as operation scenario. Declared failures could be mitigated by reconfiguration of the system or by repairs using available spare components. Feed forward logic was optimized and successfully operated during the run. The global cryogenic capacity on sectors 2-3 and 7-8 were aligned with all other cryogenic plants at guaranteed operational values of 160 W hc. Warm up of s1-2 will give additional information to study BS heat load generation. Cryogenic group proposes that Run2 (2017) is operated with the same scenario as 2016. The next operational challenge will be adaptation of the cryogenic capacity to cope with beam injection scheme of 144 and 288 bunches/train.

ACKNOWLEDGMENT

Many thanks to all members of the cryogenic operation and support teams for their engagement and professional approach in 2016 Run.

REFERENCES

Abstract
While the fraction of premature beam dumps has considerably decreased during the 2016 Run in favour of programmed end of fill dumps, still 1 out of 2 beam aborts are non-programmed. The root causes of these are primarily equipment failures as well as UFOs and electrical perturbations. In this contribution we will analyse the premature beam dumps observed in 2016, with an emphasis on identifying recurring failures. An outlook on the planned mitigation strategies for the main contributors to the failure statistics will conclude this paper.

PREMATURE BEAM DUMPS IN 2016
During 2016 operation, 175 fills (out of a total of 762 fills) were brought into Stable Beams for physics production. 84 of these fills were deliberately aborted by the operators, while 86 of the fills were prematurely aborted by the protection systems [1] (not including an additional 9 fills which were aborted due to suspected radiation to electronics effects, which are discussed in [2]). Figure 2 illustrates the distribution of the 86 premature beam dumps on the various root causes. While the majority of equipment systems only exhibit a few premature dumps, 3 main contributors can easily be identified, namely beam losses (primarily due to UFOs), power converter failures and electrical perturbations. These main categories will be analysed in detail in the subsequent sections.

For systems with less than 6 beam dumps, little or no correlation can be found amongst the causes of the premature aborts, and the failure rate appears consistent with the complexity of the respective system. A few noteworthy issues are:

- Out of the 4 premature beam aborts allocated to the collimation system, 3 were traced to drifts of LVDTs on different collimators (used for position measurements and interlocking). As such drifts are typically developing over longer periods in time, a continuous and more proactive way of detecting larger drifts e.g. from Logging Data could be envisaged.
- Half of the 6 premature dumps from the quench detection system (QPS) are due to glitches on the current reading sensors of 600A corrector circuits (used for the inductive compensation of voltage signals). The suspected cause is a non-optimal shielding of the signal cabling which will be improved during the upcoming EYETS.
- Two natural training quenches were observed in the main quadrupole magnet MQ22L8 on 21st of May, respective 3rd of June 2016. This happened during a period of beams duration often above 20 h, and a possible explanation could be the development of a different current sharing in the strands when operating for extended periods at nominal current. No additional training quench was however observed during the second part of the year.
- Dynamic effects of heat load to the cryogenic system during injection and beam dump were very well mitigated in 2016 thanks to the implemented feed-forward in the cryogenic controls system. Only two occasions where cryo-maintain was lost in stable beams were observed, both of which occurred in the long straight section right of IR5 (powering subsector LR5) [3].

As depicted in Figure 1, the duration in stable beams until the occurrence of premature dumps does not show any unexpected correlation, and approaches the expected exponential decay for failures randomly distributed over time. It can be noted however that failures linked to higher beam intensities or the operational cycle (such as RF, collimator position interlocks) tend to occur early on during the fill, while magnet powering failures and quenches typically occurred at the end of longer fills.

Figure 1: Duration in stable beams for premature beam dumps
It should be noted that the above statistics is slightly biased, as after the introduction of the bunch compression and merging scheme (BCMS) and the reduction of the crossing angle in the high luminosity experiments ATLAS
and CMS, the optimal fill length for programmed dumps was first reduced to around 15, and later 10-12 hours which will impact the above distribution for bins $>10$ hours.

TECHNICAL SERVICES

Technical services were identified as the root cause for more than 30% of the premature beam dumps (27 out of a total of 86). This includes 4 dumps related to cooling and ventilation (a water infiltration in the power converter RQ4.L5B1 due to a hose badly crimped on RQT12.L5B1 converter located at the first floor, a failure of a water pump in IR2 as well as 2 interlocks due to low water flow in the water cooled DC cables of circuits RQX.R5 and RQ4.L5B2). The main contribution is given by 23 electrical perturbations which resulted in protective dumps by the Fast Magnet Current Change Monitors (FMCM). 9 of these electrical perturbations were large enough to affect well other systems (such as power converters, RF, experimental magnets, cryogenics...) including the short circuit on the 66kV transformer caused by an animal. Hence a premature dump is unavoidable for these 9 cases.

In 13 cases of electrical perturbations however only 4 magnet circuits, namely RD1.LR1, RD1.LR5, RD34.LR3 and RD34.LR7 were affected. This singularity is due to the use of a power converter using thyristor bridges for direct conversion rather than IGBT switch-mode bridges with an intermediate DC energy storage link. In addition, these converters are connected to the 18kV grid (rather than the 400V grid), hence network perturbations entering CERNs 400kV grid are more visible at this higher voltage level.

Network perturbations typically provoke current oscillations with a peak amplitude of 0.5-1 A at the output of these thyristor based power converters, which in turn would result in a perturbation of the closed orbit in the order of 3-6 $\sigma$ which is largely exceeding the allowed tolerances (in comparison the maximum excursion allowed at the TC1s of IR1 and IR5 for the nominal 2016 optics is in the order of 1 $\sigma$) [4].

While the peak amplitude of the current oscillation strongly depends on the timing, the affected phases and the network configuration at the time of the perturbation, the circuit RD1.LR5 shows a much higher sensitivity to electrical perturbations as compared to the identical magnet powering circuit RD1.LR1. This can be explained by the different network topology of the 18kV grid, as the network of SR1 is a network node and as such much more robust against perturbations, while SR5 is fed through long distribution lines from the machine network of LHC P6).

This singularity of the magnet powering system was already identified several years ago. In conjunction with the power converter group a consolidation project has been launched to produce 4 new switched-mode power converters (850A/700V) to replace the original power converters for these 4 circuits during the EYETS of 2016/17. They have been designed to withstand voltage dips of $\pm 10\%$ continuously on all three phases, up to $-20\%$ on a single phase for 100ms or $-15\%$ on all 3 phases for 100ms without any impact on the output current (see as well EDMS Doc. Nr. 1451491). This will allow to mitigate the majority of protective dumps observed in 2016. A first power converter of this new SATURN family has already been successfully tested in building 287 and will soon be installed in the surface buildings of the LHC. By the end of the EYETS, all 4 power converters will have been exchanged, with the previously used power supply remaining in the SRs as hot standbys. In order to fully qualify the performance of the new power converter type in conjunction with the FMCMs it is highly recommended to perform dedicated tests with deliberate injections of perturbations in building 287 and/or to perform a longer term reliability run in at least one of the surface buildings during the commissioning period following the EYETS.
POWER CONVERTERS

A total of 15 premature beam dumps had their root cause in one of the more than 1700 power converters powering the LHC magnets. Many of the mitigations deployed by the power converter group in previous YETS (consolidation of auxiliary power converters, revision of interlock/alarm strategy for less critical failures...) have proven very successful and little to no correlated faults have been observed during 2016. Six of the failures are allocated to R2E effects, which predominantly occurred in 600A power converters located in radiation exposed areas such as the RR5 around IR1 and IR5. Four failures were allocated to internal/external power converter failures (bad contacts, water fault and an external current lead over temperature), two failures to communication issues, two issues related to the orbit feedback and QPS settings and a last failure due to a spurious trigger in the interface with the magnet interlock system.

UFO’S AND MAGNET QUENCHES

Thanks to the beam conditioning that took place during the 2015 Run, UFO occurrences and subsequent beam aborts and magnet quenches have (only) accounted for 13 premature dumps during the 2016 Run. As depicted in Figure 3, UFO occurrences can be divided in 4 main categories:

- Beam Losses: Four of the premature dumps were triggered by beam losses, three of which in long straight sections and one in the arc of sector 23. The region of 5L1 to 6L1 in particular have shown increased UFO rates. Corrections of BLM thresholds were already applied during the year to further mitigate the impact of UFOs in the long-straight sections.
- Beam Losses in Sector 12: Following the suspicion of an inter-turn short of the main dipole magnet 31L2, the beam loss thresholds in sector 12 have been lowered by up to a factor 10 as one of the mitigation measures to avoid UFO induced quenches [5]. These lower thresholds were deployed in mid-August 2016 and caused 3 out of the 6 additional beam dumps following UFO losses since the change of thresholds.
- Experiments: Three premature beam aborts were caused by the Beam Condition Monitors (BCMs) of the main experiments, namely ALICE, CMS and LHCb, while little or no beam losses were observed on the close-by machine beam loss monitors. Further work is planned within the BLM threshold working group to increase the coherence of beam loss thresholds between the machine and the experiments.
- Magnet Quenches (due to very fast UFOs): Only three UFOs lead to sufficient losses to trigger a beam induced magnet quench during the 2016 Run. It was noted that all 3 magnet quenches occurred during the initial 3 months of operation. Since July 2016, no UFO induced magnet quench was observed, indicating a potential conditioning effect of large and fast UFOs that could lead to subsequent magnet quenches.

In general, the strategy to increase the BLM thresholds in the arcs for 2016 to around 3 times of the expected quench limits has proven very efficient, allowing to achieve a good trade-off between protective dumps due to losses and magnet induced quenches. The strategy might however have to be reviewed after longer shut-downs and/or partial warm-ups of the machine, where a deconditioning effect of the machine could be expected.

Figure 3: UFO’s leading to premature beam dumps by subsequent losses during 2016 operation.

CONCLUSION AND OUTLOOK

The consolidation efforts by all equipment groups have very efficiently mitigated the recurrent failure modes observed prior to 2016 (R2E effects in quench protection system, weakness of auxiliary power supplies of 60-600A power supplies...). Little to no correlation could be identified in the remaining fault distribution for these systems, nevertheless several additional mitigations are planned for the YEETS. Three main fault categories remain to be addressed with the focus on the consolidation of the RD1 and RD34 power converter which will mitigate an additional 15% of the premature dumps observed in 2016. R2E remains a concern for power converters for the coming years. They are however expected to be mitigated with the deployment of FGClite (60A during YEETS, RRs during YEETS 2017-18) and eventually a radiation tolerant and redundant 600A power converter type (LS2). Little gain is expected from further optimisations of BLM thresholds, especially following periods which might lead to a deconditioning of the machine.

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OPTICS CONTROL IN 2016


Abstract

In 2016 the β-functions at the interaction points of ATLAS and CMS have been squeezed down to 0.4 m. This is below the design β* = 0.55 m at 7 TeV and has been instrumental to surpass the design luminosity. Even though the β-beating for the virgin machine was above 100% the corrections reduced it to an rms β-beating below 1% at the two main experiments and below 2% rms around the ring. These results are presented together with the β-beating deriving from the crossing angles in combination with the sextupolar errors in the IRs. A way to correct the errors using sextupolar correctors is referenced and how this could be integrated in the commissioning is outlined. Furthermore, the progress towards an automatic coupling correction is described.

INTRODUCTION

A lot of progress to improve the control of the linear optics has been done since the first optics commissioning in 2009 [1–5]. A better understanding of the non-linear magnetic errors has also been obtained. This includes studies and correction of chromatic coupling [6], non-linear coupling [7, 8], amplitude detuning [9], nonlinear chromaticity [10], and higher order errors in the Interaction Regions (IRs) [11]. This is an area which will continue to grow in importance as the LHC enters a more challenging regime with an even lower β*.

During the proton Run in 2015 a systematic offset of the waist of in IP1 and IP5 was measured [12–14]. This leads to a new correction strategy that was used during the 2016 commissioning. This significantly improved the control of the β*. It was, however, observed in simulations and indicated from measurements that the change of crossing angles have an impact on the β-beating. In this article we outline the request for the 2017 beam commissioning, which also include a correction of this effect. Furthermore, we discuss the plans for a new automatic coupling corrections tool.

Systematic offset of the β*

In 2015 it was discovered that there was a systematic offset of the β* waists in both IP1 and IP5 resulting in an increase of the β*, causing about 5% luminosity loss [12, 13]. From the measurements of the 2015 waist we clearly observe a systematic offset of the position of the waist in the direction of the focusing quad and about 10% β-beating. This was unexpected since the estimates of the magnetic error were unlikely to create such an offset. The assumptions of the gradient uncertainties were based on WISE [15, 16], which provides smaller uncertainty values than [17]. In order to estimate whether the measured errors are compatible with the corrections a test of the significance was done. The assumption is that the corrections from 2016 are reproducing the errors. Using this as an input we performed a z-value test [18], which showed that it was less than 0.04% chance that the errors are following a normal distribution with 0.11% as standard deviation and 0 as mean error. This suggests that the optics errors in the IRs are not well represented by the given RMS uncertainty in the triplet quadrupoles. The propagation of the β-function from the turn-by-turn measurement propagated to the Interaction Points (IPs) would give an accurate β* if quad errors are below 0.04% RMS as expected in [15]. Offsets of the waist of the β-functions are also important to avoid since it may reduce the available aperture. Furthermore, we also investigated the impact of a longitudinal misalignment of the triplet magnets with an RMS of 6 mm. The result shows that the impact is in the order of a few percent and hence is too small to explain the discrepancy.

2016 COMMISSIONING

The problem with the systematic β-function waist offset led to integrate the K-modulation measurements in our calculations. The K-modulation [19, 20] is performed using the two most inner magnets close to the IP. This provides a measurement of the β-function in the entire drift space between the two magnets. The β-function evaluated at the location of the two most inner BPMs are used for the correction tool. Already during the ion optics commissioning in 2015 additional corrections were performed to mitigate this issue [14]. After this experience, the tool for K-modulation measurements was fully automatized to obtain the result on-line [20–22], which then could be used in the corrections. The details of this improved procedure and corrections are described in the following sections.

Improvements in K-modulation Measurements

The K-modulation method has been used to measure the β-functions at the interaction points. The average β-functions in the triplet quadrupoles left and right of the IP can be calculated by measuring the tune changes resulting from a gradient modulation in the quadrupole, as described in [19, 21, 23]. The optics functions are then interpolated towards the IP, thus providing measurements of β* and the position of the waist. The online implementation of the K-modulation tool allows for a faster and more accurate measurement of the β*.

K-modulation measurements are done at injection tunes (Q_x = 64.28, Q_y = 59.31) which are further away from

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third order and coupling resonances than the collision tunes \( Q_x = 64.31, Q_y = 59.32 \).

![Figure 1: Linear fit of horizontal tune data for beam 2 with an illustration of the data cleaning process. The rejected data is shown in blue. An online tool is used to specify the domain of acceptance shown in green.](image)

A cleaning tool has been developed to clean outliers in the tune data online. The domain of acceptance is determined by tracing a parallelogram around the desired data. Figure 1 shows the horizontal tune data for beam 2 obtained after a modulation of the quadrupole left of IP1. The cleaned data, inside the domain of acceptance, is shown in red while the rejected data is shown in blue. This has been a crucial ingredient to clean efficiently the data in short time periods and hence obtain accurate results within the time scale of a minute.

The errors in the tune data are determined as a quadrature of the tune precision (2.5 \cdot 10^{-5}) and the standard deviation resulting from the binning of the BBQ [24] data. The binning is necessary due to the lack of synchronization between the tune data and the quadrupole current data. Linear fits of the data provide accurate \( \Delta P \) measurements, as presented in Fig. 1. The typical uncertainty of the fit is between 0.6 m^2 and 1 m^2.

**Local Corrections**

Local corrections are applied around the IPs where the magnets are individually powered [2]. The idea is to reconstruct the initial conditions at a location outside the IP and then propagate the optics parameters through the lattice as if it were a beam line. The correction is evaluated for both beams and tested for several optics with larger \( \beta^* \). Furthermore, since 2016 the \( \beta \)-functions obtained from the K-modulation are also included in the segment-by-segment technique. Figure 2 shows how the 2015 and 2016 correction both correct the phase beating but it is only the 2016 correction that is able to reproduce the \( \beta \)-function close to the IP. This illustrates why it was only the corrections applied in 2016 that were able to correct the waist shift.

In the case of well calibrated BPMs it is possible to reconstruct the \( \beta \)-functions from the amplitude of the oscillations [25, 26]. The plan was to use the ballistic optics where the triplets were turned off to calibrate the BPMs and then use them with the new calibrations in the calculation of the local corrections. However, the method was not accurate enough to provide a good constraint on the correction but was important for debugging the new K-modulation software.

**Global Corrections**

The local corrections reduced the \( \beta \)-beating to a peak of about 20%. However, to reach a lower \( \beta \)-beating a global correction approach is needed. This is needed since not all the errors are originating from the IPs. The better corrections also provide more margin for other errors in the machine and reduce the luminosity imbalance to a minimum between the experiments. The correction is based on a response matrix approach. The correction method was improved in 2016 by taking the measurement uncertainties into account as weights [27].

By including the results from K-modulation the \( \beta \)-functions at the IP are better corrected, this way minimizing the luminosity imbalance between experiments. In order to find a good trade-off among the observables, corrections are evaluated before they are applied to the machine. The evaluation consists of correcor strengths checks as well as of a prediction of the optics parameters after the correction. This in turn may serve as a figure of merit for the correction weights optimization.

**Results from 2016 commissioning**

After the local and global corrections have been applied in 2016 a final set of measurements with the AC-dipole and K-modulation were taken. As a result of the previously mentioned improvements an unprecedented rms \( \beta \)-beating below 2% was achieved in 2016. Figure 3 shows the \( \beta \)-beating for both beams at \( \beta^* \) of 40 cm. The final results have been filtered from malfunctioning BPMs. The filtering was done through removing faulty BPMs using the SVD and removing the BPMs with too high noise levels [28, 29]. Finally, also a few BPMs were removed since they were not synchronized correctly.

**EFFECT OF CROSSING ANGLES**

The optics commissioning was done without crossing angles in order to maximize the available space for beam excitation. However, the optics was re-measured in June with the crossing angles on. The differences were found to be small and were not impacting the safety of the LHC operation. The discrepancy was, however, still in the order of a few percent. It should also be noted that there were a few months between the two measurements which might also have had an impact. However, the other measurements we have observed with the exact same configuration, with month in between, shows a smaller effect. This indicates that parts of the increase is linked to the crossing angles. The results of a few percent of \( \beta \)-beating is also consistent with predictions from simulations [30]. It is therefore likely that the main part of the difference is deriving from the change in crossing angles. A \( b_3 \) error together with a horizontal offset.
feeds-down to a quadrupolar field and hence changes the \( \beta \)-beating. The effect is the same for an \( \alpha_3 \) error combined with a vertical offset.

**COUPLING CORRECTIONS**

In 2016 there were several observations of coupling changes. A decay-like change of the coupling was first observed in operation and then measured in a MD [31]. There has also been changes of the coupling at different points throughout the cycle. The change in coupling can derive from several sources such as feed down from higher order, with an orbit change or other types of movements. Using measurements of the change of tilt of the quadrupoles it is possible to predict that change in coupling [32]. The results are shown in Fig. 5. As the \( \beta^* \) is squeezed further this effect will enhanced. It has been observed that the BBQ is not reliable for coupling measurements, in particular, for small \( \beta^* \). The method that has been demonstrated to be reliable is to make a coherent driven oscillation of the beam and based on this calculate a correction. In 2016 we demonstrated a correction resulting in below a per-mil of transverse coupling [5] using the AC-dipole. This is the lowest level of coupling ever measured in the LHC. The use of the AC-dipole is limited to low intensity beams. In order to address this limitation the ADT has been equipped with an AC-dipole like excitation. This enables to excite only one bunch even in case the machine is filled with many trains. The data can then be recorded with both the normal BPMs and the DOROS BPMs [33]. This was successfully demonstrated during MDs [31, 34]. The goal for 2017 is to make this into an fully operational tool that can be used by the operators to correct the transverse coupling online.

**2017**

The time needed for the 2017 commissioning will depend on the optics configuration chosen. In case the optics is left unchanged only a re-validation is needed. In case it is decided to commission a new optics a total of 3 shifts are needed for the linear optics. The decision to select nominal or ATS optics will not influence the number of shifts needed for optics corrections.

The non-linear optics commissioning is estimated to need two shifts [30]. The goal is to remove the effect of the crossing angle on the \( \beta \)-beating.

Additional requests are to have 1 shift distributed over the commissioning to test the automatic coupling correction. In order to progress with the \( \beta \) from amplitude [25] half a shift would be needed.

Figure 6 shows the planned commissioning for 2017. The blue part is the linear part of the commissioning and is the same as in the 2016 commissioning. When it is finished it is possible to start with other commissioning activities and when convenient in the schedule continue with the non-linear commissioning of the IR sextupoles correction.

The experience gained in 2016 has shown that the combined ramp and squeeze does not pose an obstacle in reaching a good optics correction. The optics correction will therefore not set a limit on the available reach with the ramp and squeeze in 2017.
CONCLUSIONS

The LHC optics has been successfully commissioned down to $\beta^*$ of 0.4 m at 6.5 TeV, which is lower than the design value of 0.55 m at 7 TeV. This is the lowest operational $\beta^*$ used in the LHC and hence the most challenging configuration so far. Even so an unprecedented $\beta$-beating in a high energy proton collider has been achieved. These results have only been possible due to the recent improvement in obtaining $\beta$-functions on-line from the K-modulation, the incorporation of these results in the local and global corrections, the use of appropriate weights on the different optics parameters, the longer AC-dipole plateau, the N-BPM method and the reduction of the orbits drifts from the quadrupole movements. The effect deriving from the sextupolar errors in the IRs in combination with crossing angles is proposed to be corrected in 2017. This should help reducing the $\beta$-beating further for the operational beams.

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From this point other commissioning activities can start

Figure 6: The proposed schedule of the optics commissioning in 2017. The blue part is the linear commissioning and is the same as in 2016. The yellow part is the non-linear commissioning and can be done in parallel with other commissioning activities.


NONLINEAR OPTICS COMMISSIONING IN THE LHC


Abstract

So far, the LHC has operated without any dedicated commissioning of the nonlinear optics at top energy. As $\beta^*_{\perp}$ is reduced however the impact of nonlinear errors in experimental insertions may become sizable. Below $\beta^*_{\perp} = 0.8\,\text{m}$ and in particular with possible LHC configurations approaching $0.3\,\text{m}$, an operational impact from uncompensated nonlinear errors in the IRs is to be expected. Notably the contribution of normal octupole errors in IR1 and IR5 to the tune footprint becomes comparable to that created by the Landau octupoles, with implications for the performance of instrumentation and Landau damping of instabilities. In the HL-LHC compensation of IR-nonlinear sources may become a critical issue, with feed-down from IR-sextupole errors having the potential to generate substantial linear optics perturbations. This effect will require an evolution of the linear optics commissioning strategy in the LHC and HL-LHC. Current understanding of the impact of these errors and our ability to correct them will be reported. Nonlinear optics commissioning activities undertaken elsewhere in the machine cycle will also be introduced.

IR OCTUPOLE COMPENSATION

Normal octupole fields create an amplitude dependent tune spread, or tune footprint, within a bunch. For damping of instabilities in the LHC it is generally desired to introduce such a tune spread in a well controlled manner using the Landau octupole magnets located in the LHC arcs, however any octupole source present in the ring will contribute (discussion here is restricted to octupoles which dominate the tune spread for the configurations being considered, however feed-down from higher-order multipoles and feed-up from lower orders will in principle also apply).

The shape and size of the tune footprint may be quantified by its amplitude detuning coefficients. These are first and higher-order terms in a Taylor expansion describing the tune as a function of the action coordinates ($J_{x,y}$, where $x = \sqrt{2/3}\beta_x J_x \cos \phi_x$). At top energy amplitude detuning can be measured directly using the AC-dipole [1]. Figure 1 shows the amplitude detuning measured at $\beta^*_{\perp} = 0.4\,\text{m}$ during 2016 commissioning. Also shown is the detuning predicted by sixty seeds of LHC magnetic errors.

The measured amplitude detuning is $\sim 2/3$ of what is expected from the LHC magnetic model. This discrepancy precludes simple application of corrections calculated directly from the magnetic model. Correction is desired however, since in spite of being smaller than expected the measured detuning is still $\sim 1/3$ of that generated by the Landau octupoles in 2016. As linear optics in the IP is squeezed further, the contribution of IR octupole errors to the amplitude detuning increases with $\sim (1/\beta^*_{\perp})^2$. This is illustrated for the detuning coefficients in Fig. 2, which are quoted in terms of equivalent Landau octupole currents required to generate the same value of the detuning coefficient as due to the IR octupoles.

The impact of normal octupole errors in experimental insertions on tune spread is not a small effect, and can have several operational impacts. Since 2012 it has been observed that online measurement of linear coupling using the LHC BBQ could not be trusted with strongly powered Landau octupoles present in the machine [2, 3]. This is the result of an increased noise floor in the frequency spectrum due to larger tune spread with Landau octupoles powered. At low-$\beta^*_{\perp}$ however, IR octupole errors mean the LHC operates in a comparable regime even with Landau octupoles powered off. Below $\sim 0.8\,\text{m}$ therefore the online BBQ measurement of linear coupling should not be trusted.

During operation for luminosity production the LHC operates with strong Landau octupoles. The settings of these magnets are generally constant during the $\beta^*$ squeeze, and being located in the arcs the tune spread they generate is effectively unchanged throughout a nominal squeeze. The detuning generated by IR octupole errors, which as seen in Fig. 2 changes significantly during the squeeze, sums with the contribution from the Landau octupoles. Since the pattern of detuning generated in the IRs can differ quite significantly from that conventionally applied with the MO, this leads to considerable distortion of the tune footprint as the squeeze progresses. This is illustrated in Fig. 3 which shows the tune footprint obtained from effective models of detuning measurements, with Landau octupoles powered as applied during 2016 operation. Grey regions show the footprint expected in the absence of the IR contribution, red regions show the expected footprint in the real LHC if IR octupole errors are left uncompensated.

The distortion of tune footprint shown in Fig. 3 at small $\beta^*$ is substantial. Due to self cancellation of the IR contribution the detuning cross term is largely unaffected. Detuning of $Q_y$ with $J_y$ features a cancellation between the IR and Landau octupole contributions. In contrast detuning of $Q_x$ with $J_x$ is significantly enhanced. By $0.33\,\text{m}$ the footprint in the machine will bear little relation to that desired through application of the MO. Such a distortion of the tune spread within a bunch will impact the stability of the LHC beams. Figure 4 shows the stability diagram calculated from the expected tune spread at $\beta^*_{\perp} = 0.33\,\text{m}$. A significant reduction to stability is seen in the vertical plane,
Figure 1: Measured amplitude detuning at 0.4 m with Landau octupoles powered off.

Figure 2: Extrapolated amplitude detuning due to normal octupole errors in IR1 and IR5, expressed in equivalent powering of the Landau octupoles. Extrapolation is based on effective models which reproduce the observed detuning at 0.4 m and 0.6 m. The maximum powering of the Landau octupoles is 570 A.
Figure 3: Distortion of tune footprint through the $\beta^*$ squeeze. Plotted footprints are defined by first-order detuning coefficients obtained via simulation with PTC\_NORMAL. The model used consists of an effect model of the normal octupole errors in IR1 and IR5, which reproduces the observed detuning at $\beta^* = 0.4 \, \text{m}$, together with Landau octupoles powered as per operation for Luminosity production in late 2016. Grey regions show the footprint expected in the absence of the IR contribution, red regions show the expected footprint in the real LHC if IR octupole errors are left uncompensated.
while the horizontal increased. The predicted change to stability threshold implied by Fig. 4 is unlikely to be a critical challenge to operation at this stage, however it may require an increase to minimum Landau octupole powering. At some $\beta^*$ however, perhaps in the HL-LHC, it can be expected that the Landau octupoles will run out of strength to generate the tune spread required for the damping of instabilities in the presence of the IR octupole contribution. More generally the variation of the tune spread through the squeeze significantly complicates any attempt to understand and compensate for instabilities in the beam motion. For these reasons implementation of local corrections for IR octupole errors is now becoming a priority from the optics commissioning perspective.

![Figure 4: Simulated stability diagram of the LHC at $\beta^* = 0.33$ m, with and without the IR octupole detuning contribution.](image)

Local correction of the IR octupole errors can in principle be performed using dedicated $b_4$ correctors located on the left and right sides of the experimental IRs. As discussed previously however, straightforward correction based upon the magnetic measurements is not possible due to the observed discrepancy with the beam-based measurements (Fig. 1). Amplitude detuning coefficients relate directly to the octupole Hamiltonian terms it is desired to correct, and given the small phase advance over the experimental IRs locally correcting the contribution of each IP to the detuning coefficients should also minimize the resonance driving terms generally. Amplitude detuning however is a global observable and cannot distinguish between the contributions of IR1 and IR5, which together dominate the observed detuning.

To assess locally the octupole errors in the insertions, feed-down to tune was measured as a function of crossing angle in each IP individually. It was found that the second order feed-down to tune in IR1 agreed well with predictions based upon magnetic measurements. This is shown in Fig 5. In contrast the IR5 observations did not agree, and showed a notably reduced second order feed-down relative to expectation. The feed-down measurements alone are too under-constrained to facilitate an understanding of the observed discrepancies or for straightforward calculation of octupole corrections. By validating the magnetic model of normal octupole errors in IR1 however, it allows the contribution of IR1 and IR5 to the amplitude detuning to be distinguished. Corrections for the normal octupole errors were therefore determined by applying the nominal $b_4$ in IR1 (as calculated from the validated magnetic model) then minimizing the residual detuning with correctors in IR5. The success of the correction was then validated by measuring directly the $f'_{4000}$ resonance driving term (which contributes to the $4Q_x$ resonance) before and after application of the corrections. Figure 6 shows that application of corrections in IR1 and IR5 both served to compensate the octupole resonances in the accelerator.

![Figure 5: Measured and modelled feed-down to $Q_x$ at $\beta^* = 0.4$ m, as a function of a vertical crossing angle orbit bump applied through IR1. Simulated predictions for the sixty wise seeds are shown in blue. An effective model for the skew sextupole errors has been utilized to compensate for a discrepancy in the linear part of the feed-down.](image)

One of the key advantages to correcting IR-octupole errors locally is that the corrections are approximately independent of $\beta^*$. The IR1 correction applied to minimize detuning at 0.4 m was also observed during 2012 to compensate second-order feed-down to tune as a function of crossing angle at 0.6 m [4]. More significantly when lifetime challenges were encountered during an ATS MD [5] at $\beta^* = 0.14$ m application of the $b_4$ correction determined at 0.4 m was observed to give a significant improvement to beam lifetime. This is illustrated in Fig. 7, which shows the fractional intensity change calculated from two minutes prior to application of the IR octupole correction (red), compared to the fractional intensity change calculated from the end of the $b_4$ correction trim. Data during the time the correction was being applied is excluded due to transient losses generated by tune feed-down.

The studies of IR octupole correction performed during 2016 commissioning and MD time have validated our ability to compensate IR octupole errors in the LHC. For the reasons outlined above it is desired to implement these corrections operationally in 2017. The corrections have been consistent between 2012 and 2016, and shown to be valid over a wide range of $\beta^*$. Commissioning of this aspect
Figure 6: Histograms of the $f_{4000}$ resonance driving term measured at the location of $\sim$ 500 LHC BPMs. Measurements are shown without correction for normal octupole errors in the experimental insertions, with only corrections in IR1 applied, and with corrections in IR1 and IR5.

Figure 7: Surviving fractional intensity determined from LHC BCT data. The fractional intensity is calculated from a time 2 minutes prior to application of the IR octupole correction (red), and for two minutes from the time the correction trim completed. Data while the trim was taking place is excluded due to transient losses generated by tune feed-down.
of the nonlinear optics should therefore be straightforward, requiring only $\sim 1/2$ shift for re-validation of the $b_4$ correction tested in 2016.

**IR SEXTUPOLE IMPACT**

Normal octupoles are not the only errors in experimental insertions which are of concern in regard to beam optics. During operation for luminosity production the LHC and HL-LHC will operate with significant crossing schemes applied. Due to the offset of the beams through IR magnets however, the nonlinear errors will feed-down to generate linear optics perturbations. Given the small $\beta^*$, optics errors in the HL-LHC have the potential to pose serious operational challenges. Figure 8 shows histograms of simulated beta-beating in the HL-LHC at $\beta^* = 0.15 \text{ m}$ due to feed-down from normal and skew sextupole errors for a $295 \mu \text{rad}$ crossing scheme. Simulations were performed over sixty seeds of the target error tables for the HL-LHC. The peak $\beta$-beating around the HL-LHC ring is shown in blue, and the $\beta^*$ imbalance between ATLAS and CMS is shown in red.

In several of the seeds considered IR-sextupole feed-down alone generated a $\beta$-beat which exceeds safe limits for machine operation. A significant number of seeds also fail to provide sufficient margin in the linear optics quality to accommodate residuals from the linear optics commissioning or $\beta$-beating from beam-beam within machine protection limits. Finally the $\beta^*$ imbalance between ATLAS and CMS is intolerably high in the majority of seeds considered. Correction of IR-sextupole errors is likely therefore to be an operational issue in the HL-LHC.

Measurements of beta-beating in the LHC in 2016 imply a peak beta-beat from IR feed-down at about the 3 % level [6], however measurements were not performed concurrently and may therefore include a contribution from the drift of $\beta$-beating with time. The 3 % figure is of a comparable magnitude to the $\beta^*$ imbalance obtained in simulation with effective models of the sextupole errors, which reproduce measurements of tune feed-down as a function of crossing angle at 0.4 m. While not a concern in regard to machine protection in the LHC, such an imbalance will scale linearly with $\sim 1/\beta^*$ and is thus a key limitation to achieving the desired optics quality in the LHC. Further, given the significant challenge IR feed-down may pose to optics commissioning in the HL-LHC, it will be important for the optics team to gain experience commissioning for $b_4$ and $a_3$ errors in the LHC before compensation becomes a machine protection issue.

Initially optics commissioning should proceed as normal, with local and global corrections determined for a flat orbit. As the IR-sextupole correction does not currently represent a machine protection issue, commissioning of the nonlinear optics may then proceed in parallel with other commissioning tasks. Feed-down to tune and coupling will be measured as a function of the crossing scheme, and where beam-based and magnetic measurements agree the nominal corrections determined from the magnetic model can be applied [4]. Where magnetic measurements are inconsistent with observations of the machine, beam-based corrections can be performed by minimizing the tune shift with crossing angle using dedicated correctors in the IRs. In simulation this is shown to reduce beat-beating. Linear optics quality can then be rechecked with crossing angles applied. If necessary additional corrections to the quadrupole magnets can be applied to optimize the linear optics quality with the crossing scheme present in the machine. Nonlinear optics commissioning would therefore require two shifts: one to perform initial measurements of the sextupole errors (in conjunction with validation of the normal octupole corrections), and one to implement the sextupole correction and perform final linear optics checks.

**CHROMATIC COUPLING**

Chromatic coupling is the first-order change of $|C^+|$ with $\delta_\phi$. It is generated by skew sextupoles in horizontally dispersive regions, and normal sextupoles in regions of vertical dispersion, with the former being the dominant source. It can be quantified by measuring the change of the $f_{1001}$ resonance driving term as a function of relative momentum offset with AC-dipole kicks. Consequently it can be measured for free when measurements of normalized dispersion are performed during linear optics commissioning.

Correction of the chromatic coupling using skew sextupole correctors in the LHC arcs was demonstrated during dedicated machine development tests in Run 1 [7]. An example of a successful correction at 4 TeV in 2012 is shown in Fig. 9. Corrections were also calculated in 2015, but compensation of chromatic coupling has never been implemented operationally. Since correction should allow for an improved control of linear coupling with a negligible commissioning overhead, it is desired to incorporate correction of chromatic coupling into the standard suite of optics commissioning activities in 2017.

**NONLINEAR DYNAMICS AT INJECTION**

At injection in the LHC, octupole and decapole errors in the main dipoles are supposed to be compensated via octupole and decapole spool piece corrector magnets mounted on the ends of every second dipole. Measurements of amplitude detuning and nonlinear chromaticity at 450 GeV during Run 1 revealed normal octupole sources in the arcs approximately an order of magnitude larger than expected [9, 8]. This has since been explained through hysteresis effects of the octupole spool pieces in combination with an unexpected influence of the decapole spools on the octupole fields [8, 12]. The decapole correction was also found to be a factor $\sim 2$ stronger than required to compensate the decapole errors, leading to substantially larger third-order chromaticity than expected. The source of the decapole discrepancy remains unknown.
Figure 8: Simulated $\beta$-beat due to IR sextupole feed-down in sixty seeds of the HL-LHC error tables at $\beta^* = 0.15$ m, 295 $\mu$rad.

Figure 9: Change of the linear coupling resonance driving term with relative momentum offset, as measured in the LHC BPMs, before (red) and after (blue) correction of chromatic coupling using skew sextupole correctors in the arcs.

Annual measurements of second and third order chromaticity have demonstrated the situation at injection to be extremely stable. Figure 10 compares the nonlinear chromaticity measured in 2011 to that measured in 2015.

Beam-based minimization of the nonlinear chromaticity using the octupole and decapole spool pieces was tested in MD during Run 1 [11]. It was shown to also improve amplitude detuning, dynamic aperture, and the decoherence of kicked beams [10]. Figure 11 shows an example of the decoherence of kicked beams before and after application of the beam-based octupole and decapole corrections. During Run 2 beam-based correction of the nonlinear chromaticity at injection has been implemented in conjunction with linear optics commissioning [12].

The above discussion concerns the situation at injection with depowered Landau octupoles. During regular operation the Landau octupoles are powered. In 2016 there was a substantial increase in their strength applied at injection, leading to some concerns over the impact on dynamic aperture.

In 2012 Landau octupoles were powered $\sim 6$ times
weaker than in 2016. In this case the single particle dynamic aperture (for $\sim 3 \times 10^5$ turns) was limited by the third and fourth order resonances, reached at $\sim 9 \sigma_{\text{nominal}}$ [10]. In 2016 DA was measured at injection using both AC-dipole and single kicks during MD. The short term DA with AC-dipole was again limited at the third order resonance, around $\sim 2 \sigma_{\text{nominal}}$. This is consistent with the expected change in detuning relative to 2012 due to increased octupole powering and the effect of the driven oscillation [1]. Single kicks encountered the third order resonance at $\sim 4 \sigma_{\text{nominal}}$, consistent with the AC-dipole measurement. Unlike 2012 however only modest losses were observed. It was possible to kick the beam beyond the third order resonance, reaching an ultimate DA limit at $\sim 7 \sigma_{\text{nominal}}$. Figure 12 shows the fractional intensity loss after $1 \times 10^5$ turns for the applied kicks during the 2016 dynamic aperture MD. Figure 13 compares the measured DA to the predicted DA over the same time-scale in SIXTRACK. It is seen that the simulated DA agrees well with the DA limit observed beyond the third order resonance. Losses at the third order resonance were not observed in these SIXTRACK simulation however, potentially implying some missing sources in the model. Still, while DA has clearly been reduced relative to 2012, with the $3Q_y$ resonance now being reached at $4 \sigma_{\text{nominal}}$ as opposed to $9 \sigma_{\text{nominal}}$, the situation in terms of dynamic aperture does not appear to be critical in spite of the dramatically increased Landau octupole powering in 2016.

**CONCLUSION**

As $\beta^*$ is reduced in the LHC, the contribution of normal octupole errors in experimental insertions to the tune footprint becomes an operational concern. Their influence is expected to be detrimental to the performance of beam instrumentation, and distortion of the footprint through the squeeze has a negative influence on the damping of instabilities. Correction of IR-octupole errors was achieved during 2016 through a combination of feed-down and amplitude detuning based studies. The positive effects of the correction have been validated through direct observation of octupole resonances and beam-lifetime. It is desired to incorporate this correction operationally in 2017.

Sextupole errors in experimental IRs also become a concern at small $\beta^*$, as feed-down from these errors has the potential to generate linear optics perturbations. In the HL-LHC compensation of these errors is a concern in regard to both machine protection and the luminosity imbalance between the ATLAS and CMS experiments. At this stage, correction of IR-sextupole errors is not believed to be a critical issue in the LHC. Given the considerable challenges facing optics commissioning in the HL-LHC however, it is desired to incorporate these effects into the LHC optics.

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**Figure 11:** Decoherence of kicked LHC beams at injection, before and after application of beam-based corrections for the nonlinear chromaticity.

**Figure 12:** Fractional intensity loss $10^5$ turns after application of AC-dipole and single kicks at injection.

**Figure 13:** Comparison of $10^5$ turn DA simulations in SIXTRACK, to single-kick measurements performed in the LHC at injection.
commissioning strategy with a view to gaining the experience necessary to ensure successful operation after the high-luminosity upgrade.

It is also desired to incorporate correction of chromatic coupling operationally in the LHC. Control of coupling is essential to the successful operation of the LHC, and compensation of its momentum dependence can be achieved with a negligible commissioning overhead. At injection beam-based compensation of octupole and decapole errors has been applied operationally since the start of Run 2, again with a negligible overhead. During operation in 2016 Landau octupoles were powered significantly stronger than in previous years, however measurements and simulations do not reveal any critical challenge to such an operational scenario arising from the dynamic aperture.

ACKNOWLEDGMENTS

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REFERENCES


EXPERIENCE WITH ATS OPTICS

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Abstract

The Achromatic Telescopic Squeezing (ATS) scheme is a novel optics concept which was built up in order to cope with the optics requirements of the HL-LHC, i.e. a clean (achromatic) and strong reduction of $\beta^*$ compared to the LHC nominal optics. This paper will summarize the status of the optics and the experience gained during the 2016 LHC run through a series of dedicated machine development sessions, following the first ATS tests which actually took place in Run I (2011-2012).

INTRODUCTION

The Achromatic Telescopic Squeezing (ATS) scheme is a novel optics concept enabling the matching of ultra-low $\beta^*$ in the LHC (and other hadron circular colliders), while correcting the chromatic aberrations induced by the inner triplet [1]. This scheme is essentially based on a two-stage telescopic squeeze. In a first phase, a so-called pre-squeeze is achieved by using exclusively, as usual, the matching quadrupoles of the high luminosity insertions IR1 and IR5. In a second phase, the squeeze continues by acting only on the insertions located on either side of IR1 and IR5 (i.e. IR8/2 for the telescopic squeeze of IR1, and IR4/6 for IR5). As a result, sizable $\beta$-beating bumps are induced in the four sectors on either side of IP1 and IP5. These waves of $\beta$-beating are then also necessary in order to boost the efficiency of the chromatic correction performed at constant strength by the lattice sextupoles located in the sectors 81, 12, 45 and 56. In principle the first and second phases can be exchanged, interleaved or even be run in parallel (e.g. to further gain in squeeze time), as soon as the first phase has pushed $\beta^*$ below a transition $\beta^*$ of the order of 2 m.

The ATS scheme forms the keystone of the HL-LHC project and its complete validation at high intensity is therefore a very important milestone in the overall upgrade plan of the LHC. The first series of ATS MDs took place in Run I (2011 and 2012), where most of the ATS principles were demonstrated, but only with pilot beams:

- the first ATS MD [2] commissioned the new ATS injection optics and its ramp up to 3.5 TeV,
- the second ATS MD [3] demonstrated an achromatic pre-squeezed optics with $\beta^* = 1.2$ m at IP1 and IP5, and then a further squeeze of IR1 down to $\beta^* = 30$ cm using the telescopic techniques of the ATS scheme,
- the third ATS MD [4] pushed the pre-squeezed $\beta^*$ down to 40 cm at IP1 and IP5,
- the fourth ATS MD [5] deployed the telescopic part of the squeeze in order to reach $\beta^* = 10$ cm, both in IR1 and IR5, starting from the above pre-squeezed optics at $\beta^* = 40$ cm.

A common feature is however systematically present in all LHC and HL-LHC ATS optics versions developed so far. It concerns very unfavorable phase advances, nearly equal to 90 degrees in the horizontal plane, between the extraction kickers in IR6 and some tertiary collimators TCTs in IR1 and IR5, in particular the most exposed one in case of asynchronous dump (TCT.R5B2). When discussing the possibility to directly use ATS optics in order to restart the LHC after LS1, this feature was showed to be a clear weakness of ATS optics for the LHC [6], which rapidly discarded this option, but also raised some question marks related to the $\beta^*$ reach of the HL-LHC. In practice, it also prevented to gain real experience and confidence with ATS optics at high intensity. Very recently, a new generation of ATS optics was then deployed in order to bring a definite cure to the above mentioned problem, offering phase advances very close to optimal (within 20 - 30 degrees) between the MKDs and TCTs, for both beams and both IR1 and IR5 [7]. The next section will discuss the status of the new ATS optics generation, while the main results obtained during the 2016 ATS machine development sessions will be highlighted in the third section.

ATS OPTICS NEW GENERATION: A SUMMARIZED OVERVIEW

In order to match an horizontal phase advance close to optimal between the extraction kicker MKD in IR6 and the TCTs of both beams in both IR1 and IR5, i.e. close to 0 or 180 degrees, the non-connectivity of the IR6 tunability diagram [8] was used (see Fig. 1). More precisely, the dump insertion was rematched at more or less constant vertical phase but with a phase shifted by $\pi/2$ in the horizontal plane. Due to the missing Q6 and Q7 in IR6, this phase shift is actually confined in a new waist of the beta-functions located on the right side of the MKD for beam1, and on the left side for beam2 (see Fig. 2). This localization is optimal to pass from a worst to good configuration in terms of phase advance between the LHC extraction kickers and the TCTs of both beams in IR5. For IR1 the MKD-TCT phase optimization can be achieved at constant tune using other sources of optics flexibility, as for instance the main quadrupoles of sectors 23/34/67/78. This change being done, the phase advances of other insertions were also

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Figure 1: IR6 tune-ability diagram (from old LHC layout version [8]). The jump from one disconnected domain to the other requires to remove some optics constraints during the jump. The different tunability domains explored so far are emphasized for the nominal optics, the various versions of the Phase I optics [9], and the previous generation of ATS (LHC and HL-LHC) optics.

Figure 2: Modification of the dump insertion optics when shifting by \( \pi/2 \) its overall horizontal phase. This shift is confined on the right and left sides for beam1 and beam2, respectively, which is fundamental to correctly settle the MKD-TCT horizontal phase advance for both beams from IR6 to IR5, without compromising on any ATS optics functionalities.
modified in order to improve their functionality (e.g., IR4 for increasing the beta functions at the BSRT, similarly to the changes of nominal optics deployed between 2014 and 2015, or IR2 in order to improve its squeeze-ability for ion operation), but without compromising on the compatibility with the telescopic squeeze. The overall tunes were then rematched to 62.31/60.32 (62.28/60.31 at injection), while keeping the horizontal and vertical phase advances between IP1 and IP5 strictly equal to those of the nominal optics, let us say for a sake of precaution with respect to beam-beam effects. It is however worth noting that this phase is totally free of constraints in the vertical plane only. It was scanned during the last ATS MD at $\beta^{*} = 33$ cm in the presence of head-on beam-beam effects (no long-range), showing some potential gain in beam lifetime by up to a factor of 2 to 3 (which justifies further investigations in the LHC to fully optimize it with beam). This new LHC phasing configuration being defined, a brand new set of optics and the corresponding LHC hypercycle were built up, and extended with the telescopic part of the ATS squeeze down to a $\beta^{*}$ of 10 cm at IP1 and IP5.

For the injection, the ramp and the pre-squeeze, the basics of the nominal LIJC hypercycle were closely followed, but also improved whenever it was found to be possible or needed (see [10, 11] for more details), with in particular:

- a combined ramp and squeeze (see Tab. 1), ending up with a $\beta^{*}$ of 3 m at IP1, IP5 and IP8, and 10 m at IP2 (compared to 3m/10m/3m/6m at IP1/2/5/8 for the nominal cycle), and which also warrants the 7 TeV equivalent gradient of all triplet quadrupoles to be less than 205 T/m, in particular in IR2 and IR8,

- a squeeze duration of only 470 s from $\beta^{*} = 3$ m down to 40 cm at IP1 and IP5 (more than a factor of 2 shorter than the 1070 seconds taken by the nominal squeeze used for operation in 2016), only 8 intermediate matched optics from 3 m to 40 cm (see Tab. 2), and linear optics distortions not exceeding the 1% level between two consecutive matched points.

The beam process containing the telescopic part of the squeeze is then described in Table 3, with as well 8 intermediate matched optics from 40 cm to 10 cm, and taking a little bit more than 800 seconds (see [12] for more details). For each optics, new correction knobs, standard and ATS specific ones (for tune, chromaticity and coupling, but also for correcting the spurious dispersion induced by the cross-ing angles) were made available, together with the spool-piece and tune shift quadrupole settings, and the IP knobs (crossing bumps) for the four experimental insertions. Empirical settings and additional knobs were also directly im-ported from the nominal LHC cycle and successfully re-used, namely:

- the closed orbit corrector settings of the flat machine at injection, which allowed to thread the beam immediately following the first injection during the first ATS MD of the year,
- the tune and chromaticity empirical correction for the entire ramp (on top of FIDeL), which certainly contributed to the immediate success of the first ATS ramp,
- the local coupling and optics correction knobs (i.e. the MQSX pre-settings and MQX trims for controlling the triplet induced coupling and $\beta$-beating during the squeeze) [13, 14, 15, 16, 17], which granted a smooth pre-squeeze ending up with not more than 15-20% $\beta$-beating at $\beta^{*} = 40$ cm before further global correction (see later).

In order to further accelerate the overall squeeze process, a certain fraction of the pre-squeeze from 3 m to 40 cm could still be accommodated in the ramp. More precisely, a $\beta^{*}$ of about 1 m at IP1 and IP5 (and 10 m/3 m at IP2/8) seems to be a reasonable target for the end of the ramp, offering a sufficiently large normalised crossing angle in order to neglect the long-range beam-beam effects at flat top, while reducing the pre-squeeze segment by about 200s (see Table 2). Furthermore, below a pre-squeezed $\beta^{*}$ of 2 m, it is worth reminding that pre-squeeze (IQP functions in IR1/5) and telescopic squeeze (IQP functions in IR8/2/4/6) are modular enough to be combined (exchanged or interleaved). All together it is therefore not at all excluded to envisage a scenario where the 470 seconds of the present pre-squeeze could be re-distributed over the ramp and the telescopic squeeze for the HL-LHC, and something similar for the LHC. On the other hand the 40 cm ATS pre-squeezed optics needs to be re-optimized with respect to the version tested in 2016 in order to improve the beam conditions, more precisely the normalised dispersion, at the roman pots of the forward physics experiments (AFP and CT-PPS). A snapshot of this new optics is ready, together with new possible position of the roman pots [18], and offering beam conditions very close to the ones achieved in 2016 for these two experiments. The new optics transition (from 2 m to 40 cm) remains however to be worked out. In this exercise the pre-squeeze duration is expected to re-increase by about 200 s due to the net reduction of the Q6 gradient at $\beta^{*} = 40$ cm, being noted that the telescopic part of the squeeze will not be impacted by the re-manipulation of the pre-squeeze sequence.

Finally, amongst the other optics work to be completed in order to reach to same level of readiness as for the nominal optics, it is worth mentioning (i) the squeeze sequence of IR2 from 10 m to 50 cm for ion operation (being said that an optics snapshot with $\beta^{*} = 50$ cm at IP2 is demonstrated for the new IR2 phase advance), (ii) the de-squeeze sequence of IR1/2/5/8 towards $\beta^{*}$ values of 20-30 m for so-called "Van der Meer optics" (which is expected to be a non-issue), and towards $\beta^{*} = 90$ m for TOTEM-like experiments (being said that a new snapshot of the 90 m optics is available, rematched to the new arc optics and with the new IR1/5 phase advances).
Table 1: Beam process RAMP-SQUEEZE-6.5 TeV-ATS-3m-2016 V1 for the ATS combined ramp and squeeze. The first matched points at constant optics are used for orbit correction in the early part of the ramp. The squeeze proper starts at step number 8 (≈ 2.4 TeV) and is finished at step number 18 (≈ 6 TeV). $\beta^*$ is reduced from 11 m (resp. 10 m) down to 3 m at IP1 and IP5 (resp. IP8). It is kept constant and equal to 10 m at IP2, but the overall IR2 optics is still modified with in mind its compatibility with 7 TeV operation (205 T/m for the maximum allowed 7 TeV equivalent gradient of the triplet quadrupoles).

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Table 2: Structure and timing of the ATS pre-squeeze (SQUEEZE-6.5 TeV-ATS-3m-40 cm-2016 V1) from $\beta^* = 3$ m down to $\beta^* = 40$ cm.

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Table 3: Structure and timing of the telescopic squeeze (SQUEEZE-TELE-6.5 TeV-ATS-40 cm-10 cm-2016 V1) from $\beta^* = 40$ cm down to $\beta^* = 10$ cm. For practical reasons when running the MDs proper, this beam process was actually split into two separate pieces, above and below $\beta^* = 33$ cm, but without changing the functions and timing of each segment.

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HIGHLIGHTS FROM THE 2016 ATS MACHINE DEVELOPMENTS

Out of the 5 MD blocks programmed in the 2016 LHC schedule, ATS activities were organized in block 1 (with two shifts of 10 h and 8 h on 27/7/2016 and 30/7/2016, respectively), and in block 3, 4 and 5, with one 10 h shift for each of these three blocks (11/9/2016, 3/10/2016 and 29/10/2016, respectively). Two types of ATS MDs took place, namely:

- MDs for optics measurements and correction in block 1 (down to $\beta^* = 40 \text{ cm}$) and block 4 (down to $\beta^* = 10 \text{ cm}$), achieved with probe beams, with the crossing bumps generally switched off and relaxed collimator settings in order to maximize the available aperture, and with all maskable interlocks actually masked,

- MDs with a major component related to collimation in block 3 (at $\beta^* = 40 \text{ cm}$) and block 5 (at $\beta^* = 33 \text{ cm}$), run with (quasi-)nominal collimator settings in IR3/6/7, and with a filling scheme containing two nominal bunches (to establish collisions at the four IPs) and/or sparse non-colliding pilot bunches (for loss maps and/or aperture measurement).

**ATS MD in block 1: 40 cm pre-squeezed optics with probe beam**

The primary goal of the first ATS MD was to commission, i.e. to establish, measure and correct, the new ATS injection optics, its ramp up to 6.5 TeV, and the pre-squeeze down to $\beta^* = 40 \text{ cm}$ at IP1 and IP5 (3 m at IP8), using low intensity (pilot) beams and a flat machine (crossing bumps switched off). As for any optics commissioning, the following activities were planned:

- beam threading, orbit, tune, chromaticity and coupling corrections at injection,

- then the demonstration of the ramp with optics measurement taken on the fly,

- followed by the (pre-)squeezing with optics measurements and correction at some intermediate $\beta^*$ and at $\beta^* = 40 \text{ cm}$, including as well the first analysis of the chromatic properties of the pre-squeezed optics (non-linear chromaticity, off momentum beta-beating at $\beta^* = 40 \text{ cm}$),

- and ending up with the test of the various knobs available, in particular the IP and spurious dispersion correction knobs.

To aim two shifts of 10 h and 8 h were allocated to ATS activities in the MD block 1. They were carefully programmed at the beginning (27/7/2016) and in the end (30/7/2016) of the MD period, in order to give enough time to properly calculate and fine tune off-line the optics correction knobs to be applied. In summary, 242 fills were actually needed in the first and second ATS shifts (fills 5123 - 5124, and fills 5138 - 5139, respectively). All the above objectives, and even beyond, were successfully met, in particular with

- an optics correction to the 5-10% level in terms of $\beta$-beating at injection, flat top, and at $\beta^* = 40 \text{ cm}$ (see Fig. 3),

- dedicated chromatic measurements achieved at $\beta^* = 40 \text{ cm}$, showing an as-expected off-momentum $\beta$-beating pattern and a vanishing non-linear chromaticity, which is one key feature of the ATS scheme,

- a complete fill dedicated to the demonstration of the IP knobs using (nearly or exactly) nominal settings for the crossing bumps from injection to $\beta^* = 40 \text{ cm}$. The idea was also to use this first MD to measure (with BPMs) and pre-set accordingly the new TCT centers for the forthcoming ATS MD which was already planned in block 3 with more beam intensity.

Figure 3: Beta-beating measured at $\beta^* = 40 \text{ cm}$ for beam1 (top) and beam2 (bottom) before and after (global) correction. A local correction knob (MQX trims) was preset based on the 40 cm nominal optics. The AC-dipole was not available for B1H to re-measure after correction. Courtesy of A. Garcia-Tabares and OMC team.
**ATS MD in block 3: 40 cm pre-squeezed optics with nominal bunches**

In view of the success of the previous MD, the 40 cm pre-squeezed optics was considered to be mature enough to be tested with a few nominal bunches. This formed the program of the second ATS MD were the goal was to demonstrate the ATS cycle, from injection to collision at $\beta^* = 40$ cm, with two nominal bunches, and nominal or quasi-nominal collimation and machine protection settings, namely: (i) to establish a new reference orbit, and find and optimize the collisions at all four IPs, (ii) to realign the TCT centers and perform betatron loss maps at injection with nominal collimator and machine protection settings, (iii) to conduct a beam-based (re-)alignment campaign of the collimators in IR3 and IR7 at flat top, and idem for the TCT’s at flat top and at $\beta^* = 40$ cm with the beam separated and in collision, and (iv) to study the losses at the TCT’s after a (programmed) asynchronous dump in order to validate the new MKD-TCT phase advances. A few fills were needed to achieve this set of objectives (from 5296 to 5300).

