

NOVEL MATERIALS FOR COLLIMATORS AT LHC AND ITS UPGRADES*

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Abstract

Collimators for last-generation particle accelerators like the LHC, must be designed to withstand the close interaction with intense and energetic particle beams, safely operating over an extended range of temperatures in harsh environments, while minimizing the perturbing effects, such as instabilities induced by RF impedance, on the circulating beam. The choice of materials for collimator active components is of paramount importance to meet these requirements, which are to become even more demanding with the increase of machine performances expected in future upgrades, such as the High Luminosity LHC (HL-LHC). Consequently, a far-reaching R&D program has been launched to develop novel materials with excellent thermal shock resistance and high thermal and electrical conductivity, replacing or complementing materials used for present collimators. Molybdenum Carbide - Graphite and Copper-Diamond composites have been so far identified as the most promising materials. The manufacturing methods, properties and application potential of these composites will be reviewed along with the experimental program which is to test their viability when exposed to high intensity particle beams.

INTRODUCTION

The introduction in recent years of new, extremely energetic particle accelerators such as the Large Hadron Collider (LHC) [1] brought about the need for advanced cleaning and protection systems, such as collimators, in order to safely increase the energy and intensity of particle beams to unprecedented levels. LHC collimators must adopt materials able to withstand the extreme conditions (temperatures, pressures and densities) induced by the accidental impact of particle beam pulses; on top of outstanding thermal shock resistance, these materials are typically required a number of additional relevant properties, such as high electrical conductivity, geometrical stability and resistance to radiation damage. These requirements are set to become even more compelling in consideration of the High-Luminosity upgrade of the LHC (HL-LHC) [2], expected to increase by a factor of two beam intensity and energy: Carbon-

Carbon (C-C) composites used for primary and secondary collimators may limit the accelerator performance as a result of the high impedance induced by C-C low electrical conductivity, while the Tungsten alloy (Inermet180) used in tertiary collimators has very low robustness in case of beam impacts.

To face these challenges, an intense R&D program has been launched at CERN in recent years to explore or develop a palette of novel materials which are to combine the excellent properties of graphite or diamond, specifically their low density, high thermal conductivity, low thermal expansion, with those of metals and transition metal-based ceramics possessing high mechanical strength and good electrical conductivity. This article presents the most promising materials identified so far, namely Molybdenum Carbide - Graphite (MoGr) and Copper-Diamond (CuCD).

MOLYBDENUM CARBIDE - GRAPHITE

Pure molybdenum possesses very high melting point, low Coefficient of Thermal Expansion (CTE) and excellent mechanical strength and electrical conductivity, while graphitic materials feature low density, extremely high service temperature, large damping properties (particularly useful in attenuating shock waves) and, if graphite crystallite ordering is sufficiently extended (high graphitization degree), excellent thermal conductivity and very low CTE, at least in the direction aligned with graphite basal plane. At high temperatures, molybdenum rapidly reacts with carbon, forming stable carbides (MoC_{1-x}) which, in spite of their ceramic nature, retain a good electrical conductivity; in this respect, MoGr is therefore a ceramic-matrix composite. Several MoGr grades, in the frame of a collaboration between CERN and Italian SME BrevettiBizz, were investigated, with processing temperatures ranging from 1700° C to 2600° C [3].

A broad range of compositions, powder types and dimensions were tested: the best results so far were obtained for a sintering temperature of 2600° C. The C-phase can be composed of natural graphite flakes or by a mixture of natural graphite and mesophase pitch-based carbon fibres (Fig. 1).

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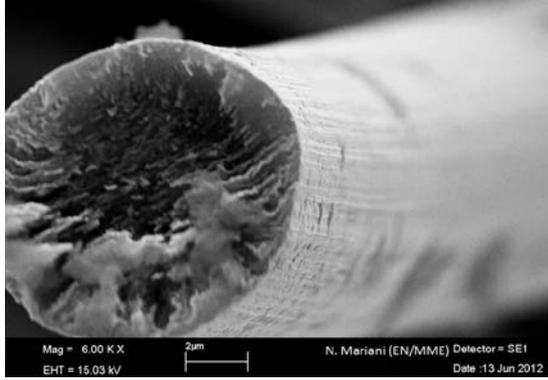


Figure 1: Micrograph of a pitch-derived carbon fiber.

The material is produced by Liquid-Phase Sintering (LPS) at a temperature above the melting point of molybdenum carbide (2589° C); the final result is a very homogeneous structure with a regular distribution of carbide particles and a high degree of graphitization of the carbonaceous phase.

