IMPEDANCE REDUCTION FOR LHC COLLIMATORS

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Abstract

The LHC at CERN is equipped with a sophisticated collimation system, aimed at protecting superconducting magnets against quenches in case of losses from the circulating beams. The collimation system is one of the major contributors to the machine impedance at top energy. A relevant hardware upgrade of the system will take place in the context of the High Luminosity LHC (HL–LHC) project; one of the main objectives is to make stabilisation of the brighter HL–LHC beams reachable within the capabilities of the Landau octupoles. In fact, a relevant fraction of the carbon–based collimators will be exchanged with new ones, the jaws of which are made of materials more optimised in terms of impedance; hence, the footprint of the collimation system will be significantly reduced. The present contribution gives an overview of the baseline low–impedance upgrade of the LHC collimation system as foreseen by the HL–LHC project and the expected impact on impedance. Additional options that could further improve the footprint of the collimation system on the machine impedance are briefly summarised.

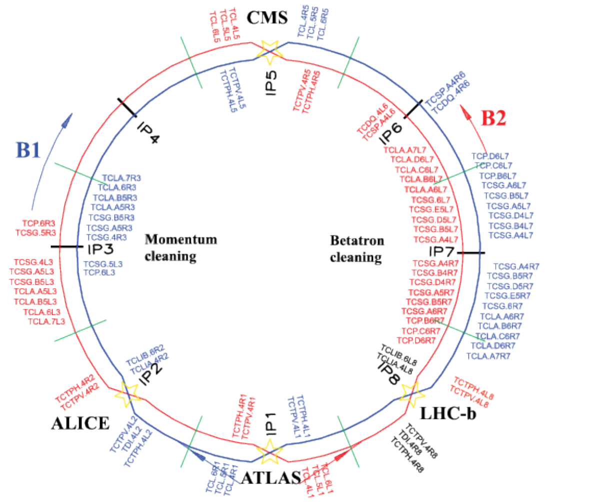

Figure 1: Layout of the LHC collimation system as of Run 2 [17].

INTRODUCTION

The Large Hadron Collider (LHC) [1] at CERN is equipped with a sophisticated collimation system [2], fundamental to protect the machine against regular and abnormal beam losses. Since the LHC is a superconducting machine, its magnets can quench[1] if local losses are not kept within acceptable levels, leading to considerable machine downtime [3]. To ensure high–efficiency operation, the system meets very challenging design criteria, ranging from handling unprecedented power losses of up to 500 kW while granting a global cleaning efficiency as high as 99.99 % to precise jaw positioning, down to 5 µm, and reproducibility of the mechanical movements [4].

The operation of the LHC requires a distance between the beam and the material of the collimator jaws as small as 1 mm for the collimators closest to the beams [5,6]. Carbon–based materials are extensively deployed in the LHC collimation system, due to the very good thermo–mechanical properties, which make them suitable for standing high loads caused by losses [4]. Therefore, the LHC collimators have a substantial impact on the total machine impedance budget, making them one of the main contributors [7]. While impedance–driven instabilities have never been a show–stopper during LHC operation so far [8], collimator settings have been set increasingly tighter during the first two periods of exploitation of the LHC (i.e. Run 1, 2010–2013, and Run 2, 2015–2018) [5,6], still always ensuring stable operation with Landau octupoles within limits on currents [9–12].

The High-Luminosity LHC (HL–LHC) project [13,14] aims at boosting the integrated luminosity collected by the LHC high luminosity experiments by a factor of 10. To do so, it envisages a thorough hardware upgrade, aimed at achieving more focussed beams at the interaction points and with a better geometrical overlap between colliding bunches. At the same time, thanks to the hardware upgrade implemented by the LHC Injectors Upgrade (LIU) project [15] in the LHC injection chain, HL–LHC beams will be brighter than those typically injected in the LHC, thanks mainly to the doubled bunch population. Such an increase in the beam brightness poses new challenges in terms of robustness of the collimation system and beam stability. In particular, if no collimation upgrade takes place, the octupole currents required to stabilise the HL–LHC beams would be too high, leaving no margin to compensate for sources of beam instability other than impedance [16].

