THE MECHANICAL DESIGN FOR THE LHC COLLIMATORS

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Abstract

The design of the LHC collimators must comply with the very demanding specifications resulting from the highly energetic beam handled in the LHC: these requirements impose a temperature on the collimating jaws not exceeding 50ºC in steady operations and an unparalleled overall geometrical stability of 25σm on a 1200 mm span. At the same time, the design phase must meet the challenging deadlines required by the general time schedule.

To respond to these tough and sometimes conflicting constraints, the chosen design appeals to a mixture of traditional and innovative technologies, largely drawing from LEP collimator experience. The specification imposes a low-Z material for the collimator jaws, directing the design towards graphite or such novel materials as 2-D or 3-D Carbon/Carbon composites. An accurate mechanical design has allowed to considerably reduce mechanical play and optimize geometrical stability. Finally, all mechanical studies were supported by in-depth thermo-mechanical analysis concerning temperature distribution, mechanical strength and cooling efficiency.

INTRODUCTION

In the early operation period of the LHC (phase 1), the collimation system baseline will be mainly formed by a 3-stage system including Primary (TCP), Secondary (TCS) and Tertiary (TCT) collimators; for each collimator type several geometrical configurations are foreseen (horizontal, vertical, skew) [1].

The design of these components must comply with the very demanding functional specification resulting from the highly energetic beam handled in the LHC rings.

These requirements represent a major challenge for the mechanical design, since, among other, they impose:

- High deposited heat loads
- Very accurate geometric precision and dimensional stability (*25 σm* over *1200 mm*)
- Limited maximum temperature (temperatures in excess of 50º C are accepted only on a very limited portion of the jaw)
- Robustness in nominal and accident scenarios.

At the same time, the design phase must meet the tough deadlines required by the general time schedule [2].

In addressing these severe constraints, it was decided to give the highest priority to the Secondary collimators (TCS) as they are the most critical ones from the mechanical point of view.

THE DESIGN CONCEPT

The present design (Figure 1) is the result of the analysis of a wide spectrum of options and alternatives [3]; the guiding principle has been the use and optimization of proven technologies, mainly based on LEP collimator experience [4]. However, due to the very demanding specification, it was also necessary to consider innovative technologies and novel materials, such as Carbon/Carbon composites. The main technical features of the LHC secondary collimator design are:

- An internal alignment system allowing both lateral displacement and angular adjustment of the jaw.
- A jaw clamping system ensuring good thermal conductance, free thermal expansion and limited deformations.
- An efficient internal cooling system.
- A precise actuation system driven by stepper motors, including a semi-automatic mechanical return and a misalignment prevention device.
- A plug-in external alignment system, allowing a quick and simple positioning of the collimator assembly in the LHC machine.

The feasibility of the technical concept has been widely verified during the manufacturing of three full-scale prototypes.

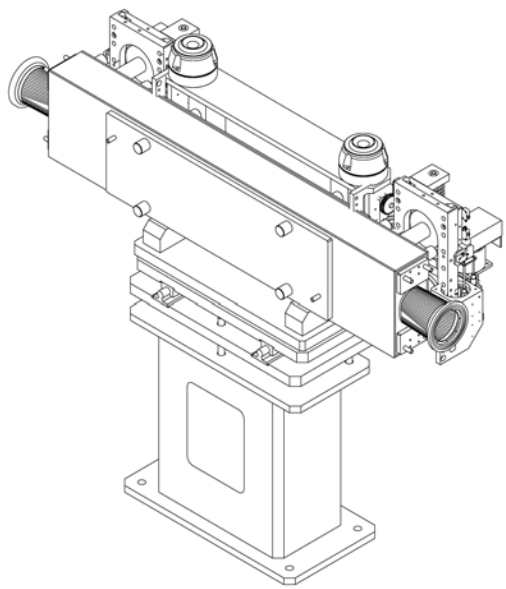

Figure 1: General layout of the LHC secondary collimator.

The jaw assembly design

As required by the functional specification, the collimating jaws must evacuate a high thermal power, maintaining low temperature and, at the same time, ensure

mechanical robustness and keep deformations under an extremely low limit. On top of that, the collimator induced electrical impedance must be kept to a minimum. To meet this requirement and ensure a sufficient mechanical robustness, only low-Z materials like graphite or carbon-carbon composites (C/C) could be used for the jaws [5].

The chosen design of the jaw assembly was based on the *clamping concept*: the graphite or C/C jaw is pressed against the copper-made heat exchanger by a Dispersion Strengthened Copper (Glidcop®) bar on which a series of steel springs is acting. The jaw assembly is held together by Glidcop® plates (Figure 2).

