MECHANICAL ENGINEERING AND DESIGN OF NOVEL COLLIMATORS FOR HL-LHC*

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Abstract

In view of High Luminosity LHC (HL-LHC) upgrades, collimator materials may become a limit to the machine performance: the high RF impedance of Carbon-Carbon composites used for primary and secondary collimators can lead to beam instabilities, while the Tungsten alloy adopted in tertiary collimators exhibits low robustness in case of beam-induced accidents. An R&D program has been pursued to develop new materials overcoming such limitations. Molybdenum-Graphite, in addition to its outstanding thermal conductivity, can be coated with pure molybdenum, reducing collimator impedance by a factor of 10. A new secondary collimator is being designed around this novel composite. New high-melting materials are also proposed to improve the robustness of tertiary collimators. New collimators will also be equipped with BPMs, significantly enhancing the alignment speed and the beta-star reach. This implies additional constraints of space, as well as detailed static and fatigue calculations on cables and connectors. This paper describes the mechanical design and the engineering calculations of such future collimators, focusing on the study via state-of-the-art numerical methods of interactions between the particle beams and the new materials adopted.

INTRODUCTION ON NEW COLLIMATOR MATERIALS

The LHC collimation system is designed to intercept and absorb high-intensity losses at unprecedented levels [1]. The jaws of primary and secondary collimators are made of carbon-carbon composites (CFC). Although CFC guarantees extremely high robustness against beam-induced accidents [2], it may possibly limit the machine performance in terms of total beam intensity because of the high RF impedance. This is a concern in view of the nominal operation as well as of the High-Luminosity LHC upgrade (HL-LHC). The main goal of the collimation material R&D programs is to develop and characterize novel materials to possibly replace CFC; in this framework, a comprehensive experiment, HRMT14, was successfully completed at the CERN HiRadMat facility in 2012, in order to characterize the behaviour of 6 relevant materials under intense proton beam impacts [3]. Copper-Diamond (CuCD) and Molybdenum-Graphite (MoGr) exhibited the highest resistance to the thermal shock caused by beam impacts; in particular, the two lightest, carbon fibre-reinforced MoGr grades seemed completely undamaged (Fig. 1).

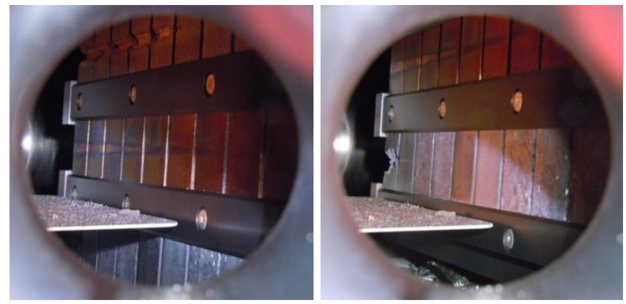

Figure 1: Cu-CD (left) and MoGr (right) samples impacted by 1.95E13 protons at 440 GeV in HiRadMat.

Table 1 compares the relevant properties of MoGr and CFC. The materials are orthotropic: the values are referred to the most favourable orientation.

Table 1: CFC vs. MoGr - Thermophysical Properties

	CFC-AC150k [4]	MoGr [5]
Density	1.65 g/cm^3	~2.7 g/cm^3
Flexural strength	120 MPa	85 MPa
Thermal conductivity	220 W/m/K	770 W/m/K
Coefficient of thermal expansion	$-1.3\cdot10^{-6}\div0$ K^{-1}	$1.3\cdot10^{-6}$ K^{-1}
Electrical conductivity	0.2 MS/m	1.1 MS/m 18 MS/m when Mo-coated

MoGr higher thermal properties guarantee a better geometrical stability of the collimator jaw in nominal operation. Furthermore, RF analyses on a secondary collimator were performed to evaluate the effects on the impedance when the CFC is replaced with Mo-coated MoGr. The results showed a reduction by a factor of 10 in the collimator impedance for frequencies over 10 MHz [6] (Fig. 2).

For these reasons, a new design of secondary collimator with MoGr jaws is being studied, in view of the possible installation of a prototype in the LHC at the end of 2015. The design features several improvements that can be adapted to different jaw materials, in case better options are found in the meantime.

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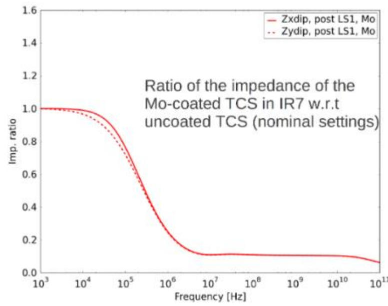

Figure 2: RF impedance, Mo-coated MoGr vs. CFC.