After a brief presentation of the present LHC collimation system, this contribution summarises the foreseen baseline collimation upgrade that will be carried out in the context of the HL–LHC project and the expected performance; the focus is only on impedance aspects. Afterwards, dedicated measurements with beams to benchmark predictions are briefly presented, showing the solidity of the planned upgrade. The contribution is closed by an overview of other options of modifications to the LHC collimation system presently under study and their impact on impedance.

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[1] A quench is the sudden transition of the magnet from the superconducting state to the normal conducting one.

THE LHC COLLIMATION SYSTEM

The LHC collimation system is mainly located in two Insertion Regions (IRs) of the LHC, namely IR3 and IR7 for momentum and betatron cleaning, respectively (see Fig. 1). While the former is responsible for cleaning away off–momentum beam particles, like uncaptured beam at the beginning of the energy ramp, the latter ensures that the machine aperture is well protected against transverse beam losses, e.g. in case of transverse instabilities. Single–turn losses when injecting or extracting beams are dealt with by protection devices specifically installed in IR2 and IR8, where beams are injected, and in IR6, where the beams are extracted. Finally, a few collimators are installed in the IRs where the experimental detectors are located, in order to lower the experimental background induced by the machine [18, 19], and provide local protection to superconducting magnets against fast failures [20, 21] and leakage from IR7 or collision debris.

The LHC collimators are made of two parallel jaws centered around the circulating beam [22, 23]. Collimators are organised in families, where every family absorbs the unavoidable leakage out of the upstream one. Primary collimators (TCPs) are the devices impacted first by the beams; they are located in IR3 and IR7. Their jaws are 60 cm in length, made of carbon–fiber composite (CFC), a special carbon–based material specifically chosen for its enhanced thermo–mechanical properties. IR3 and IR7 are equipped with secondary collimators (TCSGs), 1 m long and made of CFC, located downstream of the TCPs, and with showers absorbers (TCLAs), 1 m long and made of a tungsten–based alloy called Inermet 180, installed towards the end of IR3 and IR7. The IR7 collimation system is further complemented by tertiary collimators (TCTs), located in the experimental IRs; the hardware is similar to that of TCLAs. This hierarchy is fundamental for the optimal performance of the system, and it is assured by setting collimator families at increasing jaw opening with sufficient operational margins between adjacent families.

Contribution to Impedance

At top energy, the LHC collimators are the main contributors to the impedance budget (see Fig. 2) [24]; IR7 TCPs and TCSGs give the largest footprint, because they are numerous (3 and 11 units per beam, respectively), their jaws are made of CFC, which has a non optimal resistivity, and their openings are the smallest in the ring.

Throughout Run 2, beam sizes at the collision points were made progressively smaller [25, 26], implying a smaller machine aperture available at every step. Therefore, IR7 collimator settings were made progressively tighter [6], implying an increasing contribution to machine impedance; this was carefully verified with measurements in the LHC and with simulations at every change of settings. In this detailed benchmark, it was found that the predicted effective imaginary impedance of the present system is similar to that reconstructed with beam measurements, even though in many occasions a discrepancy by ~50 % is found [16, 27]. Such a discrepancy is still under investigation while a continuous effort in improving the LHC impedance model is on–going.

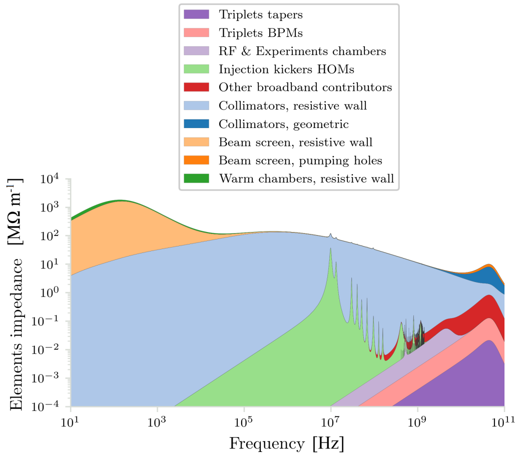

Figure 2: Expected real part of the dipolar horizontal impedance of the LHC at 6.5 TeV with 2018 operational parameters [24]. The breakdown of contributions from various systems is shown as a function of frequency.

