The High-Luminosity upgrade of the Large Hadron Collider (HL-LHC) will double its beam intensity for the needs of High Energy Physics frontier. In order to ensure coherent stability until the beams are put in collision, the transverse impedance has to be reduced. As the major portion of the ring impedance is supplied by its collimation system, several low resistivity jaw materials have been proposed to lower the collimator impedance and a special collimator has been built and installed in the machine to study their effect. The results show a significant reduction of the resistive wall tune shift with novel materials, in agreement with the impedance model and the bench impedance and resistivity measurements. The largest improvement is obtained with a 5 \( \mu \)m Molybdenum coating of a Molybdenum-Graphite jaw. This coating can lower the machine impedance by up to 30\% and the stabilizing Landau octupole threshold by up to 120 A. The collimators to be upgraded have been chosen based on the improvement of the octupole threshold, as well as the tolerance to steady state losses and failure scenarios. A half of the overall improvement can be obtained by coating the jaws of a subset of 4 out of 11 collimators identified as the highest contributors to machine impedance. This subset of low-impedance collimators is being installed during the Long Shutdown 2 in 2019-2020.

Effects like long-range beam-beam [11] interaction, coupling [12], magnet imperfections, damper noise [13, 14], optics errors [15], 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 margin between the threshold, predicted for an ideal machine from impedance only, 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).
II. PROTOTYPE LOW-IMPEDANCE COLLIMATOR

In order to reduce the transverse impedance of HL-LHC several low resistivity material options have been considered for its collimators. First, the jaws of the most critical primary and secondary collimators can be replaced with Molybdenum-Graphite (MoGr) that is characterized by a factor of five lower bulk resistivity than the presently used Carbon Fibre Composite (CFC): 1 vs 5 $\mu\Omega$m. On top of that, a jaw can be coated with a thin layer of a low resistivity Molybdenum (Mo) coating with a bulk resistivity of 0.05 $\mu\Omega$m. A 5 $\mu$m coating thickness is sufficiently greater than the skin depth of the coating at the high frequencies, relevant for the single-bunch dynamics ($\sim 1$ GHz), making the impedance at these frequencies nearly independent of the material behind the coating [16].

In order to test the novel materials with beam, a special test collimator has been installed in LHC. This prototype jaw made of MoGr has a 10 mm wide coating stripe of Mo along with a stripe of an uncoated bulk, it also has a Titanium-Nitrite (TiN) coated stripe for additional reference measurements (Fig. 3). The jaws can move in the transverse plane, exposing the beam to one of the stripes at a time, and thus effectively selecting the coating to study. The third BPM for orbit measurements in the plane orthogonal to the collimator jaw movement is added to measure the orbit position in that plane. This so-called three-stripe collimator was installed next to a standard secondary collimator, allowing comparing the performance of its materials with the presently used CFC.

The design of the new collimator (Fig. 3) relies on a modular concept that allows embarking different absorber materials in the jaws, with no other impact or modifications to the other collimator components. This design can thus be adopted indifferently for primary, secondary, and tertiary collimators, which is advantageous for series production. A BPM for orbit alignment in the plane orthogonal to the collimator jaw movement is installed to measure precisely the orbit position in the collimator.

III. BEAM MEASUREMENTS

A relevant measure that quantifies each material is the magnitude of the resistive wall tune shift, created when the collimator jaws are brought closer to the beam. To measure the tune shift the collimator gap was cycled between a large gap, where the collimator impedance is negligible, and a small gap of 4-6 reference beam sizes. At each gap transverse beam oscillations were excited by the transverse feedback system [18] (Fig. 4). Two separate measurements were performed with single bunches of nominal $1.2 \times 10^{11}$ p and high intensity $1.9 \times 10^{11}$ p, at 6.5 TeV (Table I). In both tests chromaticity and octupole current were optimized to increase the decoherence time to $\sim 1000$ revolutions, which allowed accurately determining the tune at each collimator opening with the SUS-SIX [19] algorithm, while ensuring the transverse stability of the circulating bunch.

