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LOW-IMPEDANCE COLLIMATORS FOR HL-LHC*

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Abstract

The High-Luminosity upgrade of the Large Hadron Collider (HL-LHC) will double its beam intensity for the needs of High Energy Physics frontier. This increase requires a reduction of the machine's impedance to ensure the coherent stability of the beams until they are put in collision. A major part of the impedance is the resistive wall contribution of the collimators. To reduce this contribution several coating options have been proposed. We have studied numerically the effect of the novel coatings on the beam stability. The results show that a decrease of up to 30% of the machine impedance and a reduction of up to 120 A in the stabilizing octupole current threshold can be achieved by coating the secondary collimators with Molybdenum. Half of that improvement can be obtained by coating the jaws of a subset of four collimators identified as the highest contributors to machine impedance. The installation of this subset of low-impedance collimators is planned for the Long Shutdown 2 in 2019-2020.

LHC COLLIMATION SYSTEM AND TRANSVERSE BEAM STABILITY

The collimation system is an essential part of the Large Hadron Collider (LHC), protecting its superconducting magnets from quenches or damage in case of beam losses [1, 2]. The system is mainly located in two designated Insertion Regions (IRs): IR7 for betatron cleaning and IR3 for momentum cleaning (Fig. 1).

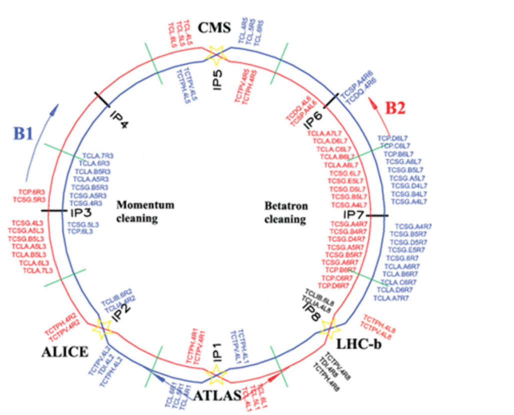

Figure 1: Schematics of the LHC collimation layout [2].

The collimation system is the single highest contributor to the machine transverse impedance at top energy [3]. As the High-Luminosity upgrade nearly doubles the bunch population to 2.3×10^{11} ppb (at injection) [4], the impedance has to be reduced to ensure beam stability. The LHC stability margin is typically expressed in terms of current in its Landau Octupole system, providing Landau damping of collective instabilities. Although the octupole threshold is expected to be within the capabilities of the system, a safety margin is required, since in a real machine the impedance can only be worse than in the ideal model. Effects like long-range beam-beam [5] interaction, coupling [6], magnet imperfections, damper noise [7], optics errors [8], and uncertainty of beam distribution might also affect the tune spread, distorting the stability diagram. Based on the present operational experience at LHC, we consider it is necessary to have at least a factor of two safety margin between the predicted threshold and the hardware limit of 600 A (the system has been commissioned only to 570 A), and that requires a dramatic reduction of collimator contribution to the octupole threshold (Fig. 2).

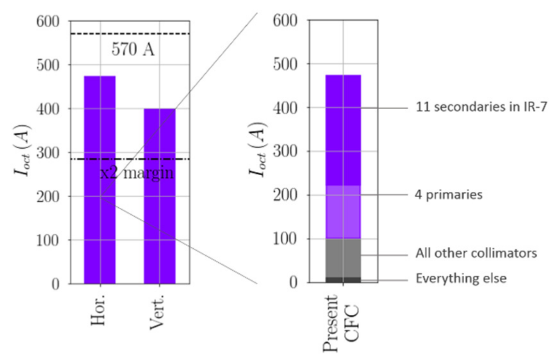

Figure 2: Impedance of LHC collimators has to be reduced for the Hi-Lumi upgrade. It is responsible for nearly all the octupole current required to stabilize the beam at the top energy, with ~50% coming from 11 secondary collimators. E = 7 TeV, BCMS beam, Ultimate operational scenario [9].

HL-LHC COLLIMATOR UPGRADE

In order to reduce the machine impedance and ensure stable operation at high intensity the collimator system will be upgraded. The upgrade will involve the highest contributor to the octupole threshold, the betatron cleaning primary and secondary collimators in IR7 (Fig. 1). Their jaws will be replaced with Molybdenum-Graphite (MoGr) that has a factor five lower DC resistivity than the present Carbon Fibre Composite (CFC). In addition, the jaws of the secondary collimators will be coated with a 5 µm low resistivity layer of Molybdenum (Mo) (Table 1). This coating has been chosen for its strong robustness to beam impact [10] and good adhesion to the MoGr substrate. Its thickness is sufficient to effectively screen the bulk of the jaw at high frequencies, thus improving single-bunch dynamics and providing a sufficient margin for the transverse beam stability. The novel collimation materials have been

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tested in a prototype collimator (Fig. 3), where a significant reduction of the resistive wall impedance of the jaws has been clearly observed [11]. The measurements also revealed that the Mo coating might have a higher resistivity than its bulk (Table 1), although there are other effects that could explain the measurement (e.g. coating roughness).