The first fill was used to re-establish a good reference orbit with the crossing bumps switched on, at injection, flat top and $\beta^* = 40$ cm (the half-crossing angle was set to $\pm 140 \mu$rad at IP1 and IP5). The collimator and machine protection settings (center and gap) were pre-set to their nominal value in mm in IR3/6/7 (profiting from the very small changes of ATS optics w.r.t. the nominal optics in these 3 insertions), while the TCT/TCS centers were preset based on the beam measurements performed in block 1. After collapsing the separation bumps (but no collision proper due to a mistake in the selected filling scheme), the new TCT/TCS centers were determined and loss maps were performed. This first fill did not show any anomalies in the collimator hierarchy and inefficiency, even without need of re-aligning the IR7 collimators [19] (see e.g. the case of B1H in Fig. 4). This fill was ended up by studying the TCT losses after an asynchronous dump (and the TCT’s at $9\sigma$ in IR1 and IR5). This measurement was rather conclusive for beam1 but not for beam2 for which bucket 1 was unfortunately left empty.

In the second and third fills, loss maps were achieved at in-
jection, with injection protection devices in and out, which again did not show any peculiar behaviour in terms of collimation hierarchy and inefficiency [19].

The last fill was ramped up and pre-squeezed to 40 cm, collisions were then rapidly established and optimized at all 4 IPs (with a typical lumi of 5E30 in ATLAS and CMS). The TCT/TCS and IR7 collimator were then re-aligned in collision with marginal changes found w.r.t. the nominal optics for the IR7 collimator [20] (see e.g. Fig. 5 for the case of beam1). A second asynchronous beam dump test took place with the TCTs set a 8σ in IR1 and IR5. This second test confirmed the good behaviour of beam1, with beam2 in the right ballpark compared to expectations [21].

![Collimator Centers for Beam1](image)

**Figure 5:** IR7 collimator centers for beam1, as measured at flat top with the nominal optics after TS1, and with the ATS optics at β* = 40 cm. Courtesy of A. Mereghetti and collimation team.

**ATS MD in block 4: 10 cm telescopic optics with probe beams**

Considering the several validation steps already taken with the 40 cm pre-squeezed optics, the third ATS MD was dedicated to the (re-)validation of the telescopic techniques of the scheme. The target was fixed to the HL-LHC ultimate β* of 10 cm at IP1/5, and passing through a moderately telescopic optics with β* = 33 cm, which is an interesting candidate for running the LHC in 2017. One single fill (fill 5356) was sufficient to achieve this goal. Probe beams were injected, ramped and pre-squeezed (in one step of 470 s) down to 40 cm, where the crossing bumps were switched off, and the collimator and machine protection settings relaxed in order to liberate enough aperture to reach a β* of 10 cm. The mechanics of the telescopic squeeze was successfully demonstrated down to β* = 20 cm. First optics measurements took place at β* = 33 cm, showing not more than 20% peak β-beating, which was deemed small enough in order to continue the telescopic squeeze without applying any correction yet. The first global optics corrections (since 40 cm) were calculated and successfully implemented at β* = 21 cm, bringing the β—beating level back to the range of 5-10% (see Fig. 6). The Montague functions also showed as expected behaviour, with off-momentum β—beating waves induced by a dedicated powering of the lattice sextupole families in the sector 81/12/45/56 adjacent to the high luminosity insertions, and arriving exactly in phase in order to compensate for the chromatic betatron kicks induced by the inner triplets (see Fig. 7). Finally, optics measurements also took place at β* = 14 cm and 10 cm. The results obtained became however more and more noisy when reducing β*, due to the aperture limitations therefore constraining the maximum possible AC dipole excitation and hence the measurement accuracy. Nevertheless, from these measurements, a β-beating not exceeding 20-25% can still be inferred at β* = 10 cm without any additional correction below 21 cm (noting that the global corrections at β*=21 cm were left in the machine down to β*=10 cm). Dispersion measurements taken at 10 cm also indirectly confirmed the good behaviour of the optics at such low β* (see Fig. 8).

![Beta-beating measured at β* = 21 cm for beam1 (top) and beam2 (bottom) before and after (global) correction. A local correction knob (MQX trims) was preset based on the 40 cm nominal optics. Courtesy of J. Coelho De Portugal and OMC team.](image)
ATS MD in block 5: 33 cm telescopic optics with nominal bunches

The last ATS MD focused on a (moderately) telescopic collision optics with $\beta^* = 33$ cm and a half-crossing angle of $\pm 140 \mu\text{rad}$ at IP1 and IP5 (corresponding to a normalised crossing angle of $9.0 \sigma$ assuming a normalised emittance of $\epsilon = 2.2 \mu\text{m} \times 13 \text{TeV c.m. energy}$). This optics is indeed a very interesting candidate for running the LHC in 2017. More specifically, the aim was (i) to measure the triplet aperture in the end of the squeeze, (ii) to establish and optimize the collisions at all four IPs, and (iii) to assess the collimation system via a series of loss maps (on- and off-momentum, with the beams separated or in collision at $\beta^* = 33$ cm). Since a $\beta$-beating correction knob was not established and properly tested at $\beta^* = 33$ cm in the previous MD, the one calculated and validated at 21 cm was used instead, bringing on paper the $\beta$-beating back to about 10% at 33 cm. Two consecutive fills (5476 and 5477) were needed to meet the objectives of this last MD.

The first one was dedicated to triplet aperture measurement, filling each ring with 8 pilot bunches. First all collimators were opened at 33 cm, then a pilot bunch was excited in a given beam and a given plane. The triplet quadrupole corresponding to the aperture bottleneck was then easily found by looking at the BLM response (spikes) during the excitation, and the aperture finally determined via a beam-based alignment of the TCT in front of the triplet under consideration. A normalised aperture larger than or equal to $9.7 \sigma$ was measured for both beams and both planes, more precisely $9.7 \sigma$ for B1H (reached at Q3.L1/Q3.R5), $9.7 \sigma$ for B1V (reached at Q3.L1), $12.6 \sigma$ for B2H (reached at Q2.R5) and finally $9.8 \sigma$ for B2V (reached at Q3.R1). The plan was to finish this fill with an asynchronous dump. The beam was however dumped prematurely because real time tune trims were sent to zero by mistake, resulting in power converter trips for some RQTD circuits. In the second fill, collisions were successfully established and optimized in all 4 IPs (with a lumi of about 8E30 recorded by CMS). Before and after putting the beams into collisions at $\beta^* = 33$ cm, the TCT centers were realigned based on BPM data, and loss maps were conducted, both on and off-momentum in collision, namely applying an RF frequency trim of $\Delta f = \pm 30$ Hz corresponding to a momentum shift of about $\delta p \sim \pm 2.5 \times 10^{-4}$. These measurements again did not show any unexpected features (see [22] for more details, and Tab. 4). Figure 9 shows a condensed summary of the collimation inefficiency measurement results which took place over the full 2016 LHC run both for the nominal and ATS optics, which is another illustration of the robust behaviour of the collimation system for ATS optics.
Table 4: Collimation inefficiency [$10^{-4}$] for telescopic ATS optics, as measured in various conditions at $\beta^{*} = 33$ cm and with $\pm 140\mu$rad for the half-crossing angle in IR1/5.

<table>
<thead>
<tr>
<th>Case</th>
<th>Beams separated on-momentum</th>
<th>Beams colliding on-momentum</th>
<th>Beams colliding off-momentum (-30 Hz)</th>
<th>Beams colliding off-momentum (30 Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1H</td>
<td>2.3</td>
<td>2.2</td>
<td>2.3</td>
<td>1.4</td>
</tr>
<tr>
<td>B1V</td>
<td>1.2</td>
<td>1.1</td>
<td>0.9</td>
<td>n/a</td>
</tr>
<tr>
<td>B2H</td>
<td>2.5</td>
<td>2.6</td>
<td>2.6</td>
<td>2.5</td>
</tr>
<tr>
<td>B2V</td>
<td>2.0</td>
<td>1.6</td>
<td>2.1</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Figure 9: Measurements of collimation inefficiency summarized over the 2016 LHC run for various optics and machine conditions. Courtesy of D. Mirarchi and collimation team.

**SUMMARY AND OUTLOOK**

The 2016 year was certainly very prolific for the validation steps of the ATS scheme, where the latest ATS optics solution was used with close to optimal phase advances between the extraction kickers in the dump insertion IR6 and the tertiary collimators in the high luminosity insertions IR1 and IR5. The fundamental principles of the scheme were re-demonstrated with probe beams, in particular the telescopic squeeze down to $\beta^{*} = 10$ cm at constant sextupole strength beyond the 40 cm pre-squeezed optics. But also, state-of-the-art optics and coupling measurement and correction techniques, which were developed for the LHC nominal optics [13, 14, 15, 16, 17], such as $\beta^{*}/\alpha^{*}$ measurement with K-modulation, segment by segment local corrections and weighted global corrections, were successfully applied for the first time to telescopic optics, demonstrating their universality but also robustness at unprecedentedly small $\beta^{*}$ (21 cm). Last but not least, ATS pre-squeezed optics or moderately telescopic optics were tested for the first time with a few nominal bunches, to establish and optimize collisions in all experimental insertions, but also to re-assess the LHC collimation system with ATS optics. All together the main LHC milestone has been undoubtedly met, which was to demonstrate the readiness of the pre-squeezed 40 cm ATS optics for operating the LHC in 2017, and actually going even beyond with an optics of even lower $\beta^{*}$ (33 cm) in the pipeline. In the same effort, the full validation of the ATS scheme for the HL-LIIC is now very well-engaged. Regardless of the decision to directly switch to the ATS optics in 2017, the continuation of the ATS MD program in 2017/2018 will cover the production and commissioning of flat optics (e.g. 60/15 cm), very likely with synergies which will be established with the long-range beam-beam compensation program using electromagnetic wires (putting the so-called HL-LIIC Plan B in perspective [23, 24]). In the same (HL-)LHC framework, the ATS program will
also further develop and benchmark with beam its intrinsic long-range beam-beam compensation techniques, relying on telescopic collision optics (which could be compatible with the LHC aperture when increasing the pre-squeezed β∗) and switching back to negative the polarity of the Landau octupoles. This operational mode also corresponds to the baseline running scenario of the Landau octupoles in the HL-LHC [25], which is still to be demonstrated. Last but not least, some priority will be given in order to motivate, develop and validate with beam, de-squeezed optics of intermediate or very high β∗, using the telescopic techniques of the ATS scheme.

ACKNOWLEDGEMENTS

The successful beam tests with ATS optics obviously required the joint and coordinated effort of many different LHC teams, in particular the LHC Operation team, but also the Optics Measurement and Correction, the Collimation, the ADT and the LHC Beam Dump teams, without forgetting the constant support and advices from the Machine Protection Panel, the LHC MD coordination and the management, namely: M. Albert, G. Arduini, Y. Le Borgne, C. Bracco, R. Bruce, F. Carlier, J. Coello De Portugal, P. Collier, A. Garcia-Tabares, K. Fuchsberger, R. Giachino, M. Lamont, E. Maclean, L. Malina, A. Mereghetti, D. Mirarchi, D. Nisbet, L. Normann, G. Papotti, T. Persson, M. Pojer, L. Ponce, S. Redaelli, B. Salvachúa, P. Skowronski, M. Solfaroli, R. Suykerbyuk, R. Tomas, J. Uythoven, D. Valuch, A. Wegscheider, J. Wenninger, D. Wollman, possibly forgetting many others... Finally I would like to thank R. Tomas who kindly accepted to replace me in order to present these results during the Evian workshop proper.

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COLLIMATION: EXPERIENCE AND PERFORMANCE


Abstract

The main task of the LHC collimation system is to ensure safe and efficient operation, acting as first element of machine protection and minimizing the risk of magnet quenches induced by beam loss. The year 2016 has been very successful in terms of achieved LHC performance, thanks also to the reliability of its collimation system. No magnet quenches due to losses from circulating beam were recorded and an excellent cleaning inefficiency of about $10^{-4}$ with 6.5 TeV beams was achieved. The key elements in the set up of an efficient collimation system, together with the performance obtained with both proton and ion beams, are presented. Main operational improvements with respect to the 2015 run and plans for further upgrades are discussed. Highlights from collimation Machine Development (MD) studies and their implications on collimation performance on the different timescales are also reported.

INTRODUCTION

During the 2016 operation, a stored beam energy of more than 250 MJ was reached, as shown in Fig. 1. This large amount of stored energy was safely and efficiently handled by the collimation system [1] and no quenches from circulating beam loss were recorded. This achievement was made possible thanks also to the very good beam lifetime and orbit stability. On the other hand, the key contribution remained an efficient collimation system. The excellent precision and stability of the collimator alignment, which is performed during the initial commissioning after the winter shutdown (YETS), ensured more than in previous years operational efficiency. After the YETS a Beam Based Alignment (BBA) [2] is carried out for all the 86 movable collimators in the two LHC rings (i.e. without considering dump and injection protection collimators) both at injection and flat top [2]. Tertiary collimators (TCP), acting as protection of the inner triplets in the four interaction points (IPs), are aligned also after the squeeze and with colliding beams. Detailed aperture measurements are performed during the initial commissioning and along the year, both at injection and with squeezed beams (both separated and colliding). Precise collimator settings, driven by functions, are then deployed based on the outcome of such measurements, and the system performance is fully validated through loss maps. Future operational scenarios and upgrades of the system are carefully studied during dedicated MDs, focusing on both the short-term and long-term operation of the collimation system. In this paper, the key aspects of these activities related to the commissioning of the LHC collimation system are reviewed.

LHC APERTURE

AND COLLIMATION SETTINGS

LHC aperture

A key parameter in the definition of settings for the entire collimation system is represented by the available machine aperture. Detailed measurements are performed at injection and with squeezed beams (both separated and colliding). A new measurement technique was used in 2016 after a complete validation with respect to the previous technique used [3]. This new method allowed much faster and precise measurements. The main steps are:

1. A few pilot bunches are injected in the machine. Nominal bunches are also injected to establish the correct orbit, which are then blow out using the active transverse damper (ADT) [4].
2. All collimators are moved to parking position, and octupoles are switched off to minimize coupling between planes.
3. A selected bunch is gently excited in the desired plane (horizontal or vertical) using ADT until losses arise at the bottleneck.
4. A BBA of primary collimators (TCP) and/or TCTP is performed.
5. Overshoot of the BBA could lead to underestimation of the available aperture. Thus, the selected collimator is retracted of 0.1 σ and a gentle beam blowup is made.

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Table 1: Measured available aperture at injection and with squeezed beams at $\beta^* = 40$ cm, together with the element where the bottleneck was found.

<table>
<thead>
<tr>
<th>Date</th>
<th>Config</th>
<th>B1H [$\sigma$]</th>
<th>B1V [$\sigma$]</th>
<th>B2H [$\sigma$]</th>
<th>B2V [$\sigma$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3rd April</td>
<td>Inj.</td>
<td>12.5 - 13.0 (MBCR.4R8)</td>
<td>12.0 - 12.5 (Q6L4)</td>
<td>12.5 - 13.0 (TCDQM.4L6)</td>
<td>12.5 - 13.0 (Q4R6)</td>
</tr>
<tr>
<td>10th April</td>
<td>Coll.</td>
<td>11.3 (Q3R5)</td>
<td>10.0 (Q3L1)</td>
<td>11.6 (Q3R1)</td>
<td>10.7 (Q3R1)</td>
</tr>
<tr>
<td>17th April</td>
<td>Coll.</td>
<td>11.0 (Q3R5)</td>
<td>9.9 (Q3L1)</td>
<td>12.1 (Q3R1)</td>
<td>10.4 (Q3R1)</td>
</tr>
</tbody>
</table>

Table 2: Settings in 2016 of the entire collimation system at static points of the cycle.

<table>
<thead>
<tr>
<th>Collimator</th>
<th>Beam process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Family</td>
<td>Collimator</td>
</tr>
<tr>
<td>TCP</td>
<td>7</td>
</tr>
<tr>
<td>TCSG</td>
<td>7</td>
</tr>
<tr>
<td>TCLA</td>
<td>7</td>
</tr>
<tr>
<td>TCP</td>
<td>3</td>
</tr>
<tr>
<td>TCSG</td>
<td>3</td>
</tr>
<tr>
<td>TCLA</td>
<td>3</td>
</tr>
<tr>
<td>TCL4/5/6</td>
<td>1/5</td>
</tr>
<tr>
<td>TCSP</td>
<td>6</td>
</tr>
<tr>
<td>TCDQ</td>
<td>6</td>
</tr>
</tbody>
</table>

This procedure is repeated until losses move again from the collimator to the bottleneck. For measurements at injection a reduced resolution of 0.5 $\sigma$ is used.

6. Thus, the measured half-gap at the largest collimator opening where the losses were still at the selected collimator, represents the aperture of the bottleneck.

A selected subset of aperture measurement results at injection and with squeezed beams are reported in Table 1. The complete set of measurements can be found in [3,5,6]. Measurements at injection are consistent with the 2015 results, and the top-energy measurements with squeezed beams show a good agreement with the expectation from the scaling of the 2015 results at the same energy but with a $\beta^* = 80$ cm [7]. In both cases, the measured aperture were compatible with the nominal injection configuration and suitable for the proposed $\beta^* = 40$ cm for physics.

Collimation settings

Settings of the entire collimation system are defined depending on the available machine aperture in the various stages of the cycle. Taking into account the beam centres measured with the BBA, dedicated functions for all collimators are set up to connect different settings in each static points of the cycle [8]. This ensures an efficient collimation performance also during dynamic phases, such as the energy ramp, squeeze and adjust. The complete list of settings used during the 2016 operations is reported in Table 2. An overview of gaps for IR7 collimators in [mm] at injection and top energy is reported in Fig. 2. The main differences with respect to 2015 operation are:

- In 2016 the initial part of the squeeze is performed during the energy ramp, the so called Ramp&Squeeze [9]. Thus, TCTPs in IRs 1/5/8 are closed as protection of the inner triplet that represent the machine bottleneck already at flat top, with an aperture of about 27 $\sigma$. Complex changes of the crossing and separation bump, that also depend on the $\beta^*$, also have to be accounted for. The corresponding setup is eased by the new Beam Position Monitors (BPM) functionality.

- The optimised phase advance between the beam dump kickers (MKD) and TCTPs allowed to reduce margins between the dump protection collimators (TCDQ) and TCTPs [10]. Thus, it was possible to close the TCTPs from 13.7 $\sigma$ in 2015 with $\beta^* = 80$ cm, to 9.0 $\sigma$ in 2016 with $\beta^* = 40$ cm.

- The collimation hierarchy in IR7 was also tightened, moving primary/secondary/tertiary collimators (TCP/TCSG/TCLA) from 5.5/8.0/14 $\sigma$ in 2015 to 5.5/7.5/11 $\sigma$ in 2016. The primary betaatron cut was left unchanged to reduce the uncertainty on beam spike behavior during the cycle.

- Dump protection collimators TCDQ and TCSP were tightened consistently, from 9.1 $\sigma$ to 8.3 $\sigma$ in 2016. As in 2015, both TCDQ and TCSP are kept at the same settings.
Luminosity debris collimators (TCL) are kept open until collisions are established. Only TCL4 and TCL5 and were moved to dedicated settings during the adjust beam process. The TCL5 were retracted when Roman Pots (XRP) of the forward physics experiment TOTEM [11] were put in place, to allow a larger mass spectrum reach. At the same time, TCL6 (placed after the XRPs) were then closed to provide an efficient absorption of physics debris.

**COLLIMATION PERFORMANCE**

**Alignment**

Significant improvements in the time needed for the collimator alignment were achieved. An overview of time spent for the alignment as a function of the year is shown in Fig. 3.

The blue bar in Fig. 3 includes the alignment of ring collimators in both beams, performed at injection and top energy after the YETS. More than 200 collimators were aligned in about 5 hours. The key upgrade was the higher acquisition rate of Beam Loss Monitor (BLM) signal, on which the feedback used for the BBA\(^1\) is based.

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1. 100 Hz data were used in 2016, while 12.5 Hz data were used in 2015.

The red bar in Fig. 3 includes mainly alignment of TCTPs during changes of machine configuration along the year. Although the number of TCTPs alignments is about the same as in previous years, the amount of time spent in 2016 is almost invisible in Fig. 3. The main upgrade is the fully automated and parallelized alignment procedure based on BPM embedded in the four corners of the two collimator jaws of TCTPs and TCSPs [13, 14]. An example of the time needed to perform this alignment with and without BPMs is shown in Fig. 4. In previous years a BBA based on BLMs was needed. Thus, TCTPs (that are set at relatively large gaps) had to be carefully closed until the primary beam was touched. Using BPMs, the collimator jaws are moved just by the amount necessary to equalize the signals of the four BPMs. In conclusion, about 1 hour was needed to align the 8 TCTPs present in the ring using the BLM-based techniques, while less than 1 minute is required using BPMs and parallelizing the alignment of all the TCTPs. It is important to recall that in 2016 the commissioning time for machine configuration changes was therefore determined by the number of fills for validation.
Table 3: Qualification loss maps performed for the validation of the collimation system performance during the protons run, and number of fills required.

<table>
<thead>
<tr>
<th>Comm.</th>
<th>Loss map</th>
<th>Fills</th>
<th>450 GeV</th>
<th>6.5 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>YETS</td>
<td>100</td>
<td>12</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>TS1</td>
<td>20</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>TS2</td>
<td>24</td>
<td>5</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Validation procedure

The cleaning performance of the system is evaluated through betatron and off-momentum loss maps. All of them (i.e. betatron in the two planes of both beams and both signs of $\delta p/p$) are performed at each static point of the cycle, during the initial commissioning after YETS.

Periodic validation of the system performance is carried out after each Technical Stop (TS), changes of machine configuration (such as change of crossing angle), or after the expiration of a validation period of 3 months (never attained in 2016). Only a subset of loss maps is requested for the most critical points of the cycle. Moreover, in 2016, betatron loss maps were performed for the first time during dynamic phases of the cycle (i.e. Ramp&Squeeze and Squeeze) after YETS, as part of required validation. This allowed to evaluate the system performance as a function of beam energy, and that the unprecedented $\beta^* = 40$ cm could be reached safely. An overview of the loss maps performed is reported in Table 3.

Betatron loss maps are carried out using the ADT, with which artificial and controlled high losses are generated. This is a very efficient procedure because it is possible to excite a single bunch in the plane of interest. Thus, it is possible to perform all loss maps in a single cycle.

A new method of off-momentum loss maps has been developed during 2015 and benchmarked with respect to the previous one during dedicated studies [12]. These loss maps are performed by applying an RF frequency shift that brings the beam on a off-momentum orbit. A frequency shift smaller than in previous years is now applied. However, a faster trim is used and feedbacks on BLMs signal were put in place to stop this RF shift and restore the nominal RF frequency. Thus, it is now possible to perform both signs of off-momentum loss maps in the same fill (possibly leaving enough beam for an asynchronous dump test), whereas a dedicated fill for each off-momentum loss map was needed previously. This led to a significant reduction of time and number of fills required. Indeed, despite the largest number of loss maps performed in 2016 with respect to previous years, the smallest number of fill was necessary. The number of fills needed could be further reduced by simplifying the machine cycle, reducing fixed points were a significant amount of time could be spent during operations.

Figure 5: Example of betatron loss map performed in physics for the vertical plane of beam 1. The losses on collimators are shown by black bars, while cold and warm elements are displayed in blue and red, respectively. Losses on Roman Pot are reported in green.

Figure 6: Zoom on IR7 of the betatron loss maps shown in Fig. 5. The magnetic lattice is shown on top, where collimators are reported as black bars, while quadruple and dipole magnets are shown as blue and white boxes.

Cleaning

An example of betatron loss map performed in physics for the vertical plane of beam 1 is shown in Fig. 5. Only BLM ionization chamber are used, and the background is subtracted. The local cleaning inefficiency in each point of the machine is then evaluated as:

$$\eta_i = \frac{BLM_i}{BLM_{TCP}}.$$

As clearly visible in Fig. 5 the limiting location of the entire ring in terms of losses is represented by the Dispersion Suppressor (DS) of the betatron cleaning insertion (IR7). A zoom of the IR7 is reported in Fig. 6, and the cleaning performance of the system is given by the highest normalized losses in the DS.

A summary of the cleaning inefficiency with 6.5 TeV proton beams during the Run II is reported in Fig. 7. A good stability of performance along the years is observed. In 2016 a tighter collimation hierarchy than in 2015 was present. The improvement of cleaning with these new settings is clearly visible. Note that such performance is obtained with only one alignment per year. Only betatron cleaning performance of the system are discussed here and a complete overview
of all qualification loss maps, including off-momentum, can be found in [15].

A summary of the cleaning performance along the entire cycle is shown in Fig. 8. The expected worsening of efficiency as a function of energy is observed, while the performance is stable after flat top. Note that the IR7 optics remains constant after flat top, and cleaning is expected to be also constant. The change of inefficiency observed in the horizontal plane of beam 1 during the squeeze was given by a small bump (of about 100 μm) building up toward the TCLAs, which was corrected by the orbit feedback only when establishing collisions in IP1 and IP5. This was corrected during TS1, and a B1H loss map was performed at β* = 55 cm as test. The cleaning measured was then consistent with respect to values at flat top and in collisions (i.e. 2.0 × 10−4). Betatron loss maps during dynamic phases of the cycle can allow to identify even very small drifts from the ideal machine configuration, while the collimators are moved according to predefined functions.

Another useful outcome of continuous loss maps during the squeeze was the possibility to monitor losses on TCTPs while going to β* = 40 cm. Normalized losses on TCTPs for horizontal loss maps of beam 1 are reported in Fig. 9. This represents both a useful input for the benchmarking of beam loss pattern simulations, and a confirmation that losses on TCTPs were under control during the squeeze.

### ION BEAMS COLLIMATION

Different activities were carried out during the various phases of the lead ions Run. The proton-lead ions Run in 2016 was particularly demanding because it involved two beam energies (4 Z TeV and 6.5 Z TeV) and different particle species circulating in the two rings. Protons and lead ions were injected in beam 1 and beam 2, respectively, for the 4
Z TeV physics. Same injection configuration was used in the first part of the 6.5 Z TeV physics. Finally, beam species were switched once the required integrated luminosity was reached. All these changes of machine configuration took place in about one month.

In order to provide an efficient collimation performance and ensure the machine safety during the 4 Z TeV physics, all collimator ramp functions had to be redone, and alignment and function generation had to be done also for the TCTPs at flat top and in collision.

Regarding the 6.5 Z TeV physics, the same ramp functions as deployed for the 6.5 TeV proton-proton physics could be used. The main activities carried out were the alignment and function generation of TCTPs at: Flat Top (new \( \beta^* \) after combined Ramp&Squeeze), End of Squeeze and Collisions.

An overview on the qualification loss maps performed in the different commissioning phases is reported in Table 4. The minimum set of required loss maps was performed, given the relatively short time of the ion Run. For example, qualification loss maps at injection for the 6.5 Z TeV physics with the same beam configuration as for the 4 Z TeV were not performed.

As for the proton-proton physics configuration, the cleaning performance of the system is evaluated through betatron and off-momentum loss maps. An example of a betatron loss map performed in physics at 6.5 Z TeV for the horizontal plane of beam 1 is shown in Fig. 10. The IR7-DS is still the limiting location in terms of losses around the entire ring. However, other significant loss peaks around the ring are present, which are due to ion fragments with different rigidity that are able to emerge from the IR7 insertion [16, 17]. A significantly worse cleaning than with protons (about a factor 100 worse) is observed, which is mainly due to fragmentation and dissociation processes that take place in the collimator jaws. A zoom of the IR7 insertion is reported in Fig. 11.

A summary of the cleaning performance with lead ion beams during Run II is reported in Fig. 13. The cleaning performance of the system remains relatively constant along the years, regardless of changes of collimator settings and beam energy.

HIGHLIGHTS FROM COLLIMATION MDs

A large variety of Machine Development (MD) studies were performed and supported by the collimation team in 2016, with topics related to both the short-term and long-term operation of the collimation system. Regarding outcomes already used to improve the operational efficiency in 2016, the collaboration with BI-OP and BE-BI led to the development of a new FESA class for the control of losses during off-momentum loss maps. Key topics of 2016 MDs useful for the proposal of collimators settings for 2017 operation [6] were:

- Collimation hierarchy limits [18].
- Single collimators impedance [19].
- Operation with TCPs at tighter settings [20].
- Detailed IR aperture measurements [3].
- TCTPs induced background [21].

Studies of collimation aspects of ATS optics, such as cleaning performance and aperture measurement, were also performed within the ATS optics MDs [22]. An example of a loss map with ATS optics, \( \beta^* = 33 \) cm and colliding beams,
is shown in Fig. 12. The beam loss patterns observed for both planes and both beams do not shown any concern in terms of spurious losses around the ring. A comparison with respect to cleaning efficiency obtained with the present optics and ATS is reported in Fig. 14. Consistent collimation performance is observed with both optics.

Regarding studies for possible applications in the High Luminosity upgrade of the LHC (HL-LHC) [23], the main topics treated were:

- Crystal collimation, where cleaning performance and channeling stability during dynamic phases of the machine were measured [24].
- Halo scraping, useful for measurement of diffusion speed and tail population in view of scaling to HL-LHC beam intensity [25].
- Active halo control, considering both narrow band excitation and tune ripple methods [26, 27].
- Coronagraph, that aims to a non-destructive halo population measurements [28].

**CONCLUSIONS**

A safe and efficient LHC operation was ensured by the collimation system in 2016. No magnet quenches due to beam loss were recorded, with more than 250 MJ of stored energy routinely in the machine. The main elements in the set up of an efficient collimation system, together with the performance obtained with both protons and ions beam, were presented. A stable cleaning inefficiency of about $10^{-4}$ with 6.5 TeV beams was achieved along the entire year, with a single collimator alignment. The cleaning inefficiency is increased to about $10^{-2}$ with ion beams.

Key improvements such as faster BLMs acquisition rate, automatic and parallelized TCTPs alignment based on BPMs, and a new off-momentum loss map procedure, lead to a significant reduction of time needed for collimation activities during the various commissioning phases.

Highlights from collimation MDs were also reported.

**ACKNOWLEDGMENT**

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ANALYSIS OF 2016 BEAM LOSSES AT THE LHC

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Abstract

The analysis of operational beam losses at the LHC is crucial to assess the performance of the accelerator. In the context of the LHC collimation studies, systematic analyses are carried out during the operation to assess the performance of the beam halo collimation. Various tools have been developed for this purpose, which are now also used for more general applications. In this paper, the analysis of losses throughout the cycle, as computed from the measurements of collimator beam losses and from the LHC beam current monitors, is presented. The BLM analysis at primary collimators of the betatron and off-momentum cleaning insertions allows also a decomposition of losses that provides an insight of the main source of losses (transverse horizontal or vertical, or off-momentum). The results of this analysis are also discussed.

INTRODUCTION

The LHC collimators are the closest aperture restrictions at the Large Hadron Collider (LHC) in all operational phases. Primary collimators (TCPs) of the betatron (IR7) and off-momentum (IR3) cleaning insertions represent respectively the transverse and off-momentum aperture bottlenecks of the accelerator, as required to protect the cold magnets from operational losses that could cause quenches. Primary beam losses from diffusive mechanisms are consistently observed at the location of the 4 primary collimators: horizontal, vertical and skew in IR7 and horizontal in IR3. The monitoring of TCP local losses provides a means to diagnose the losses precisely, thanks to the high dynamics range of the beam loss monitoring (BLMs) system of about 8 orders of magnitudes. Dedicated calibrations of the BLM signals are used to calibrate the BLM signals in protons/s and use this measurement to compute beam lifetime. This method is presented in detail in [1].

This analysis is carried out systematically for all the operational phases until the physics mode is established (see [2] for an analysis of losses during the collision process). Our main focus is on the phases at 6.5 TeV where the beam stored energy is larger and operational losses are a concern for collimation and machine protection purposes. The resulting beam losses are presented per mode and in each case, the loss decomposition analysis is also presented. This was achieved thanks to a new analysis of BLM loss maps that uses reference loss patterns and an SVD-based algorithm to identify the horizontal, vertical and off-momentum content of losses [3].

2016 MACHINE CONFIGURATION

The relevant parameters of the 2016 configuration are given per phase of the operational cycle in Table 1. The combined ramp and squeeze was deployed for the first time at the LHC in 2016, reaching $\beta^*$ values of 3 m in ATLAS and CMS at 6.5 TeV. This was followed by a classical squeeze performed at constant beam energy. The "adjust" mode where collisions are prepared follows the squeeze. The "stable beams" mode corresponds to the quiet data taking period and is declared when collisions are setup and optimized for all experiments. Note that the crossing angles in IR1/5 were changed in Sep. 2016 from 185 $\mu$rad to 140 $\mu$rad. This change was implemented during the adjust mode by changing the crossing angle at constant $\beta^*$ values in IR1/5. Therefore, no changes were made in the squeeze beam process.

The operational cycle in 2016 was particularly complex because of the need for adding, before entering in collision, a special bump around IR5 for the Roman pots based CT-PPS experiment. This is referred to as "TOTEM bump". A total of three distinct “collision beam processes” were implemented respectively to switch ON this new bump at the end of the squeeze, to bring ATLAS and CMS in collisions, and then to bring ALICE and LHCb in collisions. This gymnastic brought the average duration of the adjust mode to about 16 minutes [4, 5]. High-luminosity collisions were established in ATLAS and CMS a few minutes before preparing collisions in the low-luminosity points.

The primary betatron and off-momentum cuts, expressed in units of betatron beam size $\sigma_{\beta,5,\mu\text{m}}$ that uses the nominal 3.5 $\mu$m emittance, are also listed in Table 1. The real betatron cuts have to be scaled by using the real beam emittance. The off-momentum cuts were typically of the order of $2 \times 10^{-3}$. Collimators in IR3 and IR7 reach their final settings for physics at the end of the combined ramp-and-squeeze and were kept the same throughout the year. See the companion paper [6] for more details on the 2016 collimation system 2016.

Figure 1 shows the proton stored beam energy as a function of the fill number in 2016, taking into account only fills that made it to stable beams. After the initial intensity ramp up, typical values of 250 MJ were routinely achieved, only interrupted by mini-intensity ramp up periods that followed schedule stops of proton operation (Technical Stops, TSs, and Machine Developments, MDs, are indicated in Fig. 1 by the black dashed lines). The bunch intensity was limited to $1.1 \times 10^{11}$ protons per bunch because of vacuum problems with the injection kickers [7]. The total number
of bunches was also limited by the SPS extraction, from limitations to the beam dump block [8]. These limitations played a role in the overall beam loss performance in 2016.

**BEAM LOSS AND LIFETIME MEASUREMENT TECHNIQUES**

Details on how the lifetime is calculated in the context of collimation studies can be found in [1]. The technique based on the beam loss measurements has been recently further improved by adding an analysis of decomposition of losses by loss planes [9]. This decomposition is computed with an SVD method that relies on the information from the ratio of losses measured between BLMs, calculated as the sum of protons lost on the beam intensity.

During machine validation periods, controlled beam losses are generated on purpose in different planes. This is done with very low intensity in the machine (< 3·10¹¹ protons) and is used to measure the collimation cleaning efficiency. The six basic loss maps used for the decomposition are:

- Beam 1 and Beam 2 horizontal and vertical losses due to high betatronic oscillations (4 difference scenarios);
- Beam 1 and Beam 2 off-momentum losses (2 different scenarios).

The signal from the IR7 BLMs immediately downstream of primary collimators contains information about the loss plane. In IR3 there is only one horizontal primary collimator that is sufficient to intercept off-momentum losses because by design a large horizontal normalized dispersion is created at this location. In these cases one can distinguish the different loss patterns between the transverse and off-momentum scenarios. The losses are mainly in IR7 (positions 19400 m to 20600 m from IP1) for transverse losses and the losses are distributed both in IR7 and in IR3 (located between 6100 and 7300 m) for off-momentum losses. The distributions of losses for each beam are also very different, as the BLM signals are peaked at the IR side where the respective primary collimators are located, and decreases in the beam direction. The identification of the loss plane, vertical vs horizontal, is less straightforward. It relies on the information from the ratio of losses measured downstream of the IR7 collimators.

The signals read from a selection of monitors (6 per beam) can be used to built a vector and the vector can be decomposed as linear combination of the 5 loss maps (4 transverse and 1 off-momentum). A singular value decomposition is applied to the scenario matrix and its Moore-Penrose pseudoinverse is then calculated. This enables the determination of the contributions from different loss scenarios. The measurement of the beam current is used to normalize the result of the decomposition in number of protons lost in each scenario. Details can be found in [9, 10].

Finally, the lifetime, assuming an exponential decay, is calculated with the following equation:

\[
\tau_i = \frac{-1}{\ln (1 - \frac{P_{blm}}{N_i})}
\]

where \(i\) is an iterator over time, \(P_{blm}\) is the proton loss rate from BLMs, calculated as the sum of protons lost on the 3 planes (horizontal, vertical and off-momentum), and \(N_i\) the beam intensity.

---

Table 1: Main beam parameters and primary collimator settings for the 2016 LHC run configurations. A change in crossing angle in IR1/5 was implemented in TS2, from 185 µrad to 140 µrad.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Set 1</th>
<th>Set 2</th>
<th>Set 3</th>
<th>Set 4</th>
<th>Set 5</th>
<th>Set 6</th>
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<td>GeV/</td>
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<td>6500</td>
<td>6500</td>
<td>6500</td>
<td>6500</td>
<td>6500</td>
</tr>
<tr>
<td>Maximum number of bunches</td>
<td>unit</td>
<td>6500</td>
<td>6500</td>
<td>6500</td>
<td>6500</td>
<td>6500</td>
<td>6500</td>
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<td>Bunch intensity</td>
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<td>1.10</td>
<td>1.10</td>
<td>1.10</td>
<td>1.10</td>
</tr>
<tr>
<td>Transverse beam emittance</td>
<td>µm</td>
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<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>β*(in IR1/5)</td>
<td>m</td>
<td>11.0</td>
<td>3.0</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>β* in IR2</td>
<td>m</td>
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<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>β* in IR8</td>
<td>m</td>
<td>10.0</td>
<td>6.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Half crossing angle IR1 (V)</td>
<td>µrad</td>
<td>-170</td>
<td>-185</td>
<td>-185</td>
<td>-185(-140)</td>
<td>-185(-140)</td>
<td>-185(-140)</td>
</tr>
<tr>
<td>Half crossing angle IR5 (H)</td>
<td>µrad</td>
<td>+170</td>
<td>+185</td>
<td>+185</td>
<td>+185(+140)</td>
<td>+185(+140)</td>
<td>+185(+140)</td>
</tr>
<tr>
<td>Half crossing angle IR2 (V)</td>
<td>µrad</td>
<td>+170</td>
<td>+200</td>
<td>+200</td>
<td>+200</td>
<td>+200</td>
<td>+200</td>
</tr>
<tr>
<td>Half crossing angle IR8 (H)</td>
<td>µrad</td>
<td>-170</td>
<td>-250</td>
<td>-250</td>
<td>-250</td>
<td>-250</td>
<td>-250</td>
</tr>
<tr>
<td>Half separation IR1 (H)</td>
<td>mm</td>
<td>-2.0</td>
<td>-0.55</td>
<td>-0.55</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>Half separation IR5 (V)</td>
<td>mm</td>
<td>+2.0</td>
<td>+0.55</td>
<td>+0.55</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
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<tr>
<td>Half separation IR2 (H)</td>
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<td>+2.0</td>
<td>+2.0</td>
<td>+2.0</td>
<td>+2.0</td>
<td>+2.0</td>
</tr>
<tr>
<td>Half separation IR8 (V)</td>
<td>mm</td>
<td>-3.5</td>
<td>-1.0</td>
<td>-1.0</td>
<td>-1.0</td>
<td>-1.0</td>
<td>-1.0</td>
</tr>
<tr>
<td>“TOTEM BUMP” IR5 (H)</td>
<td>mm</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td>Primary cut IR7 (H, V, S)</td>
<td>σ₃.₅µm</td>
<td>5.7</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Primary cut IR3 (H)</td>
<td>σ₃.₅µm</td>
<td>8.0</td>
<td>15.0</td>
<td>15.0</td>
<td>15.0</td>
<td>15.0</td>
<td>15.0</td>
</tr>
</tbody>
</table>
BEAM LOSSES IN 2016

Beam losses in the energy ramp are shown in Fig. 2 where the intensity transmission from start to end of the ramp is given as a function of the fill number. This analysis is carried out by using the fast beam current transformer (FBCT) data because the calibrations of the BLM signals to p/s is not optimized for the energy ramp when primary collimators are moving. Losses during the ramp are typically below 1%. This is an excellent result that shows that the beam dynamics in this phase was very well controlled. Note that BCMS beams were deployed in the middle of July 2016, corresponding to fill numbers larger than 5100 and were kept for the rest of the year. The effect on losses with these beams, which features a smaller emittance than the standard beams, are not apparent.

The beam transmission as calculated from the BLM analysis in the squeeze and adjust modes is given as a function of the fill number in Fig. 3. The corresponding minimum beam lifetime is given in Fig. 4. Overall, the performance in 2016 was very good also in these phases. Losses remained well below 0.5% throughout the squeeze beam process. They are slightly larger during the adjust. It is however important to note that the adjust mode in 2016 included some minutes with head-on collisions already established in IR1/5, so some losses can be attributed to the burn-off from high-luminosity collisions. By looking at the
beam lifetime computed in this analysis (Fig. 4), one can see that peak losses remained under good control also in adjust, with minimum lifetime values consistently above 1 h (to be compared with the design value of 0.2 h for the collimation system). Larger losses of Beam 1 were observed throughout the year, in particular after the change of crossing angle. This feature, though not worrying as absolute losses were under good control, remains to be understood.

The corresponding peak power loss for the adjust mode, where losses were larger, is given in Fig. 5. This corresponds to primary beam losses lost from the beam core and intercepted by the primary collimators in IR7. Their energy is primarily disposed of within IR7. Thresholds of the BLMs in IR7 were set to allow a 200 kW peak loss [6], to be compared to the collimation system design limit of 500 kW [11]. It is clear that the LHC was operated with significant margins for beam losses. Note that no fill was lost because of IR7 losses, which is a remarkable result.

Squeeze and adjust losses, expressed as histogram distributions of the total loss per mode, are compared in Fig. 6 to the respective measurements from the 2015 Run. Squeeze losses are significantly lower in 2016, despite the final $\beta^*$ was smaller by a factor 2. This result can be attributed, amongst others, to a better control of the beam orbit during the squeeze [12]. In 2016, adjust losses are similar, or even slightly better, than in 2015, with the caveat already mentioned that in 2016 the collisions in IR1/5 were integrated for longer times to accommodate additional collision beam processes. Deeps of lifetime drops lead to total power losses that remained below the typical values achieved at the end of 2015.

A preliminary analysis of loss decomposition of squeeze and adjust losses, carried out with the formalism introduced in the previous Section, is shown in Fig. 7 and Fig. 8, respectively. For each beam, the fractions of total losses identified as betatronic horizontal, betatronic vertical and off-momentum are given. During the squeeze, the main plane of loss is changing over the run whereas in adjust one sees a dominant contribution (vertical for Beam 1 and horizontal for Beam 2) through the year. Between fills 5150 and 5250, squeeze losses of both beams show an increase of vertical content. This feature is not yet understood. Off-momentum losses that manifest themselves through impacts on the IR3 primary collimators are very low for Beam 1 but they could reach more than 50% of the losses for Beam 2 during squeeze. Note however that absolute loss levels were small in this mode.

During adjust, the losses are mainly in the transverse plane, with the largest contribution being the horizontal one. After the reduction of crossing angle (fills above 5300) there were several fills with higher vertical losses for Beam 1. This was corrected by an optimization of the vertical tune that was shifted away from the third order resonance [3]. This recovered the qualitative loss sharing observed before the crossing angle change (see Fig. 8).
In 2016, the LHC beam losses were kept under very good control throughout the operational cycle. Typically, less than 1% of the beams were lost in the energy ramp according to the beam current measurements. The combined ramp and squeeze, deployed for the first time in operation, apparently played no significant detrimental role in the loss performance during the beam acceleration to 6.5 TeV. Squeeze losses were kept well below 0.5% with stored beam energies of about 250 MJ routinely achieved in physics fills. This is definitely a remarkable result considering that the $\beta^*$ in the high-luminosity experiments was 40 cm, i.e. a factor 2 smaller than in 2015 and 30% less than the LHC design value of 55 cm for the operation at 7 TeV.

Losses in adjust, when the collisions are setup and optimized in all experiments, were also at very modest levels. Minimum beam lifetime values did not go below 1 h throughout the year, therefore remaining a factor 5 above the design value for collimation beam losses of 0.2 h. Maximum power losses were consistently below the 200 kW conservative set point for interlock settings on IR7 losses, and no dumps from beam loss were recorded. On the other hand, absolute losses in adjust did reach levels above 1-2%. Even though this can be attributed partly to the complexity of the orbit gymnastic in the collision points, rather than to intrinsic problems of beam stability, this remains definitely an area for possible improvements in 2017.

Preliminary results of loss decomposition were also shown for squeeze and adjust losses. This work will continue in 2017 and be applied systematically to operational loss analysis, as it provides insights of the source of losses which cannot be derived from the standard loss analysis from beam current measurements.

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HOW WELL DO WE KNOW OUR BEAMS?


Abstract

Intensity, transverse emittance and bunch length are key parameters defining the LHC luminosity reach. This paper gives an overview of the available beam instrumentation to measure these parameters, and estimates how well they can be measured. The evolution of these parameters during 2016 proton physics operation is also presented and the impact of the machine configuration and bunch production schemes are highlighted.

INTRODUCTION

Following e.g. [1], the luminosity of a collider with Gaussian bunches is given by

\[ L = \frac{T_{rec}N_1N_2n_b\gamma}{4\pi\beta'\sqrt{\epsilon_x\epsilon_y}} G \]  

where \( \epsilon_{x,y} \) are the normalized transverse emittances\(^1\), \( N_{1,2} \) are the intensities per bunch, \( n_b \) is the number of colliding bunch pairs and \( G \) is the geometric reduction factor due to bunches of a finite length \( \sigma_z \) crossing at an angle of \( \alpha \) in the interaction point, where \( \epsilon_{x,y} \) is the transverse emittance in the crossing plane.

\[ G = \left( 1 + \sqrt{\frac{\gamma}{\epsilon_{x,y}^2\beta'\sigma_z^2}}\frac{\alpha}{2} \right)^{-0.5} \]

From Eqn. 1, 2 it is clear that for a given machine configuration (energy, \( \beta' \), crossing angle, number of bunches), the key beam parameters defining the luminosity are the intensity, the transverse emittance, and the bunch length. In the following, we will provide an overview of the available measurements of these quantities at the LHC and their evolution during 2016 proton physics operation.

INTENSITY

Intensity Measurements

The reference intensity measurement at the LHC is given by the DC Beam Current Transformer (DCBCT) and the FBCT at the start of collisions. Additionally, the relative distribution of charges in either beam is also measured by the longitudinal profile monitors: the LHC Beam Quality Monitor (BQM) and the longitudinal synchrotron light monitor (BSRL). These data can be combined with the total intensity measurement from the DCBCT to derive bunch-by-bunch intensities.

Intensities in 2016

In Fig. 2, the evolution of the average bunch intensity throughout 2016 is shown. After the initial intensity ramp-up, the bunch intensity at the start of collisions was first pushed to \( \sim 1.2 \cdot 10^{11} \) protons per bunch. In the second part of the run, the operational limit was \( \sim 1.1 \cdot 10^{11} \) protons per bunch due to the interlocked vacuum conditions at the injection kicker magnet for LHC beam 2 (MK18) [4].

TRANSVERSE EMITTANCE

Beam Instrumentation

Wire Scanners The Wire Scanners (WS) are the reference devices to measure bunch-by-bunch transverse emittances for each beam and plane. The WS can measure the emittance throughout the full LHC machine cycle including the energy ramp, provided that the total intensity in the machine is limited to \( \sim 240 \) nominal bunches at 450 GeV and \( \sim 12 \) nominal bunches at 6.5 TeV.

\(^1\) In the following, the normalized transverse emittance will be referred to as "emittance".
The accuracy of the wire scanner measurement is limited by the accuracy of the scale of the wire position measurement. In 2015, measurements of the WS length scale using closed orbit bumps and the beam position monitors (BPM) have shown discrepancies < 5% on the beam position which is within the uncertainty on the BPM length scale [6].

The precision is limited by noise, both on the wire position and on the photomultiplier signal readings. In online measurements, a scan-to-scan spread of ~10% on the measured eminences has been observed. When reprocessing the WS data offline, the position readings can be smoothed by applying a linear fit, while the noise on the signal can be reduced for isolated bunches by scanning and subtracting the noise in empty bunch slot just before each bunch [6] [5].

BSRT The Synchrotron Radiation Telescopes (BSRT) provide a continuous operational bunch-by-bunch measurement of transverse eminences by imaging the synchrotron radiation coming from a dedicated undulator at 450 GeV and from a bending dipole at energies > 2 TeV. The BSRT is calibrated against the WS during low-intensity fills. The BSRT measurements are very precise when averaging over several acquisitions. The accuracy is mainly limited by the accuracy of the calibration. In 2016, three calibrations were made:

- The first calibration was done during the initial commissioning in April 2016. The calibration covers eminences down to ~2.2 um, as smaller bunches were not available at this point. The BSRT readings given by this calibration were found to agree with other emittance measurements and eminences derived from luminosity.

- A second calibration was done in August (as of LHC fill 5251), covering also lower eminences down to ~1 um. While the readings of BSRT and WS were self-consistent during the calibration fill, this calibration was found to give unphysically low emittance readings. This calibration will not be used in the following.

- The third calibration was done in October (as of LHC fill 5406) to overcome the problems of the second calibration. The new corrections can be back-propagated to the period of the second calibration, and the measured eminences were found to agree with other emittance measurements.

Data from Experiments

In collisions, additional data on the beam profiles can be gathered from the LHC experiments.

Emittance from Luminosity The convoluted effective emittance can be derived from the absolute luminosity in ATLAS and CMS by inverting Eqn. 1 if the bunch intensities and the bunch lengths are known. It is to be noted that due to the geometric reduction factor, this calculation yields different results for ATLAS (vertical crossing) and CMS (horizontal crossing) if the beams are not round. The accuracy depends on the accuracy of the absolute luminosity measurements from the experiments, which is typically < 5% for offline data.

Emittance Scans Small beam separation scans ("emitance scans") were done throughout 2016 at the CMS experiment. From the luminosity measurement during the scan, the beam overlap area is measured, from which the transverse emittance can be derived [7]. The precision of these measurements is at the percent level, as the statistic uncertainty on the luminosity measurements from the experiments is essentially negligible at high luminosity.

In the CMS separation plane (vertical), the accuracy only depends on the linearity of the luminosity measurement, on the accuracy of the separation bump and on the $\beta^{*}$ in IP5. The expected error on the emittance is ~7%.

In the CMS crossing plane (horizontal), the longitudinal distribution is folded in due to the crossing angle. If the longitudinal profiles are measured, this effect can be compensated for, but in the 2016 no continuous operational measurement of longitudinal profiles was available. Hence the 2016 data was compensated for a reference profile acquired by an on-demand measurement in August 2016, with a residual systematic uncertainty of ~20%.

LHCb Beam-Gas Imaging and ATLAS/CMS Luminous Region Data An online analysis system for the LHCb beam-gas vertex reconstruction measurement was commissioned in 2016, which provides an online transverse emittance measurement for the bunches not colliding in IP8. This method measures the emittance in both planes of both beams at the same time. The uncertainty is dominated by systematics which are in the process of being studied at the time of writing. However, a realistic estimation could be ~20%.

Additionally, data from the luminous region measurements from ATLAS and CMS could also give an indication of the beam size and hence the transverse eminences as well as the bunch length. However, the online data is not
corrected for the detector resolutions and the final offline-reconstructed data only becomes available after the run.

**Emittances in 2016**

**Convolved Emittances** The convoluted transverse emittances at the start of collisions are compiled in Fig. 3. As of LHC fill 5079, the Batch Compression Merging and Splitting (BCMS) beam production scheme was used operationally in the LHC injectors to allow for lower transverse emittances. During a transition phase (until LHC fill 5105), the transverse emittances were decreased gradually in the injectors from ~2.7 μm to ~1.7 μm at LHC injection. At the beginning of collisions, the average emittances were $3.27 \pm 0.47 \mu m$ before the transition and $2.05 \pm 0.26 \mu m$ afterwards.

![Figure 3](image)

**Figure 3**: The average convoluted emittances at the start of collisions. The second (bad) BSRT calibration was retrospectively replaced by the first one.

**Beam Roundness** Throughout 2016, it was observed that the CMS luminosity was consistently ~10% higher than the ATLAS luminosity at the start of collisions. A possible explanation for this is a difference in the geometric reduction factors $G$ (Eqn. 2) due to alternating crossing and non-round beams. If the beams are larger in the horizontal plane than in the vertical one, the experiment crossing in horizontal (CMS) is privileged by a larger $G$ with respect to the experiment crossing in vertical (ATLAS).

As shown in Fig. 4, a non-roundness of the beams was indeed observed on the BSRT, as well as on the LHCb beam-gas and the emittance scan data. The non-roundness is compatible with the luminosity difference for a large part of the run [8]. However for the last part of the year (after LHC fill 5406), the beams appear to be more round, which is in disagreement with the ATLAS to CMS luminosity ratio (indicating non-round beams).

![Figure 4](image)

**Figure 4**: The average emittances by plane at the start of collisions. The second (bad) BSRT calibration was retrospectively replaced by the first one.

**LONGITUDINAL DISTRIBUTION AND BUNCH LENGTH**

**Measurements**

The bunch length is operationally measured by the LHC Beam Quality Monitor (BQM). It uses a wall current monitor pick-up with an 8 GS/s ADC to acquire the longitudinal profiles. The full-width half-maximum of the waveform is then measured and converted to a bunch length assuming a Gaussian longitudinal distribution [9]. While this measurement is precise, the measured bunch length only accurately represents the r.m.s. width provided that the longitudinal distribution is Gaussian.

Additionally, the longitudinal synchrotron radiation monitor (BSRL) continuously measures the longitudinal distribution of charges in the beams. It uses the same synchrotron light source as the BSRT, but it measures the temporal distribution of the incoming light. A histogram of 50 ps bins is filled over 5 minutes. The long integration time allows to reach a dynamic range of several orders of magnitude. While the BSRL is already used operationally for monitoring ghost
charges and satellite bunches in the LHC, the longitudinal profile measurement is still under development.

For on-demand measurements and diagnostics, two 40 GS/s scopes connected to wall current monitor pickups are installed in SR4. The transfer functions of the pickups and cables were measured and are available for deconvolution [10]. The scopes can acquire a longitudinal profile of either beam over a full LHC turn.

**Longitudinal Distribution in collisions**

To avoid instabilities due to the loss of Landau damping the bunches in the LHC are blown up longitudinally during the energy ramp by injecting phase noise [11]. This leads to a longitudinal distribution which is significantly non-Gaussian at the start of collisions. A change in longitudinal distribution is also observed when the longitudinal bunch flattening in collisions introduced in 2016 [10] is used.

When untouched over the course of several hours in collisions, the longitudinal distribution becomes Gaussian again (Fig. 5).

![Figure 5: Evolution of the longitudinal bunch profile in LHC fill 4964, measured using the 40 GS/s scopes in SR4, one acquisition per 30 min.](image)

**Bunch Length in 2016**

The bunch lengths as measured by the BQM at the start of collisions are compiled in Fig. 6. After the longitudinal bunch flattening in collisions was operational, the bunch length target for the blow-up during the ramp was gradually reduced from 1.25 ns to 1.1 ns (as of LHC fill 5038). This lead to a decrease of the bunch length at the start of collisions from 1.2±0.01 ns to 1.06±0.01 ns.

![Figure 6: BQM bunch length at the start of collisions.](image)

For Beam 1 and 1-2% for Beam 2. The average bunch intensity was $1.08 \pm 0.12 \cdot 10^{11}$ ppb and the total beam intensity $2.4 \pm 0.15 \cdot 10^{14}$, limited by the MKI8 vacuum interlock.

The operational transverse emittance measurement was the BSRT, which is calibrated against the Wire Scanners. Also, small beam separation scans (emittance scans) were done regularly in CMS, and for the second part of the year, LHCb provided emittances from beam-gas vertex measurements. The emittance measurements have a typical systematic uncertainty of 10-20% on the scale, while the relative precision is much better.

As of June, the BCMS beam production scheme was used operationally in the injector complex. This lead to a decrease in transverse emittance from $3.27 \pm 0.47$ um to $2.05 \pm 0.26$ um at the start of collisions. The beams were not round for a large part of the year, leading to a difference in the geometric luminosity reduction factors in ATLAS and CMS, and thus a difference in the delivered luminosity.

The bunch length is measured by the BQM using a full width half maximum algorithm. The longitudinal distribution differs significantly from a Gaussian at the start of collisions, while over the course of several hours in collisions it becomes Gaussian shape. This behaviour will be taken into account in a future version of the LHC luminosity model.

The bunch length was 1.2±0.01 ns at the start of collisions in early 2016, and 1.06±0.01 ns in June after the change of the target for the longitudinal blow-up during the ramp.

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CAN WE PREDICT LUMINOSITY?

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Abstract

In these proceedings, a luminosity model based on the main components (intrabeam scattering, synchrotron radiation, elastic scattering and luminosity burn-off) responsible for the LHC luminosity evolution, is compared with data from the 2016 Run of LHC. Based on a bunch-by-bunch and fill-by-fill analysis, the data are compared to the model predictions and possible sources of luminosity degradation are discussed. The impact of the degradation mechanisms on the integrated luminosity is also presented.

