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PRELIMINARY DESIGN OF THE HIGH-LUMINOSITY LHC BEAM SCREEN WITH SHIELDING*

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Abstract

A new beam screen is needed in the High-Luminosity LHC (HL-LHC) final focusing magnets. Such an essential vacuum component, while operating in the range 40-60 K, has to ensure the vacuum performance and to prevent the beam-induced heating from reaching the cold bore which is at 1.9 K. In addition, it has to shield the cold mass from physics debris coming from the nearby beam collision points. To such purpose, energy absorbers made of tungsten alloy are installed onto the beam screen in the vacuum system. In this contribution, the proposed mechanical design is shown; it covers different thermomechanical aspects such as the behaviour during a magnet quench and the heat transfer from the tungsten absorbers to the cooling tubes. Assembly and manufacturing tolerances are also considered to evaluate the impact on the aperture. Results obtained with a short prototype assembly test are discussed.

INTRODUCTION

The beam screen is a complex object with a variety of functions [1]. HL-LHC beam screens are to be inserted into the separation dipole (D1) and the inner triplet (IT) quadrupoles (Q1 to Q3) of the LHC long straight sections 1 and 5. The main purpose is to intercept the beam induced heat load before it reaches the cold mass. It has also to shield the cold bore inner surface from direct particle impingement, which would lead to important outgassing while assuring high effective pumping speed on the cold bore toward pumping slots to fulfil vacuum requirements. It is equipped with shielding made of tungsten alloy to absorb the particle debris generated in the collision points [2].

The beam screen with shielding has to withstand the Lorentz' forces induced by eddy currents during a quench. The temperature of the beam screen must be actively controlled in a given temperature range: 40-60 K, where vacuum stability is guaranteed [1]. The system must be compatible with the global LHC impedance and with the machine aperture.

DESIGN OF THE BEAM SCREEN WITH SHIELDING

Preliminary design relied on the soldering of the absorbers made of tungsten alloy (Inermet® 180) on the beam screen shell [3]. This concept raises few critical aspects:

- Feasibility: how to accommodate the large differential thermal contraction between the tungsten alloy (around 0.09% at 50 K) and the beam screen shell in stainless steel (around 0.29 % at 50 K).
- Manufacturing: the brazing has to be done under vacuum and requires therefore a long furnace. The risk to have a bad brazing of one element is not negligible and would lead to the reject of the whole beam screen.
- Assembly: The tolerances obtained after brazing are not well managed. In addition, the beam screen obtained after the brazing of the tungsten alloy blocks would be very stiff and difficult to insert into the cold bore. This would require large assembly tolerances.

A concept based on a mechanical assembly of the tungsten absorbers is proposed here (Fig. 1). As for the standard LHC beam screen, the shell is perforated with oblong holes to provide sufficient pumping speed of the desorbed gas. The cooling is provided by four tubes, whose diameter depends on the type of magnet (external diameter of 16 mm and 10 mm for the Q1 and Q2-D1, respectively). The tungsten blocks are positioned on the beam screen by pins, welded onto the shell. Dedicated slots are used on one side of the block to allow differential thermal contraction; an overlap is used to reduce the number of pins. Elastic rings, in titanium grade 5, block the tungsten shields onto the beam screen. Copper strips are installed between the absorbers and the cooling tubes to assure a good heat transfer.

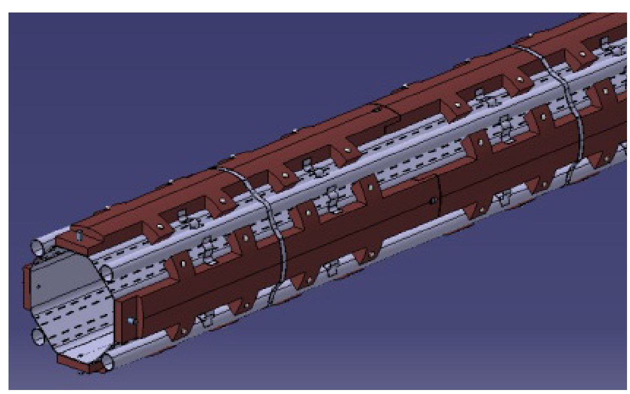

Figure 1: New beam screen design.

THERMAL MECHANICAL BEHAVIOR OF THE BEAM SCREEN

Self-weight Deformation

The weight of the tungsten absorbers is rather high (53 kg/m for the Q1 beam screen). The self-weight deformation has been assessed. The vertical deformation

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is around 0.2 mm (Fig. 2) and the stress in the beam screen wall is around 15 MPa.