MECHANICAL DESIGN

The improved jaw design which is proposed aims at the optimization of the contact pressure between the active jaw and the Glidcop housing (Fig. 3), in order to enhance the performance of the cooling system.

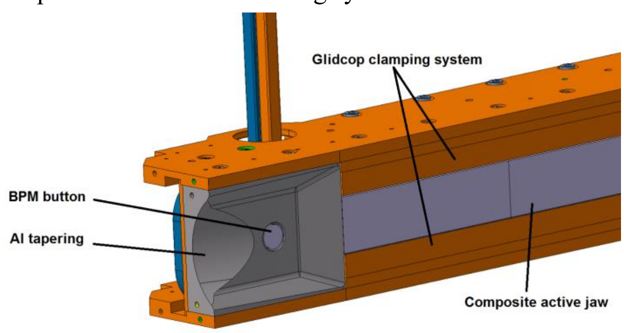

Figure 3: New secondary collimator, 3D view of the jaw.

For manufacturing reasons, the 1 m active jaw is made of 8 separate composite blocks. Due to the brittleness of ceramic composites, the blocks cannot be screwed to the Glidcop housing: a clamping system was therefore studied and is detailed in Fig. 4.

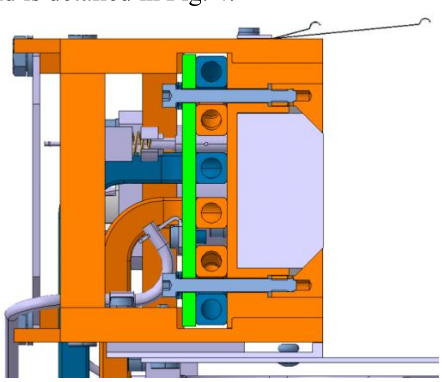

Figure 4: Jaw section, view of the clamping system.

In comparison with the present collimator design, the main differences are:

- The clamping force is now provided by screws instead of springs, with higher contact pressure at the Glidcop/MoGr interface (18 bar vs. 3 bar).
- A modified back-stiffener is increasing the rigidity of the jaw.
- The brazing between cooling pipes and stiffener is no more foreseen, simplifying manufacturing.
- Stand-alone, adjustable aluminium taperings are used to decrease the energy absorption compared to the Cu ones.
- BPMs are embedded, to speed up the alignment procedure and improve the efficiency of the machine.
- A number of thermal probes is added to the cooling circuit, to better monitor water heating in case of abnormal operation.

ENGINEERING CALCULATIONS

Two scenarios were analysed: in nominal operation, the thermal-induced stresses on the jaw are low and the behaviour of the collimator components is verified against static forces only (clamping force, self-weight, etc.). On the contrary, in an accident scenario, beam particles can directly impact the active jaw; the rapid temperature increase causes a fast local deformation and the consequent propagation of stress waves.

Nominal Operation: Structural Calculations

2D and 3D structural analyses were performed to compare different solutions for the clamping system (Fig .5). The maximum stress is lower than the ultimate strength of the material by a factor of 4 (see Table 1).

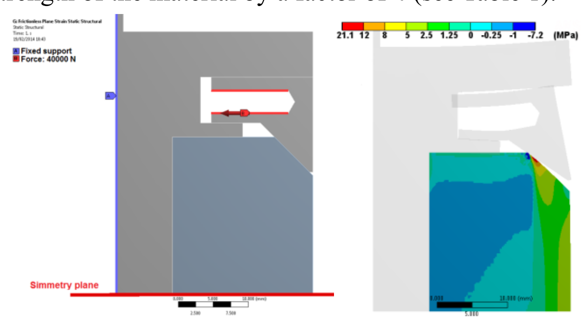

Figure 5: 2D analysis of the clamping system. Boundaries (left) and maximum principal stress (right).

Another calculation was performed on the BPM coaxial cables. In operation, one side of the cable is fixed to the tank and the other is connected to the jaw, following its movements for a total stroke of 35 mm (-5/+30 mm). The static stresses, calculated with a non-linear analysis with large deformations, are not an issue for the 304L cable, which has a yield stress of 190 MPa [7].

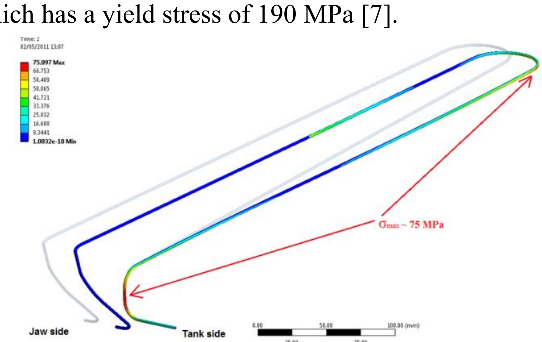

Figure 6: Maximum equivalent stress on the BPM cable.

