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SINGLE-COLLIMATOR TUNE SHIFT MEASUREMENT OF THE THREE-STRIPE COLLIMATOR AT LHC*

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Abstract

Several options of low resistivity coating have been proposed for the collimator upgrade of the Large Hadron Collider. In order to study their effect on the beam dynamics a special collimator has been built and installed in the machine. Its jaws are coated with three different materials and can be moved transversely to selectively expose the beam to the chosen coating. We have measured the resistive wall tune shifts of each coating material and compared them with that of a standard Carbon Fibre Composite (CFC) collimator jaw. A resolution of the tune shift of the order of 10^{-5} has been achieved in the measurement. The results show a significant reduction of the resistive wall tune shift with novel materials. The largest improvement is obtained with a 5 µm Molybdenum coating of a Molybdenum-Graphite jaw. The observed tune shifts show a good agreement with the impedance model and the bench impedance and resistivity measurements. Obtained results can be used to further improve the precision of the impedance model.

HL-LHC COLLIMATOR IMPEDANCE

The collimation system is the single highest contributor to the transverse impedance of LHC at top energy [1]. As the High-Luminosity upgrade nearly doubles the bunch population to 2.3×10^{11} ppb [2], the impedance has to be reduced to ensure beam stability [3]. Although the expected octupole tune spread, required to provide Landau damping of impedance-driven collective instabilities, is within the capabilities of the HL-LHC Landau Octupole system, the margin is insufficient to account for the imperfections of the simplified impedance model and other possible destabilizing effects (such as e.g. loss of Landau damping due to linear coupling [4], damper noise [5], or long-range beam-beam interaction [6] or a destabilising effect of resistive feedback [7]). Based on the past operational experience at LHC, at least a factor of two safety margin is necessary, and that requires a considerable reduction of collimator impedance (Fig. 1).

THREE-STRIPE COLLIMATOR

Several upgraded collimator material options have been considered to reduce the impedance of HL-LHC. 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). On top of that, a jaw can be coated with a thin layer of a low resistivity coating, such as Molybdenum (Mo) or Titanium-Nitride (TiN). A 5 µm coating thickness is sufficiently greater than the skin depth of the coating at the high frequencies, relevant for the single-bunch dynamics (~1 GHz), making the impedance at these frequencies nearly independent of the material behind the coating [8].

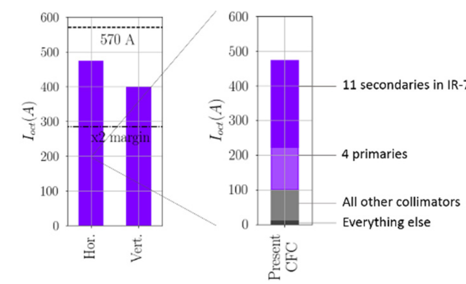

Figure 1: Impedance of LHC collimators is responsible for nearly all the octupole current needed to stabilize the beam, and has to be reduced to provide a stability margin for the Hi-Lumi upgrade [3]. BCMS beam, 7 TeV, beginning of the luminosity levelling process, β*=41 cm.

In order to test the novel materials with beam, a special test collimator has been installed in LHC. This unique prototype, made of MoGr, has two 10 mm wide coating stripes of Mo and TiN along with a stripe of an uncoated bulk (Fig. 2). 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. 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.

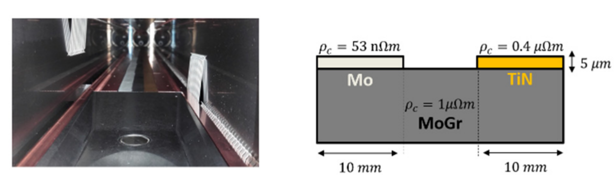

Figure 2: The prototype collimator has two 10 mm wide low resistivity (Mo and TiN) stripes on a MoGr substrate. Left - photo of the collimator assembly; right - schematic drawing of the collimator jaw.