To favour liquid carbide infiltration and material compaction rate, a significant quantity of molten carbides is allowed to flow out of the moulds during LPS, so that the final density of the material is reduced to $\sim 2.5 \text{ g cm}^{-3}$; thanks to the extensive graphitization process occurring during high temperature sintering, very likely catalysed by the carbide liquid phase, MoGr possesses in the preferential direction, an electrical conductivity of $\sim 1 \text{ MSm}^{-1}$, one order of magnitude higher than the Carbon-Carbon composite used in Phase I collimator. This property can be further increased up to 18 MSm^{-1} by cladding or coating the external surface with pure molybdenum; excellent adhesion was obtained between Mo layer and bulk material thanks to the formation of a homogeneous carbide interface (Fig. 2).

Electromagnetic simulations were performed to evaluate the effects on beam impedance when, on a LHC secondary collimator jaw, C-C 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 [4] (Fig. 3).

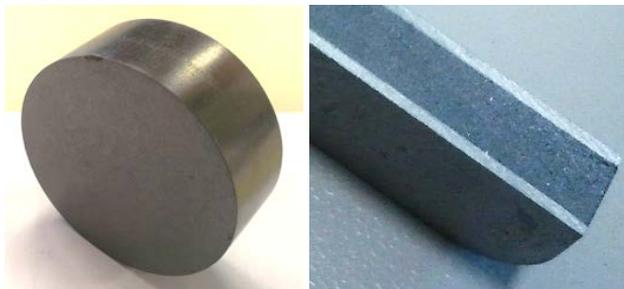


Figure 2. MoGr sintered plate, H=25mm and D=90mm (left); Mo-coated MoGr specimen (right).

On top of low density and good electrical conductivity, MoGr presents outstanding thermal properties: the thermal conductivity at room temperature (RT) is $\sim 770 \text{ Wm}^{-1}\text{K}^{-1}$ (Fig. 4), almost twice that of pure copper while

CTE in the preferential plane is $1.8 \times 10^{-6} \text{ K}^{-1}$ for temperatures spanning from RT to 2000 °C.

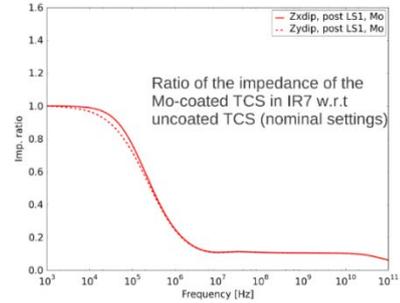


Figure 3: Collimator beam impedance: ratio of a Mo-coated MoGr to a C-C jaw.

Relevant reference properties of MoGr are provided in Table 1.

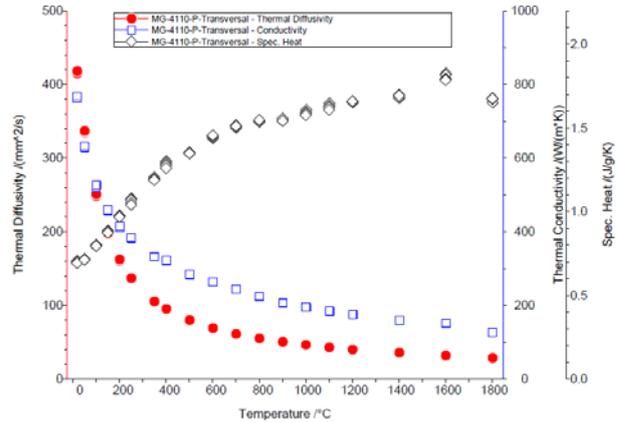


Figure 4: Thermal conductivity, diffusivity and specific heat of MoGr between RT and 1800° C.

Table 1: MoGr Properties

Density ρ	2.5 g/cm^3
CTE α_{\perp} (RT to 1000° C)	$1.8 \times 10^{-6} \text{ K}^{-1}$
CTE α_{\parallel} (RT to 1000° C)	$12 \times 10^{-6} \text{ K}^{-1}$
Thermal conductivity λ_{\perp} (RT)	$770 \text{ Wm}^{-1}\text{K}^{-1}$
Thermal conductivity λ_{\parallel} (RT)	$85 \text{ Wm}^{-1}\text{K}^{-1}$
Electrical conductivity σ_{\perp} (RT)	$1\text{--}18 \text{ MSm}^{-1}$
Electrical conductivity σ_{\parallel} (RT)	0.3 MSm^{-1}
Young's Modulus E (Flexural)	53 GPa
Ultimate Strength R_m (Flexural)	85 MPa

COPPER-DIAMOND

Copper-Diamond is produced by RHP Technology (Austria) by Solid-State Sintering; the initial volumetric composition is 60% diamond, 39% copper and 1% boron. A higher content in diamond would not allow a good material compaction, which is also pursued by making

use of diamonds of various sizes, in order to optimize the filling of the interstitials. Unlike MoGr, the main issue for the material adhesion is the low chemical affinity between the two main elements, which leads to a lack of bonding between copper and diamond: this would jeopardize not only mechanical strength, but also thermal conductivity. Boron is added to offset such limitation, since this element promotes the formation of carbides at the diamond/copper interface, improving material internal bonding (Fig. 5).

