TOWARDS OPTIMUM MATERIAL CHOICES FOR HL-LHC COLLIMATOR UPGRADE*

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Abstract

The first years of operation at the LHC showed that collimator material-related concerns might limit the performance. In addition, the HL-LHC upgrade will bring the accelerator beyond the nominal performance through more intense and brighter proton beams. A new generation of collimators based on advanced materials is needed to match present and new requirements. After several years of R&D on collimator materials, studying the behaviour of novel composites with properties that address different limitations of the present collimation system, solutions have been found to fulfil various upgrade challenges. This paper describes the proposed staged approach to deploy new materials in the upgraded HL-LHC collimation system. Beam tests at the CERN HiRadMat facility were also performed to benchmark simulation methods and constitutive material models.

INTRODUCTION

The High-Luminosity (HL) upgrade of the Large Hadron Collider (LHC) [1] plans higher stored energy up to 700 MJ, smaller beam emittance and higher luminosity. The present multi-stage LHC collimation system [2, 3] was designed to handle 360 MJ stored beam energy and withstand to beams of lower damage potential. The challenging beam parameters necessary to achieve the integrated luminosity goal of 3000 fb^{-1} with a bunch intensity almost doubled with respect to the design [4] poses strong concerns also for collimators, which must be adequately upgraded to ensure the success of HL-LHC.

Important limitations come from material-related constraints. In particular, the HL-LHC beam cannot be stable unless the contribution of non-metallic collimators to the machine impedance budget is reduced. The robustness and operational efficiency should also be improved for the IR7 collimators. Moreover, the reach in β^* and the achievable luminosity for HL is concerned by the safe margins to account for the protection of collimators upstream of the LHC experiments, which are not robust enough to stand large losses as consequence of fast beam failures. Beam losses at the high dispersion locations must be also efficiently reduced to prevent magnet quenches with HL-LHC beams [5].

Over the last years, an intense R&D program [6] has been pursued to develop novel materials with excellent properties to cope with these limitations. In particular, Molybdenum carbide-Graphite (Mo-Gr) composite, co-developed by CERN and Brevetti Bizz [7], has high thermo-mechanical properties and low electrical resistivity (up to factor 10 better than other carbon composites). Copper-Diamond (Cu-CD) composite, produced by RHP-Technology Gmbh [8], keeps most of the thermo-electrical properties of copper while reducing density and improving structural behaviour.

In this paper, proposals will be made of advanced collimators based on novel composites for a reduced impedance, more robust collimators in the betatron cleaning as well as in the interaction regions. Validation with beam of the compatibility of new collimator materials and design in extreme beam conditions and accidental scenarios have been carried out and preliminary results are also discussed.

LOW IMPEDANCE SECONDARY COLLIMATORS

During Run I, the LHC beam was already at the limit of transverse beam stability. Recent studies [9–11] showed that the stability of the HL-LHC beam can be guaranteed only if the large contribution to the machine impedance from secondary collimators (TCSG) in the betatron cleaning insertion (IR7) is reduced. They are made of a carbon fiber-reinforced composite (CFC) that provides good thermo-mechanical properties but suffers of limited electrical conductivity.

Simulation results [9, 10] prove that an average impedance redaction of ~ 30% can be obtained by replacing the CFC TCSGs in IR7 with Mo-Gr collimators. This improvement is not sufficient to ensure the beam stability within safe margins. A solution for larger stability area (Figure 1) can be achieved by coating Mo-Gr jaw with a thin layer of pure metals (Mo or Cu) or ceramic materials (TiN or TiB_2). Up to 55% impedance reduction can be achieved with 5 μm Mo-coating over Mo-Gr [12]. TiN and TiB_2-coating, although more compatible with the Mo-Gr substrate, would be respectively 30% and 10% less effective than pure Mo [12].

Note that cleaning efficiency is only mildly improved because the present limitations come from particles that only interact with primary collimators [13].

The new low-impedance secondary collimators also have a completely new jaw design with integrated BPMs [14]. It is planned to install a few units in the second Long Shutdown (LS2) and to complete the installation, i.e. replace all TCSG of IR7, in LS3.

ROBUSTNESS OF TUNGSTEN TCTs AGAINST FAST BEAM LOSSES

Loads from beam losses are simulated as an input to material choice for the upgrade of the tertiary collimators (TCTs), presently made of tungsten heavy alloy (Inermet® - IT180),

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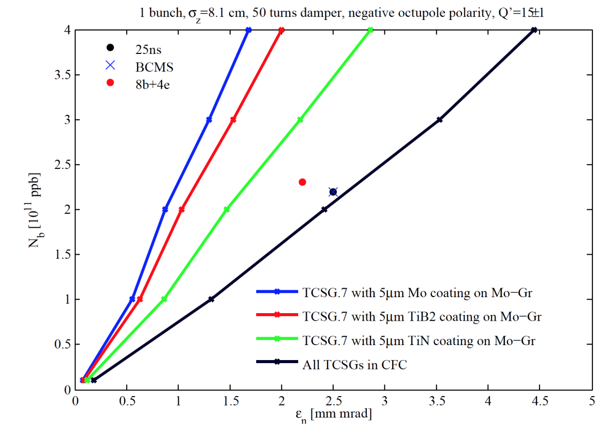

Figure 1: HL-LHC beam stability for different secondary collimator configurations in IR7. Note that the stability area is on the right of each curve.

which provide local protection of the triplet in the experimental insertions.