Typically, a standard CFC secondary collimator creates a tune shift up to $\sim 10^{-4}$ for a $\sim 10^{11}$ p bunch. The three low-impedance materials are expected to produce tune shifts two to ten times lower. In order to resolve such a tune shift, one has to be able to measure the tunes with a precision level of $10^{-5}$. One of the challenges is the drift of the tune over the period of the measurement, arising from temperature fluctuations or the noise in the orbit feedback system. In LHC the magnitude of this slow ($\sim 100$ s period) tune jitter, can be as large as $10^{-4}$ [20], which is significantly greater than the expected tune shift of the best coatings. The tune drift can be removed from the data using a special measurement procedure where the collimator gaps were cycled fast between their open and closed positions while continuously exciting the beam and measuring its tune (Appendix A).

To separate the resistive wall component of the tune...
shift from the geometric one, an input from a numerical LHC impedance model is used. The model treats the geometry of collimator transitions in the flat taper approximation \[ \Delta Q_{\text{geom}} \approx g^2, \] which was found to be in good, 10–15% level agreement with numerical simulations (see App. B). Under the flat-taper approximation the geometric tune shift \( \Delta Q_{\text{geom}} \) is inversely proportional to the square of the gap \( \Delta Q_{\text{geom}} \propto 1/g^2 \). The resistive wall component has a steeper dependence on the gap:

\[ \Delta Q_{y}^{\text{RW}} \propto \sqrt{\rho/g^3}, \tag{1} \]

where \( \rho \) is the electrical DC resistivity of the jaw material.

 Accounting for the geometric tune shift and fitting the data with Eq. (1) one can clearly distinguish between the different coating options and assess their benefits (Fig. 5). A significant decrease of the resistive wall tune shift compared to CFC is observed for MoGr and each type of coating. The largest reduction, as expected, is measured for the Mo coating that has the lowest resistivity. The fitted experimental data for CFC, MoGr bulk, and TiN agree with the predictions of the LHC impedance model within 10 to 20%.

IV. INVESTIGATING THE HIGHER RESISTIVITY OF MO COATING

Several physical effects may contribute to the higher than expected tune shift observed in the Mo-coating. First, the Mo coating has a column-like microstructure (Fig. 6, left); the size of the columns decreases for thinner films, increasing the number of transitions an electron crosses when moving in the material and thus increasing the resistivity. Four-point measurements show a significant increase of Mo thin film resistivity at or below the thickness of 5 \( \mu \text{m} \). High DC resistivities have been measured in some Mo-coated samples at CERN (Table II). SEM imaging also shows significant roughness of the coated surface: the average size of inhomogeneities is of the order of several microns and is measured to be up to 10 \( \mu \text{m} \) for the test sample with 8 \( \mu \text{m} \) coating thickness (Fig. 6, right). Such roughness, not seen in other coatings, should lead to an increase of the imaginary part of impedance in the long-bunch limit. The additional imaginary impedance scales as \( \sim 1/g^3 \) making it thus indistinguishable for the resistive wall component (1) in the measurement. The effect though is rather small – at least an order of magnitude lower than the expected resistive wall impedance even for a large size of roughness “bumps” of 5 \( \mu \text{m} \), similar to the thickness of the coating.

The hypothesis of the influence of the microstructure was supported by a RF resonant wire measurement, performed on the three-stripe collimator on a bench at several frequencies relevant for single bunch dynamics. In this test, the variation of the real part of the longitudinal
FIG. 6. SEM imaging [25] reveals that Mo coating is not uniform: it has a column-like fine structure (left) and inhomogeneities up to 10 µm on its surface (right) that may affect the measured tune shift.

The measured difference in the real part of the longitudinal impedance suggests a higher than expected resistivity of the Mo stripe. Resonant wire measurement, performed in a test stand prior to the installation of the prototype in LHC [26].

This result suggests an extra resistivity of the Mo coating, which is consistent with the results of beam measurements (Table II). Further investigations, including DC and RF measurements for various substrates and different coating procedures are under way [26]. Preliminary results of those studies indicate a improvement of coating resistivity to below 0.07 µΩm, which is achieved with good reproducibility when using a high-power impulse magnetron sputtering process [26]. Nevertheless, a potential inferior coating conductivity up to 0.25 µΩm is taken into consideration for stability analysis.

