WHAT CAN BE LEARNT IN RUN 2 for RUN 3 and HL-LHC RUNS

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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 (2.3×10^{11}ppb and $\varepsilon_n = 2.1\,\mu$m at LHC injection, thus providing 2.2×10^{11}ppb and $\varepsilon_n = 2.5\,\mu$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 $150\,\mathrm{fb}^{-1}$ in order to reach the goal of $300\,\mathrm{fb}^{-1}$ 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 $1.75 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [4]. The beam parameters needed to reach the required virtual luminosity are expected to be obtained by a reduction of collimators' gaps, of β^*, normalized crossing angle, and normalized emittance.

The goal of HL-LHC is to integrate at least $3000\,\mathrm{fb}^{-1}$ 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, β^* 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, β^*, small Piwinsky angle) that exceed the luminosity limit since the gain from luminosity levelling saturates rapidly. Is 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 β^* 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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Figure 1: Long-term LHC planning with projected performance figures (ring energy, peak and integrated luminosity).

Table 1: Summary bunch population (ppb), normalized emittance (ε_n), number of injection to fill the LHC, bunches per injection (BPI), and colliding bunches in ATLAS/CMS, Alice, LHCb. The number of collisions per crossing marked with * has been calculated through a scaling rather than the development of a filling scheme [6].

Production scheme	ppb $[10^{11}]$	$\varepsilon_n[\mu\text{rad}]$	Injections	Bunches per Injection	Colliding in IP 1,5/2/8
Standard	1.3→2.3	2.8→2.1	13	288	2748/2494/2572
BCMS	1.3→2.3	2.5→1.7	20	144	2544/2205/2308
			12	288	2736/2258/2378
8b+4e STD	1.6→2.5	2.4→2.1	13	144	1960/1163/1806*
8b+4e BCMS	1.6→2.5	1.2→1.8	20	96	1696/1470/1538*
80b	1.3→2.3	1.3→2.1	14	240	2732/2476/2549
			12	320	2800/2246/2606
50 ns	1.8	1.8	13	144	1374/1247/1286
Single	> 3.0	> 1.5	n/a	1	n/a

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.

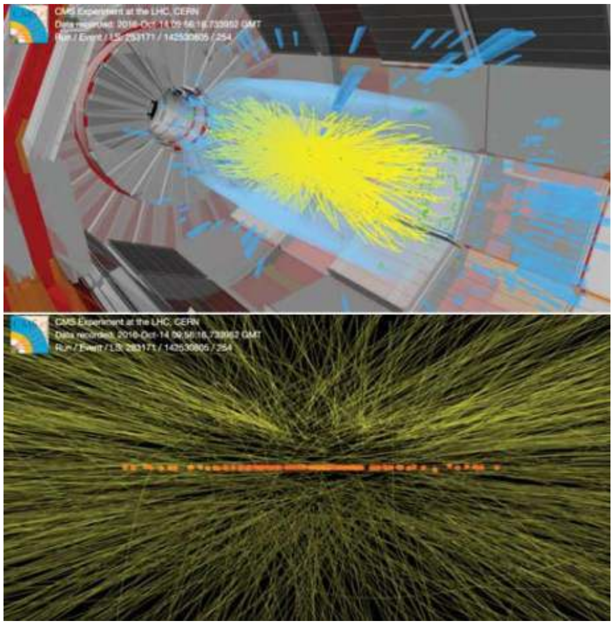

Figure 2: Example of high pile-up events (about 150) in ATLAS and CMS.

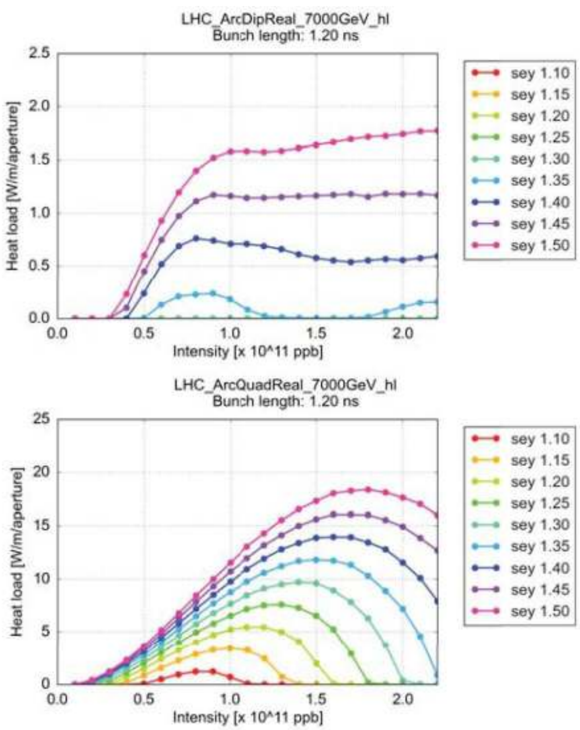

Figure 3: Model of heat load for dipoles (upper) and quadrupoles (lower) as a function of bunch population and SEY. A small variation in the model parameters has a sizeable impact on the heat load (see Fig. 4) since the relationship between beam intensity and heat load is not monotonic.

