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DETAILED ELECTROMAGNETIC CHARACTERISATION OF HL-LHC LOW IMPEDANCE COLLIMATORS

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Abstract

The High Luminosity Large Hadron Collider (HL-LHC) project will upgrade the LHC machine to allow operation with increased luminosity for the experiments. In order to achieve this goal, different operational parameters of the machine need to be pushed beyond the present design values, including the stored beam energy. One of the main challenges related to the achievement of the upgraded performance is the beam collimation system and its contribution to the overall machine impedance budget. In this perspective, new low impedance collimators have been designed, fabricated, and installed in the LHC. In this study, we will present their detailed electromagnetic (EM) characterization by means of radio frequency (RF) measurements and EM simulations.

INTRODUCTION

The LHC [1] is equipped with a sophisticated multistage collimation system [2]. Collimation systems in particle accelerators are designed to protect the machine from unavoidable beam losses and clean the beam halo. The collimation system of the LHC is classified into families [3] comprised of primary (TCP), secondary (TCS), tertiary (TCT), debris (TCL), and special collimators for injection and dump protection.

Most of the collimators in the LHC have movable jaws, and each type is distinguished by distinct characteristics, including geometry, absorber material, and RF shielding. Due to their number, the electrically resistive jaws and their proximity to the circulating beam in the LHC, the collimation system is one of the major contributors to the machine beam coupling impedance [4].

Based on the experience gained during Run 1 (2010-2013) [5] and Run 2 (2015-2018) [6], the LHC was operating close to the limit of the transverse beam stability [7]. Transverse instabilities are expected to become more critical at the higher bunch intensity and brightness foreseen for the HL-LHC operation [8]. The impedance has to consequently be reduced to ensure beam stability. Reducing the resistivity of the jaw material is one of the methods to minimize the collimators' impedance contribution. Studies of low impedance collimators [9] show that beam stability can be effectively improved by replacing the present Carbon-Fibre Carbon composite (CFC) jaw material used in primary and secondary with Molybdenum-Graphite (MoGr) which features a factor five lower DC resistivity. In addition, the jaws of the secondary collimators (the TCSPMs) are coated with a 6 µm layer of Molybdenum (Mo) further boosting the conductivity effectively seen by the beam. This coating has been chosen for its robustness to beam impact and good adhesion to the MoGr substrate. Given the significance of the collimators' impedance, it is crucial to assess it for each device to correctly predict related beam instabilities and beam induced heating.

In this paper, we discuss the detailed EM characterisation of HL-LHC low impedance collimators by means of numerical simulations and RF measurements, particularly focusing on the characterization of the modes resonating in their structure as well as on the assessment of the jaw surface resistivity.

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BENCH MEASUREMENTS

Various impedance measurement techniques [10] can be used to characterise accelerator devices from the EM point of view before installing them in the machine.

Since it was decided not to perform wire measurements due to the inherent risk of damaging the jaw material surfaces, we performed measurements on separated jaw samples with a cylindrical resonator operating in the H_{011} (or TE_{011}) mode [11] to characterise the electrical resistivity of Mo coated MoGr jaw materials.

Figure 1 shows the overview results of electrical resistivity measurements of Mo coated samples measured along the TCSPM production: the resistivity is in line with the expected resistivity of pure Mo.

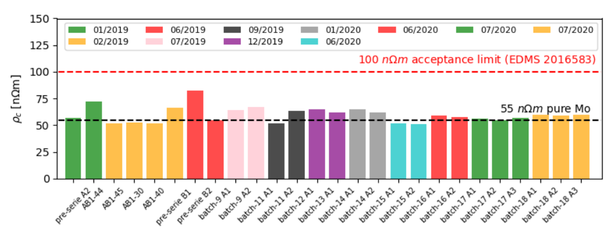

Figure 1: Electrical resistivity of Mo coated samples measured following the TCSPM production.

In order to detect the possible resonant modes, probe transmission measurements are performed on the HL-LHC low impedance collimators (TCSPMs, TCPPMs) and on the new TCLDs before installation. Figure 2 shows one

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of the measured TCSPM collimators together with the RF measurements setup in which probes are inserted to measure the reflection and transmission scattering parameters from the vector network analyser (VNA).

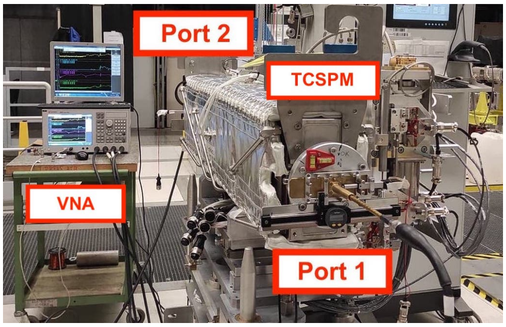

Figure 2: The TCSPM collimator together with the RF measurement setup. Ports 1 and 2 are the VNA ports used for probe reflection and transmission measurements.