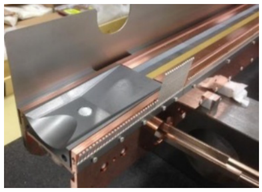

Figure 3: The jaw of the prototype collimator that was used to study different coatings in LHC [12].

IMPACT ON HL-LHC BEAM STABILITY

The effect of low-impedance collimators on the transverse beam stability has been estimated using the HL-LHC impedance model and the latest beam and optics parameters (Table 2). We focused on the most critical case for single-beam stability, just before the beams are brought into collision, at the beginning of the luminosity levelling process, when β^*=41 cm (for the ultimate luminosity of 7.5×10^{34} cm^{-2}s^{-1}) and has not yet reached its minimum value of 15 cm. The simulations were performed with DELPHI [13], a Vlasov solver capable of treating combined head-tail and coupled-bunch motion. It determines the coherent tune shift of the most unstable mode, which is then converted into the octupole strength required to stabilize that mode using a stability diagram approach and assuming the modes are independent (far from the Transverse Mode Coupling Instability (TMCI) threshold).

The greatest impact on beam stability is expected from the coating of the secondary collimators due to their large share of the octupole threshold. Since low-frequency coupled-bunch instabilities can be efficiently suppressed by the feedback, the threshold is governed by the high frequency part of beam impedance, relevant for head-tail instabilities, above the RF frequency of 400 MHz. Upgrading the collimators reduces it by 30%, and a half of the total impedance reduction is obtained by coating a subset of four collimators, chosen for LS2 (Fig. 4). Using a lower resistivity Cu coating instead of Mo does not lead to a considerable further reduction of impedance, since it starts being dominated by other collimators and tapered transitions. Nevertheless, Cu might be favoured if the higher impedance of Mo coating is confirmed in future studies.

To find the octupole threshold we, first, compute the nonlinear detuning, required to stabilize impedance-driven instabilities (Fig. 5) using a stability diagram approach. The diagrams are calculated for a pessimistic case, where the tails of the transverse distribution are cut at 3σ [14], and assuming no emittance blow-up at injection (Table 2). The octupole thresholds are then computed from the detuning, neglecting the enhancement of the octupole footprint due to telescopic optics [15] and the detrimental long-range beam-beam interaction.

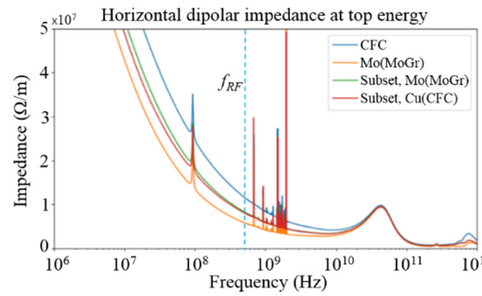

Figure 4: Low-impedance secondary collimators decrease the machine impedance by 30% at the frequencies ~1 GHz, relevant for the single-bunch coherent dynamics. Coating a subset of four collimators provides a half of the reduction. Chromaticity Q' = 0; 7 TeV; narrow spikes near 1 GHz correspond to the higher order modes (HOMs) of HL-LHC crab cavities. RF frequency shown by a dashed line.

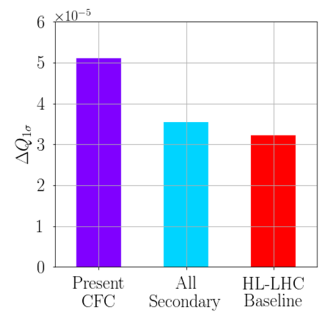

Figure 5: Threshold rms detuning required to stabilize the most unstable mode reduces significantly with low-impedance collimators. Most critical, horizontal plane.

The upgrade of the betatron cleaning secondary collimators in IR7 significantly lowers the octupole threshold, with a larger gain for the BCMS beam due to its lower emittance (Fig. 6). For the standard beam the reduction is ~120 A. It becomes somewhat smaller – 100 A if one assumes the Mo resistivity from the beam measurements. Additional upgrade of the primary collimators (two per beam) in IR7 allows further improving the octupole threshold by up to 30 A, to the point where it stays at least a factor of two lower than the maximum available current of 570 A, leaving a significant operational safety margin. Without the upgrade the long-range beam-beam interaction would bring the octupole stability threshold at the hardware limit for the BCSM beam in the ultimate operational scenario [16].

Table 1: Bulk resistivities of several materials considered for the HL-LHC collimators (nΩ-m); in parenthesis – resistivities of collimator coatings, measured at CERN.