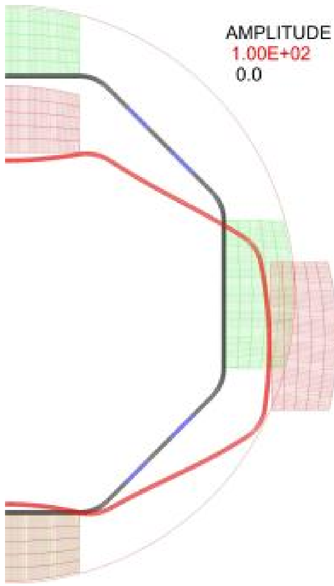

Figure 2: Self-weight deformation (amplification 100).

Mechanical Behaviour during a Quench

The fast decay of the magnetic field leads to the development of Foucault' currents that induce Lorentz' forces, especially in high electrical conductivity material such as copper. For a quadrupole magnetic field, characterised by a magnetic gradient G, the specific Lorentz' forces 'f' for long and symmetrical geometries are given by Eq. 1:

$$f \propto \frac{G.\dot{G}.r^3}{\rho} \quad (1)$$

ρ denotes the electrical resistivity and r the radial coordinate. The behaviour of the assembly is driven by the 80 µm thick copper layer and the tungsten alloy absorbers; their electrical resistivities have been assumed to be $1.9.10^{-10}$ Ω.m and 3.10^{-8} Ω.m [4], respectively. The value for the Inermet has been measured at 50 K. The analysis doesn't take into account the magneto-resistance and is therefore conservative. The specific resultants of the Lorentz' forces, per quadrant, are around 230 N/mm and 310 N/mm for the copper layer and tungsten absorbers, respectively. The beam screen assembly has been designed to be rather elastic and therefore the tungsten absorbers go in contact with the 4 mm thick cold bore, which can withstand the high magnetic forces during the magnet quench (Fig. 3). The contact force between the tungsten and the cold bore is around 370 N/mm. The maximum Von Mises stress in the cold bore is around 650 MPa which is below the yield strength (860 MPa). The maximum stress in the beam screen wall is around 840 MPa, whereas the yield stress is around 1150 MPa [5]. This value is driven by the initial gap between the tungsten and the cold bore. It has therefore to be carefully controlled.

Figure 3: Deformation of the beam screen during a magnet quench.

Thermal Behaviour of the Beam Screen

The expected heat load on the absorbers is 20 W/m (for the whole beam screen). The thermal power has to be efficiently transferred to the cooling circuit to control the beam screen temperature and avoid hot spots in the system. The heat transfer is assured by thermal links made of copper installed between the tungsten absorbers and the cooling tubes. Presently, 4 thermal links, 20 mm wide and 0.5 mm thick, are considered per blocks. A helium flow rate of 1g/s per cooling tube is considered. The inlet helium temperature is 40 K. The heat transfer coefficient by convection between helium and the cooling tube has been evaluated with different empirical formulas (Colburn, Dittus-Boelter, Petukhov) and finally assumed to 150 $W.K^{-1}.m^{-2}$. For the thermal links, the thermal conductivity of the copper is temperature dependent; the value at 50 K is 800 $W.K^{-1}.m^{-1}$.

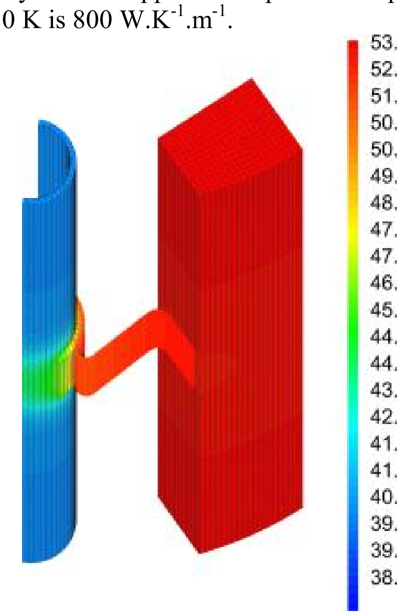

Figure 4: Temperature profile of the heat transfer from the tungsten absorber to the cooling tubes.

The temperature difference between the cooling cryogen and the tungsten blocs is around 13 K. The temperature gradient in helium, along the cooling tube, is

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0.5 K.m^{-1}. The number of thermal links or their width can be increased to improve the thermal performance (Fig. 5).

