Beam intensity limitations

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This work is part of HiLumi LHC Work Package 2: Accelerator Physics & Performance.
This document is the final deliverable report of the Task 2.4, where the collective effects are discussed (except beam-beam, which is treated in Task 2.5). The LHC experience during Run I (which finished at the end of 2012 for the high-intensity proton operation) is first reviewed. Then, predictions are made with the HL-LHC parameters [1] for the Intra-Beam Scattering, the longitudinal and transverse impedance models, the beam-induced heating, the impedance-induced instabilities in both the longitudinal and transverse planes and with a single or a double harmonic RF system, the limitations from electron cloud and some beam-beam effects on transverse beam stability.
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### Delivery Slip

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Executive summary

This document is the final deliverable report of the Task 2.4, where the collective effects are discussed (except beam-beam, which is treated in Task 2.5). The LHC experience during Run I (which finished at the end of 2012 for the high-intensity proton operation) is first reviewed. Then, predictions are made with the HL-LHC parameters [1] for the Intra-Beam Scattering, the longitudinal and transverse impedance models, the beam-induced heating, the impedance-induced instabilities in both the longitudinal and transverse planes and with a single or a double harmonic RF system, the limitations from electron cloud and some beam-beam effects on transverse beam stability.

1. INTRODUCTION

Section 2 is devoted to the LHC experience during Run I, Section 3 to Intra-Beam Scattering (IBS) and Section 4 to the impedance model. Beam-induced RF heating is then discussed in Section 5, while the impedance-induced longitudinal and transverse instabilities are treated in Section 6 and 7 respectively, for both cases of a single and a double RF system. The electron cloud effects are examined in Section 8 and some beam-beam effects on transverse beam stability are analysed in Section 9. Finally, the conclusions and future work are summarized in Section 10.

2. LHC EXPERIENCE DURING RUN I

At the end of Run I a record peak luminosity of ~ 77% of the design luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ has been reached at 4 TeV with a betatron function ($\beta^*$) at the High Luminosity Interaction Points (IPs) 1 and 5 of 60 cm, with 1374 colliding bunches spaced by 50 ns with $\sim 1.6 \times 10^{11}$ p/b within transverse rms normalized emittances at the start of the fills of $\sim 2.5 \mu\text{m}$ ($\sim 2.2 \mu\text{m}$ was also reached). This means that the bunch brightness was more than 2 times larger than nominal. However, several types of instabilities perturbed the intensity ramp-up and transverse coherent instabilities have been observed in various phases of the cycle [2,3]: at injection, during acceleration at ~ 2 TeV with a nominal single bunch (without Landau octupoles in 2010), at flat-top (before the betatron squeeze), at the end of the squeeze, in adjust and in stable beams. All the observed instabilities could be cured except the instability at the end of the squeeze, which was still present at the end of the Run I and which represents therefore a potential worry for future operation at higher energy, higher beam intensity and high beam brightness.

The knobs, which are available to damp the transverse coherent instabilities, are:

1) Transverse tunes (and tune splits between the 2 beams),
2) Linear coupling between the transverse planes,
3) Chromaticities (value and sign),
4) (Landau) octupoles (value and sign),
5) Transverse damper, called ADT, (gain and bandwidth: either not fully flat / bunch-by-bunch or flat / bunch-by-bunch),
6) Bunch length and / or longitudinal profile.

The initial recommended settings at the beginning of the 2012 run (based on single-beam impedance considerations) were:

1) 1-2 units of chromaticity ($Q^*$) in both horizontal and vertical planes,
2) -450 A in the focusing Landau octupoles (as -200 A were used at the end of 2011 and the transverse impedance should have increased by a factor 2.3 due to the tight collimators setting, according to the impedance model),

3) An increased rms bunch length from 9 cm used in 2011 to 10 cm to minimize beam-induced RF heating. The effect on single-beam stability is expected to be limited taking into account the effect of the non-linear chromaticity $Q''$ introduced by the Landau octupoles, which can reduce the longitudinal tune spread \[4\],

4) Reduced ADT gain to avoid unnecessary noise.

During the 2012 run it was decided at some point to change the sign of the Landau octupoles as the tune spread induced by beam-beam and octupoles had opposite sign \[5\], reducing the available tune spread for Landau damping and a series of instabilities were observed in the horizontal plane during the squeeze and when going in collision in IP1 and 5. Furthermore, new values for the ADT gain, the chromaticities and the Landau octupoles were suggested after the implementation of a new analytical approach \[6\]. It was then decided to run with about maximum ADT gain (i.e. with a damping time of 50 turns), high chromaticity (+15-20 units) and high focusing Landau octupoles current (+ 500 A). In parallel, many studies have also been performed with beam-beam: stability diagrams with both octupoles and beam-beam \[7\], mode coupling with both impedance and beam-beam \[8,9\]. At the end of the Run I, the observations for the instability at the end of the squeeze can be summarized as follows:

1) It is observed only with 2 beams,
2) It is observed only for $\beta^*$ smaller than about 1.5 m,
3) It affects only a few bunches at the very end of bunch trains,
4) The rise-time increases with the octupole current,
5) The rise-time increases with the chromaticity,
6) It is very reproducible and mostly in the vertical plane of Beam 1,
7) Once in collision, no instability is observed anymore.

Possible explanations were proposed, such as a modification of the stability diagram in the presence of a transverse damper and noise \[9\], or a three-beam instability involving also electron cloud \[10\].

The sign of the Landau octupoles current is an important knob as for a positive current in the focusing octupoles (LOF > 0) a positive amplitude detuning is generated while for a negative current in the focusing octupoles (LOF < 0) a negative amplitude detuning is introduced. This amplitude detuning will then add or subtract to the amplitude detunings coming from

1) Space charge, whose amplitude detuning is positive,
2) Beam-Beam (both Head-On – BBHO - and Long-Range - BBLR), whose amplitude detuning is also positive,
3) Electron cloud, whose amplitude detuning is negative (at least for single bunch effects).

The beam-induced RF heating of some equipment was also a major concern, which has been closely followed up to assess all the possible future limitations \[11\]. Some successful impedance reductions have been already achieved, as for instance on a module of the injection kickers \[12\] but further modifications will be required for the HL-LHC era.