INTRODUCTION

The performance of a collider is best described by the luminosity (integrated over time) which, in general, is given by [1]:

\[ L(t) = \frac{n_b f_{neq} N_1(t) N_2(t)}{2n_0 \sigma_s(t) \sigma_v(t)} \mathcal{H}_s, \]

where \( n_b \) the number of colliding bunches, \( f_{neq} \) the revolution frequency, \( N_{1,2} \) the number of particles per bunch for each beam and \( \sigma_v, \sigma_s \) the rms horizontal and vertical beam sizes at the collision point. Due to the crossing angle at collision \( \phi \) and the fact that the beta function varies rapidly around the interaction point (IP), a geometric factor \( \mathcal{H}_s(\sigma_v(t), \beta^*) \) and the hourglass effect reduction factor \( \mathcal{H}_s(\sigma_s, \beta^*) \) should be considered, where \( \sigma_v \) and \( \beta^* \) are the rms bunch length and the beta function in the interaction point (IP) collision (assuming round optics) respectively.

Although luminosity is a macroscopic indicator of global collider performance, the observed bunch-by-bunch (bbb) variations in the transverse and longitudinal emittances and in current, impacts its evolution and finally the integrated luminosity per fill. A bbb model was developed based on the three main mechanisms of luminosity degradation in the LHC [2]: intrabeam scattering (IBS), synchrotron radiation (SR) and luminosity burn-off. Here, the model is compared with the LHC beam data from the 2016 Run.

MODEL DESCRIPTION

The emittance evolution of the beams in the LHC during the Flat Bottom (FB), the ramp and the first part of the Flat Top (FT) (before the squeeze) is dominated by the intrabeam scattering (IBS) effect [3]. During collisions a combination of effects including burn-off, IBS, beam-beam, noise, etc., cause emittance blow up and/or particle losses [4]. Based on the assumption that IBS and Synchrotron Radiation (SR) are the dominant effects for the emittance evolution during collisions, the evolution of different injected beam parameters (transverse emittances (\( \varepsilon_x \)), bunch length (\( \sigma_e \)), bunch current (\( N_b \)) were calculated using the “ibs” routine of MADX with synchrotron radiation [9, 10]. The transverse emittance and bunch length evolution were then fully parameterized with respect to the initial beam parameters and the time, using multi-parametric fit functions. Finally the combined effect at any plane can be calculated through:

\[ \left( \frac{d \varepsilon_x}{dt} \frac{d \epsilon_y}{dt} \frac{d \sigma_e}{dt} \right)_{IBS+SR} = f(E_n, N_{bd}, \varepsilon_{bd}, \epsilon_{bd}, \sigma_{bd}, \sigma_{el} dr) \]

where \( dt \) the time interval for which the calculation is performed and \( E_n \) the energy. The procedure is described in more details in [2].

The contribution from the proton-proton collisions elastic scattering to the transverse emittance growth [4, 5], is also included, based on:

\[ \left( \frac{d \varepsilon_{el}}{dt} \right)_{elastic} = N_{ip} \sigma_{el} \mathcal{L}(\varepsilon_{el} \langle \Phi_{el} \rangle) / (n_b N_p), \]

where \( N_{ip} \) is the number of interaction points, \( \sigma_{el} \) the elastic cross section and \( \langle \Phi_{el} \rangle \) is the rms proton-proton scattering angle.

The emittance evolution along the fill can then be estimated, for any time interval for which the bunch current \( N_b \) variation is small, using the differential equation:

\[ \frac{d \varepsilon}{dt} = \left( \frac{d \varepsilon}{dt} \right)_{IBS+SR} + \left( \frac{d \varepsilon}{dt} \right)_{elastic} \]

The main mechanism of the bunch intensity degradation during collisions is the luminosity burn-off, causing the bunch current decay due to the collisions themselves. The burn-off decay time is given by:

\[ \tau_{nuc} = \frac{N_{bd}}{k L_0 \sigma_{tot}}, \]

where \( N_{bd} \) is the initial bunch intensity, \( I_0 \) the initial luminosity, \( k \) the number of interaction points and \( \sigma_{tot} \) is the proton-proton total cross section and is energy depended as shown in Fig. 1 [11]. At 6.5 TeV \( \sigma_{tot} \approx 110 \text{ mb}, \sigma_{el} \approx 30 \text{ mb} \) and \( \sigma_{nuc} \approx 80 \text{ mb} \) [11]. In the case of the LHC with very small beta functions at the interaction points, only the inelastic part of the proton-proton collisions is expected to contribute to the burn-off losses, while the elastic part is causing transverse emittance blow up described by eq. (3) [6].

The bunch current evolution can then be calculated through:

\[ N_b = N_{bd} / (1 + t/\tau_{nuc}). \]

Combining equations eq. (1), eq. (2), eq. (3), eq. (4), eq. (5) and eq. (6) and iterating in small time-steps (such that
the current variation in each time-step is relatively small) provides a self-consistent calculation of the beam parameters, and thus the luminosity evolution in time. The infrastructure allows the user to select the model or the data for each specific parameter in a transparent manner.

Four different modes are defined and will be used in the next:

1. Pure model:
   - Initial values of bunch intensities, emittances and bunch length taken from the data
   - Model iteration to compute intensity, emittance, bunch length and luminosity evolution

2. EmpiricalBlowUpBurnOff:
   - Transverse emittance evolution taken from the data
   - Model iteration to compute bunch intensity, bunch length and luminosity evolution

3. IBSEmpiricalLaunches:
   - Intensity evolution taken from the data
   - Model iteration to compute emittance, bunch length and luminosity evolution

4. EmpiricalBlowUpEmpiricalLaunches:
   - Intensity and emittance evolution taken from the data
   - Model iteration to compute luminosity evolution

DATA ANALYSIS

In 2016, the LHC operated with a center of mass energy of 13 TeV and similar beam parameters as in 2015, but with a lower $\beta^*$ of 40 cm (in 2015 $\beta^*$=80 cm), resulting in a significant increase in the integrated luminosity; in 2015 the LHC delivered to CMS an integrated luminosity of 4.2 fb$^{-1}$ while in 2016 42.1 fb$^{-1}$ [7].

For the analysis that follows all the fills of the production period of 2016, after the intensity ramp-up were analyzed.

Those are fills corresponding to the time period from June to October 2016. In order to apply the model, the bunch by bunch transverse emittances, bunch lengths and bunch intensities are required. The bunch by bunch luminosity data are also needed for comparison. For this, the following datasets have been used:

- The bunch-by-bunch intensity sharing is measured by the Fast Beam Current Transformer (FBCT)
- The bunch-by-bunch emittance measurements for both beams and both planes from the synchrotron radiation telescopes (BSRT)
- The bunch-by-bunch bunch lengths as measured by the beam quality monitor (BQM)
- The bunch-by-bunch luminosity data as published from ATLAS and CMS (Massi files)

A more detailed description is presented in [8].

EMITTANCE EVOLUTION FROM INJECTION TO SABLE BEAMS

Figure 2 shows the average horizontal (top) and vertical (bottom) emittance, for all the production fills of 2016, at different times in the LHC cycle. The emittance at injection is shown in blue, at the beginning of the ramp in green, at the end of the ramp in red and at the beginning of stable beams in cyan. The error-bars correspond to the one standard deviation over all the bunches. Here only the data from beam 1 are shown, however, the situation is very similar for beam 2 as well. At the beginning of the year standard beams were injected in the LHC, with the average horizontal/vertical emittance fluctuating around 2.8/2.5 $\mu$m-rad and arriving at the beginning of stable beams around 3.5/2.9 $\mu$m-rad. With the introduction of the BCMS beam production scheme, the emittance was gradually decreased to 1.6/1.5 $\mu$m-rad at injection and 2.5/2.0 $\mu$m-rad at the beginning of stable beams. It is interesting to notice
the large emittance blow up (defined as $\varepsilon_\beta/\varepsilon_\alpha - 1$) from injection to stable beams, of the order of 25/16 % in the first part and 55/33 % after the transition to BCMS. This is induced mainly during the Ramp where the intrabeam scattering effect for the range of bunch parameters of 2016 can explain only a small fraction of it; for an injected transverse emittance of 1.5 $\mu$m-rad and bunch intensity of 1e11 a horizontal emittance blow up of 13 % from injection to stable beams is expected due to ibs and only 3 % of it is induced during the ramp while no effect is expected in the vertical plane.

The average bunch intensity in the LHC for 2016 was kept in similar levels as in 2015. More specifically, for the first part of the year the average bunch intensity was $N_b \sim 1.2 \times 10^{11}$ while later went down to $N_b \sim 1.1 \times 10^{11}$, with negligible losses along the cycle (from injection to stable beams). Figure 3 shows the evolution of the average bunch intensity (red), horizontal (blue) and vertical (green) emittance values at the beginning of stable beams along the year, for beam 1 (top) and beam 2 (bottom).

**LUMINOSITY IMBALANCE ALONG THE YEAR**

Due to the fact that the experiments of ATLAS and CMS have a different crossing plane (vertical for ATLAS and horizontal for CMS) and the horizontal and vertical emittances are not equal during collisions, an imbalance in the luminosity delivered to the two experiments was observed. Aiming to understand further this effect, the average peak luminosity for all the fills was calculated through eq. (1) using the measured bunch parameters (transverse emittances, bunch intensity, bunch length) at the beginning of stable beams, for both ATLAS and CMS. This calculated peak luminosity was then compared to the average measured peak luminosity provided by the experiments and the results are shown in the top part of Fig. 4. The calculated values are shown in crosses while the measured ones in circles. The results for ATLAS are shown in blue while for CMS in red. The bottom plot of Fig. 4 shows the luminosity imbalance (defined as $(\mathcal{L}_{CMS} - \mathcal{L}_{ATLAS})/\mathcal{L}_{ATLAS}$) between the two experiments using the same marker convention as in the top one. During the first part of the year, before the transition to BCMS beams, very good agreement between the calculated and measured peak luminosities is observed. After the transition to BCMS, even though the calculated and measured imbalance agrees well, the absolute values start to diverge. In the third part, on the other hand, after the crossing angle reduction, a disagreement is observed both in absolute values and in imbalance. It is important to notice here that a recalibration of the BSRT system was performed before the transition to BCMS and before the crossing angle change. The impact of the calibration factors in these observations is currently under scrutiny.

In order to better understand the observed imbalance between ATLAS and CMS, an experiment was performed where 4 bunches with different pile up density (or brightness) were brought to collision and the crossing angle was gradually reduced to 0 $\mu$m-rad, as shown in Fig. 5. In the left part of the figure the evolution of the pile-up density of the 4 bunches is presented while in the right the imbalance between ATLAS and CMS. At the beginning of the fill, a 5-8% geometric effect is observed, higher for the higher brightness bunches. At the end of the fill where the crossing angle was reduced to 0, a 5% imbalance is still observed, even though for zero crossing angle theoretically the two experiments should not see any difference. Further investigation is in progress in order to understand this observations.
**LUMINOSITY EVOLUTION**

![Figure 5](image1.png)

Figure 5: Left: Evolution of the pile-up density of the 4 bunches with different brightness. Right: Luminosity imbalance between ATLAS and CMS. The crossing angles is gradually reduced and at the end the bunches are colliding with zero crossing angle.

![Figure 6](image2.png)

Figure 6: Luminosity evolution comparison between the pure model (green) and measurements (gray).

![Figure 7](image3.png)

Figure 7: Luminosity evolution comparison between the model using the empirical emittance evolution (“Empirical-BlowUpBurnOff”) (green) and measurements (gray).

In order to validate the luminosity model and identify possible sources of luminosity degradation in 2016, the model was applied bunch-by-bunch to all the production fills of 2016, under different assumptions as described in section “Model description”. Figure 6 (top) shows the comparison of the average luminosity evolution as measured by the experiments (gray) and computed by the “pure” model (green), of a typical fill of 2016 (fill 5198). The predicted luminosity evolution using the “pure” model is overestimated with respect to the measurements. The same observation is valid for the luminosity evolution of all the fills of the year and consequently for the evolution of the bunch-by-bunch transverse emittances, bunch length and bunch intensity as well. Instead, if we use the empirical emittance evolution from the BSRT data, and reiterate the model in order to compute the prediction of the bunch length, bunch intensity and luminosity evolution, the agreement becomes much better, as shown in fig. 7. Eventually, using both the empirical emittance and bunch intensity evolution, the luminosity evolution is very well reproduced. For the example fill, already by using only the empirical emittance blow up the luminosity evolution is very well predicted, showing that the main source of the luminosity degradation for this particular case is an extra emittance blow up mechanism. However, for other fills not only extra emittance blow up but also extra losses were observed. In this respect, a statistical approach was adopted in order to understand the behavior of the luminosity evolution and degradation mechanisms over the year.

**EXTRA EMITTANCE BLOW UP**

In order to understand the behavior of the extra emittance blow up along the year, the average expected emittance growth per fill from the model was compared to the measured one and the results are shown in fig. 8. The model prediction is shown in green while the BSRT measurements are shown in blue. The results for both horizontal (top) and vertical (bottom) planes are shown. The error-bars indicate the one standard deviation over all the bunches per fill. It is interesting to notice a constant difference between the model prediction and the measurements, which seem to be independent on the bunch brightness. Both planes show an extra emittance blow up of around 0.05μm/h, with respect to the model. Analysis is in progress to understand further the mechanism that induces this extra emittance blow up.
EXTRA LOSSES

As discussed earlier, extra beam losses on top of luminosity burn off losses, were observed for most of the 2016 physics fills. In order to have a better understanding of the effect, the instantaneous loss rate normalized to the luminosity was calculated bunch by bunch for all fills and the average effect over all the bunches per fill is shown in fig. 9. The results for beam 1 are shown on the left while the results for beam 2 on the right. In the case of burn off dominated losses, this should reveal the value for the inelastic cross section of the proton-proton collisions (thus \( \sim 80 \text{mb} \)). However, this is not the case and a similar trend is observed for all the fills, for both beams; fast losses occur during the first 2-3 h in stable beams, while later the losses become burn-off dominated. The effect is more pronounced for beam 1 than beam 2. In the top plots of fig. 9 each color corresponds to a different fill, while in the bottom one the average effect over all the fills and the one standard deviation interval are shown. The red solid line indicates the inelastic cross section limit of the 80 mb.

Figure 10 shows the average normalized losses over the first hour in stable beams, for all the physics fills. The results for beam 1 are shown in blue while for beam 2 in red. It is very interesting to notice that the losses behavior is very much affected by all the machine changes. The highest losses were observed during the first part of the year while during the middle part, the losses were minimized, and for beam 2 they were very close to the burn-off limit. Systematically for both these periods, beam 1 suffered more from losses than beam 2. After the crossing angle reduction, the losses were again increased, however beam 1 and beam 2 behaved in a much more similar way.

Another very interesting observation is the fact that the losses are minimized when the LHCb was operating in a positive polarity, while they get maximized in the opposite case. Within the same polarity, the losses are larger for larger emittances, which become more pronounced in the first part of the run, with nominal beams and standard emittances (see fig. 3). It should be noted the impact of the tune optimization on the losses behavior. A tune optimization, based on the dynamic aperture studies presented in [13], has a positive impact on the losses behavior. To summarize, the effects and machine conditions that were observed to have an impact on the losses behavior are: the LHCb polarity, the emittance magnitude, the tune and the crossing angle reduction.

The impact of the beam-beam long range effect is also under investigation and some first observations are shown in fig. 11. The colorbar in these plots show the burnoff-corrected losses computed over 10 minutes windows, expressed as percentage of the total intensity for the first hour in SB, before (top) and after (bottom) the crossing angle reduction. The horizontal axis shows the 25 ns bunch slot. Darker color indicates higher losses. In the top plot, with the large crossing angle, the losses are higher at the end of each train, which is a well known signature of the electron cloud effect. On the other hand, after the reduction of the crossing angle, the situation becomes different for many trains where the highest losses are observed in the middle of the trains, which is a signature of the beam-beam long range effect. The effect is more pronounced for beam 1, where the extra losses are higher, as discussed earlier. It is though observed for beam 2 as well. Further investigation is in progress in order to quantify also from simulations the impact of the long-range beam-beam effect on the luminosity lifetime [13].
Figure 12: Integrated luminosity loss due to the extra losses (blue) and due to the extra emittance blow up (green) for the physics fills in 2016.

**IMPACT OF DEGRADATION MECHANISMS ON THE INTEGRATED LUMINOSITY**

The extra emittance blow up and the extra intensity losses that were observed during collisions and discussed in the previous sections cause a luminosity degradation. In order to quantify this effect, the luminosity model was called under different assumptions for each fill and the integrated luminosity for each case was computed after 3 h in stable beams. Three different cases are compared: EmpiricalBlowUpBurnOff (2), IBSEmpiricalLosses (3) and EmpiricalBlowUpLosses (4). Case 4 is the one which represents the real data. The ratio between (4) and (2) reveals the integrated luminosity loss due to the extra emittance blow up while the ratio between (4) and (3) due to the extra losses. The results are presented in fig. 12. It is interesting to notice that the evolution of the integrated luminosity loss due to the emittance blow up (green) is rather smooth along the year. On the other hand, the loss due to the extra losses varies along the year and it follows the machine changes in the same way as the extra (on top of burn-off) intensity losses.

**SUMMARY**

A luminosity model based on the main components responsible for the LHC luminosity degradation (intrabeam scattering, synchrotron radiation, elastic scattering and luminosity burn-off) was applied to the LHC data from the 2016 Run. The model was applied bunch by bunch to all physics fills and under different assumptions. The comparison between the model predictions and the measured evolution of the bunch characteristics (intensity, horizontal and vertical emittances and bunch length) and thus the luminosity led us to some interesting conclusions for the performance of the machine in 2016.

At first, the emittance evolution from injection to stable beams was discussed. An extra emittance blow up, coming mainly during the ramp, was present in all fills. This cannot be explained by the intrabeam scattering effect. Arriving at stable beams a comparison between the peak luminosity as computed from the measured bunch characteristics and as measured by the experiments of ATLAS and CMS was performed. Before the transition to the BCMS beams, very good agreement is observed both in absolute value and in ratio between the two experiments. After the transition to BCMS a divergence start to appear, however the ratio still agrees very well. In the last part of the year, both the absolute values and the ratio disagree. This discrepancy needs further investigation; the impact of the calibration of the BSRT instrument and the calibration of the experiments are under scrutiny.

During collisions, both an extra emittance blow up and extra losses, especially at the first 2-3 h in stable beams are observed. Higher losses were observed for standard beams with larger emittances while the minimum losses were observed for the BCMS beams with small emittances. A clear impact of the LHCb polarity is observed; higher losses are observed when the LHCb operates with negative polarity. The losses were then again increased after the crossing angle reduction. A tune optimization after this, had a clear positive impact on the minimization of the losses. It is also interesting to notice that after the crossing angle reduction, signatures of the long-range beam-beam effect start to be present in the losses patterns.

Finally, the impact of the degradation mechanisms to the integrated luminosity over the first 3 h in stable beams was studied. The impact of the extra emittance blow up is very smooth along the year, while the impact of the extra losses varies, depending on the changes taking place in the machine.

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LONG-RANGE AND HEAD-ON BEAM-BEAM INTERACTIONS : WHAT ARE THE LIMITS?

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Abstract
The present understanding of the performance limitations due to beam-beam interactions in the LHC is detailed based on data obtained during the physics run as well as dedicated experiments in 2016.

INTRODUCTION
The effect of beam-beam interactions manifests itself as a deterioration of the beam quality through various mechanisms. The understanding of these mechanisms is crucial in order to operate the machine in optimal conditions. The best performance is obtained in conditions that maximise the physics reach of the different experiments with different needs. In particular, the need for dynamic control of the luminosity, or levelling, in the different experiments, together with the operational constraints given by the control system and the machine protection needs to be taken into account in the understanding of the beam-beam driven limitations on the performance.

In the following section the effects of long-range beam-beam interactions observed in 2016, as well as the operational strategy for the setting up of the crossing angle and $\beta^*$ w.r.t long-range limitations is exposed. Dedicated tests to probe the limitations linked to strong head-on beam-beam effects are detailed in the third section. The effect of luminosity levelling with a transverse offset in both the low and high luminosity IPs are discussed in the forth and fifth sections respectively. The emphasis is put on experimental data, detailed simulations and extrapolations to future scenarios are discussed in [1].

LONG RANGE INTERACTIONS

Crossing angle scans
In order to evaluate experimentally the minimum crossing angle at which the LHC can be operated in given conditions, the crossing angle in the two main IPs are reduced simultaneously in steps. The steady state losses measured at each of these steps are reported in Fig. 1, averaged over bunches experiencing different number of long-range interactions. The detrimental effect of the non-linearities of long-range interactions is most significant on bunches experiencing a larger number of interactions [2]. For beam 1, we observe that the decay rates are identical for all bunches for half crossing angle larger than 130 $\mu$rad, the losses are therefore not driven by long-range beam-beam effects. At smaller crossing angles, nominal bunches (pink) lose more than the other bunches. This angle correspond to the onset of long-range driven losses, which risk to compromise the integrated luminosity by reducing significantly the beam lifetime in collision as experienced for example during the 2012 proton Run [3, 4]. The strength of the long-range interactions is well characterised by the bunch intensity and the normalised separation between the beams at the location of the interaction given for the interactions in the drift space around the IP given by:

$$S_{\text{drift}} \approx 2 \sqrt{\frac{\beta^* \gamma \epsilon}{\epsilon_n}} \theta,$$

with $\theta$ the half crossing angle. The onset of long-range driven losses was therefore measured at a crossing angle corresponding to a normalised separation of 8.6 $\sigma$ for a bunch intensity of 1.2·10^{11}. In beam 2, long-range driven losses were visible below 105 $\mu$rad, corresponding to a normalised separation of 7 $\sigma$. The asymmetry between the beams is not fully understood, nevertheless a significant tune shift was observed in beam 1 when reducing the crossing angle. By comparing the spectrogram of the bunch colliding head-on only (Fig. 2a) and those colliding long-range in IPs 1 and 5 (Fig. 2b), it is clear that the tune shift is not due to a drift of the machine tune, but is driven by long-range interactions. The drift increases the vertical tune shift towards the third, as well as few other detrimental long-range driven higher order resonances, which could explain the losses observed in the vertical plane of beam 1 shown in Fig. 2c [5]. The measured variations show an increase of the vertical tune simultaneous to a decrease of the horizontal tune. Such effect is expected for a tune shift driven by long-range interactions, but should however be cancelled by the passive compensation between IPs 1 and 5, due to the alternating crossing angle in the horizontal and vertical plane [6]. Consequently the observations suggest that the passive compensation is broken, either due to a difference between $\beta^*$ in the two IPs, or a difference in crossing angle.

The presence of uncompensated long-range driven tune shifts were confirmed in another experiment [7], where a single low intensity bunch in beam 1 collided against a full 48 bunch train in IPs 1 and 5. While the crossing angle was reduced, beam transfer functions were measured on the low intensity beam. The tune shift as a well as an estimation of the transverse tune spread are reported in Fig. 3, based on a fit of the measurements [8]. A relative difference in the order of 30% [9] shared between the crossing angle and the $\beta^*$ would explain the measured tune shifts. However neither the $\beta^*$ [10] nor the measured...
nominal crossing angle [11] are compatible with measurements. The presence of significant coupling at the location of long-range interactions at one or the other IP could also generate such an effect and is not incompatible with local coupling measurement [12]. Since the passive compensation is an important mechanism to obtain a good dynamic aperture, it is likely that by understanding the mechanism and restoring the compensation, the impact of long-range interactions could be reduced. Dedicated orbit and optics measurement, including local coupling, would be needed.

**Observation during operation**

The onset of losses observed in dedicated experiments in 2016 is consistent with the 8.4 σ obtained in 2015 in similar conditions [4]. The crossing angle for the 2016 Run (185 μrad) was chosen based on these experiments, assuming an emittance in collision of 3.5 μm and including a margin of 2 σ to allow for operational margins on the machine parameters and to account for uncertainties on the beam quality in collision, mainly due to the unknowns on the electron cloud effects at injection. After the implementation of the BCMS scheme, the same crossing angle corresponds to more than 12 σ thanks to the reduction of the emittance 3.5 to below 2.5 μm [13]. The bunch intensity is also reduced at about 10^{11} protons per bunch. In the period between the implementation of the BCMS scheme and the reduction of the crossing angle, the LHC was operated in relaxed conditions, far from long-range driven limitations. This is consistent with the low level of losses observed in that period [14].

Taking advantage of the reduced emittance and reducing the margins to 1 σ with respect to the measured onset of long-range driven losses profiting from the stability of the beam parameters in collision, the half crossing angle could be reduced from 185 μrad to 140 μrad, corresponding to a normalised separation of 9.2 σ, with and emittance of 2.5 μm [15]. The reduction of the crossing angle led to an increase of the losses in the first fills of operation for physics after the technical stop with a pattern indicating the presence of long-range effects. These losses could however be mitigated by first correcting the long-range induced tune shift that was measured in dedicated experiment, resulting in an improvement to a level of losses similar to prior the crossing angle change, as illustrated by the maximum power loss during ADJUST shown in Fig. 4 [5]. The ADJUST beam process included the reduction of the crossing angle, the implementation of the TOTEM bump as well as the collapse of the separation bump. Even prior to the tune adjustment, the level of losses remained well below the limitation of the collimation system [16].

Despite the correction of the uncompensated long-range driven tune shift, the losses in the first hour of stable beam were still significantly higher than prior to the change of crossing angle reducing the performance by few percent [14]. A second step of optimisation of the tunes allowed for a re-

Figure 1: Intensity and luminosity decay rates averaged over bunches with identical number of long-range beam-beam interactions in IPs 1 and 5, while reducing simultaneously the full crossing angles.
Figure 2: BBQ spectrogram in the vertical plane of beam 1 of different bunches (upper plots) when reducing the crossing angle in IPs 1 and 5. The evolution of the vertical tune peak is highlighted with a blue line, for bunches colliding long-range in IPs 1 and 5 (middle plot), whereas the tune of bunches colliding head-on (top plot) remains steady at 0.32. The losses decomposed by plane during the reduction of the crossing angle are shown in the bottom plot, with the corresponding half crossing angle at the time of the loss spikes.

Figure 3: Tune shift and spread measured in beam 1, with a single low intensity bunch colliding long-range against a 48 bunch train in IPs 1 and 5. The parallel separation was kept on to avoid head-on collisions and the crossing angle reduced in steps simultaneously in the two IPs.

Figure 4: Minimum lifetime drop during the ADJUST process during consecutive fills with different tunes.

Previous studies at injection highlighted prohibitive degradation of the luminosity lifetime when colliding with large beam-beam parameters, as reported in Fig. 6. Such a degradation was no longer observed at top energy in dedicated experiments in 2016, reaching a total beam-beam tune shift of -0.02 with collisions in IPs 1 and 5. The beam lifetime was dominated by luminosity burn-off, while the transverse emittances suffered from a growth mechanism resulting in a few percent per hour additional to the effect of intrabeam scattering [20]. These experiments were performed with high intensity bunches, requiring special settings of the transverse damper (ADT). As a result, the noise that the latter introduces was increased. This effect could explain the growth mechanism and will be further discussed in next section.

HEAD-ON INTERACTION

Operation with large beam-beam parameters
A strong degradation of the beam quality was observed during the high-\(\beta\) run when colliding beams with large beam-beam tune shift and keeping the injection tunes. When moving to collision tunes, the preservation was restored as expected, resulting in stable operation with beam-beam parameters as large as -0.025 [21]. Due to the significantly different configurations with respect to proton physics, in particular because of the larger \(\beta^*\) and due to the frequent tail scraping in order to minimise the background, a detailed comparison with the proton physics run is difficult.

The effect of external sources of noise

In the presence of a large tune spread within the beam, external sources of noise result in an emittance growth through decoherence. Currently, the emittance evolution in collision can be understood within few percent per hour considering the effect of synchrotron radiations and intrabeam scattering [14]. The remaining is compatible with the effect of external sources of noise acting on the beams with an amplitude normalised to the beam divergence around \(8 \cdot 10^{-5}\). The dipole's power converter ripple and the ADT are the main potential sources for such a noise. If we were to assume that the noise is dominated by the ADT, a finite resolution of \(0.2 \mu m\) on the measured beam position used in the feedback loop would be sufficient to explain the observations. Further beam tests are needed to evaluate the strength of the different sources, in particular the impact of the ADT can be singled out by varying and optimising its parameters, such as gain and bandwidth. The strong-strong theory predicts an improvement of the efficiency of the ADT in mitigating the effect of external sources of noise on the emittance. This effect could in principle be used to improve the performance, however it relies on precise machine and beam conditions [22]. A proper understanding of the conditions within which this mechanism can be reliably achieved in the LHC is needed to allow for an optimisation in that respect. By introducing artificial noise using the ADT and varying the beam-beam tune shift as well as the ADT gain, it was shown that the weak-strong theory [23, 24] is in reasonable agreement with the observations. In particular Fig. 7 shows the predictions of the two models along with the measurements, showing that the conditions to profit from the beneficial effects predicted by the strong-strong theory are not met in this configuration. Further tests are needed to try an establish those conditions.

The tests with large beam-beam tune shifts highlighted an important difference in the behaviour of the bunches of different intensities and different ADT gain, already prior to the injection of artificial noise. The data points obtained without artificial noise reported in Fig. 7 illustrate this effect. The bunch experiencing the larger ADT gain is growing more than the others, suggesting that the ADT is the cause for this extra growth. Since the settings of the ADT were not optimal in these tests due to the large
The contribution of burn off to beam losses was subtracted. The bunches that do not collide head-on in IP8 are designated with a blue or red stars corresponding to beam 1 or beam 2 respectively.

Figure 9: Tune footprint arising from long-range interactions in IP8 (small red and green footprints) and both long-range and head-on interaction (big red and green footprints) for the negative and positive polarity of the LHCb spectrometer respectively (according to LSA convention). The transverse separation is chosen to obtain the same reduction factor, corresponding to the situation at the beginning of a physics fill.

intensities with respect to regular operation, it is not possible to directly extrapolate those results for proton physics operation. However, this highlights the importance of the ADT settings in the observed emittance growth and motivates an optimisation of those parameters in regular physics fills. Keeping in mind that, while the impact on performance is marginal with current machine and beam parameters (the total beam-beam tune shift is around -0.007 in regular operation for proton physics), these effects become significant when pushing the machine and beam parameters (higher sensitivity to quadrupole vibrations with reduced $\beta^*$, higher intensities, larger tune spread).

THE IMPACT OF IP 2 AND 8

The long-range effects in IPs 2 and 8 are negligible, thanks to the larger normalised separation with respect to the two main IPs. Indeed, the crossing angle and $\beta^*$ are usually set to avoid an uncompensated tune shift and spread higher than $10^{-4}$ which could result in dynamic aperture reduction [4]. In particular for the 2016 configuration after the reduction of the crossing angle, positive vertical tune shift rapidly result in a reduction of the dynamic aperture, as shown in Fig. 5 [1].

The luminosity is levelled with a transverse offset in both IPs, resulting in total normalised separation between the beams at the IP in the order of 4 $\sigma$ in IP2 and 2 $\sigma$ in IP8 at the beginning of luminosity production. The tune shift and spread due to the interaction at the IP is therefore significantly stronger in IP 8 w.r.t. IP 2. Consistently, no detrimental effects could be linked to the collisions in IP2, however a significant effect of the collisions in IP8 was visible right after the change of crossing angle and of the polarity of the LHCb spectrometer. Bunches without collisions in IP8 experienced less losses in the first hour of stable beam with respect to others in both beams (Fig. 8). The effective crossing angle at the IP is different for the two spectrometer polarities, resulting in different luminosity reduction factor. To achieve the same target luminosity, the initial separation at the IPs is different for the two polarities, resulting in different beam-beam effects. This difference is illustrated with the corresponding tune footprints in Fig. 9. Since, as shown in Fig. 5, the dynamic aperture is particularly sensitive to positive tune shifts in the vertical plane, the increase of the vertical tune shift due to the head-on interaction with an offset at IP8 can explain the increase of the losses when swapping the polarity. Consistently, this effect was no longer visible after the tune optimisation mentioned above [25].

The effect of IP8 did not represent a limitation of the operation in the 2016 Run, since its detrimental effects remained under control and could be mitigated adjusting the tune. Nevertheless, the sensitivity to the tune shift induced by head-on interaction in IPs 2 and 8 could be reduced by levelling the luminosity with equal offsets in the two transverse planes in each of the IPs, resulting in tune shifts along the diagonal and potentially reducing the impact on dynamic aperture and lifetime.

LEVELLING WITH A TRANSVERSE OFFSET IN IPS 1 AND 5

As the LHC outperforms its design in terms of peak luminosity, the need for luminosity levelling to mitigate the high pile up in the two main experiments can not be excluded in a near future. Whereas other levelling schemes such as dynamic modifications of the $\beta^*$ offer several advantages from the beam dynamics point of view [26], levelling with a transverse offset at the IP appears as the most simple solution from an operational point of view [27]. In particular, it has been already successfully used operationally in the two lower luminosity experiments. Consequently, the procedure was validated operationally for the two high luminosity experiments within regular physics fill. The luminosity was
Figure 10: Evolution of the luminosity during the physics runs with a luminosity levelled with a transverse offset at the IP, along with a comparison of the integrated luminosity with physics fill without levelling.

levelled by manually adjusting the orbit at IPs 1 and 5 to obtain a constant luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ in the first test and $8 \times 10^{33}$ in the second and fourth tests. The luminosity during those tests is shown in Fig. 10, along with the corresponding integrated luminosity as a function of the time spent in stable beam. The latter allows for a comparison with other physics fills. Assuming a luminosity evolution only driven by luminosity burn-off, one expects a loss of integrated luminosity of 10% for the last two tests. Within the uncertainty due to the fill to fill variation of the beam parameters, the integrated luminosity obtained during the test is in agreement with the expectation, showing that the levelling scheme did neither cause significant additional mechanisms deteriorating the beam quality, nor mitigated the ones present without levelling. Yet, a more detailed comparison of the beam losses during the fill shows an increase of the losses in the first hour in the first and second tests. These losses were mitigated profiting from the stability margins that were demonstrated in another test (fill 5443 in Fig. 10a). The current in the octupoles could be reduced from 470 A to 220 A and the chromaticity reduced from 15 to 10 units, without experiencing any instabilities while varying the separation at the IPs in the range of interest. The implementation of these reductions, together with a tune optimisation allowed to recover beam losses similar to regular physics fills in the last test (fill 5450).

CONCLUSION

The operational crossing angle and $\beta^*$ are usually defined before the start of the physics run, based on the observed reduction of the beam lifetime when reducing the crossing angle in dedicated experiments with similar machine and beam parameters, as well as comparison and extrapolations using dynamic aperture simulations. Significant margins with respect to the fundamental limit are needed due to uncertainties on the beam parameters in collision, to allow for operational flexibility during the recommissioning and in some cases due to the inherent uncertainties in the beam dynamics model when extrapolating experimental data obtained under different conditions. For the first time, the crossing angle was reduced during the proton run in the LHC, not only profiting from the reduced emittance with BCM5 beams but also from the relaxing of the margins that were no longer needed allowing to operate closer to the long-range limit. The success of this operation motivates operational efforts towards more flexibility in the control of the crossing angles during the physics run.

When operating closer to the long-range limit, subtle effects become relevant. A good understanding of the interplay between both the low and high luminosity IP, of the optics at the location of the beam-beam interactions, the effect of the chromaticity and the octupole settings have a significant impact on the beam dynamics. These detrimental effects could be observed in different conditions during the 2016 Run, yet they remained under control in terms of beam quality degradation and beam losses. These observations and their comparison to beam dynamics models, in particular to dynamic aperture simulation, allowed for a deeper understanding of the machine. Nevertheless, discrepancies observed in the measured tune and tune spread when reducing the crossing angle suggest that the long-range limit is not yet entirely understood.

Currently, the head-on beam-beam interactions do not limit the operation of the LHC. Experimental tests were conducted to probe these limitations with single bunches of high brightness. Total beam-beam tune shifts in the order of 0.02 were reached and the beams were showing an excellent lifetime. The transverse emittances were, however, significantly affected. The effect of external sources of noise needs to be further investigated in order to define limitations for future scenarios with pushed machine and beam parameters.

Levelling the luminosity with a transverse offset in the two main experiments was demonstrated with regular physics beam and therefore could be used if needed during the next runs. Keeping in mind that beam-beam interactions with an offset lead to an important tune shift that may have an impact...
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INSTABILITIES AND BEAM INDUCED HEATING IN 2016


Abstract

Coherent instabilities have been regularly observed during operation in 2016. Issues relating to linear coupling at injection in 2015 were no longer observed in 2016 due to new applications that were made operational, however new instabilities that caused emittance blowup were sporadically observed in the Adjacent and Stable Beams that do not yet have a full explanation. Several MD’s were performed that tried to make measurements of these instabilities, while also shining new light on some new stabilising mechanisms at the end of the squeeze. The latest issues with beam induced heating will also be discussed.

INTRODUCTION

Many instabilities were observed throughout 2016, many that were able to be cured quickly thanks to improved diagnostics and a better understanding of the relationship between linear coupling and collective effects, and others that were able to be mitigated but whose exact mechanism requires further study.

Several MD’s were also carried out in 2016 that highlighted the importance of non-linear corrections in the insertion regions (IR’s) as well as testing new possible stabilising mechanisms in the LHC. The effect of the amplitude detuning from non-linearities was negligible in 2015 when running with $\beta^* = 80cm$. But when squeezing to smaller values the beta-function in the triplets become much larger. This creates amplitude detuning which is not corrected. The same can be said for $Q^*$, which has a contribution from the lattice for smaller values of $\beta^*$. Tune shift measurements were also carried out to test the DELPHI prediction for collimator running scenarios in 2017.

Several components also suffered more from beam induced heating in 2016. While none of the components limited performance, some of the more seriously affected will be described with plans on future mitigation.

These proceedings will start by providing some detail on the addition of linear coupling to the stability model, before describing observations in each stage of the machine cycle. Single bunch and single beam measurements will also be shown before an update on the beam induced rf heating will be provided.

LINEAR COUPLING

In 2015, many issues were observed at injection that appeared to be related to linear coupling. These issues arose when the tunes drifted closer together whilst injecting and the closest tune separation (\(|C^-|\)) was left uncorrected.

Many simulations into the effect of linear coupling on transverse stability were performed during the technical stop at the end of 2015 [1, 2]. Figure 1 shows the tune footprint from Landau Octupoles at 6.5 TeV (plotted to 4$\sigma$ amplitude) for three different values of \(|C^-|\) where for each case it has been rematched to collision tunes (which is what happens in the machine when coupling is increased with the tune feedback on). The black point marks a typical coherent mode that would need to be damped in both x and y (this can also be shown by a stability which is the more complete way of showing the same damping mechanism, but for simplicity just the footprint is shown). It can be seen that the detuning coefficients are strongly modified in this case, which can easily lead to a loss of Landau damping as the spread no longer covers the coherent mode. This can provide an increase in the required octupole current for stabilisation by up to a factor 5 for intermediate values of \(|C^-|\).

![Figure 1: Tune footprint tracked in MADX to 4$\sigma$ for different values of \(|C^-|\) with a typical coherent unstable mode represented by the black point. For stabilisation to occur the tune spread of the bunch has to cover the coherent mode.](image)

This mechanism was also verified by measurements made in the LHC during commissioning in early 2016 [3]. The global coupling was increased to \(|C^-| = 0.01\) and the tunes were slowly moved closer together with $J_{oct} = 283A$. It was found that the bunch became unstable with a factor 3 more octupole current than is required. This verifies that the mechanism itself can have a strong impact on the transverse beam dynamics.

At injection in 2016, two vital applications were developed to prevent issues related to linear coupling. The first tool was developed by M. Schaumann and corrects the Laslett tune shift during the injection process [4]. The tool calculates the approximate shift that is expected as the beam inten-
sity increases and then ensures that the tunes remain well separated [5]. The second tool was developed by T. Persson [6] and corrects the $|C^-|$ when the probe is present just before the injection process. No further issues related to linear coupling were observed at injection due to these two applications.

**INSTABILITIES IN OPERATION**

With less than 100 bunch trains (72b or 2x48b trains) with 25ns spacing coming from the SPS due to issues with the TIDVG, electron cloud was not going to be as dominant an effect as it was in 2015. The strategy in 2016 was to begin with parameters that would safely allow good emittance and intensity transmission from injection to collisions, and then try and check chromaticity and octupole margins at several points throughout the year. Chromaticity is effective at stabilising electron cloud instabilities, octupoles can provide the tune spread which is required for Landau damping of the unstable modes. However in reality, a combination of the two is needed in the presence of a strong transverse feedback (ADT).

**Injection**

Initially the nominal beam was in operation with $\epsilon_{x,y} = 3.5\mu m$. With $Q^* = 15/15$ and $J_{oct} = 20A$, injection was going very smoothly with no emittance blowup.

When the full BCMS beam was deployed with emittances of $\epsilon_{x,y} = 1.5\mu m$, emittance blowup was observed in the horizontal plane of both beams. This was due to a reduction in the tune spread because of the reduction in the emittance. Therefore $J_{oct} = 40A$ was required to account for $\frac{1}{2}$ the emittance. This cured all observed instabilities and allowed clean injections.

Measurements of the margin performed towards the end of 2016 showed very little margin for a reduction in chromaticity or octupoles, however a test was performed in a MD with an 8b+4e beam in which the machine was able to be completely filled with $J_{oct} = 6A$ and $Q^* = 5/5$ with no instabilities being observed [7]. This confirms that all the issues seen at injection are related to electron cloud as this observation matches what is expected to stabilise an instability caused by impedance only.

**Ramp**

Emittance blowup was observed shortly after TS2 in both B1H and B2H and it could be traced to exactly the start of the ramp. The issue was caused by a reduction in chromaticity that is linked to the correction of the b3 snapback after a pre-cycle [8]. Typically this is well corrected (as no issues had been observed before from this effect) but it is likely that the corrections were more accurate for fills following a ramp-down rather than a pre-cycle. The issue was cured by ensuring that the chromaticity remains higher during the early stages of the ramp. However it is not currently known why it became an issue after TS2.

**Flat Top**

At flat top, a short MD was performed during commissioning to verify the stability threshold with the 2016 flat top collimator settings ($\beta^* = 3m$). This measurement showed that the stability threshold for a single bunch agreed with the prediction from DELPHI [9], which is that for $Q^* = 9/9, N_p = 1.2 \times 10^{11}$pb, $\epsilon_{x,y} = 2\mu m$, the threshold octupole current is $J_{oct} \approx 80A$.

During operation no issues were observed at flat top, although margins were not checked at all throughout 2016. Tune shift measurements along the batch were performed which allowed a first point on the level of local electron density at 6.5TeV. It was shown to be smaller than 4e-4 in both beams and planes [10], however with large error bars.

**Squeeze**

During the squeeze, maintaining control of the coupling is critical due to the reduced tune separation. Observations of instabilities that could have been related to coupling were observed both for single bunch fills and multi-bunch fills. During fill 5332 (a 600 bunch fill during the intensity ramp up after TS1), instabilities were observed shortly after reaching $\beta^* = 40cm$ [11]. It was noted that for $\beta^* \leq 45cm$, the $|C^-|$ calculated from the BBQ showed high values. While this measurement cannot be trusted for high beam intensities, it can be used as an indication that something in the machine changed at this point.

The next fill was therefore used for optics measurements which verified that there was one unmatched coupling point during the squeeze which was at $\beta^* = 40cm$, which corresponded to $Q_{sep} \approx 90cm$ [12]. These values are large enough to cause instabilities.

Once these corrections were input, the following fills showed no sign of similar instabilities.

**Adjust**

Emittance blowup was observed sporadically in B1V that was correlated with activities during Adjust [13]. The emittance blowup typically happened for bunches at the beginning of the train (which can rule out electron cloud), and no correlation could be found with either intensity, emittance or LHCb polarity. Figure 2 shows the typical timing of the emittance blowup and it can be seen that it approximately correlates with the implementation of the TOTEM process. In the particular example shown (fill 5093) a delayed Adjust (one where 5-10 min waits occur between each step) was employed to allow better sampling of the BSRT in order to separate the TOTEM process and the separation collapse.

Figure 3 shows the occurrence of this instability throughout the latter part of 2016 [14]. There were two main occurrences of the instability, after TS1 until shortly after the deployment of the full BCMS beam, and before TS2 until after TS2. See the accompanying presentation for a fully annotated version of this figure. A correlation has not yet
been found between either beam parameters or the timing of their occurrence.

Further research into this instability will be continued if it reappears in 2017. The Headtail monitor was not able to be triggered due to its dependence on a trigger based on the BBQ (which does not show activity for 2220 bunches). Development of an instability trigger for the ADTObsBox will allow much greater insight into the effect of the TOTEM process on the transverse beam dynamics, as well as triggering the Headtail monitor.

**Stable Beams**

Early in 2016, emittance blowup was consistently being observed several hours into stable teams for 72 bunch trains [15]. Typically it was always bunches towards the end of each train. A plot of the bunch by bunch luminosity from CMS can be found in Fig. 4 for fill 4964. The luminosity of each bunch was normalised to 1 at the start of Stable Beams, and a red point was marked for any abrupt reduction in luminosity, signifying emittance blowup. For subsequent fills, the chromaticity was increased from $Q'V = 15$ to $Q'V = 22$ and the issue was strongly mitigated. Due to the fact that it was mostly bunches going unstable at the end of the trains, electron cloud was strongly suspected as the driving mechanism. The bunches at the end of the train are typically the ones with the lowest intensity, and it was observed in the past that for decreasing bunch intensity there could be an increase in the local electron density (but a decrease in the total electron density).

This was explored with simulations in PyHT-PyECcloud [16]. Figure 5 shows the electron density in a dipole as a function of the horizontal position for different bunch intensities. In this case, the proton bunch would be passing through at 0mm. It can be seen that as the intensity decreases, the electron density at the location of the bunch increases. This local electron density is plotted in Fig. 6 as a function of the bunch intensity. It can be seen that for nominal bunch intensities and above ($N_b > 1 \times 10^7$ ppb) the local density is very small and therefore has a minimal effect on the beam dynamics. However, if the bunch intensity drops to approximately $N_b \leq 0.8 \times 10^7$ ppb, the local density becomes much larger and exceeds the electron density instability threshold which could cause emittance blowup.

While this is currently only a theory that is backed up by simulations, it is a strong contender as an explanation for this instability. However, it needs to be corroborated with measurement results in order to be completely satisfactory.

**INSTABILITY MEASUREMENTS IN 2016**

**Tune Shift Measurements**

In 2017 there is a possibility of further squeezing to $b^* = 30/33$ cm which will require tighter collimator settings. Several measurements of the single bunch instability threshold were made in 2016 with the primary collimators (TCP’s) at 5.5$\sigma$ and for different secondary collimator (TCSG) gaps [17]. The results can be found in Fig. 7 compared with the DHLPHI predictions. Reasonable agreement can be found for the TCSG gaps of 6$\sigma$ and 6.5$\sigma$, however a jump is seen between gaps of 6.5$\sigma$ and 7.5$\sigma$ which is not yet understood.

The plan in 2017 is to go to a TCP gap of 5$\sigma$ and a TCSG gap of 6.5$\sigma$. The expected octupole threshold in this scenario is $b_* \approx 200$ A. This should be fine for the case of a single bunch, but some work is still needed to understand the MD results.

**Beam Stability at $b^* = 40$ cm**

Measurements at $b^* = 40$ cm show that both a single bunch and full beam (2076 bunches) are stable for $b_* = 0$ A [18]. At end of squeeze (EOS) there are two additional stabilising mechanisms present that could cause the beam to be stable. The first is $Q''$ from the lattice, and the second is non-linearities from the high value of $\beta$-function in the IR’s which can provide strong amplitude detuning. Due to a knob developed by R. De Maria [19], it is possible to either introduce or correct $Q''$ at both flat top and end of squeeze by varying the strength of the main sextupoles. $Q''$ can stabilise either by shifting the unstable mode (by changing the interaction between the machine impedance and the bunch power spectrum) or by providing Landau damping by a spread which is introduced that depends on the $\alpha^2$. MD1831 sought to disentangle between these two effects [19].

The MD made 2 key conclusions [20]. Firstly that it is possible to stabilise a single bunch using only $Q''$ at flat top, and second that the stability at the EOS is coming only from the amplitude detuning that arises from the non-linearities in the IR’s. This will be explored further in 2017, but it is clear that if agreement with the stability model is desired, then the corrections to the non-linearities must be implemented.
Figure 3: Instabilities in B1V vs fill number. Most clusters of points can be attributed to MD's or other tests. There were two main times the Adjust instability appeared, after TS1 and then shortly before and shortly after TS2. Also shown is the LHCb polarity (red). The green dots are instabilities in the non-colliding bunches, and the blue crosses are instabilities in the colliding bunches. For a fully annotated version of this diagram, see the accompanying presentation.

Figure 4: Bunch by bunch luminosity from CMS normalised to 1 at the start of stable beams. Abrupt reductions indicate emittance blowup which is marked by a red point.

Figure 5: Local electron density versus horizontal position in dipoles for different bunch intensities.

Figure 6: Central electron density versus bunch intensity. The electron density instability threshold stays the same as in single bunch stability thresholds.

BEAM INDUCED HEATING

**General**

In 2015, most heating issues were effectively addressed by redesigning the problematic components and in cases adding new cooling systems. Issues with the TDI heating were addressed, but new strange vacuum behaviour while injecting has been observed which requires further study [21]. The MKI was addressed with additional temperature probes and observed no performance limiting behaviour in 2016. Some of the issues observed in 2016 will be addressed below.

**VMSI**

After TS2, a spring detached on the LSS8 vacuum module, such that the rf fingers are no longer in contact. This is shown in Fig. 8. Simple impedance modeling show significant resonant modes at $\approx 200\text{MHz}$. These modes could potentially extract $\approx 200\text{W}$ from the beam (of which about 30% to 60% could go to the rf fingers) if the modes sit on the beam spectrum. However, this did not limit performance in 2016, and will be replaced during the BYETS.

**BGI**

Temperature probes were connected to the BGI and confirm that there is heating. There is a clear dependence on
be deposited by the beam if the spectrum lies on the narrow modes at \( \approx 500\text{MHz} \).

Figure 9: BGI temperature after a beam dump for fills that were in collisions for approximately 4 hours. A clear dependence on beam intensity can be seen.

CONCLUSION

2016 was a very successful year from the point of view of coherent instabilities. During the high pileup test, a bunch with a brightness that is 1.4 times more than the HL-LHC brightness was taken to collisions without suffering an instability.

The instabilities in operation that limited performance were able to be cured, whereas those that require further study had little impact on the luminosity output.

A greater understanding of the interplay between optics and collective effects has been gained, both in terms of fundamental instabilities as well as in specific machine configurations.

There were no performance limitations related to beam induced heating in 2016, but there is always the possibility for non-conformities in 2017. Increasing the intensity per bunch to \( N_b = 1.25e11 \) and the number of bunches to \( N = 2760 \) should increase the power loss by around 40\% for all devices.

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ELECTRON CLOUD IN 2016: CLOUDY OR CLEAR?
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Abstract

The proton physics run in 2015 confirmed that electron cloud poses a significant challenge to LHC operation with beams of 25 ns bunch spacing. Despite evident conditioning of the electron cloud during the 2015 Run, full suppression did not occur, and hence also the 2016 proton physics Run suffered the presence of e-cloud. This contribution reviews the electron cloud situation throughout the 2016 Run. The conditions at the beginning of the run, including the scrubbing and intensity ramp-up, are covered and compared to 2015. Studies and observations of the evolution during the run are described, along with ongoing efforts to interpret them. Finally, some future implications are discussed. Detailed considerations and plans for 2017 operation are presented elsewhere [1].

INTRODUCTION

As anticipated, electron cloud caused important limitations to the performance of the LHC in 2015, the first year of luminosity production with 25 ns beams at a top energy of 6.5 TeV [2]. Initially, the electron cloud severely degraded the beam quality at injection, whereas the induced heat load on the beam screens in the cryogenic magnets limited the amount of beam that could be stored at 6.5 TeV throughout the year. Although a clear reduction of electron cloud build-up could be observed over the 2015 Run, significant electron cloud was evidently still present at the end of year.

Since the LHC arcs were kept under vacuum during the 2015-2016 Year End Technical Stop (YETS), a complete reset of the Secondary Electron Yield (SEY), as observed at the beginning of operation in 2015, was not expected for 2016. Some de-conditioning of the beam screens could nevertheless be foreseen; de-conditioning was regularly observed in 2015 after breaks in standard proton physics, in particular when running with relatively high-intensity beams with low or no e-cloud formation. In these cases, however, the previous condition of the beam screens could typically be recovered with only a few hours of scrubbing with standard 25 ns beams.

Based on these considerations up to four days of dedicated scrubbing at 450 GeV were allocated in 2016. The scrubbing could be implemented prior to and interleaved with the intensity ramp-up in physics, as needed, with the aim of achieving sufficient beam quality for efficient luminosity production. Continued scrubbing dose to further reduce the heat load in the arcs could subsequently be accumulated in parallel with physics, as was done during the 2015 Run.

START UP

The dedicated scrubbing run took place on the 25th of April, following a period of commissioning with low-intensity beams. In the first few fills clear signs of beam screen de-conditioning with respect to the situation at the end of proton physics in 2015 could be observed [3]. Strong e-cloud instabilities occurred at injection, often triggering beam dumps. When beam dumps were avoided, significant emittance growth and beam degradation was seen. The de-conditioning could be confirmed also through the measurements of arc heat loads and bunch-by-bunch energy loss from the RF stable phase measurement.

The scrubbing was interrupted after about 24 hours, due to the detection of a vacuum leak in the SPS high energy beam dump (TIDVG) [4]. At this point up to 1800 bunches per beam, in trains of 216 bunches per injection, had been stored in the machine at 450 GeV, without significant beam degradation. Injections of 288 bunches, which were planned to be used during the scrubbing, could initially not be set up due to instabilities, and were thus not used.

As a consequence of the vacuum leak, the intensity that could be accelerated in the SPS was limited for the remainder of the run to 96 LHC bunches, allowing for injections of a single batch of 72 bunches, or two batches of 48 bunches into the LHC [5]. The conditioning achieved during the initial 24 hours of scrubbing was sufficient to carry out the intensity ramp-up at 6.5 TeV up to 2040 bunches per beam, the maximum number that could be stored in trains of 72 bunches, without any major problems caused by e-cloud effects.

The arc heat loads during a fill at the end of the intensity ramp-up (Fill 4980) are shown on the bottom right in Fig. 1. On the left in the same figure are the heat loads during a similar fill with 2040 bunches at the end of the 2015 proton Run (Fill 4536). In both fills, the heat loads are significantly larger than the dashed curve in the bottom right graph, which shows the expected heat load due to impedance and synchrotron radiation. This indicates a dominant contribution to the heat load due to electron cloud. Furthermore, the comparison shows very similar heat loads for the two fills, confirming the expectation that any de-conditioning observed after the YETS could be quickly recovered. Also the difference in heat load between the machine sectors that was observed during 2015 remains essentially the same. The origin of this difference could not be determined in 2015 (see [2]) and is still unclear.

Despite the significant levels of electron cloud present in the machine, both the scrubbing run and the intensity ramp-up suffered less from electron cloud effects compared to the corresponding periods in 2015. This can be mainly attributed to the conditioning that took place during the 2015 Run, which was evidently mostly preserved over the

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Figure 1: Heat loads measured in two similar fills with 2040 bunches: Fill 4536 at the end of proton physics in 2015, and Fill 4980 right after the intensity ramp-up in 2016. Average values for the heat loads in each sector of the machine are shown, given in W/half-cell.

YETS. In addition, further improvements of the cryogenic feed-forward control effectively limited problems with the cryogenics at injection [6], while beam stability and lifetimes were improved by adopting, immediately at the start of the 2016 Run, the settings found beneficial during 2015: high chromaticity and octupole current, along with adjusted transverse tunes to accommodate the large tune footprint [2, 7]. The dynamic pressure in the injection kicker (MK1) area in Point 8 still occasionally reached the interlock values, preventing further injections [8]. However, the issue could effectively be mitigated by limiting the bunch intensity to roughly 1.1 × 10^{11} pbunch.

**EVOLUTION DURING PHYSICS**

During most of the proton physics Run in 2015, the LHC was operated at the limit of the available cooling capacity on the arc beam screens, and several measures were taken to reduce the heat load per proton in order to allow for a higher beam current in the machine. In 2016, by contrast, the beam current was limited by the SPS, and instead measures were taken to maximize the luminosity for a given current.

The evolution of the total beam intensities during the 2016 run is shown at the top of Fig. 2, below which the main changes made in beam parameters are outlined. Injections of single trains of 72 bunches were replaced by two trains of 48 bunches, which could still be accelerated in the SPS, allowing for a maximum of 2220 bunches in the LHC. With this filling pattern, the Batch Compression Merging and Splitting (BCMS) production scheme could be used in the PS, in order to increase the beam brightness. Simultaneously, the target bunch length for the controlled longitudinal blow-up on the ramp was gradually decreased from 1.25 ns to 1.1 ns.

The middle graph in Fig. 2 shows the average heat load measured on the arc beam screen, sector by sector. The maximum heat load allowed by the cooling capacity, roughly 160 W per half-cell or 3 W/m, was reached only briefly at the beginning of the run. The graph on the bottom of the figure shows the evolution of the heat loads, normalized to the total beam intensity. An overall reduction of the heat load of roughly 25% over the full run can be observed. This is the combined effect of the conditioning due to the accumulated scrubbing dose and the adjustments to beam parameters.