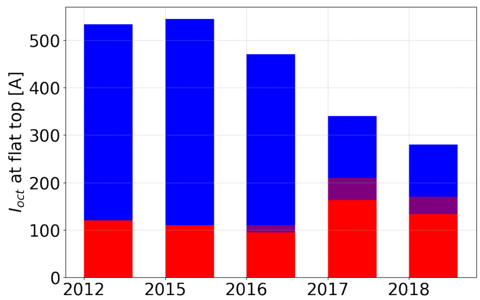

Figure 3: Current of Landau octupoles as expected by simulations (red bars) and required by operation (blue bars) [8]. The shaded bars show the stabilising contribution from long range beam–beam encounters. Values are for a chromaticity of ~15 and a damper gain set for damping oscillations within 50 – 100 turns.

LHC operation in Run 1 and Run 2 was characterised by a high current of the Landau octupoles, significantly above predictions by numerical simulations (see Fig. 3) [8]; the discrepancy with respect to predictions was made progressively smaller, thanks to the increasing knowledge and control of the machine, attaining a factor 2 in 2017 and 2018. While only a fraction of such a discrepancy can be explained by limits of the impedance model, the interplay between the different phenomena leading to instability needs to be analysed in detail [16, 28–31]. Therefore, with such an analysis still on–going [8, 16], the factor 2 of uncertainty in the stability model must be taken into account for estimating octupole currents necessary to stabilise LHC beams in future configurations; this is the most accurate assumption based on the

Table 1: LHC operational (as of the 2018 run) [25] and HL–LHC [32] (both nominal and ultimate values are reported for standard beams) parameters: β function at the high-luminosity collision points (β^*), peak luminosity (L_{peak}), integrated luminosity (L_{int}), beam energy (E_b), number of bunches (n_b), bunch population (N_p), and normalised emittance (ϵ_N).

Parameter	LHC 2018	HL–LHC Nominal	HL–LHC Ultimate
β^* [cm]	25	15	
L_{peak} [10^{34} cm^{-2} s^{-1}]	2	5	7.5
L_{int} [fb^{-1} year^{-1}]	66	262	325
E_b [TeV]	6.5	7	
n_b	2544	2760	
N_p [10^{11} per bunch]	1.2	2.2	
ϵ_N [µm] (flat top)	1.9	2.5	

present knowledge. In any case, predicted octupole currents should not exceed the maximum available, i.e. 570 A.

THE HL–LHC CHALLENGE

The HL–LHC [13, 14] is an upgrade of the LHC aimed at increasing the integrated luminosity collected by the LHC high luminosity experiments by one order of magnitude compared to the LHC baseline program. Table 1 compares key machine parameters expected for the HL–LHC era [32] to those achieved so far in the LHC as of 2018 [25]. In the context of the HL–LHC project, the IR7 collimation system will be substantially upgraded, to lower its impedance and to stand the losses of the HL–LHC beams, expected to double the LHC ones following the increased bunch population (see Table 1).

Present Baseline and Expected Performance

The backbone of the HL–LHC collimation impedance upgrade of IR7 [33] is the change of jaw material of those collimator families impacting impedance the most, i.e. TCPs and TCSGs. The existing collimators will be exchanged with new ones, where materials of lower resistivity [16, 34–36] will be deployed in the jaws instead of CFC:

TCPs the horizontal and vertical TCPs will be replaced by new collimators (TCPPMs), the jaws of which are made of MoGr, a composite material made of Molybdenum and graphite, thanks to the consolidation project but for the jaw material, paid by the HL–LHC project;

TCSGs 9 out of 11 TCSGs per beam will be replaced by new collimators (TCSPMs), the jaws of which are made of Mo–coated MoGr jaws (TCSPMs).

The upgrade will proceed in stages [37], with the TCPPMs and 4 TCSPMs per beam installed in LS2 (2019–2020); the remaining TCSPMs will be installed in LS3 (2023–2024).