V. OUTLOOK FOR HL-LHC

A total of 22 secondary betatron cleaning collimators are foreseen to be replaced as a part of the HL-LHC upgrade. The new design follows that of the three-stripe prototype: a MoGr active part coated with 5-6 µm Mo layer. It also includes two in-jaw BPMs for collimator alignment and a BPM for orbit measurements in the plane orthogonal to the collimation plane (Fig. 8). Details of other design improvements can be found in [27].

In addition to the secondary collimator upgrade, four betatron primary collimators (1 per beam per plane) will be replaced with the MoGr ones.

A. Impact on transverse 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 III). 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 \( \beta^* = 41 \) cm (for the ultimate luminosity of \( 7.5 \times 10^{34} \) cm\(^{-2}\)s\(^{-1}\)) and has not yet reached its minimum value of 15 cm. The simulations were performed with Vlasov solvers NHT [28] and DELPHI [29], 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).

To find the octupole threshold we, first, compute the nonlinear detuning, required to stabilize impedance-driven instabilities using a stability diagram approach. The diagrams are calculated for a pessimistic case, where the tails of the transverse distribution are cut at 3.2σrms [30], and assuming no emittance blow-up at injection (Table III). The octupole thresholds are then computed from the detuning, neglecting the enhancement of the octupole footprint due to telescopic optics [31] and the detrimental long-range beam-beam inter-action [32].
FIG. 9. Low-impedance secondary collimators decrease the machine’s horizontal dipolar impedance at the top energy by 30% at the frequencies $\sim 1$ 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.

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. 9).

B. Simulation in LHC

The low-impedance coating of the secondary collimators has been tested with equivalent collimator settings in LHC during the TMCI study [33]. 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 $3.4 \times 10^{11}$ ppb, which is in good agreement with the measurements of mode 0 tune shift (Fig. 10). The deployment of low-impedance secondary collimators will increase the threshold to about $6.0 \times 10^{11}$ ppb 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. 10).

C. Staged Collimator Upgrade

The HL-LHC project strategy is to pursue a staged deployment of the low-impedance collimators, consisting of two phases: a first installation in the Long Shutdown 2 (LS2, in the period 2019–2020) followed by a second installation in LS3, in 2023–2024 [10]. This approach has various advantages. It already provides an important reduction of the collimator impedance for the LHC Run III, when the upgraded beam parameters from the LHC Injector Upgrade (LIU) program will progressively become available. This will provide important benefits to the LHC operation and will allow studying better the possible impedance limitations. In addition, a staged deployment allows possible further iterations on the new collimator design for the second production line for LS3. The staged approach also allows distributing resources that would otherwise have to be made available in LS3, when various other parallel activities for different HL-LHC upgrades will be on-going, in particular the collimation upgrade of the high-luminosity insertions IR1 and IR5 [10].

For an optimum deployment of low-impedance collimators in Run III, various studies were carried out to identify the IR7 secondary collimator slots to be upgraded with highest priority. This analysis started with an assessment of the slots that contribute most to the collimator impedance and also included other considerations related to the overall performance of the collimation system. Based on analysis of impedance, cleaning efficiency, and reliability a solution excluding the replacement of the collimators that are the most exposed to regular collimation losses (in terms of energy deposition) has been chosen. This option also features the largest impedance reduction in the most critical horizontal plane [34].

Analysing potential options one can see that, first, the complete upgrade of the betatron cleaning secondary collimators in IR7 significantly lowers the octupole thresh-
old, with a larger gain for the BCMS beam due to its lower emittance (Fig. 11). For the standard beam the reduction is \( \sim 120 \) A. It becomes somewhat smaller \( \sim 100 \) 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 BCMS beam in the ultimate operational scenario [17].

VI. WAYS TO FURTHER REDUCE THE IMPEDANCE

As the resistive wall part of the impedance is reduced thanks to the low-impedance coatings, it now becomes important to model more accurately other sources of impedance, in particular the geometric impedance of the collimators. For the full collimator upgrade the total collimator resistive wall component amounts to 7.8 MΩ/m (54\%) and the total geometric - to 3.5 MΩ/m (24\%) out of 14.5 MΩ/m overall effective machine dipolar impedance in the vertical plane and 7.6 MΩ/m (46\%) and 5.5 MΩ/m (33\%) out of 16.6 MΩ/m in the horizontal plane respectively. The remaining 20\% come from various sources, predominantly the beam screens: their resistive wall impedance and the broadband impedance of the pumping holes.

