THE HL-LHC IMPEDANCE MODEL AND ASPECTS OF BEAM STABILITY

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Abstract

The LHC upgrade to the HL-LHC foresees new challenging operational scenarios from the beam dynamics point of view. In order to ensure good machine operation and performance, the machine impedance, among other possible sources of instabilities like beam-beam and electron cloud, needs to be carefully quantified profiting also from the current LHC operation. In this work we present the HL-LHC impedance model mainly focusing on the contribution of low-impedance collimators and crab cavities: the first reduces the broad-band impedance baseline thanks to the higher jaw material conductivity, the second increases the machine luminosity at the price of increasing the coupled bunch stabilizing octupole current threshold. Other elements like the injection protection absorber (TDI) will be also discussed.

INTRODUCTION

In this work[1] we present the studies performed on the HL-LHC impedance model focusing on the collimator and crab cavities upgrade. In the first part we will discuss the need of the collimation system upgrade focusing on the material choice and the selection of collimators to be changed towards HL-LHC [1].

In the second part we will study the impact of the crab cavities high order modes (HOM) on transverse beam stability in single and coupled bunch regimes deriving a HOM tolerance criterium useful in the crab cavity design and optimization stage.

The last section presents a brief summary of the impedance studies on other new or upgraded elements foreseen for the HL-LHC.

LOW IMPEDANCE COLLIMATORS

The collimation system represents at present the highest impedance source in the LHC machine [2]. According to the beam instability observations performed during 2012 [3], an extrapolation of the brightness limitations for the future HL-LHC beams revealed the necessity of the upgrade of the collimation system [4–6].

The present LHC collimation system has a high impact on the impedance budget especially considering the set of secondary collimators in IP3 and IP7 [7] made of Carbon-Fibre Composites material (CFC, with resistivity $\rho = 5\,\mu\Omega$m). Making use of new possible bulk materials such as Molybdenum (Mo, $\rho = 53.5\,$nΩm) and Molybdenum-Graphite (MoC, $\rho = 1\,\mu\Omega$m), and coatings of Cu, Mo or TiN, a set of detailed simulations were performed in order to study the impedance impact of these materials [8, 9], their impact on vacuum and their effectiveness in terms of cleaning process [10]. At present, the most promising scenario satisfying these constraints is replacing the LHC secondary collimators with ones made of MoC coated with $5\mu m$ of Mo.

The choice of coating only the IP7 or IP3 hierarchy, or both, was studied in detail based on the present impedance model. Figure 1 compares the bunch intensity versus emittance curves obtained with DELPHI [11] simulations and ***scaled*** with respect to the 2012 instabilities in the case of $M = 2748$ equispaced bunches with $\sigma_z^{rms} = 8.1$ cm bunch length, assuming the effect of a perfect (infinite bandwidth) damper of 50 turns damping time, maximum octupole current at 550 A with negative polarity at $Q' = 15$ units (with $Q' = \xi Q$, where ξ is the machine chromaticity and Q the machine tune). The curves refer to different collimator scenarios: CFC secondaries as in the LHC, coated secondaries in IP3 and IP7, coated only in IP7, or only in IP7 with IP3 secondaries further retracted. A beam is stable if the intensity/emittance point is in the area below the curves: with respect to the CFC scenario, already coating only the IP7 secondaries ensures enough stability and this can be further improved opening the IP3 secondaries as a back up solution.

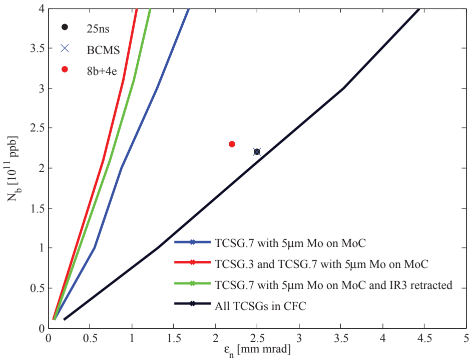

Figure 1: Intensity versus emittance curves for different secondary collimator coating scenarios. Intensity N_b versus normalized transverse emittance ε_n points in the area below (above) the curves are stable (unstable). The curves are *scaled* w.r.t. 2012 instabilities.

On the way from the LHC to the HL-LHC, a subset of secondary collimators in IP7 is being chosen for impedance reduction after the next long LHC shutdown LS2 [12].

CRAB CAVITIES

In order to increase the luminosity in collision, 8 crab cavities [13] (2 per beam/plane) will be installed in the IP1 and IP5 triplet region. From the impedance point of view, the RF Dipole (RFD) and the Double Quarter Wave (DQW) designs

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[1] Research supported by the High Luminosity LHC project

have been extensively studied and followed up already since design stage [14–16]. The crab cavities impedance model has been recently updated to include the latest version of HOMs [17,18]: these can be potentially harmful to the beam stability due to the very high β function (up to 3600 m for the minimum β^* of 15 cm) at the crab cavity location.