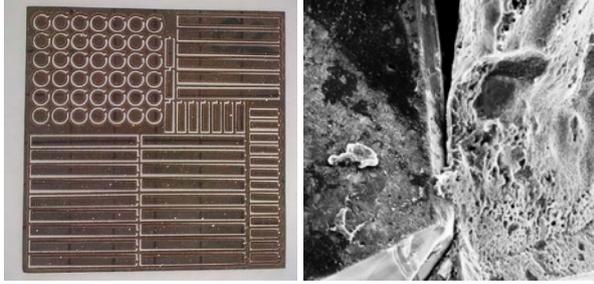


Figure 5: CuCD specimens (left); micrograph of CuCD fracture surface: note small B carbide platelet bridging diamond grain to Cu matrix (right).

CuCD possesses very good thermal and electrical conductivity (Table 2). However, density and CTE are higher than MoGr, and the industrialization of the material is difficult: while thin samples of constant section can be produced via water-jet cutting (Fig. 6), more complicated shapes with precise tolerances are extremely difficult and expensive to machine.



Figure 6: CuCD samples after water-jet cutting; marks in the water flow direction and porosity are clearly visible.

Table 2: CuCD Properties

Density ρ	5.4 g/cm ³
CTE α (RT to 900° C)	6÷12x10 ⁻⁶ K ⁻¹
Thermal Conductivity λ (RT)	490 Wm ⁻¹ K ⁻¹
Electrical Conductivity γ (RT)	12.6 MSm ⁻¹
Young's Modulus E (Flexural)	220 GPa
Ultimate Strength R_m (Flexural)	70 MPa

FIGURES OF MERIT

In order to classify and rank potential materials against the large number of requirements which are defined for beam interacting devices in general and collimators in

particular, Figures of Merit (FoMs) were proposed in the past [5,6]. In this paper, we partly redefine FoMs on the basis of the experience gathered in the last years, exploiting the data acquired during two characterization campaigns launched in 2012 at CERN HiRadMat facility [7,8]. The new indexes rely on constant, uniform material properties at an arbitrary reference temperature; for anisotropic materials, relevant properties are averaged over the 3 directions. The most relevant figures of merit are:

- Thermomechanical Robustness
- Thermal Stability
- Electrical Conductivity
- Radiation Resistance

Thermomechanical Robustness

An index, called Thermomechanical Robustness Index (TRI), is proposed to evaluate the material robustness against particle beam impacts. This index is based on the ratio between material admissible strain and actual strain: in fact, thermal shock problems are to a large extent governed by the thermal deformation induced by a sudden temperature change.

$$TRI = \frac{\varepsilon_{adm}}{\varepsilon_{ref}} \cdot \left(\frac{T_m}{\Delta T_q} - 1 \right)^m \quad (1)$$

ε_{adm} and ε_{ref} are respectively the admissible strain and the actual strain induced by a reference beam impact; T_m is the melting (or degradation) temperature; ΔT_q is the temperature increase generated by the reference energy deposition; m is a coefficient related to the material loss of strength with temperature increase. These quantities are expressed by Equations (2), (3) and (4).

$$\varepsilon_{Adm} = \frac{R_M}{\bar{E} \cdot (1 - \nu)} \quad (2)$$

$$\varepsilon_{ref} = \bar{\alpha} \cdot \Delta T_q \quad (3)$$

$$\Delta T_q = \frac{C_R \rho^n}{c_p X_g} \quad (4)$$

\bar{E} is the (averaged) Young's modulus, ν the Poisson's ratio, $\bar{\alpha}$ the (averaged) CTE, c_p the specific heat, X_g the geometric radiation length, C_R an arbitrary scaling factor and n a constant related to the energy distribution generated by the impact.

Eq. (4) implies that the energy deposited by a given number of particles, and therefore the material temperature increase, is related to the material density and to the geometric radiation length; we have empirically observed that the coefficient n for materials impacted by protons at several hundreds GeV is ~ 0.2 .

