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OVERVIEW OF MATERIAL CHOICES FOR HL-LHC COLLIMATORS*

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Abstract

In view of the High-Luminosity upgrade of the Large Hadron Collider (HL-LHC) at CERN, different materials were investigated for the upgrade of the LHC collimation system. A key objective was to determine how the jaws of the new collimators could be manufactured to meet the demanding requirements of HL-LHC, such as thermomechanical robustness and stability, beam coupling impedance, Ultra-High Vacuum (UHV), etc. During the Long-Shutdown 2 (LS2), five primary and ten secondary low-impedance collimators were already produced using novel materials. For LS3, in addition to more secondary collimators, the production and installation of other types of devices, including tertiaries and physics-debris collimators, is planned. This paper details the final material choices and rationale for each collimator family.

INTRODUCTION

In the Large Hadron Collider (LHC), more than 100 collimators are installed to protect other accelerator equipment from operational and accidental beam losses. The system is made of multiple stages, with collimators placed at different distances from the beam [1-3].

The High Luminosity LHC upgrade (HL-LHC) [4] foresees an upgrade of the LHC collimation system in two stages. During the Long-Shutdown 2 (LS2, planned for 2019-21), five primary collimators with Molybdenum-Carbide Graphite (MoGr) absorbers and 10 additional secondary collimators with Mo-coated MoGr blocks were installed. This novel material was identified as the best solution for low-impedance collimators [5], combining excellent thermo-physical and mechanical properties [6], and Ultra-High Vacuum (UHV) compliance [7]. Other important upgrades are discussed in [4]. During the LS3 (planned for 2026-28), it is foreseen to install 10 secondary collimators, 12 tertiary collimators, and 8 physics debris collimators. Table 1 summarizes the operational collimators to be produced for LS3.

Table 1: Collimators to be Produced for LS3

Collimator family	Name	Total installation
Secondary	TCSPM	10
Tertiary	TCTPXH	4
	TCTPXV	4
	TCTPM	4
Physics Debris	TCLP	4
	TCLPX	4

The collimator designs vary to meet the functional specifications and integration constraints at the installation points. However, the key jaw components directly interacting with the circulating beams are essentially the blocks and the tapering, as shown in Figure 1.

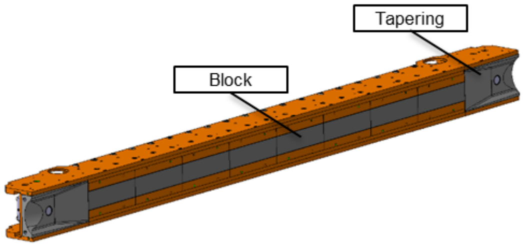

Figure 1: TCSPM collimator jaw, showing blocks and taperings.

This paper first recalls the requirements for absorbers. In the following paragraphs, the experimental tests and studies performed to support the material choice is presented for each type of collimator family. The authors concentrate on the criteria and reasoning used to finalize the decision for the LS3 collimator production.

MATERIAL REQUIREMENTS

The choice of material for collimator absorbers relies on various specifications, from the standard ones such as availability, manufacturing feasibility and cost, to specific requirements such as geometrical stability, mechanical robustness, resistance to high temperatures, cleaning efficiency, low contribution to beam coupling impedance, resistance to radiation, and UHV compatibility.

The beam-matter interaction produces several phenomena, which make it difficult to set threshold values for individual thermo-physical and mechanical properties. A useful approach is to introduce indexes of figure of merit [8].

The thermal stability of a material is estimated with the thermal stability index (TSI), which combines the thermal conductivity λ, the coefficient of thermal expansion α, the radiation length X_g, and the material density ρ.

$$TSI \propto \frac{\lambda X_g}{\alpha \rho^n} \quad (1)$$

The thermomechanical robustness index (TRI) includes additional mechanical and thermal properties (Young modulus E, and Poisson ratio ν, failure strength R_M, specific heat c_p, and melting temperature T_M). The exponent m and n are empirical values related to material properties [8].

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$$TRI \propto \frac{R_M c_p X_g}{E*(1-\nu)\alpha\rho^n} \cdot \left(\frac{T_M c_p X_g}{\rho^n} - 1\right)^m \qquad (2)$$

This index provides a good estimate of the material behaviour but is not experimentally benchmarked to the extent that precise robustness threshold limits can be set. For this reason, the material robustness is often evaluated in an experimental way, mainly in the CERN HiRadMat facility [9], where the power density deposition of the HL-LHC beam can be reproduced.

