TOWARDS DESIGN OF THE PHASE II COLLIMATORS FOR LHC


Abstract

For the LHC to reach its nominal and ultimate performances, it is foreseen that the Phase I collimation system, installed for the initial low luminosity runs, be complemented by new upgraded collimators (Phase II). These units are due to overcome the predicted limitations of phase I collimators, in particular their high RF impedance and low cleaning efficiency, theoretically hindering the beam intensity. Draft specifications of Phase II collimators require a factor ten improvement on both aspects. To conceive a mechanical system able to attain these challenging goals, an ambitious R&D program, led by TS department, has been set up, involving practically all services within MME group and focussing on the identification of novel materials and innovative design concepts. The organization and program of the TS working group, the status of research on promising materials and the preliminary design orientations and technologies will be discussed.
1 INTRODUCTION

Given the unprecedented energy and intensity handled by the LHC, 2 to 3 orders of magnitude higher than present state of the art [1], the design of its collimation system is particularly challenging. Taking into account the very tight development time within LHC schedule (the preliminary design phase started in summer 2003), it was decided from the very beginning to split its commissioning in several phases: phase I was mainly aiming at high robustness, at the cost of lower efficiency, while Phase II was to ensure the attainment of the LHC nominal and ultimate performances.

As of today, it is foreseen that only Phase II secondary collimators (TCSM) be built: all other collimators of the phase I system should remain in place also for Phase II. In detail, Phase I secondary collimators (TCSG) would be active during the injection and the fill-in phases of the LHC operation; once the nominal intensity is attained, the beam is stabilized and the energy starts to ramp, the TCSG jaws would be driven back and the TCSM jaws would be moved in to reach nominal and ultimate performances of the machine. However, it is not excluded that other elements of the Phase I system be replaced (e.g. Primary collimators) if this is required.

2 LIMITS OF PHASE I COLLIMATION SYSTEM

Phase I collimators were designed with very challenging specifications, among others good cleaning efficiency, minimized RF impedance, accurate dimensional stability and high robustness against nominal and accidental beam losses. When the study was launched in 2003 it became immediately evident that only low-atomic number (low-Z) materials were able to survive the destructive effects of several full LHC particle bunches at injection (450 GeV) and nominal energies (7 TeV). This imposed the choice for the collimating jaw of low-Z Carbon-based materials like graphite and Carbon/Carbon composites. Phase I collimators proved their ability to fully withstand these accident scenarios in several dedicated tests on real prototypes.

However, the choice of carbon as jaw material inherently implied several limitations on RF impedance, efficiency and possibly radiation hardness. Studies of transverse impedance have shown that the phase I collimation system would generate a beam tune-shift that the Landau Octupoles is not able to handle (figure 2): this would finally lead to beam instability. Calculations show that the LHC beam can be stabilized by Landau damping only up to 30-40% of the nominal intensity (with 25 ns bunch spacing) [2].

![Image](image.png)

Figure 1: RF stability diagram for the Phase I at top energy showing the effect of Phase I collimators at various jaw apertures (gap).
One of the key functions of the collimation system is to prevent high energy particles escaping their nominal orbit (beam losses) from hitting highly sensible equipment, in particular Superconducting Magnets, which quench at very low energy depositions. The parameter governing this phenomenon is Cleaning Inefficiency $\eta$, given by the number of particles escaping the collimators divided by the number of particles stopped by the collimators: for a nominal intensity beam at 7 TeV only two particles out of 100000 are allowed to escape.

The choice of a low-Z material implies that the cleaning efficiency cannot be as low as for high-Z materials, like most metals and Copper in particular: efficiency studies predict that the phase I collimation system allows the safe operation of the LCH up to a beam intensity of 37% in ideal conditions [3].

Another potential weakness of phase I collimators could be the radiation hardness of the Carbon / Carbon composite: tests carried out show an erosion of Carbon fibres when irradiated by high energy heavy particles (Carbon ions) (figure 2) [4]; other studies carried out with proton irradiation at high fluences show a strong reduction of thermal conductivity of Carbon-based materials (a factor 3 to 6 for 0.2 dpa damage) [5], with potential severe effects on maximum temperature and geometrical stabilities of the collimator jaw. Studies allowing to scale these test results to the LHC collimators actual irradiation conditions are still ongoing.

