HiLumi LHC
FP7 High Luminosity Large Hadron Collider Design Study

Milestone Report

Collation of Data for Parameter Optimization

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24 March 2015

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

This work is part of HiLumi LHC Work Package 2: Accelerator Physics & Performance.

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The operation of the LHC and the machine studies conducted during Run 1 have provided important input for the validation of some of the choices that are at the base of the HL-LHC upgrade scenario but it has evidenced also some potential limitations [1]. Progress has been made in their understanding, but some open points remain to be further studied to optimize the operational scenario and performance (e.g. stability during the squeeze and collision process, electron cloud effects with 25 ns beams). The required studies necessary for the collation of data for parameter optimization will be presented.
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The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404. HiLumi LHC began in November 2011 and will run for 4 years.

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</tbody>
</table>
TABLE OF CONTENTS

1. INTRODUCTION ........................................................................................................................................ 4
2. BASELINE SCENARIO .............................................................................................................................. 4
   2.1. ATS OPTICS ............................................................................................................................................. 4
   2.2. OPERATION WITH 25 NS BUNCH SPACING ................................................................................................. 5
   2.3. CRAB CROSSING ...................................................................................................................................... 5
   2.4. $\beta^*$ LEVELLING/COLLIDE AND SQUEEZE .................................................................................................... 6
   2.5. BEAM-BEAM EFFECTS .............................................................................................................................. 7
   2.6. DYNAMIC APERTURE ................................................................................................................................... 8
   2.7. BEAM-INDUCED RF HEATING .................................................................................................................. 9
   2.8. BEAM STABILITY ..................................................................................................................................... 9
3. VARIANTS AND OPTIONS ....................................................................................................................... 9
   3.1. FLAT OPTICS .......................................................................................................................................... 10
   3.2. BEAM-BEAM LONG RANGE COMPENSATION ........................................................................................... 10
4. CONCLUSIONS AND OUTLOOK .......................................................................................................... 11
5. REFERENCES ........................................................................................................................................... 12
6. ANNEX: GLOSSARY ................................................................................................................................ 15
Executive summary

The operation of the LHC and the machine studies conducted during Run 1 have provided important input for the validation of some of the choices that are at the base of the HL-LHC upgrade scenario but it has evidenced also some potential limitations [1]. Progress has been made in their understanding, but some open points remain to be further studied to optimize the operational scenario and performance. The required studies necessary for the collation of data for parameter optimization have been identified and will be performed during Run 2.

1. INTRODUCTION

The High Luminosity LHC (HL-LHC) will push the performance of the LHC well beyond the presently explored range [1-2], which has already exceeded the nominal parameters in some cases.

Some of the challenges underlying the HL-LHC performance are listed below:

- operation with low $\beta^*$ optics with well-behaved chromatic properties;
- electron-cloud effects with 25 ns beams;
- large crossing angle and crab crossing to minimize the geometric reduction factor and pile-up density;
- $\beta^*$ levelling as a means of limiting the event pile-up at the experiments and the heat deposition on the low-$\beta$ quadrupoles;
- large beam-beam tune spreads resulting from head-on and long range effects;
- beam halo measurement and control, particularly to cope with possible crab cavities failure scenarios;
- minimization of impedance to maximize beam stability and reduce the beam-induced RF heating;
- operation at higher stored beam energies;
- interplay between several mechanisms (incoherent and coherent) such as impedance, nonlinearities (machine and Landau octupoles), space charge (at low energy), transverse feedback, beam-beam and electron-cloud effects.

A summary of the information collected so far and of the main studies and machine experiments (in LHC and SPS) that are required to validate the main choices in terms of operational settings and scenarios or hardware are presented, together with the possible variants and options that could enhance performance or address performance issues.

2. BASELINE SCENARIO

2.1. ATS OPTICS

The Achromatic Telescopic Squeezing (ATS) scheme is presently the only existing optics solution able to reduce the $\beta$ function at the interaction point both for “round” (equal $\beta$ functions in the horizontal and vertical planes) or “flat” (different $\beta$ functions in the horizontal and vertical planes) optics configurations down to unprecedented values for a hadron collider (i.e. 10 cm for round optics or 5 / 20 cm for flat optics) while controlling the induced chromatic aberrations [3]. Machine Development (MD) studies performed in 2011-2012 have demonstrated the pre-squeeze and the achromatic telescopic squeezing down to a value of $\beta^*$ of 10 cm, in the baseline round optics, the feasibility of correcting beta beating in
the LHC with this optics configuration and have confirmed the excellent chromatic properties of such optics solution [4-8].