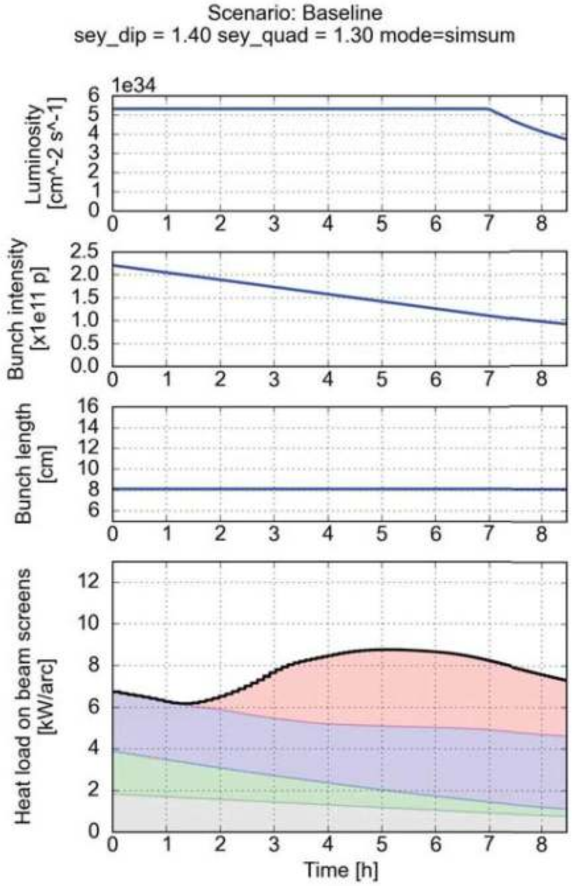

Figure 4: Expected evolution of the heat load during a typical HL-LHC fill of the HL-LHC that relies entirely the features of present models that are still speculative, see Fig. 3

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 β-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 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 β^*-reach, where HL-LHC could profit from the Run 2 experience. In 2016, β^* 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 β^* 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.

Settings	**2017**	**HL-LHC**
TCP IR7	**5.0**	**5.7**
TCSG IR7	**6.5**	**7.7**
TCLA IR7	10	10
TCP IR3	15	15
TCLA IR3	18	18
TCSG IR6	20	20
TCDQ IR6	**7.3**	**9.0**
TCT IR1/5	7.5	10.9
TCT IR8	15	15
Protected Ap. IR1/5	**8.5**	**12.3**
Protected Ap. IR8	16	17
Protected Ap. Arc	18	18

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 β^*); reduce orbit interlock tolerance for instance using BPM in use TCSP to mitigate optics constraints in IR6.

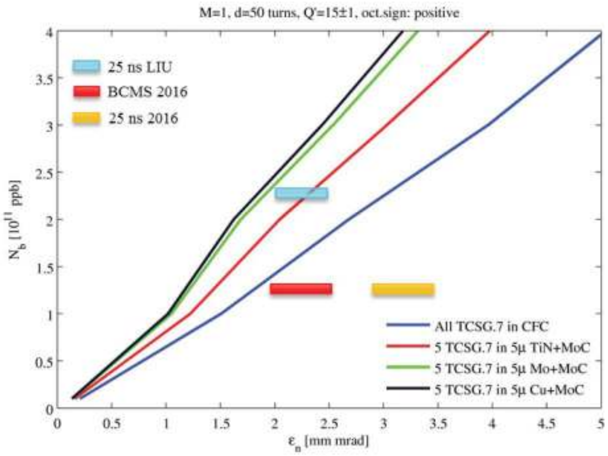

Figure 5: Expected stable region for different collimator materials and beam parameters.

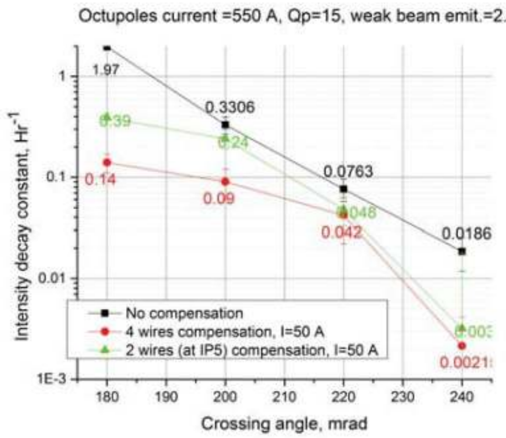

Figure 6: Expected lifetime drops as a function of the crossing angle with or without wire compensator for a scenario with large positive octupoles and large Q' [14].