3 PRELIMINARY SPECIFICATION FOR THE PHASE II COLLIMATORS

An official functional specification has not been released yet, among other reasons, because of the high number of unknowns the LHC machine protection system will face.

However, in order to meet the challenging goals of the LHC collimation system in nominal and ultimate conditions, preliminary requirements demand an increase of a factor 10 in efficiency and a reduction of a similar amount in RF impedance.

4 PROJECT ORGANIZATION

Given the complexity of the project and the challenge posed by its objectives, the Project management has proposed to face the study of Phase II from different perspectives and with alternative approaches, in the framework of an international collaboration. Several laboratories and universities in Europe (also through European research program FP7) and the U.S. are involved in dedicated studies, for instance on material characterization and on the effects of radiation exposure. California-based Stanford laboratory (SLAC), within the scope of US-LARP collaboration, is to design and manufacture a collimator prototypes based on the principle of rotatable jaws: the idea is to have a Copper-based jaw which can be turned in case of permanent damage to the collimating surface. At CERN alternative concepts, with respect to the one being developed by SLAC, shall be studied: the responsibility for research and development, mechanical and material engineering, material and technology testing, integrated design, prototype drawings, prototype manufacturing and qualification has been assigned to TS-MME. Ideally, two different concepts should be initially evaluated: out of these one would be chosen for manufacturing.

To face such a complex project, a multidisciplinary team has been set up within TS-MME, covering aspects linked to design, mechanical engineering, material science, vacuum technologies, surface coatings, metrology, assembling techniques, machining etc. Design meetings are held every two weeks, involving experts in RF field, particle tracking, energy deposition etc. A dedicated task force is working on the critical issue of identification of a suitable material for the collimator jaw. At the same time, a review of Phase I design is ongoing so to identify potential weaknesses in present collimators profiting from past experience to enhance Phase II design.
5 PRELIMINARY DESIGN STATUS

Preliminary studies on the Phase II collimators started in January 2008 and were oriented on two main axes: investigation of potential materials for the collimator jaw and novel design concepts for the jaw assembly. Jaw material should be ideally able to improve electrical conductivity, cleaning efficiency and radiation hardness with respect to phase I; at the same time the excellent robustness against accident scenarios of phase I jaw should be as much as possible conserved. It is evident that these requirements are intrinsically conflicting, as good cleaning efficiency pushes towards high-Z materials whereas strong robustness requires low-Z materials. New design concepts of the jaw assembly should ensure the geometrical stability, the thermal efficiency and the accuracy which is required for the collimator to work effectively.

5.1 Jaw material R&D

As said above, the ideal material should have a set of properties which are to a large extent mutually incompatible. However, to try to identify those candidates seeming to approach most this “magic” material, a large R&D effort has been launched. First, a series of figures of merit has been identified to give a numerical assessment of the critical parameters and class materials; most relevant are: electrical conductivity $\gamma [\Omega^{-1}m^{-1}]$, which is related to RF impedance; geometrical stability parameter $k_1 [W/m]$, giving an indication of the thermal power required to induce a given jaw deflection in steady-state; thermal shock parameter $k_2 [J/kg]$, providing an assessment of the highest energy per unit mass that can be deposited by the beam before damage occurs; mass density $\rho [kg/m^3]$ related to cleaning efficiency. These figures of merit were then used to pinpoint most interesting materials. In Figure 2, $k_1$ is plotted versus $k_2$ for various materials: best materials are those sitting in the upper right corner of the plot. It is clearly shown that ceramics and refractory materials like graphite possess a clear lead over most metals when it comes to thermal shock resistance and geometrical stability.