This optics is mature to become operational and its implementation in operation, possibly in 2016, is one important milestone for HL-LHC. In preparation of that, machine studies are required for the validation of collimation efficiency and machine protection aspects during the 2015 run [9].

2.2. OPERATION WITH 25 NS BUNCH SPACING

Operation with 25 ns bunch spacing is mandatory in order to reach the target integrated luminosity of 250 fb⁻¹/y while maintaining the event pile-up level within a range acceptable by the detectors of the high-luminosity experiments in the Interaction Points (IP) 1 and 5. Important electron-cloud effects have been observed in machine experiments conducted during Run 1 in the arcs and interaction regions [10]. Signs of reduction of the Secondary Electron Yield (SEY), responsible for the electron cloud build-up, have been observed in the LHC dipoles during dedicated “scrubbing runs”. Beams with a bunch time structure (“doublet beams”) [11] aimed at enhancing the electron-cloud build-up have been conceived and tested in the SPS with the aim of enhancing the electron dose and consequently the speed of the scrubbing process to reach SEY values lower than 1.3 in the LHC beam screens. That would allow suppressing electron cloud build-up at least in the main dipoles for LHC beams with 25 ns spacing. The threshold value of the SEY above which multipacting is expected in the quadrupoles and in particular in the common regions, where both counter-rotating beams are sharing the same vacuum chamber, is too low (~1.1) to be considered within reach during the scrubbing runs. The present estimates indicate that the available beam screen cooling power is sufficient for operation in the presence of electron cloud in arc quadrupoles even for the HL-LHC beam parameters [12,13].

For HL-LHC beam parameters, the heat load in the beam screens of single-aperture magnets (triplet quadrupoles and D1 recombination dipoles) will exceed the available cooling power. Moreover, no electron-cloud suppression is expected for SEY values of 1.3, which could be reasonably achieved after scrubbing. For that reason it is planned to coat the triplet and D1 beam screens in all interaction points with amorphous carbon that has shown SEY < 1 at room temperature.

Laboratory tests are ongoing to characterize the properties of these coatings at cryogenic temperatures and a coated beam screen maintained at cryogenics temperatures has been installed in a test area of the SPS ring (COLDEX) to validate the behaviour at cryogenics temperatures with beam during the SPS scrubbing run in 2014 and 2015. Irradiation tests are foreseen in order to evaluate possible ageing effects that could have an impact on the properties of these surfaces with respect to SEY. The preliminary results are being analysed [14] and further measurements will be performed in 2015.

The design of low impedance clearing electrodes (tested successfully at DAφNE – INFN, Frascati [15]), is also considered as a possible back-up solution, though it would require a specific design to be fitted in a cryogenic environment with limited space available.

2.3. CRAB CROSSING

Crab crossing by means of crab cavities has been considered as part of the HL-LHC baseline scenario to suppress the luminosity geometric reduction factor due to the large crossing angle required to minimize the effect of beam-beam long range encounters. In this way, the virtual luminosity (i.e. the peak luminosity that could be delivered to the experiments if no limit in
the event pile-up rate would exist) is increased without increasing the event pile-up density. Crab cavities can also be used to act on the event pile-up longitudinal or temporal distribution (e.g. with the so-called “crab-kissing” scheme [16]).

Crab cavities have never been installed in proton machines and several aspects related to their operation in these conditions need to be studied, in particular:

- impedance effects, like transverse instabilities and High Order Mode (HOM) power;
- validation of operational modes and cavity control for this modes and in case of failure;
- effect of phase and amplitude noise on beam quality and in particular on transverse blow-up and halo generation.

For that reason a module with two crab cavities will be installed in the SPS to conduct tests with LHC-type beams during the 2017-2018 runs. Measurements will include:

- beam-induced heat load,
- emittance blow-up,
- beam stability

for different operating modes.