Finally, initial tests with bunches spaced by 25 ns (instead of 50 ns as used in Run I) were encouraging with respect to the mechanisms linked to electrons cloud but this beam still need to be studied in more detail in the LHC to identify possible bottlenecks. In parallel, the
operating experience with electron cloud clearing electrodes at DAFNE has been reviewed [13,14,15], revealing a very beneficial impact of clearing electrodes.

3. **INTRA-BEAM SCATTERING**

IBS in the LHC proton beams will be stronger in the future HL-LHC [16] than at present because of the higher beam intensities, small emittances and new ATS (Achromatic Telescopic Squeezing) optics [17]. The luminosity decay will be due to both IBS and “burn-off” by the luminosity. The IBS emittance growth rates have been computed with MADX [18] and the Collider Time Evolution (CTE) program [19,20] for two ATS optics versions, ATS-V6.503 [21] and SLHCv3.1b [22], and different settings of the crossing angle and required corrections. The calculations were done for injection (450 GeV) and collision (7 TeV) energy for various beam conditions. Moreover, CTE simulations of the emittance, bunch length, intensity and luminosity evolution during a fill have been performed. Similar studies for the LHC in 2012 can be found in Ref. [23].

The growth rates increase with increasing intensity and decreasing emittance, leading to stronger IBS effects for the beam parameters of the beam spaced by 50 ns as compared to 25 ns. Furthermore, higher IBS growth rates at injection are due to the lower energy and the smaller longitudinal emittance (see Table 1, where it can be seen the growth times of ~ 10 h at injection and ~ 20 h in collision are expected).

Throughout the squeeze to $\beta^*$ values as low as 10 cm, using the ATS optics scheme, the longitudinal IBS growth rate improves by about 20%, whereas the horizontal growth rate increases by about 20%. The reason for this was understood in detail by investigating the local IBS contributions around the ring, where the growth in the horizontal plane strongly depends on the lattice. The dependence on the lattice parameters of the longitudinal growth is less dominant and hence the average longitudinal IBS contribution is even reduced. The calculations for the flat machine compared to a setup with crossing angle and dispersion correction are in very good agreement. For a machine with uncorrected dispersion after introducing the crossing angle the transverse growth rates rise while the longitudinal one is improved. It has to be noted that the vertical growth rate can be neglected in a corrected machine, but may become comparable with the horizontal and longitudinal plane in the presence of vertical dispersion (even without significant betatron coupling). The correction of the spurious dispersion, in particular for the vertical plane, is a new feature of the ATS optics which is not available for the nominal optics.

The effect of radiation damping turns out to have a positive effect on the emittance growth, and even leads to a decreasing bunch length.
Table 1: Summary of the HL-LHC beam parameters and the corresponding IBS growth rates calculated with MADX for the ATS-V6.503 optics version at injection and collision energy.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>$E$ [GeV]</td>
<td>450</td>
<td>7000</td>
<td>450</td>
<td>7000</td>
</tr>
<tr>
<td>$\beta^*$ [m]</td>
<td>11</td>
<td>0.15</td>
<td>11</td>
<td>0.15</td>
</tr>
<tr>
<td>$N_b$ [$10^{11}$ charges]</td>
<td>2.2</td>
<td>3.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\epsilon_n$ [µrad]</td>
<td>2.5</td>
<td>3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\epsilon_l$ [eVs]</td>
<td>1.0</td>
<td>2.5</td>
<td>1.0</td>
<td>2.5</td>
</tr>
<tr>
<td>$\alpha_{IBS,1}$ [1/h]</td>
<td>0.096</td>
<td>0.049</td>
<td>0.124</td>
<td>0.062</td>
</tr>
<tr>
<td>$\alpha_{IBS,2}$ [1/h]</td>
<td>0.096</td>
<td>0.054</td>
<td>0.103</td>
<td>0.058</td>
</tr>
<tr>
<td>$\alpha_{IBS,3}$ [1/h]</td>
<td>$-6.4 \times 10^{-4}$</td>
<td>$-1.5 \times 10^{-6}$</td>
<td>$-6.9 \times 10^{-4}$</td>
<td>$-1.6 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

4. IMPEDANCE MODEL

The construction of the impedance model is the first very important step before starting to make beam stability analyses, to study the interplay with other mechanisms such as beam-beam or electron cloud, and to try and optimize the beam parameters [24].

Up to now, the LHC impedance model included the contributions (all weighted by the local beta functions for the transverse plane) of: (i) the resistive-wall impedance of collimators; (ii) the resistive-wall impedance of beam screens and warm vacuum pipe (with several different cross-sections); and (iii) a broad-band model from the design report [25], including pumping holes, Beam Position Monitors (BPMs), bellows, vacuum valves, the geometric impedance of collimators (assuming round tapers) and other Beam Instrumentation (BI) instruments. This first model was initially developed to account well for the transverse coupled-bunch instabilities, whose most critical frequency range is quite low, from ~ 8 kHz to ~ 40 MHz.

A comparison between HEADTAIL [26] simulations and measurements of the transverse coupled-bunch instability rise-time vs. chromaticity revealed a good agreement at 450 GeV [27]. At 3.5 TeV, the measured rise-time was larger by a factor ~ 2-3 but a higher uncertainty on the values of the chromaticity was expected due to the octupole feed-down errors which were not correctly taken into account at that time.

A comparison between HEADTAIL simulations and measurements of the transverse coherent tune shifts (when moving collimator families at 4 TeV with $Q' \sim 1-5$) revealed a factor ~ 2 (and a factor ~ 3 at injection) discrepancy [28]. This is a good result, considering the complexity of all the parameters playing a role in the effective impedance and such a factor 2 was also observed in many other machines in the past. However, the impedance model has been refined recently to try and understand this discrepancy factor.

Three possible explanations for this discrepancy were proposed and studied: (i) the effect of finite length on the collimator impedance model, (ii) the change of the resistivity of the collimator jaws (for instance due to the effect of radiation over the years), and (iii) the collimator geometrical impedance contribution.
The example of the dipolar impedance of a carbon collimator (with a resistivity of 10 μΩm) reveals a relative increase of the low-frequency part (reactive impedance) but only for very short lengths. This effect is negligible for long (meters) devices and therefore for the LHC collimators [29].

The primary (TCP) and secondary (TCS) collimators (made of CFC, whose resistivity has been measured to be 5 μΩm, which is the value assumed to build the impedance model [27]) are more exposed to radiation and their resistivity might therefore increase with time (ageing). As can be seen in Fig. 1, an increase of the resistivity by a factor ~ 4 is needed to explain a tune shift discrepancy by a factor ~ 2. As we don’t have for the moment a measurement of the actual resistivity, the initial resistivity of 5 μΩm is still assumed.