A. Momentum cleaning collimators

Figure 12 depicts individual collimator contributions to the RW (left) and geometric (right) parts of effective imaginary dipolar impedance at flat-top. RW contributions are computed assuming the current baseline scenario [18]. Most of the RW contribution comes from three sources: the primary collimators (TCPs), the secondary collimators (TCSGs) in IR-7, and TCSGs in IR-3 (in the vertical plane). The momentum cleaning TCSGs in IR-3 show extra potential for impedance reduction, since they are not upgraded in the baseline, but could be replaced with low-impedance collimators if needed. The upgrade of IR-3 secondaries would further reduce the machine impedance in the vertical plane.

B. Cu coating

Copper, having a factor 3 larger DC conductivity then Molybdenum, can further significantly reduce the resistive wall component of an individual collimator. But since the overall impedance of the machine is also affected by many other sources, such as the resistive wall impedance of its beam screens or the geometric collimator impedance, Cu coating of the collimators only marginally decreases the overall impedance of LHC (Fig. 9).

The downside of the coating is its lower tolerance to beam losses compared to Mo, which was observed in HiRadMat tests at CERN [35]. Nevertheless, the coating might still be used in certain collimators based on the
FIG. 12. Resistive wall (left) and geometric (right) contributions of individual collimators to the overall dipolar effective imaginary impedance of the machine. Top energy $E = 7$ TeV, $\beta^* = 41$ cm, $Q^* = 10$, Beam 2. Beam 1 collimators have similar impedance.

outcome of energy deposition and failure scenarios studies. The most favorable candidates, if any, seem to be the skew collimators, less exposed to failure case losses.

C. Optimal taper geometry

Taper transitions of LHC collimators have already been optimized in order to lower their geometric impedance [36]. The new double taper design of the transitions with a smaller tapering angle closer to the beam offers a factor two decrease of the broadband imaginary impedance of the tapers (see App. B). A further gain can be achieved by using an optimal non-linear geometry as suggested by [37]. The shape is designed such as to minimize the geometric impedance contribution of a taper profile $g(z)$:

$$Z_{dip} = -\frac{i\pi w}{c} \int_0^L \frac{g'^2}{g^3} dz$$

for a given tapering length $L$, width $w$, height $g(0) - g(L) = \Delta g$, and collimator half-gap $g(0) = g_0$ [22]. The resulting profile follows

$$g(z) = g_0 \times \left[ 1 - \frac{z}{L} \left( 1 - \sqrt{\frac{g_0}{g_0 + \Delta g}} \right) \right]^{-2}.$$  

Simple estimates show that this approach can further lower the geometric impedance by up to a factor two depending on the gap (Fig. 13). The downsides of this approach might be that the shape remains optimal only for one specific collimator opening and that it is rather complex, i.e. may be costly to manufacture.

A simpler similar more viable shape could be obtained for example with an arc of a circle. Considering, for example, the closest to the beam 5.71 deg transition of the secondary TCSPM tapers, one can see that the optimal shape of this $L = 80$ mm, $\Delta g = 8$ mm can be approximated with arc of a circle of a $R = 80$ mm radius. The arc provides a comparable impedance reduction in a wide range of practical collimator openings (Fig. 13). The improvement can be as large as a factor two for sufficiently small collimator openings.

D. Additional collimator retraction

Since the resistive wall impedance of the collimators is a steep function of their gap, $\propto 1/g^3$, an intuitive way to lower it is by retracting the collimators. This has only a limited impact on the overall machine impedance though due to collimator impedance being already relatively low after the low-impedance upgrade and the impact of other impedance sources, i.e. beam screen. On top of that, this process has significant associated risks: limiting the $\beta^*$ reach or increasing the steady-state losses. At the moment of writing of this paper it seems potentially possible to retract the collimation hierarchy by $1 \sigma$ (corresponding to $2.5 \mu m$ normalized emittance) while still protecting the triplet aperture in the most challenging scenarios and maintaining acceptable level of beam losses seen by the equipment. This approach could potentially yield up to $\sim 40$ A reduction of the octupole threshold for the BCMS beam ($\sim 7\%$ of the octupole system’s capacity). A greater improvement can be achieved for the previously discussed partial secondary collimator upgrade.
VII. 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 operational margin for the ultimate operational scenario when the long-range beam-beam interaction and feedback noise is taken into account. The collimator impedance, therefore, has to be reduced in order to guarantee transverse beam stability of the HL-LHC beams.