BEAM MEASUREMENTS

The impedance of each material is quantified in terms of 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

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4-6 reference beam sizes. At each gap transverse beam oscillations were excited by the transverse feedback system (ADT) (Fig. 3). The measurement was performed with a single nominal intensity bunch (1.2×10^{11} p) at 6.5 TeV (Table 1). The chromaticity and octupole current were optimized to increase the decoherence time to ~1000 revolutions, which allowed accurately determining the tune at each collimator opening with the SUSSIX [9] algorithm.

Typically, a standard CFC secondary collimator creates a tune shift up to ~10^{-4}; the three low-impedance materials are expected to produce tunes shift 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 (~100 s period) tune jitter, can be as large as 10^{-4} [10], which is significantly greater than the expected tune shift of the best coatings.

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. 3). 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. 4). With a sufficiently large number of samples this procedure allows resolving the individual tunes at the required 10^{-5} uncertainty level after correction.

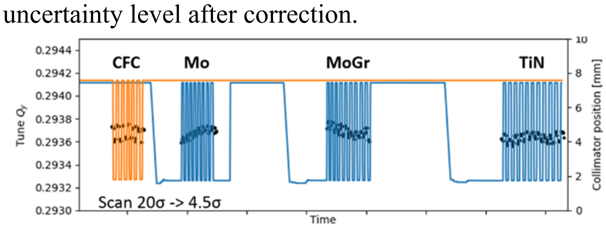

Figure 3: The raw tune data shows a clear reduction of the tune shift with the new coatings with respect to the CFC. A significant tune drift during the measurement can also be seen. The orange line depicts the position of the standard CFC secondary collimator, the blue line – the 3-stripe collimator. Black dots show individual tune measurements.

Table 1: Key Parameters of the Measurement. In collimator Settings, σ is the Beam Size for 3.5 μm Reference Emittance

Beam energy	6.5 TeV
Bunch intensity	1.2×10^{11} p
Normalized emittance	2 μm, rms
Chromaticity, x and y	5, 5
Octupole current	270 A
Coll. retraction cycle	20 $\sigma\rightarrow$ 3.5 – 6.0 σ

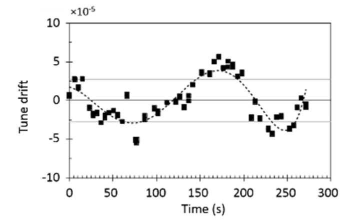

Figure 4: A slow tune jitter with a ~100 s period and an rms spread of $\pm2\times10^{-5}$ (thin grey lines) is observed during the ADT excitation tune measurements.

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 tapers in the flat approximation and assumes the same geometric impedance for the standard and the 3-stripe collimator [11]. Under the approximation the geometric tune shift is described as [12]:

$$\Delta Q_y^{geom} \propto 1/g^2, \qquad (1)$$

where g stands for the collimator gap. The resistive wall component is inversely proportional to the cube of the gap:

$$\Delta Q_y^{rw} \propto \sqrt{\rho}/g^3, \qquad (2)$$

where ρ is the resistivity.

Accounting for the geometric tune shift and fitting the data with (2) 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%. A larger discrepancy, up to a factor of two is observed for the Mo coating, indicating a possibly larger than expected resistivity of the coating. Table 2 summarizes the findings in terms of effective resistivity.