Since the thermal expansion coefficient of copper is about three times larger than that of graphite, a fixed joint between the jaw and the copper plate is not possible; the contact must allow for relative slipping between the two surfaces. At the same time, to ensure proper heat conduction at the contact interface, a certain pressure has to be applied between these surfaces. The pressure was estimated through a semi-analytical model [6] and set to 5 bars. To validate the concept, an experimental campaign has been set up: results show very good agreement with analytical and numerical calculations [7].

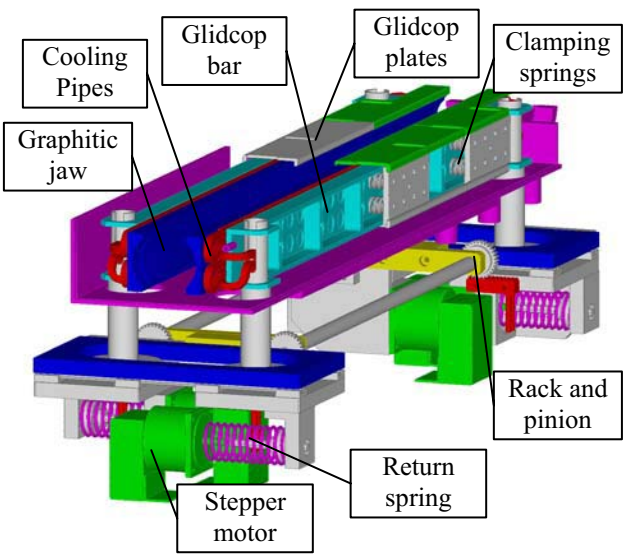

Figure 2: Horizontal secondary collimator components including motorization and actuation system.

The jaw cooling system

Each jaw is cooled by the water of the general cooling circuit of LHC sectors 3 and 7. The heat exchanger is constituted by two OFE-copper pipes per jaw brazed on one side to a copper plate and on the other to the Glidcop® bar. Each pipe has three turns to increase the heat exchange capability. To ease the brazing and avoid harmful air traps, the pipe section is squared. The inner diameter of the pipes is 6 mm. The water flow rate is 5 l/min per pipe, leading to a flow velocity of ~3 m/s: indeed, this value is rather high and might lead to erosion-corrosion problems on the soft copper pipe bends; however it is necessary to ensure the evacuation of the high heat loads (up to 32 kW) while minimizing the temperature gradients. Inlet water temperature is 27º C. This system has been conceived also to limit the thermally induced deformations; the heat sink is sandwiched between the jaw and the bar, having opposed temperature gradients: this is exploited to mutually compensate the natural thermal deformations of the bar and the jaw and so to restrain the overall deflection. A simplified model to predict thermally induced deflections has been developed.

The actuation system

Each jaw is independently actuated by two stepper-motors (Figure 2). This allows both lateral displacement and angular adjustment. Excessive tilt of the jaw is prevented by a rack and pinion system which avoids relative deviation larger than *3 mm* (i.e. *3 mrad*) between the two axles. Vacuum tightness is guaranteed by four bellows which can be bent sideways. The system is preloaded by return springs to make it play-free. The return springs also ensure a semi-automatic back-driving of the jaw in case of motor failure. The position control is guaranteed by the motor encoder and by four linear position sensors. Stops and anti-collision devices for jaw motion are also foreseen.

THERMO-MECHANICAL CALCULATIONS

Thermal and mechanical calculations of the collimators were carried out from the early stages of the project to direct and validate the design choices, making use both of analytical models and Finite Element coupled-field analyses. Several ANSYS® FE models were studied (2-D, partial 3-D and full-scale 3-D) (Figure 3), with various materials for jaws, heat exchanger and support bar (C/C, graphite, steel, OFE-copper, Glidcop®), considering temperature-dependent material properties. Input thermal loads were directly drawn from particle physics simulations (FLUKA code) for several scenarios: nominal operating conditions, peak beam loss and the accident cases, as defined in the load specification [1].

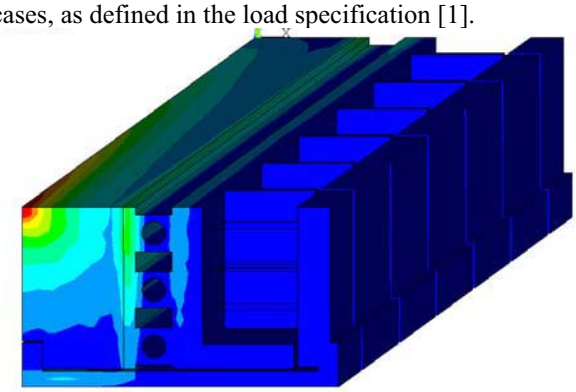

Figure 3: The FE 3-D coupled-field model showing the thermal load (from FLUKA simulations).