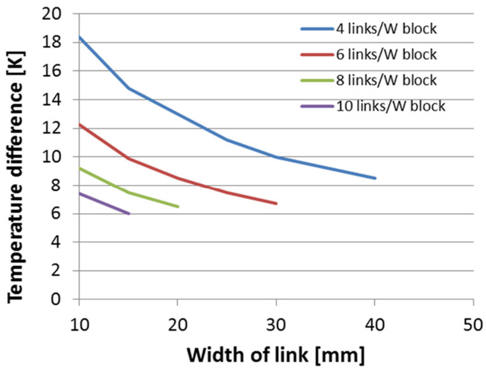

Figure 5: Influence of the number and width of the thermal links on the temperature difference between the cooling He gas and the W absorbers.

BEAM SCREEN ASSEMBLY AND TOLERANCES

The beam screen is supported elastically in the cold bore. Elastic spring in titanium and ceramic balls are used to minimize the heat loads to the cold mass. The expected specific stiffness of the supporting system is 750 N.mm^{-1}.m^{-1}. The cold bore inner diameter has to be precisely machined since this dimension drives the behaviour of the beam screen assembly during a quench. An inner diameter of 139 0/+0.1 mm and a straightness of 0.3 mm/m have been fixed (ϕ139H8 specified) and seems achievable. A short prototype, 1.2 m long has been manufactured and good results have been obtained. A first short beam screen prototype has been also manufactured for assembly and proof of concept purpose (Fig. 6).

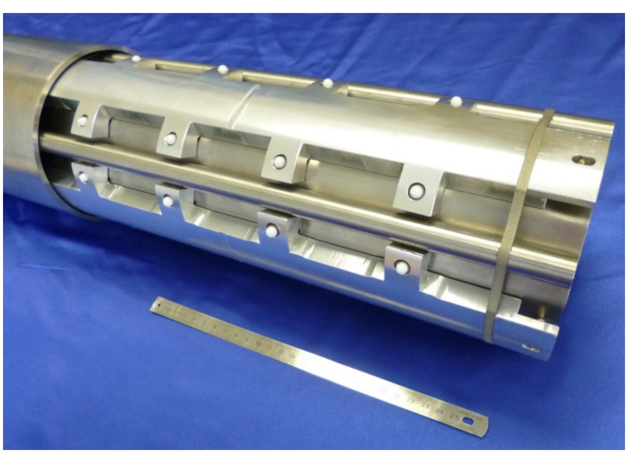

Figure 6: First beam screen prototype.

The beam screen tolerance will depend on the manufacturing process, and the number and position of welds. Investigations are ongoing to define the best manufacturing process taking into account impedance requirements as well. The shape and tolerances of the beam screen integrated into the cold bore have been studied for different initial shape and geometrical tolerance (Fig. 7). The cold bore is assumed to be clamped at its extremities and simply supported in the middle. It turns out that the overall behaviour of the assembly is driven by the cold bore imperfection and deformation. Therefore, the latter has to be carefully aligned into the cold mass. First results have indicated that a standard deviation of 0.5 mm of the beam screen axis position could be achieved.

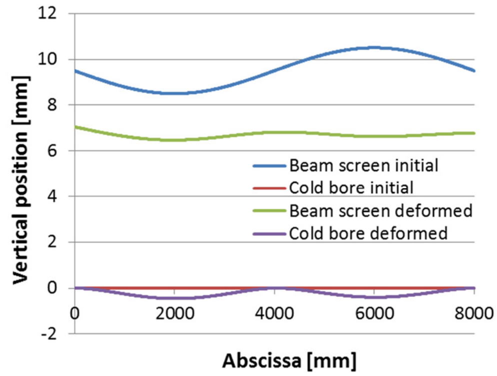

Figure 7: Deformation of the beam screen inserted into the cold bore.

CONCLUSION

The design of the HL-LHC beam screen with shielding is challenging. It has to integrate large absorbers in tungsten alloy in which high heat load is deposited. The concept of this design relies on a flexible solution on the contrary to a stiff assembly that would present several main drawbacks. The thermal and mechanical aspects have been considered for the design, in particular during a magnet quench. A first prototype with non-final materials is being assembled to prove the concept feasibility. Then, other prototypes with the correct materials and updated geometry will be manufactured and characterized. In addition, the vacuum pressure profiles in the final focusing triples are being estimated by Monte Carlo simulations [6] and amorphous carbon coating, an electron-cloud mitigation solution, is being qualified in an accelerator environment [7].

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