Alternative scenarios have been devised and would imply a reduction of the crossing angle by using flat optics (with larger $\beta^*$ in the crossing plane) and possibly implementing beam-beam long range compensators to control the tune spread resulting from long-range parasitic encounters [17].

### 2.4. $\beta^*$ LEVELLING/COLLIDE AND SQUEEZE

The proposed scheme for levelling the luminosity compatibly with the event pile-up rate that can be accepted by the detectors is based on the so-called $\beta^*$ levelling. According to this scheme the $\beta$ function at the IP ($\beta^*$) is reduced progressively during the physics fill down to its minimum value so to maintain the luminosity constant at the desired value (smaller than the virtual peak luminosity) until the minimum value of $\beta^*$ is reached. From that time onwards the luminosity will decay because of reduction of the beam current due to luminosity burn-off and/or other effects and because of unwanted transverse emittance ($\epsilon$) growth. Such a scheme has the advantage of providing a larger normalized long-range beam-beam separation ($\propto \sqrt{\frac{\beta^*}{\epsilon}}$ for a constant crossing angle $\theta$) at the beginning of the fill when the bunch population is larger. Strong Landau damping could be obtained during the squeeze by performing that process with the beams in collision and profiting of the large tune spread provided by head-on beam-beam interaction. That might be required to stabilize the beams at high energy, during the squeeze, when:

- the impedance due to the collimators is maximized, as their gap is reduced to protect the triplets that would otherwise become the aperture bottleneck during this process;
- the effects of the impedance of the crab cavities increase with the corresponding increase of the $\beta$ function at their location.

The feasibility of such scheme has been demonstrated in a configuration with up to nominal bunch population but at low total beam current intensity in three dedicated experiments in 2012 [18-20]. Figure 1 shows the relative evolution of the luminosity (normalized to the value at the end of the squeeze) during the reduction of the $\beta^*$ in IP1 and 5 and compares it with the
expected evolution in the absence of unexpected sources of emittance blow-up. The observed blow-up is small.

Figure 1: Evolution of the ATLAS and CMS luminosity during the $\beta^*$ levelling experiment as compared to the expected evolution [18].

In spite of the positive results it must be stressed that these tests have been performed with a small number of bunches and no experience could be gathered on the reproducibility of the orbit on a cycle-by-cycle basis. In particular instabilities might occur when operating at high intensity if the beams separate during the squeeze process. Instabilities have been observed during physics when the beams were separated by approximately 1.5 $\sigma$ (see for example [21,22]). Systematic studies of this phenomenon should be performed with controlled machine settings (e.g. chromaticity, Landau octupole current and polarity, and damper gains). If confirmed this phenomenon might be even more critical for HL-LHC due to the smaller beam size at the IP as compared to that available in 2012 in the LHC at 4 TeV.

Machine studies are required to develop and test the tools necessary for $\beta^*$ levelling, among others a feed-forward/feedback system allowing to keep the beams in collision during the $\beta^*$ levelling process. It is worth noting that luminosity levelling might be required even before the HL-LHC upgrade in case of operation with low $\beta^*$ (40 cm) and with high brightness BCMS (Batch Compression Merging and Splittings) beams [23].

2.5. BEAM-BEAM EFFECTS

HL-LHC will operate at unprecedented beam-beam parameters with head-on beam-beam tune spreads larger than 0.01/IP, at least in two IPs (if $\beta^*$ levelling is implemented in ATLAS, CMS), and the additional contribution of beam-beam long-range effects. This might have an impact on dynamic aperture and emittance blow-up and therefore on the integrated luminosity performance. For that reason, the validation of this mode of operation is mandatory with simulations and experiments to confirm the criteria used for the definition of the operational scenarios and of the corresponding performance. At present the same criteria that have guided the LHC design are used, with a minimum dynamic aperture of 6 $\sigma$ (computed with the beam emittance) from simulations considered to be acceptable [24,25].

Experiments have been performed to study the machine performance with large beam-beam head-on tune spread (but with a small number of bunches) and values as large as ~0.017/IP have been achieved in two IPs, but in the absence of long-range effects [26-30].

Long range effects and their scaling with beam and machine parameters have been studied with 50 ns beams and, although only preliminarily, with 25 ns beams with the aim of
benchmarking simulations and provide additional experimental evidence for the design criteria above mentioned [31,32].