An important new result is that the contribution of the geometric impedance dominates the impedance of the tungsten collimators for all the considered gaps between the jaws, and the geometric impedance is not negligible with respect to the resistive-wall impedance of (relatively opened) CFC collimators (in IR6, or TCP/TCS at injection) (see Fig. 2 left) [30]. As concerns the beam screen presently installed in the LHC, the effect of the longitudinal weld has been modeled, using 3D CST [31] simulations, by a frequency dependent factor which can be more than 2 for the dipolar horizontal impedance (see Fig. 2 right) [32]. This result has been found to be very weakly dependent on the beam screen size.

![Figure 1: Effect of the electrical resistivity on the coherent tune shift.](image)
Figure 2: (Left) geometric transverse kick factor of current collimators (red) compared to the resistive-wall component for CFC (blue) and tungsten (green) as a function of the half-gap in mm [30]. (Right) impact of the longitudinal weld on the resistive-wall impedance of beam screen (the factor G is defined with respect to the same structure but without the longitudinal weld) [32].

A comparison between the “new” (updated) and the “old” (previous) impedance model reveals that the low-frequency part remains the same whereas the high-frequency one has been increased by 40% close to 1 GHz, which explains 10-15% of the discrepancy observed on the transverse coherent tune shifts.

The first important modification during the HL-LHC era will be the change of the beta functions due to the ATS optics [17]. The beta functions will be much higher in IR1 and 5, but also in the arcs due to the very principle of the ATS optics.

The other changes will be: (i) possible Molybdenum or Mo-coated (or even better a coating of Molybdenum on a composite made of Molybdenum and graphite, called MoC or Mo-Gr) secondary collimators to improve the electric conductivity; (ii) different geometric impedance of new collimators with BPM buttons (installed during LS1); (iii) new triplet region with new apertures, tapers and BPMs; (iv) new CMS and ATLAS vacuum chamber transitions; (v) crab cavities and possibly (vi) beam-beam wire compensators.

A first estimate of the transverse impedance for HL-LHC is shown in Fig. 3 for the vertical dipolar impedance only, considering neither the crab cavities nor the beam-beam wire compensators, without and with Mo collimators for the TCS in IR3 and IR7, which are very efficient to decrease the total impedance.

Taking into account both crab cavities and beam-beam wire compensators, it can be seen in Fig. 4 (a) that only the crab cavities have a significant (visible in the log-log plot) effect on the vertical dipolar impedance. The horizontal dipolar impedance and longitudinal impedance are depicted in Fig. 4 (b) and (c) respectively.

The detailed contributions of the various components of the vertical dipolar impedance are shown in Fig. 5, where it can be seen that the main impedance contributors are the collimators (resistive-wall and geometric effects), the pumping holes and the crab cavities.
Figure 3: First estimate of the vertical dipolar impedance compared to LHC. Crab cavities and beam-beam wire compensators are not included. The impact of the replacement of the CFC secondary collimators (TCS) with Molybdenum ones in LSS3 and LSS7 is clearly visible in the small box.
Figure 4: First estimate of the (a) vertical dipolar impedance of HL-LHC compared to LHC, including both crab cavities and beam-beam wire compensators, (b) horizontal dipolar impedance and (c) longitudinal impedance.

Figure 5: Detailed contributions of the various components of the HL-LHC vertical dipolar impedance: (left) real part of the impedance and (right) imaginary part.
5. BEAM-INDUCED RF HEATING

Both the impedance and the electron cloud (see Section 8) induce heat loads on the cryogenics system [33]. The computations of the impedance-induced heat loads with the HL-LHC beam parameters [1] for several key systems are summarized in Table 2. In the analysis it is assumed that no forward physics detectors (e.g. ALFA and TOTEM) will be installed during the HL-LHC era. For the beam screens, these values have to be compared with the beam screen heat load local limit (due to the dimensions of the beam screen capillaries), which is 2.4 W/m/aperture, i.e. 4.8 W/m (for both apertures). There is also a global limit for the cryo-plant, which is 3.8 W/m.

Table 2: Summary of the impedance-induced heat load computations for several key systems.

<table>
<thead>
<tr>
<th>Element</th>
<th>Expected heat load [W]</th>
<th>Conclusion / comment</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment with RF fingers</td>
<td>Negligible for conforming RF fingers</td>
<td>Robust mechanical and quality control required during the installation phase</td>
<td>[34]</td>
</tr>
<tr>
<td>Experimental beam pipes (resonant modes)</td>
<td>ATLAS: no significant mode expected. ALICE: potentially* more than 1 kW. CMS: potentially* more than 350 W. LHCb: potentially* more than 250 W (* if the longitudinal modes overlap with beam harmonic frequencies)</td>
<td>During Run II, the temperature should be closely monitored in the large diameter regions of ALICE, CMS and LHCb. The impact of these potentially expected heat loads on hardware integrity and outgassing should be assessed</td>
<td>[35-39]</td>
</tr>
<tr>
<td>All types of beam screens</td>
<td>See Table 3, where the power losses have been computed vs. temperature (between 20 K and 70 K)</td>
<td>The effects of the longitudinal weld, the two counter-rotating beams and the magneto-resistance have been taken into account. Decoupling of the cryogenics for the IR elements and the RF will provide more margin for the acceptable heat load in the arcs</td>
<td>[40] and Table 3</td>
</tr>
<tr>
<td>Triplet Beam Position Monitors</td>
<td>0.2 W/m for the (most critical) 50 ns beam</td>
<td>This assumes no interferences between the two beams electromagnetic fields (worst case) and copper coating</td>
<td>[41]</td>
</tr>
<tr>
<td>New collimators with integrated BPMs and ferrites</td>
<td>100 W (of which 5 to 7 W would be dissipated in the ferrites, and 4 to 6 W in the RF fingers)</td>
<td>More thorough simulation studies as well as bench measurements are under way to confirm these results. This should be acceptable</td>
<td>[42]</td>
</tr>
<tr>
<td>Injection kickers (MKIs)</td>
<td>Between 125 W/m and 191 W/m (based on measurements of 9 MKIs upgraded to have the full complement of 24 screen conductors). For comparison, most of the MKIs before the LS1, had a power deposition of 70 W/m (which did not limit the LHC operation)</td>
<td>It is of the order of heat loads (160 W) estimated with pre-LS1 parameters for the MKI8D for which a non-conformity was found. This required significant time to cool down after physics fills. For HL-LHC we are looking at: (i) further reducing the power deposition; (ii) improving the cooling; (iii) using high Curie point ferrites</td>
<td>[43,44]</td>
</tr>
<tr>
<td>Crab cavities</td>
<td>In the multi kW range if the longitudinal modes overlap</td>
<td>The design should allow detuning the longitudinal modes from multiples of</td>
<td>[45]</td>
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### BEAM INTENSITY LIMITATIONS