The new hardware will come with a new design (see Fig. 4 for the design of the TCSPM) [38], characterised by:

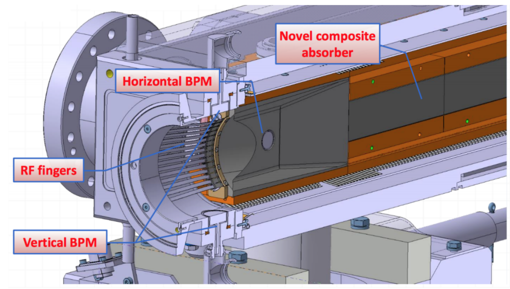

Figure 4: Zoom on the jaw of the TCSPM collimator design [38].

- in–jaw button beam position monitors (BPMs), for precise jaw alignment and monitoring of the beam closed orbit. There will be also the possibility to interlock the BPM readouts;
- a tank BPM, monitoring the beam orbit on the plane orthogonal to that of cleaning;
- the possibility to move the entire collimator assembly along the direction orthogonal to that of cleaning, in order to expose to the beam a fresh new surface following scratching or accidental beam impacts (so called 5$^{\text{th}}$ axis functionality);
- a universal housing of the absorbing material and improved thermal conductivity between the absorbing material and the jaw structure;
- smoother tapering, i.e. transition to the region exposing the absorbing material to the beam.

The key characteristics of the design have been thoroughly tested with beam in the HiRadMat test facility [39]; the collected measurements [40–43] allowed to conclude that the design of the new hardware is adequate for the planned upgrade.

Figure 5 shows the Landau octupole current necessary to attain single–beam stability in the HL–LHC era for different IR7 layouts, as predicted by numerical simulations [16]. As it can be seen, the present LHC collimation system would not allow to keep the required octupole current below the maximum with the HL–LHC brighter beams. On the contrary, the full HL–LHC impedance upgrade of IR7 (labelled as "LS3 upgrade" in the figure) is fundamental to substantially meet the requirements on the Landau octupole current. The partial upgrade foreseen for LS2 will provide more than half of the impedance reduction already in Run 3 (2020–2023); at the same time, it will allow to swallow the progressively brighter beams available in the LHC injectors, and get acquainted with the new hardware.

Even with the low–impedance upgrade of IR7, the LHC collimators will remain one of the major contributors to machine impedance at flat top (see Fig. 6) [16].

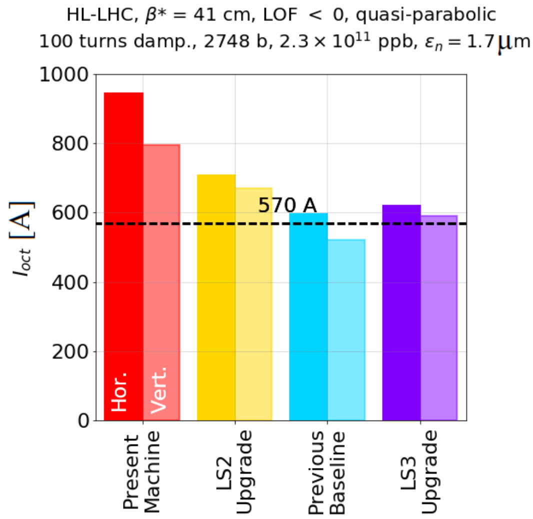

Figure 5: Landau octupole current predicted by numerical simulations in the HL–LHC era for different IR7 layouts [16]. Predictions refer to the single beam stability. Key parameters used in the estimations are reported in the figure. "Previous baseline" refers to the exchange of all TCPs and TCSGs with the upgraded ones. Predictions take into account the factor 2 of uncertainty in the stability model.

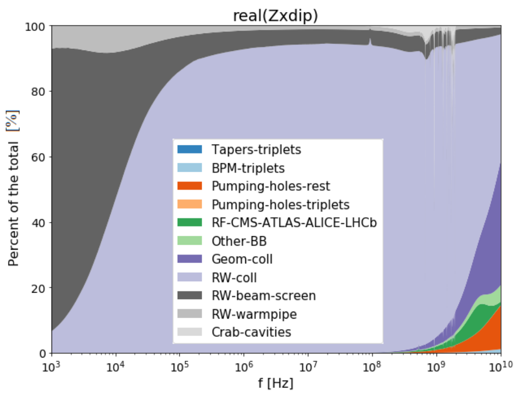

Figure 6: Expected real part of the dipole horizontal impedance of the HL–LHC at 7 TeV [16]. The breakdown of contributions from various systems is shown as a function of frequency.