To assess if an evolution of the conditioning with the accumulated dose can be observed, Fig. 3 shows the value of the normalized average heat load per sector, measured at the end of the "Squeeze" beam mode for fills during the 2015 and 2016 proton Runs. In 2015, a reduction of approximately 30% can be seen over the run, which took place over a period of roughly two months. In 2016, a slightly smaller reduction occurred over the full period, spanning nearly six months. Furthermore, the majority of the reduction in 2016 seems to have occurred during the beginning of the run, whereas only a small change can be seen over the latter part. In all sectors, the heat load remains significantly larger than the estimate due to impedance and synchrotron radiation.

Although Fig. 3 does not distinguish between reduction in heat load due to changed beam parameters and reduction due to conditioning, even after a careful analysis, the change in rate of heat load reduction cannot be correlated with any apparent change in settings, implying that it very likely is due to a change in the rate of conditioning with scrubbing dose.

In order to evaluate the conditioning independently of the beam parameters, three reference fills were performed during the run, at roughly two month intervals. The three fills, marked with blue arrows in Fig. 2, were performed with similar beam parameters as possible. The full operational cycle to bring the beams into collision was performed, and the fills were used for luminosity production. The filling
Figure 2: Evolution of the beam intensity (top), average heat loads in the arcs (middle), and average arc heat loads normalized to the beam intensity (bottom) during the 2016 proton Run.

Figure 3: Instantaneous normalized average heat load per sector at the end of the “Squeeze” beam mode for proton fills in 2015 and 2016. Calculated heat load estimate due to impedance and synchrotron radiation in grey.

pattern consisted of 2040 bunches per beam, in trains of 72 bunches, using the standard production scheme in the PS. The target bunch length for the controlled blow-up on the ramp was set to 1.25 ns, and settings for chromaticity, octupole current and the transverse damper were identical.

In Fig. 4, on the top left, the evolution of the bunch length at 6.5 TeV during the reference fills can be seen, given as a function of the average bunch intensity, which decreases during the fill due to the luminosity burn-off. The bunch lengths are nearly identical, especially for the first and last of the fills, whereas the second fill has slightly shorter bunch lengths. The remaining graphs in the figure show the evolution during the reference fills at 6.5 TeV of the average arc heat loads due to electron cloud per sector, i.e. with the expected contribution from impedance and synchrotron radiation removed from the measured values.

A reduction of the heat load over the four month period covered by the reference fills can be observed in all sectors. In most sectors, there is a larger reduction in heat load between the first two reference fills compared to the latter
Figure 4: Bunch length (top left) and average arc heat loads due to electron cloud at 6.5 TeV, as a function of the average bunch intensity during the reference fills.

two, supporting the conclusion that the conditioning rate decreased during the run.

Dedicated studies of the scrubbing process in the laboratory indicate that the rate of conditioning achieved with a given electron dose decreases as the conditioning progresses [9], providing a possible interpretation for the observations described above. The effective scrubbing dose of electrons deposited on the beam screens during machine operation can be inferred from the integrated heat load, combined with information on the geometric distribution and energy spectrum of the impacting electrons from PyECLOUD simulations [2]. The accumulated dose during 2016 proton operation, estimated in this way, is roughly a factor four times larger than the corresponding dose in 2015.

DEDICATED STUDIES

The LHC beam screens are typically kept at a temperature of 5–20 K during operation. In order to investigate if the operating temperature of the beam screens might have an effect on their conditioning process, a dedicated study was performed. For roughly two weeks of luminosity production (26th of August – 12th of September) the beam screens in selected cells in the arcs were operated at a temperature of 50–80 K, to observe if any impact on the conditioning could be detected [10].

In general, the cell-by-cell heat load pattern along the machine is very reproducible from fill to fill, in particular for a given bunch configuration [11]. Figure 5 displays the heat loads at injection and top energy for individual cells in Sector 23, during a fill before the beam screens were warmed up (top) and a similar fill after the warm-up (bottom). The cells marked with blue bands belong to the family of cells in which the beam screen temperature was changed. As in the cells shown here, no evident effect on the measured heat load can be observed in any of the cells that underwent a temperature change, neither immediately after the exercise nor after a longer period of time [12, 13]. Based on this study there is no indication that the temperature plays a role
Figure 5: Cell-by-cell heat loads in Sector 23, at 450 GeV and 6.5 TeV. Measured values shown before (top), and after (bottom) the beam screens of selected cells, marked by blue bands, were operated at a temperature of 50–80 K.

Figure 6: Bunch-by-bunch beam power loss, as estimated from the RF stable phase measurements, for a hybrid filling scheme alternating trains of 25 ns BCMS beam and 8b+4e beam.

on the conditioning, but it cannot be excluded that exposure to higher temperatures or for a longer period of time could show an effect.

In the event that the beam screens cannot be conditioned sufficiently to keep the heat load of the nominal filling pattern (2760 bunches) within the cooling capacity, it may be necessary to use bunch patterns that reduce the electron cloud build-up. The “8b+4e” bunch pattern, with trains of 56 bunches made of short trains of eight bunches with 25 ns bunch spacing separated by four empty slots, was shown in 2015 to effectively suppress the e-cloud [2]. Since the 8b+4e filling scheme has roughly 30% fewer bunches than the nominal 25 ns scheme, a hybrid scheme tailored from standard 25 ns and 8b+4e beam, has the potential to maximize the beam current while keeping the heat load within the available cooling capacity.

The effectiveness of such a filling scheme was tested during Machine Development in 2016. A hybrid filling scheme with 1908 bunches was used, consisting to 55% of 25 ns BCMS beam and to 45% of 8b+4e beam, resulting in 15% fewer bunches than the equivalent standard filling scheme. The e-cloud suppression could be confirmed both through the measured arc heat load and the beam energy loss estimated from the RF stable phase. A 40% reduction of the heat load was observed in the most critical sector of the machine.
and the bunch-by-bunch pattern of the beam energy loss (Fig. 6) shows that the 8b+4e trains stay e-cloud free [14].

CONCLUSION

Although significant electron cloud was present in the LHC during the 2016 Run, the machine performance was not severely affected. As a result of the conditioning of the beam screens in 2015, as well as the experience acquired in operating with e-cloud, problems due to e-cloud instabilities and transients on the beam screen temperature were mostly avoided.

With the number of bunches that could be stored in the machine restricted by the SPS, the total beam current was not limited by the available cooling capacity, but by the constraint on the bunch intensity due to the pressure rise in the MKI area. In 2017, on the other hand, when both of these constraints are foreseen to be relaxed, the heat load on the arc beam screens is again expected to limit the total current [1].

The beam screens continued to condition in 2016, but a significant decrease in the rate of conditioning was observed after the first months of operation. A test where selected beam screens were kept at a higher temperature showed no improvement in their condition. It remains to be seen in 2017, if operating with longer bunch trains and/or higher bunch intensities can enhance the conditioning again.

If this is not the case it may be beneficial, in particular after Long Shutdown 2 when higher bunch intensities will be available, to use hybrid filling schemes to tailor the heat load to the available cooling capacity.

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Abstract
The paper will discuss the LHC control system performance during 2016 operation. It aims to answer the following questions: In retrospect, which controls facilities, if any, were missing and what could be improved? How did we perform on follow-up of requests from Evian 2015? Human errors committed while interacting with the control system are discussed and suggestions made for possible mitigation measures. Looking forward to EYETS (the extended year end technical stop), the planned control system changes and their impact will be presented.

INTRODUCTION
The LHC Control System was very stable in 2016. During five full years of operation with beam, the LHC suite of applications, fixed displays and feedbacks have evolved and matured to a high level of efficiency and reliability. All critical problems were cured in a very reactive manner (e.g. Early in the year some problems of slowness when re-generating setting for beam-processes were temporarily mitigated by increasing the database cache size). Nevertheless, some ideas and requests for improvements remain which will be discussed in the following sections.

PRIORITIES SET AT EVIAN 2015
An OP perspective on LHC controls was presented at Evian 2015 [1]. This paper established a list of the top five priorities of software improvements. These priorities were later re-evaluated in follow-up discussions [2].

Top five priorities
The following priorities were established following discussions within BE-OP-LHC.

- Improved filling diagnostics.
- Improve integration of QPS, PIC, EquipState.
- Improve automation of sequencer and scripting.
- Know the state (of the machine) at a given time.
- Improve window management on consoles.

SOFTWARE DEVELOPMENTS 2016
This is a non-exhaustive overview of some key new software developments used for the first time during the 2016 Run.

Improved filling diagnostics
At the top of the list, following a discussion of application software priorities, was a need for improved filling diagnostics. Much time was lost in previous years diagnosing injection problems between the SPS and LHC. To improve this situation an application was developed with a generic architecture in mind. The analysis framework can be reused in other applications. A beta version of this application was available for tests towards the end of the 2016 physics Run.
This application maintains a survey of power converter currents in tolerance at a given time in a beam process. It is linked to the Software Interlock System. The most recent improvement on this system provides an interlock on Quadrupole currents, to ensure that the phase advance between the beam dump kicker and tertiary collimators at the experiments is respected. The GUI display also provides a means to monitor the time remaining in a transitory beam process, such as the ramp or squeeze.

To improve the robustness of this facility, there remains a requirement for an improved state machine to be able to follow the state of the machine at a given time (rather than relying upon time elapsed following the broadcast of a timing event, as is currently the case).

Measurements and corrections of Tune and Chromaticity are frequently performed in routine LHC beam operation. A new application was introduced in 2015, and further developed in 2016, to make carrying out these routine measurements and trims more fast and convenient.

To improve the configuration and management of the upper tier of fixed display screens in the LHC island of the CCC, start-up scripts were implemented to define the application displays and their window positioning, to be executed upon re-start or reboot.
**HUMAN ERROR AND CONTROLS**

Different studies focus on the interplay of humans with complex systems and the resulting system failure modes [3]. The general conclusion is that human variability is a force that can be relied upon, and therefore should be harnessed. This is particularly true in a control room environment involving shift work, 24 hours a day, as well as an often busy working environment with many incoming phone calls and visitors to the control room. Therefore when an instance of human error occurs, rather than blame the individual, it should be seen as an opportunity to analyse why the control system defences did not catch the error. An analysis was made of instances of human error in LHC operations in 2016. Machine protection defences against these incidents proved to be very robust, and in all instances errors were caught with clean protection dumps of the beam. However downtime incurred due to human error could be improved.

There were 52 events classified as “operational mistake” in 2016, distributed over different operational phases, as illustrated in Fig. 7. A protection dump at injection may have a small impact on downtime. However, the further along the operational phases in preparing beams for physics, the greater the impact.

![Figure 7: Distribution of Operational Mistakes](image)

**Human Error Examples**

The following is a non-exhaustive list of instances of human error, showing the most common mistakes.

- Errors while overriding the Safe Beam Flag (SBF) with Setup beam. Unintentionally forcing SBF to false. Errors with masks and hidden interlocks. Intensity over allowed threshold with respect to energy.
- Incorrect sequence execution. For example, switching on the ALICE Dipole instead of the Solenoid.
- Errors in MD setup and recovery from MD. E.g. loading coarse collimator settings without BETS-TCDQ mask set.
- Preparing a Hypercycle change with circulating beam, resulting in changes to Safe Beam Parameters.

**Human Error and EquipState**

A frequently occurring task in LHC beam operations in 2016 was the recovery from power converter faults. This process requires an interplay between three separate applications. Equip State, the QPS Circuit Synoptic and the PIC controller (see list of priorities from Evian 2015 [1]) During this process of re-arming and resetting, there is, amongst others, a non-negligible risk of switching off the power converters in a complete sector by mistake, as EquipState has no requirement to confirm global execute commands. In such cases the impact on downtime can be one extra precycle taking 40 minutes.

**Human Error Defences**

While human error can never be completely eradicated, attempts can be made to catch commonly occurring errors before they provoke a protection beam dump or have other impact on machine downtime. Mitigation measures were already added to the Sequencer and Software Interlock System in reaction to some operational mistakes. The following are some more suggestions based on the errors experienced in 2016.

- Confirmation of critical or global execute commands. Popup confirmation should be used where (and only where) there is a risk of errors.
- Improved checks from state machine or sequencer when Safe Beam Flag is overridden should be implemented.
- Working in pairs as a team can often help prevent mistakes and is highly recommended. This is especially important outside normal working hours, during the night or during special modes of operation which break from the normal routine.

**PLANS FOR EYETS**

Plans for the Extended Year End Technical Stop are outlined as follows [4].

- Controls maintenance from 5th to 13th January. CO services will not be available during this period.
- Development on core controls services to be frozen by 8th March 2017.
- All application software will have to be ported to the CBNG build tool. Training is required for application software developers and will be given in due time.

![Figure 8: EYETS Controls Schedule](image)
Work in the LSA Team
The main work plans within the LSA team is as follows.
- Introduction of Functions and Function List types in FESA3, CMW and FGCs.
- Better setting archiving, to properly resolve the slowness issues experienced with setting regeneration. Maintain reasonable limits on dataset cache size.
- Consolidation of LSA Suite. With a view to the eradication of individual applications.

Work in the OP Software Team
The main focus of the OP software team will be on further developments to the Luminosity Scan client and server, with a view to eradicating the old Luminosity Scan application (which was still required in 2016 for luminosity levelling in the separation plane). It will later be extended to include facilities for crossing-angle levelling and Beta* levelling.

When developing new software, care is taken to maintain a layered control system, where the application client layer can remain thin and light, and tools from the underlying business layer can be easily reused by different applications.

CONCLUSION
The LHC Control System has reached an excellent level of stability and efficiency in 2016. New tools are contributing to fast and efficient operation. The human factor should be kept in mind, and attempts made to analyse and catch errors before they have an impact on downtime. A teamwork approach to software development projects is the way forwards. There is much work in progress during EYETS 2017. Notably for CBNG build tool, consolidation of LSA suite and further developments to the luminosity scan facility.

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BREAKING THE WALL BETWEEN OPERATIONAL AND EXPERT TOOLS

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Abstract

Most of the time, for the daily operation of the LHC, dedicated operational applications are used, and the expert have their own applications to control their equipment, do specific machine developments and studies. In some cases, these expert applications need to be used by the operation’s team, even if not really adapted. This presentation will demonstrate why this systematic split between “operational” and “expert” applications implies a lot of disadvantages. In addition, commons problems and requirements which are easily identified in all groups are shown. Finally it will propose an alternative approach to overcome these issues.

INTRODUCTION

To control the different systems and equipment of the accelerators, two types of applications are usually available. The expert applications are designed to give a very detailed view of the system, displaying information for experts for a complete diagnostic of the system. They are most of the time developed by the equipment software experts. The choice of development’s language and practices is the responsibility of the equipment groups only. Very often, beside the expert applications, simpler operational applications are developed by the operations group, exclusively in JAVA. The purpose of this applications is to give at one glance the general state of the system. The information displayed is filtered to be relevant and meaningful to an accelerator operator, and the possible actions are limited.

EXPERT AND OPERATIONAL APPLICATIONS

For a lot of accelerator systems, both expert and operational applications are available. The expert application is perfectly adapted to the experts needs, and the independent operational application is designed for OP. This situation looks perfect for everybody.

Nevertheless, this is far from ideal, the main drawback being the development and maintenance of much more applications while every group lack of manpower. Often it implies a lot of code duplication between expert and operational code. In addition, in case of low level software modification, all the involved operational applications will have to be modified. It happens that the modification is not well communicated and it breaks the operational application, and can cause accelerator downtime.

For some accelerator systems, the expert application itself is used by operators. Sometimes because there is no manpower in OP to develop a new application that would be more adapted, or because the expert tool is useful as such for some diagnostics or measurements that OP wants to perform. Some actions that were done only by experts at the early commissioning of the LHC are with time delegated to OP, and the operators use the existing expert application for that.

In one hand, having a single application presents advantages: only one application to maintain, possibility to control the actions authorized for OP by using RBAC.

In the other hand, the expert applications are not designed for OP’s needs:

• They can be difficult to use for non-expert even sometime simple things as finding the relevant device name are not straightforward
• The expert applications often present too much details, this is confusing and leads to wrong diagnostic, and at the same time the information interesting for OP is lost.
• In some cases the expert applications have a direct access to the devices. It happens that the multiplication of clients in the control room is not managed properly and creates performance issues. The parameters are not always in LSA and therefore the application doesn’t benefit of LSA settings management features.
• Most of the time no real training on how to use the application is provided, and there is a tendency to try every buttons to see if it solves a particular problem.

WHAT IS NEEDED TO IMPROVE THE SITUATION

Common problems

It is easy to see that all the equipment groups, accelerator physicist or operations team, have commons problems with the software development.
Flexibility and independency: for equipment experts and physicist, the applications have to be flexible and easy to update and improve. They want to choose the programming language that is best adapted, for example they use the powerful mathematic libraries of Mathematica or Python when developing software for complicated analysis.

Accessibility: being independent doesn’t mean that the software is isolated from the rest of the accelerator control systems. It has to be able to access theses control systems, and the control systems have to be able to use the expert libraries even if not written in Java.

Maintenance and evolution: In all groups there is a lot of software, but not enough developers. The code needs to be maintained and evolved, either to adapt to a new hardware or simply to follow the control system upgrades.

Sustainability: often the developers are non-professional and only temporarily at CERN, and when they leave their software as to be taken over or die.

Different solutions

To face the problems, this is very common that different groups have their own solution and develop their own tools.

For example, RF expert applications are developed in LabView, because it’s easy to create nice graphical user interfaces. In operations group, a GUI framework called Inspector was developed to create simple user-interfaces without programing any Java, configured only with xml files.

In the ABP group, a library was developed to access the logging database from Python (pyTimber), and in BI a library was developed to access FESA devices via JAPC from Python scripts.

Such individual initiatives are very useful and other groups are interested to use the same solutions, but face several limitations:

- The products are not scaled or adapted to be used intensively
- The developers did not foresee to maintain and evolve their libraries for everybody’s needs.
- Difficult to make sure that the products are sustainable

Eventually these products will need to be taken over for long term support, with the usual problem of resources.

Common needs that should find a common solution

GUI framework

The production of user interfaces in Java is always painful and difficult and takes a lot of resources. In addition, all the applications of the control system are using different look and feel, there is no uniformity in the GUI used in the CCC. With a common framework used by all the developer, lot of time could be gained in the equipment groups, a lot of code repetition could be avoided making the code easier to maintain.

High level software layer [1]

Some features and functionality are needed in many applications, for example reading the actual tune of the LHC beam, combining some timber data into meaningful information, subscribing and combining java parameters etc… As it is done now, the same code is re-written or copy-pasted each time an application has to implements such or such functionality. Instead, all these common functionalities should be identified and implemented in a product accessible by everybody.

Consolidation of the interfaces with the control system.

The use of other languages than Java for the expert or operational applications can’t be avoided, developer should keep the freedom to use what is most adapted for their need. It should then be easy to access the control system from these other languages, typically Python. The existing libraries should be consolidated and given a long term support in order to be usable by everyone.

HOW TO FULFIL THESE NEEDS EFFICIENTLY?

The experience so far with a client/provider approach between the control group and the equipment’s or operations group has shown limitation in term of efficiency: CO group may be overloaded with work and unable to fulfil all requirements, while unsatisfied clients start their own development in an attempt to unblock their situation. Experiences of more collaborative approach across groups like the LSA project have demonstrated the interest and efficiency of working together.

Therefore, knowing that groups can agree on needs and priorities, creating teams across groups to develop tools and frameworks needed by everyone would be the way to go. In this approach, free contributions to improve and evolve the software has to be allowed, providing that the code quality is respected. All groups have to agree on common principles and practices, like the way the software is structured, the tools and the rules for testing and reviews.

The benefits of working together are many. The products would have more chance to fit the needs of everybody. The code would be re-used instead of duplicated or rewritten for every application, this will save resources and time. The software could evolve in a more dynamic way if everybody contributes and it will enforce a standardisation of the code, the tools and the software structure.

A central place to get help, advice and information for any new development is needed, also for sharing experiences and expertise. This would benefit for
experienced software programmer as well as physicist developing their first application.

CONCLUSIONS

Commons problems and commons requirement concerning the software development can be identified for all the groups in the BE department. Nevertheless coming to commons solution is not as straightforward as it should. It has been already demonstrated, thanks to some projects like LSA, that a well organised collaboration across groups is very beneficial: better efficiency and quality of the delivered product, knowledge sharing and mutual trust and respect. While being aware of the organisational difficulties and the need of commitment of all the developers in every groups, efforts in this direction should continue to be encouraged and valued by the management. It will pay at longer term and mitigate the difficulties faced by everybody thanks to a common effort.

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HOW TO IMPROVE INTERACTIONS WITH THE CONTROL SYSTEM

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Abstract

The availability of the LHC control system has been excellent in 2016, with only 0.11% of the machine unavailability attributed to Controls. Nevertheless, many other criteria can be maximised in order to improve the LHC control system and this paper focuses on the user experience. After having identified the main users, we detail some of the perceived problems, e.g. long development cycles, and areas where improvements can be made such as the standardisation of interfaces and integrated tooling. Finally, we propose organisational and technical solutions that we aim to apply in the near future in order to try to optimise the user experience.

INTRODUCTION

Several criteria can be used to evaluate the control system and the system availability is without question the highest-ranking criterion. Indeed, no matter how good your control system is in terms of, for example, features and performance, if it is not available to control your accelerator, its value is close to zero. 2016 has been a very good year for the accelerator control. According the Accelerator Fault Tracking (AFT), a mere 0.11% of the beam unavailability was attributed to the accelerator controls. Figure 2 is an extract of the system unavailability chart for the year 2016.

Other important criteria can be used when assessing the control system. For example, one could look at the financial aspects such as the hardware cost, taking into account both the cost of a new installation but also the cost generated by the periodic renovation one has to perform. One could also consider the software cost with license fees that one has to pay every year to use the commercial software used in the controls system. Looking beyond CERN, one could consider the exportability of the system to be an important aspect. Figure 1 depicts the author’s subjective evaluation of the current accelerator control's infrastructure. This article focuses on yet another aspect: the user experience. Due to time and space constraints, we do not study specific applications, which are built using the infrastructure but instead look at the general user experience of the control system infrastructure as a whole.

USER EXPERIENCE

According to Wikipedia, the user experience (UX) refers to a person’s emotions and attitudes using a particular product, system or service [1]. Other definitions highlight the human-product interaction, the quality of this interaction. In our context, it is worth noting that the interaction is not limited to human-computer. Even though usability is often seen as the most important aspect of UX, there are many more such as flexibility. Flexibility is understood to be how easy and quickly the system can be used and extended to accommodate new needs, with “new” being the keyword. Examples of new needs could be new ways to post-process data or new features to enhance the infrastructure or solve a common problem. For our work on the control system infrastructure, we look mainly at the usability and the flexibility. We concentrate on how the control system empowers users or impedes them in their daily job. Improving the user experience is a way to improve the control system, nevertheless, it must be done without degrading the other criteria, mainly the availability, from today’s high-level.

Before going further, we need to define who the control system’s users are. Accelerator operators and accelerator physicists (AKA MD users) are clear end-users of the controls solutions. But, as we talk about the infrastructure itself, we have also a lot of developers working at different levels of the infrastructure implementing specific controls solutions. The high-level application developers implement GUIs and scripts for interfacing with high-level services such as the logging, LSA, the post-mortem system, etc. Low-level software developers mainly work on FESA classes and kernel drivers with little to no interaction with the high-level services; at least until the operational deployment. Finally, the hardware developers design electronic boards with FPGA and implement their logic using HDL (High-level Description Language). Whenever the infrastructure or a specific solution does not work, operators call the support team for diagnostics and intervention (1st-line Diagnostics and controls experts). The examples above are by no means exhaustive and there are more user categories. When looking at the interactions between the control system and the users, it becomes clear that we should not define the users as community of human beings but rather take into account that a user has multiple roles that he/she will take depending on the task in hand. A person can be on shift for the LHC, but alternating their roles and tasks between those of an LHC operator and those of a 1st-line diagnostic expert. The next day, the same person might be the machine expert post-processing data acquired during the shift. So, there are different interactions with the control system and different needs depending on the role.
PERCEIVED UX LIMITATIONS

By interviewing key user representatives, one can identify two common problems with the control system infrastructure. The first problem is its complexity and how it is exposed, and therefore the steep learning curve encountered when starting to work with it. The second problem is its lack of flexibility; which is both technical and organisational. In other words, the control system infrastructure is perceived by the users as heavy and complex. In addition, the inadequacy of some tools for common tasks is often mentioned. Tools have to be taken in a general sense as this comment applies to GUI tools such as, for example, the APEX CCS editors but also the development languages available.

The current situation is not surprising. Indeed, the recent years were focused on availability and maintainability of the infrastructure with renovation and consolidation projects such as ACCOR & InCA. Therefore, even if there are still about 900 FECs to be renovated before end of LS2, we have a system that is appropriate for long-lasting, stable operation phases. In addition, the release and deployment phases are also well-organised and the post-technical-stop recovery time is shorter than a few year ago. Furthermore, as the first years of LHC operation were very important, the focus was more on the accelerator operator role than on the other roles such as the software developer. The consequences of those choices are that the control system is less well-adapted for a quick-and-dirty test, fast-iteration development, or simply final validation using the whole infrastructure.

The root causes of the problems mentioned above are well known. The control system’s complexity is too exposed to the users. It lacks homogenous interfaces and the integration of the different layers could be improved. The tools, end-user applications, and programming languages are inadequate for specific tasks typically performed by some expert roles.

Today’s control system infrastructure can be seen as a set of independent components. At runtime, those components collaborate to achieve the expected behaviour but from a developer or accelerator expert’s point of view, the whole internal structure is exposed and a (very) good knowledge of the different components and layers is required. Furthermore, the integration could be improved as today’s level of integration has two main consequences. Firstly, simple tasks can require many actions and there are no straightforward, easy-to-remember connections between them. The workflows are sets of steps without clear relationships and are based on tools as different as web applications and shell scripts can be. Secondly, the lack of integration leads to disparate and sometimes incompatible feature sets between the control layers. For example, some extensions were implemented at the front-end layer for specific use-cases but these extensions are
incompatible with the high-level concepts. For a seasoned developer, this will not be a problem but a junior programmer can potentially lose a lot of time when he realises that incompatible features are used and his design needs to be reworked.

With respect to the interfaces’ homogeneity, there is no common API to access all of the high-level services, even for the basic use cases. To give an example, one cannot subscribe to a power converter in the SPS for all the SFT cycles since yesterday with a single consistent API. Instead, it is necessary to fetch the past data from the logging service and then subscribe to the actual device for live data using another API.

All the points mentioned above are neither critical nor blocking but as the system’s operational maturity is reached, improvements in those areas have started or are in the pipeline. In the next sections, we will go through different ways of improving the usability and the flexibility of our system. Some are still at the level of suggestions but they will clearly shape the evolution of the control system over the coming years. Other proposals are already being taken into account as part of recent developments.

**IMPROVING USABILITY**

In order to improve the usability of the controls tools and of the system in general, more emphasis has to be put on the control system’s use-cases rather than focusing on a specific service’s needs. For a developer, that means a better full-vertical integration with compatible features that make sense throughout the layers of the control system. Another example are the configuration tools. They should not be a set of heterogeneous service-specific tools but instead a single tool, or at least tools with a single-entry point, which guides the user through the process required to assemble all necessary information. Furthermore, if different tools are required to perform a task, these tools should be linked so that the end-user does not need to remember the list of tools to be used.

This is the approach taken in the new Controls Configuration Data Editor (CCDE). Figure 3 depicts a mock-up of the new hardware configuration editor, which is part of the CCDE. The top panel of the interface assembles information from different sources so that the end user does not need to gather data from different tools, web pages, etc. Whenever a new service is put in place, it will be integrated into the existing tool rather than providing a new service-specific tool. This better integration immediately helps to reduce the so-called configuration marathon. It is important to note that this approach does not mean that the resulting tool is a bulky application difficult to maintain. Indeed, the modern web-based applications, distinct tools can be seamlessly integrated.

In addition, we want to apply a principle known as “convention over configuration” to the control system’s configuration. Today, every single bit of the control system can be configured and most of it with opt-in behaviour (i.e. you need to indicate that you want to use a given service). In recent years, more general attributes, such as the control device state, have been introduced. Thanks to this simple piece of information, more conventions will be put in place and more default behaviours can be inferred from it. For example, it is planned to rely on the device’s state attribute to decide by default whether the alarms should be monitored, which settings to be managed, etc.

![Logical configuration - inline edition](image)

**Figure 3: Mock-up of the new Controls Configuration Data Editor (CCDE)**
Returning to the interfaces’ homogeneity, we have to emphasize the difference between the needs of the end-users and the need for a proper maintainability; which can be seen as opposing forces. The fact that the control system is a set of islands is actually a benefit from the maintenance point-of-view. Every complex system should be easily decomposed into simpler modules in order to manage the complexity. That being said, what is clearly missing in the current system is a common interface to access the different services (islands) as, from a user perspective, the source of data (FESA, InCA acquisitions, LSA historical settings, CALS, Post-Mortem, etc.) should not matter. The control system is built around a data model that commonly referred to as the device/property model. In a few words, the device-property model says that the independent entities are devices and the devices have properties that can be read and written. Obviously, this model is not going to cover the most exotic cases but this is the direction we want to take for the future, especially whenever we have opportunities to renovate services such as the CERN Accelerator Logging System (CALS). We will know that we have reached our goal when it will be possible to seamlessly retrieve logged data from two days ago and live data from the accelerator with the same API.

To finish the discussion on usability improvement, we need to look at it from a developer’s perspective and how easy it is for them to quickly iterate in their development cycle, as well as validate their development without impacting the operational accelerators. The main issue is that the system has been solidified for many years to ensure excellent operational reliability but shortcuts required for agile development are not in place yet. Furthermore, and rightly so, developers are encouraged to work on the General Purpose Network (GPN) where not all of the services are available. In recent years, more and more effort has been invested in the setup and use of testbeds. In BE-CO, most of the low-level frameworks and libraries are extensively tested on the so-called Controls TestBed (CTB). With an even bigger ambition, TE-MPE is putting in place a complete hardware and software test bench as described in [2]. There is also an ongoing effort to provide high-level services on the non-operational GPN network so that validation can be done without having to pass through formal steps such as code release and deployment. Finally, the topic of simulation has recently received more attention and many usability issues could be solved by providing out-of-the-box simulation modes whereby one could limit its dependencies on external systems. For example, a simulation mode for the timing system would simplify the testing with different beam sequences without depending on the actual accelerator schedule.

**IMPROVING FLEXIBILITY**

Several initiatives have been launched in the recent months to improve the flexibility of some of the controls components. Furthermore, we would like to experiment with different organisation of the work that, among other things improve the organisational flexibility. One of the areas that needs improvement is the rapid application development, i.e. solutions that provide an easy-to-use language for the situation where a quick test or validation must be done and where a full development is not practical. The Python language has been seen by many as a valid solution for cases such as Machine Development (MD) slots and also for low-level hardware validation. Inspector, a tool to quickly design GUIs, is another successful example on how to add flexibility in the controls offering. In both cases, we want to work differently and build stronger collaborations. In the past, one of the central controls groups would have taken over the support of the technology or the tool. Indeed, we believe that the end-result can be much better if all CERN users could, if they wanted and had time to, contribute to the tools. Of course, any attempt to modify the way we work and collaborate cannot be done without ensuring that the current levels of availability are kept and bearing in mind our long-term needs in terms of maintainability. This change of organisation means that we depart from the usual client/provider approach. This approach does not scale very well and introduces delays between new needs and the availability of the solution, in other words, organisational inflexibility. This problem has been solved for a long time by open-source communities for software as big as Linux.

![Figure 4: Taurus & Sardana community development (Courtesy C. Pascual-Izarra et al.)](image)
Nevertheless, one must keep in mind that we have specific constraints in terms of long-term stability and therefore responsibilities must remain clear. Figure 4 depicts the workflow of two Tango products Taurus and Sardana. This workflow relies on modern software engineering tools and concepts such as Git, pull requests (PR), and code reviews. We believe that such an approach should be attempted for the support of the Python technology. Instead of expecting a central entity to develop and support everything related to that technology, we build a community around a focus group where people can share their experience, problems and solutions but also decide collectively on the creation of new components or libraries and the evolution of existing ones. The support is then given by the main authors but the community acts as back-up should the experts be unavailable (holidays, sick leave, etc.). To ensure that the required discussions take place and that the community is kept alive, a central controls group such as BE-CO should organise the focus group. If the approach is successful, the same should be applied to other core frameworks such as FESA. One could very well imagine that new features are introduced by a framework user after discussion and validation by the core team. Later, the developer submits (aka make a pull request in Git terms) to the team that performs a code review and verifies that the long-term requirements (code quality, tests, etc.) are satisfied. As the last step, the new feature is available in the latest release and the whole community can profit from it. Compare to an approach where all the requests are sent to a single team, prioritised and worked on by them, it is evident that a more collaborative approach brings flexibility in our organisation.

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Abstract

The Accelerator Control system is developed by the Controls Group in collaboration with numerous software developers from equipment groups to provide equipment experts and operation crews with general and specific control and supervision software. This presentation proposes a review of the different strategies applied for testing, validation and deployment of the software products. The risk and impact of these strategies on the LHC [1] performance and availability will be studied, and possible evolution to continuously improve this performance will be discussed.

INTRODUCTION

This paper intend to present a review of common software engineering activities which are testing and deployments, and how it impacted the performance of the LHC in 2016.

Software testing is a way to prove that the software is performing in the way it is required by the stakeholders. It is also a way to inform both stakeholders and other developers of the behavior and the quality of the software.

Software deployment is the process of ultimately using the software in a production environment. This process can consist of few or many steps, depending on the choices of the software engineers and users of the software.

As any software engineering activity, numerous ways to perform them have been advertised, demonstrated, accepted or denied by the software engineering community.

This papers focuses on Java, C++ and Python technologies and on high level software, ranging from Front-End Controller software (e.g. FESA [2]) to User Interfaces, Services and Analysis Tools. This papers references multiple times to controls software or controls environment, which means the software and infrastructure produced by the Controls Group and the Equipment Groups together.

This study was done following a top-down approach, where the ultimate upper goal is the performance of the Accelerators. From the estimated impact on the performance, one could identify issues in the deployment strategies and the testing strategies.

The first section describes the investigation performed to review the impact of control software on LHC performance. The second section describes the testing strategies applied during development, release and deployment of the control software. The third section describes the deployment strategies that are used for software in the control system. The fourth and last section gives an outlook of possible directions for the future.

REVIEW OF TEST AND DEPLOYMENT IMPACT ON LHC PERFORMANCE

Tracking Tools

The accelerator control system relies on a multitude of tools to track events, faults and actions: logbook, AFT [3], central tracing service, etc. Coordination initiatives complete this list: Exploitation Meetings and Smooth Upgrade Working Group (SUWG).

The most visible and exploitable tool is the logbook where every step of the accelerator operations are recorded. Entries can be added manually by operators or experts, or automatically by software tools such as the LHC Sequencer. The logbook will typically record every software deployment that was announced to the operators. The fact that these recordings are written by hand, and only when announced, proves the analysis to be difficult as some deployments are indeed not referenced, and the referenced deployments are reported in very different ways. Nonetheless, if a quantitative evaluation was impossible for 2016, a qualitative evaluation has been performed and one can see that deployments have had a negative impact on the performance of the LHC, and multiple hours of operations were compromised after software deployments. There were different causes:

- lack of tests and validation before the deployment to operation
- validation could only be performed with beams
- impact on dependent systems was underestimated

This last point is very significant, as it is frequently mentioned, not only during deployment and integration in operation, but also during the development phases when the contribution of other software teams is often underestimated.

Correlating data from the logbook with other tools proved to be difficult and extremely time consuming. A deployment tracking system is clearly required in order to supervise this activity and allow the collection of performance metrics. It could help identifying all deployments: major deployments, bug fixes and rollbacks.

Coordination of deployments

Another source of useful information was the Smooth Upgrade Working Group. It reviews and coordinates the deployment of software product for each technical stop. It evaluates the risk for operation, how the software can be validated, and if it can be rolled back. In addition it tries to identify the outgoing and incoming dependencies.
of the software. In spite of all the dedication and expertise of its members, it is difficult if not impossible to oversee all dependencies and prevent all issues, and it keeps track of them as they raise. The amount of upgrades that are reported to the SUWG is very important. This brings difficulties in identifying the risk of all of them while it relies on manual analysis. The SUWG could take advantage of some software support, like a dependency tracking system that would report that a software A is used by software B and C, and that an upgrade of Software A needs to be reviewed with software B and C developers.

From this investigation, one can see that some software is required to better support the deployment of software product in the LHC environment. Software could:

- help planning the deployments, by providing an accurate and exhaustive understanding of the controls environment and the dependencies on the deployed software.

- collect metrics about deployments, improving the identification of shortcomings induced by this activity.

**REVIEW OF TESTING STRATEGIES**

Testing is a wide term and numerous type of software testing can be identified. The following ones are considered in this paper:

- Unit tests that focus on an isolated unit of code, typically a function or a class.

- Integration tests that validate the interactions of multiple components together.

- User Acceptance Tests to confirm that the user specifications are fulfilled.

- Testing on a Staging environment, which is ideally as close as possible to the production environment.

- Final Validation in production, the time devoted to this last validation is reduced if other testing strategies are applied.

If writing tests has an initial costs, it also brings numerous advantages to the product, hence a valuable return on investment, particularly on long term projects like in the controls environment. They can be seen as documentation for a function, a class or a feature. They ease the long term maintenance of the software applications as they help engineers new to the project understand the source code and prove that it behaves as expected, and make them confident in refactoring - e.g. modifying the existing code - when fixing bugs or adding new features. The automation and repeatability of the tests also helps understanding the impact of any modification in the source code or in a third party dependency on the application behavior.

Unit testing and integration testing are two kind of tests that must be considered at design time. All software is not unit testable, but all software can be written in a testable way. The ability to test the source code of an application also highly depends on the third party software components on which the application relies. In the controls environment, different strategies have been applied through time, and depending on the interests of the providers of these third party tools. It results in a discrepancy of the ability to test controls software. For instance the FESA framework makes it complicated to write unit or integration tests as it is very difficult to isolate the logic under test from the FESA framework. This is a common issue with frameworks that force the user code to be coupled with them. On the other hand, when using a library like CMW, JAPC, Post Mortem, it is rather simple to add an abstraction between the source code of the application and the third party library, which in turn makes the application source code testable without depending on the third party library.

In a machine like the LHC, where the objectives are ambitious and the machine protection risks significant, it is important to consider that core components used by many applications should not impair the testability of these applications.

Software testing is supported by metrics that helps understanding the presence and quality of the tests. Two very important metrics are the coverage of lines of code and of branches. A line of code is covered if it is executed once by a test. Branch coverage highlights the fact that all conditions of a branch (e.g. if statement) are tested. The controls environment registers 654 Java projects. 365 of these projects have less than 50% of line of code coverage. This means that more than half of the software that runs the controls environment is not tested. These metrics only concerns Java because it was simple to integrate the entire controls software stack thanks to an homogeneous development strategy. C++ and Python remain not monitored at the moment, except on the initiative of the developers. These metrics are exposed publicly at CERN via SonarQube [4]. Exposing these metrics to users of the product could encourage the developers to provide high quality software and improve the user confidence in the product.

While unit and integration testing are very good tools to validate the way the source code behaves, user acceptance tests are of tremendous significance to highlight that the software is acting the way it should. Combined with automation, they guarantee that a feature stays available for the lifetime of the software product. These tests usually need to run in a staging environment in order to be effective. They however often must rely on third party systems that are not available in the staging environment, for instance beams. It is usually possible to compensate this with simulated or mock components. A successful design of user acceptance tests in a staging environment is for instance the Orbit Feedback system, which relies on automated tests performed without beams. This testing strategy helped in understanding the legacy software system, and reduced the testing time in operation with beams, that requires both operators and experts to be there to validate
the software. Many initiatives exist to provide test environments, for CMW, Timing and FESA, or for FGCs. Machine Protection is currently implementing a project of a test bed for magnet protection and interlock equipment.

At the moment, controls and equipment groups usually all have their own staging environment, which is usually limited to their area of concern and rarely provides possibilities of integration with systems from other equipment groups. Based on the experience gathered during numerous hardware commissioning, and foreseeing the work necessary to further automatize the machine commissioning and beam checkout, the MPE group is currently working on a staging environment that will enable performing integration testing on entire powering systems, comprising FGCs, QPS, interlocks systems and controls software.

The controls environment currently brings some limitations to the proper implementation of staging environments: there are too many dependencies on the Technical Network infrastructure, where the operational systems are also running. A proper staging environment would require a correct separation between itself and the operational environment. Numerous attempts had been performed in this direction but they were always unsuccessful. The Controls Group under the CO3 impulse is currently reviewing their numerous project and will come back with recommendations on providing core services to staging environment out of the Technical Network.

The more time is spent on unit testing, integration testing, user acceptance testing and staging, the less time is required for validation in the production environment. There is of course a lack of metrics illustrating this in our environment. Such metric could be provided by a deployment service, that would help comparing the time required to validate software in operation with the software code coverage.

**REVIEW OF DEPLOYMENT STRATEGIES**

The fact of deploying an application consist of following a process. Two types of applications must be considered here: Graphical User Interfaces (GUIs) and services. Both do not follow the same deployment strategies. Services can then be split into two categories: FECs with e.g. FESA, and Java services.

**GUIs**

In the controls environment, deploying a GUI consists of one step: a release. A release will deliver the GUI product to a shared file system with its version number. The delivered product is a JNLP (Java Network Launch Protocol) that can be started anywhere provided that a Java Runtime Environment is available.

A PRO release will update a symbolic link that is usually referred by numerous users, as it is the link to the latest production ready GUI. When a PRO release is performed, the previous PRO release is aliased with the PREVIOUS alias. This simple mechanism ensures that either users can rollback to the previous valid version of the application by modifying the link they use, either developers can modify the PRO link to the previous stable version.

The particularity of the deployment area is that it is mutable, and modifications of the deployed production GUIs are sometimes performed in particular situations where a core service or library needs all its clients to be updated. The danger in this operation is that production GUIs are not tested after this modification and it could lead to unexpected behaviors.

Some alternative processes are implemented by other equipment groups. For instance, BI is relying on a single and common classpath for all their applications. It guarantees the compatibility of their application between each others, while all applications are modified if new releases of core components are performed. In this environment, a strong validation step is required to ensure validity of the applications. Another example of alternative process is used in MPE, where the GUI deployment process is composed of three steps: a release, an automated validation, and an immutable deployment. This process guarantees that the application is validated by automated user acceptance tests before it can be used in operation, and that the application used in operation will never be modified. Any modification even a simple modification of dependencies must go through the automated validation step.

**Services**

Java servers deployments in the controls environment consists of two steps: a release, and a deployment on the server that hosts the service. In order to deploy, the developers authenticate to the operational server and elevate their privileges to run some deployment commands and start-up commands. With their elevated privileges, the developers can unintentionally perform actions that might impact other services, there is no protection against that at the moment. After deployment, previous versions of the service are kept to be used for roll back.

Rolling back a service doesn’t rely on commands, but on file system and symbolic link manipulations. There is currently no consistent solution offered for multi-layer applications that consist of server, database and GUI. It can be a challenge to rollback all these at once.

Here MPE and BE-CO-DS are using Continuous Integration and Continuous Delivery in order to support fast delivery of features to their services. These implementations rely on scripts that automate the deployment based on the authentication and privilege elevation aforementioned. It removes the risks that a human does not interact anymore directly with remote machine, but the underlying mechanism is still the same and can still be error prone.

In addition, a link must exist between the General Purpose Network and the Technical Network in order for developers to deploy their services. A clean deployment strategy could provide capabilities to developers to release and deploy their applications without having to act on themselves on the operational infrastructure. This would help
reducing the risks of human errors. Deploying a FESA class is yet another but very similar procedure. The difference mainly consists in the fact that the API of the FESA class is exposed in a database. In the current environment, there is no restrictions on the deployment of operational software, whether GUIs or servers. A deployment can be performed at anytime without any constraints coming from the beam presence or operation planning. Indeed responsible people are aware of these constraints and coordinate as best as possible with their interested colleagues for a deployment. The risk of deploying anytime and the entanglement between development environment and operational environment could be avoided with an integrated deployment tool.

Deployment Service
This paper identified the following possible areas of improvements in the testing and deployment of software packages:

- Testing out of the production environment in order to minimize the validation time in production
- Simple and safe deployments and rollbacks that can be performed by Operation Crews when they judge that there is a time window to do so
- Tracking of the time spent to validate a software product in production, until it is accepted or rejected
- Proper separation of the development environment from the operational environment
- Tracking of dependencies between services and API versions

Such a deployment service is an investment that would make the software deployment step safer and more transparent. It cannot be built and provided at once, but should rather grow step by step. A first milestone would simply be the tracking of the deployed versions and the incoming versions that operators could deploy and validate. A valuable extension that could come afterward is the tracking of the dependencies between the software services, and their versions.

Numerous open source tools can support parts of such a deployment service.

OUTLOOK
This paper has explained that it could not rely on any quantitative metrics of the impact of testing and deployment strategies of control software on the accelerator performance. This illustrates however a scarcity in the controls environment that can be fulfilled. This paper has illustrated that most of the Java software stack remains uncovered by unit and integration tests, and that such metrics are missing for other programming languages. It shows however that controls and equipment groups are equipped with testbeds that allow them to validate their software in a closed staging environment. Larger testbeds can be implemented to validate the integration of software services together. This paper illustrates that the ways deployment are performed are not optimal and comport some risks, and that a technical solution to improve this could actually provide valuable metrics in order to better understand the performance of software deployments.

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OPERATIONAL LIMITS FROM INTERCEPTING DEVICES

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ABSTRACT

LHC operation in 2016 was limited by the constraints on the maximum allowed intensity in the SPS due to the vacuum leak at the internal dump. The present baseline foresees the replacement of the TIDVG with a new upgraded hardware during the upcoming EYETS. This would allow providing nominal 25 ns to the LHC as well as beams with a brightness well beyond design. Nevertheless, the consequences of an accidental impact of such beams on the intercepting devices in the SPS-to-LHC transfer lines and in the LHC injection regions have to be carefully evaluated. At the same time potential dangers related to faults during the extraction of high intensity beams at top energy have to be taken into account. The survival of all the protection elements and the downstream machine components have to be insured for every operational scenario. Past and present assumptions on possible failure scenarios, their likelihood and effects are reviewed together with the estimated damage limits. Potential intensity and performance limitations are therefore derived for the 2017 Run in view of the specific beams available.

2017 OPERATIONAL SCENARIOS

At present, the SPS can produce beams with intensity and brightness higher than the LHC design parameters (1.15×10^{11} ppb and 3.5 mm mrad normalised emittance) as shown in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>ppb [10^{11}]</th>
<th>Norm. emittance [mm mrad]</th>
<th># bunches</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 ns</td>
<td>1.3</td>
<td>2.7-2.8</td>
<td>288</td>
</tr>
<tr>
<td>BCMS</td>
<td>1.3</td>
<td>1.4</td>
<td>288</td>
</tr>
<tr>
<td>80 bunches</td>
<td>1.2</td>
<td>2.8</td>
<td>240-320</td>
</tr>
</tbody>
</table>

A vacuum leak was identified inside the SPS internal dump (TIDVG) shielding and this reduced the maximum allowed beam intensity in 2016 to 96 LHC BCMS bunches or 2.2×10^{13} protons per pulse for the Fixed Target (FT) beams. The present baseline is to replace the TIDVG during the EYETS with a new upgraded design [1]; this would allow to remove the past limitation and provide high intensity and high brightness beams to the LHC (see Table 1). In case of delay in the new TIDVG production, either the present dump will be kept in the tunnel or will be replaced by a refurbished one and operation will be accordingly limited.

KEY ASSUMPTIONS

Several beam stoppers and collimators are installed in the SPS, the SPS-to-LHC Transfer Lines (TL) and in the LHC ring (see next session). All these equipment were designed for operation with LHC ultimates beams (i.e. 1.7×10^{11} ppb and 3.5 mm mrad normalised emittance), they have to withstand possible direct beam impacts and provide enough attenuation to prevent the damage of the downstream machine components. Materials and geometries were decided based on FLUKA and ANSYS calculations, to assess the energy density profiles and the stress and strain distribution, plus beam tests. In particular, a so called “damage test” was performed in 2004 in the TT41 beam line and allowed to declare as safe a beam intensity corresponding to 2×10^{12} protons (~1 mm radius spot size) [2]. An attenuation factor A [3] can be calculated from:

\[
\frac{I_{\text{after}}}{\varepsilon_{\text{after}}} = \frac{1}{A} \cdot \frac{I_{\text{beam}}}{\varepsilon_{\text{beam}}}
\]

where the ratio between the beam intensity (I_{\text{after}} and I_{\text{beam}}) and the normalised emittance (\varepsilon_{\text{after}} and \varepsilon_{\text{beam}}) defines the beam brightness before (right term) and after (left term) the impact of the beam against an intercepting device. The brightness of the impacting beam, for ultimate intensity, has to be attenuated by a factor A ~ 20 to be reduced below the safe limit, with the conservative assumption of a negligible emittance blow up (or equivalently that the beam spot size at some downstream location is comparable to that of the original impacting beam).

INTERCEPTING DEVICES FOR \leq 450 GEV BEAMS

The main intercepting devices installed in the SPS are:

- The SPS internal dumps: TB5J (26 GeV), TIDH (28 GeV) and TIDVG (450 GeV),
- The TL beam dumps TED (450 GeV) and stoppers for personnel safety TBSE (450 GeV),
- The SPS betatron and momentum scrapers TIDP (450 GeV),
- The SPS extraction septa protection elements TP5G (450 GeV)

Collimators are then placed at the end of the TL (TCDIs) to protect the injection septum (MSI) and the LHC aperture from mis-extracted beams from the SPS. These objects are space by 30° in phase advance to provide the best phase space coverage while minimising the number of needed jaws. Finally the TDI, which is installed in the LHC injection regions at 90° phase advance from the injection kickers (MKI), protects the LHC aperture in case of MKI failures affecting the injected and/or circulating beam.
INTENSITY LIMITATIONS BEFORE LS2

After the TIDVG replacement, all the SPS intercepting devices will be ready for operation with the maximum achievable intensity and brightness\(^1\). The TDI underwent several upgrades and the present design, consisting of 4.2 m long jaws composed of blocks of graphite followed by high Z materials (CuCIZr), is compatible with operation with high brightness beams [4]. Instead, according to the actual knowledge on damage limits, due to the extremely small spot size at certain collimators (down to \(\sigma_x = 247\ \mu m\) and \(\sigma_y = 473\ \mu m\)), the 1.2 m long graphite jaws of the TCDIs would not survive an impact of more than 240 BCMS bunches. Moreover, the provided attenuation is a factor of two too low for BCMS beams (twice higher brightness than ultimate LHC beams) and the TCDIs could provide the adequate protection only for up to 144 bunches.

*Are we too conservative?*

Lately the question if the assumed constraints for the TCDI attenuation were too strict was risen. The design of the full system was based on the principle that in case of any possible, even unknown, failure and consequent impact of the “transmitted beam” (scattered primary protons from the TCDIs) on the MSI and/or the LHC aperture no damage would have been caused. Two main aspects have to be considered to answer this question:

- The actual knowledge of the damage limits,
- The typology and likelihood of the failure scenarios which could determine a beam impact on the MSI/LHC aperture and the consequent effective energy deposition.

HiRadMat tests are foreseen for next year and should allow to improve the damage limit knowledge for different materials including the coils of the superconducting magnets. Several layers of protection, mainly based on hardware and software interlocks, exist to prevent mis-extraction and mis-transfer of the beams from the SPS towards the LHC. In particular, Fast Extraction Interlock (FEI) combined with Fast Current Change Monitors (FMCM) and Beam energy Tracking System (BETS) provide protection against the failure of critical extraction and transfer line magnet circuits. In case of fault of one of these systems the extracted beam would hit the TCDIs, which are set at 5 \(\sigma\), with a grazing or quasi-grazing impact (0 \(\sigma\) and 1 \(\sigma\) impact parameter respectively). Double failures are excluded but would translate in a large impact parameter if reaching the TCDIs, depending on where the failure occurred in the line. An erratic or asynchronous firing of the SPS extraction kicker (MKE) would sweep and dilute the beam on the different TCDIs. On the other hand, an internal breakdown of the MKE when pulsing could still extract the full beam on one TCDI with a fixed impact parameter (between grazing and \(\sim 7\ \sigma\), i.e. up to 12 \(\sigma\) amplitude oscillations in the TLs). Even if the recent reconfiguration with short-circuit terminations reduced the MKE voltage and thus the risk of flashover [5], this eventuality cannot be completely excluded. Finally a beam with an energy up to \(\sim 0.6\ \%\) different with respect to the nominal one could be extracted on the dispersive orbit and hit the TCDI sitting at the highest dispersion location. Also in this case, depending on the energy offset, the impact parameter could vary from grazing up to \(\sim 5\ \sigma\).

The estimated LHC arc aperture at injection is 11.2 \(\sigma\) and local bottlenecks exist which correspond to 10.8 \(\sigma\) and 11.0 \(\sigma\) in IR6 and IR7 for Beam 1 and Beam 2 respectively. Assuming that one of the mentioned failures occurs, that the beam intercepts only one TCDI and “enough” beam goes through the MSI (0°-180° phase advance between the intercepted TCDI and the MSI), then the LHC aperture could be hit and possibly damaged. In case of quasi-grazing impact, a maximum amplitude of 8.4 \(\sigma\) (considering a maximum escaping amplitude of 7.4 \(\sigma\) due to a non perfect phase coverage and to TCDI positioning errors) can be reached so that the probability of hitting the machine aperture is quite low (the effect of local orbit bump should not be neglected). On the other hand, even if unlikely, failures corresponding to larger oscillations could occur and dedicated tracking and FLUKA studies have to be performed to quantify the actual amount of beam which would impact the machine and the consequent local energy deposition. The worst possible failure scenario should be identified to decide if the constraints on the minimum required attenuation provided by the TCDIs could be relaxed. Moreover the gain in peak Luminosity has to be carefully weighted with respect the potential risk of injecting more than 144 BCMS bunches.

LIMITATIONS AT TOP ENERGY

The risk of damaging the protection elements installed in the dump region in case of failure at 6.5 TeV of the extraction (MKD) and/or dilution (MKB) kickers was also evaluated.

The TCDS and the TCDQ have to intercept the swept beam in case of an asynchronous beam dump or an
erratic firing of the MKDs. They protect, respectively, the extraction septa (MSD) and the superconducting quadrupole installed immediately after the extraction region (Q4) plus the arc and the collimators in the low-β insertions. Both the TCDS and the TCDQ were built to withstand ultimate intensities knowing that, at top energy, the beam size plays only a marginal role. During the reliability runs performed in 2015 a new type of MKD erratic (Type 2), with a different rise time than a standard one (Type 1), was identified. This translates in a different number of mis-kicked bunches intercepting the TCDQ and a particle density [6], close to the jaw surface, which can be more than a factor of 5 higher than the design assumptions (Fig. 2), depending on the half-gap. Bunches are instead almost uniformly distributed on the TCDS front face independently from the erratic type. The possibility of setting the TCDQ at 7.3 σ is being explored since this would allow reaching a β* of ~30 cm in IP1 and IP5 [7]. The peak dose along the TCDQ jaw was calculated for a Type 2 erratic using BCMS bunches and assuming a half-gap of 7.3 σ and 9.1 σ (2015 setting); in both cases the aperture was reduced by 0.5 σ to take into account possible setup errors (Fig. 3). The resulting stresses at the TCDQ are estimated to be within the damage limits. The highest energy density is expected at the downstream Q5 quadrupole and could reach up to 20-25 J/cm². This value seems to be acceptable but the final confirmation will be given by the HiRadMat tests on the damage limits of NbTi coils.

The survival of the dump block (TDE) and its upstream and downstream windows in case of two horizontal MKBs failing was also considered and no limitation for operation with 2017 achievable beam parameters was found.

CONCLUSIONS

No intensity limitation is expected in the SPS if the new TIDVG dump will be ready and installed during the EYETS. Based on the present knowledge of the damage thresholds, the TCDS will limit operation to 144 BCMS bunches if the condition of guaranteeing a sufficient beam attenuation, independently from the failure scenario, is maintained. Detailed tracking and FLUKA studies will be performed to identify the worst possible failure scenario and assess the consequences of a beam impact in the injection region (including the MSI) and further downstream in the LHC. The outcome of these studies and an improved knowledge of the damage limits could require a re-evaluation of the present constraints. Particular attention has to be dedicated to ensure that the worst case was indeed evaluated, decide if the low probability of such a failure would justify the taken precautions and limits on high brightness beams. Finally the gain in peak Luminosity has to be weighted with the increased risk of damage.

No limitation for high energy operation with 2017 beam parameters and settings (TCDS, TCDS and TDE).

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MKI PERFORMANCE DURING 2016 AND PLANS FOR EYETS


Abstract
Substantial upgrades were carried out to the MKI beam screen during LS1: MKI heating has not limited LHC operation since LS1, and is not expected to do so during Run 2. Similarly, during LS1, the vacuum systems on the interconnects between MKI magnets were upgraded: as a result there haven’t been any issues with SIS vacuum thresholds on the interconnects between adjacent MKIs. However, during 2016, dynamic pressure increase on the MK18D-Q5 interconnect limited the number of bunches that could be injected for Beam 2. The MK12D kicker magnet caused several issues during 2016, including limiting the length of the field pulse from August onwards and a high impedance contact from October. As a result of further deterioration of the high impedance contact the MK12D was exchanged during TS3. During November the Surveillance Voltage Monitoring system interlocked the MK12 installation on several occasions. This paper reviews the MKI performance during 2016, the plans for the EYETS and the expected performance during 2017.