An electric probe (i.e. terminated with a straight pin) provides a good coupling mainly to the electric field of possible resonant modes while a magnetic probe (i.e. terminated with a small loop) couples mainly to the magnetic field. Probes can be inserted with different depths inside the collimator and displaced transversely with respect to the central beam axis thanks to an ad-hoc positioning system manufactured for these type of measurements. In the absence of wire measurements, one of the main targets of probe measurement was to assess potential unexpected large modes that could point to device non-conformities.

Figure 3 shows the simulation of a typical probe measurement performed with Computer Simulation Technology (CST) [12] on the TCSPM model. Changing the probe insertion length, the S11 and the S22 scattering parameters show a large resonance moving from ≈580 MHz to ≈650 MHz. These are probe-related modes, which correspond to the quarter-wave resonance characteristic of the coaxial resonator made by the probe (which acts like the inner conductor) and the device (which acts like the outer conductor). The frequency of the probe-related modes varies as the probe position is changed: this allows to easily distinguish, especially in transmission, probe-related modes from the collimator-related modes, weakly affected by the probe displacement. This principle is used to achieve weak coupling on all the resonant modes in the structure below 1.5 GHz (collimator cut-off frequency) and for different half gaps. The unloaded Q factor is then directly obtained computing the 3 dB bandwidth in transmission.

Figure 4 shows the overview result: low Q modes (between ~ 50 and ~ 320 for all the measured collimators) are measured from 200 MHz to about 1.2 GHz. In the past, a similar collimator, the TCSPM prototype, was characterised [13] with probe and wire measurements, and further validated with beam during Run 2. Given the similarity of the measured Q factors to the one of the TCSPM prototype, and as measured resonant modes are in line with the results

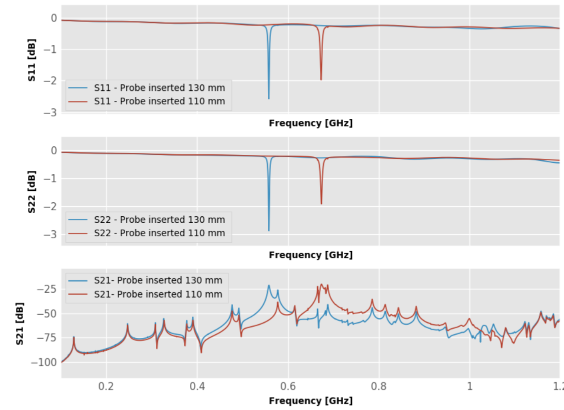

Figure 3: Simulated reflection parameters (S11, S22) and transmission parameters (S21) versus frequency for two different probe positions in the TCSPM. Probe-related modes are visible in reflection, while collimator-related modes are mainly observed in transmission.

of the numerical simulations, the modes were classified as uncritical. The devices have therefore been installed in the LHC for Run 3 [14, 15].

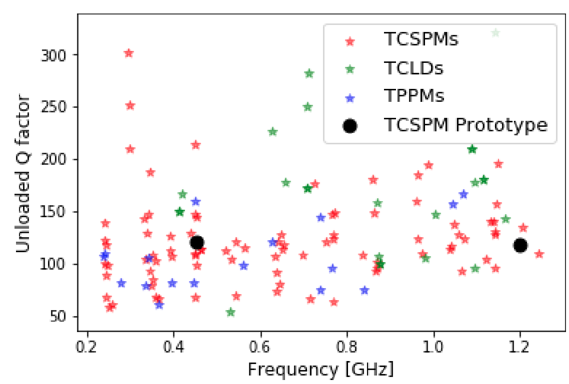

Figure 4: Measured Q factors versus frequency of TCSPM, TCLD, TCPPM and TCSPM prototype collimators for 10 mm half-gap.

NUMERICAL SIMULATIONS

In order to benchmark the measurements in detail and be able to correctly predict the shunt impedance of the measured modes, we have performed simulations on the TCSPM collimator model through CST Eigenmode and Frequency Domain (FD) solvers.

To begin with, we have used a simplified CAD design, mainly including the vacuum tank, jaws, and RF contacts. Figure 5 shows the comparison of the unloaded Q factors simulated with Eigenmode and FD solvers for a 10 mm jaw half-gap position. The results are in good agreement supporting the methodology used in the measurements.

Figure 6 shows the EM field distribution of the resonant mode at 239 MHz: as for the other modes, the EM field is mainly resonating in the tank.