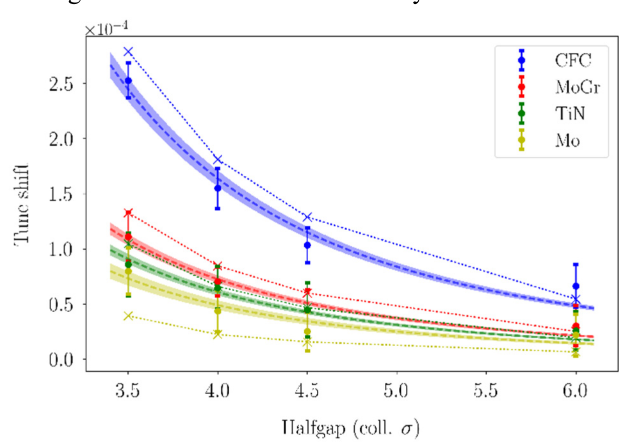

Figure 5: The use of MoGr (red) reduces the resistive wall tune shift compared to the uncoated CFC (blue); each type of coating: TiN (green) and Mo (yellow) further improves the conductivity and can be clearly differentiated. For most materials the results (dots show the measured data and dashed curves – its fits with their ±1 rms uncertainties) are within 10-20 % of the model predictions (dotted lines).

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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, unlike the other coatings, 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. 4-point measurements show a significant increase of Mo thin film resistivity at or below the thickness of 5 µm [13]. High DC resistivities have been measured in some Mo-coated samples at CERN (Table 2).

SEM imaging also shows significant roughness of the coated surface: the average size of inhomogeneities is of the order of several micron and is measured to be up to 10 µm for the test sample with 8 µm 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 surface roughness [14].

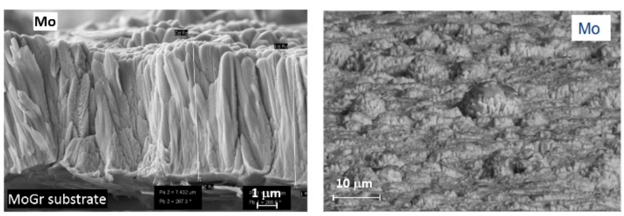

Figure 6: Mo coating is not uniform: it has a column-like fine structure (left) and inhomogeneities up to 10 µm on its surface (right) SEM image results [15].

The hypothesis of the influence of the microstructure is supported by a RF resonant wire measurement, performed on the three-stripe collimator jaw at the lab. The measurement was done at several frequencies, relevant for single-bunch dynamics. In this test, the variation of the real part of the longitudinal impedance with respect to the bulk MoGr matched the expected values within uncertainties for the TiN stripe, while the Mo stripe showed a lower than expected impedance reduction (Fig. 7). This result suggests an extra resistivity of the Mo coating, which is consistent with the results of beam measurements (Table 2).

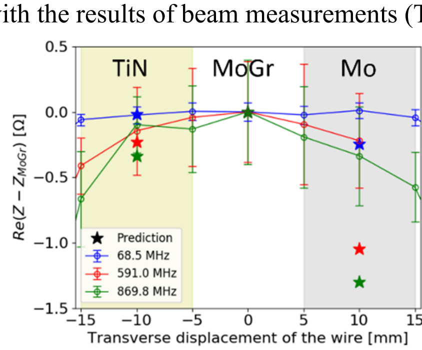

Figure 7: The measured difference in the real part of the longitudinal impedance suggests a higher than expected resistivity of the Mo stripe. Resonant wire measurement, performed in a test stand prior to the installation of the three-stripe collimator in LHC.

Table 2: Comparison of the Measured and Expected Resistivities (nΩ-m)

Material	Model	Beam	Lab: DC	Lab: RF
CFC	5000	4030 ± 380	5000 – 6000	-
MoGr	1000	760 ± 60	900 ± 100	-
TiN	400	340 ± 40	-	~400
Mo	52	250 ± 50	100 – 300	~300

CONCLUSION

A three-stripe collimator has been installed in LHC to study the effect of low impedance coatings on beam dynamics for the High-Luminosity 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. A 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 of 2, and the largest improvement, a factor of 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. The discrepancy could be explained by the effect of surface roughness, which is supported by SEM surface imaging, or the microstructure of the coating, which is in agreement with the resonant wire measurements. The roughness should affect only the real tune shift but not the growth rate of impedance-driven instabilities, while the coating structure directly increases its resistivity, affecting both the tune shift and the growth rate. An extensive follow-up study is planned to examine these effects. Obtained results can be used to further improve the precision of the impedance model and the HL-LHC stability predictions.

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