Benchmark Measurements

The beneficial effects of the TCSPM design on impedance were verified with an extended campaign of measurements with beam. In early 2017, a prototype of TCSPM was installed in the LHC for this purpose [45]. The prototype was characterised by jaws with three stripes of materials to be tested (see Fig. 7); two of them were the materials chosen for the design (i.e. MoGr and pure Mo); the third one was TiN, considered as possible alternative to Mo with a higher robustness. The chosen installation slot was adjacent to a regular TCSG, for direct comparisons to CFC; the slot is also characterised by the smallest beam size on the cleaning

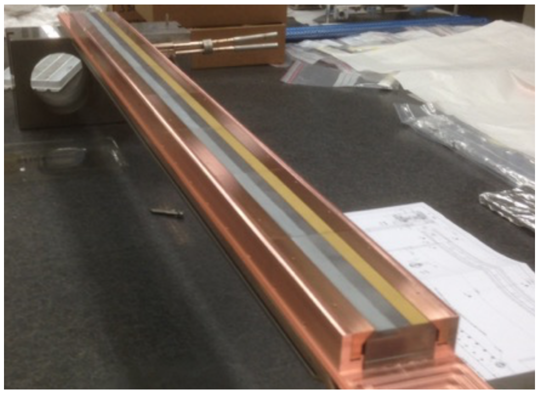

Figure 7: Jaw of the TCSPM prototype jaw installed for impedance measurements. The yellow stripe is made of TiN, whereas the light grey one is made of pure Mo; the central stripe is the bulk MoGr.

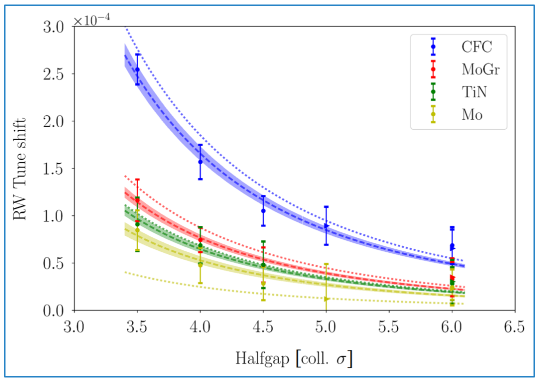

Figure 8: Comparison between tune–shift measurements obtained with the TCSPM prototype and the adjacent TCSG collimator (points with error bars) and the simulation predictions (densely dashed lines); fits through data (dashed lines) are also given (shaded areas represent 1 σ uncertainty of fit error). Results from all materials are shown. Measurements were carried out with typical LHC single bunches and with HL–LHC–like single bunches; in the latter case, results have been scaled to match the LHC bunch population to fit into the plot.

plane among all the IR7 TCSGs, such that signatures from impedance were as clear as possible.

The measurements were carried out cycling the collimator gap and monitoring the tune signal reconstructed from the damped oscillations after kicking the whole bunch. The measurements were challenging, especially because of the sensitivity in the tune shift that had to be achieved, i.e. in the order of 10^{-5}, in order to correctly resolve tune variations from the resistive wall impedance of the materials under test. As it can be seen (see Fig. 8), measurements are in good agreement with predictions, apart from the case of Mo, where measurements are constantly twice the expectations. Further investigations have shown the importance of the micro–structure of the substrate below the coating layer as well as the quality of the coating process, which would explain the higher measured values [46]. After these measurements took place, the supplier of Mo–coated MoGr jaws managed to build jaws for which the Mo conductivity is now very close to the theoretical value of the pure metal [46].

Other Options

The presented estimates of the Landau octupole current necessary to stabilise the HL–LHC beams take into account the factor 2 uncertainty in the stability model. Even though the origin of the discrepancy is presently not fully understood [16], there is no better extrapolation to the HL–LHC era as of writing. At the moment, it is believed that part of the discrepancy could come from a larger than expected impedance (maybe due to a higher resistivity than anticipated) and part of it from the destabilising effect of noise on beam stability [47].