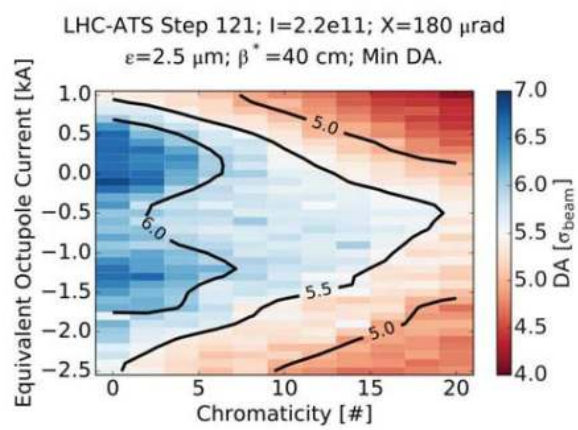

Figure 7: Expected dynamic aperture (DA) as a function of octupoles and Q' for the ATS optics pre-squeezed to 160 cm and telescopically squezed down to 40 cm (ATS ratio = 4). The equivalent octupole current is defined as the standard current multiplied by the ATS ratio. The DA shows better values for negative octupole polarities (see also [16]).

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 8b+4e with full trains to confirm achieved brightness in multi-bunch and no e-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 $\left(\beta^*_{\text{crossing plane}} > \beta^*_{\text{parallel plane}}\right)$ where the natural H-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]. 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 inv iew of beam tests in 2017-2018 [17] and the leverage on negative octupoles 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 β^* 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 β^* 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 β^* 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. $\beta^* = 60/15$ 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 larger pre-squeeze optics (e.g. β^* =1.6 m) could be used to study aspect related to aperture and collimation cleaning in the arcs with large β 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 β^* (see Fig. 8) since the optics sensitivity with respect to quadrupole strength errors makes both the measurement and correction of β^* 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 β^* 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 ($\sigma = 7 \rightarrow 5\,\mu\text{m}$) 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 β^* 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 β^* 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 β^* and σ^* 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 μmwith DOROS) to be compatible with HL-LHC IP beam size (7 $\rightarrow$ 5 μm), 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 β function from amplitude data with AC dipole to avoid (or complement) k-modulation in the triplet.

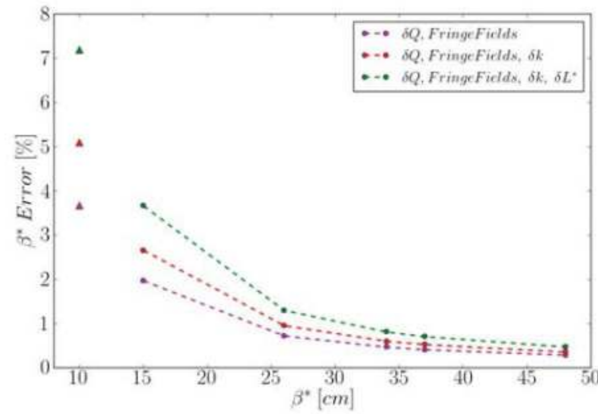

Figure 8: Expected β measurement error at the IP due to K-modulation in HL-LHC.

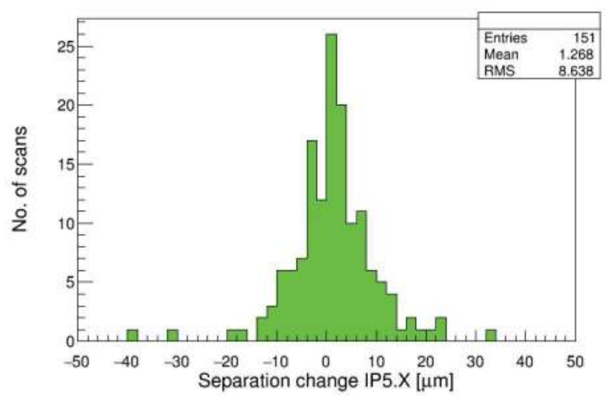

Figure 9: Expected orbit error at the IP in the LHC.

Beam halo studies will benefit from the synchrotron radiation coronagraph. Emittance monitor, which is crucial for the understating of 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 $\sigma = 3.5 \times 10^{-6}\ \mu\text{m}$. HL-LHC apertures use parameters defined in [21] assuming worst case scenarios for alignment imperfections.