<table>
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<th>with beam harmonic frequencies</th>
<th>20 MHz by ~0.5 MHz</th>
<th>[38]</th>
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<tr>
<td>Injection protection dump (TDI)</td>
<td>The present design already suffers from beam induced heating (in the kW range for the injection settings) with nominal LHC parameters due to inefficient cooling.</td>
<td>The present design of the TDI is not compatible with the HL-LHC parameters and a new design is being studied, with installation foreseen for LS2.</td>
</tr>
<tr>
<td>Synchrotron Radiation Monitor (BSRT)</td>
<td>The power deposited in the ferrite absorbers (heated at ~250-350 deg according to simulations and measurements) during 2012 operation could not be efficiently transferred leading to damage.</td>
<td>A new design is being studied and installed during LS1. The usability of this design for HL-LHC will need to be assessed after LS1.</td>
</tr>
</tbody>
</table>

**Table 3: Summary of the impedance-induced heat load computations for the different types of beam screens (taking into account the effects of the longitudinal weld, the two counter-rotating beams and the magneto-resistance) vs. temperature: the values are given for both the 25 ns beam and for the 50 ns beam (in parenthesis).**

<table>
<thead>
<tr>
<th>Power loss [W/m]</th>
<th>20 K</th>
<th>30 K</th>
<th>40 K</th>
<th>50 K</th>
<th>60 K</th>
<th>70 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1 (49 mm – 6.9 T)</td>
<td>0.23 (0.28)</td>
<td>0.24 (0.31)</td>
<td>0.28 (0.35)</td>
<td>0.34 (0.43)</td>
<td>0.40 (0.51)</td>
<td>0.47 (0.59)</td>
</tr>
<tr>
<td>Q2-Q3 (59 mm – 8.3 T)</td>
<td>0.19 (0.24)</td>
<td>0.20 (0.26)</td>
<td>0.23 (0.29)</td>
<td>0.28 (0.35)</td>
<td>0.33 (0.42)</td>
<td>0.38 (0.49)</td>
</tr>
<tr>
<td>D1 (59 mm – 5.6 T)</td>
<td>0.17 (0.22)</td>
<td>0.19 (0.24)</td>
<td>0.22 (0.28)</td>
<td>0.27 (0.34)</td>
<td>0.32 (0.41)</td>
<td>0.38 (0.48)</td>
</tr>
<tr>
<td>D2 (42 mm – 4.5 T)</td>
<td>0.25 (0.32)</td>
<td>0.27 (0.34)</td>
<td>0.32 (0.40)</td>
<td>0.39 (0.50)</td>
<td>0.47 (0.59)</td>
<td>0.54 (0.69)</td>
</tr>
<tr>
<td>Q4 (32 mm – 3.7 T)</td>
<td>0.34 (0.43)</td>
<td>0.37 (0.47)</td>
<td>0.44 (0.56)</td>
<td>0.54 (0.68)</td>
<td>0.64 (0.81)</td>
<td>0.74 (0.94)</td>
</tr>
<tr>
<td>Q5 (22 mm – 4.4 T)</td>
<td>0.59 (0.74)</td>
<td>0.63 (0.80)</td>
<td>0.72 (0.91)</td>
<td>0.86 (1.09)</td>
<td>1.01 (1.28)</td>
<td>1.16 (1.46)</td>
</tr>
<tr>
<td>Q6 (17.7 mm – 3.5 T)</td>
<td>0.79 (0.99)</td>
<td>0.84 (1.06)</td>
<td>0.96 (1.22)</td>
<td>1.14 (1.44)</td>
<td>1.32 (1.68)</td>
<td>1.51 (1.91)</td>
</tr>
<tr>
<td>Q7 (17.2 mm – 3.4 T)</td>
<td>0.82 (1.03)</td>
<td>0.87 (1.11)</td>
<td>1.00 (1.26)</td>
<td>1.18 (1.49)</td>
<td>1.37 (1.74)</td>
<td>1.56 (1.98)</td>
</tr>
</tbody>
</table>

### 6. IMPEDANCE-INDUCED LONGITUDINAL INSTABILITIES

The LHC longitudinal collective effects (with the current 1 RF system operating at 400 MHz) are first reviewed in Section 6.1 before extrapolating to HL-LHC and discussing the case of 2 RF systems in Section 6.2.

#### 6.1. WITH 1 RF SYSTEM

The LHC longitudinal impedance is predicted be very small according to Refs. [25,47], where the imaginary part of the longitudinal effective impedance was expected to be \( \text{Im} \frac{Z}{n} \approx 0.1 \Omega \). This value is much smaller than that of the CERN SPS (4 \( \Omega \)) and that of the CERN PS (20 \( \Omega \)), which makes it difficult to measure with beam using the existing methods. Furthermore, it should be mentioned that there is no longitudinal instability in the LHC for operational beam parameters (so far). Some single-bunch instabilities were observed during the ramp at the very beginning of Run I due to the very small longitudinal emittance used but it was rapidly cured by controlled longitudinal emittance blow-up.

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There is a relatively good agreement between measurements and the simple theory of loss of Landau damping. However, simulations suggest that: (i) the bunches are shorter than measured; (ii) the impedance is larger than predicted by a factor ~ 3; (iii) different criteria are needed to decide whether some oscillations are damped or not.

The comparison between LHC measurements and simulations is still ongoing. Using as reference single bunch measurements at 4 TeV, whose intensity threshold was $10^{11}$ p/b for and RF voltage of 12 MV, a longitudinal emittance of 1 eVs and a $4\sigma$ bunch length of 0.8 ns (scaled from the measurement of the full width at half maximum) and scaling to HL-LHC parameters (16 MV, 2.5 eVs) leads to an intensity threshold of $3.4 \times 10^{11}$ p/b.