INTRODUCTION
The Large Hadron Collider (LHC) is equipped with two injection kicker (MKI) systems for deflecting the incoming particle beams onto the accelerator’s equilibrium orbits. Counter-rotating beams circulate in two horizontally separated beam pipes. Each beam pipe is filled by 12 consecutive injections, at 450 GeV. The injected beam is first deflected in the horizontal plane by a series of septum magnets followed by a vertical deflection by four MKI systems [1]. The total deflection by the four MKI magnets is 0.85 mrad, requiring an integrated field strength of 1.3 T m. Reflections and flat top ripple of the field pulse must be less than ±0.5%, a demanding requirement, to limit the beam emittance blow-up due to injection oscillations.

A low impedance (5 Ω) and carefully matched high bandwidth system meets the stringent pulse response requirements. An MKI kicker system consists of a multi-cell PFN and a multi-cell travelling wave kicker magnet [2], connected by a matched transmission line and terminated by a matched termination resistor (TMR). Each travelling wave magnet has 33 cells. A cell consists of a U-core ferrite sandwiched between HV conducting plates: two ceramic capacitors are sandwiched between a HV plate and a plate connected to ground (Fig. 1). The magnets are operated in vacuum of ~10^-1 mbar. The complete magnet is baked out at 300°C before HV conditioning and tests.

BEAM INDUCED HEATING
With high LHC bunch intensity and short bunch lengths, integrated over many hours of a good physics fill, the impedance of the magnet ferrite yoke can lead to significant beam induced heating. To limit longitudinal beam coupling impedance, while allowing a fast magnetic field rise-time, an alumina tube with screen conductors lodged in its inner wall is placed within the aperture of the magnet [2]. The conductors, which provide a path for the image current of the beam, are connected to the standard LHC vacuum chamber at one end and are capacitively coupled to it at the other end. Prior to Long Shutdown 1 (LS1) the MKIs generally had only 15 of a possible 24 screen conductors installed, positioned closest to the return busbar: the other 9 were omitted due to issues with surface flashover during magnet pulsing [3]. For one MKI magnet which limited LHC operation, the screen conductors were found not to be straight, but had a 90 degree twist over their length: based on impedance measurements the beam induced power deposition in this MKI was ~160 W/m average, compared to ~70 W/m average for a magnet with 15 straight conductors [4]; these power depositions assume that, as a worst case, all the power deposition is in the ferrite yoke. During LS1 the number of screen conductors was increased to the full complement of 24 [4, 5].

Figure 1: MKI kicker magnet.

There are toroidal ferrite rings mounted around each end of the alumina tube, outside of the aperture of the kicker magnet. The purpose of the rings mounted on the end where the screen conductors are connected to the beam pipe was to damp low-frequency resonances [6]. Each set of nine toroids has two types of Ferroxcube NiZn ferrite, namely: 4M2 and 4B3, with a Curie point of 200°C and 250°C, respectively. During Run 1 of the LHC one set of toroids, at the capacitively coupled end, of the beam screen, occasionally reached 193°C measured; all others remained below 100°C measured [6].

During Run 2 it was noted that the measured temperatures at the upstream (capacitively coupled) end of the MKI magnets were consistently higher than those measured at the downstream ends [7]. Thus studies were launched to understand this behaviour. CST Particle Studio [8] allows the placement of frequency dependent volume loss monitors, compatible with ferrite materials, in the simulation - volume losses are considered as the majority of losses in the system [9]. The predicted longitudinal distribution of volume losses of the post-LS1
kicker magnets is non-uniform - the ferrite rings at the capacitively coupled end of the structure experience more than 25% of the total power deposition, for a structure that has relatively little volume. The power deposition in the yoke is predominantly in the upstream end of the magnet, with losses being relatively low in the downstream half of the magnet: the first cell, at the upstream end, experiences ~9% of the total power deposition.

Thermal simulations have been carried out using ANSYS in order to confirm that the calculated power losses for Run 2 correspond to the measured temperatures during LHC operation. To compare the results with the measurements it must be taken into account that the PT100 temperature sensors are located on a side plate of each magnet. There is good agreement between measurements and simulations of the side-plate temperature: this validates both the power loss calculations and the thermal model [9]. From the measurements and simulations:

- Maximum measured side-plate temperature during Run 2 is 57°C, at the upstream end of MK18D (fill #5069, 1.25x10^11 ppb, 2076 bunches, 25.5 h stable beam);
- From steady-state thermal simulation 57°C corresponds to a temperature, in the first cell at the upstream end, of ~80°C and a total power deposition of almost 100 W in the magnet.

Scaling total power deposition linearly with the number of bunches, to 2808 bunches, and assuming 1.25x10^11 ppb, the total expected power is almost 150 W. The corresponding predicted temperature, in the first cell at the upstream end, is 107°C and a "measured" side-plate temperature, at the upstream end, is 77°C. The 107°C is below the Cure temperature (125°C), hence no issues with MKI heating are expected during Run 2. Therefore no changes are planned during the EYETS. Nevertheless, if necessary the bake-out jackets could be removed during a Technical Stop (TS): this would reduce the highest temperature rise in the ferrite yoke, above ambient, by approximately 7%.

**ELECTRON CLOUD**

Significant pressure rise, due to electron-cloud, occurs in and nearby the MKIs: the predominant gas desorbed from surfaces is H₂. Conditioning of surfaces reduces electron-cloud, and thus pressure rise, but further conditioning is often required when beam parameters (e.g. bunch spacing, bunch length and bunch intensity) are pushed.

Voltage is induced on the screen conductors during field rise (up to 30 kV) and fall (to ~17 kV). Rise in vacuum pressure, at the capacitively coupled end, can result in breakdown/flashover – hence there is an (SIS) interlock to prevent injection when this pressure is above threshold. In general these SIS thresholds, for the interconnects, are 5x10^-8 mbar.

During LS1, the vacuum systems on the interconnects between MKI magnets were upgraded:

- Interconnects NEG coated;
- Prior to LS1, ion pumps provided a nominal pumping rate of 30 l/s of hydrogen.
- During LS1, a NEG cartridge was integrated to give a nominal pumping speed of 400 l/s for H₂.

The alumina tube of each of the MKIs upgraded during LS1 has a high secondary electron yield (~10) when installed and required conditioning with beam, together with metallic surfaces facing the beam (e.g. screen conductors). However, during Run 2, there haven't been any issues with the SIS vacuum thresholds, on the interconnects between adjacent MKIs, limiting injection of beam.

By mid-2016 electron cloud resulted in a factor of ~20 rise in pressure, in comparison to the background pressure, in most MKI8 interconnects: the pressure rise in the MKI tanks was a factor of ~10. However, in the MK88D-Q5 interconnect, electron cloud resulted in a factor of ~1000 rise in pressure. Figure 2 shows the pressure in the MK88D-Q5 interconnect, and beam B2 intensity during June 2016: the SIS threshold on this interconnect rise set to 6x10^-8 mbar.

![Figure 2: pressure in the MK88D-Q5 interconnect, and beam B2 intensity during June 2016: the SIS threshold on this interconnect was set to 6x10^-8 mbar.](image)

Figure 3 shows pressure normalized to the number of protons for interconnect MK18C-MK18D, tank MK18D, and interconnect MK88D-Q5: in addition, beam B2 intensity is shown. Figure 4 shows a zoom of Fig. 3 for 24 June through to 27 June.

![Figure 3: pressure normalized to the number of protons for interconnect MK18C-MK18D, tank MK18D, and interconnect MK88D-Q5. In addition, beam B2 intensity is shown.](image)
During Technical Stop 3, 2016, it was necessary to replace magnet MK12D (see below). Hence, although electron cloud around MK12D has not limited injection during Run 2, the alumina tube in the new MK12D will not have seen high intensity proton beam and will require conditioning after the EYETS. To assist the conditioning two new NEG cartridges of 400 l/s each (nominal speed for H2) will be integrated in new modules of vacuum sector ISL2 (Fig. 6).

![Figure 6: new layout of vacuum sector ISL2, with two new NEG cartridges of 400 l/s each.](image)

Nevertheless, despite the upgrade to the ISL2 vacuum sector, the rise in pressure in the MK12D-Q5 interconnect is expected to initially limit injection of LHC beam 1. Figure 7 show the normalized pressure in the MK12D interconnects, following the installation of MKIs with new alumina tubes during LS1.

![Figure 7: normalized pressure in the MK12D interconnects, following the installation of MKIs with new alumina tubes during LS1.](image)

Assuming an SIS interlock threshold of 6x10^-8 mbar, to remain below this threshold with 1.25x10^13 ppb and 2808 bunches, requires a normalized pressure of not more than 1.7x10^-13 mbar/p. The ISL2 vacuum sector upgrade will assist to more rapidly increase the number of bunches; nevertheless, from Fig. 7, it is expected that 200-300 hours with high-intensity, 25 ns spaced, beam may be required before the nominal beam B1 can be injected. As per fills $\#5043$ and $\#5045$, the normalized pressure could be reduced by including an appropriate gap between batches of an injected train.
For the longer term a coating of \( \text{Cr}_2\text{O}_3 \), applied to the inside of the alumina tube by magnetron sputtering, is promising. Measurements in the lab show that the naked alumina has an SEY of approximately 10. A 25 nm or 50 nm \( \text{Cr}_2\text{O}_3 \) coating applied by magnetron sputtering, reduces the maximum value to approximately 2.3: bombarding the surface with electrons further reduces the SEY to less than 1.4 (Fig. 8).

Two sets of aluminium liners have been sputtered with the 50 nm \( \text{Cr}_2\text{O}_3 \) coating; these liners will be installed in the SPS, during the current EYETS, for tests with beam. The other set of liners will be installed in a multipacting setup.

**MKII2D FLASHOVERS**

<table>
<thead>
<tr>
<th>Date</th>
<th>PFN Voltage</th>
<th>Pulse Length</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-Oct-15</td>
<td>50.8 kV</td>
<td>Top of rising edge, very close to magnet centre</td>
<td>Spark during SS</td>
</tr>
<tr>
<td>24-Jul-16</td>
<td>48.53 kV</td>
<td>~3.6 ( \mu )s into flat-top, very close to magnet input</td>
<td>Spark during injection</td>
</tr>
<tr>
<td>02-Aug-16</td>
<td>50.7 kV</td>
<td>~2.5 ( \mu )s into flat-top, very close to magnet input</td>
<td>Spark during SS</td>
</tr>
</tbody>
</table>

Table 1 summarizes the electrical breakdowns in magnet MKII2D (MKI1MA-08 T-11 MC-09) during Run 2. Until mid-July 2016 there had been only a single electrical breakdown, and this occurred during a SoftStart (SS) at a PFN voltage ~1.3 kV above the normal operating voltage. On 24th July 2016 there was an electrical breakdown of the MKII2D magnet, during injection, close to the input of the magnet. On 2nd August 2016 there was another electrical breakdown of the MKII2D magnet, during a SS, again close to the input of the magnet: subsequently there was vacuum activity on every pulse (Fig. 9). Investigations showed that, for a given voltage, the breakdowns and thus vacuum activity were correlated with longer pulse lengths. Hence from August 2016 to TS3 2016 the MKIs were operated with ~3 \( \mu \)s field pulse flattop.

Figure 8: Measured SEY of 50 nm \( \text{Cr}_2\text{O}_3 \) coating, applied by magnetron sputtering on high-purity alumina (blue & green curves): bombarding the surface with electrons further reduces the SEY to less than 1.4 (red & cyan curves). [Measurements courtesy of E. Garcia-Tabares Valdivieso and H. Neupert].

Figure 9: MKI2D tank pressure (blue), pressure on Q5 side of MKI2D (red) and pulse length (green).

The MKI2D magnet was exchanged during TS3, 2016, and thus no further activity is planned during the EYETS.

**MKII2D HIGH IMPEDEANCE CONTACT**

During early October 2016 a high impedance contact issue developed in the MKII2D magnet, at the input end. This issue was characterized by this magnet not initially carrying current (Fig. 10): the dashed curves in Fig. 10 shown currents for MKI2C and solid curves for MKI2D – these two curves should be more or less identical.

Figure 10: First pulse of a SS (at 20 kV): dashed curves are magnet MKI2C, solid curves are for MKI2D.

Figure 11: MK1 input – red boxes show possible position of high impedance contact.
An analysis of the waveforms, combined with simulating faults using PSpice, show that the fault is likely due to a high impedance on or close to the feedthrough at the entrance of the magnet (Fig. 11). The MKI2D magnet was exchanged during TS3 2016 as the high impedance contact showed evidence of further deterioration. The removed MKI2D was carefully examined mid-January 2017: it was not possible to inspect, in the clean room, before this date due to the high priority of EYETS MKE and MKP preparation work. The inspection confirmed that the problem was a high impedance contact at the magnet input. Since MKI2D has already been exchanged, no further work is planned in the tunnel, for EYETS, concerning this magnet.

MKI2 SVM FAULTS

Surveillance Voltage Monitoring (SVM) of ±5V and ±15V, for the MKI, was introduced during TS#1 and TS#2, 2016: the decision to do this was based on LBDS experience. The SVM system worked correctly until November 2016: subsequently non-existent faults started to be indicated by the SVM system, interlocking the MKI2 system — hence it was necessary to mask SVM signals. The source of the SVM faults is an incorrect value of resistors mounted on the PCB during hardware production and not detected during lab tests before installation. The concerned hardware will be returned for correction during EYETS and then reinstalled.

MKI1: ERRATIC TURN-ON

One Main Switch (MS) thyatron erratic (spontaneous turn-on), during resonant charging of the PFN in preparation for injection, occurred on 2nd September 2016 (on MKI2D system!): at the time there were 876 circulating bunches, of which approximately 210 were miskicked.

Since November 2014 there has been a total, for the two MKI systems, of ~1.2 million pulses. During 2015:
- 20% of the pulses were for injection;
- 80% of the pulses were during SoftStarts;
- Almost 60% of the pulses were at or above the nominal injection voltage.

Since November 2014 there has been a total of three erratics (all on MS’s): one at each of P2 and P8 during SS’s, both at voltages >2 kV above nominal. The erratic on 2nd September 2016 was the only one that occurred below nominal voltage.

Based on the above, the estimated probability of a Main Switch erratic during resonant charging is ~4x10^-6 per pulse per system. The probability of an erratic occurring is known to be dependent upon the magnitude of the reservoir voltage of the thyatron. Hence, during the EYETS, the setting and output voltage of the reservoir power supplies will be checked.

SUMMARY

MKI2:
- Several issues occurred with MKI2D during 2016 including electrical breakdowns, a high impedance contact; and a Main Switch erratic;
- As a result of a deteriorating situation with the high impedance contact, magnet MKI2D was exchanged during TS3 2016;
- An upgrade of the MKI2D-Q5 vacuum sector is planned for EYETS to increase the pumping speed. This upgrade will reduce the conditioning time of the new MKI2D alumina tube with beam.

MKI8:
- No magnet exchange planned during EYETS;
- An upgrade of the MKI8D-Q5 vacuum sector is planned for EYETS to increase pumping speed. As a result the MKI8D-Q5 SIS interlock is no longer expected to limit injection with the nominal number of 25 ns bunches.

REFERENCES

ADT AND OBSBOX IN 2016

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Abstract

A performant transverse feedback is vital for accelerators like LHC. The LHC transverse feedback (ADT) provides a lot of important data and functionality outside of the “damping envelope”. The contribution summarizes the ADT performance in 2016, and presents the newly implemented and commissioned features. Among those is the most awaited online instability detection system, but also new excitation modes allowing to perform precision beam measurements like the tune shift along the batch, excitation for automatic coupling correction or single jaw collimator impedance.

ADT PERFORMANCE IN 2016

Similar to previous years, operation of the ADT was very smooth in 2016. Thanks to multiple redundancy of the low-level RF (LLRF) system and the power system it is very rare that a blocking failure occurs. In total three events were recorded for 2016. A digital to analogue converter (DAC) was hanging after a major power cut in the surface building SR4, where the LLRF system is installed. The signal processing chain produced a feedback signal, but no analogue drive was outputted from the DAC. Consequently, the feedback experienced a longer damping time, which under presence of strong transverse activity dumped the beam. The second recorded fault was a gigabit link failure. The beam position modules send bunch by bunch, normalized transverse position data to the digital signal processing unit by means of gigabit serial links, using both metallic and optical media. The signals are split in the optical domain to feed also the observation system (ADTObsBox [1]). During the year one of the serdes transceivers on the beam position module failed, hence received data for one pickup were corrupted. As a result the optical distribution for this pickup was reconfigured at a cost of loss of redundancy. Finally, the third LLRF system failure has happened after maintenance works on the LHC master oscillator. Thereby the missing clock caused loss of synchronization and ADT lost position of bunch 1. The issue was solved by a power cycle of the digital logic. There was no downtime, but the problem prevented doing loss maps.

Failures of the power system are much less apparent to the operation, as the power system is quadruple redundant. Thus a trip of one amplifier causes 25% loss of loop gain (or 33% longer damping time). The ADT power team keeps a cold-spare power amplifier in the RF zone, making the response time in case of a failure very short.

Eight power tetrodes (RS2048) reached their designated operating time of 20'000 hours and were preventively replaced during TS2 to provide constant and uniform amplifier gain. The average tetrode operating time is 14'000 hours.

NEW DEVELOPMENTS FOR 2017 RUN

ADT is a vital system for LHC. It does not only combat the coupled bunch transverse instabilities, or selectively excites the beam, but it is also commonly used as a very valuable instrument for various machine development studies, or special transverse beam manipulations. The majority of developments every year are invested in all kinds of new functionality. More bunch by bunch diagnostics is always requested, more sophisticated excitation schemes and signals are required, or a close collaboration with other instruments all over the ring is desired. Additionally, certain effort is also invested into system performance improvements.

New generation Anode resistor

The power amplifier delivers the final ~37 dB of gain, providing 10 kV of kick voltage. A push-pull, class AB amplifier is equipped by two tetrodes and two 900 Ohm anode resistors. The resistors are one of the most delicate and challenging components in the signal chain, as they have to withstand high voltage (15 kV), dissipate high power (25 kW) and have a flat frequency response up to higher 10’s of MHz. Figure 1 shows the currently used resistors which were custom developed for CERN by industry. As during the years it became increasingly difficult to obtain spare parts, the BE/RF/PM section launched a development program to design and manufacture a replacement in house. The first samples were successfully tested in the laboratory and the first amplifier populated by new resistors should be installed in LHC in the summer of 2017.

![Figure 1: The currently used anode resistor (right) and the newly developed replacement resistor (left).](image)

Online instability detection system

One of the most awaited instruments in LHC is a robust transverse instability detection tool/system. The ADT has the bunch by bunch, turn by turn beam transverse position information available within its digital signal processing
system. This information was made available for users external to the feedback by means of a so called Observation Box. The transverse box, also known as ADTObsBox (see Fig. 2), is a very powerful computer system, which receives data from up to four pickups (a 1 Gb/s data stream per pickup). The observation system was designed to record and publish the data for offline analysis, but also perform the computationally intensive online analysis.

![Diagram of ADTObsBox and Beam Dynamics](image)

Figure 2: Integration of the ADTObsBox into the transverse feedback system.

The very first true online analysis application for the observation system is the online transverse instability detection. Data from each pickup are published in chunks of 4096 turns by the ObsBoxBuffer FESA class running in the ADTObsBox. The online analysis system is implemented also as a FESA class, called ALLADTCopra [2], running in the very same computer. It subscribes (at the time of writing) to the Q7 buffer of both beams and both planes and receives a data array of 4096 turns by 3564 bunches. By means of digital signal processing [3] the instantaneous transverse oscillation amplitude is extracted from the data stream and the trend is analysed with three different time constants (256, 1024 and 4096 turns) to search for the onset of a coherent activity (see Fig. 4). In case a positive trend and predefined conditions are met, a trigger is sent to the LHC instability trigger network LIST [4].

The major leap this instability detection system brings is the transverse activity analysed for the first time bunch by bunch and for all bunches. When the activity is detected the information about which bunches became unstable and an indication of time constant is available already at the very moment when the trigger is being sent. This greatly simplifies the search for activity, as other observation instruments can already know "where to look". Consequently this avoids a need to continuously blindly trigger and download long data buffers and offline search for transverse activity. The analysis results and information are properly logged. A side product of the instability detection system is an online transverse activity monitor – a fixed display will be made available in the CCC, which shows the oscillation amplitude (calibrated in mm) of every bunch in real time.

**Damper performance analysis tool**

Most concerns expressed by the operation group concerning the ADT in the past years were if the feedback operates correctly. Another analysis tool, named ALLADTDiag [5], also running in the ADTObsBox was prepared in 2016. The tool subscribes to the injection oscillation buffer (for both beams and both planes) and after every injection it calculates the bunch by bunch damping time and bunch by bunch fractional tune. The curves are presented in the CCC in a form of an ADT diagnostics fixed display (see Fig. 3). Data from as few as 15 turns are required to calculate the tune – the tune value is available to the operator even before the RF capture – this makes the tool very valuable e.g. at accelerator restart after a long stop.

![Example of beam oscillation transient analysis](image)

Figure 3: Example of the injection oscillation transient analysis by the ALLADTDiag FESA class. The plots are available to the operator as part of a fixed display.

**AC dipole-like excitation**

The ADT was already equipped by signal synthesizers to excite and clean the beam in the abort gap and the injection gap. With a well controlled impulse response of the entire ADT signal chain it became apparent that a more demanding excitation schemes can be implemented and safely executed through the whole LHC cycle. The most recent addition is an AC-dipole like excitation, called "ADT-AC dipole" for clarity. Unlike the real AC dipole magnet, the ADT-AC dipole excitation strength is much lower, providing a maximum of 2 μrad @ 450 GeV. This constraint is well compensated by a full freedom and flexibility of the number of targeted bunches to be excited anywhere in the ring, the excitation frequency starting already at DC (i.e. a dipolar kick), the unlimited number of excitation turns, or a possibility to excite only every n-th turn. The rise and fall times of the excitation waveform are also fully programmable.

The presented features make the ADT-AC dipole an invaluable complementary tool to the "real" AC dipole for precision, or automatic measurements. The first measurements have been already performed in 2016. It was demonstrated, that a single bunch within a 25 ns train can be excited, or selected bunches can be excited for 10’s of thousands of turns without noticeable emittance blow-up.
for coupling measurements. The new excitation functionality was immediately used in various studies (e.g. [6] [7] [8]).

![Image]

Figure 4: Demonstration of the instability detection process. The top plot shows the input pickup position data after injection. The second plot shows the oscillation amplitude, followed by three activity detection windows of 256, 1024 and 4096 turn length. The red curve represents the “bunch unstable” flag.

**PRECISION MEASUREMENTS WITH ADT**

The ADT is a complex system involving multiple devices, which are interconnected and synchronized. This opens endless possibilities in performing sophisticated measurements. For example the beam can be passively observed by the ADTObsBox, data stored, or immediately analysed in the box, including analysis of various transients. This functionality was already discussed in the previous chapter. A very powerful tool is to use the ADT as an exciter and observe the beam behaviour by the ADTObsBox. Some results will be shown here.

As the excitation signals are generated by a digital LLRF system, the waveform can be easily pre-distorted in a controlled way to achieve different deflection voltage profiles on the kicker plates. The signal can be prepared such a maximum available deflection strength will be achieved at a price of exciting multiple bunches within few hundred nanosecond window. On the other hand, the signal can be pre-distorted such that only a single bunch of arbitrary position within a 25 ns train will be excited, at the price of lower kick strength. The latter method was used to measure electron cloud induced tune shift along a batch of 25 ns beam [9]. Figure 5 shows the high level of process control, when only bunches 1, 6 and 12 were excited transversally, without noticeable leakage to the neighbouring bunches. Bunches were excited to reach about 100 μm oscillation amplitude, with the oscillation transient recorded by the ADTObsBox and tune calculated offline. It is being considered to perform this kind of measurements with a full machine at flat top.

![Image]

Figure 5: Excitation of individual bunches within a 25 ns bunch train for tune shift measurement (picture courtesy of Lee Carver).

A similar method was proposed to determine a single jaw collimator impedance by means of precision tune shift measurements. The feedback gain was reduced to provide few hundred turns of good quality data, the beam was excited to an amplitude below 100 μm and the damping transient recorded by the ADTObsBox. A tune shift
between the two collimator positions in the order of 4e-5 was found, well compatible with the model (see Fig. 6).

![Graph of data](image)

Figure 6: A feasibility of tune shift measurements in the order of 4e-5, with an error bar below 1e-5 using only the ADT data was demonstrated.

CONCLUSIONS

The LHC transverse feedback provides a lot of important data and functionality outside of the “damping envelope”. There is a continuous effort to research, implement and operationally use more and more sophisticated and very advanced functions of the system, giving a way to tools like automatic coupling correction, precision tune measurements of individual bunches, beam halo cleaning by coupled noise and many more. There is also an ongoing research in possibilities for computationally very intensive online data processing from the ADTObBox devices.

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STATUS OF THE BEAM INSTRUMENTATION AT THE LHC


Abstract

In this contribution, a review of the beam instrumentation status in the LHC 2016 run is presented. The treated devices are the beam loss monitors based on diamond detectors, the beam position monitors, the wire-scanners, the beam gas vertex detector and the synchrotron radiation monitors. The new features implemented and the issues encountered during 2016's operation will be highlighted for each instrument. Additionally, the interventions and improvements planned for the coming winter shutdown will be discussed.

INTRODUCTION

During the Year End Shutdown (YETS) 2015/1016, several modifications to the LHC beam instrumentation were done, some actions were to tackle the observed limitations in 2015 operation and some were improvements allowing the implementation of new features for these devices. In the following, the beam loss monitors based on diamond detectors, the beam position monitors, the wire-scanners, the beam gas vertex detector and the synchrotron radiation monitors will be discussed. This contribution aims for highlighting the implemented changes, assessing the improvements and listing the remaining issues that will be tackled during the next Extended YETS (EYETS).

DIAMOND BEAM LOSS MONITORS

The existing Beam Loss Monitor (BLM) system using ionization chambers is not adequate to resolve losses with a time resolution below some 10μs neither to measure very large transient losses, e.g. beam impacting on collimators. The diamond beam loss monitors (dBLM) are therefore complementarily used for beam loss diagnose in the ns range time resolution resolving single bunch level beam loss signal, with a dynamic range exceeding 4 orders of magnitude [1]. The diamond beam loss monitors consist of pCVD diamond detectors (10 mm x 10 mm x 10 mm) with gold electrodes on both sides operated with a bias voltage.

Presently, two readouts are available for these monitors, distributed around the ring as shown in Fig. 1. The first one, based on LeCroy oscililloscopes, is installed for the diamonds in the injection region and the beam dump lines. It offers an output in a "waveform" mode with 2 · 10^5 samples at 1 GHz. The second one, a commercial system "Rosy" from CTVIDEC, is FPGA-based for on-line, real-time, and deadtime-free data processing. It offers two readings:

- Waveform mode, a buffer of 10^9 samples at a sampling rate of 5 · 10^9 samples/s.
- Histogram mode, a buffer of 256 · 10^6 samples with 1.6 ns binning and 1.2 ns time jitter for loss measurements that are synchronized with the LHC revolution period and a beam-loss-based tune measurement for all circulating bunches in parallel.

On one hand, a FESA class developed in 2016 allows the acquisition of the LeCroy oscilloscopes data synchronized with injections and stores the loss data waveform in the Post-Mortem. On the other hand, expert tools developed in python allows configuring the device and storing the data on EOS servers. Also a GUI is available for offline viewing of these data.

Figure 1: The distribution of dBLM along the LHC circumference, with their main use and their readout system.

Interesting studies took place during the year to probe the usability of the dBLMs, both during the LHC operation and in special MDs, from losses lasting only few turns up to steady state losses in collision. Alternatively to abort gap monitoring using synchrotron light, tests were carried out to verify the applicability of diamonds for monitoring such a low proton population [2]. Additionally, studies aiming to understand losses at the primary collimators in collisions were carried out. A possibility of using these data for fast UFO bustling was also considered. However, the most interesting use of the dBLM, as shown in Fig. 2, was found for injection losses diagnostics where it is a key instrument in identifying the sources of the losses across the accelerators [3].

Therefore, integrating the diamonds in the control system easing the access and the use of the diamonds data is of big interest since it would improve the operation.

After the present YETS, since no change to the infrastructure is foreseen, the bunch-by-bunch losses waveforms acquired for every injection with the LeCroys scopes will be available through FESA to the Injection Quality Check

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Figure 2: A typical dBMLs loss signal in the injection region and its synchronization with SPS extraction kickers and LHC injection kickers rise time.

(IQC). It is worth mentioning that some operational experience will be required needed to set the thresholds for the diamonds losses.

Finally, a plan of standardizing the dBMLs readout is ongoing, where VME FMC Carrier (VFC) card based acquisition will be adopted. It will allow for a fast sampling (~600 MSPS) of the diamond signal and will replace both the LeCroy oscilloscopes and the Rosy boxes since also the histogramming will be integrated at the firmware level. A final review of the specification is taking place now and a final test system is foreseen to be installed in the laboratory, in the SPS (BA1) and in the LHC (in parallel to the existing readout) to validate the full chain performance. Profiting of the synergy with the recent fBCT readout development (based on the same VFC card), only few changes are expected to adapt the existing FESA class for the dBMLs. Once the validation of the system is completed, the deployment of the new electronics for all the diamonds systems in the LHC is supposed to be relatively easy and transparent.

**BEAM POSITION MONITORS**

The LHC beam position system consists of more than 2000 measurement channels distributed along the LHC underground tunnel. The electronic readout of the pick-up signals is based on Wide Band Time Normalisers (WBTN) capable of processing the analogue signals from the pick-up at 40MHz. The WBTN principle encodes the position information for each passing bunch into a pulse width modulation, sent via optical fibres to the acquisition electronics on surface. This readout chain can provide several different parallel orbit modes:

- the default mode, “Asynchronous orbit”, where each incoming bunch data from a particular BPM enters a moving average filter (implemented as an exponential response IIR filter). The time constant of this filter can be configured and therefore it provides the average beam position over some chosen time. This mode is used in the orbit feedback.

- the “Synchronous orbit” (to be used mainly in the directional strip-line monitors) allows certain bunches to be masked (i.e. not taken into consideration) for calculation of the orbit. Here the average position of selected bunches are averaged over a set number of turns. This mode is needed to operate with asymmetric beam intensities (as in the case of proton and lead collisions).

- the “Capture” acquisition mode, provides the orbit of individually selected bunches turn by turn position over a configurable number of turns. This mode is needed for the dedicated optics measurement Runs and for the injection quality checks.

In YETS 2015/2016 and during operation this year, a new firmware was deployed, addressing several issues to enhance the BPMs performance improving the system stability and maintainability. A solution for the observed conflict between the two “Asynchronous Orbit” and “Capture” acquisition modes was implemented and the synchronization handling was optimized to improve the “Capture” data reliability. Additionally, the new firmware allowed a higher accuracy (more bits) averaging in the “Orbit” mode improving the position’s resolution. Finally, the “Synchronous Orbit” acquisition mode was also enabled permitting its use during the proton-lead physics Run. The FESA class was accordingly adapted to cope with the new firmware.

In conclusion, despite its size and complexity, the system performed well during the 2016 Run; nevertheless some issues were uncovered during operation:

- Non optimal LSA settings and bunch selection (presence of colliding encounters) prohibited the usage of the “Synchronous Orbit” during the ions Run; this issue was solved by establishing the good settings to use.

- Spurious orbit reading, called “Dancing BPMs”, was sporadically observed. This issue in the electronics seems to be solved by replacing some acquisition cards; new diagnostics were put in place to study it further.

- Problems in the “Capture” acquisition mode:

  - Some were diagnosed to the absence of the beam synchronous triggers, where the reboot of the BST was enough to solve the issue. Since this affects several systems, new diagnostics were put in place to monitor the triggers for additional investigations. The latter will allow to probe the “De-phasing” effect that is still not fully understood.

**Diode orbit and oscillation system**

The Diode ORbit and Oscillation System (DOROS) system was designed for measuring beam orbits in the BPMs
embedded in the LHC collimators jaws [4]. Compared to standard WBTN electronics, orbit measurements are characterized by a higher signal to noise ratio. In fact, sub-micrometre orbit resolution (≈0.1 μm) and micrometre stability was achieved with relatively simple and robust hardware, despite the relatively low signal amplitudes available from the small button electrodes of the collimator BPMs [5].

Based on a peak detection scheme, DOROS measurements should not be sensitive to any fluctuations of the signals temporal shape, however no bunch by bunch information is derived. The system is now operationally used for automatic positioning of the collimator jaws and for the continuous monitoring of the beam position at the collimator locations. Further developments involving the generation of beam interlocks from collimator BPMs are ongoing.

Even though DOROS was optimised for position resolution and absolute accuracy for centred beams in the collimators, the same system was also installed on some 20 LHC BPMs located around the LHC interaction regions for comparison with the standard LIIC BPM system. It was found that the residual non-linearity of the orbit diode detectors causes systematic orbit errors at the level of tens of micrometres, as shown in Fig. 3.

![Figure 3: Position change caused by the nonlinearity of the compensated diode detectors (laboratory) [5].](image)

The effect dominated the fill to fill reproducibility where the lack of adequate control of the system parameters enhanced the non-linearity observed when the gains are adjusted to accommodate to the amplitude drop caused by the beam intensity decay.

The relative change in signal amplitude with respect to the dynamics of the ADC induces fake orbit drifts and is clearly enhanced by the beam offset to the BPM centre, or when the beam intensity varies.

The effect is under investigations and is reproduced and quantified in the laboratory where extensive studies are currently carried out to linearize the detector characteristics.

Additionally, the DOROS system can also be used for observing beam spectra and deriving beam parameters from driven beam oscillations [6]. The beam spectra in the frequency range from DC to ≈100 Hz can be analyzed using DOROS orbit data while the range from 0.5 to 5 kHz can be covered with the dedicated oscillation data channel. Since it provides high resolution measurements over many turns, better than an order of magnitude improvement in the beam spectra noise floor was observed compared to WBTN. Moreover, one of the applications of DOROS oscillation data is for local coupling measurement, which has been demonstrated with very small beam excitation. Recently, an improvement of the acquisition synchronization of the "capture" mode in FESA with the ADT excitation allowed minimizing also the excitation time to what is just needed to measure the coupling. In the future, it is also planned to use DOROS for beta-beating measurements using the synchronous detection implemented in the DOROS FPGA.

**WIRE SCANNERS**

Wire scanners (WS) are the reference instruments for transverse beam size and emittance measurements in the LHC. They are also used for calibrating other devices, such as the BSRT. Their working principle consists of a thin carbon wire moving across the beam at the speed of 1 m s⁻¹; the radiation produced by the interaction of the protons with the wire is observed by means of downstream scintillators coupled to Photo Multiplier Tubes (PMT). This charge deposition is proportional to the local density of the beam and is used to measure the beam density profile [7].

The noise in the PMT signal acquisition chain was investigated by studying the spectrum of 100 scans with no beam in machine. Originating from the High Voltage supply or coupled to the analog signal in long cables, this noise was suppressed using the background subtraction technique. It consists of picking a bucket in the abort gap as a noise reference and subtracting it from the bunch profile in the filled buckets; it was unfortunately found that this treatment could enhance the noise at higher frequencies and contribute to the worsening of the WS precision. In 2016, investigations to mitigate this disturbance to the PMT signal took place and a cure was found at the hardware level, by disconnecting the "turn" acquisition mode cables in the tunnel installation, breaking important ground loops that undermined the signal quality. It is worth mentioning that this acquisition mode is not in use in the LHC operation and was conceived for internal sanity checks of the acquisition chain of the instrument. The obtained benefit was more visible on B1. The studies will continue to identify the dominating sources for the residual noise on B2 as shown in Fig. 4.

Figure 5 shows the contribution of the uncertainty on determining both the shower intensity (via the PMT) and the wire position on the emittance measurement accuracy for the horizontal plane of LHC beam 2.

In fact, once the noise coupling to the PMT signal is mitigated, errors on the absolute scale of the wire movement translates directly into an error on the measured beam size [8]. Therefore, a parallel method to validate the WS potentiometer measurements is being developed: the integra-
Figure 4: Beam 2, bunch by bunch, normalized emittance during a BSRT cross-calibration fill with 10 circulating bunches.

Figure 5: Emittance measurement accuracy as a function of errors on potentiometer and PMT readings for LHC beam 2.

The full installation was completed in 2016 on B2, and the detector was fully commissioned. First data and beam profile measurements show that the complete detector and data acquisition system (SciFi detector planes, trigger, readout, CPU farm, control and DAQ software) are operating as expected. The dead channels were found to be less than 1% of the total. The detector was successfully operated with a neon gas injection adjusted such as to provide an adequate trigger rate, without disturbing the beam. A pressure of approximately $6 \times 10^{-3}$ mbar in the interaction volume was used during data-taking campaigns in 2016 under various beam conditions in parallel to operation and in dedicated MDs.

The observed rate of events matches expectations and the distribution of the z-coordinates at which the impact parameter is minimized, displayed in Fig. 6, shows that the measurements are well inside the limits of the gas target and are correlated with the expected gas pressure profile [10].

The measurements were crucial to assess the system performance, understand the limitations and plan the next steps. In fact, for the Run in 2017, an upgrade of the triggering mechanism is planned, where an additional hardware trigger (L0 confirm) is planned to be installed during the EYETS to improve the cross-talk between the two beams. Moreover, further refinement of the vertexing algorithm along with better event selection through improved triggering will be required to reduce this rather large statistical error and allow a full comparison with other LHC profile measurement devices. The offline analysis for high precision track and vertex reconstruction is planned to be incorporated in the CPU farm for real-time measurement.

**BEAM GAS VERTEX DETECTOR**

The Beam Gas Vertex (BGV) detector is a beam profile monitor being developed as part of the high luminosity LHC upgrade.

Its working principle consists of reconstructing the beam-gas interaction vertexes, where the charged particles produced in inelastic beam-gas interactions are measured with high-precision tracking detectors, to obtain the 2D beam transverse distribution.

The BGV allows for non-invasive beam profile and position measurements to be made throughout the full LHC cycle, irrespective of beam energy or luminosity. The detector has been designed to estimate the individual bunch transverse width with a precision of about 5% in approximately 5 minutes of integrated beam time, however the installed demonstrator aims at measuring the average transverse beam profile with a precision of about 10% in approximately 5 minutes of integrated beam time [9].

Figure 6: The distribution of Beam-gas interactions Point Of Closest Approach (POCA) along the beam passage (z-distribution) at 6.5 TeV.

In conclusion, the BGV operating parameters are now being optimized and the reconstruction algorithms developed to produce accurate and fast reconstruction on a CPU farm in order to provide real time beam profile measurements to
the LHC operators and to the logging databases are being put in place.

SYNCHROTRON LIGHT MONITOR

The Beam Synchrotron Radiation Telescope (BSRT) monitors image the synchrotron light generated by the beam traversing a dedicated super-conducting undulator and a D3 type dipole located in IR4. This section will cover the upgrades of the SR imaging system and new observations on the cross-calibration technique with the WS [11]. Additionally, the SR interferometer and coronagraph, installed on B1 and B2 respectively, will be discussed.

SR Imaging

The BSRT imaging system was reliably used in operation throughout 2016 for bunch-by-bunch beam size measurements. It has been crucial for several studies (beam-beam, instabilities and EC studies) and often crosschecks with independent emittance measurements, such as the luminosity scans, were carried out and confirmed the accuracy of the BSRT beam size measurement, found to be at the level of 10% as shown in Fig. 7. The BSRT cross-calibration to the wire-scanners took place in the intensity ramp up fills (where the first stable beam fill of 3 colliding bunches was replaced with a 10 colliding bunches fill). This allowed parasitic three calibration Runs this year in April, August and October. August calibration was not successful and resulted in an underestimation of the beam emittance. Investigations are still ongoing to understand the results, however important hints on the dependence of the BSRT calibration on machine conditions, optics and beam modes are observed. In fact, Fig. 8 shows the variation in the calibration factors whether beams were colliding or not in IP1 and IPS. The successive calibration (in October) was made such as no optical elements were moved in the system, hence the calibration factors found could be applied backwards to correct the measurements between calibration 2 and calibration 3, and no data loss is expected. Investigations are also in place to identify the source of the big spread in the beam size measurement observed on BSRT B1 and check whether it is correlated with beam behavior such as orbit drifts or oscillations.

Figure 8: Correlation of uncorrected BSRT beam widths with beam size measured via WS in function of the beam mode at Flat Top.

At the software level, the BSRT FESA class was ported to FESA 3 and allows now on-demand logging of bunch by bunch profiles. It is worth mentioning that both the abort gap monitor and the Longitudinal Density Monitor (LDM) were in good shape all over year and were essential during Van Der Meer luminosity calibrations Run.

In YETS, in the framework of the BSRT consolidation, digital “Basler” cameras and new “Hamamatsu” intensifiers will replace the analog intensified “Proxitronic” cameras and the FESA class will be adapted accordingly to increase the acquisition rate to ~200 frames per second (>50 bunches per second). Additionally, a big intervention is planned on the BSRT hardware where all optics will be removed to replace the optical table mounting to allow the extracting the optical table from the shielding enclave to ease maintenance.

SR Interferometer

As the SR parameters approach the diffraction limit, direct imaging for beam size measurement is highly challenging and very sensitive to the cross-calibration techniques. SR Interferometry is the best alternative to measure the small beam size with visible SR. It consists of determining the size of a spatially incoherent (or partially coherent) source by probing the spatial distribution of the degree of coherence after propagation, with a theoretically achievable resolution of a few microns.

This technique was therefore implemented in the LHC, for the first time in a proton machine [12]: In 2015, a prototype was installed on the B1 optical table, side by side to
the imaging system. The experience gained in some MDs allowed finalizing the interferometer setup and its installation in June 2016.

It features a new slit assembly that allows the measurement of the horizontal and the vertical beam sizes with the possibility to change the slit width, separation, height and center remotely. The system can also be operated as a 2D interferometer by inserting at the same time the horizontal and the vertical slits. The light polarizer used in 2015 (seen to introduce additional focusing with strong astigmatism) was replaced with a high quality precision linear polarizer constructed by laminating a polymer polarizing film between two high-precision glass substrates (flatness better than λ/6).

In 2016, a comprehensive set of measurements were performed to qualify the interferometer comparing its results to the standard imaging system at both the injection energy and 6.5 TeV. A deep analysis of all systematics was carried out, studying the SR wave front distortion, its dependence on the wavelength, the polarization, on the double slit center and height, and the detector properties such as exposure gain and linearity.

A good agreement was observed at injection energy, while a scaling factor of about 1.3 is yet to be understood between the two systems at top energy. Nevertheless interferometry was able to provide coherent relative bunch size measurements at 6.5 TeV. Moreover, the feasibility of 2D interferometric measurements has also been demonstrated. During the YETS, the alignment of the interferometer is to be improved to allow parallel measurements without compromising the quality of the imaging system. This would allow in 2017 Run, to accumulate statistics to cross-calibrate the measurements to the WS at top energy and check stability of the system, validating its accuracy and precision.

**SR Coronagraph**

The coronagraph is a spatial telescope used to observe the sun corona by creating an artificial eclipse. The concept of this apparatus consists of blocking the glare of the sun central image allowing to observe its corona. An observation of the beam halo at the LHC using a coronagraph is planned in two phases. Phase I, following the installation of a demonstrator on the B2 optical table side by side to the imaging system, aims at measuring halo with $10^3$ to $10^4$ contrast with respect to the beam core [13].

Parasitic studies took place in 2016 to check the system alignment and validate the optical configuration. Additionally, a dedicated experiment was scheduled in MD time and aimed at demonstrating the coronagraph working principle, its background and the achievable contrast.

The MD took place at injection energy and the beam halo was successfully measured for the first time with a coronagraph [14]. In fact, an artificial increase of protons population in the halo region was achieved via a controlled transverse emittance blow-up using the transverse damper. A direct correlation of light increase in the imaging plane of the coronagraph with the emittance growth was observed. Successively, the gap of the primary collimators in IP7 was reduced in both planes respectively, shaming the halo population to probe any light variation in the coronagraph images as shown in Fig. 10. A linear relation between the intensity lost as measured by the fast beam current transformers and the SR light lost in the halo region was obtained. A contrast of $2 \times 10^{-3}$ was reached. It is worth mentioning that for lack of time in the MD only one "core block" with a fixed was used, therefore the reached contrast (that depends on the block diameter) is not to be taken as the limit of the actual coronagraph demonstrator. Finally, parallel to opera-

![Image](image.jpg)

Figure 9: 2D Interferograms recorded for simultaneously inserted slits in the H and V plane.

![Image](image.jpg)

Figure 10: Measurement of an artificially created beam halo via emittance blowup with the ADT (upper images) and scraped beam halo via collimators closing (lower images).

**CONCLUSIONS**

This paper summarized the challenges some of the LHC beam instrumentation faced in 2016's operation and highlights the major changes they will undergo in the coming B4YETS. Several studies targeted the use of dBLMs for new loss scenario studies, mostly for injection losses diagnostic.
It was observed that the exploitation of such data is valuable and efforts in standardizing the readout systems for these devices will continue aiming to integrate the data in the control system. Additionally, the changes in the firmware of the WBTN readout of the BPMs was highlighted along with the benefits of using the synchronous orbit in operation with ions. The new features implemented at the software level to improve the “phase-in” procedure were also discussed. The accuracy of the beam orbit processed with the DOROS electronics was also presented and the strategy to tackle the systematics with a better control of the system’s parameter at the FESA level was shown. The improvements in the triggering of the oscillation channel in FESA was also mentioned and could allow potentially online coupling measurements. Moreover the encouraging BGV recent studies allowed verifying the integrity of the system and plan the trigger upgrade during YETS for an improved online beam size reconstruction in 2017’s Run. Slight modification in the WS hardware to reduce the noise on the PMT readings were presented and the foreseen studies to verify the accuracy of the wire position readings to tackle the challenges of small beam size measurement were also highlighted. Finally the status of the synchrotron radiation monitors was discussed: the plan to upgrade the imaging system to digital cameras for faster acquisitions was shown; the successful beam halo measurements at injection with the coronagraph were presented and the interferometer studies in 2016 were summarized.

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OPERATIONAL AND BEAM DYNAMICS ASPECTS OF THE RF SYSTEM IN 2016

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Abstract

The operation of the LHC RF system and beam dynamics studies in 2016 are presented. A fault summary is given, showing a reliable operation. Power consumption and promising studies of the full-detuning scheme are discussed. Diagnostics and software improvements done or to be done are detailed. As for beam dynamics, important advances in drift loss of LHC bunching and bunch flattening in 2016. Open questions related to controlled emittance blow-up and how PS-SPS-LHC bunch-to-bucket transfer studies helped to improve LHC injection losses are discussed. Finally, future improvements and studies are presented.

Power consumption

Originally, it was planned to recommission the klystrons to 300 kW, which is their design specification value. Most klystrons, however, saturated around 270 kW, and some even below this value. On the other hand, the klystron forward power is calibrated based on thermal measurements in the heat load, so the power is known with a limited accuracy of about 20%.

Due to issues with the SPS beam dump, the 48-gap-48 bunches batch pattern was used in 2016. With this batch pattern, beam-loading effects were relatively weak and the average klystron forward power remained well below saturation in 2016, see Fig. 2. Yet, the heating of the cavity

OPERATIONAL ASPECTS

RF faults

The RF system was very reliable in 2016. Only 31.5 h of downtime, that is about 0.6% of the LHC operation time, was associated to the system over the whole year. In total, 39 faults and 10 beam dumps in different machine modes occurred.

The distribution of the different types of RF faults is shown in Fig. 1. Hardware-related faults were dominated by issues with the 24 V power supplies and hardware controls (50%), as well as klystron crowbar events (30%) that occurred mostly after klystron restart; the remaining issues being related to tetrodes and various other things. In the low-power level RF (LLRF) category, the operational delays were caused by re-synchronisation problems and adjustment time needed for LLRF settings. Child faults were typically electrical glitches or cryogenic failures. Controls issues were related to malfunctioning of FESA classes, blocked front-ends, wrong PLC measurements, or communication issues with the hardware.

![Figure 1: Distribution of RF faults in 2016 operation.](image)

Figure 2: Typical average klystron forward power in 2016 operation with full beam. Data taken on 23rd October 2016.

main couplers was a recurrent issue, especially on cavity 7B1.

Despite the limited power demanded, the peak power had still some transients of up to 250 kW. Based on 2015 operational experience with 144 bunches, the klystron power could be insufficient with batches of 288 bunches in the future, at least with the present beam-loading compensation scheme.

An alternative scheme to the presently operational `half-detuning' scheme is the cavity voltage phase modulation or `full-detuning' scheme, which is also the baseline for HL-LHC. Full detuning has been successfully demonstrated in MDs in 2016 [1], showing a power reduction from 160-180 kW to only 60-70 kW at flat top, see Fig. 3. A first test is Physics machine mode [2] showed a modulation of the collision time w.r.t. the bunch clock (in all IP's) and a modulation of z-vertex (in IP's 2&8, see Fig. 4), in agreement with predicted values.

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memory leak has been fixed. New FESA classes have been created to log high-resolution profiles and stable phase oscillations from the longitudinal ObsBox; these classes will be available for the start-up in 2017. The RF phase noise on Beam 1 has been reduced as well by exchanging its VCO crystal oscillator module.

Several developments are yet to be made in the future. A fixed display for the high-resolution beam profiles is planned and the FESA3-migration of FESA classes will have to be completed. Commissioning tools are planned to be migrated from Matlab to python as well. The documentation of the peak-detected Schottky system is still to be done. Interruptions of the beam spectrum logging due to communication issues with the instrument are under investigation. Also, for a smoother recovery of the LLRF system after a power cut or a power cycle, tests in the laboratory will have to be performed.

In order to ensure the continued functioning of commissioning and expert tools that are indispensable for RF operation, CO support for pyjacc and java libraries (maintained in the past by BI and CTF3, respectively) is of vital importance.

**BEAM DYNAMICS ASPECTS**

**Loss of Landau damping**

Measurements in 2016 showed that the coupled-bunch stability threshold for a full machine is higher than the single-bunch one [3], at least for the current operational parameters. Therefore single-bunch loss of Landau damping dominated in long fills, and it occurred in physics with beam parameters according to predicted threshold [4]. With the operational bunch intensity of about $(1.1-1.15) \times 10^{11}$ pb, bunch length oscillations around 0.9 ns have been observed with time constants of several hours, see Fig. 5.

Long-lasting, undamped injection oscillations have also been observed at arrival to flat top [3]. Analysing different cases, it was shown that the bunch phase oscillations at arrival to flat top depend on the time spent at flat bottom, see Fig. 6. The damping time of oscillations is about an hour on flat bottom. It is still unclear how undamped oscillations survive the noise injection of the controlled emittance blow-up during the ramp and make it to flat top.

**Bunch flattening**

With the positive polarity of the LHCb magnet, the vertex reconstruction is not accurate enough for bunch lengths below 0.9 ns [5]. Bunch flattening using sinusoidal RF phase modulation was used operationally to regulate the bunch length [6]. With the operational modulation settings that target the very core of the bunch, the bunch length typically increased by 150-200 ps, see Fig. 7a. The corresponding estimated loss in integrated luminosity after the bunch flattening was in the range of about $2.5-4.5\%$ in IPs 1&5, see Fig. 7b. The mechanism of bunch flattening proved to be completely loss-free under the operational conditions.
**Controlled emittance blow-up**

In 2016, the controlled emittance blow-up applied during the ramp was close to the limit of stability (leading to large bunch length spread), as the target bunch length was decreased from 1.25 ns to 1.1 ns [7]. For better convergence of the bunch lengths along the machine, the target bunch length was kept at 1.25 ns during the first two-thirds of the ramp, and decreased to 1.1 ns only during the last third. This reduced the bunch length spread from 410-450 ps to 120-160 ps, see Fig. 8.

Latest beam dynamics simulations on controlled emittance blow-up show that the operational procedure is closer to resonant excitation than to diffusion and has island creation in longitudinal phase-space as a consequence. In line with this observation, peak-detected Schottky spectra show a depleted region close to the centre of the bunch after the blow-up, see Fig. 9. This cannot be detected on the beam profile and shows how powerful this diagnostics is to measure the synchrotron frequency distribution.

**PS-SPS-LHC bunch-to-bucket transfer**

2016 brought also repeated satellite investigations in the SPS and the LHC, as LHC injection losses were recurrently close to the BLM dump threshold. The SPS-LHC transfer losses, however, are on the per mille level and it is hard to improve this performance. The main origin of the LHC satellites is actually the ‘S-shaped’ bunches injected into SPS after the PS bunch rotation, see Fig. 10. ‘S-shaped’ bunches lead to particles being captured in nearby buckets that extend beyond the extraction kicker flat top and thus lead to losses at LHC injection.

Switching on the spare 40 MHz PS cavity with the optimised settings proposed in 2012 [9] reduced the PS-SPS transfer losses from 5 % to 2.5 %, as predicted. In the LHC, the satellite population reduced by a factor 5-10 as a consequence [10]. An operational use of the spare cavity requires some consolidation of the PS 40 MHz system and an additional power converter for the LIU-era [11].

**Forthcoming and continued studies**

Several open questions remain that require further research. Full detuning, if not becoming operational in 2017, will have to be studied in MDs. The limitations and possibly the optimisation of the controlled emittance blow-up remain to be investigated. Concerning coupled-bunch instabilities, the studies of 2016 need to be continued also for the nominal LHC beam, as well as coupled-bunch instabilities due to the fundamental cavity impedance. Studies on using band-limited RF phase noise for bunch flattening and to counteract synchrotron radiation damping are planned, as well as studies on the longevity of injection oscillations. Measurements of the 400 MHz cavity HOMs are intended, too.

**CONCLUSIONS**

The operation of the RF system was smooth in 2016. Many studies have been performed and there were several highlights during the year. The full-detuning scheme for beam-loading compensation has been successfully tested to lower klystron forward power compared to the operational half-detuning scheme. Loss of Landau damping has been observed in long physics fills in agreement of previous measurements of the LHC machine impedance. Bunch flattening has been implemented to control the bunch length in physics and has been used operationally when the LHCb magnet had positive polarity to prevent the bunch length from dropping below 0.9 ns. The controlled emittance blow-up has been operated at the limit of convergence in 2016 and studies are required to improved the present blow-up method. Beam satellites causing large injection losses in the LHC have been reduced significantly by applying the optimised PS bunch rotation according to earlier studies. Diagnostics and software improvements continue to be performed. Also, open questions will be addressed in continued studies in the coming year.
ACKNOWLEDGEMENTS

The continued effort and kind support of our RF colleagues B. Bielawski, T. Bohl, Y. Brischetto, R. Calaga, H. Damerou, G. Hagmann, M. Jaussi, T. Levens, T. Mastoridis, J. Molendijk, A. Pasinlin, N. Schweg, and M. Therasse is gratefully acknowledged.

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Figure 8: Bunch length spread caused by controlled emittance blow-up during the ramp with decreased target bunch length.

Figure 9: Peak-detected Schottky spectrum of bunches after controlled emittance blow-up and arrival to flat top.

Figure 10: PS-SPS bunch-to-bucket transfer (simulation with BLonD [8]).
R2E

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Abstract

The R2E ("Radiation to Electronics") project [1] mandate is to follow up on the equipment failures related to radiation and propose mitigation strategy. One of the key parameters to evaluate the cause of the failures and the strategy on how to avoid them is a precise knowledge of the radiation field around the machine. An overview of the radiation levels for the 2015 and 2016 in the LHC is reported along with the scaling factors to be used for the future runs. The link between radiation levels and failures on the electronic equipment for the 2016 run is discussed in this work with a particular stress on the causes of failures and the mitigation actions which have been or will take place. The future impact of the non-mitigated failures on the LHC operation is also discussed.

INTRODUCTION

The R2E mitigation strategy effects can be dated back in the 2011. Several shielding campaigns and 'on the fly' relocation had been set up before the 2011 in order to reduce the failure rate in the shielded areas and in the tunnel [2] [3] [4]. Every year since then, the R2E project is committed to reduce the failures due to the radiation by means of strategic relocation, shielding and support of new radiation tolerant developments when the two first options are not possible.

This work aims at understanding the achievements obtained up to the 2016 Run and what has still to be done in terms of mitigation and prevention. For this scope, the knowledge of the radiation levels around LHC critical areas and the LHC tunnel is fundamental. The radiation levels of the 2015 Run are compared with the 2016 measurements to highlight the effect of the accelerator parameters. In the second paragraph, the equipment failures of the 2016 operation are analysed for the critical equipment in the tunnel and the failure rates are reported for the 2016/2017.

RADIATION LEVELS AND PARAMETERS SCALING

The radiation-induced failures on electronic equipment observed during 2016 LHC operation are mainly Single Event Effects (SEE). The probability of having a SEE is proportional to the cumulated High Energy Hadron (HEH) fluence. The radiation levels in the LHC tunnel and in the shielded areas have been measured using the RadMon system [5]. The HEH fluence measurements are based on the reading of the Single Event Upsets (SEU) of SRAM memories whose sensitivity has been previously calibrated at various facilities [6] [7].

