

ADVANCED MATERIALS FOR FUTURE PHASE II LHC COLLIMATORS

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Abstract

Phase I collimators, equipped with Carbon-Carbon jaws, effectively met specifications for the early phase of LHC operation. However, the choice of carbon-based materials is expected to limit the nominal beam intensity mainly because of the high RF impedance and limited efficiency of the collimators. Moreover, C/C may be degraded by high radiation doses.

To overcome these limitations, new Phase II secondary collimators will complement the existing system. Their extremely challenging requirements impose a thorough material investigation effort aiming at identifying novel materials combining very diverse properties. Relevant figures of merit have been identified to classify materials: Metal-diamonds composites look a promising choice as they combine good thermal, structural and stability properties. Molybdenum is interesting for its good thermal stability. Ceramics with non-conventional RF performances are also being evaluated.

The challenges posed by the development and industrialization of these materials are addressed in a collaboration program, involving academic and industrial partners and complementing material research with an innovative design.

INTRODUCTION

The functional specification of the LHC Collimators requires, for the start-up of the machine and the initial luminosity runs (Phase I), a collimation system with maximum robustness against abnormal beam losses in operating conditions. To ensure that the collimator jaws survive such accident scenarios, low-Z materials were chosen, driving the design towards Carbon reinforced Carbon composites [1] with successful results obtained during beam impact tests [2]. Nevertheless, Phase I collimators are expected to limit the LHC nominal beam intensity. This is mainly due to the high RF impedance of collimators potentially inducing beam instabilities and to the limited ratio of intercepted to escaping particles of the Phase I collimation system. Moreover, Carbon reinforced carbon jaws may experience strong degradation of their thermo-physical and mechanical properties due to high radiation doses. For all these reasons, as it was foreseen since the beginning of the LHC collimation project, new Phase II secondary collimators are necessary to complement the existing system overcoming its limitation and ensuring the LHC nominal performances [3].

Preliminary RF studies indicate two possible solutions for Phase II collimator jaws depending on the method used to stabilize the LHC beam: metallic jaw (high electrical conductivity) if relying on Landau Octupoles stabilization, non-metallic (dielectric) jaw in case of active transverse feedback [4]. Final decision will be supported by LHC operation experience.

Collimation efficiency requirements would lead to the choice of higher-Z materials (with respect to Phase I jaws), however these materials would compromise jaw geometrical stability because of higher energy deposition. Furthermore, thermal shock resistance of high-Z materials presents some critical aspects for the robustness of the collimation system in case of beam impacts.

PRELIMINARY DESIGN SOLUTION

To respond to these tough and sometimes conflicting requirements, material research needs to be supported by an innovative design of the jaw assembly. A preliminary solution is shown in the scheme of Fig. 1. The presented modular design concept foresees a common baseline for the jaw assembly and allows the use of alternative materials for the jaw itself. This approach permits the development of diverse solutions (conductive vs. non-conductive jaw) with a single supporting structure.

The jaw assembly is composed of a rigid back stiffener, an equipped jaw with cooling circuit and a an adjustment system. As shown in the scheme of Fig. 1, back-stiffener and equipped jaw are independently supported at the extremities and linked via the fine adjustment system.

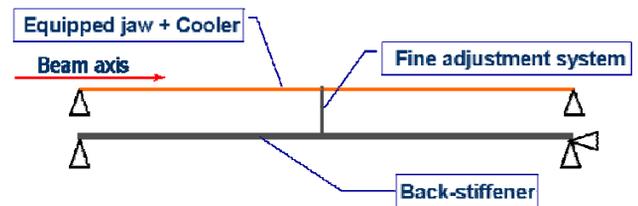


Figure 1: Scheme of modular design concept of Phase II collimator jaw assembly.

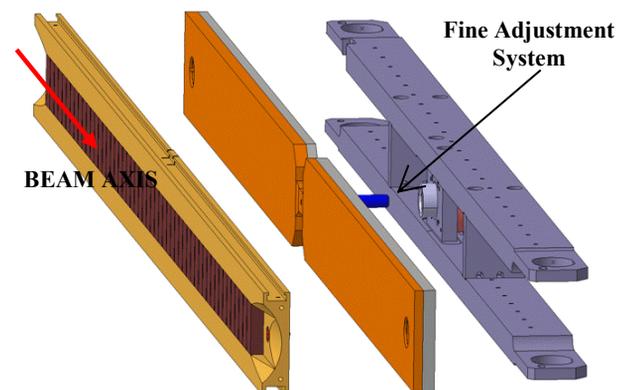


Figure 2: Preliminary design solution for Phase II jaw assembly. Modular design including (from left to right) equipped jaw, cooling system and back-stiffener.