A three-stripe prototype collimator has been installed in LHC to study the effect of low impedance coatings on beam dynamics for the HL-LHC upgrade. Its jaws are made of MoGr with two low-resistivity coating stripes: TiN and Mo, and can be moved transversely to selectively expose the beam to the chosen material. Resistive wall tune shifts have been measured as a function of the collimator opening to assess the impedance of each material. An unprecedented tune shift resolution of the order of 10^{-5} has been achieved, allowing distinguishing the impedance reduction of different low-resistivity coatings.

The results show a significant reduction of the resistive wall tune shift with novel materials compared to the presently used CFC. Uncoated MoGr reduces the tune shift by a factor 2, and the largest improvement, a factor 4, is obtained with a 5 µm Mo coating. The tune shifts for the current CFC collimator and two of the new materials: MoGr and TiN-coated MoGr agree within 10-20% with the predictions of the current LHC impedance model in a wide range of collimator openings, suggesting a good identification of both the geometric and the resistive wall contributions in the experiment. The Mo coating demonstrates a two times larger resistive wall tune shift than the one expected from its DC bulk resistivity. Following studies, such as resonant wire measurements confirmed the greater than expected resistivity of the coating, which seems to be connected to its microstructure.

Based on the experimental findings, 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 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 and 2 primary betatron cleaning collimators per beam will be upgraded [34]. 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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[18] W. Hofle et al., 5th Joint HighLumi LHC - LARP Meeting Fermilab, USA, 28 Oct 2015


Appendix A: Correcting for the tune drift in the beam measurement data

The tune drift has been removed thanks to a special measurement procedure where the collimator gaps were cycled fast between their open and closed positions while continuously exciting the beam and measuring its tune (Fig. 1). Combining the measurements at different gaps one obtains the dataset, consisting of the tune jitter (plus random errors of the measurement), which is independent of the gap. Assuming the tune drifts slow enough, one can interpolate it with a low order polynomial and use the results to apply a correction to the measured tunes (Fig. 14). With a sufficiently large number of samples, about 100 measurements per coating stripe per collimator gap, this procedure allows resolving the individual tunes at the required $10^{-5}$ uncertainty level after correction (Fig. 15).

FIG. 14. A slow tune jitter with a $\sim 100$ s period and an rms spread of (thin grey lines) is observed during the ADT excitation tune measurements.

FIG. 15. By correcting for the tune jitter one can achieve tune resolution of $\sim 10^{-5}$ and clearly distinguish the tune shift created by low impedance coatings. Tune measurements for the collimator jaws open and closed: top - before, bottom - after the correction. TiN stipe, 4.5$\sigma$ halfgap. Solid lines represent 1 rms deviation from the mean (dashed lines).

Appendix B: Geometric taper impedance

Different types of tapers can have drastically different geometric impedances. HL-LHC secondary collimators feature three distinct taper geometries: TCS – the most common one presently in the machine; TCSP – an upgraded geometry with an integrated BPM, installed on several collimators; and TCSPM – a longer transition featuring a BPM and optimized for impedance reduction [36], the choice for the devices to be installed in the framework of the collimator upgrade (Fig. 16, top). While the flat taper model is in good agreement with simulation for present LHC TCS tapers, it may be underestimating the impedance of TCSPM tapers by nearly a factor two (Fig. 16, bottom). Thus in order to make accurate stability predictions all existing taper geometries were numerically modelled in CST software [38]. Thanks to the small share of the geometric impedance in the overall impedance of the ring, the impact of the real taper geometries turned out to be minor, at the percent level [39].

FIG. 16. Transverse impedance as a function of half-gap in mm from CST [38] simulations of the current TCSG taper (green dots), the TCSP taper (red dots), or the TCSPM taper (blue dots) compared to the flat taper theory [22] used for the model (black dashed line); solid lines represent extrapolation of simulation data toward small gap heights, where numerical simulation becomes computationally intensive. Subplot in the top right corner focuses on the difference between the model and the simulation results at large gaps.