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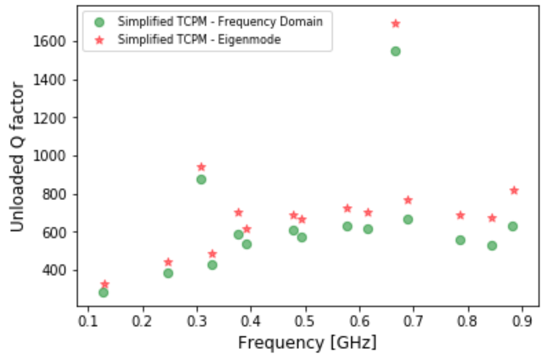

Figure 5: Unloaded Q factors simulated with Eigenmode and FD solvers for 10 mm jaw half-gap position of the TCSPM.

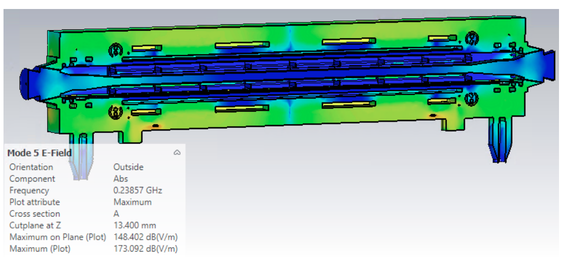

Figure 6: Electric field distribution of the mode at 239 MHz for 10 mm half-gap position.

Comparing the results of probe measurements of Fig. 4 to the ones of the simulated simplified model of Fig. 5, we observe higher Q factors in simulations than in measurements. In order to perform more realistic simulations, the CAD model was gradually brought closer to reality by including cooling pipes, beam position monitors and their cables, and temperature probe cables. In particular, the addition of BPM cables and thermal cables had the effect of reducing high-Q modes in the simulation bringing the results within a factor 2 of the measurements as shown in Fig. 7. This was deemed acceptable given the device complexity. The most recent model was used to simulate the longitudinal and transverse shunt impedances otherwise not accessible in the absence of wire measurements.

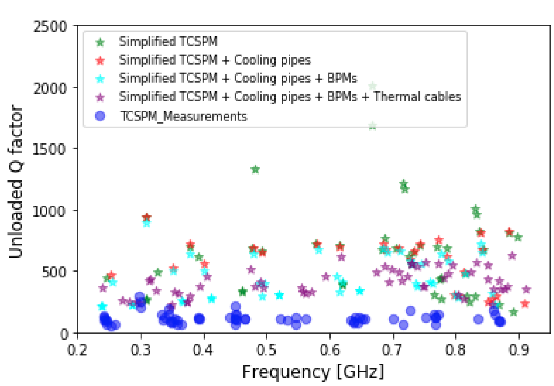

Figure 7: Simulated Q factors for different complexity of the TCSPM compared to measurements at 10 mm half-gap.

The resulting longitudinal, horizontal and vertical shunt impedances obtained with Eigenmode simulations [16] are shown in Fig. 8. The shunt impedance for both longitudinal and transverse planes is not considered an issue for the current LHC and HL-LHC operations based on [17, 18].

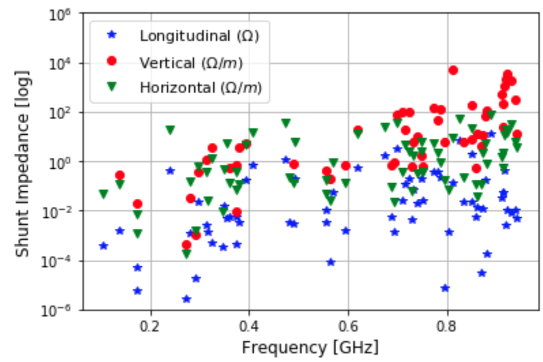

Figure 8: Simulated longitudinal and transverse TCSPM shunt impedances, for 10 mm half-gap.

CONCLUSION

In this study we presented the EM characterization of the new low impedance collimators during Long-Shutdown 2 (LS2) in view of the HL-LHC upgrade. Due to the low resistivity surface, standard wire measurements were not performed. The electrical resistivity of Mo coated MoGr jaw material samples was characterised with a cylindrical resonator operating in the H_{011} mode and the results were in line with the theoretical resistivity of Mo. Resonant modes were systematically measured for all the installed TCLD, TCPPM and TCSPM collimators by means of probe measurements. Based on analogous measurements done on the TCSPM prototype installed in the LHC during Run 2, these modes have been safely assumed as uncritical for LHC operation. Simulation with CST Eigenmode and Frequency domain solvers were performed. The features in the simulated model were progressively enhanced in order to bring the measured Q factors within a factor 2 of the simulated ones. Given the device complexity this is considered acceptable. Longitudinal and transverse shunt impedances have been derived from Eigenmode solutions for the TCSPM model and confirmed not to be an issue for current LHC and future HL-LHC operations. These results will serve as a basis for the future LHC Run 3 operation when complementary based beam impedance measurements will be performed on the newly installed low impedance collimators.

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