### 6.2. WITH 2 RF SYSTEMS

So far a double RF system [50-55] is not necessary for beam stability in the longitudinal plane. A preliminary cavity design of the 800 MHz RF system for LHC exists [56] and some tests of the effect of a “flat” bunch distribution in a single RF system on beam-induced RF heating were performed in the LHC in 2012. A double RF system can be used to (i) modify the line density distribution (“flat” bunches in Bunch Lengthening Mode - BLM); (ii) to increase the synchrotron frequency spread for beam stability (BLM or BSM – Bunch Shortening Mode); (iii) to increase the RF bucket size (only BLM). It must be noted that a flat longitudinal distribution can be achieved with a single RF system by applying a band-limited RF noise but the concurrent effect of IBS, RF noise and synchrotron radiation must be evaluated.

Recently, the use of a low harmonic RF system in the LHC (200 MHz) as the fundamental RF system has been suggested [57] with the following motivations: (i) it provides longer bunches, reducing (although marginally) the pile-up density for the experiments; (ii) together with the existing 400 MHz RF system, it could be used for luminosity levelling; (iii) it could help accepting longer bunches and therefore higher bunch population from the SPS; (iv) it could help to improve IBS, beam-induced RF heating and electron cloud effects; (v) it also has a beneficial effect for ions and the momentum slip-stacking scheme in the SPS [58]; (vi) a new design has been proposed for a compact superconducting cavity [59].

In 2012, a voltage of 12 MV led (at 4 TeV) to a longitudinal emittance of 2.2 eVs and a full ($4\sigma$) bunch length of 1.25 ns. To have the same bunch stability at 7 TeV, we would need a longitudinal emittance of 3.0 eVs in 400 MHz and 4.0 eVs in a single 200 MHz RF system. It must be noted that the 200 MHz RF system should be used together with the 400 MHz RF (as a high harmonic system) in BSM to preserve beam stability as for the same longitudinal emittance the stability threshold (proportional to $h^2$, where $h$ is the harmonic number) is 4 times lower while in a double RF system in BLM, the limit on the bunch length would be 3.4 ns to avoid the loss of Landau damping.

Finally, the expected benefits of a double RF system should be weighted against the impedance increase and the possible reduced reliability.

### 7. IMPEDANCE-INDUCED TRANSVERSE INSTABILITIES

Using the transverse impedance model described in Section 4, the transverse instabilities have been studied using both the HEADTAIL tracking code [26] and the newly developed analytic Vlasov solver for impedance-driven modes (called DELPHI) [60]. Note that other codes have
been developed in the past to solve the Vlasov equation [6,61]. Some can include multi-bunch operation, chromaticity, amplitude detuning and transverse damper, but they all consider linearised longitudinal motion and only dipole wake fields, which can be a significant limitation for the HL-LHC case.

### 7.1. WITH 1 RF SYSTEM

Assuming an ideal bunch-by-bunch transverse damper (with a damping time of 50 turns), no Landau octupoles, a linear RF bucket and considering only the dipolar impedance, the horizontal single-bunch imaginary tune shift (for the bunch population of $1.5 \times 10^{11}$ p/b, which was used in the LHC in 2012) vs chromaticity ($Q'$) revealed a very good agreement between HEADTAIL and DELPHI.

If one looks at the Transverse Mode-Coupling Instability (TMCI) intensity threshold for a single bunch with a chromaticity $Q' = 0$, in the horizontal plane (a similar result is obtained for the vertical one), without transverse damper, a relatively good agreement is reached between HEADTAIL and DELPHI and HL-LHC should be very similar to the LHC in 2012, with an intensity threshold slightly higher (between $3.5$ and $4 \times 10^{11}$ p/b), which confirms the result of Ref. [62, slide 5].

If one now looks in more detail at the effect of the crab cavities (e.g. from ODU/SLAC), which are modelled as a set of HOMs (High Order Modes) [63], the effects on both single-bunch and multi-bunch stability are significant and more important for the multi-bunch case. These crab cavities are therefore a potential worry for the future transverse beam stability.

Low impedance collimators (as described in Section 4) have a clear impact on the transverse impedance and beam stability in the worst case of collision collimation settings provided the transverse damper is active. A coating of $5 \text{µm}$ of Molybdenum seems to be the good choice (ideally even on Mo-Gr instead of CFC in case of degradation of the coating). Low impedance collimators double the TMCI threshold (in the absence of crab cavities) with collision collimation settings. The TMCI intensity threshold at injection is already quite high ($5 \times 10^{11}$ p/b) even with the present collimators.

If one tries to extrapolate the HL-LHC single-beam stability limits (intensity vs. transverse emittance) from the LHC 2012 worst instabilities observed, Fig. 6 is obtained in the presence of the transverse damper. This shows that if the instabilities observed in 2012 were mainly single-bunch (i.e. even in the presence of the damper) we will not be able to stabilize the HL-LHC beams in the case of the CFC collimators and ODU/SLAC crab cavities, but beam stability could be recovered with low impedance (Mo-coated) collimators. Note that the situation improves with the negative polarity of the Landau octupoles, but the results are qualitatively the same. Note that if the instabilities observed in 2012 were mainly coupled-bunch (i.e. not damped by the transverse damper), we will not be able to stabilize the HL-LHC beams for any scenario. In this case, the Mo collimators would make the situation even worse. Here again, negative polarity of the Landau octupoles improves the situation, but the results are qualitatively the same.
Figure 6: Single-beam (25 ns) intensity limit vs. transverse emittance with transverse damper (50-turn damping time) at top energy, for a chromaticity $Q' \sim 15$ for the two extreme cases (CFC collimators with ODU/SLAC crab cavities and Mo-coated collimators without crab cavities) and for positive polarity of the Landau octupoles. The values and names for the different HL-LHC beams have been used assuming the most critical case of the beam parameters at injection (as the expected beam loss and emittance blow-up are not very well known).

7.2. WITH 2 RF SYSTEMS

Both the longitudinal phase space profile and the incoherent synchrotron tune spectrum have an influence on the transverse beam stability. The effect of two RF systems, the main one at 400 MHz and a double harmonic one (800 MHz) in both BSM and BLM (see Section 6.2), on the transverse beam stability is discussed in this section, using the HL-LHC transverse impedance model of Section 4 [64].