Settings	**ATS 2017**	**ATS MD 2016**	**HL-LHC**
β^* final	33 cm	10 cm	20 cm to 10 cm
β^* pre-squeeze	40 cm	40 cm	50 cm
β^* peak	7.2 km	24 km	16 km to 32 km
Crossing Angle	290 μrad	0 μrad	$\leq 590\ \mu$rad
Aperture	9σ	6.8σ	$\leq 12.3\sigma$
Telescope	1.2	4	2.5 to 5

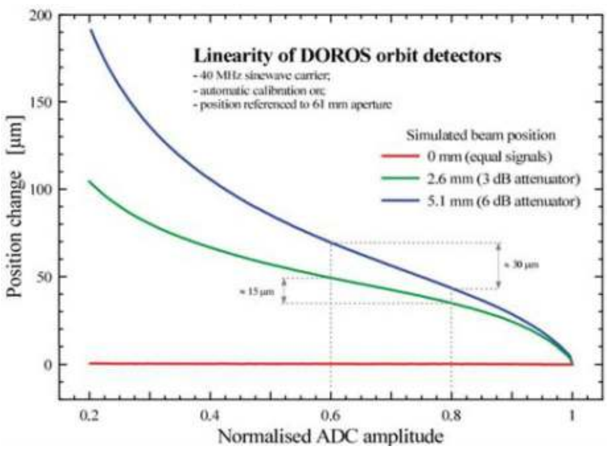

Figure 10: Linearity of DOROS orbit detectors as a function of the offset.

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 trip-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 beam-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

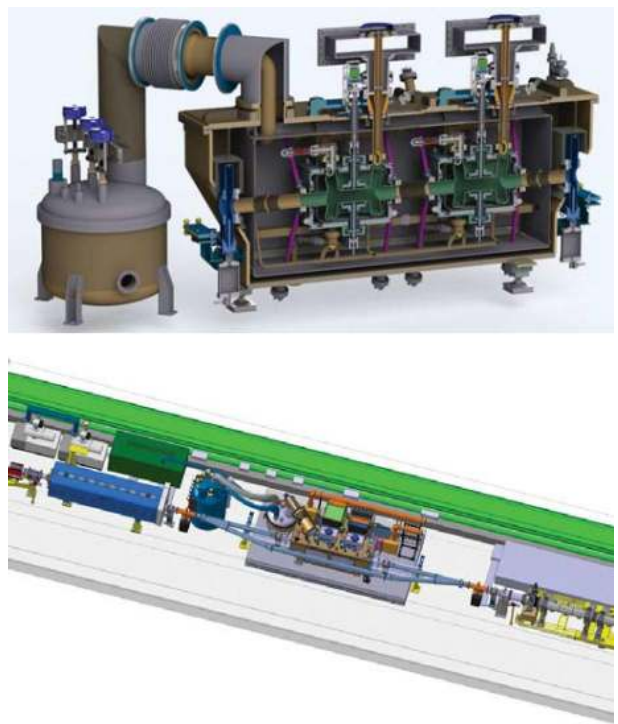

Figure 11: Models of the crab cavity cryomodule (top) integrated in the SPS ring in LSS6 (bottom).

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

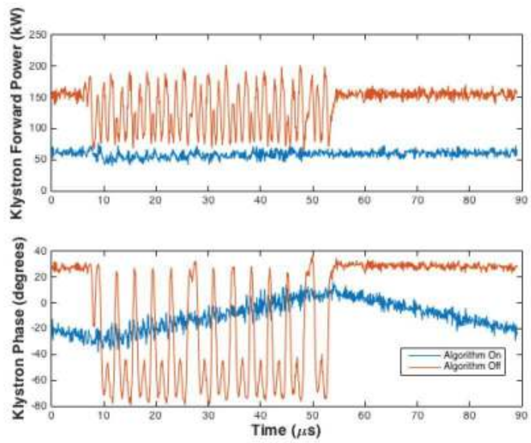

Figure 12: Comparison of klystron forward power (top) and klystron phase (bottom) using the previously operational half-detuning (red) and full-detuning (blue) schemes for the main RF in the LHC.

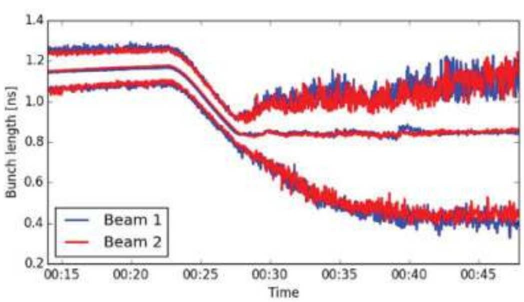

Figure 13: Observed bifurcation of bunch lengths during the controlled longitudinal emittance blow-up, showing the limitations of the presently operational blow-up method.

to schedule then 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 HL-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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