The LHC radiation levels depend on the operational parameters of the accelerator. The levels are related and scale with several factors: (a) integrated luminosity, (b) integrated beam intensity (c) optics, (d) vacuum pressure in the beam pipe, (e) shielding, (f) electronic system positions.

![Figure 1: Radiation levels expressed as HEH fluence for the cells from 4 to 20 considering all the LHC points except the 7.](image)

As an example, the 2015 Run was characterized by higher radiation levels with respect to the 2012 mainly because of the different bunch spacing [4][8]. The 2016 the Run had the same bunch spacing of the 2015 (25 ns) and thus the radiation levels were not impacted by this parameter.

Comparing the 2015 and 2016 radiation levels, it is possible to categorize the losses in 'luminosity driven', 'integrated intensity driven' and 'localized losses'. The HEH fluences measured by the RadMons in the LHC tunnel are depicted in Fig. 1 considering only the proton Runs. The HEH hadron fluences are calculated per each cell considering all the points together (apart from point 7).

Luminosity Driven cells

For the cell below number 8 and the odd cells above the number 9 (up to 15), the HEH fluence in the 2016 is higher than the one of the 2015 of around a factor 10, which corresponds to the integrated luminosity difference between the two years (4.2 fb⁻¹ and 41 fb⁻¹ for the 2015 and 2016 respectively). This is a clear sign that in those cells the losses scales with the integrated luminosity. This has been verified looking at the RadMon readings in one of the above mentioned cells in the reference LHC fill 5096. In Fig. 2, the HEH fluence measured in cell 11R5 is depicted along with the integrated luminosity. A similar trend of the two quantities is noticeable. In Fig. 3, the intensity and the radiation levels are depicted in the different beam modes. The radiation levels increase when the beams are in collision ('stable beam' mode), indicating that in that cell the luminosity drives the radiation levels. With these assumptions, it is possible to normalize with the luminosity the
HEH fluences in the tunnel areas for the luminosity driven cells. In such a way, it is possible to foresee the fluences in the future Runs and evaluate the possible equipment failure rate. In the Table 1 the HEH fluences normalized for the luminosity are reported for the cells 11 and 9 in point 1 and point 5.

![Graph showing HEH fluence in cell 11R5]

**Figure 2:** The HEH fluence in the cell 11R5 follows the integrated luminosity.

**Localized losses**

In some cases, there have been losses in not expected locations. For example in the 2016 Run, in cell 13 of the left side of point 3 the radiation levels were 80 times higher than the one of 2015. The measurements of both RadMon and Beam Loss Monitor (BLM) were in agreement as depicted in Fig. 4. The cell 13 of the left side of point 3 and the cell 12 of the right side of the point 1 showed also higher losses with respect to the 2015 Run. These localized losses might have been caused by an orbit bump but this assumption has still to be verified.

**Table 1: Normalized HEH fluence for the luminosity driven cells**

<table>
<thead>
<tr>
<th>Cells</th>
<th>HEH/cm2/pb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>11L1</td>
<td>806.2</td>
</tr>
<tr>
<td>11L5</td>
<td>568</td>
</tr>
<tr>
<td>11R1</td>
<td>1590.5</td>
</tr>
<tr>
<td>11R5</td>
<td>963.8</td>
</tr>
<tr>
<td>9L1</td>
<td>945.5</td>
</tr>
<tr>
<td>9L5</td>
<td>846.5</td>
</tr>
<tr>
<td>9R1</td>
<td>516.7</td>
</tr>
<tr>
<td>9R5</td>
<td>1007.8</td>
</tr>
<tr>
<td>11L1</td>
<td>806.2</td>
</tr>
</tbody>
</table>

**Integrated intensity driven cells**

In the 2016 Run, the integrated luminosity produced was provided by the half of the integrated intensity with respect to the 2015 Run [9]. This was mainly due to the improvement on the β* and crossing angle made in the 2016. The lower integrated intensity led to around a factor 2 less radiation than expected [9].

In Fig. 5, the BLM doses normalized for the intensities in the 2016 and 2015 are compared. The ratio between the normalized doses is around 0.5. This means that the radiation levels did not scale proportionally between the two years following the integrated intensity. This could be due to the lower than expected beam-gas interactions, potentially induced by a lower vacuum pressure.

**Shielded areas**

During the LS1, thanks to the R2E mitigation strategy all the sensitive equipment has been relocated in the UJs leaving few to none sensitive electronics. For this reason, only the RR are analysed in this work.

Usually, being the shielded areas close to the interaction point their radiation levels scale with the integrated luminosity. This statement is not valid for the RR73/77 where the radiation levels scale with the beam losses. Indeed, in the areas close to the collimators the radiation levels can change drastically depending on the collimators settings [2-3].

The HEH fluences for the most critical shielded areas where electronic equipment is installed are reported in Fig. 6. The HEH fluences are compared inside and outside (tunnel side) the shielded areas for the 2015 and 2016. The comparison between the inside and the outside of the shielded areas gives information on the efficiency of the shieldings. In the RR of Point 1 and Point 5 the shielding reduces the HEH fluence inside the RR of a factor around 10 while in the RR of Point 7 the factor is around a factor 80 (due to the more shielding put in place). Comparing the two years is possible to notice that during 2016 in Point 5, the levels inside the RR were similar to the tunnel areas fluences in the 2015. The cause and the effects of the higher levels in the RR of Point 5 will be clarify in the next paragraph.

![Graph showing HEH fluence in cell 11R5]

**Figure 3:** The HEH fluence in the cell 11R5 start to increase when there is the stable beam condition.
FAILURES OBSERVED IN 2015 AND CORRESPONDING MITIGATION ACTIONS

The main sources of information were the LHC e-logbook, the meeting on the LHC operation follow-up, daily held at 8h30 [10], the Accelerator Fault Tracker (AFT) tool [11] and via the Radiation Working Group (RADWG) [12]. During the year, the collaboration of all the equipment groups was highly appreciated and permitted to improve the performed failure analysis. Once a failure is suspected to be related to radiation effects, the type of failure, the location and the equipment affected are collected. In some cases, it is not clear whenever a failure was effectively due to radiation effects. Thus, the event is marked as to be confirmed and a further analysis is required to understand the reproducibility of the failure.

During LS1, all remaining possibly sensitive equipment has been moved from the critical areas (UJ14/16/56/76, US85, and UX45) to safer areas (mainly UAs and US); additional shielding has been installed in the RR areas to reduce further the radiation levels. These actions and several equipment upgrades made possible to reduce the number of failures for most of the equipment group.

While in the 2015 Run all the events where ‘soft’ and the equipment did not require a replacement [ref]. In 2016 few destructive events have been recorded.

Table 3 shows the failures due to the SEE’s comparing the 2012, 2015 and 2016.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Dump 2012</th>
<th>Dump 2015</th>
<th>Dump 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPS</td>
<td>32</td>
<td>2</td>
<td>0 + 2* ion</td>
</tr>
<tr>
<td>Power Converter</td>
<td>15</td>
<td>5</td>
<td>6 + 1* ion</td>
</tr>
<tr>
<td>Cryo</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>EN/EL</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Vacuum</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Collimation</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>TE/ABT</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RF</td>
<td>1</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Others (hidden)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3 /fb⁻¹</strong></td>
<td><strong>3 /fb⁻¹</strong></td>
<td><strong>0.15 /fb⁻¹ (proton Run)</strong></td>
</tr>
</tbody>
</table>

The failure rate normalized per fb⁻¹, considering only the proton Run were 3 dumps per fb⁻¹ in 2012 and 3 dumps per fb⁻¹ considering the RF failures in 2015. In the 2016 the rate where 0.15 per fb⁻¹.

In the following subsections, the failure analysis and the envisaged mitigation actions for all the affected equipment groups are briefly summarized.
QPS

During the 2012 operation QPS equipment was the main cause of beam dumps for the LHC. The equipment relocation, the firmware upgrades and the new radiation tolerant nDOQDI system deployed during the LS1 have proven to be effective reducing the beam dumps to only 3 in the 2015 Run. The deployment of the new radiation tolerant 600A protection system during the YETS of the 2016/2017 has proven to be effective in reducing the number of failures during the 2017 proton Run. The two events in the ion Run were localized in point 8 and point 1. The one in point 1 was destructive. The causes of these failures have still to be confirmed if they are radiation related.

EPC

The EPC equipment can be divided in the control part and power part. The events in the 2012 affected the 600A power supply, the FGC control cards and the 120A power supply. The 7 failures observed during the 2015 affected both the FGC and 120A circuit. In the 2016, 3 events were recorded on the control part (only one during the ion Run) and three on the power part. Two destructive events were recorded on the power part during the 2016. Several EPC failures happened in the shielded areas RR of point 5 (RR53 and RR57). As discussed in the previous paragraph, the radiation levels in these zones were higher then expected. In the 2016 Run the TCL6 collimators of point 5 were closed at 20 sigma in most of the physics Run. In the picture 7 is possible to notice that when the TCL were closed the average flux of HEH is about 7.2 x 10^6 HEH/h while when the TCL are open the average flux in the RR is 5.4 x 10^5. This means that closing the TCL6 increase the flux and thus the cumulated fluence of a factor 13. The increase in the flux and consequently of the fluence increase the probability of a failure. Indeed, as depicted in Fig. 7 the EPC failure in the RR of point 5 happened when the collimator was closed.

The deployment of the radiation tolerant FGClite system is foreseen during the 2016/2017 YETS reducing the number of failures due to the control part.

RF

In the 2012 three RF events were recorded on a power supply and on vacuum gauges in UX45. These events have not been confirmed as radiation induced and in the 2015 no events happened on these devices. The 2015 events affected the ARC detector circulator/load and klystron window. Those cases have not been confirmed to be related to radiations. However, mitigation strategies have been put in place to reduce the risk of failure. Because of that, in 2016 Run, no events were recorded on both the systems.

Others: Cryo, Collimation, EN/EL

All the sensitive equipment has been relocated during the LS1. The relocation actions has been confirmed to be effective in the 2015 and 2016 leading to no failures.

CONCLUSION

A summary of the radiation levels and the induced failures for the LHC operation in 2016 has been reported. About 6 beam dumps during the proton Run were provoked by radiation effects during the 2016 Run. Three events have been recorded during the ion Run. The impact of the radiation effects would have been significantly higher without the countermeasures that were applied in the past years. Additional mitigation actions are planned for the EYEITS period to further reduce the radiation vulnerability of the equipment. In particular the deployment in the tunnel areas of the radiation tolerant FGClite. The monitoring of the radiation levels permitted to highlight the parameters with which we can scale them properly for the future. In particular, the cells ‘luminosity driven’, ‘integrated intensity driven’ along with the ‘localized losses’ have been identified. A point of discussion for the future availability of the machine is the impact of the TCL6 in Point 1 and 5 on the failure rate. It has been reported in this work that having the TCL6 closed could led to fluxes of HEH up to a factor 13 higher in the shielded areas just downstream the collimator. This effect, eventually, could led to a higher failure rate in the future Runs.

Finally, the radiation monitoring will be a continuous job which aims at reducing the uncertainty factors, mainly related to the beam gas effects and the losses in the collimation areas, as well as to closely monitor the long-term radiation impact on exposed electronic systems. This will permit to verify the design assumptions and schedule preventive maintenance/rotation of the equipment when required. The detailed followup of the system upgrades and developments remains crucial to reach the above goal.

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MACHINE PROTECTION DURING RUN 2016 - REVIEW OF MP STRATEGY

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Abstract

In this contribution the strategy for the initial intensity ramp-up, the ramp-ups after short stops and the machine protection validations (loss maps, asynchronous beam dump tests) will be reviewed and improvements proposed. Operating the LHC with important systems in a degraded mode will be reviewed and discussed on the basis of two examples. A new fast failure case, causing orbit kicks on the beam in case of a quench will be presented. Finally, the machine protection classification and approval strategy of machine developments (MDs) is reviewed.

INTRODUCTION

2016 has been an excellent year with the LHC surpassing the design value for instantaneous luminosity and delivering about 40 $fb^{-1}$ integrated luminosity to the two high luminosity experiments. Besides many others, the LHC machine protection systems and the teams responsible for them were an important part of this success. The well established machine protection strategies and procedures, which were enforced and documented for standard operation and machine developments, ensured the safe operation of the LHC in 2016. This contribution analyses and reviews critically the 2016 machine protection strategy and proposes further improvements.

INTENSITY RAMP-UP STRATEGY AND MACHINE PROTECTION VALIDATIONS

As in previous years, a step wise increase of the stored beam intensity was performed in 2016 following the beam commissioning. For each intensity step a minimum of 3 fills and 20 hours of stable beams were required. The correct functioning and response of all machine protection relevant systems was carefully analysed for these fills - from beam injection to dump - and the results were documented in so-called check lists. The defined intensity steps were 3/12, 48/72, 288, 570, 860, 1200, 1700 and 2300 bunches. The increase of stored beam intensity was interleaved with the increase in the length of the injected bunch trains, to avoid increasing both simultaneously. The first intensity step (3/12 bunches) is in general focused on establishing the LHC machine cycle. The second part (48 - ~ 1000 bunches) is designed to verify the correct functioning of all machine protection systems and to identify and mitigate potential issues. Intensities above 1000 bunches are usually dominated by intensity related limitations, like e-cloud, RF heating or UFDs. During the latter the increase of the stored beam intensity is not performed in big steps, but rather by incrementally adding one bunch train more from fill to fill, until limitations appear. In this phase, check lists are performed on a 6-weekly basis and are then called intensity cruise check lists.

Excluding a several day long stop of the whole accelerator complex due to a problem with the powering of CERN’s Proton Synchrotron (PS), intensities > 1700 bunches (equivalent to stored beam energies above 200 MJ) were reached only 15 days after the start of the intensity ramp-up (see Fig. 1). In total, 7 intensity increase and 4 intensity cruise check lists were filled during the proton - proton run in 2016 and documented in EDMs [1].

Figure 1: Intensity ramp-up 2016 from the end of the beam commissioning until technical stop one (TS1). The blue and red lines indicate the stored beam intensity in the two LHC rings in charges. The dashed lines symbolise intensity check lists before stepping to the next intensity. The stored number of bunches per beam is shown in orange.

For restarts after stops of nominal operation longer than 48 h two scenarios were defined in 2016. Scenario one applies to stops with little hard- or software interventions and requires in total two ramp-up fills. In this case the LHC cycle has to be revalidated with pilots bunches, if additional optics measurements are required. Otherwise a fill with 2-3 nominal bunches should be performed. In addition, to disentangle wrong settings, de-conditioning etc. from the intensity dominated effects at full pre-stop intensity, a ~ 600 bunch fill with 2-5 hours stable beams is required. Afterwards, operation can be continued at pre-stop intensity. The second scenario covers a stop with numerous hard- and software interventions, as in a usual technical step, and requires three to four fills: one fill with either pilot or 2-3 nominal bunches for cycle validation (as above), one fill with ~ 50 bunches and 1-2 hours stable beams, one fill with ~ 600 bunch and 2-5 hours stable beams and, finally, in case intensities > 2000 bunches had been reached before the stop, a fill with about half the maximum achieved number of bunches with about 5 hours stable beams. Afterwards, operation can be continued at pre-stop intensity. The correct behaviour of all machine protection critical systems needs to be carefully monitored during these short intensity ramp-ups to allow a quick identification and mitigation of possible issues.

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In 2016, scenario one has been successfully applied to the ramp-up after the stop due to the PS powering problem, technical stop one, machine development block one (MD1), MD2 and MD4. Scenario two was used for the ramp-up after MD3 / technical stop two (TS2). Figure (2) illustrates the use of the two scenarios in 2016. As the experience with the two scenarios in 2016 was very positive it is proposed to also apply them during the LHC run in 2017.

Figure (3) shows a table with the number of loss maps and asynchronous beam dump tests performed for validation of cleaning and passive protection during the 2016 Run. In total, the impressive amount of 204 betatron loss maps, 38 off-momentum loss maps and 40 asynchronous beam dump tests have been performed as part of the initial beam commissioning, re-validation campaigns after technical stops and the different validations during the proton - ion run [2]. These machine protection tests have been followed-up systematically, regularly and timely and were essential to gain confidence in the safe operation of the LHC with \( \beta^* = 40 \) cm. relying for the first time on the phase advance between tertiary collimators respectively triplets and the dump kickers in IP6.

It is important to point out that betatron loss maps have a significantly smaller operational footprint than off-momentum loss maps and asynchronous beam dump tests, as the beams are usually lost as part of the latter. The use of the so-called gentle off-momentum loss maps allowed to perform multiple off-momentum loss maps with the same beam, which increased the operational efficiency of these tests. One of the reasons for the comparably big number of validation tests performed in 2016 was the subdivision of the LHC cycle. A simplification of the cycle would allow to reduce the number of loss maps and asynchronous beam dump tests significantly. In addition, so-called continuous loss maps were performed during the ramp and the squeeze beam process, which provided important data on the cleaning performance during these parts of the LHC cycle. Based on the 2016 experience the standard, minimal scenario should be reviewed and possibly optimised. Furthermore, performance studies should be consequently separated from machine protection validations. For the future it should be studied, if the analysis of loss maps and asynchronous beam dump tests can be further automated, and how regular physics fills and their dumps can be used to validate the correct settings of the protection devices. Finally, the DOROS BPM interlocks implemented for the tertiary and IP6 secondary collimators should be unmasked and an automatic analysis implemented.

<table>
<thead>
<tr>
<th></th>
<th>Betatron loss maps</th>
<th>Off-momentum loss maps</th>
<th>Async. dump tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commissioning</td>
<td>100*</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>After TS1</td>
<td>20</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>After TS2</td>
<td>24</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>p-Pb 4 Z TeV</td>
<td>20</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>p-Pb 6.5 Z TeV</td>
<td>16</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Pb-p 6.5 Z TeV</td>
<td>24</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Total Proton run</td>
<td>144</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Total Ion run</td>
<td>60</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>Total 2016</td>
<td>204</td>
<td>38</td>
<td>40</td>
</tr>
</tbody>
</table>

*breakdown: 32 classical betatron loss maps, 36 loss maps during ramp & squeeze, 32 loss maps during during squeeze

Figure 3: Overview of loss maps and asynchronous beam dump tests performed in 2016.

**OPERATION OF SYSTEMS IN DEGRADED MODE**

During the 2016 Run there were two prominent examples, where a system was operating in a degraded mode, potentially impacting machine protection. In both cases a detailed risk analysis and extensive tests were performed, operational system parameters were adapted, interlock levels tightened and additional interlocks for short/mid-term mitigation were implemented. This was then complemented by a vigilant supervision of the respective systems. Therefore, time consuming repairs could be delayed to the extended year end technical stop 2016/17 (EYETS).

**Nitrogen leak in the LHC dump block (TDE)**

Figure (4) depicts the nitrogen pressure in the TDE line (TD68.DB) during the LHC Run 2016. A leak developed at the beginning of April and was discovered a few days later. The discovery was followed by a period of investigation and step-by-step adjustment of the operational pressure before a stable situation was reach by then end of May 2016. In addition to the existing LBDS-XPOC injection inhibit of the TDE nitrogen pressure, SIS interlocks and BigSister announcer warnings were introduced for the two beam dump blocks. During the EYETS 2016/17 the leak rate was reduced following mechanical interventions. Studies on the criticality of repeated high energy beam impacts on the carbon dump blocks in the presence of a nitrogen leak are ongoing. The implementation of a hardware warning for the TDE nitrogen pressure, possibly later complemented by a hardware interlock, as proposed by the 134th MPP [3], has been prepared and will be finalised in a technical stop during the 2017 Run.
Suspected inter-turn short on main dipole A31L2

On June 10th and August 3rd 2016, unusual voltage signatures in the main dipole A31L2 were detected by the quench protection system during a ramp down of the circuit and triggered the firing of the quench heaters. The two events took place at 547 A and 295 A respectively. The measured voltage over the magnet ($U_{\text{diode}}$) and the derivative of the circuit current for the first event are depicted in Fig. 5. With simulations it was shown, that this signature could be explained by the (dis-)appearance of an inter-turn short in this magnet. An inter-turn short poses the risk of magnet and collateral damage in case of a quench or a fast power abort in the concerned magnet or circuit. Following the second event, the powering of this circuit was stopped, special detection equipment was installed and powering tests were performed. As no further indication of an inter-turn short was observed, the operation was resumed. The special measurement equipment was left in the LHC tunnel to improve the supervision of this magnet and the data were regularly analysed. To reduce the probability of a magnet quench or fast power abort in the main dipole circuit of sector 12 the so-called global protection mechanism of the powering interlock controller (PIC) was deactivated for this sector. The beam loss monitor thresholds of the dipole magnets in sector 12 were reduced significantly below the quench level, accepting additional UFO dumps [4]. Furthermore, the triggering threshold of the quench protection system was increased for the concerned dipole magnet. Ultimately, the main dipole A31L2 was replaced during the EYETS 2016/17.

NEW FAST FAILURES: QUENCH HEATER FIRING WITH CIRCULATING BEAM

During the analysis of an UFO quench of the main dipole C28L5 on June 12, small losses in the IR7 collimation system were discovered just before the beam dump. An orbit oscillation of ~ 10μm caused by a skewed dipole field due to the discharge of the quench heaters, was identified as the source of these losses (see Fig. 6). Further investigations around previous quenches and a dedicated beam experiment in a machine development block confirmed that the LHC beams are still circulating for 35 turns or ~ 3 ms after the triggering of the quench heater discharge by the quench detection system, before they are dumped. Table 1 summarizes the expected kicks for a subset of most relevant superconducting magnets respectively sets of magnets in the LHC. The expected kicks of single magnets are non-negligible at 450 GeV but small at 6.5 TeV. In case of the simultaneous firing of quench heaters in three neighbouring dipoles or a quench in one of the triplets, the kicks reach 0.49, respectively 1.1 σ. This will cause significant losses in the LHC collimation region. For the new HL-LHC magnets, especially the Nb3Sn triplets, the kick will be even stronger. Thus, it is important to choose a quench heater layout, which minimizes the skew dipole field and to ensure that the quench heaters and comparable protection equipment are only fired after the beams have been dumped [5].

Figure 6: Vertical rms orbit change after quench of main dipole C28L5 at 6.5 TeV

<table>
<thead>
<tr>
<th>Kick in σ</th>
<th>450 GeV (σ)</th>
<th>6.5 TeV (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main dipole</td>
<td>0.82</td>
<td>0.21</td>
</tr>
<tr>
<td>three main dipoles</td>
<td>1.92</td>
<td>0.49</td>
</tr>
<tr>
<td>D1 (IP 2&amp;8)</td>
<td>0.82</td>
<td>0.22</td>
</tr>
<tr>
<td>D2 (IP 2&amp;8)</td>
<td>0.58</td>
<td>0.16</td>
</tr>
<tr>
<td>Triplet</td>
<td>0.8</td>
<td>1.1</td>
</tr>
</tbody>
</table>

MACHINE DEVELOPMENTS

As in previous years detailed procedures were submitted for each requested machine development test (MD) by the
requestors of the MD. Based on the detailed information in
the procedures, MDs were classified by machine protection
experts in three classes:

- class A: set-up beam ($< 5 \times 10^{11}$ protons at 450 GeV
  and $2 \times 10^{10}$ protons at 6.5 TeV) using nominal settings
  on all protection systems.
- class B: high intensity beam with nominal settings in
  all protection systems
- class C: high intensity beam and changes of settings of
  protection systems

Of all MDs in 2016 6% were classified class A, 68% class
B and 26% class C. All class C MDs were discussed in the
restricted Machine Protection Panel (rMPP) and the proce-
dures were approved and documented in EDMS [1]. Overall
this approach worked well in 2016. Nevertheless, vigilance
is required from all involved players to ensure the optimal
preparation and safe performance of the MDs. The cumula-
tion and re-scheduling of MD blocks to accommodate unfore-
seen limitations was challenging for the MD teams as well
as for the rMPP validation process. Although the commu-
ication between the MD team and the engineer in charge
(EIC) link person during the preparation phase worked in
general well, an earlier involvement of the EIC link person
would be beneficial.

Several ad-hoc end of fill MDs at the end of the proton
proton run, which required a last minute check and approval
by the rMPP, clearly illustrated that a proper machine pro-
tection validation can only be ensured if all MDs follow
the usual process of approval by the MD coordination team,
classification and validation by rMPP and implementation
by the operations crew.

CHANGES TO THE CORE OF THE
MACHINE PROTECTION SYSTEM

During the ion Run in 2016 amplifiers were added on the
interlocked BPMs in IR6 to shift their sensitivity region to
lower bunch intensities in anticipation of limitations. This
change had previously been discussed, but its implemen-
tation was only foreseen, if unnecessary beam dumps by
the IR6 BPMs occurred. When reviewing the impact of the
changes, it was discovered that the additional amplifiers re-
duced the overall reliability of the system. Therefore, the
amplifiers were removed at the next occasion.

The above example shows that any changes to the core
of the machine protection system in the LHC should be dis-
cussed in and approved by the Machine Protection Panel
(MPP), which comprises experts from all different machine
protection systems and allows for an independent feedback.
In that way the consequences of changes can be first fully
evaluated before they are implemented. In the future, the
MPP will ensure to be more proactive during situations as
described above.

CONCLUSION

The strategy for the intensity ramp-up after the beam
commissioning in 2016 proved to be very efficient and al-
lowed to reach an intensity of ~ 1700 bunches, i.e. about
75% of the maximum stored intensity, after only 15 days.
The correct functioning and response of all machine pro-
tection relevant systems was carefully analysed and docu-
mented. Therefore, it is proposed to apply the same strat-
 egy for the 2017 intensity ramp-up. Two standard scenarios
for ramp-ups after short stops have been defined and used
successfully in 2016. Thus, it is proposed to apply these
scenarios also in 2017.

An impressive amount of loss maps and asynchronous
beam dump tests has been performed, analysed and vali-
dated in 2016. To reduce the load on the respective teams
and to further reduce their foot print on machine availa-
bility, a simplification of the LHC cycle and a critical review
of the minimum sets required during beam commissioning,
after technical stops and optics changes has been proposed.

The classification and approval process of machine develop-
ment tests worked well in 2016. In the future, all end of
fill and parallel MDs should be covered by the same process.

In 2016 two important systems were operated in a de-
graded mode (suspected inter-turn short in main dipole
A31L2 and nitrogen leak in the LHC beam dump). The im-
plementation of mid-term mitigations following a detailed
analysis allowed to postpone lengthy repairs to the EYETS
2016/17. Such cases can also be expected in the future and
require a case-by-case analysis.

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BLM THRESHOLDS AND UFOS


Abstract

In 2016, the thresholds of more than half of the LHC Beam Loss Monitors connected to the Beam Interlock System were changed throughout the year. Many of the changes were in one or another way related to losses induced by micron scale dust particles often referred to as Unidentified Falling Objects (UFOs). This paper summarizes the UFO trends, the number of UFO-induced dumps and quenches in 2015 and 2016, and shows how dumps were distributed between arcs and straight sections. The impact of 2016 threshold changes on the number of dumps in the arcs is analyzed and it is estimated how many dumps and quenches would have occurred if other threshold strategies would have been adopted. The paper concludes with a brief summary of non-UFO-related threshold changes and an outlook for 2017.

INTRODUCTION

Presently there are more than 3500 Beam Loss Monitors (BLMs) connected to the LHC Beam Interlock System (BIS). In 2016, the beam abort thresholds of more than 2000 BLMs were adjusted for the proton run (6.5 TeV), and of about 50 BLMs for the heavy ion run (4 ZTeV and 6.5 ZTeV). The thresholds applied in the machine are the product of master thresholds and a monitor factor. The master thresholds are a function of beam energy and BLM integration time, and they are identical for all BLMs in a family (a family groups BLMs at equivalent positions). The monitor factor is constant, but can vary for different family members. The majority of all threshold changes carried out in 2016 (~83%) involved a concurrent modification of the master thresholds and the monitor factor, while in 6% of the cases only the master thresholds were changed, and in the reminder only the monitor factor was changed. All master threshold changes were empirical corrections based on operational experience gained in 2015 and 2016. The corrections were applied on top of the models which had been established before Run 1 (collimators and Roman Pots) or in Long Shutdown 1 (magnets) [1, 2, 3].

Figure 1 provides an overview of the threshold changes carried out for the 2016 proton run. Multiple threshold changes affecting the same BLM are counted separately if thresholds were active for at least one week of operation. The total number of changes was more than a factor of two less than in the previous year, when about 5700 threshold modifications had been carried out [4]. A large fraction of the changes in 2016 involved a threshold increase, with the main goal to avoid unnecessary UFO-induced dumps while tolerating some quenches. This strategy, which has been proposed in [5, 6], had a positive impact on machine availability, although it had to be partially revoked because of different reasons, for example to reduce the risk of symmetric quenches in independently power quadrupoles (IPQs) in the dispersion suppressors, and to reduce the probability of a fast power abort in Sector 12 (suspected inter-turn short in a dipole). Threshold adjustments were also necessary because of new collimator settings, higher luminosities and longitudinal losses during injections.

This paper summarizes the changes in 2016 and analyses their impact on machine availability. The main focus is given to UFO-induced losses, which were the primary cause of premature BLM dumps, and the only cause of beam-induced quenches at top energy in regular operation. The two next sections are dedicated to UFO losses in the arcs/dispersion suppressors and insertion regions, followed by a brief discussion of non-UFO-related threshold changes, including changes for the proton-Pb ion Run at

Figure 1: BLM threshold changes for the 2016 proton Run carried out in the Year-End Technical Stop (YETS) 2015/16 and during 2016 operation. Changes involving a threshold increase are indicated in blue, while changes involving a decrease are shown in yellow. Modifications carried out in the YETS 2015/16 are only counted if they resulted in thresholds which were different from the ones active at the end of 2015 proton Run. This excludes for example the reversal of thresholds which had been modified for the 2015 Pb Run.
2015 | 2016

Figure 2: Number of arc UFO events (cells ≥12) per hour of stable beams in 2015 and 2016. The events were recorded with the UFO Buster application [8]. Each bar represents a different proton fill. The algorithm for counting UFO events was the same in both years. The green arrows indicate periods when the UFO rate exhibited a decreasing trend over many weeks of operation. The periods when the number of bunches exceeded 1000 (2015) and 2000 (2016) are indicated in the upper part of the figure.


UFO-INDUCED LOSSES IN THE ARCS AND DISPERSION SUPPRESSORS

In Long Shutdown 1 (LS1, 2013–2014), more than 700 BLMs were relocated from MQs to MB-MB interconnects to improve the detection of UFO-induced losses in MBs [1, 2, 3]. The relocation significantly reduced the variation of the BLM response versus loss position, which is fundamental for setting BLM thresholds without limiting availability. Despite the much better spatial BLM coverage in Run 2, unnecessary dumps can still not be fully avoided if a quench-preventing BLM threshold strategy is deployed. This can mainly be attributed to the remaining variation of the BLM response depending on the UFO position inside MBs. If losses occur at the upstream end of a MB, the signal per proton lost in the closest downstream BLM is a factor of 3-4 lower than if losses occur towards the end of the MB, whereas the shower-induced energy density in coils remains approximately the same [3]. If the BLM thresholds are set to prevent UFO-induced quenches for less sensitive loss locations, one can therefore not avoid unnecessary dumps by UFOs which are closer to BLMs.

Change of threshold strategy from 2015 to 2016

In 2015, UFOs gave rise to 3 quenches and 12 BLM dumps without quench in the arcs and dispersion suppressors (all at 6.5 TeV, not counting the dumps and quenches caused by the obstacle in cell 15R9). An analysis of the dumps showed that only in one case a quench was possibly prevented [5, 6]. In most of the other cases the losses were not even cut short since it takes 1-3 turns until beams are extracted once the thresholds have been exceeded [5, 6]. At the same time, thresholds would have needed to be a factor of 2-3 lower in order to avoid the quenches, which would have meant many more unnecessary dumps [5, 6]. The overall impact on availability would have been much worse than the gain due to the prevented quenches. Based on the experience in 2015, a different threshold strategy was adopted in 2016, with the goal to avoid unnecessary dumps while tolerating some quenches [5, 6]. For this purpose, the thresholds at MBs and MQs were increased in the Year-End Technical Stop (YETS) 2015/2016 to be three times higher than in 2015 [7].

UFO trends, dumps and quenches in 2016

The new threshold strategy had a positive impact on availability in 2016. While the number of quenches remained small (3, like in 2015), the number of dumps in the arcs and dispersion suppressors could be kept to a minimum (4 dumps, three of them being in Sector 12 where thresholds had been decreased by a factor of 10 in August 2016 as a temporary measure to reduce the risk of quenches in view of a suspected inter-turn short in MB.A31L2, see next section). An important factor contributing to the improved availability in 2016 was a strong decline of the UFO event rate in the arcs at the end of 2015, which also continued throughout the first months in 2016. Figure 2 illustrates the evolution of the cumulative event rate for all arc cells ≥12 recorded by the UFO Buster application [8]. Unlike in Run 1, the UFO rate did not increase after the YETS and eventually levelled off at 1–2 events/hour at the end of the 2016 proton run. A declining trend has also been observed in 2011 and 2012, however an absolute comparison with Run 1 event rates (see Fig. 1 in Ref. [2]) is not possible because of the BLM relocation in LS1.
UFO position, however it still provides a rough idea of the severity of events. Based on different events in 2015 and 2016, one can establish the critical BLM dose below which a UFO does not have the potential to induce a quench at 6.5 TeV even if it were at the least sensitive location with respect to the BLM. The critical dose is indicated as a vertical line in Fig. 3 (strictly speaking, the ability of a UFO to cause a quench depends also on the duration of the event; here we consider the most limiting cases). As can be seen in the plots, the occurrence of events with high signals follows the general trend, i.e. large events become less frequent if the overall UFO rate decreases. Considering that only a relatively small number of events had the potential to induce a quench and that the occurrence of such events was subject to large statistical fluctuations, it was a coincidence that the number of quenches was exactly the same in 2015 and 2016.

**BLM threshold reduction in Sector 12**

Following the observation of a sudden voltage change in a dipole (MB.A311.2 in Sector 12) during two QPS trips in June and August 2016, it was suspected that an inter-turn short might be present in the magnet [9]. In presence of such a short, it cannot be excluded that the magnet suffers damage if it quenches or if there is a fast power abort in the sector at high current [9]. In order to reduce the probability of UFO-induced quenches and hence the risk of a fast power abort, the BLM thresholds were decreased by a factor of 10 in the entire sector in August 2016 (i.e. the thresholds were a factor of 3.33 lower than in 2015) [10]. The effectiveness of such a reduction in preventing quenches is discussed in the following, at the example of previous quenches at 6.5 TeV.

Figure 4 shows the time profiles of BLM signals measured during UFO events which lead to a magnet quench in 2015 and 2016. In all cases, the BLM with the highest signal amplitude is displayed. Most of the time profiles are asymmetric, with loss durations between 80 and 440 µsec (full width at half maximum). In two of the three events in 2015, BLMs triggered a beam dump and likely shortened the loss duration. The point in time when the signals exceeded the thresholds are indicated as vertical red lines. The losses were still increasing for 1.5-2 turns once thresholds had been surpassed and hence the quenches could still develop, as already pointed out in a previous analysis [5].

The factor by which thresholds would have needed to be lower in order to prevent the quenches differs slightly from event to event. The black vertical lines in Fig. 4 illustrate the point in time when BLMs would have triggered the dump if thresholds would have been the same as in Sector 12 after the reduction in August 2016. These settings would have likely prevented the quenches in four out of the six cases. In one case (first quench in 2016) it is doubtful if the quench would have been avoided since the trigger would have come only 1.5 turns before the loss peak. In the last case (third quench in 2016) the loss event was very fast and it cannot be established with certainty if the quench...
Figure 4: Time profile of BLM signals measured during UFO events which lead to a magnet quench at 6.5 TeV in 2015 (top) and 2016 (bottom). In each case, the BLM with the highest signal is shown, which was in five cases a BLM above the MB-MB interconnect and in one case a MQ BLM. The red vertical lines indicate the points in time when BLM thresholds were exceeded (in two cases only), whereas the black line indicates the time when thresholds would have been exceeded if they would have been the same as in Sector 12 from August 2016.

...could have been avoided at all with the BLM system. This shows that, even with strongly reduced thresholds, a risk remains that UFOs induce a quench.

The impact of the reduced thresholds in Sector 12 on availability was small since only one sector was affected. If a quench-preventing strategy like in Sector 12 would have been employed in all sectors for the full operational year, UFOs would have been a dominating factor for machine availability. An analysis of the events at 6.5 TeV in 2016 indicates that a dump would have occurred on average every 17 h of stable beams. In total, more than 40% of the physics fills in 2016 (71 out of 173) would have been affected if multiple occurrences per fill are only counted once. At the same time, the analysis in the previous paragraph showed that 1–2 of the quenches would have likely not been avoided with these threshold settings. This clearly confirms previous assessments [5, 6] that it is by far more beneficial for availability to avoid unnecessary dumps than to prevent quenches. It is therefore foreseen to retain the present threshold strategy (factor 3 above quench level) also in the following years if there is no necessity to reduce the risk of quenches like in Sector 12.

**BLM threshold reduction at Q10 magnets**

In addition to Sector 12, an adjustment of thresholds was also necessary for Q10 magnets of MQM-type. Like for other IPQs, the detection of quenches in Q10s relies on the differential voltage between two coils in the same cold mass and aperture, i.e. a quench can only be detected if there is an asymmetry in the particle shower-induced energy deposition in the coils [11]. In order to enhance the quench detection level, it was recommended to decrease the QPS thresholds at MQM magnets operated at 1.9 K [11]. Because of relatively high noise levels on the Q10 quench detection cabling, a reduction of Q10 QPS thresholds was however not favourable as this could have lead to a significantly increased number of false trips [11]. As an alternative mitigation measure, the BLM threshold increase introduced in the YETS 2015/2016 was revoked at Q10s (and monitor factors were decreased) to reduce the probability of UFO-induced quenches [12]. The lower thresholds did not give rise to any premature dumps in 2016.

**UFO-INDUCED LOSSES IN THE LONG STRAIGHT SECTIONS**

In contrast to the arcs and dispersion suppressors, the number of UFO-induced dumps in the Long Straight Sections (LSS) doubled from 7 in 2015 to 14 in 2016. The UFOs typically occurred several tens of meters upstream of the monitors which triggered the dump. UFO events are often visible at collimators (TCLs and TCTs) and Roman Pots as these devices represent a local aperture bottleneck and therefore intercept secondary particles from inelastic proton-UFO collisions. About one third of the dumps in 2016 (5 out of 14) were due to UFOs in a single cell (SL1). Another third (5 dumps) was triggered by the Beam Condition Monitors (BCM) of the experiments, compared to...
only one BCM dump in 2015. More details about these
dumps are presented in the following sections. It is not triv-
ial to establish a trend chart of UFO event rates as in Fig. 3
for the Long Straight Sections. Contrary to the arcs, one
cannot rely on the periodicity of cells (and BLMs) to col-
clect sufficient statistics. In addition, UFO-induced losses
need to be detected on top of a steady-state background
(collision losses, collision debris), which can lead to am-
biguous or false triggers in the UFO Boster application. It
can therefore not be determined if a similar decline of the
event rates took place as in the arcs.

**Dumps due to UFOs in cell 5L1**

The spatial BLM patterns measured during five UFO-
induced dumps in IR1 showed similar (although not fully
identical) features, indicating that the UFOs must have
been located in similar locations in cell 5L1 (losses were
on Beam 2). The dumps were triggered by BLMs at the
Q5.L1/Q6.L1 magnets and/or the TCL.5L1, and happened
during different beam modes (adjust, squeeze and stable
beams). In two cases, the dumps occurred during the move-
ment of the TCL.5L1 jaws. It seems likely that in these
two events the loss location was in or around the collimator
(high BLM signal at the TCL.5L1), while in the other cases
the UFOs appeared to be somewhat more downstream (in
or around the Q5). Several of the events exhibited multiple
loss spikes separated by tens or hundreds of msec.
Each spike had a typical UFO-like time structure and duration.
Some of the dumps were only triggered by thresholds in
longer BLM integration times because of the dose accumu-
lated over several spikes.

The number of dumps in cells 5L1/6L1 could be success-
fully mitigated in the second half of the year by increas-
ing the BLM thresholds at insertion region quadrupoles to
the quench level, and by applying threshold corrections for
the TCLs [13]. The thresholds at quadrupoles up to the
Q6 had previously been kept at more conservative settings
to enable further investigations about the protection level
in case of symmetric quenches. In July it was concluded
that BLM thresholds could be raised [11]. After the thresh-
old increase at quadrupoles and TCLs, only one dump oc-
curred in cell 5L1 over a period of 3 months. As an ad-
ditional measure, thresholds were also increased at TCTs
and TotEM Roman Pots since a few UFO dumps had pre-
viously been triggered at these devices [13].

**UFO-induced dumps by BCMs**

In 2016, UFOs gave rise to dumps in all four experi-
ments, once in ATLAS, ALICE and CMS, and twice in
LHCb. The spatial BLM patterns suggest that in all cases
the UFOs were either in the triplet or in the D1, i.e. sev-
eral tens of meters upstream of the Interaction Points (IPs).
In two of the events (ALICE and CMS), the signal-to-
threshold ratio at triplet BLMs reached more than 60%,
while it remained below 10% in the three other cases. Al-
though the latter UFOs were rather small, they were still
well visible up to the matching section on the other side
of the IP. A more detailed assessment is needed to deter-
mine if premature dumps by the BCMs can be avoided in
the future.

**BLM Threshold Changes Not Related to UFOs**

**Adjustments for luminosity, collimation and injection losses in 2016**

Because of the new record luminosities achieved in AT-
LAS and CMS, thresholds at triplet quadrupoles, TCLs and
TCTs had to be increased to avoid premature dumps due to
the hadronic collision debris [7, 14]. The thresholds were
adjusted such that debris-induced signals remained below
warning level (i.e. below 30% of the thresholds). This pol-
icy was adopted to avoid too many messages in the BLM
application which could hide other warnings.

The BLM thresholds had been tuned in 2015 to trig-
ger a dump if the power loss in the collimation system
exceeds 40 kW in steady-state conditions, and or if it ex-
ceeds 200 kW for shorter durations up to 10 sec. Because
of tighter collimator gaps in 2016, the BLM response per
proton lost increased at different collimators (up to a fac-
tor of 6 at the TCTs) and thresholds had to be adjusted to
re-establish the same policy as in 2015 [14].

When changing to BCMS beams in July 2016, high in-
jection losses close or above the BLM dump thresholds
were observed at the TDIs because of satellites kicked on
the TDI jaws. The BLM thresholds at the TDI were al-
ready at the electronic maximum and could therefore not be
raised further. The issue could be mitigated by extend-
ing the injection cleaning to the rising MKI pulse edge and,
in addition, by exchanging the filter at the most limiting BLM
at the TDI in IR2 with a larger one [15], which attenuated
the signal in short integration times.

**Adjustments for the heavy ion run 2016**

In 2015, a machine development study with 6.37 ZTeV
Pb ions was carried out to assess the performance limita-
tion of the collimation system due to fragments leaking to
the neighbouring dispersion suppressor [16]. The losses in
IR7 were deliberately increased until a dipole quench was
provoked in cell 9 [16]. The BLM measurements in the test
showed that the signals at cold magnets at the onset of the
quench were higher than the BLM thresholds used in regu-
lar heavy ion operation (during the test, the thresholds had
been increased) [17]. Based on this observation, the thresh-
olds in cell 9 and 11 were modified for the heavy ion run
in 2016 to avoid premature dumps well below the quench
level [17]. The corrections were only adopted at 6.5 ZTeV
(increase of up to a factor of 5.4), while scaling to 4 ZTeV
indicated only minor bottlenecks and hence no adjustments
were made for the 4 ZTeV run [17].

Complementing the increase in the dispersion suppress-
s, thresholds were decreased at selected collimators in
IR7. The cleaning inefficiency is about a factor of hundred
worse for Pb ions than for protons and therefore the signal-to-threshold ratio would be more than ten times lower at IR7 collimators than at dispersion suppressor magnets if proton thresholds are kept for Pb ions [17]. In order to avoid that, in case of beam instabilities, dumps would be triggered first at cold magnets, the thresholds at secondary collimators were decreased by a factor of 20 and 29, respectively, such that the signal-to-threshold ratio was higher than in the dispersion suppressor [17]. The modified dumping hierarchy worked as intended. In several cases of transverse instabilities, dumps were triggered at secondary collimators, which would have otherwise been triggered at dispersion suppressor magnets.

SUMMARY AND OUTLOOK FOR 2017

In 2016, UFOs were as expected the main cause of premature BLM dumps, and the only cause of beam-induced quenches at top energy. While the number of dumps in the arcs and dispersion suppressors was significantly less than in 2015 thanks to a new threshold strategy, more dumps were observed in the long straight sections. By applying several threshold adjustments at TCLs, TCTs, Roman Pots and IPQs, the impact of UFOs in the straight sections could however be mitigated in the second half of the year. It is to be determined if similar adjustments are possible for the BCMs of the experiments, which accounted for one fourth of all UFO dumps in 2016. In general, the impact of UFOs on availability improved with respect to 2015, considering that the number of quenches did not increase (3 in both years) and the total number of dumps decreased from 19 to 18, despite many more hours accumulated in stable beams.

The main reason that only 3 quenches occurred in 2016 was a significant decline in the UFO event rate in the arcs at the end of 2015 and throughout 2016. In particular, the activities carried out in the YETS 2015/16 had no detrimental effect on the UFO rate. It can however not be excluded that some degradation takes place in the EYEYETS 2016/2017 as the event rate at the end of 2016 was considerably lower than at the end of 2015. In addition, some deconditioning can be expected for Sector 12 because of the warm-up needed for the dipole exchange in cell 31L2. However, even with a higher UFO rate in Sector 12, UFOs are not expected to be a major limitation for availability in 2017, although some quenches might be unavoidable since thresholds in Sector 12 will be reverted to their initial 2016 settings.

Only minor threshold changes are foreseen to be carried out for the start-up in 2017. They include a revision of old threshold models for dipole monitors in the dispersion suppressors, and a modification of master tables for redundant monitors at IPQs which are presently set to the electronic limit. As in the previous years, several adjustments are expected to be carried out throughout operation.

REFERENCES


Abstract

During 2016 operation, all beam dump requests were properly executed by the LBDS. Nevertheless, many redundant failures in LBDS subsystems occurred, leading to LHC downtime. In this talk, some LBDS operational statistics for 2015 and 2016 are compared. Details are given on the main recurrent failures of LBDS and the foreseen corrective actions. The various Reliability Runs and Dry Runs planned for the EYETS are explained, as well as the LBDS needs for cold-checkout and recommissioning at start-up.

LBDS OPERATION STATISTICS

We studied and compared data extracted from the Logging Database, to provide statistics about the usage of LBDS during 2015 and 2016.

Number of dumps performed at various energies

We analysed the number of LBDS triggers for LOCAL test pulses (at any energy), and REMOTE pulses at injection, flat-top and ramp energies.

Figure 1 shows the profile of a number of dumps over the year. We see the pulses in LOCAL (black) that show the various test performed before operation start, and during every technical stop, to validate and improve HV generator performance. We performed many more tests in LOCAL in 2015 after LS1 than in 2016. It should be noted that not all generators are ON during these LOCAL tests, sometimes only one generator was pulsed for tests, and this is not reflected in these statistics.

Table 1 shows the total number of triggers for B1 and B2 in various operational conditions. We see that slightly less dumps at flat-top occurred in 2016 wrt 2015, probably because the average flat-top length increased. There were also fewer dumps during ramp in 2016 than in 2015.

Number of days spent at various energies

We also analysed the time spent at various energies during the year, LOCAL tests and REMOTE operation mixed.

Figure 2 shows the profile of time spent at various energies over the years 2015 and 2016. We see that in 2015, about the same time was spent at injection and flat-top during tests before April, then more time spent at injection during operation. In 2016, we clearly see more time spent at flat-top in operation starting around April.

Table 2 shows the total number of days spent at various energies for 2015 and 2016. We see that about 30% more time was spent at flat-top in 2016 vs 2015, and about 50% less time at injection.
Table 2: Days spent at various energies

<table>
<thead>
<tr>
<th></th>
<th>B1 Total 2015</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5 TeV</td>
<td>100.8</td>
<td>129.9</td>
</tr>
<tr>
<td>450 GeV</td>
<td>123.2</td>
<td>60.1</td>
</tr>
<tr>
<td>STANDBY</td>
<td>75.7</td>
<td>67.2</td>
</tr>
<tr>
<td>B2 Total</td>
<td>2015</td>
<td>2016</td>
</tr>
<tr>
<td>6.5 TeV</td>
<td>101.1</td>
<td>142.8</td>
</tr>
<tr>
<td>450 GeV</td>
<td>113</td>
<td>56.9</td>
</tr>
<tr>
<td>STANDBY</td>
<td>73.9</td>
<td>64.6</td>
</tr>
</tbody>
</table>

This means much higher constraints on the system in 2016 wrt 2015, as the voltage in the HV generator is almost proportional to the energy, and the higher the voltage, the bigger the risk of self-trigger or damage in the HV generator.

**LBDS FAULTS DOWNTIME**

Based on the Accelerator Fault Tracking (AFT) database, we analysed the LBDS faults responsible for machine downtime, and we performed statistics on the LBDS subsystems that were responsible for the longer downtime.

In 2015, the main contributor of total LBDS downtime is clearly the extraction kicker HV generator (MKDG) with about 61h of cumulated downtime, followed by the horizontal dilution kicker HV generator (MKBHG) with about 34h of cumulated downtime (Figure 3).

In 2016, the main contributor of total LBDS downtime is clearly the horizontal dilution kicker HV generator (MKBHG) with about 44h of cumulated downtime, followed by the State Control and Surveillance System (SCSS), with about 23h of cumulated downtime, and the High Voltage Power Supplies (HVPS) with about 8h of cumulated downtime (Figure 4).

Table 3 shows the total number of LHC downtime due to LBDS in 2015 and 2016.

We see that there was about 15% less total LHC downtime due to LBDS in 2016 wrt 2015, even with a much higher number of constraints on the system, as explained in the above section 'Number of days spent at various energies'.

Only one asynchronous dump occurred in 2015 due to a self-trigger of MKD, but none in 2016.

Table 3: Total LHC downtime due to LBDS faults

<table>
<thead>
<tr>
<th>Year</th>
<th>Downtime</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>106 h</td>
</tr>
<tr>
<td>2016</td>
<td>91.6 h</td>
</tr>
</tbody>
</table>

**MAIN LBDS FAULTS IN OPERATION**

This chapter gives more information on the main failures responsible for the downtime of LHC in 2015 and 2016.

MKDG self-trigger (Asynchronous dump)

This problem occurred once in 2015 (04.06.2015), but never in 2016.

One HV switch in an extraction kicker HV generator (MKD.CB2) did a self-trigger, yielding to an asynchronous beam dump properly executed.

Only four bunches were present in the machine at 6.5 TeV, and by chance, no beam was present on the rising edge of extraction kicker currents, so this asynchronous dump was clean.

The intervention took 13h, to replace the switch and revalidate the HV generator.

No MKD self-trigger occurred in 2016, thanks to the numerous spark surveillance measurements performed during TSs and the various measures taken from LS1, which seem to have paid off!

We plan to implement a continuous surveillance of the sparking activity in the HV generators during LS2, in order to be able to detect any degradation before a self-trigger occurs.
**MKBHG self-trigger (Synchronous Dump)**

Five events occurred in 2015, only two in 2016 (+one generator exchanged preventively due to high sparking activity).

The HV switch in a horizontal dilution kicker HV generator did a self-trigger, discharging its capacitor into a dilution magnet.

The Beam Energy Tracking System (BETS) detected the capacitor discharge and requested a synchronous beam dump after about 1ms.

The other MKB HV generators can be triggered in phase opposition, with the remaining current in the self-triggered magnet, resulting in a total horizontal dilution lower than the expected 75% (one kicker lost out of four). Example: Loss of 1 Gen + 0.2 Gen (remaining current) in phase opposition, yields ~70% total horizontal dilution (this is not the worst case, see further below).

The longest intervention took 17h, to exchange the HV generator and revalidate it.

MKBH faults in 2015 were spread over the year, but in 2016 both faults occurred within a month so it was more visible.

**MKBHG self-trigger (Retrigger coupling)**

This event never occurred in operation, but only during tests in LOCAL without beam, in 2016.

During a reliability Run of MKBH at 7TeV, one MKBH did a self-trigger and the two generators next to it were triggered a few microseconds later. This yielded up to three MKBH being self-triggered!

This event was unexpected, as by design the MKBH generators do not inject energy in the retrigger line, to avoid triggering the MKD asynchronously.

As the remaining MKBH generator can be triggered in phase opposition, a possible reduction of total horizontal dilution down to 10% is possible in such a case.

From first analyses in laboratory and tests in the tunnel, it appears that the coupling between MKBH generators originates from a grounding problem. A first workaround was tested successfully (insulation of retrigger boxes), to be further validated. This problem should be fixed during the EYETS.

**Strategy for MKB retrigger - Impact on TDE**

Following the event of multiple self-triggering of MKBH HV generators, and the fact that remaining MKBs can be in phase opposition with the self-triggered ones, we launched studies to analyse the impact on the dump target (TDE).

We compared various options of retriggering of MKBs in case of self-triggering, for instance:

- Increase MKB damping factor to reduce remaining current in phase opposition.
- Studies are still ongoing to define the strategy for MKB retriggering, with the aim of implementing a better system during LS2, if needed.

**TSU failure**

This event never occurred in 2015, only once in 2016. On 01.07.2016, one TSU failed and caused a synchronous beam dump, properly executed by the redundant TSU, which successfully detected the failure.

The intervention took 7h, to exchange the faulty TSU card and revalidate the Trigger Synchronisation and Distribution System (TSDS) from CCC, by testing all dump request sources of the TSUs (BRF, BETS, SCSS, BLM and Inject&Dump).

The investigations in laboratory on the faulty TSU card showed a power supply shortcut caused by the FPGA. In addition, we measured a high level of noise on the FPGA power supply, which could explain the failure of the card.

We will address this problem of TSU power supply during the EYETS.

**Other failures**

We recorded other recurrent failures that we addressed in a manner to improve LBDS availability.

**State Control and Surveillance System (SCSS):**

LBDS suffered many failures of the ASi-bus power supply in 2016. We sent the power supplies to Siemens for investigation. We will renovate the LBDS ASi-bus architecture during the YETS to prevent such a failure in the future. We will also implement a surveillance of the UPS supply parameters, to make sure that an early ageing effect of the ASI power supply is not coming from the electrical distribution side.

The longest intervention time was 4h30, to exchange a power supply.

**High Voltage Power Supply (HVPS):**

One principal (35kV) and one compensation (350V) power supplies failed in 2015, two compensation (350V) power supplies in 2016. The failure rate is quite high for these components, and we are investigating this problem with the manufacturer. We suspect grounding problems.

The longest intervention time was 3h, to exchange a power supply and revalidate the system.

**Low Voltage Power Supply (LVPS):**

No event occurred in 2015, but two LVPS (PK55) failed in 2016. The longest downtime was 3h, to exchange the power supply and revalidate.

**Intervention Strategy in case of LBDS fault**

General remarks regarding LBDS intervention strategy, given that LBDS is a part of Machine Protection:
All internal failures are fatal;
We do not run in degraded mode (i.e. we do not
mask faults / adjust thresholds ...)
Each faulty element is repaired / replaced;
Full recommissioning is performed after each
repair, following procedures (these might be
improved to reduce intervention time, to be
discussed with MPP).

This approach guarantees that the system returns to an
‘As Good As New’ state after every fault / intervention.
By bad luck, many major failures occurred during nights
and weekends, yielding an increased average intervention
time.

UPGRADES PLANNED DURING EYETS
This chapter describes the upgrades planned on LBDS
during the EYETS16-17.

Closing of MKBH HV generators
We know that dust in the generator or on the GTO stack
can be an explanation to the sparking activity, yielding self-
triggering of the generator. To prevent dust entering the
generator, we will completely close the top part of MKBH
HV generators, and will add a separation between the GTO
stack and the Power Trigger Unit (PTU) on the bottom part.

Addition of resistors to GTO gate-cathode on
MKB
To reduce the sensitivity of GTOs to external noise or
sparking inside the generator, we will add resistors on all
outputs of trigger transformer, between the gate and
cathode of each GTO. We already performed this
modification on all MKD HV generators during YETS
2015/16.

Deployment of IPOC system on MKBH HV
generators
Currently, we only capture the magnet current of dilution
kickers for each trigger of LBDS. We want to add the
acquisition of Power Trigger Modules (PTMs) and switch
current, to improve diagnosis in case of self-triggering. We
installed such a system on MKD HV generators during
LS1.
We plan to add new IPOC system to the eight MKBH
during the EYETS16-17 and as a second stage on the ten
MKBV during YETS17-19.

Consolidation of MKB retriger line
After the event seen during testing in LOCAL at 7TeV,
where three MKBH generators self-triggered, we want to
improve the decoupling between MKBH generators
through the retriger line.
We will insulate the retriger boxes from the top plate of
generators (showing huge voltage jumps wrt. ground when
pulsing) and add nanocrystalline cores around retriger
line cables to absorb common mode current.

Consolidation of the TSU card
Following the failure of a TSU card in 2016 and the
identification of a new asynchronous trigger source (glitch
on BRF signal), we will perform corrections on the power
supply circuit, and fix issues in the FPGA gateware of the
TSU cards [3].

New CIBDS card deployed by TE/MPE
Following the identification of various problems in the
architecture of CIBDS cards in operation, such as linked
logic between BIS loop A/B detectors, TE/MPE will
deploy a new version of the hardware and gateware [1].