Unfortunately, ceramics electrically insulating properties are hardly compatible with the required RF stability, since low electric conductivity would increase the imaginary part of transverse impedance $Im(Z_t)$ and make Landau damping even more difficult ($Im(Z_t)$ is related to the real part of the tune shift – high $Im(Z_t)$ leads to high $Re(DQ)$ which is more difficult to damp – see figure 1). However, a different approach to RF stability may allow reconsidering these materials; in fact, if,
instead of the classical Landau octupoles, one relies on the transverse feedback to stabilize the beam, fairly high $\text{Im}(Z_t)$ would be acceptable [6] and, on top of this, one may count on the lower $\text{Re}(Z_t)$ which can be obtained with higher resistivities, specially in the range 1-10 $\Omega\text{m}$. Even higher resistivities can be considered, but, in this case, problems due to accumulation of electrostatic charges (possibility of breakdown) and influence of imperfect dielectric properties (lossy dielectric) may appear. A material to be considered for its resistivity in the range 1 to 10 $\Omega\text{m}$, although not the best in class for thermal shock resistance, is Silicon Carbide: in this case, as electric continuity is not an issue, a series of relatively thin (~5 mm) tiles would be brazed on a metal support acting as electrical conductor.

It is also worth to note the interesting properties of Diamond-based metal composites which were initially developed for thermal management problems in the semiconductor industry and are obtained from infiltration of liquid metals (typically copper or aluminium) in a mould where fine diamond particles (~100 $\mu\text{m}$) are present [7]. These materials exhibit a low coefficient of thermal expansion (CTE) while keeping a large amount of the electrical properties of their matrix; they also have higher densities than ceramics making them very interesting candidates for metallic jaws. An R&D program to study their applicability to Phase II jaws and the possibility to embed cooling pipes directly in the moulding phase is currently under way.

5.2 Design Concepts

Figure 2 clearly shows that, so far, no new material can attain the excellent thermal shock resistance of carbon materials; at the same time the expected improvement in geometrical stability is not outstanding: this clearly indicates that to meet Phase II requirements one has to count as well on innovative design concepts. When it comes to geometrical stability, a first approach would be trying to reduce the free deformation length of the jaw, as maximum jaw deflection goes with more than the square of this length. On this basis and bearing in mind that heat deposition mainly affects components close to the beam, the concept of back stiffener was proposed: a rigid stiffener is placed behind the jaw (with respect to the beam), on the assumption that this support element does not deform as it is weakly heated and is stiff enough to keep the jaw straight. To enhance geometrical stability an additional link is created at mid-span between the jaw and the stiffener; this link is obtained via a fine-tuning screw allowing to adjust jaw flatness once it is inserted into the collimator vessel. As opposed to phase I, in this concept the jaw should be as flexible as possible to minimize the load acting on the stiffener: to achieve this, the jaw cooler is “split” in two and two notches are added at the centre of the jaw.

![Figure 3: Schematic principle of the Phase II jaw assembly](image)

The material for the back stiffener was chosen to maximize the “Stabilization Parameter” which is given by the ratio $E_k/\alpha$, where $E$ is the Young’s modulus, $k$ is thermal conductivity and $\alpha$ is the CTE. A high stabilization parameter ensures that the stiffener is rigid to prevent the jaw from deforming and its bending due to non-uniform thermal expansion is small. For its high stabilization parameter molybdenum is currently being considered as candidate material.

One of the potential issues of phase I collimators is also the degree of accuracy in the knowledge of jaw location with respect to the actual beam position: to eliminate this uncertainty the possibility to insert Beam Position Monitors (BPM) pick-ups directly in the jaw is being considered.
CONCLUSIONS

According to simulations, the present (Phase I) collimation system might limit LHC intensity to 30-40% of its nominal value, because of high RF impedance and limited cleaning inefficiency. In order to attain the nominal and ultimate performances of the LHC, Phase I Secondary collimators (at least) must be complemented by new (Phase II) collimators. The demanding requirements for these components have called for a large R&D effort involving various international partners. TS-MME has been assigned the responsibility of the R&D, development, design, manufacturing and qualification of two prototypes, possibly based on alternative concepts, to be tested in the accelerator. A large effort, involving all services within the group, is ongoing aiming at the identification of novel materials and innovative concepts for the jaw assembly design. Among most interesting materials, Silicon Carbide ceramic and Diamond based metal (Cu or Al) composites were singled out. Promising design principles are also being investigated.

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