The back-stiffener, placed far from the particle beam, should ideally remain at almost uniform temperature and, thanks to its high stiffness, must ensure high geometrical stability to the jaw surface under thermal load.

The jaw is equipped with an optimized cooling circuit, brazed to the jaw itself, to absorb high expected heat-loads. The adjustable system allows jaw flatness control to compensate gravity sag and minimize thermal deflection. This configuration maximizes the effective length of the jaw thus improving collimator cleaning efficiency. The described design solution is shown in Fig 2; main components of the 3D model are presented.

FIGURES OF MERIT

An intense effort is being devoted to material investigation in order to identify new solutions that could comply with extremely demanding specifications of Phase II collimators. The following guidelines, as anticipated in the introduction, led to the choice of potential candidates:

- Tailored electrical conductivity to improve RF stability.
- High thermo-mechanical stability to limit thermal deformations in working conditions.
- Sufficient robustness to withstand without major problems possible beam accident at high energy and intensity.
- Higher density (high-Z) to improve collimation efficiency.
- Strong resistance to particle radiation.

Relevant figures of merit have been identified to classify materials and rank their performances:

Electrical Resistivity

Electrical resistivity [$\Omega \cdot m$] is directly related to resistive impedance. Preliminary studies provided important indications in order to improve the RF stability; two potential solutions were identified in relation to the beam stabilization method to be employed:

- Very high electrical conductivity (Landau octupoles) implying the use of metallic jaws (electrical resistivity of copper $17 \cdot 10^{-9} \Omega \cdot m$ is the reference value).
- Tailored electrical resistivity $10^0 \div 10^2 \Omega \cdot m$ (transverse feedback stabilization) in order to exploit at best the inductive by-pass effect (see [4] and [5] for details).

The second option entails the use of non-conductive material (for the jaw absorber) to be bonded on a conductive support. Design proposal, as shown in Fig. 2, foresees the use of short dielectric tiles bonded on a metal (good conducting) support.

Steady-state Geometrical Stability Parameter

Steady-state geometrical stability parameter R1 [W/m], is the ratio between thermal conductivity k and coefficient of thermal expansion CTE α as shown in expression (1). This parameter indicates the power required to induce a

given thermal deflection and is fundamental to assess the performance of the collimator jaw in terms of geometrical stability. It is important to remember that the required flatness is $20 \div 50 \mu m$ over a length of more than 1m.

$$R1 = \frac{k}{\alpha} \quad (1)$$

Transient Thermal Shock Parameter

Transient thermal shock parameter R2 [J/kg] provides an indication of the highest acceptable deposited energy during a beam impact before damage occurs. In expression (2) σ_y is the thermal stress damage limit, ν is the Poisson's ratio, c_p the specific heat, E the Young's modulus and α the coefficient of thermal expansion.

$$R2 = \frac{\sigma_y (1 - \nu) c_p}{E \alpha} \quad (2)$$

Mass Density

Mass density [kg/m^3] is related to the cleaning efficiency of the jaw and proportional to the energy absorbed.

POTENTIAL CANDIDATES

Several materials were classified and ranked following the figures of merit presented above. Furthermore, the choice of promising materials was carried out considering the functionality of the different components according to the design solution presented above. The combined approach of material and design optimization allowed the identification of a potential material for each component of the jaw assembly:

Back-stiffener – Molybdenum

The main function of the back-stiffener is to ensure, through the fine adjustment system, geometrical stability for the active part of the jaw assembly. Therefore the stiffness of this component is of paramount importance (high Young's modulus). Moreover the back-stiffener should ideally have a very high thermo-mechanical stability, i.e. a high ratio $E \cdot k / \alpha$. Upon this considerations, several materials were considered (molybdenum, tungsten, silicon carbide, carbon-carbon composite...). Molybdenum looks a promising choice, not only for its suitable thermo-mechanical properties but also from the manufacturing point of view and for its expected radiation hardness. Positive feedbacks were received on the feasibility of this solution from potential material suppliers

Cooling System – Copper and Stainless Steel

The use of higher-Z materials implies the increase of deposited energy. Improved cooling efficiency was obtained through a cooling circuit directly machined from a solid bloc with a brazed cover. OFE-Cu and Stainless Steel (see Fig. 3) are used to ensure high reliability of the brazed joint and to avoid any problem concerning UHV tightness of the cooler.