For the longitudinal plane, the increase in tune spread obtained with a double harmonic system gives rise to increased Landau damping. The longitudinal tune spread may translate into an increased spread in the transverse plane which may also lead to improved Landau damping. However, it is also known, that the synchrotron tune itself plays an important role for the transverse beam stability. To address the beam dynamics in the presence of collective effects, taking into account the nonlinear synchrotron motion in the multi-harmonic RF systems together with the HL-LHC impedance model, macroparticle tracking codes need to be incorporated. All simulations were performed using PyHEADTAIL which is a recent advancement of the HEADTAIL code. The 3 modes of operation described in Table 4 have
been considered. In addition the effect of small phase errors was studied for the BLM (± 5 deg). This was done, since any phase error in BLM immediately has a strong impact on the tune spectrum as the two voltages do no longer cancel for small amplitude particles.

Table 4: Parameters of the double harmonic RF system for the different operation modes. The stable phase above transition is assumed to be $\pi$.

<table>
<thead>
<tr>
<th></th>
<th>Single RF</th>
<th>Bunch shortening mode</th>
<th>Bunch lengthening mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>V400</td>
<td>16 MV</td>
<td>16 MV</td>
<td>16 MV</td>
</tr>
<tr>
<td>V800</td>
<td>0 MV</td>
<td>8 MV</td>
<td>8 MV</td>
</tr>
<tr>
<td>Relative phase</td>
<td>0</td>
<td>$\pi$</td>
<td>0</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>0.264 ns</td>
<td>0.232 ns</td>
<td>0.304 ns</td>
</tr>
</tbody>
</table>

A large set of simulations was required to study the 5 RF operation modes at different chromaticities while scanning the intensity. The dependence of the TMCI rise time on bunch population and chromaticity for the 5 operation modes above considered is presented in Fig. 7 for the collimation settings in collision. Negative chromaticity immediately drives a transverse instability. For low positive chromaticities below approximately 10 units, the highest instability threshold is still reached for the BSM. However, Fig. 7 suggests to extract a new type of threshold which can be defined as the minimum chromaticity to reach stabilization for high intensities. This value should be as low as possible, since high chromaticity comes with other problems such as, for instance, reduced beam lifetime. From this point of view, the situation is inverted in the sense that the lowest threshold is now obtained using the different BLMs. Here, the phase error does not have a large impact. In contrast, the BSM has the highest minimum required chromaticity.
Figure 7: Contour plots of the rise times vs. chromaticity and intensity for the different RF operation modes: a) single RF, b) BLM, c) BSM and d) BLM with a phase error of -5 deg. The red crosses highlight the intensity threshold for TMCI. The green lines indicate the minimum chromaticity required for full stabilisation.

The presence of a transverse damper may significantly change the coherent mode spectrum and the characteristics of the transverse instabilities. Therefore, the study was repeated in the presence of an ideal transverse damper, in the sense that it includes zero delay and no noise. For low gain values, this is a good approximation. Bandwidth limitation was included in that it acts purely on the bunch centroid motion. As such, it is in principle blind to any intra bunch motion. Adding chromaticity to the picture now has a different impact depending on the RF operation mode. Basically, the full picture is shifted towards higher intensities for the BSM, whereas all thresholds move towards lower intensities for the BLMs. However, the region where an increased chromaticity may lead to full stabilisation for the BLMs is shifted far beyond the considered intensities and beam stability is, thus, no longer a problem.
8. **ELECTRON CLOUD EFFECTS**

When the LHC is operated with bunches closely spaced an electron cloud can develop in the beam chamber due to secondary electron emission. Depending on the Secondary Electron Yield (SEY) of the beam chamber electrons can accumulate with adverse consequences such as beam quality degradation (instabilities, losses, emittance growth), dynamic pressure rise and heat load (on cryogenic sections). The SEY reduces with electron bombardment and therefore a possible mitigation is the beam-induced scrubbing. In the main magnets in the arcs, the experience during Run I showed that with 50 ns beams, electron cloud effects could be fully suppressed by scrubbing. However, a much longer scrubbing time is needed for 25 ns beams and the full suppression was not achieved in 2012. A dedicated scrubbing beam is under study for the LHC restart in 2015 and the coming experience with the 25 ns beams in the LHC in 2015 will be very important for the future HL-LHC operation. In the inner triplets, the presence of two counter-rotating beams enhances the electron cloud and if suppression measures (like low SEY coating or clearing electrodes) are not put in place, important heat loads are expected on the beam screens. The status of the different studies are discussed below. The simulations have been performed with the PyECLOUD code [65].

8.1. **IN THE ARC MAIN MAGNETS**

For the HL-LHC era, the arcs will be practically the same but we will need to cope with about two times more bunch intensity. Figure 8 shows the heat load from electron cloud vs. bunch intensity for both an arc dipole and an arc quadrupole and for different SEYs. Provided that we manage to access a low SEY regime, the increased bunch intensity should be acceptable for heat load, but the effect on the beam stability still needs to be assessed.

![Figure 8: Heat load from electron cloud vs. bunch intensity in the arc main magnets as a function of the SEY.](image)

The aim of the scrubbing run is to reach a SEY below 1.35 in the arc main magnets (for both the LHC and HL-LHC, because the intensity dependence of the SEY threshold on bunch intensity in the dipoles is weak), i.e. below the threshold for the onset of electron cloud in the main dipoles. It is worth noting that the quadrupoles have a threshold below 1.1, which cannot
be reached by scrubbing but the heat load is expected to be compatible with the available cooling capacity.

A dedicated scrubbing beam (called “doublet” scrubbing beam, see Fig. 9) with an hybrid bunch spacing (5 + 20 ns) having lower threshold SEY as compared to the 25 ns beam will be used to enhance the scrubbing at injection and reach the above mentioned SEY as required for operation with 25 ns beams.

![Figure 9: Some characteristics of the “doublet” scrubbing beam which has been proposed to achieve lower values of SEY compared to what was achieved in 2012.](image)

**8.2. IN THE INNER TRIPLETS**

Simulating the e-cloud build-up in the inner triplets required the introduction of new features in PyECLOUD due to the presence of the two beams with different transverse positions (off center), different transverse shapes and arbitrarily delay with respect to each other (no real bunch spacing). Furthermore, a quadrupolar magnetic field and a non elliptical shape of the vacuum chamber had to be taken into account. Looking at few snapshots of the electron distribution in the current LHC and the future HL-LHC triplets reveals that thicker stripes develop along field lines farther from the center of the chamber for HL-LHC (see Fig. 9). Note that the values in the D1 dipole are comparable or higher than the values in the quadrupoles.
Figure 9: Few snapshots of the electron distribution for the current LHC and the future HL-LHC triplets.