It will be vital to complete the studies on the scaling of long-range effects with 25 ns beams during Run 2 and identify and quantify all contributions (i.e. chromaticity and Landau octupoles)

Possible alternative scenarios in case of limitations due to the beam-beam head on tune spread or to beam-beam long-range effects include the levelling by separation in IP8 and the implementation of a Beam-Beam Long Range (BBLR) compensation scheme, respectively. The second scheme has been proposed initially in Ref. [33] and possible tests in the LHC will be discussed later.

2.6. DYNAMIC APERTURE

The evaluation of the impact of field quality on machine performance and its steering during the design and construction phase has been one of the reasons of LHC excellent performance (the unprecedented beam-beam tune shifts achieved is likely one of the results of that). The impact of field quality has been so far evaluated in terms of dynamic aperture that is the region in phase space where stable motion occurs, at least for a given amount of machine turns (typically $10^5$ to $10^6$ turns depending on whether beam-beam effects are included).

During the LHC design, the limited experimental data available, limitations in computing power and uncertainties in the magnetic model led to the decision of considering an important (approximately a factor 2) safety margin between the dynamic aperture and the aperture defined by the collimators [34]. Already before the LHC start-up, efforts have been made to correlate measurable quantities (e.g. losses) with the expected asymptotic value of the simulated dynamic aperture for an increasing number of turns [35-37]. During Run 1 a number of MDs have been carried out to measure the dynamic aperture, either using the proposed relationship with intensity evolution [38, 39], or the more standard method based on kicking the beam towards high amplitude to observe the sudden losses [40]. The latter experiments have shown that the estimated accuracy of the dynamic aperture simulations is 20 to 30% at injection (see Fig. 2).

![Figure 2: Comparison of dynamic aperture data from simulations (green and blue corresponding to different two values of the coupling coefficient $|C|$) with those inferred from measured loss data (red) in one of the machine studies conducted in the LHC at injection [38].](image)

Although in general there is an excellent agreement between the LHC optics linear and non-linear model and the measurements, some discrepancies still persist [41] that need to be addressed during Run 2 together with the performance of the correction algorithms. This will
be extremely important for the operation at low $\beta^*$ and of the correction of the non-linearities of the triplet magnetic field during HL-LHC operation.

2.7. BEAM-INDUCED RF HEATING

Beam-induced RF heating in several LHC types of equipment has been observed during the 2011 and 2012 runs (with 50 ns bunch spacing), when the beam intensity was increased and/or the bunch length reduced [42]. This caused outgassing and damage to equipment. For that reason the r.m.s. bunch length was increased to 9 cm in 2011 and 10 cm in 2012, whereas the nominal value is 7.5 cm (for both the LHC and HL-LHC).

RF heating is therefore being closely followed-up in view of LHC operation with 25 ns spacing beams and in view of HL-LHC operation [43]. Some equipment has been re-designed to minimize RF heating and more temperature probes have been installed in the LHC during LS1 to monitor the temperature of sensitive equipment during beam operation during Run 2. Furthermore a reduction of the bunch length to the required value will be studied to try and identify other possible critical components.

2.8. BEAM STABILITY

The LHC performance in 2012 was limited by a transverse instability occurring at the end of the squeeze (at 4 TeV), with close to maximum Landau octupoles current (550 A – corresponding to a factor 3 to 4 times higher than the value expected from our current single beam stability model [44]). The transverse feedback gain was set close to maximum (corresponding to a damping time of 50 turns at 4 TeV) and the transverse chromaticities were increased to about 15 units. The origin of this instability, that could not be cured, remains unexplained. Its understanding is required before finalizing the operational scenario.

The study of the interplay among several mechanisms (impedance, beam-beam, electron-cloud effects in the presence of Landau damping and transverse feedback) in simulations (with the additional complexity that this entails) is being pursued to understand the origin of the above instability and machine studies will be performed to tests some possible hypotheses [44-46].

Impedance reduction of existing components and impedance control of new components (particularly those installed in high $\beta$ regions like the crab cavities) is mandatory to guarantee beam stability at high energy. In particular it will be necessary to install new Molybdenum-Graphite – MoGr – collimators with 5 $\mu$m thick Molybdenum coating. The installation of a MoGr collimator in the LHC during the winter stop in 2015 is being considered in order to validate the impedance properties.