New value of CIBDS trigger delay
After the deployment of CIBDS v5, providing the
separation of logic between BIS loop A/B, cases where the
asynchronous trigger inserted on the LBDS retriger line
could occur before the synchronous trigger, yielding
asynchronous beam dumps, have been identified.
To eliminate this source of asynchronous dumps, we will
increase the value of the CIBDS re-trigger delay from
270us to 320us [2].

Renovation of ASi bus architecture
To avoid in the future the recurrent problems
encountered with the LBDS ASi bus power supplies during
2016 operation, we replaced all ASi bus power supplies
and we will change the interface between the ASi
controller and the LBDS master PLC.

Consolidation of the variable BAGK
implementation.
After TIDV problems, the intensity in SPS was limited
to a maximum of 144 nominal bunches. As the Abort Gap
Keeper (AGK) generated at LBDS is fixed at a length of
288 bunches operation, the last injection of 144 bunches
was blocked.
During TS1 in 2016, we implemented a first solution to
this problem. We regenerated the AGK signal at MKIs
based on the rising edge of the AGK signal coming from
LBDS, using CTRV cards [5].
During the EYETS, we will consolidate this
implementation by replacing the analogical optical
transmission from LBDS to MKI with digital optical
transmission, using BE/RF pulse transmitters and
receivers. Also, fine delays will replace CTRV cards, to
lower the jitter on the regenerated AGK signal. The Fast
Inhibit Boards (FIB) will implement a continuous check of
the period and width of the regenerated AGK signal, and
block injection through the BIS in case any problem is
detected. All AGK regeneration and check parameters will
be stored in the LSA.
We have to provide a procedure for the update and
validation of the AGK length.
We implemented all these changes to limit the number
of cases yielding the injection of the beam in the abort gap,
even if having a beam in the abort gap and dumping it at
injection is an accepted failure mode.
General maintenance on HV generators

During EYETS, we will also perform the usual maintenance tasks on all LBDS HV generators. We clean all generators to remove the dust that could have entered the generator during operation. HV reliability Runs and sparking tests allow to detect the weakest HV switches and to replace them.

RELIABILITY RUN AT 7 TEV OVER X-MAS BREAK

To re-assess the performance of LBDS for operation at 7 TeV and evaluate the available safety margin, we want to perform a minimum of 2 weeks of reliability Runs at 7 TeV over the two weeks of Christmas break.

The programme foreseen is to simulate cycles of 24h:
- Injection energy: 3h;
- Ramp up: 1h;
- Flat-top at 7 TeV: 20h.

This will result in more than 300 h at 7 TeV.

The LBDS experts will monitor and control the system remotely. We will also implement in the PLC a logic to detect a self-trigger and automatically stop the HV power supplies.

As we decided not to exceed 7 TeV during the Christmas break, we cannot evaluate the safety margin available for a continuous operation at 7 TeV. We will decide whether we continue the reliability Run in January 2017 to increase the energy to 7.1 TeV.

We foresee to have a full upgrade programme of HV switches of MKD and MKBH HV generators and power trigger modules during LS2.

RE-COMMISSIONING STRATEGY AT THE END OF EYETS

As described previously, we foresee many upgrades on LBDS during EYETS. We therefore request a full revalidation of the TSDS and all the HV Generators.

First, we need to perform a dry Run with LOCAL BIS loops [4]. We will execute cycles with many pulses at injection energy to revalidate the upgraded TSU and CIBDS cards, and with long flat-tops to validate the LBDS pulse generators under operational conditions. We will profit from this dry Run to implement and validate a new XPOC analysis module, which will check that the TSU and CIBDS pulses on the LBDS re-trigger lines are present and at the correct time.

We will then perform the standard LBDS machine protection procedures during the Cold Check-Out period. No new functionalities need to be tested, but we have to plan sufficient time to perform these tests before the injection of the first beam in LHC.

Eventually we will perform the standard LBDS machine protection procedures with beam, before the injection of a first unsafe beam in LHC. In particular, we need time to validate the new variable AGK length mechanism and resynchronise the AGK with beam. We still need to provide the detailed procedure for this test.

SUMMARY

During 2016 operation, LBDS properly executed all dump requests. No asynchronous beam dump occurred.

The operation conditions in 2016 were more demanding for LBDS than in 2015, due to much more time spent at 6.5TeV, nevertheless we recorded a lower LBDS downtime in 2016 than in 2015.

We noted too many MKBH self-triggers, and we will address this problem during EYETS.

We also discovered a problem of MKBH retrigger line coupling, yielding simultaneous self-triggering of three MKBH HV generators during tests at 7 TeV, and we will solve this problem during EYETS.

We plan to perform a reliability Run at 7 TeV during the two weeks of Christmas break to re-assess LBDS availability at 6.5 TeV operation, and re-evaluate its ability to operate at 7 TeV.

We request a reliability Run with local BIS loops needed to revalidate the system at the end of the EYETS, after upgrades to the triggering system and HV generators.

We will perform the standard machine protection procedures during cold checkout and recommissioning with beam at the end of the EYETS.

REFERENCES

QPS PERFORMANCE DURING THE 2016 LHC RUN

J. Steckert, R. Denz, CERN, Geneva, Switzerland

Abstract

The LHC quench protection system consisting of more than 13000 quench detectors and more than 6000 actuators (quench heater power supplies and energy extraction systems) reached an impact availability of 99.49% during the 2016 proton Run. This is an improvement by 80% compared to the 2015 figures. Changes to the systems in the YETS 2015/16 comprise the introduction of the new radiation tolerant 600A quench detectors in the RR-areas as well as a firmware update of the crate controllers of the nQPS system throughout the LHC tunnel. Preventive maintenance had been performed on all 13kA energy extraction systems as well as on selected 600A energy extraction systems. The 2016 performance is compared system by system to the 2015 figures. Radiation to electronics effects, a big issue in 2015, has not lead to a false trigger of a quench detector in 2016 although two crate controllers might have been affected during the proton-ion run.

QPS OVERVIEW

The quench protection system (QPS) of LHC’s superconducting magnet circuits is located in the LHC tunnel and adjacent underground areas. As a large distributed system, it consists of approximately 29000 circuit boards equipped with active components. This number accounts only the quench detection part of the system, and excludes the energy extraction systems which itself consist of several thousand elements. Once a quench is detected, dedicated hardware interlocks transmit the information to other systems as power converters and the beam interlock system (BIS). In total 14000 circuit boards capable of activating these interlocks are installed in the QPS system. Since each of these interlocks can trigger a beam dump via the BIS, the system has to be extremely reliable and available. The table below shows the systems’ main elements and their quantity installed in the LHC. [1]

Table 1: Main interlocking elements of the LHC QPS

<table>
<thead>
<tr>
<th># installed</th>
<th>System</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>EE13kA</td>
<td>Energy extraction 13kA circuits</td>
</tr>
<tr>
<td>202</td>
<td>EE600</td>
<td>Energy extraction 600A circuits</td>
</tr>
<tr>
<td>6084</td>
<td>DQHDS</td>
<td>Quench heater power supplies</td>
</tr>
<tr>
<td>1624</td>
<td>iQPS</td>
<td>QDS base layer for MB and MQ circuits</td>
</tr>
<tr>
<td>4032</td>
<td>DQQDL</td>
<td>Quench detector</td>
</tr>
<tr>
<td>436</td>
<td>nQPS</td>
<td>QDS second layer for MB and MQ</td>
</tr>
<tr>
<td>1632</td>
<td>DQQDS</td>
<td>Symmetric quench detector</td>
</tr>
</tbody>
</table>

ACTIVITIES DURING YETS 2015/16

During the year end technical stop of LHC (YETS) of winter 2015/2016 several maintenance activities had been conducted and some systems had been upgraded:

- Replacement of 600A quench detectors type DQQDG with radiation tolerant version nDQQDG in RR13/17, RR53/57 and RR73/77
- Upgrade of RU-circuit QDS to nDQQDG quench detectors and installation of a DCCT for current measurement to replace the noisy hall probe.
- Firmware updates for nQPS systems on 436 crates in all sectors enhancing stability of local communication and enhancing intelligent fault management.
- Conducted annual maintenance of 13kA energy extraction systems
- Selective maintenance on 600A energy extraction systems which showed signs of degradation

SYSTEM PERFORMANCE

In the following sections the system performance throughout the year 2016 will be shown and compared to the systems’ performance of 2015. The analysis is based on data registered in LHC’s accelerator fault tracking system (AFT).

Performance of 2016 pp Run

Figure 1 shows the LHC impact fault time and the impact availability of the QPS during the 2016 pp run.
The average availability of the system during the proton run was 99.49% which is well above the target availability for the QPS which had been set to 98%. Even in May 2016 where some technical problems with the RU protection systems lead to an increased amount of impact fault time the availability was above 98%. In terms of impact fault time the system caused in average 3.9h per month.

Fault time evolution 2015 to 2016

As it can be seen the year 2016 shows a significant improvement of the system availability over the year 2015. A main contributor to this improvement was the exchange of some radiation sensitive circuits boards during TS#2 2015 which already reflects in increased availability of the months September to October 2015.

Fault analysis for the year 2016

As it is clearly visible, most faults are caused by the 600A QDS. This is clearly an effect of the introduction of the rad-tol detector boards on which we gained operational experience during 2016. The second most faults (9) had been created by the nQPS system where a loss of internal communication lead to difficulties re-starting the system after a fast power abort.

If we look at the amount of raw fault time caused by sub-system, the result changes. As shown in Figure 5, the nQPS system caused the most raw fault time which accumulates to 24.2 h while the QDS600, despite the number of faults, is second. The EE600 system however caused 3.8h caused by only two events and is hence on the third place. This shows that the number of errors is not necessarily reflected
in total fault time. In the case of the nQPS, the long fault time can be explained by a new error mode which was relatively difficult to analyse during its first few occurrences.

**Piquet interventions in 2016**

Compared to the year 2015 the number of piquet interventions during 2016 were reduced by 80%. As shown in Figure 6 the number of remote interventions was reduced over-proportionally due to a modification in the treatment of a binary signal blocking the restart of a sector in 2015.

![Figure 6 Number of piquet interventions 2015 vs. 2016](image)

**DETAILED VIEW ON SEVERAL ASPECTS OF SYSTEM PERFORMANCE**

This section will describe several topics of system performance in more detail.

**Details of 600A quench detection systems**

Due to their complex algorithm, the 600A quench detection systems had been traditionally prone to false triggers often created by external non-quench events. With the upgrade of the systems located in RR13/17, RR53/57 and RR73/77 we introduced a completely new and technically different version of this type of quench detectors [2]. The new design allows to change several operational parameters remotely. With no operational experience with these detectors some filter parameters had been set too conservatively which lead to unnecessary triggers especially during the precycle. With improved filter settings events like the zero-volt crossing of the 600A power converters which leads to a perturbation in voltage and current were mitigated. In the end we identified only two circuits which had been responsible for 46 out of 52 triggers related to zero volt crossings. Another challenge was the parametrization and the cabling of the new 600A quench detectors for the undulator circuits in point 4. Due to the installation of DCCTs for current measurements the cabling layout changed. After two interventions these issues had been solved. Overall the largest source of 600A circuit fast power aborts had been the global interlock which shuts of the power converters which leads to a trigger of the quench detection.

**Radiation to electronics**

In 2016 no radiation-to-electronics (R2E) induced trigger of the quench detection system had been observed. This shows that the upgrade of the 600A quench detectors to a radiation-tolerant version was successful. Furthermore we could not identify any unmitigated R2E-related malfunction during the 2016 pp Run. However two events during the 2016 ion-proton Run which lead to malfunction of crate controllers in B8L8 and B9R1 are suspected to be related to R2E effects.

**CONCLUSIONS**

After numerous upgrades in 2009/10 and in Long Shutdown 1 as well as the YETS 2015/2016 the system had reached its nominal configuration in 2016. This is reflected by the excellent R2E performance which fully proves the effectiveness of the implemented measures. As consequence none of the quench detectors suffered from malfunction due to radiation. The system availability improved considerably in 2016 which is reflected in the reduction of system raw fault time of 80% compared to 2015. One important factor contributing to this improvement is the absence of faults provoked by the massive upgrade campaigns of LS1. These faults, mostly cables & connectors as well as cards which were not properly inserted, had been corrected during 2015. Most of the faults of the new 600A quench detectors were related to installation and configuration of the new system. As consequence, no major changes to the system are foreseen up to LS2.

**REFERENCES**


PERFORMANCE OF THE COLLIMATION SYSTEM DURING 2016 - HARDWARE PERSPECTIVE


Abstract
The commissioning experience of the LHC collimation system in 2016 is reviewed together with the hardware performance. Despite of the limited changes in hardware and software, the time spent in commissioning, set-up and qualification activities has been reduced thanks to system upgrades like the deployment of 100 Hz BLM logging for collimator alignment and detailed commissioning of embedded BPMs. In particular, the reliability and stability shown by embedded BPMs allowed to systematically align TCT collimators and accommodate beam manipulations at the IPs; furthermore, following the gained experience, a proposal of SIS interlock based on the readout of embedded BPMs is made. The LHC collimation system experienced a limited number of faults, which is reported. Hardware changes foreseen for EYETS 2016, mainly dedicated to MD activities, are outlined.

INTRODUCTION
2016 was an unprecedented year of physics production for LHC, with half of machine time spent in stable beams [1], peak luminosity being pushed beyond the nominal value of 10^{34} cm^{-2} s^{-1}, and total integrated luminosity reaching ~40 nb^{-1}, surpassing by far the original target of 25 nb^{-1}. The quality of the performance of each LHC system was at the basis of these achievements [2]. Among them, the collimation system performed reliably and accommodated the numerous machine configurations deployed over the year.

The LHC collimation system saw limited hardware and software updates during the Year End Technical Stop of 2015 (YETS 2015), but these were relevant for speeding up commissioning and set-up activities in 2016. Reliability and reproducibility were at the heart of the system performance throughout the year.

HARDWARE CHANGES DURING YETS 2015
The collimation system saw limited hardware changes during YETS 2015, mainly dedicated to the implementation of the “5th motor axis” functionality [3]. This functionality allows to move transversely the whole collimator (including the tank) in the non-cleaning plane by ±10 mm to offer a fresh surface to beam cleaning after a local damage of the jaw.

The necessary hardware changes were applied to the metallic collimators in cell 4 in the high luminosity insertion regions (IRs), i.e. to the tertiary collimators (TCTs) in IR1 and IR5 and the physics debris absorbers nearby (TCL4). The LHC areas where the involved collimators are installed are particularly complicated for intervention [4] (see Fig. 1); in spite of many small problems found during the intervention, it was possible to fully recover the functionality at the horizontal collimators, whereas only half-movement (more precisely, the one inwards) was recovered at the vertical collimators. The intervention was carried out with no impact on machine availability.

It should be noted that nowadays the necessity of the 5th axis functionality is less stringent, thanks to the optimised phase advance between extraction kickers (MKDs) and closest TCT collimators [5].

SYSTEM AVAILABILITY
The operation of the LHC collimation system in 2016 was affected by twelve faults as from the post mortem (PM) database data browser [6]. Half of them occurred at injection energy; two occurred during ramp; one took place at flat top (FT), and three in stable beams (SB). These statistics do not cover beams dumped by BLMs at collimators following UFO events [7]. The breakdown of fault reasons are reported in Tab. 1, sorted by occurrence.

Faults taking place during manual operations mainly refer to machine development (MD) activities and optics measurements, hence when collimators were controlled not by functions coded in the LHC control system. Wrong collimator set-up refers to incorrect or obsolete values in functions of the LHC control system; in particular, faults in 2016 involved only limits to jaw movements left in the control system immediately after the fault of the power converters of the Proton Synchrotron (PS) occurred on the 21st May [8] and after the Van der Meer scans. These functions set tolerances between the expected position of the jaw corners and the actual readout from the Linear Variable Differential Transformer (LVDT) sensors [9]; when tolerances are exceeded, a preventive beam dump is triggered.

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Table 1: Breakdown of causes of faults of the LHC collimation system: number of occurrence, main cause and active beam process when the fault took place. Since half of the faults took place at injection, only those happening during other beam processes are reported in the third column.

<table>
<thead>
<tr>
<th>#</th>
<th>Cause</th>
<th>Beam Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>manual operations</td>
<td>1 at FT</td>
</tr>
<tr>
<td>3</td>
<td>related to IR3 flooding</td>
<td>2 in SB</td>
</tr>
<tr>
<td>2</td>
<td>wrong collimator set-up</td>
<td>1 in ramp, 1 in SB</td>
</tr>
<tr>
<td>2</td>
<td>temperature sensors</td>
<td>1 in ramp</td>
</tr>
</tbody>
</table>

Figure 2: Progress in the time required to align the full collimation system.

Three beam dumps were triggered by collimators in IR3, i.e. fills 5068, 5075 [10] and 5194 [11]. These were the consequence of the water flooding in IR3 that took place on 21st June 2016 [12], which involved the false floor of U133. During flooding, cables carrying the LVDT signals were in contact with the water; this caused a slow deterioration of the cables, with consequent changes in the inductance of the cables and drifting of signals.

HARDWARE PERFORMANCE

Commissioning

Several changes were done to the collimation software [13]. In particular, changes to several application programming interfaces (APIs) were incorporated in the new release of the Java applications. Moreover, new devices from the ATLAS Forward Proton (AFP) [14] experiment were included in the collimation LSA [15] table and in the Java application. Finally, the names of the crystal goniometer were updated in both the Java application and in the FESA [16] class.

The LHCCollAlign FESA class was updated to handle 100 Hz BLM data, a data stream set-up on purpose. Therefore, it was possible to increase the collimator trigger rate and hence the alignment feedback loop to 50 Hz, considerably shortening the alignment time. In fact, it was possible to align the entire collimation system in 1h 45min, allowing the continuation of the trend in shortening alignment time (see Fig. 3). This was also possible thanks to the full deployment of Beam Position Monitors (BPMs) for collimator alignment. It should be noted that in 2016 the full BLM alignment of all TCTs was anyway performed at injection and flat top, to get the measured beam sizes; the required time is included in the blue bar of the alignment time bar chart. It is planned to update the alignment software with an automated procedure for angular alignments; moreover, a new FESA class is under development to handle the coordination of the alignment of many collimators in parallel, presently handled by the Java application.

Angular scans were performed at selected secondary collimators (see Fig. 3). These revealed the necessity to introduce in future large jaw angles (i.e. in the order of few hundreds of microrad) in order to compensate the apparent angle between the beam closed orbit and the collimator jaw, introduced by e.g. tank misalignments. These tilt angles play a fundamental role in restoring the correct hierarchy between collimator families when the retraction between primary and secondary collimators is pushed down to 1 σ [17].

An exhaustive commissioning of BPMs at collimators was carried out before the alignment campaigns; therefore, it was possible to deploy the automated BPM beam-based alignment of all the tertiary collimators (TCTs) in parallel as much as possible. The commissioning included extensive collimator scans [18] for determining the coefficients for correcting non-linearities in BPM signals. The scans were carried out recording the BPM readout while varying both jaw opening and absolute positions (jaw offset). BPMs were available since the very beginning of the initial commissioning with beam, being up and running for the whole time, save for a couple of instances when the FESA class was down. No issues were reported as of Technical Stop (TS) 1.

The alignment data at TCTs were used to build time-dependent functions of the collimator centres [19]. These have been obtained scaling the time profile of the closed orbit at each TCT as predicted by MADX to the position of the beam at the beginning and end of each beam process, measured during the alignment campaigns. In particular, BPM beam-based alignment data have been extensively used to generate the functions. BPM readouts during fills preceding or following the alignment have been used to cross-check
Figure 4: Centre function of TCTPH.4L5.B1 for the ramp and squeeze beam process (yellow dotted line) superimposed to BPM readouts during some fills with different intensities.

Figure 5: Upper frame: orbit offset with respect to the TCT centre during stable beams; the average between upstream and downstream BPM readouts is shown. Lower frame: estimated number of beam dumps for a given threshold in orbit offset.

the generated functions (see Fig. 4). A function for each TCT in every beam process used in 2016 was generated.

Proposal of SIS Interlock Based on TCT BPM Readouts

The orbit as measured by BPMs at TCTs and at the TCSP collimators in IR6 were monitored throughout the year. In total, 155 fills for proton-proton operation in 2016 in different machine configurations were analysed [20], computing the excursions with respect to the collimator centres. Given the good orbit stability (see Fig. 5), a SIS interlock based on the maximum allowed excursion at the TCT has been proposed. Computing the number of dumps that a given threshold would have triggered in the analysed fills (see Fig. 5), a threshold of 600 μm is proposed.

VALIDATION

Loss maps allow to validate the set-up of the collimators for selected machine configurations. During the period of the initial commissioning with beam, they are measured once final collimator functions have been generated and imported into the LHC control system. Qualification loss maps are systematically performed also after relevant hardware interventions or long periods without beam like a technical stop.

Given the complexity of the LHC hyper-cycle with many beam processes in 2016, several machine configurations had to be qualified, implying to perform and analyse a large number of loss maps. Nevertheless, there was a limited impact in terms of number of fills required, thanks to the development of the new FESA class for off-momentum loss maps [21]. The new class include the handling of an automatic feedback to the RF trim, which is cut in case losses exceed pre-defined values, in advance before the dump is triggered. Some MD time [22] was specifically allocated for the final assessment of using the new class for loss maps.

Symplifying the LHC hypercycle would imply less loss maps to be performed.

HARDWARE CHANGES DURING YETS 2016

Hardware changes foreseen for the Extended Year End Technical Stop 2016 (EYETS 2016) are mainly aimed at MD activities. In particular, new hardware will be installed, namely:

- a low-impedance secondary collimator, i.e. TCS.PM.D4R7.B2. This collimator is equipped with jaws in MoGr, characterised by a higher conductance than graphite. Moreover, the surface of the jaw is coated with three different materials in separated stripes, i.e. Mo, MoGr and a ceramic material, so that, following impedance measurements, the choice of the optimum coating can be done. Tests of this collimator with beam are extremely important, for starting the procurement of all the secondary collimators to be exchanged in view of the High Luminosity LHC (HL-LHC) project [23,24]. The collimator is also equipped with upstream and downstream BPMs embedded in the jaws and a third BPM in the non-cleaning (horizontal, for this specific collimator) plane, which is at a fixed aperture;

- two collimators with wire embedded in the tungsten jaws for long-range beam-beam effects compensation studies, namely TCL.4L5.B2 and TCTPH.4R5.B2. Moreover, these collimators are equipped with BPMs;
a TCP collimator with a consolidated design, i.e. with BPM buttons. The concerned collimator is TCP.C6L7.B1;

- two crystal goniometers in beam 2.

All the installation activities will be carried out in close collaboration with EN/STI and EN/MMI.

CONCLUSIONS

The performance of the collimation system in 2016 has been reviewed. During YETS 2015, the system underwent limited hardware and software upgrades; nevertheless, these have proved to be relevant for speeding up commissioning and set-up activities, e.g. RF trim for off-momentum loss maps, the deployment of 100 Hz BLM data for BLM beam-base alignment, and using BPM data at TCTs.

Over the entire 2016, reliability and reproducibility have been at the heart of system performance. In particular, the orbit stability at the TCT collimators allows to make a proposal of SIS interlock on drifts of the closed orbit.

During YETS 2016 new hardware will be installed, meant in particular for MD activities, especially in an HL-LHC perspective.

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EXPERIMENTS - EXPERIENCE AND FUTURE

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Abstract

The talk discusses the input from the experiments that is relevant to define next year’s program. It covers the target for integrated luminosity for 2017 and the requests for special runs (high $\beta^*$, VdM scans, low energy runs, high or low pile-up running). The impact of LIIC parameters and conditions on the experiments is also discussed, including the effect of pileup, bunch length, background etc... In addition the need and different possibilities for luminosity leveling in ATLAS/CMS will be discussed, as well as feedback on the observed luminosity difference between ATLAS/CMS in 2016 running.

2016 RUNNING

2016 was an extremely successful year for the LHC complex and the experiments, with all parts of the scheduled programme exceeding expectations. Figure 1 shows the delivered luminosity to the experiments as a function of time during the 2016 $pp$ run. About 40 fb$^{-1}$ of $pp$ data at 13 TeV was delivered to ATLAS and CMS (with 25 fb$^{-1}$ the goal), with nearly 2 fb$^{-1}$ delivered to LHCb and more than 10 pb$^{-1}$ to ALICE, allowing a large number of searches for new physics, and physics measurements to be carried out. Four days of special running at a $\beta^*$ of 2.5 km delivered 350 $\mu$b$^{-1}$ to TOTEM and ATLAS (ALFA) for total cross-section measurements. The year ended with a very successful four weeks of running with proton-lead collisions at both 5 TeV and 8 TeV nucleon-nucleon centre-of-mass energy, allowing to satisfy the different physics requests from the experiments.

The high luminosity $pp$ running benefited from an excellent availability with $\approx 50$ % of the available physics time spent in stable beams, and a peak luminosity of $\approx 1.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ (50 % above the design luminosity). The high peak luminosity and the limited number of bunches (limited to 2220 by the SPS beam dump vacuum) meant the peak pileup in ATLAS/CMS was nearly a factor of two higher than the design. This stressed the experiments, but they were able to cope with these harsh pileup conditions. A significant issue in 2016 was the apparent imbalance in luminosity delivered to ATLAS/CMS, with ATLAS receiving $\approx 10$ % less luminosity than CMS.

During the high luminosity running the CT-PPS roman pots were inserted during routine operation to 15 $\sigma$ from the beam without problems (the ATLAS(AFP) pots were inserted, on one side of the IP, during the intensity ramp-up for fills with up to 600 bunches). During the year a bunch length levelling procedure was implemented to keep the average bunch length above 0.9 ns as requested by LHCb to reduce the pileup density during operation with their dipole in positive polarity. Beam related backgrounds were generally very low in 2016, and about a factor of three lower than in 2015. There was a short period where high losses at injection caused problems for the ALICE detector, but this was solved when an additional 40 MHz RF cavity was used in the PS.

During 2016 there were a number of very useful test fills carried out for the experiments, for example testing leveling the luminosity in ATLAS/CMS using beam separation, a fill where the crossing angle was reduced to zero to study the IP1/5 luminosity imbalance and a high pileup fill to allow the experiments to test running at higher pileup.

2017 RUNNING

The experiments view 2017 as a luminosity production year. Due to the extended year end technical stop (EYETS) there is no ion run scheduled, giving a similar number of $pp$ physics days in 2017 and as in 2016 with the current schedule.

Nominal running

In order to maximize the integrated luminosity in 2017 both ATLAS/CMS would like to continue with the low emittance BCMS beam. Both experiments believe they will be able to deal with the high pileup that this will lead to. Improvements to the experiment systems over the shut down should allow them to cope with peak pileup values up to 60 and luminosities up to $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$. If one or both experiments prefer to reduce the pileup at the begin-
ning of the fills, we believe this can be achieved using luminosity levelling by beam separation, which was demonstrated in 2016 tests. The luminosity may anyway need to be levelled to lower values due to the limits on the triplet cooling in IP1/5.

In general the experiments do not have strong opinions on the choice of the \( \beta^* \) and the type of optics (ATS or standard) for 2017 running, as long as changes do not significantly increase the setup time. Although there is a preference for non-ATS optics from CT-PPS (as discussed later).

For 2017 high luminosity running both the CT-PPS and AFP roman pots request to be inserted to 15 \( \sigma \) from the beam.

CMS request that the beam-line is re-aligned in IP5 during the EYETS such that the collision point is 2 mm lower. This would give more uniform illumination of the pixel detector which is important for the detector lifetime.

**Special run requests**

For the rest of Run-2 (so including both 2017/2018) the experiments have requested the following special running periods:

- **Running at intermediate \( \beta^* \) (\( \approx 90 \) m) - requested by TOTEM for glue-ball and low mass SUSY searches. The LHCC suggest this is done in 2018 and could be 1-2 weeks of running and setup time.

- **\( pp \) running at 5 TeV centre-of-mass energy** (as reference for the ion data with nucleon collision energy of 5 TeV). This is requested by ATLAS/CMS and ALICE, although the length of the request is driven by ALICE as they take the data at low rate. During discussions at the LHCC it was suggested that a good time for this could be at the end of 2017 running, where data taking could act as a cool down period. It is foreseen that it would take about ten days to acquire the requested data set.

- **There is interest from TOTEM/ATLAS(ALFA) for a total cross-section measurement (with very high \( \beta^* \) data) at low energy (900 GeV or 2 TeV) which could be scheduled in Run-2 if there is sufficient time (otherwise this could be done in Run-3).**

We believe that the relevant accelerator experts should work on the optimal machine configurations in order to satisfy the above requests in the most efficient manner. The exact scheduling of these will depend on the re-start after the EYETS and the LHC performance in 2017, but a baseline planning could see the 5 TeV \( pp \) reference run taking place at the end of 2017 running.

In addition to the above it is also foreseen to have van der Meer scans taken in 2017 with the same configuration as in 2016.

**Forward physics during high luminosity running**

Both the CT-PPS and AFP roman pots systems request to be inserted during nominal high luminosity running in 2017. This allows studies of central exclusive production of rare Standard Model processes, as well as searches for new physics. In 2016 the physics acceptance of CT-PPS was found to be poor with the 40 cm \( \beta^* \) optics and a special orbit bump (the so-called TOTEM bump) was introduced in order to improve this, in addition the pots were allowed to be inserted to 15 \( \sigma \) from the beam after TS1 which also improves the acceptance. In preparation for 2017 running both CT-PPS and AFP have tested possible optics configurations (with standard and ATS optics) to assess the acceptance for each option. For AFP the pots are inserted in the separation plane, which gives reasonable acceptance for the different optics sets. However for CT-PPS the pots are in the crossing plane, and this limits the acceptance as the dispersion from the crossing angle partially cancels that from the D1 magnets. CT-PPS therefore prefer to have a smaller crossing angle to reduce this effect. The CT-PPS acceptance is considerably better for the non-ATS optics (as shown in Fig. 2). CT-PPS request an orbit bump in order to improve the dispersion and their acceptance. The feasibility of an orbit bump depends on how much corrector strength is available which in turn depends on how the realignment of the CMS beam-line is carried out. If this can partially be done with a mechanical realignment around the IP, this would free up corrector strength for a possible orbit bump.

**ATLAS/CMS luminosity imbalance**

The measured delivered luminosities by ATLAS/CMS show that \( \approx 10 \% \) less luminosity was delivered to ATLAS than CMS. This difference is significantly larger than the luminosity measurement uncertainty. Studies suggest that this is mainly coming from the fact that the horizontal emittance is generally larger than the vertical emittance, which coupled with the vertical/horizontal crossing plane in IP1(5) would give different geometric factors, and therefore different luminosities at the two IPs. A model taking into account the measured emittances in the two planes, predicts a luminosity imbalance between the two IPs consistent with what is observed for much of the year, however for the last \( \approx 15 \) fills in 2016 the emittance measurements suggest the beams are round, whereas the luminosity imbalance is still observed in these fills [1][2]. In order to study this further a test was carried out where the crossing angle in IP1/5 was reduced in steps to zero, and the luminosity and beam size was measured. This test suggests that the luminosity imbalance is driven by the crossing angle (the luminosity difference was reduced from 11 \% at nominal crossing angle to 4 \% with zero crossing angle). A full analysis of this test can be seen in Ref. [3].

If it is confirmed that the luminosity imbalance is coming from emittance differences in the two planes, this can be corrected for by normalizing the value of the crossing angle by the emittance in the relevant plane, which has the advantage of correctly compensating beam-beam effects in the two IPs. However it remains an open question how to reliably determine the emittances to set the crossing angles.
A simple scheme should be adopted where the crossing angle is not changed often, to minimize any re-validation overhead, but can be modified at technical stops to allow corrections based on the recent running experience.

In parallel a Z-boson counting analysis is ongoing in ATLAS/CMS to give an additional comparison of the delivered luminosity which is independent of the nominal luminosity measurements from the experiments. Preliminary results confirm the luminosity imbalance at the level of that observed with the nominal luminosity measurements.

**ACKNOWLEDGMENT**

We wish to thank in particular the Run Coordinators of ALICE, ATLAS, CMS, LHCb, LHCf and TOTEM for their essential input as well as our colleagues working on the LHC and injectors operations for countless explanations and discussions about machine parameters and constraints.

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Figure 3: The ratio of the peak luminosity in IP1 to the peak luminosity in IP5 as a function of fill number, for all the stable beam fills in the 2016 $pp$ data taking period. The luminosity values from the experiments are using non-final offline calibrations.
BEAMS FROM THE INJECTORS

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Abstract

During the LHC proton physics run in 2016 the injectors were regularly providing 25 ns beams, in both the standard and the high brightness, i.e. BCMS, variant. In this paper, the achieved parameters for these two beam production schemes are analysed and compared to the expected performance reach of the LHC injector complex. It is shown that the standard beam could be produced close to the known performance limits, while the high brightness BCMS beams suffered from emittance blow-up especially in the PS. First results from machine development studies addressing this issue are presented, showing the potential for mitigating at least part of the blow-up in the future. An outlook of the expected beam parameters from the injectors in 2017 is given, including also special beam variants like the 8b4c, the 80 bunches and the doublet scrubbing beam.

INTRODUCTION

The LHC proton physics production Run in 2016 was based on beams with the nominal 25 ns bunch spacing [1]. For the first half of the run the LHC was using the 25 ns beam produced with the nominal scheme in the injectors as described in the LHC design report [2]. This beam is nowadays referred to as the “standard” beam. In order to push the luminosity in the LHC experiments, the high brightness variant of the 25 ns beam produced with the Batch Compression bunch Merging and Splitting (BCMS) scheme [3, 4] was used in the second half of the run. In this paper the 2016 achieved performance of these two beam types is analyzed and compared to the expected performance reach of the LHC injector complex at the present stage. In addition to the measures for reducing losses at the PS-to-SPS transfer already implemented in 2016, possibilities for improving the emittance preservation along the injector chain are illustrated through promising results from machine development (MD) studies. Other available beam types such as the 8b4c, the 80 bunch scheme and the doublet scrubbing beam are also briefly discussed. For each of these beam types an outlook of the beam parameters to be expected in 2017 is given in a summary table at the end of this paper.

25 ns STANDARD AND BCMS BEAMS

Figure 1 summarizes the achieved beam parameters for the standard 25 ns beam: The graph on the left hand side shows the average transverse emittance measured with the LHC Beam Synchrotron Radiation Telescope (BSRT) right after injection as a function of the average intensity per bunch for the 26 LHC physics fills between June 11 and July 7. The shaded areas indicate beam parameters which are not accessible due to the known performance limitations of the LHC injector chain, taking into account intensity loss and emittance growth budgets of 5% in the PS and 10% in the SPS, respectively. Space charge in the PSB and the PS are expected to limit the achievable beam brightness. The presently available RF power for beam loading compensation in the SPS allows extracting 25 ns beams with up to about $1.3 \times 10^{11}$ p/b. There is quite some spread in the measured beam parameters from fill to fill in particular regarding the transverse emittances. However in some cases the standard beam could be produced very close to the performance limits of the injector chain.

The graphs on the right hand side of Fig. 1 show the horizontal (top) and vertical (bottom) emittances along the injector chain measured with the standard beam during the same period. This data was extracted from the LHC supertable [5], which associates the automatically logged wire scanner measurements of the LHC beams performed routinely by the injectors operation crews with LHC fill numbers. The error bars indicate the spread in the measurements. The measurements in the PSB are performed just before extraction. There are no measurements available for Ring 4 of the PSB, as its wire scanners were out of order. Apart from a short period at the beginning of the run (until end of April, i.e. before the period analyzed here) during which the working points in the PSB rings were not at the optimized values for LHC beams, the transverse emittances out of the PSB basically followed the expected brightness curve imposed by space charge effects at low energy [6]. Only minor emittance degradation is observed along the rest of the injector chain up to the LHC, except for a significant blow-up that appears to occur at the transfer from the PSB to the PS. In fact about 40% larger horizontal and about 15% larger vertical emittances are measured after injection in the PS compared to the values at PSB extraction. Some blow-up is expected due to the known dispersion and optics mismatch between the two machines, which is difficult to avoid with the present transfer line configuration before the LHC Injectors Upgrade in Long Shutdown 2 (LS2). However according to the available optics models this blow-up should be less than 10% for the standard beam [7]. Machine development studies on this subject were not yet conclusive and further investigations need to follow in 2017. It should also be mentioned that the measured beam profiles in the horizontal plane in both the PSB and the PS have large contributions from the beam momentum spread (through dispersion), which has almost a parabolic distribu-
Figure 1: Transverse emittance as function of intensity at LHC injection for the 25 ns standard beam operationally achieved in 2016 (left) and details on the emittance evolution along the injector chain (right).

Figure 2: Transverse emittance as function of intensity at LHC injection for the 25 ns BCMS beam operationally achieved in 2016 (left) and details on the emittance evolution along the injector chain (right).

evaluation of the horizontal emittances in these conditions is also being investigated, e.g. performing a deconvolution of the betatronic and the dispersive beam profile contributions using the reconstructed longitudinal distribution from the Tomoscope [8, 9].

Figure 2 shows a similar analysis for the BCMS beam operationally delivered to the LHC: As can be seen on the graph on the left hand side, the expected performance limit of the BCMS beam could not be reached during the period between July 21 and August 25 of the 2016 run\(^1\). It appears as if the brightness degraded with beam intensity. While the beam brightness extracted from the PSB follows again closely the expected curve [6], there is considerable emittance degradation along the injector chain as shown in the graphs on the right hand side of Fig. 2. As for the standard beam, there is a horizontal blow-up at PS injection which needs to be understood (50% observed in measurements compared to 20% expected from the optics mismatch for BCMS beam parameters [7]). In addition, there is also vertical blow-up along the PS cycle. Before addressing this point in more detail, it should be mentioned that in routine operation no emittance measurements were performed on the SPS flat top for the BCMS beam because the resolution of the existing wire scanners is insufficient for a reliable beam profile reconstruction.

\(^1\)This period corresponds to the time after the voluntary emittance blow-up requested by the LHC in the transition period from standard to BCMS beams and before the BSRT in the LHC was re-calibrated.

Figure 3 shows measurements of the vertical emittance along the PS cycle for the BCMS beam in operational conditions. The bunches of the first bunch suffer from about 10% blow-up along the injection plateau, which can be ex-
explained by the large direct space charge tune spread exceeding the vertical integer resonance. Right after the injection of the second batch the measured emittance is reduced, because the wire scanner measures the average emittance of all bunches. When arriving at the 2.5 GeV intermediate plateau the total emittance growth reaches about 15% compared to the value at injection. During MDs in 2016 it could be shown that this blow-up is due to the bunch shortening caused by the large RF voltage used for acceleration (200 kV), which further enhances the space charge detuning. The vertical blow-up in the PS could be significantly reduced by a) slightly increasing the vertical tune from $Q_y = 6.24$ to $Q_y = 6.25$ in combination with a reduced RF voltage on the injection plateau in between the two injections and b) using an RF voltage function that provides constant bucket area during acceleration in order to avoid as much as possible the bunch shortening. Figure 4 shows the emittance evolution for an MD cycle with these optimizations. Slightly higher losses are encountered during acceleration to 2.5 GeV, which might be avoided by further optimization of the voltage program. These studies give prospect of improved emittance preservation for the high brightness beams in 2017.

Another critical point for the production of LHC beams with 25 ns bunch spacing are losses in the SPS encountered on the flat bottom and during the beginning of the ramp, which reach a total of more than 10% in some cases. MDs in 2016 showed that most of these losses (even the ones on flat bottom) are longitudinal [10]. An important contribution to these losses comes from uncaptured beam directly resulting from the “S” shape of the longitudinal distribution at PS extraction: For injection into the SPS 200 MHz bucket the bunch length needs to be reduced from about 11 ns to 4 ns, which is achieved by bunch rotation at PS extraction using a combination of 40 and 80 MHz cavities. Optimizing the bunch rotation scheme with increased RF voltage at 40 MHz using a second cavity (usually served as hot spare) allowed reducing the losses in the SPS by 40% [11]. This optimized scheme was used in routine operation during the last months of the proton run. Almost as a side product, losses at LHC injection improved by a factor 10 due the reduced population of ghost bunches [12].

Due to a vacuum leak that developed inside the SPS high energy internal beam dump (TIDVG) shielding at the beginning of 2016, the total intensity per LHC injection had to be restricted throughout the run. The standard 25 ns beam was delivered only in single batches, i.e. trains of 72 bunches. For the BCMS beam up to two batches could be transferred per LHC injection, i.e. trains of $2 \times 48 = 96$ bunches. It is planned to install a new SPS high energy beam dump (TIDVG#4) during the EYETS 2016/17. After the TIDVG replacement, all the SPS intercepting devices will be ready for operation with the maximum achievable intensity and brightness, and the only constraint on the maximum intensity at the transfer from SPS to LHC will come from the TCDI transfer line collimators [13]. Based on the present knowledge of the damage thresholds, the TCDIs will limit the operation to 144 BCMS bunches, while up to the nominal 288 bunches of the standard beam can be transferred.

A summary of the beam parameters to be expected in 2017 is given in Table 1. The quoted emittance values are the parameters achieved operationally in 2016, while the values in parenthesis correspond to the expected performance reach of the injectors and should be achievable, e.g. by implementing the optimizations discussed above on the operational cycles. It should be emphasized that the minimum batch spacing (i.e. the SPS injection kicker gap) for 2017 will be 200 ns instead of the nominal 225 ns used in 2016. This reduced batch spacing has been fully validated during proton MDs in 2016 and was already operationally used during the p-Pb Run at the end of 2016 [12].
Table 1: Beam parameters to be expected from the LHC injectors in 2017.

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<tbody>
<tr>
<td>25 ns standard (nom. intensity)</td>
<td>1.15</td>
<td>2.5 (2.4)</td>
<td>200</td>
<td>1-4 x 72 → 288</td>
</tr>
<tr>
<td>25 ns standard (max. intensity)</td>
<td>1.30</td>
<td>2.8 (2.7)</td>
<td>200</td>
<td>1-4 x 72 → 288</td>
</tr>
<tr>
<td>25 ns BCMS (nom. intensity)</td>
<td>1.15</td>
<td>1.7 (1.4)</td>
<td>200</td>
<td>1-3 x 48 → 144</td>
</tr>
<tr>
<td>25 ns BCMS (max. intensity)</td>
<td>1.30</td>
<td>1.9 (1.6)</td>
<td>200</td>
<td>1-3 x 48 → 144</td>
</tr>
<tr>
<td>25 ns 80 bunch (nom. intensity)</td>
<td>1.15</td>
<td>2.6 (2.4)</td>
<td>200</td>
<td>1-3(4) x 80 → 240</td>
</tr>
<tr>
<td>25 ns 80 bunch (max. intensity)</td>
<td>1.30</td>
<td>2.8 (2.7)</td>
<td>200</td>
<td>1-3(4) x 80 → 240</td>
</tr>
<tr>
<td>8b4e (nom. intensity)</td>
<td>1.20</td>
<td>1.8 (1.6)</td>
<td>200</td>
<td>1-3 x 56 → 168</td>
</tr>
<tr>
<td>8b4e (max. intensity)</td>
<td>1.60</td>
<td>2.4 (2.1)</td>
<td>200</td>
<td>1-3 x 56 → 168</td>
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SPECIAL BEAMS

The 80 bunch scheme has the potential to either increase the total number of bunches in the LHC (using 320 bunches per injection after LS2), or for mitigating total current limits in the SPS for the same LHC performance (using 240 bunches per LHC injection) [14]. In this scheme 4+3 instead of 4+2 bunches are injected into the PS at harmonic h = 7. After the triple splitting one bunch is eliminated using either the transverse damper or the PS extraction kicker. The remaining 20 bunches are accelerated to flat top and twice double split into 80 bunches. All RF gymnastics are identical to the standard production scheme and thus the same brightness as for the standard scheme can be expected. The 80 bunch scheme (using the PS extraction kicker for bunch elimination) was successfully tested in LHC MDs in 2016. Slightly higher losses compared to the operational beams were observed, but this is not unusual for a beam that is not used in routine operation. This might simply be resolved by optimizing the scraper settings in the SPS. It is expected that similar maximum intensity per bunch as compared to the standard 25 ns beam can be achieved as shown in Table 1.

The 8b4e beam is considered as a back-up for the standard 25 ns beam in case the e-cloud remains a limitation for the operation of the LHC during the IL-LHC era [15]. The e-cloud build-up is significantly reduced by the micro-batch train structure. Starting from 7 bunches from the PSB, the triple splitting in the PS is replaced by a direct h = 7→21 bunch pair splitting, which results in pairs of bunches separated by empty buckets. Each bunch is split in four at PS flat top such that the bunch pattern 6x(8b4e)⊕8b is obtained. This scheme was successfully tested in LHC MDs in 2016: a hybrid filling scheme with 55% of 25 ns BCMS batches combined with 45% of 8b4e batches allowed reducing the heat load in the most critical LHC sector by about 40% while the total number of bunches was only 15% less compared to the equivalent standard filling scheme [16]. As for all LHC type beams in the SPS, the intensity of the 8b4e is limited by the available RF voltage in presence of beam loading. Since the filling time of the SPS RF cavities is about 600 ns and the average line charge density over 300 ns is reduced to 2/3 compared to the normal 25 ns beams, the present intensity limit for the 8b4e is estimated around 1.6 × 10^{11} p/b as summarized in Table 1.

The doublet beam was originally proposed for enhancing the scrubbing efficiency in the SPS at low energy [17], but could also be of interest for scrubbing of the LHC. This beam is produced by injecting a 25 ns beam with enlarged bunch length (τ ≈ 10 ns full length) from the PS onto the unstable phase of the 200 MHz RF system in the SPS. By raising the SPS RF voltage within the first few milliseconds after injection, each bunch is captured in two neighboring RF buckets resulting in a train of 25 ns spaced doublets, i.e. pairs of bunches spaced by 5 ns. The doublet beam was sent to the LHC for first tests in 2015, but not in 2016 due to the vacuum leak on the TIDVG in the SPS. It could be made available again for the LHC by mid 2017. There is an interest to use this beam with intensities ranging between 0.6 and 1.6×10^{11} p/doublet for assessing its scrubbing potential in the LHC (for lower intensity the stripes of high e-cloud density move to the central region). This would also provide points for an experimental benchmark of the dependence of the e-cloud build-up on the bunch (doublet) intensity.

SUMMARY AND CONCLUSIONS

The 2016 operationally achieved beam parameters of the 25 ns beam produced with the standard scheme was close to the expected performance limit of the LHC injector chain. However the observed blow-up at the PSB-to-PS transfer needs to be studied further. Emittance preservation along the chain is clearly more challenging for the BCMS high brightness variant of the 25 ns beam, for which an additional vertical blow-up along the PS cycle was observed. Based on promising MD results from end 2016, it is expected that the latter can be mitigated mainly by an optimization of the RF voltage program to reduce the space charge tune spread. Losses in the SPS and at injection into the LHC could be improved in the second half of 2016 by deploying an optimized bunch rotation scheme at PS extraction using an additional 40 MHz cavity. Special beams such as the 80 bunch scheme, the 8b4e beam and the doublet beam have been successfully tested in LHC MDs and can be made available if requested by the LHC.
ACKNOWLEDGEMENTS


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FILLING SCHEMES AND E-CLOUD CONSTRAINTS FOR 2017

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Abstract

Several measures implemented in the 2016-17 Extended Year End Technical Stop (EYETS) should allow the increase of both the number of bunches per injection into the LHC and of the intensity per bunch for the 2017 Run.

This contribution reviews the possible filling patterns, in particular comparing the high brightness scheme (Batch Compression Merging and Splitting – BCMS – scheme in the PS) against the nominal production scheme. In particular we analyze possible limitations due to electron cloud induced heat load on the beam screens of the cryogenic magnets.

Scrubbing requirements for the 2017 Run are also presented, taking into account that one of the LHC sectors (S12) needs to be warmed-up and vented to exchange one of its main dipole magnets.

POSSIBLE FILLING SCHEMES FOR 2017

In 2016 the presence of a vacuum leak in the SPS high energy beam dump (TIDVG) limited the intensity that could be accelerated in the SPS [1]. For this reason the number of bunches per injection into the LHC was limited to 96, in the configuration with two batches of 48 bunches produced using the high brightness scheme (BCMS) in the PS. Under these conditions the maximum number of bunches that could be stored in the LHC was 2220, corresponding to the filling scheme in the top part of Fig. 1.

A new beam dump for the SPS is being manufactured and will be installed before the 2017 LHC startup. This will remove the present intensity limitations and allow the injection of [1, 2]:

- Trains of 288 bunches (in the configuration 4×72b) for the standard 25 ns beam (standard production scheme in the PS), as foreseen in the LHC design [3];
- Trains of 144 bunches (in the configuration 3×48b) for the high brightness 25 ns beam variant (BCMS production scheme in the PS).

Moreover, studies conducted in 2016 have shown that shorter rise-times can be achieved both for the SPS injection kickers (MKPs) and for the LHC injection kickers (MKIs), reducing the spacing between PS batches to 200 ns (it was 225 ns in 2016) and the spacing between injections in the LHC to 800 ns (it was 900 ns in 2016).

Profiting from these improvements and assuming that the abort-gap keeper is adjusted to the actual train length, optimized filling schemes can be prepared for the 2017 Run as shown in Fig. 1. In particular, for the high brightness case (BCMS), 2556 bunches can be stored in the LHC, i.e. 15% more compared to the maximum number of bunches reached in 2016. Using the standard scheme (low brightness) instead, the number of bunches can be increased to 2760 bunches, i.e. 7% more compared to the BCMS case.

The bunch intensity was limited to about $1.1 \times 10^{11}$ p/bunch in 2016, due to the dynamic pressure rise in the injection kicker (MKI) area in Point 8 [4]. During the 2016-17 Extended Year End Technical Stop (EYETS) additional pumping modules are being added. Thanks to this improvement it should be possible to increase the bunch intensity to about $1.3 \times 10^{11}$ p/bunch, which is presently the maximum achievable in the SPS with 25 ns bunch spacing [2].

HEAT LOAD CONSTRAINTS

To estimate the beam induced heat loads in the arcs we assume that the scrubbing status is the same as at the end of 2016 (given the very slow conditioning observed in the last part of the 2016 p-p run – see Fig. 2 [5]). This condition is not true right at the beginning of the year due to the need to recover the scrubbing of the beam screens in Sector 12, which was warmed-up and vented during the EYETS in order to change one of its main dipole magnets.

Heat loads are estimated for the sectors with the highest loads (i.e. S12 and S81), starting from the values that were measured at the end of 2016. Both the effect of the filling pattern (train length, number of gaps) and of the bunch intensity need to be taken into account.

The impact of the filling scheme can be estimated knowing the e-cloud rise-time from the RF stable phase measurements (see for example Fig. 3). Due to the e-cloud buildup along the trains, bunches at the head of each train generate very little heat load while bunches at the tail of long trains generate a significant load.

The heat load dependence on the bunch intensity was measured in a Machine Development (MD) session in 2016, with three consecutive fills performed with the same bunch length and filling scheme but with different bunch intensities. The results of these measurements are shown in Fig. 4. The measured heat loads are fitted quite well with a linear dependence with an intensity threshold. Since the dependence is quite steep, a sizable effect can be observed when increasing the bunch charge from $1.1 \times 10^{11}$ p/bunch to $1.3 \times 10^{11}$ p/bunch. The intensity threshold is in the range from 0.4 to $0.7 \times 10^{11}$ p/bunch, depending on the sector.

The heat loads expected for the different filling schemes in Fig. 1 are shown for different bunch intensities in Fig. 5.

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Figure 1: Filling scheme used for physics production at the end of 2016 (top) and possible options for 2017 operation, both for the BCMS scheme (middle) and for the standard scheme (bottom).

Figure 2: Evolution of the heat load at high energy normalized to the beam intensity during the 2016 p-p Run.

Figure 3: Bunch-by-bunch energy loss along two trains of 72 bunches, as measured from the RF stable phase (data courtesy of J. Esteban Muller).
Figure 4: Dependence of the arc heat loads on the bunch intensity as measured in a Machine Development session in 2016. Measured points and corresponding linear fit.

(top). By comparing the heat load values with the maximum available cooling capacity from the cryogenic system, namely 160 W/hec [6], we can estimate the number of bunches that can actually be stored in the machine for the different configurations, as shown by the full bars in Fig. 5 (bottom), in comparison with the maximum allowed by the filling scheme (dashed bars).

The prospect for the different schemes can be summarized and follows:

- **BCMS 2016**: filling scheme allowing for a maximum of 2220 bunches in injections of $2 \times 48b$. This is the filling scheme used in 2016 and will have to be kept for 2017 operation in case the faulty beam dump in the SPS cannot be replaced. As observed in 2016, with this filling scheme and with a bunch intensity of $1.1 \times 10^{11}$ p/bunch, some margin is available with respect to the available cooling capacity. This can be used to increase the bunch intensity up to $1.3 \times 10^{11}$ p/bunch without limitations on the number of bunches.

- **BCMS 2017**: filling scheme allowing for a maximum of 2556 bunches in injections of $3 \times 48b$. For this filling scheme, allowing for 15% more bunches with respect to the “BCMS 2016” case, it should be possible to operate without limitations from heat loads with bunch intensities up to $1.2 \times 10^{11}$ p/bunch, while the limit is exceeded by about 10% if the bunch intensity is increased to $1.3 \times 10^{11}$ p/bunch.

- **Standard 2017**: filling scheme allowing for a maximum of 2760 bunches in injections of $4 \times 72b$. Due to the longer bunch trains and to the smaller number of gaps, the average heat load per bunch with this scheme tends to be significantly larger than for the BCMS cases. For this reason the heat load reaches the available cooling capacity already for $1.1 \times 10^{11}$ p/bunch.

For larger bunch intensities this scheme is limited to a number of bunches that is even lower than for BCMS.

Assuming end-2016 scrubbing status, due to heat load constraints, the standard scheme does not really allow for a larger number of bunches compared to the BCMS case. For this reason the BCMS beam seems to be the natural choice for luminosity production in 2017, profiting from the increased brightness (see [7] for detailed performance comparison). In this scenario, the intensity ramp-up will probably be fast (as in 2016) and it will be easier to deal with the scrubbing recovery for Sector 12, if needed. But most likely further conditioning of the beam screens, and the consequent reduction of the heat loads, will be very limited. This will not have much impact on performance in 2017-18, since we have enough cooling capacity to practically profit from the full performance reach of the BCMS beam. Nevertheless e-cloud induced heat loads might come back as a performance limitation for Run 3 and HL-LHC.

**SCRUBBING RUN**

After the 2015-16 Year End Technical Stop (YETS) de-conditioning of the beam screens was clearly observed [5, 8], inducing instabilities and strong emittance blow-up. The reconditioning was very fast and the 2016 beam quality was recovered with about 24 h of scrubbing at 450 GeV. Based on these observations, it might be convenient to allocate 1-2 days for scrubbing at the beginning of each year, mainly to recover an acceptable beam quality before starting the intensity ramp-up in physics.

The situation for the 2016-17 EYETS will be different since the sector 12 has to be warmed-up and vented to replace a dipole suspected to have an inter-turn short. Based on the experience from the Long Shutdown 1 (2013-14) the Secondary Electron Yield (SEY) of the beam screen surfaces will be reset. Nevertheless scrubbing preservation might be better thanks to the larger accumulated dose compared to Run 1, but no direct experience is available in this respect.

In case compared to 2015 it should be easier to preserve an acceptable beam quality since only one out of eight arcs has been exposed to air and our knowledge on how to stabilize the beam has significantly improved [5, 9, 10]. Moreover the cryogenics system will be less sensitive to heat load transients thanks to improvements on the feed-forward control deployed in 2016 and to increased interlock levels on the beam screen temperatures. The intensity increase during the 2017 scrubbing could also be limited by pressure rise in one of the injection kickers in Point 2, which was exchanged before the 2016 ionRun and has never been conditioned with high intensity 25 ns beams.

Taking all these aspects into account, seven days have been allocated for scrubbing at the beginning of the 2017 Run. The Scrubbing Run will be performed at 450 GeV, using exclusively 25 ns beams. The standard production
scheme (low brightness) will be used in order to have longer bunch trains. In particular in 2017 it should be possible, for the first time in Run 2, to inject and store trains of 288 bunches from the SPS. This will provide important information on the scrubbing efficiency which can be achieved with this scheme.

Doublet beams [9, 11] will not be used during the 2017 Scrubbing Run, mainly due to the lack of time for preparation in the injectors. In 2016 doublets were not available for injection into the LHC due to the aforementioned limitation from the SPS TIDVG. In 2015, due to strong transverse instabilities, it was possible to accumulate only trains of 24 doublets (up to 250 doublets in total). This was sufficient to prove the enhancement on the heat load per bunch compared to normal 25 ns trains but to achieve a significant scrubbing efficiency we need to store significantly more bunches (in the order of 1000 doublets) and in longer trains (48-72 doublets/train).

Studies on doublet beams will restart in MD with the main goal of identifying optimal settings to stabilize the beam, profiting from the scrubbing accumulated in 2015 and 2016 and from tune settings optimized for the e-cloud spread. This will allow assessing the possible intensity reach. In case of a positive outcome, a longer test period to probe the scrubbing efficiency of doublet beams could be envisaged for 2017 or later.

**SUMMARY AND CONCLUSIONS**

In 2017 it should be possible to increase the number of bunches in the LHC with respect to 2016, thanks to the replacement of the faulty beam dump in the SPS, and to faster kicker rise-times in the SPS and in the LHC. From pure filling scheme constraints it should be possible to inject up to 2556 bunches for BCMS (about 15% more than 2016) and up to 2760 bunches for the standard scheme (7% more than BCMS).