The comparison of the heat load from electron cloud for the current LHC and the future HL-LHC triplets (see Fig. 10) evidences that the larger bunch population and a larger beam screen size lead to a larger heat load for HL-LHC by a factor 3 (for the same SEY, similar energy of multipacting electrons and larger number of impacting electrons). For IR2 and IR8 a similar increase is expected and the detailed simulations are being performed. For that reason coatings and/or clearing electrons will need to be installed in all new insertion magnets as well as in the triplets and D1 in IR2 and IR8.
8.3. IN THE MATCHING SECTIONS

For the current LHC and the future HL-LHC matching sections, there are in total 6 different beam screens: 4 for the current LHC and 2 for the future HL-LHC, but several different configurations need to be considered (magnetic field, gradient, beam size, beam position, energy ramp, squeeze, separation, $\beta^*$ levelling, etc.) to represent the possible cases encountered during operation. The future plan is to perform parametric studies to assess which of these dependencies strongly impact the electron cloud build-up. Some preliminary simulations revealed that the beam size and the magnetic field have non-negligible effects even if relatively small. The next step will be to try and disentangle these two effects. The effect of the beam position will then have to be studied in detail.

8.4. ALTERNATIVE SCENARIOS

The detrimental effects of the electron cloud in the LHC (heat load in cold regions and transverse emittance blow-up) can be partly mitigated by using specially conceived filling patterns. The underlying idea is to use the flexibility of the injector complex to build bunch trains with long enough gaps interspersed, such as to prevent the build-up of an electron cloud along the beam in the LHC. An alternative scenario (indicated as 8b+4e) based on beams with 25 ns spacing has been conceived to reduce the electron cloud effects in HL-LHC, if needed, in its initial phase of operation after the upgrade [66] and has been considered as part of the HL-LHC operational scenarios [67].

Operation with a 200 MHz main RF system would allow for longer bunches and would have a positive impact also on electron cloud [57]. The impact of the bunch length on electron cloud will be studied experimentally during the coming Run II (e.g. to reduce emittance blow-up at low energy).

Figure 10: Comparison of the total heat load from electron cloud between the current LHC and the future HL-LHC triplets.
9. BEAM-BEAM EFFECTS ON TRANSVERSE BEAM STABILITY

The interplay between impedance, Landau octupoles and beam-beam is expected to play an important role on the definition of the stability limits based on the LHC Run I experience [9]. The stability diagram with octupoles only should be about 2.5 times larger with the ATS optics compared to the nominal one, due to the larger betatron functions at the octupoles. As for the LHC case, the negative octupole polarity (negative amplitude detuning) is preferred for single-beam stability but this leads to a reduction of the stability diagram during the betatron squeeze (due to the compensation with the positive amplitude detuning from the BBLR) [5]. Below a certain beam-beam separation, the positive octupole polarity starts to give larger stability diagrams and is therefore preferred.

The ATS optics [17] has been used for these studies and comparing the tune footprint between the LHC (nominal) and HL-LHC (ATS) optics for the case of the HL-LHC parameters \(2.2 \times 10^{11} \text{ p/b within } 2.5 \mu \text{m}\) for a (maximum) octupole current of 590 A, a strong impact of the ATS is observed. Indeed, the two important consequences of this new optics are: (i) larger beta functions at the octupoles, by a factor 2.5, which implies a larger tune spread (and therefore stability diagram) by a factor 2.5; (ii) asymmetric stability diagrams between \(\text{LOF} < 0\) and \(\text{LOF} > 0\). The height of the stability diagram for \(\text{LOF} > 0\) is larger and after detailed investigation it has been found that this is due to the sextupole contribution (typical for ATS). Removing this contribution, the usual symmetric stability diagrams are recovered.

The evolution of the stability diagrams during the betatron squeeze has been studied for both \(\text{LOF} < 0\) and \(\text{LOF} > 0\), comparing the nominal and PACMAN bunches. For the nominal scenario with luminosity levelling at \(5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}\) collisions will take place starting from a \(\beta^*\) of 70 cm (corresponding to a normalized BBLR separation of \(27 \sigma\)) and in this case the negative octupole polarity provide sufficient spread and Landau damping before going in collision and even more when in collision profiting of the large tune spread provided by the BBHO. This is not the case for luminosity levelling at ultimate luminosity of \(7.5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}\) for which collisions will take place starting from a \(\beta^*\) of 45 cm. In this case squeeze in collision might be required for operation with negative octupole polarity [68].

10. CONCLUSIONS AND FUTURE PLANS

IBS has been investigated in detail and the evolutions vs. time of the main parameters were analysed. Growth times of \(~ 10 \text{ h}\) at injection and \(~ 20 \text{ h}\) in collision are expected.

The HL-LHC impedance is not dramatically higher than the LHC one but Molybdenum-coated secondary (CFC) collimators (or Molybdenum coated Molybdenum-Graphite collimators which would be better in case of degradation of the Molybdenum coating) are needed to decrease the total impedance and guarantee transverse stability. Furthermore, special attention should be given to the minimization of the impedance and number of devices in high beta regions (such as BPMs or crab cavities), as well as unshielded elements.

The beam-induced heat load computations for several key impedances are summarized in Table 2. Electron cloud effects should be suppressed in the arc dipoles by beam-induced scrubbing in the arcs (the Run II experience will be vital in that respect). The aim of the scrubbing run is to reach a SEY of \(~ 1.35\) in the arc main magnets (for both the LHC and HL-LHC, because the intensity dependence of the SEY threshold on bunch intensity in the dipoles is weak). It is worth noting that the quadrupoles have a threshold below 1.1, which cannot be
reached by scrubbing but the expected heat load is expected to be compatible with the available cryogenics power. Low SEY coatings and/or clearing electrodes in the new insertion regions will be necessary to keep the heat loads within the cooling capacity. Similar actions will be required for the beam screen of the triplets/D1 in IR2 and IR8. Finally, the matching section remains to be studied in detail.

Longitudinal instabilities are not expected to be an issue during the HL-LHC era. Using as reference single bunch measurements at 4 TeV, whose intensity threshold was $10^{11}$ p/b for and RF voltage of 12 MV, a longitudinal emittance of 1 eVs and a $4\sigma$ bunch length of 0.8 ns (scaled from the measurement of the full width at half maximum) and scaling to HL-LHC parameters (16 MV, 2.5 eVs) leads to an intensity threshold of $3.4\times10^{11}$ p/b. A high-harmonic RF system is therefore not necessary for beam stability in the longitudinal plane.