The case of the erratic beam dump caused by the asynchronous firing of the kickers, with the rising field hitting a 25 ns train of bunches, was simulated. Sixtrack [15–17] simulations were performed for the nominal 2 σ collimator retraction settings (Table 5 in [18]). Possible errors and orbit drift on top of the kicker misfiring are accounted for by scanning down TCT positions around their nominal settings at the interaction points in IP1 and IP5.

Figure 2 shows the number of particles lost at the TCTs compared with damage limits for tungsten collimators. The level of losses is already high at nominal TCT settings and very close to the onset of damage for Beam 2. Going down to tighter settings below the protections in IP6, TCT becomes more exposed to primary beam losses, increasing the risk of severe damage that should be avoided for these collimators close to experiments. For Beam 1, the losses are generally lower due to the more favourable phase advance from the kickers. A new version of the ATS optics has been proposed with an improved phase advance [19].

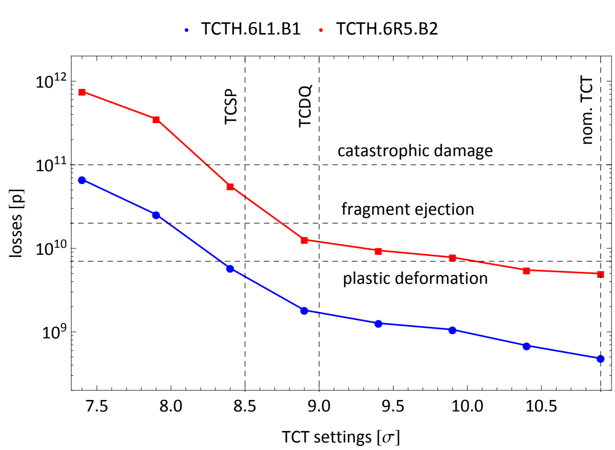

Figure 2: Losses at the most loaded TCT in IP1 and IP5 as function of collimator settings. Damage thresholds [20] are added for comparison.

It is proposed to mitigate the constraints from TCT robustness issues by replacing the present IT180 with Cu-CD. As shown below, results of beam impact tests at HiRadMat indicate that a Cu-CD jaw is about 15 times more robust [21]. This preliminary result is based on the experimental evidence that the Cu-CD jaw did not show apparent structural damage when hit by the same beam that caused catastrophic damage to IT180. Simulations are ongoing to assess quantitatively the improvement in robustness. It should be also noted that because of the reduced absorption of materials lighter than tungsten, element downstream of the TCTs will be more exposed in case of damage. While this seems acceptable for the magnets for the present LHC [22], the impact for HL-LHC in particular for the detectors [23] is being evaluated.

DISPERSION-SUPPRESSOR COLLIMATORS FOR IR7

One of the main limitations to the cleaning efficiency of the present collimation system is posed by losses in the Dispersion Suppressor (DS) magnets downstream of the betratron cleaning insertion IR7. This concern becomes even more relevant in the perspective of the higher intensities of HL-LHC beams.

The mitigation of DS losses will rely on adding two TCLD collimators per beam in IR7 [5] to clean local losses and reduce the risk of quench of superconducting magnets in the DS. Optimum implementation requires two staged installation in LS2 and LS3 following availability of 11 T dipoles [24]. IT180 is an optimum choice for TCLD jaw material because of the high density. However, with this choice collimation protection from fast beam losses adds constraints on the settings that can be deployed. Figure 3 shows how the settings would affect the losses caught by TCLDs during a beam abort failure [25].

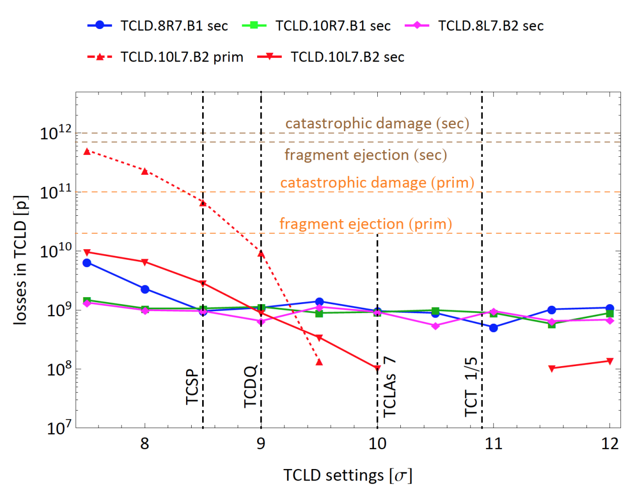

Figure 3: Simulated losses at TCLDs, following beam dump failure, as function of collimator settings. Nominal TCLD settings are set to the level of the absorbers (TCLA) in IR7. Damage thresholds for tungsten [20] added for comparison.