Combining (1), (2), (3) and (4), the TRI can be written as:

$$TRI = \frac{R_M c_p X_g}{\bar{E} (1 - \nu) \bar{\alpha} C_R \rho^n} \cdot \left(\frac{T_m c_p X_g}{C_R \rho^n} - 1 \right)^m \quad (5)$$

Thermal Stability

The Thermal Stability Index (TSI) provides an indication of the ability of the material to maintain the

geometrical stability of the component under steady-state particle losses. It is related to the inverse of the curvature of an elongated structure induced by a non-uniform temperature distribution, and is calculated with Equation (6). Here $\bar{\lambda}$ is the (averaged) thermal conductivity and C_S a scaling factor.

$$TSI = \frac{\bar{\lambda} X_g}{\bar{\alpha} C_S \rho^n} \quad (6)$$

Electrical Conductivity

Since collimators are the accelerator devices sitting closest to the circulating beam, their contribution to the machine global impedance is by far the highest. The part of the beam coupling impedance related to the resistive losses in the material surrounding the beam, the so-called resistive wall impedance, is directly related to the material electrical resistivity. Therefore maximizing the electrical conductivity of the jaw materials can play a major role in minimizing the risk of impedance-induced beam instabilities.

Radiation Resistance

Irradiation of materials by energetic particles causes microstructural defects which translate into a degradation of the thermo-physical properties. Radiation resistance is defined as the ability of the material to maintain its properties under and after irradiation. Several tests are being performed in various facilities (GSI, Kurchatov Institute, BNL) in order to evaluate the radiation resistance of the materials of interest at energies up to 1.14 GeV. First results for MoGr and CuCD should soon become available.

A summary of the first 3 FoMs for MoGr and CuCD compared to those of present collimator materials is provided in Table 3. As it can be seen, while C-C is penalized by its limited electrical conductivity in spite of its outstanding TRI, MoGr shows the best compromise as far as these 3 indexes are concerned.

Table 3: Relevant figures of merits for a selection of present and future collimator materials

	C-C	Inermet180	MoGr	CuCD
TRI [-]	1237	0.5	634	6.8
TSI [-]	44.6	0.1	69.4	9.9
γ [MS/m]	~0.14	8.6	~1÷18	~12.6

HIRADMAT EXPERIMENTS

After the first experiments performed at HiRadMat facility in 2012, CuCD and MoGr emerged as the materials which better survived the impact of 1.95×10^{13} protons at 450 GeV. The design of a new secondary collimator for the HL-LHC upgrade (TCSPM) has therefore been based on these two novel materials [9].

The proposed modular design allows to house in the collimator jaw both CuCD and MoGr inserts; for manufacturing reasons, the 1 m-long active jaw is divided

in 10 separate composite blocks (Fig. 7).

The jaw assembly is clamped, to guarantee the contact force required for an effective cooling while assuring the possibility of differential sliding between components with mismatching CTE (Fig. 8).

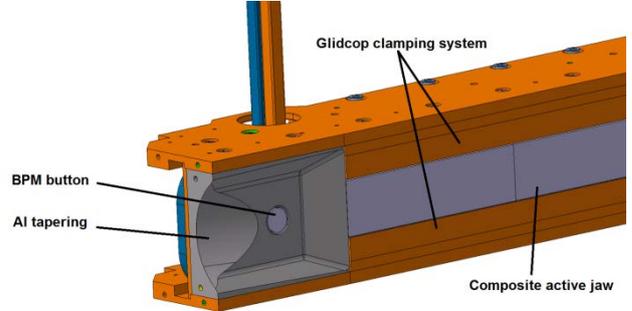


Figure 7: HL-LHC secondary collimator (TCSPM), 3D view of the jaw extremity.

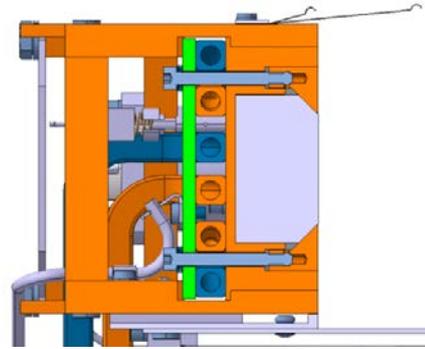


Figure 8: Jaw cross-section, view of the clamping system.

In order to test the collimator resistance against particle beam impacts at HL-LHC intensities and to select the best material for a prototype to be successively installed in the LHC, a new experiment in the HiRadMat facility is planned for late spring 2015. The experiment, named HRMT23, will consist of a stainless steel vacuum tank hosting three independent collimator jaws sharing the same supporting system (Fig. 9).