Jaw – Metal Diamond vs. Ceramics

As explained above, two options were developed following the indication from preliminary RF studies:

- **Highly conducting jaw.** This option requires the maximization of the electrical conductivity, therefore Copper or GlidCop® represent typical solutions. However, in order to improve thermo-mechanical stability and thermal shock resistance while keeping a high electrical conductivity, advanced thermal management materials can represent valid candidates, particularly Copper-Diamond (Cu-CD). Properties of relevant materials are collected in Table 1; properties of C/C from Phase I jaw are also indicated.
- **Non conducting jaw.** Tailored electrical resistivity together with good thermo-mechanical stability led to the choice of silicon carbide SiC (See Table 1). Furthermore, SiC tiles have a better thermal shock resistance with respect to Cu-CD.

Based on literature [6], both Metal–Diamond and Silicon Carbide look promising from the radiation hardness point of view. At any rate, experimental tests in high radiation dose facilities are foreseen.

Moreover, Cu-CD can be conveniently exploited not only as a material for the jaw, but also as a support for SiC tiles to match its low CTE (see Table 1 and Fig 3).

The final choice between the two options will require a trade-off between RF performances, cleaning efficiency, geometrical stability, radiation hardness and robustness requirements. More inputs will come from LHC operation and possibly from future Phase II prototypes.

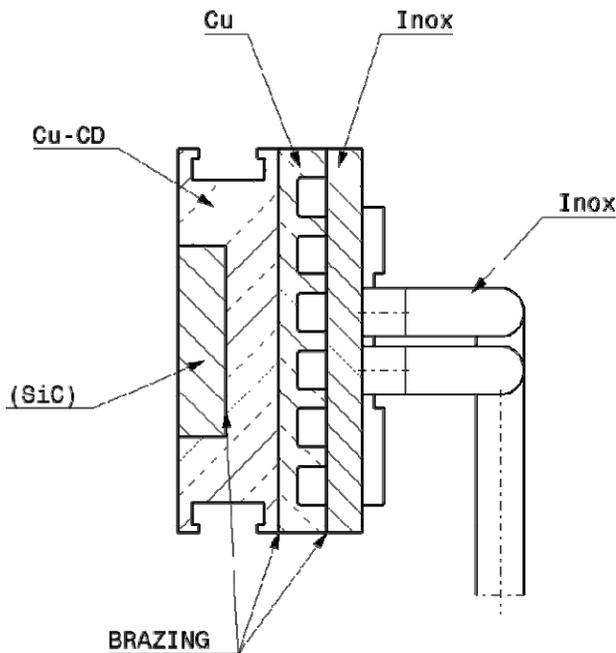


Figure 3: Phase II jaw assembly. The cooling system is brazed to the jaw. Two possible solutions: Cu-CD jaw and Cu-CD jaw with SiC inserts (both conductive and non-conductive options can be implemented).

Table 1: Material Properties

Material	Density [kg/m ³]	K [W/mK]	CTE [K ⁻¹]	ρ [$\Omega\cdot\text{m}$]
OFE-Cu	8900	395	$17\cdot 10^{-6}$	$17\cdot 10^{-9}$
Cu-CD	5500	500÷600	$6\div 7\cdot 10^{-6}$	$90\cdot 10^{-9}$
SiC	3200	250	$3.5\div 5\cdot 10^{-6}$	$10^0\div 10^2$
C/C	1650	60	$1.5\cdot 10^{-6}$	$7\cdot 10^{-6}$

CONCLUSIONS

To overcome the limits of Phase I collimation system, new Phase II secondary collimators are being developed. Given the extremely challenging and sometimes conflicting requirements, research of new advanced materials is complemented by an innovative design of the jaw assembly. A modular solution, allowing to use different jaw materials with a common supporting structure, is briefly introduced.

Material selection and ranking was carried out through the identification of relevant figures of merit. Moreover, the combined approach of material and design optimization allowed the identification of best candidates for each component of the jaw assembly: Mo for the back-stiffener, OFE-Cu and stainless steel for the cooler.

Two main options are presented for the jaw: copper-diamond and silicon carbide. Important inputs will come from LHC operation and possibly from future Phase II prototypes so to come to a final choice. The challenges posed by the development, experimental characterization and industrialization of these advanced materials are tackled in a collaboration involving academic and industrial partners in the framework of the FP7 European research program.

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