Nevertheless, limitations from e-cloud induced heat loads are quite different for the two schemes. Assuming the same situation as at the end of 2016, the BCMS option shows no limitation on the number of bunches for bunch intensities up to $1.2 \times 10^{12}$ pbunch while the standard scheme is limited to the same number of bunches as the BCMS, or even less, already for $1.1 \times 10^{12}$ pbunch.

For this reason the BCMS option seems to be the natural choice for 2017, also allowing for a faster intensity ramp-up. In this scenario, most likely we will not see more conditioning than in 2016. This will not have much impact on the performance in Run 2, but concerns remain for Run 3 and HI-LHC.

A scrubbing run of seven days has been allocated for 2017. It will be performed with 25 ns beams in long bunch trains, up to 288 bunches per injection. This will allow the recovery of some scrubbing in sector 12, which was vented to exchange one of its main dipoles, and condition the injection kicker in point 2 (MK2D), which was exchanged before the 2016 ion Run and has never been conditioned with high intensity beams. This will also be an occasion to test (for the first time in Run 2) the scrubbing efficiency with trains of 288 bunches.

Studies with doublet beams are planned to restart during MD time in 2017, with the main goal of evaluating stability.
margins and intensity reach. In case of a positive outcome, these studies could be followed-up with a longer period to assess the scrubbing efficiency.

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Abstract

In this paper, we review the strategy deployed for decreasing $\beta^*$ in the past and summarize tests done during 2016 in order to further push down $\beta^*$ in the future. Improvements are presented in particular for the collimator settings. The tests, combined with detailed aperture knowledge and input on the 2017 Run conditions, such as a smaller beam-beam separation or the prospect of adding an orbit bump to shift the CMS IP, are used to conclude on a range of feasible $\beta^*$-values for 2017.

INTRODUCTION

One way of increasing luminosity in the LHC, which is independent of the beam brightness, is to decrease $\beta^*$. The reach in $\beta^*$ in the LHC is limited by several factors. On one hand, it becomes harder with decreasing $\beta^*$ to develop an optics that satisfies constraints on e.g. magnetic strengths. On the other hand the $\beta$-functions in the inner triplets in front of the interaction points (IPs) increases as $\beta^*$ goes down, which means that the normalized aperture becomes smaller so that it risks to no longer be protected by the collimation system. This limit on aperture has been the driving constraint for allowed $\beta^*$ in the LHC so far [1]. The $\beta^*$-reach from this limit can be improved mainly by tightening the collimators, in order to protect a smaller normalized aperture, or decreasing the crossing angle, so that the normalized aperture at a given $\beta^*$ increases. A better knowledge of the aperture through detailed measurements can also help through reduced margins for imperfections.

In Run 1, an initially conservative approach was taken with rather open collimator settings [2]. Later on, a statistical approach was developed in order to reduce the margins, while still keeping the risk of exposing sensitive elements very low [1], which allowed tighter collimators and a significantly reduced $\beta^*$ in steps down to 60 cm at 4 TeV in 2012 [3, 4]. In Run 2, 2015 was be considered to be a commissioning year, when operation at 6.5 TeV and 25 ns was established, and rather relaxed machine parameters were used. The Run 1 approach to calculate collimator settings and $\beta^*$ was used, with a relaxed $\beta^*$=80 cm and an additional 2 $\sigma$ safety margin.

For 2016, a goal was set produce more than 25 fb$^{-1}$, and more than 100 fb$^{-1}$ of data should be collected in Run 2 up to the end of 2018. To meet these targets, the luminosity had to be increased significantly, and various possibilities of decreasing $\beta^*$ were studied in detail in MDs [5–9]. One of the largest limitations for tightening collimators and hence the protected aperture up to then was the risk of hitting and damaging a tertiary collimator (TCT), made of tungsten and not robust against high-intensity impacts, or the triplets behind them, with miskicked beams during asynchronous beam bumps. This risk could be effectively alleviated using a new optics, with a specially matched phase advance between the dump kickers (MKDs) and the TCTs close to 0° or 180° [10]. This allowed to reduce the margin between the dump protection (TCDQ) and TCTs by 3.9 $\sigma$ compared to 2015, which together with a 0.5 $\sigma$ tighter collimation hierarchy in IR7 and a reduction of the normalized beam-beam separation from 11 $\sigma$ to 10 $\sigma$ allowed to reach $\beta^*$=40 cm [10, 11]. This gave an important increase in luminosity and is significantly below the nominal design value of $\beta^*$=55 cm.

For 2017, luminosity production is again the highest priority, and during the year 2016, a rich MD program connected to the $\beta^*$-reach has continued [12–17], in case a further reduction in $\beta^*$ would be desired. In particular, studies have been carried out to assess whether it is possible to further tighten the collimators. A more detailed knowledge of the aperture has also been gained, and as input we use also the conclusion from the studies on the feasibility of a reduced beam-beam separation. In the following, we summarize these results and use them to conclude on the reach in $\beta^*$.

STUDIES ON COLLIMATION HIERARCHY

The LHC collimation system has shown an excellent performance in 2016 [18, 19]. It could therefore be envisaged to further tighten the settings and several options were studied. The retraction between TCP and TCSG was investigated in a dedicated MD, where loss maps were performed at different collimator settings [12]. It was discovered that the limitation found in previous MDs [7], where a breakage of the cleaning hierarchy appeared at 1 $\sigma$, was caused by an angular misalignment of the tank of one particular collimator (TCSG-D4L7.B1). Compensating for this through a beam-based alignment of the jaw corners separately to introduce a compensating tilt, a correct cleaning hierarchy was achieved also for the nominal 1 $\sigma$ TCP-TCSG retraction. The loss map with a 1 $\sigma$ retraction and compensated tilt is shown in Fig. 1.

Based on these encouraging results, we conclude that it is feasible in terms of stability of the cleaning hierarchy to reduce the retraction between TCP and TCSG in operation to 1.5 $\sigma$. This should not require more frequent collimator alignments than previously. Further studies in 2017 could show if the 1 $\sigma$ retraction, with the tilt compensation, can be used to obtain a correct hierarchy throughout the year, in which case it could be envisaged to use that retraction in 2018 if no other limitations are found.

$\beta^*$-REACH IN 2017

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1 The normalized aperture is defined as the distance between the beam centre and the mechanical aperture normalized by the local beam size.
Figure 1: A loss map from MD 1447 [12] in B1, vertical plane, zoomed in IR7. The retraction between TCP and TCSG is 1 σ and an angular alignment of TCSG.D4L7.B1 has been performed.

Figure 2: The intensity transmission through the ramp in two fills in MD 1878 [13], where the TCPs were closed to 4.5 σ and 5 σ respectively, shown together with the intensity transmission in a few standard physics fills in 2016.

Furthermore, another MD was carried out to investigate the effect of operating with a tighter TCP setting [13], which would allow all other collimators to follow. Two full cycles were carried out, where the TCPs were closed during the ramp to half gaps of 4.5 σ and 5.0 σ respectively, which should be compared to the operational setting in 2015–2016 of 5.5 σ.

Figure 2 shows the intensity transmission in the ramp for the test fills, as well as a few standard physics fills in 2016. During the MD fill where a 5.0 σ TCP setting was reached at flat top, which was carried out with trains and the standard crossing angle to have the full beam-beam long-range effects, the beam transmission and lifetime through the cycle were observed to be very similar to standard 2016 physics fills. A 5.0 σ TCP setting seems therefore feasible considering the losses and beam lifetime, and could be used in operation in 2017, however, we stress that this was tested only in one fill.

With a 4.5 σ TCP setting, the minimum lifetime in the ramp dropped by about a factor 10, and a significant reduction of the beam intensity was observed. It is, however, unclear if these effects were really caused by the tighter TCP cut, since instabilities were observed in that fill already at injection, before closing the TCP. This is not understood in detail and could be investigated in further tests in 2017.

The described studies show that the IR7 collimators can be tightened without jeopardizing the cleaning hierarchy and beam transmission. However, tighter collimators can only be used in operation if the impedance is low enough to avoid beam instabilities. The collimator impedance was therefore studied in detail in several MDs in 2016 [13, 16, 17]. Based on these results, it is concluded that a TCP setting of 5 σ and a TCSG setting of 6.5 σ is still tolerable for the LHC impedance budget with the envisaged configuration of octupoles and chromaticity [20].

It was also studied in 2016 if the TCTs could be brought in closer to the beam, thus reducing the margin to the TCDQ and to the IR7 cleaning hierarchy. If it is assumed that an optics with a specially matched phase advance between MKD's and TCTs can be used as in 2016 [10], there is not a strong constraint on the TCT setting from asynchronous beam dumps. In that case, other constraints become limiting, such as the cleaning hierarchy and the potentially increased experimental backgrounds [21], since more protons scattered from IR7 might impact the TCTs and shower onto the experiments. The TCTs risk also to intercept a larger rate of elastically scattered protons from upstream beam-gas interactions.

The impact on background was studied in an end-of-fill MD, where a physics fill with 2200 bunches per beam was taken over about two hours before it was envisaged to dump [14]. The vertical TCTs were then tightened by 0.5–0.6 σ from their standard physics setting of 9 σ, after going in adjust and still staying within the interlock limits. With these settings, the LHC was brought back in stable beams. Data were accumulated during around 1.5 h, before going back to adjust the TCTs again to their standard physics setting.

The analysis of this MD shows no visible change in background in ATLAS and CMS during the period with tighter TCTs, suggesting that at least 0.5 σ tighter TCTs should not cause background issues for the experiments from neither beam-halo nor elastic beam-gas. It should be noted that the beam lifetime was rather good during the test. Therefore, it might be that the beam-halo background component could be higher e.g. during the first hour of collisions, where a lower lifetime has been observed [22].

However, other studies based on recorded background in ATLAS during loss maps [23] support the hypothesis that the machine-induced backgrounds dominated by inelastic interactions close to the detectors and that the beam-halo contribution is negligible (below 1% of the total). In conclusion, it is very unlikely that operation with the TCTs at this smaller retraction to IR7 should cause any background problems. This is also not expected to cause issues in terms of cleaning hierarchy, since during 2016 the TCDQ and TCS
Table 1: Collimator settings used in 2016, together with two proposed sets of settings that could be used operationally in 2017. All settings are expressed in units of $\sigma$ for the nominal $\beta$-function and an emittance of $\epsilon_n=3.5$ $\mu$m.

<table>
<thead>
<tr>
<th>Collimator</th>
<th>2016</th>
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</tr>
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</tr>
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</table>

in IR6 were operated at even smaller retraction from IR7 without issues.

Based on the above studies, we present two proposals for operational collimator settings in 2017, called 2017a and 2017b as shown in detail in Table 1. In both cases we use the smaller retraction between TCP and TCSG in IR7, with the rest of the hierarchy following, as well as a smaller retraction between IR7 and the TCTs. In the proposal 2017b, we use in addition the 0.5 $\sigma$ tighter TCP setting. This is a slightly less proven concept than the other changes, since it was tested only in one fill. Nevertheless, there are no reasons to believe that this should not work in operation in 2017.

It should be noted that both proposals imply that the TCDQ in IR6 is operated at a setting that is 1 $\sigma$ tighter than in 2016. This is still judged as safe for the robustness of the TCDQ itself in case of an asynchronous dump [24], however, it should be noted that an increase of about 50% in energy density deposited by lost particles can be expected on the Q5 in IR6.

**APERTURE CALCULATIONS**

In order to calculate the required aperture at any given $\beta^*$, the corresponding crossing angle must be known, which is determined from the beam-beam separation, treated in detail in Ref. [25]. Based on the results of beam-beam MDs [26], it was concluded in August 2016 that, with the use of the small-emittance BCMS beams, the separation could be decreased from 10 $\sigma$ for $\epsilon_n=3.75$ $\mu$m, which had been used so far in 2016, down to 9.3 $\sigma$ for $\epsilon_n=2.5$ $\mu$m [27], keeping the bunch population constant at $1.15 \times 10^{11}$ protons/bunch. A reduction of the half crossing angle from 185 $\mu$rad to 140 $\mu$rad was consequently implemented in the machine, however, still staying at $\beta^*=40$ cm and not using the increased aperture margin for a further squeeze.

For 2017, a similar beam-beam separation could be used, however, in order to have comfortable margins in case of an increased bunch population, it has been proposed to have a slightly larger separation of 10 $\sigma$ for 2.5 $\mu$rad [28]. Still, this implies a gain in aperture compared to what was assumed for the 2016 Run, which could be used for a potential reduction of $\beta^*$. In the following, we study the $\beta^*$-reach for different separations: 9 $\sigma$ for $\epsilon_n=3.5$ $\mu$m (assuming that nominal beams are used instead of BCMS), 9 $\sigma$ and $\epsilon_n=2.5$ $\mu$m (as used with BCMS in the second part of 2016), or 10 $\sigma$ for $\epsilon_n=2.5$ $\mu$m, as could be envisaged for an increased bunch intensity in 2017.

In order to calculate the reach in $\beta^*$ it is also crucial to have a reliable method to estimate the required aperture in any configuration. The aperture was measured on several occasions in 2016, both during the commissioning and in a dedicated MD towards the end of the year [15]. Some of the MD results are shown in Table 2 together with the results from the commissioning. It can be seen that the minimum bottleneck of the ring was consistently found at around 10 $\sigma$ in B1, vertical plane, on the IP end of D1 on the incoming beam in IR1. It is worth noting that there are some fluctuations between different measurements over the year, and that there is more aperture available with the positive sign of the IR1 crossing angle, than with the negative sign used in 2016.

In order to calculate the aperture at any other $\beta^*$ and crossing angle than used in the measurements, we scale the worst observed aperture in the crossing plane (9.9 $\sigma$ for B1 vertical) and in the separation plane (10.6 $\sigma$ for B1 horizontal) using the method in Ref. [1]. Because of the fluctuations between different measurements over the year, we add on top of the protected aperture in Table 1 an additional safety margin of 0.5 $\sigma$, when we judge whether the calculated aperture in any given configuration is acceptable. Conservatively, we also do not use the improved aperture with the positive sign of the IR1 crossing, since it is planned by survey to smoothen the alignment in IR1.

Another important input to the estimates of the aperture is the request from CMS to introduce a vertical shift of the IP, most likely using a magnetic bump of at least -1 mm at the IP [29]. Such a bump could have a significant impact on the available aperture, and MAD-X calculations predict that a vertical bottleneck might be introduced in Q2L5 for B2, where the aperture has not been measured with beam. This introduces a significant uncertainty on the aperture calculations. A local measurement at this location could be envisaged during the commissioning.

To make an estimate of this aperture, we assume conservatively that the vertical aperture measured in Q2L5 for B1 (last line of Table 2) would be symmetric, i.e. that we have 10.8 $\sigma$ also for B2 in Q2R5, and that MAD-X predicts properly the difference between Q2R5 and Q2L5 to 0.3 $\sigma$. This gives an estimated aperture of 11.1 $\sigma$ in Q2L5 without the CMS bump. With a -1 mm bump to shift the CMS IP, MAD-X predicts a loss of 0.8 $\sigma$, so that the aperture would go down to 10.3 $\sigma$. This value is then used as an alternative starting point for the scaling of the aperture to other configurations of $\beta^*$.
Table 2: Apertures measured with beam, as well as the limiting elements, for $\beta^*=40$ cm and a half crossing angle $\phi = \pm 185$ mrad (for $\phi < 0$ unless stated otherwise) at different times in 2016. Apart from in the standard collision configuration, measurements were performed with separated beams at the end of squeeze (e.o.squeeze) and at the end of the TOTEM bump beam process (e.o.TOTEM). The results are expressed in units of $\sigma$ for the nominal $\beta$-function and an emittance of $\varepsilon_n=3.5$ $\mu$m.

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<tbody>
<tr>
<td>10/4</td>
<td>Collision</td>
<td>11.3</td>
<td>Q3/D1R5</td>
<td>10.0</td>
<td>D1L</td>
<td>11.6</td>
<td>D1R1</td>
<td>10.7</td>
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<tr>
<td>17/4</td>
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<td>D1/TAN R5</td>
<td>9.9</td>
<td>D1L1</td>
<td>12.1</td>
<td>D1R1</td>
<td>10.4</td>
<td>D1R1</td>
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<tr>
<td>17/4</td>
<td>Collision</td>
<td>IR1 $\phi &gt; 0$</td>
<td>11.8</td>
<td>D1 L1</td>
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<td>D1R1</td>
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<tr>
<td>18/4</td>
<td>e.o.squeeze</td>
<td>11.5</td>
<td>D1/TAN R5</td>
<td>9.9</td>
<td>D1L1</td>
<td>11.5</td>
<td>D1R1</td>
<td>11.0</td>
<td>D1R1</td>
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<td>e.o.TOTEM</td>
<td>&gt;11.0</td>
<td>D1 L1</td>
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<tr>
<td>10/6</td>
<td>Collision</td>
<td>&gt;11.1</td>
<td>Q3/D1R5</td>
<td>10.0</td>
<td>D1L1</td>
<td>12.0</td>
<td>D1R1</td>
<td>10.0</td>
<td>D1R1</td>
</tr>
<tr>
<td>5/10</td>
<td>e.o.TOTEM</td>
<td>10.6</td>
<td>D1 L1</td>
<td>10.0</td>
<td>D1L1</td>
<td>10.8</td>
<td>D1R1</td>
<td>10.6</td>
<td>D1R1</td>
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<tr>
<td>5/10</td>
<td>e.o.TOTEM</td>
<td>IR1 $\phi &gt; 0$</td>
<td>10.6</td>
<td>D1 L1</td>
<td>10.8</td>
<td>Q2L5/D1R5</td>
<td>10.8</td>
<td>D1R1</td>
<td>11.5</td>
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It should be noted that these calculations are performed for the nominal $\beta^*=40$ cm optics, assuming the so-called V1 version of the bump as discussed in Ref. [29]. Further checks should be carried out for ATS optics.

**$\beta^*$-Reach in Various Configurations**

The previous sections give all ingredients to calculate aperture as a function of $\beta^*$, which in turn can be compared with the protected aperture in Table 1, including the 0.5 $\sigma$ safety margin. The results are shown in Fig. 3 for the crossing plane (solid lines), for different values of the beam-beam separation discussed above, and in the separation plane (dashed lines), with and without the CMS bump. In all cases, the aperture has been scaled from the measurements in Table 2, or from the estimated using the method in Ref. [11]. From Fig. 3, the achievable $\beta^*$ for various configurations can be read out directly by comparing the estimated aperture with the protected aperture. Some key values are summarized in Table 3.

As can be seen, a significant gain in $\beta^*$ is within reach. The line in Fig. 3 corresponding to the smallest beam-beam separation and the one for the separation plane aperture without the CMS bump are both above the 8.5+0.5 $\sigma$ requirement with 2017b settings at $\beta^*=30$ cm, which could thus be a possible running scenario. In this situation, the limit comes from the separation plane. Increasing to 10 $\sigma$ beam-beam separation, the crossing plane aperture takes over and limits $\beta^*=31$ cm.

If the CMS IP shift of -1 mm is included with the pessimistic assumptions discussed above, the separation plane becomes limiting in all scenarios except if the large nominal emittance is assumed. In that case the crossing plane aperture is marginally worse around the considered $\beta^*$. With the bump included, $\beta^*$ risks to be limited to 32 cm, independently of the crossing angles considered.

These $\beta^*$-values are calculated for the 2017b collimator settings. In the scenario where the TCPs are not tightened compared to 2016, the 2017a settings in Table 1 are assumed 0.5 $\sigma$ is lost on the aperture. The corresponding loss in $\beta^*$ is 3 cm.

It should be noted that two optics schemes are considered for 2017, called nominal and ATS [30,31]. Nominal optics has been used in the LHC so far, while ATS optics is the baseline for HL-LHC [32]. For the range of $\beta^*$ considered for 2017, it is possible to produce a suitable optics with both schemes, and our $\beta^*$-calculations apply to both, as long as the betatron phase advance between MKDs and TCTs is such that asynchronous beam dumps are not limiting as in 2016. Past studies showed that this is the case for fractional phase advances closer than 30° to 0° or 180°. In the considered $\beta^*$-range, the worst phase advance in nominal optics to any TCT in IR1 or IR5 is 4°-6°, while for ATS it is 25°-26°.

Even though both optics meet the 30°-target, the available safety margins are larger with nominal optics, which in turn translates into a lower probability of critical losses on the TCTs during asynchronous dumps. However, the beams could be dumped before exceeding the safe margin if interlocks are introduced on orbit drifts using the collimator BPMs [33,34]. On the other hand, it should be noted that the better chromatic properties of ATS result in a smaller deterioration of the cleaning hierarchy for off-momentum particles, which however is not judged to be critical in the considered range of $\beta^*$. It should also be studied if the impact of the CMS bump in ATS optics is similar to the effect in nominal optics. Other considerations related to the choice of optics, such as compatibility with forward physics or chromatic properties, are not treated in detail in this paper.

**Summary**

After the very successful LHC Run in 2016, where $\beta^*$ was reduced by a factor 2 to 40 cm, the luminosity production should continue with high priority in 2017. Various ways
to further decrease $\beta^*$ have been explored, in case this is needed. Based on a range of MDs and theoretical studies, it has been concluded that the collimator hierarchy can be tightened to gain 1–1.5 $\sigma$ margin compared to 2016. The proposed collimator settings are judged to be compatible both with requirements on beam cleaning, impedance, and protection. Furthermore, the beam–beam separation can be reduced compared to the startup configuration in 2016, and a corresponding decrease in crossing angle was already carried out during the year, but without decreasing $\beta^*$. Combining the various gains, a $\beta^*$ as small as 30 cm could be envisaged, depending on parameter choices. However, the picture is complicated by the unknown influence of the IP shift in CMS, which could cause a loss of 3 cm in $\beta^*$. Any intermediate $\beta^*$-scenario is also possible, e.g. $\beta^*$ =35 cm covers all scenarios in Table 3. A smaller $\beta^*$ <40 cm could be introduced directly at the startup, or in a staged approach, where the 2017 operation starts at $\beta^*$=40 cm and $\beta^*$ is reduced later, as in 2011. This would allow gaining operational experience with any other new operation mode, e.g. if a decision is taken to use ATS optics or the tighter collimation hierarchy, before pushing $\beta^*$.

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EYETS RECOVERY
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Abstract
During the winter 2016/2017 the LHC will undertake a period of maintenance, the so-called Extended Year End Stop (EYETS). Many activities will be performed during this period to solve issues as well as to increase the LHC performance. One of the main activities is the exchange of a weak magnet in sector 12. This involves warm up of the sector, magnet exchange, cool down and subsequent recommissioning, including magnet re-training. The delicate phase of recovery from the long stop and recommissioning the LHC after all interventions will be discussed.

THE TRAINING CAMPAIGN
Due to the excellent year of operation, at the end of 2016 it was decided to perform a training campaign on some of the dipole circuits. This operation was meant to increase knowledge on the process, thus enabling correct estimate of the required effort to operate the LHC at 7 TeV. The two allocated weeks were foreseen just before the Extended Year Technical Stop (EYETS). An analysis performed on historical data allowed to identify sector 34 and sector 45 as the best candidates for this exercise. Besides, it estimated the number of required quench to 25 and 24 respectively. The uncertainty on these numbers is nevertheless high as the knowledge on the process is still limited.

The target for the training exercise was set to 12 kA (nominal current for 7 TeV operation is 11850 A) and the training campaign was carried out between December 4th and 15th: between 2 and 3 quenches per day were performed. The final results of the training campaign are shown in Tab.1.

One of the key ingredient of the success was the performance of the cryogenic system. Due to the secondary quench effect, each test resulted in an average of 13 MJoule injected in the system. Despite the high energy, the cryogenic system managed to cool down the magnets and re-establish nominal condition in less than 8 hours.

Table 1: Results of training campaign

<table>
<thead>
<tr>
<th>Sector</th>
<th>Current</th>
<th>Equivalent E</th>
<th>#quenches</th>
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<tbody>
<tr>
<td>S34</td>
<td>11415 A</td>
<td>6.74 TeV</td>
<td>8</td>
</tr>
<tr>
<td>S45</td>
<td>11535 A</td>
<td>6.82 TeV</td>
<td>24</td>
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Short to ground in RB.A34
Looking at the results shown in Tab.1, a large difference in the test performed between the two sectors is clearly visible. This is due to a problem occurred on the dipole circuit RB.A34, which resulted in a stop of the training campaign for this sector. Just after a quench occurred on C12L4, the power converter detected an earth fault in the circuit. Dedicated electrical permanent showed a permanent short-to-ground on the anode lead of the cold diode of MB.C12L4, very likely at the half-moon connection. Moreover, an X-ray scan was performed (Fig.1), showing metallic debris at the level of the diode lead.

Figure 1: X-rays of the diode lead at the level of the half-moon connection for magnet C12L4, showing the presence of metallic debris.

This event is very similar to the one occurred in March 2015 during the first training campaign. As consequence, the same method was applied and the short was removed by means of a capacity current discharge. After that a test involving all circuits of the sector was carried out to verify that the quality was not compromised, but the time allocated for the training campaign was already over.

THE EYETS
After the training campaign, the Extended Year End Technical Stop (EYETS) will take place. Many activities have to be performed in a few months to allow a safe and reliable operation of the LHC in 2017. A solid baseline for the YETSs was established in 2015/2016 with the cryogenic system securing the conditions during the stop and Electrical Quality Assurance (ElQA) measurements to be performed before powering tests are carried out. Uninterruptable Power Source (UPS) and Arrêt Urgence Generale (AUG) tests are also in the frame of the YETS, as these tests proved to be crucial for ensuring safe operation.
Besides the main frame, many activities will be performed during the EYETS. The most critical one is the exchange of the dipole magnet in A31L2, due to a probable inter-turn short. This operation is delicate as it defines the critical path and it involves many teams. Beam Loss Monitors have to be dismounted and 17 vacuum sub-sectors open, before the magnet can be removed. Due to this operation, the entire sector will be warmed up to room temperature. This condition is very interesting as the powering tests will give information on the capability of the magnets to keep memory of the performed quenches after a thermal cycle. This knowledge is crucial to plan operation for the years to come.

Besides the magnet exchange, a large set of smaller interventions will be performed with non-negligible impact on the various systems and on machine operation.

THE RECOVERY

In order to re-qualify the superconducting circuits for operation, a large set of powering tests is foreseen. As for the YETS activities, also in this case a solid baseline has been established and a clear program of powering tests defined. The only exception will be sector 12 where the full set of powering tests will be performed to re-qualify the circuits after the thermal cycle. A total of 2 weeks has been allocated at the end of April for testing all superconducting circuits, plus an additional week for sector 12. About 6500 tests will have to be executed and analyzed during this period, making this operation challenging.

Before operating the machine, the so-called machine check-out has also to be performed. This includes individual system tests, plus verification of the communication and check of the control system infrastructure. Many tests of machine protection will also be performed to ensure safe operation with high energy beam. The machine check-out will start in parallel with the last part of powering tests.

2017 LHC OPERATION

With increasing demand of performance for the LHC, the operation team is working on improving the design of the cycle. Mainly two ideas are being considered.

Combined Ramp & Squeeze

The possibility to combine the energy ramp and the betatron squeeze has been addressed through systematic studies at CERN since 2011 [2,3], then proposed [4] and implemented for 2016 operation. This operation was performed about 300 times in 2016, resulting in an overall gain of about 30 hours of operation, without compromising the quality. It is then clear that a further extension of this process is very interesting from a performance point of view. The enhanced quality of dynamic optics measurements made it possible to envisage a scenario when the beams are squeezed to less than 3 meters beta* in the high luminosity points during the energy ramp. For such reason two scenarios are at the moment under investigation:

- Squeeze to 1.2 meter beta*, resulting in a gain of 257 seconds per squeeze
- Squeeze to 1 meter beta*, resulting in a gain of 306 seconds per squeeze.

Furthermore, a Machine Development study has been proposed to try to squeeze a pilot beam until 40 cm beta* during the energy ramp.

The PPLP ramp

The present energy ramp of the LHC (so-called PELP) is composed of four parts [5]:

- Parabolic to smoothly passed through the snapback phase;
- Exponential to minimize non-linear field imperfections;
- Linear;
- Parabolic to settle up.

With increase knowledge of the powering and magnetic system and thanks to the high quality of the magnetic field in the LHC, a review of this process is proposed. Some studies, in fact, are being carried out to evaluate the possibility of increasing the speed of the ramp in view of using the LHC as injector in the FCC era. A new ramp is then proposed to be used for 2017 operation. This new ramp (so called PPLP) will have the first parabolic phase untouched to smoothly transit across the snapback. The first parabola will then match a second faster parabola to get into the linear phase. Finally, the settling parabola will be slightly more aggressive than the present one. This new design would result in a gain of 10% in the ramp length (see Fig.2).

![Figure 2: Present LHC energy ramp (PELP) versus new proposed design (PPLP)](image)

CONCLUSIONS

The training quench campaign was an extremely useful exercise and gave clear indication on the effort needed to operate the LHC at 7 TeV. Some magnets have
experienced an unexpected re-training and also due to the amount of secondary quench, preliminary analysis shows a long way to reliably operate the dipole circuits at their design energy. Sector 34 was also very useful; despite of the non-completed campaign, in fact, the experience gained in removing the fault is extremely valuable. Similar event can happen at any quench and it is important to establish a method to quickly remove the short.

Many activities will be carried out during the EYETS, including a complete warm-up of a sector and a magnet exchange. Many tests will have to be performed to ensure safe operation of the LHC in a short time. The recovery from the EYETS will be challenging.

Operation in 2017 will benefit of some improvements being studied.

ACKNOWLEDGMENT
The authors wish to express their sincerest gratitude for the useful discussions to all people involved in LHC operation.

REFERENCES
WHAT CAN BE LEARNT IN RUN 2 for RUN 3 and HL-LHC RUNS


Abstract

This contribution presents an overview of the open questions on the key operational aspects and performance figures of the LHC during Run 3 and HL-LHC era, which could be tackled and answered in the current Run 2.

INTRODUCTION

LHC performance after Run 2 will be pushed thanks to the improvements implemented by the LIU project [1] during the last part of Run 3 and by the HL-LHC project [2] from Run 4 onwards (see Fig. 1). The unprecedented operational conditions can be partially reproduced during Run 2, thus providing a means to investigate and anticipate potential issues, and in view of refining the predictions about the expected performance reach resulting from the upgrade programs.

RUN 3 AND HL-LHC SCENARIOS

Run 3 is planned to be three-year long with no extended end-of-year shutdown. The LIU upgrade will allow the injectors to provide the HL-LHC emittance and bunch population \((2.3 \times 10^{11})\)pb and \(e_n = 2.1 \mu m\) at LHC injection, thus providing \(2.2 \times 10^{11}\)pb and \(e_n = 2.5 \mu m\) in collision, but only after a substantial testing that will take place during Run 3. Nevertheless, while it is reasonable to expect that smaller emittances will be available relatively early during Run 3, larger bunch population will become available in the LHC after a longer learning process [5].

The goal of Run 3 is to integrate at least a total of \(150 \text{ fb}^{-1}\) in order to reach the goal of \(300 \text{ fb}^{-1}\) since the LHC startup, which corresponds to the expected damage limit for the triplet quadrupoles (or more precisely the epoxy resin used in the MCBXs [3] and references therein). The goal implies running at about twice the LHC nominal luminosity and partially levelled, knowing that before the HL-LHC the peak luminosity will be limited by the experiments and cryogenics to \(1.75 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\) [4]. The beam parameters needed to reach the required virtual luminosity are expected to be obtained by a reduction of collimators' gaps, of \(\beta^*\), normalized crossing angle, and normalized emittance.

The goal of HL-LHC is to integrate at least \(3000 \text{ fb}^{-1}\) counting on the increased peak luminosity (made possible thanks to new detectors, cryogenics, triplet shielding), increase of the luminous region density (achieved with bunch population with small emittance, Piwinski angle with crab cavities, \(\beta^*\) reduction, possibly flat beams). At the same time, e-cloud heating has to be kept under control and a large machine availability should guarantee about 60% efficiency (defined as the ratio between the actual recorded integrated luminosity and what would result from a series of successful fills in the same allocated physics days).

Table 1 shows a summary of beam parameter for various production schemes for Run 2, together with the projection for Run 3 and HL-LHC. One expects a smooth transition between Run 2 values to HL-LHC through Run 3. The variety of beam production schemes allows to approach Run 3 and HL-LHC conditions during dedicated studies, e.g., high brightness conditions, but with small bunch population, HL-LHC bunch parameters, even if with only one bunch or short trains for high pile-up tests.

OPEN QUESTIONS AND POSSIBLE STUDIES

A selection of studies and open questions is discussed in the following sections organized by main themes.

Experiment limits

Integrated luminosity is ultimately limited by the maximum luminosities accepted by the experiments once the LHC will be able to deliver beam parameters (brightness, \(\beta^*\), small Piwinski angle) that exceed the luminosity limit since the gain from luminosity levelling saturates rapidly. It is therefore important to know with a relatively good accuracy the instantaneous luminosity limit to make realistic projection of the integrated luminosity. The detectors' limits are related to the capability to distinguish events in the presence of high pile-up. In particular, HL-LHC relies on an average of 140 to 200 events per crossing (see Fig. 2). Tests in Run 2 can be performed with few isolated bunches with high brightness and low \(\beta^*\) without crossing angle. At the same time it would be interesting to perform similar tests with trains to probe the impact of the relative long relaxation time of the calorimeters and of the whole data acquisition chain. With nominal 25 ns trains it is not possible to approach HL-LHC luminosities per bunch without LIU beams. However short 8b-4e, BCMs trains could provide larger luminosities per bunch with respect to standard 25 ns ones, at the cost of having only 8 instead of 72 consecutive 25 ns collisions.

Short, non-colliding trains have always been requested by the experiments to be used to qualify the background. Keeping those bunches stable may require large octupole currents with HL-LHC bunch parameters that adversely

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impact the luminosity lifetime of all bunches. Experiments may want to carry out studies to avoid non-colliding bunches, since it might lead to a better performance in future.

Experiments provide essential information to accelerator physicists also via the luminosity signals, which are fundamental to bring and to keep beams into collision. More than that, the luminosity measurements are used to constrain the models of beam intensity and emittance evolution, which in future might guide the luminosity leveling. In this respect, studies on improving the accuracy and publication rate of the luminosity data will be certainly beneficial.

### E-cloud uncertainties

The presence of the e-cloud limited the LHC performance in 2015 (and most likely also in 2016 if there were no break down of the SPS internal dump) due to the difficulties of the cryogenic system in coping with the generated heat load (in sectors 12, 23, 81, more than in the others) [7, 8]. Conditioning has been proven to be a viable way to mitigate e-cloud effects for Run 2 and it is the implied assumption also the following LHC and HL-LHC runs [9]. This assumption, however, is not fully validated due to a large uncertainty on the scrubbing time needed to reach the required SEY, and on the surface model that will account for the relationship between bunch population and heat load (see Fig. 3). In addition, a worrisome saturation of the scrubbing efficiency has been observed in 2016.

During Run 2, scrubbing efficiency can be studied with nominal trains and hybrid scheme, only, due to the limits in beam current. This study is nevertheless important to show whether faster scrubbing is possible at all.

Only during Run 3, thanks to the availability of LIU beams, one might validate the scaling law of e-cloud effects with bunch intensity, and hence study the scrubbing efficiency with high beam current. In these conditions the HL-LHC scenarios can be validated (see Fig. 4) and comparisons of different filling schemes options will be then possible.
Figure 2: Example of high pile-up events (about 150) in ATLAS and CMS.

Figure 3: Model of heat load for dipoles (upper) and quadrupoles (lower) as a function of bunch population and SEY. A small variation in the model parameters has a sizeable impact on the heat load (see Fig. 4) since the relationship between beam intensity and heat load is not monotonic.

Figure 4: Expected evolution of the heat load during a typical HIL-LHC fill of the HL-LHC that relies entirely the features of present models that are still speculative, see Fig. 3.

Head-On Beam-Beam effects

The deterioration of the beam quality in the presence of strong head-on beam-beam interactions generating large tune shift and spread, together with additional sources of noise (crab cavity and tune ripple) is difficult to predict. Experimental studies are needed to reduce the uncertainty of the models available and to enable more realistic predictions on the operating condition with LIU beams. First experimental studies carried out at 6.5 TeV using the ADT as a source of noise to simulate the effect of crab cavity noise, power converter ripple or ground motion, are promising with beam-beam tune shift of up to $-0.02$ [36]. Further tests with even larger tune shift of $-0.03$ and without crossing angle in IP 1 and 5 are, however, needed. The interplay of beam-beam interactions with optics and collimation system needs to be evaluated experimentally, since the tune shift due to the strong beam-beam interactions results in $\beta$-beating larger than that of the corrected optics in absence of beam-beam interaction.

The beam-beam forces for non-round beams at the IP

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are significantly different with respect to round ones. Furthermore, the effect of flat optics, in particular the reduced overlap at the IP due to linear coupling, needs to be investigated. Similarly, the effect of beam-beam forces are significantly modified when colliding with a transverse offset at the IP. While the first results are promising for 2016 nominal machine and beam parameters [36], configurations with LIU beam parameters were not tested.

Some uncertainties still remain on the coherent stability of beams with long-range collisions at the end of the squeeze [37] or colliding with a transverse offset. Direct measurements of Landau damping using beam transfer functions are needed to fully assess experimentally the combined effect of the octupoles, triplet non-linearities, lattice imperfections, e.g., coupling, and long-range beam-beam effects on the beam stability. The margins in terms of transverse damper gain against mode coupling instability of colliding beams [38] also needs to be verified experimentally.

**Collimation**

The settings of the current HL-LHC collimation baseline are shown in Tab. 2 [25]. The baseline, including low-impedance secondary collimators (TCSPM) made of MoGr, has been shown to fulfill the design requirements [26]. Nevertheless, several studies are underway or planned with the goal to investigate the potential for further improvements.

In order to verify the design assumptions on the need for one or several 11 T dipoles and dispersion suppressor collimators, it is important to continue quench tests and simulation studies with ions and protons already in Run 2. It is scheduled to install in each beam downstream of IR7 one unit of 11 T magnets and a dispersion suppressor collimator in LS2. With these units in place, further analysis of the achieved performance should be carried out to verify that adequate performance is reached, in particular for lead ions.

From the experience in 2016 [27], tighter collimator gaps are proposed for the operation in 2017 [28]. In future studies, it could therefore be investigated whether the HL-LHC baseline can approach the Run 2 collimator settings. The key aspect to achieve such a goal is to verify with beam the predicted impedance reduction from the new materials, using a TCSPM prototype that is being installed in the LHC during the 2016-2017 EYETS. Several TCSPM units are scheduled for installation in LS2 and this could be important in case LIU beams are available in Run 3.

Further studies include the exploration of the minimum achievable retraction between primary and secondary collimators in terms of cleaning constraints and the lower limit of the primary collimator, as a continuation of previous tests [29]. In order to fully profit from such a reduction, the collimation hierarchy should be consistently moved in, keeping constant retractions. However, this might be limited by the risk of damaging the TCDQ absorber during an asynchronous beam dump. It is therefore important to quantify the lower limit of the operational TCDQ setting.

Other topics include the $\beta^*$-reach, where HL-LHC could profit from the Run 2 experience. In 2016, $\beta^*$ was significantly improved thanks to a new optics with a specially matched phase advance between the dump kickers and tertiary collimators [30], and it is planned to further explore the limits on the TCT settings and the tolerances on the phase. First studies indicate that a significant gain in $\beta^*$ could be possible also for HL-LHC, if an optics is found with a better phase advance [31].

A rich program of studies exist also for non-baseline upgrades. In particular, it is important to pursue in Run 2 and Run 3 the investigations of loss spikes caused by halo losses, and how these could be mitigated by a hollow electron lens [32, 33]. Furthermore, crystal collimation is being followed up as an alternative means to improve the cleaning efficiency also for protons [34, 35].

Table 2: Collimation settings for 2017 and HL-LHC for various class of collimators and expected protected apertures at the end of squeeze. The expected protected aperture in the arc based on scaling as it was never measured at flat top. Values marked in bold contributes to the definition of the $\beta^*$ of HL-LHC.

<table>
<thead>
<tr>
<th>Settings</th>
<th>2017</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCP IR7</td>
<td>5.0</td>
<td>5.7</td>
</tr>
<tr>
<td>TCSG IR7</td>
<td>6.5</td>
<td>7.7</td>
</tr>
<tr>
<td>TCLA IR7</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>TCP IR3</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>TCLA IR3</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>TCSG IR6</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>TCDQ IR6</td>
<td>7.3</td>
<td>9.0</td>
</tr>
<tr>
<td>TCT IR1/5</td>
<td>7.5</td>
<td>10.9</td>
</tr>
<tr>
<td>TCT IR8</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Protected Ap. IR1/5</td>
<td>8.5</td>
<td>12.3</td>
</tr>
<tr>
<td>Protected Ap. IR8</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>Protected Ap. Arc</td>
<td>18</td>
<td>18</td>
</tr>
</tbody>
</table>

**Dump system**

The LHC dump system is particularly critical for the future development because the optics requirements of the insertion enter in the optimization of the collimation hierarchy and the ATS optics. In addition, LIU beams carry much larger energy densities than those that will be available in Run 2. The following studies will help reducing the uncertainty on the materials and optics constraints [10]: TDE robustness (preventing MKB failures, study new material for the TDE core and windows); investigate TCDQ gap limits due to damage with new optics and settings strategies (end the ramp with the gap needed for the lowest $\beta^*$); reduce orbit interlock tolerance for instance using BPM in use TCSP to mitigate optics constraints in IR6.
Impedance

In the LHC, 1.4 times HL-LHC single bunch brightness has already been stabilized with the Landau octupoles at 560 A. Still, there are several areas where a quantitative understanding could reduce the uncertainty in the predictions [11]: understand sporadic instabilities during the adjust process (role of the TOTEM bump or other changes) stabilized with 470 A against a prediction of about 300 A; use of 8+4+6 with full trains to confirm achieved brightness in multi-bunch and no t-cloud; confirm the impedance model with closer TCSG (see Fig. 5); continue the checks of the impedance model at injection; study $Q''$ as additional stabilizing mechanism which is less sensitive to the shape, in particular the tails, of transverse distributions [12].

Beam-beam long range effects

The reduction of the crossing angle allows reaching increased peak luminosities (in particular without crab cavities or with partial crabbing) and/or reduced pile-up density by means of levelling techniques. In addition, regardless of luminosity considerations, a smaller crossing angle reduces the radiation dose in the triplet quadrupoles, thus improving their lifetime. The main obstacle in reducing the crossing angle is the consequent reduction of luminosity lifetime due to the long-range beam-beam effects, which impacts on the DA. This effect is present in round optics, but is even more relevant for flat optics ($\beta^*_{\text{crossing plane}} > \beta^*_{\text{parallel plane}}$) where the natural HI-V compensation is cancelled and becomes even more destructive for bunches with missing interactions due to their position in the train (so-called pacman bunches) [15].

The current limits for the crossing angle reduction have been extensively explored during RUN 2 and will continue to be probed in the future. The progressive emittance reduction and a precise tune control allow for consistent reductions of the geometric crossing angle [13]. Additional compensating techniques are currently explored [36, 39].

Figure 5: Expected stable region for different collimator materials and beam parameters.

Figure 6: Expected lifetime drops as a function of the crossing angle with or without wire compensator for a scenario with large positive octupoles and large $Q''$ [14].

Figure 7: Expected dynamic aperture (DA) as a function of octupoles and $Q''$ for the ATS optics pre-squeezed to 160 cm and telescopically squeezed down to 40 cm (ATS ratio = 4). The equivalent octupole current is defined as the standard current multiplied by the ATS ratio. The DA shows better values for negative octupole polarities (see also [16]).

The main lines of study entails the use of wires bearing DC current for long-range compensation (see Fig. 6) for which new hardware has been installed in view of beam tests in 2017-2018 [17] and the leverage on negative octupole polarity whose effectiveness is enhanced by the ATS optics (see Fig. 7).

ATS Optics

HL-LHC relies on the ATS optics [18] to reach very small values of $\beta^*$ in IP 1 and 5 in the range between 20 cm to 10 cm depending on the plane and the scenarios. ATS optics can also be used for the LHC to squeeze $\beta^*$ to similar values during MD studies [19].
Table 3 shows the different optics parameter that have been tested in the machine in 2016, an ATS optics proposed for 2017 operation [20] and the equivalent for HL-LHC [2]. One can observe that already the lowest values $\beta^*$ assumed for HL-LHC have been reached, but without crossing angle and for a 20% smaller telescope factor with respect to what is needed in HL-LHC.

The studies will continue focusing flat telescopic optics (e.g. $\beta^* = 60/15 \text{ cm}$) with synergies with the BBLR wire compensation. The setup could also be used to study experimentally the HL-LHC running scenario with negative octupole current in order to verify the expected better lifetime coming from a natural compensation of the BBLR effect and Landau octupoles.

In addition an artificially large pre-squeeze optics (e.g. $\beta^* = 1.6 \text{ m}$) could be used to study aspect related to aperture and collimation cleaning in the arcs with large $\beta$ function and large orbit bumps coming from the correction of the dispersion.

**Orbit and optics control**

Optics corrections are more critical and challenging when pushing down $\beta^*$ (see Fig. 8) since the optics sensitivity with respect to quadrupole strength errors makes both the measurement and correction of $\beta^*$ less accurate [22, 23].

Non linear optics correction for the triplet and D1 may start to be needed for flat optics in LHC [24] and mandatory for HL-LHC due to the much smaller $\beta^*$ and the field quality of the new HL-LHC magnets. It is therefore important to demonstrate the feasibility and efficiency of correction strategies using the LHC as test-bed of the HL-LHC.

Orbit corrections in the HL-LHC will be more demanding, due to the reduction of the transverse beam size at the IP ($\sigma = 7 \rightarrow 5 \mu m$) when compared to the present orbit stability (see Fig. 9). In addition, orbit gymnastics has to be compatible with two additional fixed points close to the IP: namely at the crab cavity locations, and the slow varying optics condition due to $\beta^*$ levelling. Learning how to master these control issues is already possible in the LHC and can prove the feasibility of the operations in the HL-LHC. In addition, since experiments asked for HL-LHC a $\pm 2 \text{ mm}$ tolerance on the IP position, understating how to provide this flexibility through remote realignment of magnets could reduce the demands of orbit correctors required for HL-LHC and hence improve the $\beta^*$ reach.

**Instrumentation**

LHC instrumentation is continuously improving its performance as operational experience is accumulated. For Run 3 and HL-LHC, pushed-performance requirements are being refined and studies are possible to probe these new regimes.

As $\beta^*$ and $\sigma^*$ are going towards a sensible reduction (thanks to the smaller emittance in Run 3 and larger triplet aperture in HL-LHC) all aspects related to IP orbit stability and optics correction in the triplet calls for improvements in the BPM system: improved precision and reproducibility in the triplet for IP orbit control (2 $\mu$m with DOROS) to be compatible with HL-LHC IP beam size ($7 \rightarrow 5 \mu m$), development of the "synchronous orbit" mode to reduce Beam 1/Beam 2 cross talks (to be solved in HL-LHC thanks to new BPM positions and DOROS technology), improve gain linearity (up to 1%) in turn-by-turn (also called capture) mode for measuring $\beta$ function from amplitude data with AC dipole to avoid (or complement) k-modulation in the triplet.

Beam halo studies will benefit from the synchrotron radiation coronagraph. Emittance monitor, which is crucial for understanding the beam lifetime, could improve by further developing the beam gas vertex detector. Instability and multibunch diagnostics have to be consolidated in view of higher bunch intensity after LS2. Moreover, with higher peak luminosity, there is a chance that collision debris limit the measurements of beam losses in the interaction regions that will be worth investigating.
Table 3: Optics parameters for the ATS scheme proposed for 2017, tested in MD and needed for HL-LHC. LHC Aperture are extrapolated from [27] with $\sigma = 3.5 \times 10^{-6}$ $\mu$m. HL-LHC apertures use parameters defined in [21] assuming worst case scenarios for alignment imperfections.

<table>
<thead>
<tr>
<th>Settings</th>
<th>ATS 2017</th>
<th>ATS MD 2016</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta^*$ final</td>
<td>33 cm</td>
<td>10 cm</td>
<td>20 cm to 10 cm</td>
</tr>
<tr>
<td>$\beta^*$ pre-squeeze</td>
<td>40 cm</td>
<td>40 cm</td>
<td>50 cm</td>
</tr>
<tr>
<td>$\beta^*$ peak</td>
<td>7.2 km</td>
<td>24 km</td>
<td>16 km to 32 km</td>
</tr>
<tr>
<td>Crossing Angle</td>
<td>290 $\mu$rad</td>
<td>0 $\mu$rad</td>
<td>$\leq 500 \mu$rad</td>
</tr>
<tr>
<td>Aperture</td>
<td>9$\sigma$</td>
<td>6.8$\sigma$</td>
<td>$\leq 12.3\sigma$</td>
</tr>
<tr>
<td>Telescope</td>
<td>1.2</td>
<td>4</td>
<td>2.5 to 5</td>
</tr>
</tbody>
</table>

Figure 10: Linearity of DOROS orbit detectors as a function of the offset.

RF

Crab cavities are one of the pillars of HL-LHC to minimize the impact of crossing angle and longer bunches on luminosity and event pile-up density. Dedicated beam tests in the SPS with protons (see Fig. 11) will start in 2018. These tests will validate the operation of crab cavities in a high-current, high-energy CW proton circular machine. Prior to their installation in the LHC, several aspects will be studied in detail, such as the ultra-precise control of the cavity voltage and phase, the high-rate level that is significantly below the LHC availability, emittance growth, machine protection, RF non-linearity, and instabilities.

HL-LHC relies on the main RF cavities operating at 16 MV with the full-detuning line-loading compensation scheme (see Fig. 12). Full detuning has been successfully tested with reduced voltage in 2016 and will be used operationally in 2017 to lower the RF system’s power consumption and continue studies for HL-LHC (see [43] and references therein).

Concerning Run 3 and HL-LHC, it is still not clear whether the bunch length should be maximized, in order to reduce e-cloud effects, e.g., at the beginning of each run after a long shutdown, or minimized, in order to maximize luminosity. Thus it is important to understand how to operate the RF system for a large range of operational parameters. Studies on controlled emittance blow-up (see Fig. 13) and beam stabilization methods are necessary in a regime of higher intensities and/or smaller bunch lengths. The coupled-bunch instability threshold for full nominal beam with HL-LHC bunch length and smaller longitudinal emittance is yet to be determined as well.

CONCLUSION AND OUTLOOK

A large number of studies are essential to anticipate issues and elaborate realistic predictions for Run 3 and HL-LHC performance. Run 2 offers opportunities to carry out the studies thanks to the flexibility of the beam production schemes offered by the injectors.

A ranking of the studies in order of priority is necessary
to schedule them within the time available. For Run 3 it is crucial to: learn to use LIU beams, control the e-cloud, explore the flat β* potential, master levelling techniques. For the IL-LHC it is crucial to: understand scrubbing effectiveness and scaling of heat-load with bunch population, validate the chosen levelling scenario, the operation of crab cavities with high intensity and brightness beams, the main RF operations at 16 MV. Understanding how to control the halo, the field imperfections of the new magnets and the beam-beam head-on and long-range limitations will allow to narrow down the nominal operational parameters’ range and to refine performance estimates. Non-baseline scenarios, like flat optics without crab cavities, wire compensation, e-lens, 200 MHz system, should be studied in due time before it is too late for an actual implementation.

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Abstract

The experience with the Machine Development studies in the LHC over the year 2016 is reviewed. Some results are highlighted and some difficulties encountered are analysed. A statistical analysis of the Machine Development periods of 2016 is made and a rough inventory of the 2017 requests is presented.

INTRODUCTION

The Machine Development studies (MD) in 2016 have been very successful, despite some initial difficulties due to rescheduling. As is shown Fig. 1, the MD periods were finally concentrated in the second half of 2016, with the first MD taking place at the end of July, while it was originally foreseen to start two months earlier. On the initial LHC schedule 22 days of MD were foreseen, evenly spread throughout the year. The compressed schedule allowed for 20 days of MD with protons and half a day of MD with ions at the end of the run.

Nevertheless, the MDs have been very successful. This has certainly been helped by the very good machine availability experienced throughout the year, including the MD periods. The effective hours of MD per interest group is shown in Fig. 2. It shows that most MD hours were used by the collimation team (75 hours), followed by the collective effects team (67 hours).

ORGANISATION

As in recent years the organisation of the MDs has been rather strict. The requests for MDs have first to be filled in at the Website [1], from which a selection is made by the MD coordination. These MDs are then presented at the LHC Studies Working Group [2] in which no-go’s can be identified and constructive discussions between different MD participants take place.

The MDs selected are then presented for approval at the LMC, after which written procedures are to be submitted, in general 2 weeks before the MD takes place. The procedures are classified in categories A to C, of which the category C MDs are reviewed by the restricted Machine Protection Panel (rMPP).
The results of the review and the approval of the MDs are documented in EDMS. This approval is generally released a few days before the MD block starts. It has happened in 2016 that an MD has been blocked by rMPP and a spare MD took the liberated time slot.

The year 2016 was the first year in which the MD procedures have been used systematically by the operational team and a printed version was always found on the console in the CCC. As in the previous years, there was no shuffling of the schedule during the MD period. In case of unavailability of the machine the specific MD had to be recovered in a future MD block. It was possibly to stick to this strategy by planning 2 hours of recovery time after each MD taking place at full energy. These 2 hours give a large psychological advantage and for 2016 it is foreseen to include in the planning 2 hours of recovery time for MDs taking place at injection energy.

Results of the MD were presented in the LSWG meetings and a summary was again presented in the LMC. ATS-MD notes were finally written and the collection of the Run II MD notes can be found at [3]. However, at the time of the Evian workshop only 5 MD notes were published from the 56 MDs which had taken place. This can for a very large part be blamed to the large pile-up of MDs towards the end of the year.

STATISTICS AND AVAILABILITY

In 2016 there have been 20.5 days of MD scheduled. Of these 492 hours, 416 hours were actually on the schedule because of the 2 hours of recovery time after any MD taking place at top energy. 348 hours of scheduled MD took place in 2016 which is and average availability of the machine of 84 %. This is very good and identical to the overall machine availability between the TS2 and TS3 in 2016.

The is very good machine availability does mean that of the 20.5 MD days on the schedule there have been 14.5 net MD days, which is a ‘Total Efficiency’ of 70 %.

Figure 3: Availability for the different MD blocks in %.

2016 MD HIGHLIGHTS AND EXPERIENCE

The highlights of the MDs of 2016 can for a large part be seen throughout many presentation of this Evian workshop. A few of these highlights include the RF bunch flattening with a flattened longitudinal density profile; the DOROS BPMs used for transverse couple correction with a minimum of excitation; single bunch instability studies and the tests with crystal collimation. A reduction of the crossing angle in collision to 140 μrad was applied during physics in 2016, following the good MD results. The full detuning of the accelerating RF cavities, which is crucial for operation with HL beam intensities, was successfully tested. Other MDs worth mentioning are the extraction of chromaticity values from the Schottky sidebands and high pile-up measurements for the high lumi experiments, with record beam-beam tune shifts just below 0.02.

The ATS optics was commissioned over several MD blocks with β* down to 10 cm and down to 33 cm in collisions. This ATS optics is a good candidate for 2017 operation. This is supported by the proven margin on the aperture and collimation settings, with possible primary collimation settings down to 5.5 μm.

There have been 15 so called End-of-Fill MDs. For these MD procedures have also been written and approved by rMPP. These MDs have been very useful and is an extremely efficient use of machine time.

There has been a single 12 hour ion MD. However, as the MD was moved with very little notice, the use of the parallel beam was not that well organised and not ideal from a machine protection point of view. These last minutes changes and not well organised MDs (in this case for the parallel beam only) should be avoided in the future.

INVENTORY OF 2017 MD REQUESTS

A brief survey of the key MD users was made by email concerning their requirements for MDs in 2017. This resulted in a ‘request’ of 85 different MDs with a total time requirement of 748 hours. Assuming the very good 2016 MD efficiency, this would need 44 days of MDs on the 2017 LHC schedule. There was also a request of 72 hours for End-of-Fill MDs. The distribution of the requested MD time over the different MD users is shown in Fig. 4, together with the numbers for 2016. It are the requests from the ABP group for collective effect studies and for optics studies which have increased the most compared to the 2016 numbers. According to a classification of these MDs by the users and the MD coordinators, 44 % of the MDs are related directly to LHC operation, 45 % to the future HL-LHC and 11 % to FCC.

The 44 days of dedicated MD requests need to be compared to the 15 days of MDs presently on the 2017 MD schedule.
CONCLUSIONS

The Machine Development studies in 2016 have been very successful. The net efficiency during the MDs in 2016, taking into account machine availability and recovery time between MDs, was 70%. The availability during scheduled MD time was 84%, very similar to availability during normal operation. Many interesting results of the MDs have been presented in this Evian workshop. The results are important for the short term LHC operation, but also for future machines like HL-LHC and FCC.

The recovery and clean-up of settings after the MDs can still be improved. The plan is to be even more explicit in the MD procedures. However, it is the responsibility of the OP team to carefully follow this up and roll-back any changes.

The short MD blocks are easier to manage for the MD participants than the longer MD blocks, which exhaust the people involved in several MDs.

A rough inventory of 2017 MD requests has been made. The requested 44 days of MD time are in strong contrast to the 15 days of MD presently on the schedule. Additional MD time of 3 days, as floating MD, is requested for 2017.

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