Other options for IR7 update or modification are presently under study. Even though they are not all in the HL–LHC baseline, their deployment can have a positive impact on the impedance footprint of the LHC (and hence HL–LHC) collimation system. The various options are summarised in the following.

New IR7 Optics A new IR7 optics has been proposed [48], targeting larger values of β–functions at collimators (in the collimation plane). For the same normalised settings, collimator gaps would be larger in mm, implying a lower impact on beam impedance. In addition, larger β–functions at TCPs would imply larger changes in normalized amplitude of scattered out protons. Simulation results show that this option is a promising one, reducing the integrated losses of several tens of percent and the peak ones by up to a factor of 3 with respect to the nominal LHC values. The gain in octupole current is estimated to be $\sim$25 %.

IR7 Asymmetric Collimator Settings LHC collimators are two–jaws devices with the beam passing in–between. Since halo cleaning of the circulating beam is a process taking place over multiple LHC revolutions, the same cleaning effect from a two–sided device can be achieved with a single–sided device. Fully retracting a jaw per collimator would have a beneficial effect on the resistive–wall impedance footprint of the collimation system, but may increase the leakage to the arc immediately downstream of IR7, which is essentially a single pass process. Even if the studies have not been finalised, first results show some potential in terms of impedance reduction with a limited loss in cleaning performance, even though the impedance reduction is not as sizeable as that obtained with the new IR7 optics [49, 50].

Electron Lens –Assisted Collimation In the context of the HL–LHC project, hollow electron lenses (HELs) [51] are studied [52] to deplete on purpose beam tails at specific moments during the LHC cycle, providing a method for active halo control. HELs are devices where a hollow electron beam is made travelling co–axial to the main proton beam; the electron beam is hollow, such that it transversely overlaps only with the tails of the main beam and hence the Lorentz force exerted by the electrons onto the main beam affects only the tails. When the HEL is switched on, the diffusion speed of particles in the tails is enhanced, driving them on the collimation system. Such a device is presently part of the HL–LHC upgrade as means to mitigate fast failures of crab cavities [53] or to scrape away overpopulated tails that in case of jitters of the beam orbit would trigger unnecessary beam dumps.

Even though the primary goal of the HELs in the HL–LHC baseline is not to mitigate impedance aspects, their use at flat top could open to the possibility of progressively tightening the IR7 collimator settings while beams are in collision and hence deploying more relaxed settings at the beginning of data taking, when the beam is still highly populated and the octupole current necessary to Landau–damp it is high. Such an operational mode of IR7 collimators has never been explored so far and it is not planned for the future, since the reduction of collimator gaps would imply producing uncontrolled losses during data taking, with risks of spurious dumps. In this perspective, HELs could be deployed prior to tightening the collimator gaps, generating losses in a controlled way and hence avoiding dumps.

This operational mode, not studied yet, would a priori be beneficial for the footprint of the collimation system on impedance. In fact, it would allow to deploy larger collimator gaps at the beginning of the fill, when the beam intensity is higher, and tighten collimator settings while the beam intensity is reduced because of collision burn–off.

CONCLUSIONS

The present LHC collimation system substantially contributes to the total LHC impedance budget, especially at flat top energy; without upgrading the system, the brighter HL–LHC beams would need a too high octupole current to be Landau–damped. The expectations for the HL–LHC era are based on the present knowledge of sources of beam instability in the LHC, which account for only half of the octupole current required to operationally stabilise the LHC beams as of Run 2. The origin of the uncertainty is still being investigated, while improving numerical models and understanding the interplay between destabilising processes.

The current baseline of the impedance upgrade of the LHC collimation system in IR7 has been presented. It is based on the replacement of most of the present primary and secondary collimators with new ones. The new hardware is characterised by jaws made of a low–impedance material; in particular, MoGr has been chosen as baseline material, following a rich R&D program, as best compromise between impedance improvement and adequate robustness. In addition, secondary collimators will be coated with pure Mo, to further reduce their footprint on the total machine impedance. The impedance upgrade will bring the expected octupole current required to stabilise the beam within acceptable values.

Other options, currently under study, have been summarised, possibly improving not only the footprint of the system on impedance, but also the cleaning performance. They consider a wide range of changes in IR7, including a new optics, alternative collimator settings, and innovative technologies for achieving beam cleaning.

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