Instabilities have been observed with 50 ns beams at injection energy and Landau octupoles had to be used to stabilize the beam. These effects have been observed also with 25 ns beams and higher Landau octupole current (by a factor 4) had to be applied. The analysis of the observation points to electron cloud effects as the origin of the instability and dedicated studies will be performed to fully understand this phenomenon [47].

3. VARIANTS AND OPTIONS

Possible variants and options have been conceived as alternative solutions in case of issues with some of the challenges above mentioned [16,17,48,49].
3.1. FLAT OPTICS

Flat optics (i.e. an optics providing $\beta^*_{\text{xing}} > \beta^*_{\text{sep}}$, where $\beta^*_{\text{xing}}$ and $\beta^*_{\text{sep}}$ are the $\beta$ functions at the interaction point in the crossing and separation planes, respectively) [17] promises to operate with smaller crossing angle at constant normalized beam-beam separation and with constant if not larger virtual luminosity thanks to the reduction of the crossing angle in absolute terms. This would offer the advantage of reducing the requirements on the crab cavities voltage (in case of limitations in their performance with beam or for the purpose of implementing the “crab kissing” scheme [16]) and would reduce the event pile-up longitudinal density.

Beam-beam simulations indicate nevertheless that larger normalized beam-beam separation are required for flat optics configurations, as compared to round optics, at constant dynamic aperture due to the only partial compensation of long range effects in IP1/5 even for alternating crossing. Beam-beam experiments would provide valuable input to benchmark simulations and scaling laws. The ATS optics can easily provide flat configurations that could be of interest for the LHC operation even during Run 2.

3.2. BEAM-BEAM LONG RANGE COMPENSATION

As mentioned earlier, beam-beam long-range compensation schemes based on wires or electron beams could in principle mitigate beam-beam long range effects and/or allow reducing the crossing angle in particular when combined with the implementation of a flat optics. The latter configuration would allow:

- providing margin for the “crab kissing” scheme [16];
- mitigating performance limitations from crab cavities (e.g. maximum achievable voltage, noise, etc.);
- providing flexibility for the crossing angle orientation in IP1/5 otherwise bounded to the choice of alternating crossing plane to compensate tune and chromaticity shifts due to long-range effects;
- reducing the energy deposition on the D2 recombination dipoles with the choice of vertical crossing in both IP1 and IP5.

Although very promising (see [50] for an overview of the experimental tests in the SPS), limited experience exists for the use of a beam-beam long range compensator in a hadron collider [51-53] and an experimental programme has been launched to benchmark simulations and validate scenarios that are compatible with machine protection. For this purpose, it is planned to install wire beam-beam demonstrators embedded in tertiary collimators around IP1 and IP5 during the winter stop 2015-16.

In order to obtain meaningful information for the HL-LHC implementation, additional simulation tools and diagnostics are required [54-57].

A beam-beam compensator based on an electron beam is also being considered [58], this would allow moving the electron beam closer to the circulating beam and could also allow for a bunch to bunch correction providing ideal conditions for the long-range compensation. However the electron current needed for such an application requires a factor 2 to 5 improvement over the present reach and the investment in terms of hardware for the whole system is significant.
4. CONCLUSIONS AND OUTLOOK

The HL-LHC beam and machine parameters are challenging and the solutions proposed for the baseline scenario are relying on innovative schemes that, although based on excellent results obtained during LHC Run 1, are not fully proven. The machine experiments and studies required in order to validate the main choices have been identified and will be performed during Run 2 or 3.
5. REFERENCES


[9] Summary of the 188th LMC Meeting held on 3 September 2014, https://espace.cern.ch/lhc-machine-committee/Minutes/1/lmc_188.pdf


Grant Agreement 284404


[47] E. Métal et al., 2-day internal review of LHC performance limitations (linked to transverse collective effects) during run I (https://indico.cern.ch/event/267783/).
## 6. ANNEX: GLOSSARY

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<tr>
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<td>BCMS</td>
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<td>High Order Mode</td>
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<td>IP</td>
<td>Interaction Point</td>
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<td>MD</td>
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