For an adequate cleaning efficiency, the density of the absorber materials must not be too low. During the LHC design, the cleaning was studied for secondary collimators made of Carbon-fibre-Carbon (CFC). CFC, with a density of 1.67 g/cm^3, was considered acceptable, and it is indeed the material currently installed [4]. For tertiary collimators, cleaning simulations were performed with Copper-Diamond (CuCD) blocks, with a density of 5.4 g/cm^3, and this density was considered sufficient [4].

All the materials should ideally be tested under long-term irradiation to assess the degradation of relevant properties as a function of the displacement-per-atom (dpa) and gas production induced by the proton beam.

The impedance requirements for collimators can be translated in electrical conductivity values, once the aperture settings are fixed, in order to facilitate the material choice. For secondary collimators, a minimum of 10 MS/m is required [10, 11] for a minimum coating thickness of 6 μm. For tertiary collimators, a minimum value of 7 MS/m is required [11].

Finally, collimator jaw operates in UHV, with a limited pumping speed. The outgassing of a collimator must be lower than $2\cdot10^{-7}$ mbar·l/s [12]. Considering the contribution of the tank, the total outgassing of the absorber materials has to be lower than $5\cdot10^{-8}$ mbar·l/s. The residual gas test must comply with the specification [12].

SECONDARY COLLIMATORS

For the HL-LHC secondary collimators, it was decided to apply a metallic coating on the blocks, in order to further reduce the contribution to the machine impedance. Few microns of a conductive coating are sufficient to screen the bulk material at frequencies in the GHz range (corresponding to the bunch spectrum): the presence of the coating makes the collimator's impedance independent of the substrate on which the coating is applied [13], under assumption that coating is not damaged, e.g. in case of beam accidents.

The substrate, however, must be chosen in order to provide optimal deposition conditions, which allow obtaining the required conductivity and adherence of the coating. Ideally, a good conductivity is preferred, in case of significant damage of the coating, although the details depend on the extent of damage, if any. For this reason, the CFC option was immediately discarded. The high surface roughness and porosities of the material result in a high resistivity of the coating [5]. Only MoGr and graphite are thus considered, and their figures of merit are summarized in Table 2.

Table 2: Material Properties for Secondary Collimators

Property	Graphite	MoGr
Density [g/cm^3]	1.83	2.57
TRI	2970	311
TSI	19	39
Electrical conductivity [MS/m]	0.08	1

Both materials are compliant, and they are indeed used in collimators and other beam-intercepting devices [4]. The choice is thus driven by the electrical conductivity and the resistance to beam impact of the coating applied on the bulk material.

Several tests show that the Mo-coating on graphite substrate does not reach the required electrical conductivity [5]. Preliminary measurements performed in the laboratory show that Cu-coating on graphite gives better results, especially for the High-Power Impulse Magnetron Sputtering (HIPIMS-45 MS/m), compared to the Direct Current Magnetron Sputtering (DCMS-14 MS/m).

The choice of the material for taperings is also affecting the collimator impedance performance. For this reason, the global impedance of a collimator jaw is evaluated. In Figure 2, the calculated impedance [14] of the different material options considered for TCSPM are shown. The values in the graph are normalized for the option that is providing the lowest impedance contribution, that is the Cu-coated graphite blocks with Cu-coated tapering. From this graph, it is evident that it is beneficial to coat also the taperings. The Cu-coated graphite blocks with graphite tapering is almost 50% worse compared to the option with coated tapering. It is noted that the first three options in Figure 2 provide an improvement with respect to the LS2 solution.

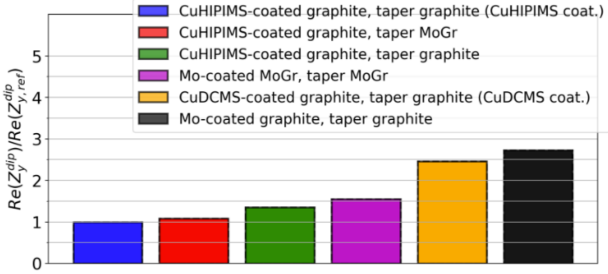

Figure 2: Impedance (real part) at 1 GHz for different materials for TCSPM, normalized to the lowest value (half-gap 1.5 mm).

In terms of robustness, it is worth recalling that the copper melting temperature and ultimate strength are significantly lower compared to Molybdenum, thus the appropriate mechanical resistance of Cu-coating should be verified. During the Multimat-2 experiment in HiRadMat, Cu-coated graphite samples were subjected to an impact of a grazing proton beam, which is similar to an injection error in HL-LHC[15, 16]. As shown in Fig. 3, the coating survived the beam impact. The area showing a change of color was analysed with the topography and no peel-off of the coating was observed, thus the mark is probably related to copper melting. These observations are in line with the findings of previous HiRadMat experiments [9,16,17], where the same materials and similar loading conditions were tested. Thus, for TCSPM, on top of the LS2 solution, another option was validated: the Cu-coated graphite blocks with Cu-coated tapering. This solution is selected for the production of LS3 TCSPM collimators.