In order to assess the HOM impact on transverse single and coupled bunch stability, we systematically studied the effect of a HOM added to the HL-LHC baseline (i.e. with low impedance MoC collimators coated with 5μm of Mo in IP7), with perfect 50 turns damper, $Q' = 5$ units, varying the resonant frequency $f_{res} \in [100\ MHz, ..., 2\ GHz]$, the shunt impedance $R_s \in [100\ k\Omega/m, ..., 100\ G\Omega/m]$ for a constant $Q = 1000$ to cover enough coupled bunch lines ($\Delta f = f_{res}/Q > f_{rev}$, with f_{rev} the revolution frequency). The HL-LHC optics version is the V1.1 with $\beta^* = 15$ cm [19]. In this study we did not consider the scaling of instability threshold to 2012 instabilities, therefore should be considered in relative.

Figure 2 shows the single bunch most unstable mode growth rate as a function of the HOM mode frequency and shunt impedance. As we can see, from a $R_s \simeq 1\ G\Omega/m$ we start exceeding the baseline impedance model.

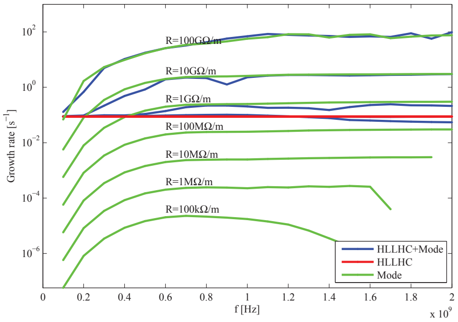

Figure 2: Single bunch most unstable mode growth rate as a function of HOM frequency and shunt impedance R_s.

Each point of the curves in Fig. 2 can be Landau damped applying enough current in the machine octupoles [20]. Considering, for example, a HOM with fixed frequency of 800 MHz, we can derive the octupole current (with negative polarity) needed as a function of the R_s. As shown in Fig. 3, the current needed to stabilize the HL-LHC baseline is $I_{oct} \simeq 30$ A. Adding a HOM will increase the octupole current needed to provide stabilization.

Considering that the maximum achievable octupole current is $\simeq 550$ A, we can calculate the R_s corresponding to a given increase in the octupole baseline threshold. Figure 4 shows the DQW and RFD R_s/Q versus frequency and the thresholds corresponding to a given increase in octupole current $\Delta I_{oct} \in [10, 100, 1000]$ A over the baseline current I_{oct}: all the HOM would produce an increase $\Delta I_{oct} < 10$ A and are therefore acceptable.

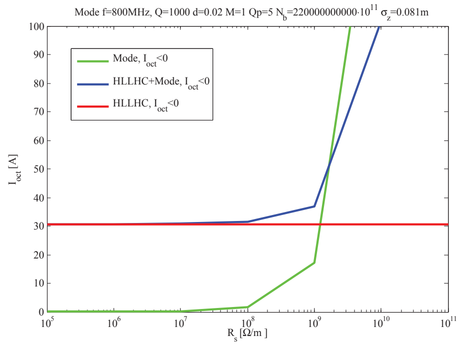

Figure 3: Single bunch stabilizing octupole current as a function of HOM R_s at $f_{res} = 800$ MHz.

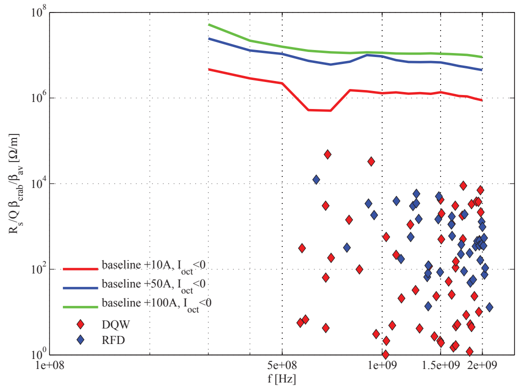

Figure 4: HOM of the DQW and RFD crab cavities and corresponding single bunch thresholds for the increase of octupole current over the machine baseline.

A similar approach can be followed for the HOM induced coupled bunch instabilities. Figure 5 shows the increase of octupole current over the machine baseline corresponding to $\Delta I_{oct} \in [10, 100, 1000]$ A: while all the RFD HOM are below the 10 A threshold, the DQW 920 MHz mode exceeds the 100 A threshold. Since the baseline octupole current is $I_{oct} \simeq 30$ A as in the single bunch case due to the effect of the damper, the increase is still below the maximum octupole current achievable. Nevertheless this would reduce the HL-LHC stability margin unless the R/Q of the 920 MHz HOM is opportunely reduced.

Figures 4 and 5 can be a useful tolerance criterium for the crab cavities HOM optimization, as well as for other equipment showing potentially harmful transverse HOMs.