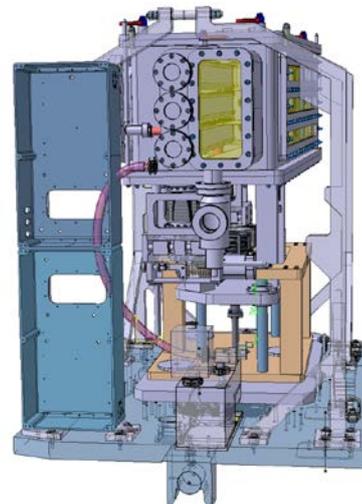


Figure 9: HRMT23 test bench.

The jaws to be tested are two TCSPM, with MoGr and CuCD inserts respectively, and a TCSP. Each jaw will be independently impacted by a number of particle pulses with increasing intensities up to the maximum available at the time of the experiment, the design case being that of HL-LHC beam injection error scenario (6.4×10^{13} protons). Simulations are being performed to evaluate the response of the different jaws to this impact scenario (Figs. 10-11).

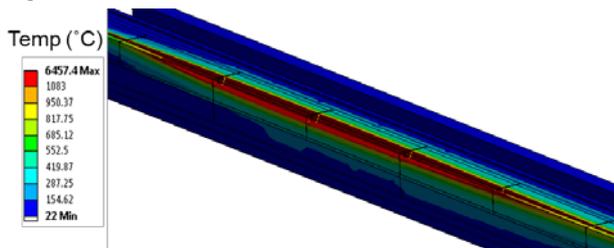


Figure 10: CuCD jaw impacted by 6.4×10^{13} protons, temperature distribution. The red region is above melting point.

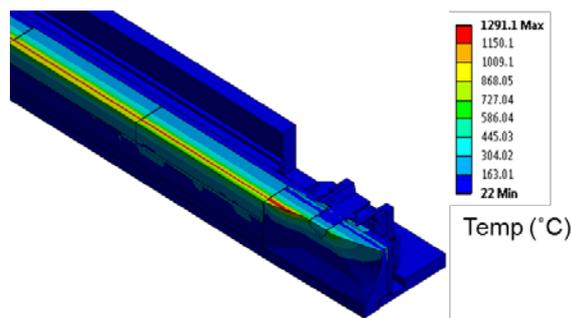


Figure 11: MoGr jaw impacted by 6.4×10^{13} protons, temperature distribution. The temperature peak is on the Glidcop tapering. No melting of MoGr inserts is expected.

The experiment instrumentation will allow to characterize in real time the component response during the impact and will likely include resistive strain gauges, temperature, displacement and vacuum probes, microphones and water pressure sensors. The most delicate instruments, such as high-speed camera and laser-Doppler vibrometer, will be positioned in a radiation-protected bunker in the tunnel TT40, parallel to the HiRadMat beam line.

CONCLUSIONS

In the frame of the future High Luminosity upgrade of the LHC, a novel class of materials combining carbon allotropes, graphite or diamond, with metals or transition metal-based ceramics has been investigated at CERN and collaborating institutes and industries in recent years. Amongst the several materials which were studied, the most interesting results have been reached with Molybdenum Carbide – Graphite (MoGr) and Copper-Diamond (CuCD). The former is obtained by rapid hot pressing up to temperature of 2600°C in the presence of a liquid phase. The high temperature reaction between

molybdenum and graphite promotes the complete transformation of molybdenum in refractory MoC_{1-x} while liquid carbides catalyse and enhance carbon re-ordering and graphitization; mesophase pitch-derived carbon fibres can also be added to further increase graphitization and mechanical strength. This leads to outstanding thermo-physical properties, with thermal conductivity in the vicinity of $800\text{ Wm}^{-1}\text{K}^{-1}$ and CTE in the range of $1\div 2 \times 10^{-6}\text{ K}^{-1}$.

CuCD, obtained by solid-state hot pressing, is particularly attractive for its high electrical conductivity, although the limited melting point somehow limits its robustness against high energy beam impacts.

A new set of figures of merit has been proposed, on the basis of the experience gathered with recent HiRadMat experiments, to compare and rank materials for beam interacting devices in general and collimators in particular.

A new experiment allowing to test under direct beam impact three independent collimator jaws is planned at CERN HiRadMat facility for late spring 2015; two of these jaws, based on a new design for the future HL-LHC Collimators, make use of MoGr and CuCD. The experiment is also aimed at validating material and design for a full-scale HL-LHC prototype to be later installed in the LHC for machine development tests.

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