However, a high harmonic RF system has been already discussed in the past as a mean to provide additional margin for longitudinal stability in BSM and to reduce IBS emittance growth rates, beam-induced heating and pile-up density by flattening the bunch profile by using the harmonic RF system in BLM.

Recently, the use of a low harmonic RF system in the LHC (200 MHz) as the fundamental RF system has been suggested with the following motivations: (i) it would allow to accept larger longitudinal emittance and therefore larger bunch population from the SPS after its upgrade; (ii) it could help to improve IBS, beam-induced heating and e-cloud effects; (iii) together with the existing 400 MHz RF system, it could be used for luminosity and pile-up levelling; (iv) it also has a beneficial effect for ions and the momentum slip-stacking scheme in the SPS. A new design has been proposed for a compact superconducting cavity. The compatibility of this scheme with 400 MHz crab cavities or the possibility of installing 200 MHz crab cavities needs to be studied further, if this scenario is considered. It must be noted that the 200 MHz RF system should be used together with the 400 MHz RF (as a high harmonic system) in BSM to preserve beam stability as for the same longitudinal emittance the stability threshold is 4 times lower. Finally, the expected benefits of a double RF system should be weighted against the impedance increase and the possible reduced reliability.

Transverse instabilities are a concern based on the experience of the LHC Run I, during which a transverse instability at the end of the betatron squeeze could not be cured. While TMCI thresholds well exceed the nominal HL-LHC bunch population both at injection and at high energy, to reach transverse single-beam stability, it is necessary to coat the collimators with 5 $\mu$m of Molybdenum (or, to coat new Molybdenum-Graphite collimators) and to guarantee the capability of the transverse damper to damp coupled-bunch instabilities up to the maximum frequency (20 MHz). It is clear that the operation of the transverse damper is vital for HL-LHC. The situation improves with the negative polarity of the Landau octupoles but the results are qualitatively the same. The design of the crab cavities has to be closely followed-up and optimized as concerns the HOMs to minimize the contribution to the coupled-bunch instabilities which will have to be stabilized by the transverse damper and for that reason the expected requirements on the characteristics of the damper will have to be finalized once the design of the crab cavities is more advanced (for the moment the impedance model of the crab cavities is quite coarse and needs to be improved). Finally, in the presence of an additional 800 MHz RF system, a detailed analysis revealed that the BSM should be the preferred scenario.

The beam stability in the presence of electron cloud (particularly in the quadrupoles) still needs to be assessed.
The interplay between impedance, Landau octupoles and beam-beam is expected to play an important role in the definition of the stability limits based on the LHC Run I experience. For the nominal scenario with luminosity levelling at $5 \times 10^{34} \, \text{cm}^{-2} \, \text{s}^{-1}$ collisions will take place starting from a $\beta^*$ of 70 cm and in this case the negative octupole polarity (preferred for single beam stability) provide sufficient spread and Landau damping before going in collision and even more when in collision profiting of the large tune spread provided by the BBHO. This is not the case for luminosity levelling at ultimate luminosity of $7.5 \times 10^{34} \, \text{cm}^{-2} \, \text{s}^{-1}$ for which collisions will take place starting from a $\beta^*$ of 45 cm. In this case squeeze in collision might be required for operation with negative octupole polarity.

It is worth mentioning that the beam-beam wire can restore the full freedom on the choice of the octupole polarity and it will be necessary anyway for dynamic aperture considerations [69].

In the future, the transverse instability at injection should be studied in the presence of space charge, as the incoherent space charge tune spread is expected to be very close to the synchrotron tune (a regime where space charge could play a significant role). Some octupoles (with a current of 6.5 A) were needed at injection during Run I to prevent some instabilities from developing on some batches. This instability (in the absence of octupoles) still remains to be understood in detail. Furthermore, the value of the octupole current was never optimized and it might be a problem in the future, for dynamic aperture considerations, if the octupole current needs to be increased.
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## ANNEX: GLOSSARY

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>ADT</td>
<td>Transverse damper</td>
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<tr>
<td>ATLAS, CMS, ALICE and LHCb</td>
<td>The 4 experiments in the LHC</td>
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<td>ATS</td>
<td>Achromatic Telescopic Squeezing</td>
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<td>BBHO</td>
<td>Beam-Beam Head-On</td>
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<td>BBLR</td>
<td>Beam-Beam Long Range</td>
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<tr>
<td>BI</td>
<td>Beam Instrumentation</td>
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<tr>
<td>BLM</td>
<td>Bunch-Lengthening Mode</td>
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<td>BPMs</td>
<td>Beam Position Monitors</td>
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<td>BSM</td>
<td>Bunch-Shortening Mode</td>
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<tr>
<td>BSRT</td>
<td>Beam Synchrotron Light Monitor</td>
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<tr>
<td>CFC</td>
<td>Fiber-reinforced graphite (used for the current LHC collimators)</td>
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<tr>
<td>CTE</td>
<td>Collider Time Evolution program</td>
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<tr>
<td>HL-LHC</td>
<td>High Luminosity Large Hadron Collider</td>
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<td>HOMs</td>
<td>High-Order Modes</td>
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<td>IBS</td>
<td>Intra-Beam Scattering</td>
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<td>IP</td>
<td>Interaction Point</td>
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<tr>
<td>IR</td>
<td>Interaction Region</td>
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<tr>
<td>LOF (LOD)</td>
<td>Focusing (Defocusing) Landau Octupoles</td>
</tr>
<tr>
<td>LS1</td>
<td>Long Shutdown 1 (2013-2014)</td>
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<tr>
<td>LSS</td>
<td>Long Straight Section</td>
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<tr>
<td>MD</td>
<td>Machine Development</td>
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<td>MKI</td>
<td>Injection kicker</td>
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<td>Non Evaporable Getter</td>
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<td>Radio-Frequency</td>
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<td>Secondary Emission Yield</td>
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<td>TCP</td>
<td>Primary collimators</td>
</tr>
<tr>
<td>TCS</td>
<td>Secondary collimators</td>
</tr>
<tr>
<td>TDI</td>
<td>Target Dump Injection</td>
</tr>
<tr>
<td>TMCI</td>
<td>Transverse Mode-Coupling Instability</td>
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