According to the crab cavities mechanical tolerances, the HOM frequency may vary within ±3 MHz [21]. In order to study the effect of the uncertainty on the HOM resonant frequency on the octupole current threshold we performed a set of 200 simulations of possible crab cavity HOM frequency configurations on top of the baseline impedance model accounting for the vertical crossing angle in IP1 and horizontal in IP5, a uniform frequency spread witin ±3 MHz at Q'=5 units and stabilizing octupole with negative polarity. Figure 6 shows the case of 4 DQW in IP1 and 4 DQW in IP5: as predicted in Fig. 5, an octupole current of $I_{oct} + \Delta I_{oct} \simeq 120$ A is obtained within 30% of the simulated cases. The probability is related to the chance of the

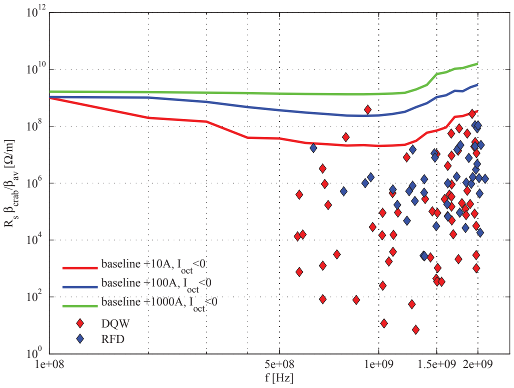

Figure 5: HOM of the DQW and RFD crab cavities and corresponding coupled bunch thresholds for the increase of octupole current over the machine baseline.

coupled bunch line to fall on the HOM, which is depending on the Q of the mode. A higher current can be required in the unfortunate case in which the same HOMs from different crab cavities are aligned in frequency.

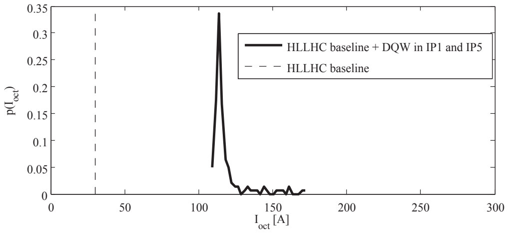

Figure 6: Probability of octupole current threshold increase for 4 DQW crab cavities in IP1 and IP5.

Details of 4 RFD cavities in IP1 and IP5, or the mixed scenario of DQW in IP1 and RFD in IP5, can be found in [16].

To complete the picture, Figure 7 summarizes the octupole stability threshold as a function of Q' for the HL-LHC impedance model with CFC collimators and with the baseline of low impedance collimators in IP7, considering a possible DQW crab cavity HOM configuration in IP1 and IP5. As we can see, the impact of crab cavities provokes an overall increase of octupole threshold, reducing the stability margin of the HL-LHC: this could be improved reducing the R/Q of the 920 MHz HOM of the DQW cavity. We remind that these curves should be considered in relative as we did not account for the scaling to the 2012 instabilities and for other possible unknown impedance sources.

OTHER EQUIPMENT

Other elements are presently under study and optimization such as the Y chambers, the new experimental beam pipes (especially the new LHCb VELO which will be closer to the beam), the 11T dipole and the new devices in the triplet region: a new octagonal carbon coated beam screen with 2 welds, stripline BPMs, new RF shielding for the bellows whose HOMs have been recently measured and simulated [22].

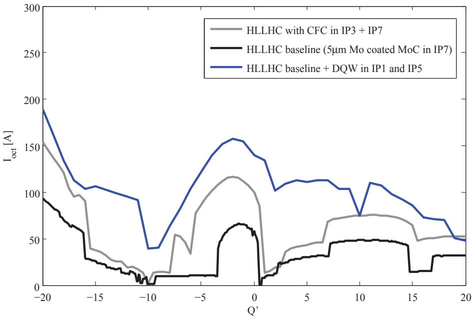

Figure 7: Octupole threshold overview as a function of Q' for the HL-LHC impedance model with CFC collimators and for the low impedance collimators baseline, accounting for the effect of a possible configuration of the DQW crab cavity HOMs in IP1 and IP5. Curves are *not scaled* to the 2012 instabilites and are calculated for $N_b = 2.2 \cdot 10^{11}$ ppb in $\varepsilon_n = 2.5\ \mu$m and $\sigma_z = 8.1$ cm.

Particular attention is being paid to the TDI redesign [23] where both HOM and resistive wall impedance optimization is taking place in design stage taking into account the performance of the present TDI [24].

CONCLUSIONS

The HL-LHC impedance model has been intensely developed over the last few years, in particular concerning the study of new low impedance collimators. The baseline foresees new secondary collimators in IP7 made of MoC coated with 5μm Mo, replacing the present ones in CFC. Scaling from the 2012 instabilities, which are not fully understood yet, we showed that replacing the IP7 collimators would be enough to ensure the stability of the HL-LHC beams. In case of issues, opening the IP3 secondaries would further increase the stability margins.

The impact of crab cavities on HL-LHC baseline with low impedance collimators have been studied for the RFD and DQW designs focusing on single and coupled bunch transverse instabilities. We showed that, while there is negligible impact in single bunch, the octupole current needed for coupled bunch stabilization would be increased by ≃ 100 A at $Q' = 5$ (in the case of DQW crab cavities in IP1 and IP5). This is mainly due to the 920 MHz mode whose R/Q should be therefore reduced.

The impedance of other elements such as the RF fingers, the BPM stripline monitors in the triplet region and the TDI are being presently studied in order to be included in the model.

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