Material	Resistivity	Purpose
CFC	5000	Current jaw material
MoGr	1000	New jaw material
Mo	52 (250)	Baseline coating
Cu	19 (26)	Alternative coating

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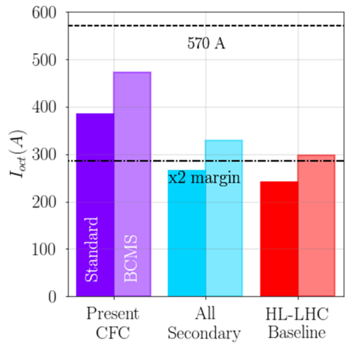

Figure 6: Novel coatings provide sufficient stability margin both for standard and BCMS beams. For a standard beam ~120 A is gained by upgrading all the secondaries in IR7 to Mo-coated MoGr and additional ~30 A – by replacing the two baseline primary collimators with MoGr. The situation in the most critical, horizontal plane is shown.

SIMULATION IN LHC

The low-impedance coating of the secondary collimators has been tested with equivalent collimator settings in LHC during the TMCI study [17]. The low-impedance collimators were imitated by a corresponding increase of the gap of the existing ones.

In LHC, the beam intensity is predicted to be limited by the coupling of modes 0 and -1 in the horizontal plane for zero chromaticity and in the absence of the transverse feedback. The present threshold is estimated to be around 3.4×10^{11} p per bunch, which is in good agreement with the measurements of mode 0 tune shift (Fig. 7). The deployment of low-impedance secondary collimators will increase the threshold to about 6×10^{11} p for the same collimation settings, nearly doubling the threshold and providing enough margin for the HL-LHC high intensity beam. A measurement of mode 0 tune shift is again in good agreement with the impedance model predictions, confirming a significant reduction of the machine impedance (Fig. 7).

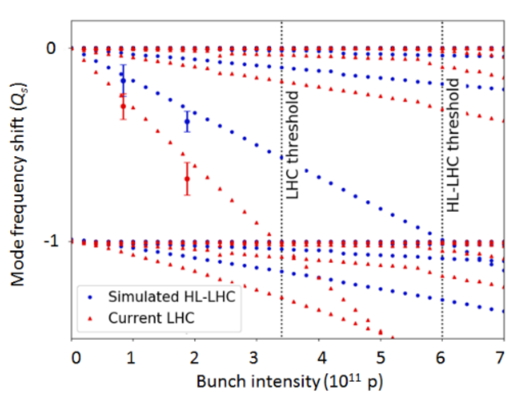

Figure 7: Collimator upgrade is expected to increase the TMCI threshold at the top energy by nearly a factor of two in HL-LHC (blue) compared to LHC (red). The measured mode frequency shifts (error bars) are in good agreement with simulation predictions (dotted lines) [17].

Table 2: Key beam and machine parameters used for numerical simulations [9]. Collimator settings are defined for 2.5 µm reference emittance.

Parameter	Standard (BCMS) beam
Energy, β^*	E = 7 TeV, β^* = 41 cm
Beam intensity	2760 (2748) bunches, 2.3×10^{11} ppb
Tunes: x, y, z	62.31, 60.32, 2.1×10^{-3}
Normalized emittance Bunch length	ε_n = 2.1 (1.7) µm, rms σ_z = 9.0 cm, rms
Damper, chroma.	d = 100 turns^{-1}, $Q'_{x,y}$ = 10
Octupole stability diagram	Negative polarity, tails cut at 3 $\sigma_{x,y}$
Collimator settings	Primary – 6.7σ Secondary – 9.1σ

CONCLUSION

Resistive wall impedance of LHC collimators constitutes a major part of its transverse impedance at the top energy. With the present collimation system the Landau octupole current, required to stabilize impedance-driven instabilities, is close to the capabilities of the hardware of ~600 A for the BCMS beam. That leaves no safety margin for the ultimate operational scenario when the long-range beam-beam interaction is taken into account. The collimator impedance, therefore, has to be reduced in order to guarantee transverse beam stability of the HL-LHC beams.

We have studied numerically the effect of upgrading the highest-contributing collimators with the novel low-resistivity jaw material. Betatron cleaning secondary collimators in IR7 are responsible for nearly a half of the LHC impedance at the frequencies relevant for the single-bunch dynamics. Upgrading them with 5 µm of Mo on MoGr reduces the total machine impedance by 30% and the corresponding octupole threshold from ~390 to ~270 A for the standard beam and from ~480 to ~330 A for the BCMS one. Additional ~30 A of in the octupole threshold can be gained by replacing the two primary collimators with MoGr. In the end, the novel jaw materials should provide sufficient stability margin both for standard and BCMS beams in all presently foreseen operational scenarios of HL-LHC.

The collimator upgrade will begin during a long shutdown in 2019-20, when the first 4 out of 11 secondary betatron cleaning collimators per beam will be upgraded [18]. The starting subset has been chosen to maximize the impedance reduction in the most critical, horizontal plane, and is expected to provide a half of the total improvement.

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