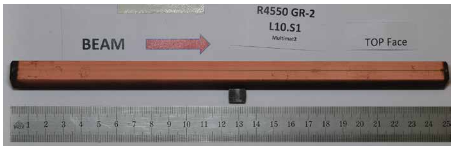

Figure 3: Cu-coating graphite impacted by the proton beam during the Multimat-2 experiment in HiRadMat.

TERTIARY COLLIMATORS

The TCTPXH and TCTPM belong to the tertiary collimator family to be installed upstream of the collision points to protect the final-focusing triplet and the experiments.

The absorber materials considered for this family and the relevant figures of merit are summarized in Table 3. For the tungsten alloy, the properties considered refer to Inermet 180 (IT180), but an equivalent W-alloy can be envisaged.

Table 3: Material Properties for Tertiary Collimators

Property	**IT180**	**CuCD**
Density [g/cm^3]	18	5.4
TRI	0.6	21
TSI	0.14	6
Electrical conductivity [MS/m]	7	8.8

For both materials, the density and electrical conductivity are compliant with the specifications. The main advantage of CuCD is the very high robustness compared to IT180, which is mostly due to the much lower density and the good thermo-mechanical properties.

The global impedance is considering the contribution of taperings. A more robust material for the taperings compared to the blocks is preferred, to avoid having a lower damage threshold on the taperings, in case of direct beam impact. In addition, to ease the fabrication of the taperings, CuCrZr taperings are selected for IT180 jaws, whereas MoGr is chosen for CuCD jaws. The global impedance of IT180 blocks with CuCrZr tapering is lower, both for TCTPM and TCTPXH collimators, as shown in Figure 4 and Figure 5. Both options are considered valuable for the blocks, but for CuCD the use of tapering with a minimum conductivity equal to the one of MoGr is recommended.

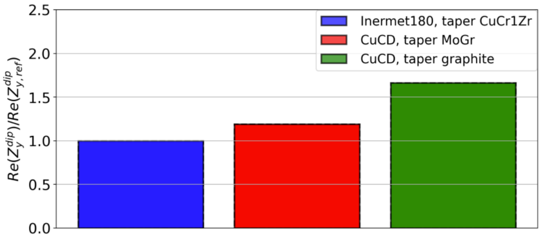

Figure 4: Impedance (real part) at 1 GHz for different materials for TCTPM, normalized to the lowest value (half-gap 7.4 mm).

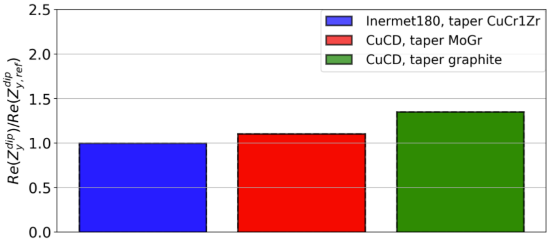

Figure 5: Impedance (real part) at 1 GHz for different materials for TCTPXH, normalized to the lowest value (half-gap 14.3 mm).

Tertiary collimator absorbers must operate without any permanent damage. Experimental tests, such as HRTM23, demonstrated that IT180 would not survive an asynchronous beam dump (ASD), while CuCD does [16,18,19]. However, it has been judged that there are enough margins for beam configurations to avoid damage of IT180 [20]. For this reason and considering also cost and the manufacturing schedule risks observed during the prototyping phase, the TCTPXH and the TCTPM and will be produced with IT180.

For the TCTPXV collimators, the use of CuCD is not considered necessary because they are not exposed to the ASD, and thus they do not have to withstand direct beam impacts. The use of IT180 is thus envisaged for these collimators.

PHYSICS DEBRIS COLLIMATORS

For the physic debris collimators (TCLP and TCLPX) the main goal is to intercept the products of particle collisions that emerge from the interaction point. For this reason, the material absorber density must be maximized in order to increase the beam interaction. Among the different materials analysed, a W-alloy is the most suitable one to fulfil this function [4].

CONCLUSION

During LS3, different families of collimators will be installed. In this paper, the main requirements of absorber materials were reviewed. For each collimator type, different material options were investigated, and the outcome of experimental tests and studies were analysed. The final choice, which takes into account production schedule and risks as well as budget considerations, is to produce secondary collimators with Cu-coated graphite blocks and taperings, tertiary collimators with W-alloy blocks with CuCrZr taperings, and physics debris collimators in W-alloy.

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