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However, the component is also subjected to fatigue and should be designed for a lifetime of 30.000 operational in/out cycles. The alternate equivalent stress is lower than the fatigue limit of the material:

$$\sigma_{a,eq}=\sqrt{\sigma_a^2+3\tau_a^2}=\sqrt{70^2+3\cdot 10^2}\sim \mathbf{72\ MPa} < \sigma_L\ (177\ MPa)\ [7]$$

With $\sigma_a = (\sigma_{max}-\sigma_{min})/2$; $\tau_a = (\tau_{max}-\tau_{min})/2$.

Accident Scenario: Beam Injection Error

The particle beam impact on a collimator jaw is described in [8]; the most critical case analysed was the beam injection error, with the impact of a full batch at 450 GeV (3.2×10^{13} protons over 7.2 µs, 1 mm^2 beam spot). The same case has been used as a reference for the new MoGr jaw to compare the robustness levels of the two designs. A preliminary FLUKA calculation [9,10,11] was performed on the active jaw, with a 10 µm molybdenum coating on the free surface (Fig. 7). The equivalent case for the HL-LHC parameters with smaller beam emittance and larger bunch population [12] has to be studied in details.

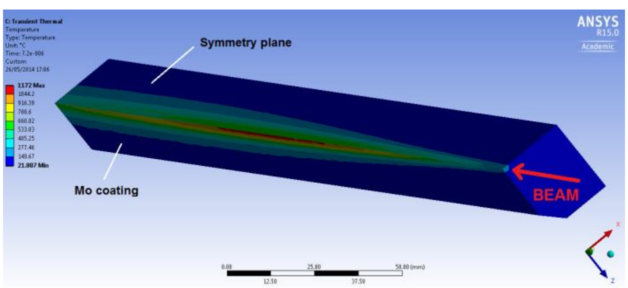

Figure 7: Temperature on the jaw at the end of the energy deposition. Impact parameter: 1 mm.

The thermo-structural analysis was performed with ANSYS. The maximum temperature calculated is 1200˚C, which is significantly lower than the melting point of the materials; nevertheless, the rapid temperature increase can induce dynamic stresses potentially harmful for the material core and for the bulk/coating interface. However, uncertainties in the simulation may arise due to the non-linear and anisotropic properties, which are not fully known; moreover, the behaviour of the bonding at the bulk/coating interface is particularly difficult to evaluate, especially at the extreme conditions expected in this scenario. For these reasons, a new test, called HRMT-1407, has been proposed in the HiRadMat facility in 2015. The test bench will include up to three different jaws, to characterize under intense proton impact different candidate materials, such as MoGr, Cu-CD, CFC, as well as heavier materials: Tungsten-Rhenium (W-Re) has recently been identified as a possible alternative to Inermet180, which is currently adopted in tertiary collimators. W-Re does not contain low-melting phases, possessing therefore higher robustness to particle beam impacts.

A preliminary setup for the HiRadMat tests is shown in Fig. 8. The jaws will be extensively equipped with *ad-hoc* instrumentation to enable a comprehensive set of measurements for a complete characterization of the response to the beam impacts. Measurements will be done in real time as in [3]. The instrumentation will most likely encompass strain gauges, laser-Doppler vibrometer, high-speed camera, temperature and vacuum probes, microphones.

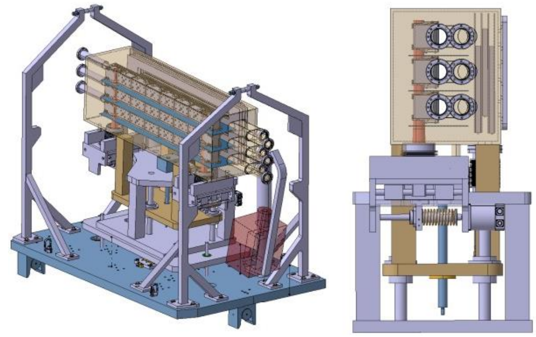

Figure 8: Proposed experiment layout in HiRadMat.

CONCLUSIONS

The R&D program on new collimator materials at CERN led to the development of novel metal-graphite compounds, such as MoGr, with excellent thermal and electrical properties. A new kind of secondary collimator has been devised around this composite; however, a modular design allows possible changes in the choice of the active jaw material.

The complexity of the solutions adopted, and the scarce information on the material properties at the conditions expected during an accident, call for an experimental validation of the component's behaviour in the HiRadMat facility. An experiment is planned in 2015, to characterize the material response under beam impacts representative of the HL-LHC extreme conditions. The test bench will contain up to three jaws with different materials.

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