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Most of the simulated DS collimators are hit by protons already scattered out from IR6 collimators (labelled as "secondary protons") and the losses are still below the damage level. However, due to the worse phase advance from the kickers, TCLD Beam 2 in cell 10 may be exposed to primary beam losses (dashed red line in Figure 3), which increase significantly once the settings are tighten in simulation to account for possible imperfections in the machine.

In these loss conditions, the damage of the tungsten jaw may not be negligible and, therefore, that calls for more robust materials that could stand such beam loads. Cu-CD could be also a viable option for TCLDs. On the other hand, the onset of significant primary losses starts at TCLD settings below 10 σ that are probably excluded by other operational constraints (e.g., betatron hierarchy limits, effective TCLD momentum cut conflicting with IR3 settings). These aspects are being evaluated.

BEAM-BASED VALIDATION OF NEW COLLIMATORS

The final material choices for the upgrade are also based on results from extensive characterisation campaigns of new materials under different beam irradiation regimes. While effects from exposure to high radiation doses are discussed in a companion paper [26], we report here highlight results recently obtained from shock impacts of high intensity beams.

Over the last 10 years, several beam-impact tests on collimators and collimator materials were performed to explore the consequences of failure scenarios on materials and equipment. Tests carried out in 2004 and 2006 validated the design of CFC primary and secondary collimators [27]. In 2012, test at the CERN HiRadMat facility showed the low robustness of the present TCTs (HRMT-09) and characterised Mo-Gr and Cu-CD for HL-LHC challenges (HRMT-14).

A recent experiment (HRMT-23) was run in August 2015 to demonstrate the validity of the design of HL-LHC secondary collimator with Mo-Gr and Cu-CD, and to verify the resistance of CFC jaw to HL-LHC parameters. The test bench used for the experiment is shown in Figure 4.

Figure 4: Assembly of HRMT-23 experiment allocating the three full collimator jaws.

Up to 288 bunches (LHC injection batch), for a total intensity of 3.8×10^{14} protons at 440 GeV, were extracted in a single kick and sent onto the jaws in CFC and Mo-Gr to compare their robustness. The total pulse length was 7.8 μs and

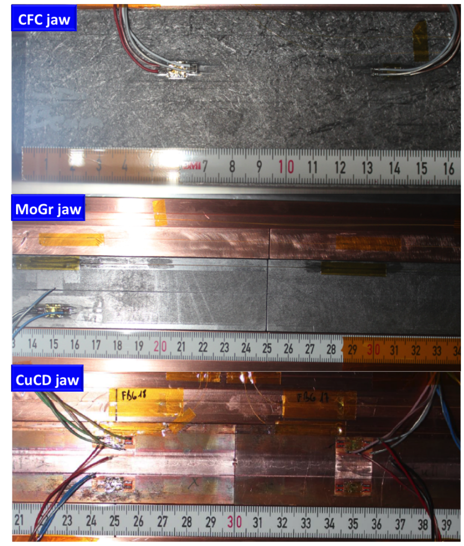

Figure 5: Collimator jaws after being tested in HRMT-23.

the area of the beam spot was $\sigma_x \times \sigma_y = 0.35 \times 0.35\,\mathrm{mm}^2$. The Cu-CD jaw, instead, was exposed to impacts of 24 bunch trains (roughly equivalent to one single LHC bunch at 7 TeV, considered as the reference scenario for TCT robustness evaluation [28]). As shown in Figure 5, both CFC and Mo-Gr survived very satisfactorily the impact roughly corresponding to the HL-LHC beam injection error. Cu-CD survived to the impact expected on TCTs in case of asynchronous beam dump failure. Preliminary results would qualify Mo-Gr from the robustness point of view as an alternative to CFC for secondary collimators, while Cu-CD as an option for TCTs and TCLDs.

Mechanical simulation results will be compared with the outcome of the tests and energy deposition studies will be performed to complete the picture of impact scenarios. However, the immediate goals of the HRMT tests will be the finalization of the design of a low-impedance, high-robustness secondary collimator prototype to be build and tested in the LHC in 2017.

CONCLUSIONS

In this paper, proposals for deploying new materials for the upgrade of the LHC collimation system were presented. Low-impedance and robust secondary collimators made of Mo-Gr are planned to replace the present CFC secondary collimators in IR7 to cope with the HL-LHC beams. Improved robustness against beam impacts for tertiary collimators and DS collimators can be provided by Cu-CD with a tolerable loss of cleaning. Successful tests at HiRadMat recently proved the robustness of these novel materials. The preliminary analysis of these tests qualifies the new materials and collimator jaw design for the upgrade. Additional work is required to finalise the choice of coating technology for the secondary collimators, required to provide sufficient margins for the HL-LHC beam stability. Detailed calculations of material response and induced losses in experiment insertions are also ongoing to finalise the choice of collimation materials.

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