The definition of boundary conditions took into account both the contact interface between the jaw and the heat

exchanger as well as the heat convection on the wet surface of the pipes. The thermal conductance at the contact interface was introduced in the FE model as a function of the local contact pressure. The convection (film) coefficient was analytically calculated as a function of the friction coefficient and of water temperature, leading, with a water flow of 5 l/min at 27º C, to a film coefficient of 12360 W/m2K on each pipe.

Thermal calculations show that, in nominal conditions, maximum jaw temperature exceeds 50ºC on a very limited area (Figure 4) and only for certain graphite grades, while temperatures up to 76ºC are reached during the 10 s peak loss transient.

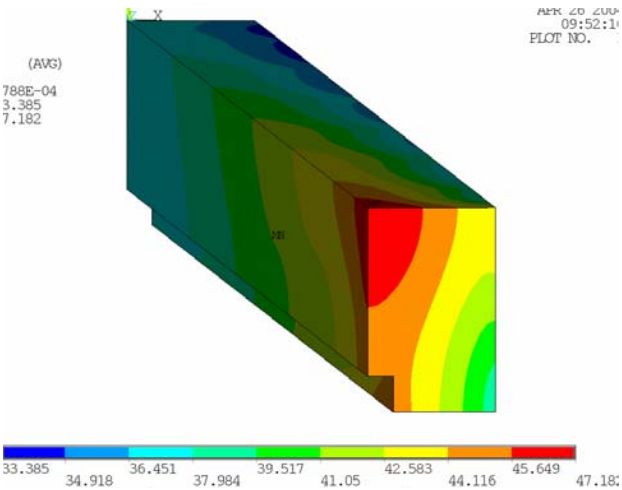

Figure 4: Thermal distribution over the 2-D C/C jaw in nominal conditions (8e10 p/s at 7TeV).

Required geometrical stability is very difficult to attain under the given heat loads: results obtained from the FE full-scale model indicate that the 25σm requirement might be attained in nominal conditions for the "softer" materials (i.e. Graphite and 2-D C/C) but not by the "stiffer" 3-D C/C.

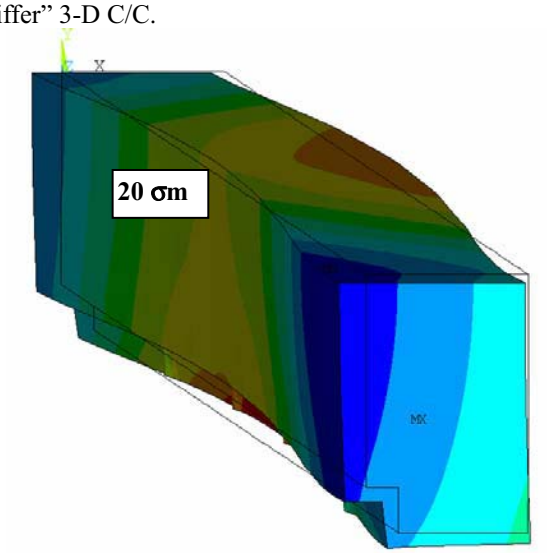

Figure 5: Deformation under thermal load of the 2-D C/C jaw in nominal conditions.

Finally, stress analysis show that quasi-static stresses do not pose a serious problem, while dynamic stresses excited by the accident case thermal shock might reach quite high values though not exceeding the material allowable strength. More detailed analyses are foreseen on this specific issue. Furthermore, thorough investigations are on their way to measure the properties of the graphitic materials, on account of the limited level of confidence in the scarce available data.

CONCLUSIONS

LHC collimator functional specification poses a serious challenge to the mechanical design of these components. The main features and characteristics of the technical concept addressing these requirements were presented, along with an outline of the thermo-mechanical calculations which led to the present layout.

Though the design is mainly "traditional" and based on previous experiences, a thorough optimization activity, along with in-depth calculations, has been performed to maximize performances and dimensional stability. When known technologies and traditional materials were not suitable, new solutions have been explored (clamping technology for the joint between the jaw and the heat exchanger and Carbon/Carbon composites for the jaw). The technical feasibility of these technologies has been tested during the manufacturing of three full-scale prototypes.

As a whole, at the present stage of development, calculation results and first preliminary tests show that the Functional Specification might be closely approached for the given heat loads provided the material properties are accurate enough.

Of course, these preliminary conclusions will have to be confirmed in the near future by additional analyses of the definitive design with measured material properties and by further results of the ongoing tests.

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