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Study on heat transfer between the High-Luminosity LHC beam screens and the He II-cooled beam tube

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Abstract. The new beam screens for the inner triplets in the HL-LHC are designed to intercept heat loads of up to 25 W m^{-1} between 60 K and 80 K. The screens need to be mechanically supported by the beam tube at 1.9 K while limiting heat transfer to the same tube to less than 0.5 W m^{-1}. Measurements for the thermal validation of the beam screens were carried out on a dedicated test stand at the Central Cryogenic Laboratory at CERN. This paper describes the first measurement campaign of a full-scale D1-type beam screen mock-up: several parameters such as base temperature and heating power were varied, and results include heat transfer mechanisms within the beam screen and more importantly to the 1.9 K beam tube that forms the physical boundary between beam screen and He II-cooled magnets.

1. Introduction

The High-Luminosity Large Hadron Collider (HL-LHC) project aims to increase the performance of the LHC, increasing its luminosity by a factor of 10 beyond the design value [1]. Important upgrades need to be put in place such as the installation of new superconducting magnets close to the interaction points of the experiments. These single-aperture magnets will feature new beam screens, which are inserted into the beam tube of the magnets with the objective of shielding them not only from electromagnetic radiation but also from collision debris. As such, the beam screens for the inner triplet magnets and D1 (pictured in figure 1) are substantially more complex than their predecessors and will need to withstand heat loads of 15 W m^{-1} (25 W m^{-1} for Q1) at temperatures between 60 K and 80 K. The thermal validation of the beam screens depends mainly on whether the heat load transferred to the 1.9 K helium bath that envelops the magnets around the screens is kept within pre-defined limits.

The beam screen features an electromagnetic screen surrounded by blocks of a tungsten-based alloy to shield the magnets from incoming radiation, which are in turn connected to cooling tubes via highly conductive thermal links. Mechanical support to the beam tube is achieved via several sets of 3D-printed titanium springs that hold a zirconium oxide sphere at the cold end; this sturdy yet thermally insulating support system is the only point of contact between the beam screens and the beam tube at 1.9 K. A more detailed description of the individual components that make up the beam screen can be found in [2].

The main thermal requirement for the D1 (and Q2, Q3)-type beam screen is that for the nominal heat load of 15 W m^{-1} the ΔT between the internal copper layer of the beam screen and the helium circulating in the cooling tube does not exceed 5 K [3]. The longitudinal temperature

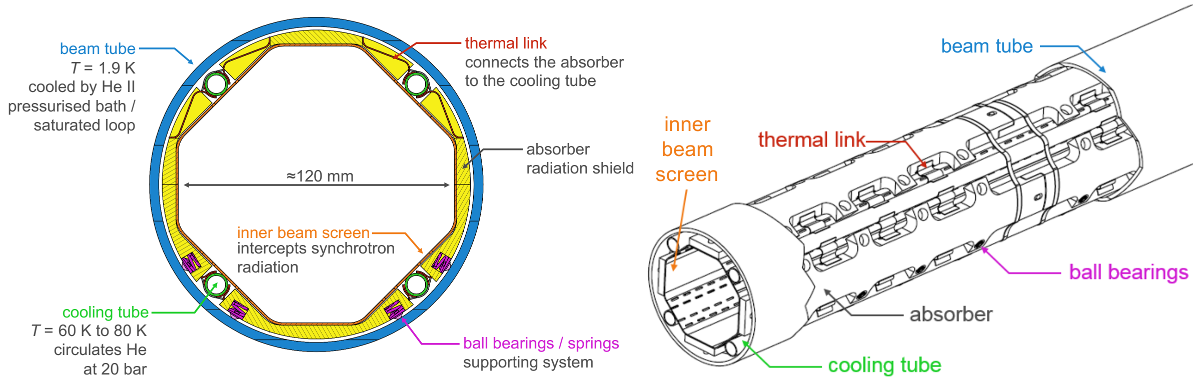

Figure 1. Cross-section and isometric views of the beam screen (D1) inserted into the beam tube, depicting the various components; adapted from [2].

gradient along the screen has been defined to be 0.25 K m^{-1}, adding up to a 15 K temperature difference along the 60 m of magnet string. This brings the operational range of the beam screen helium circuit to 55 K - 75 K and the inner beam screen range to 60 K - 80 K (taking into account the radial ΔT allowance of 5 K). These requirements result in a beam screen cooling circuit that will circulate supercritical helium gas at 20 bar and temperatures between 55 K-75 K, at a mass flow rate of 10 g s^{-1}-12 g s^{-1}. There is no limit imposed on the tungsten block temperature, although its temperature increase should be kept low to limit the heat transferred to the 1.9 K beam tube both by radiation and conduction; the total heat load to the beam tube should not exceed 0.5 W m^{-1}.

2. Thermal validation test stand

A dedicated test stand consisting of three major parts was designed for the thermal validation tests:

- The main horizontal cryostat that houses the beam screen mock-up;
- The beam screen flow conditioning circuit, responsible for the circulation and cooling of the supercritical He inside the beam screen cooling tubes;
- The He II tower, which comprises all the necessary components to create a He II saturated/He II pressurised system that emulates the cryogenic conditions of the LHC.

The horizontal cryostat is the main vacuum chamber, composed by a sliding frame that houses the beam screen/beam tube assembly and its supporting structure, which is in turn encased in two thermal shields. The warmer shield is actively cooled by LN_2 at around 100 K and the inner shield is cooled by the 2nd stage of a pulse-tube refrigerator (PTR) that varies between 6 K and 10 K. The whole test stand was designed in order to allow the mock-up to be tested in a horizontal orientation, since the weight of the beam screen on the supporting springs has an impact on the heat transfer to the beam tube.

The beam screen flow conditioning circuit is composed of a heat exchanger (HEX) attached to the 1st stage of the PTR and a cold circulator (cryofan), and the cooling tubes (see figure 2). The conditioned flow is split into four identical tubes on the beam screen, absorbing its heat load and increasing in temperature along its length, then re-collected into one single tube and circulated by the cryofan before it is re-cooled in the HEX.

The He II supply tower is depicted schematically in figure 2. The annular space in the double-walled beam tube is filled with pressurised He II (1.9 K and 1.1 bar) close to LHC conditions [4]. A heat exchanger (heatmeter) provides thermal contact but a physical barrier to a saturated

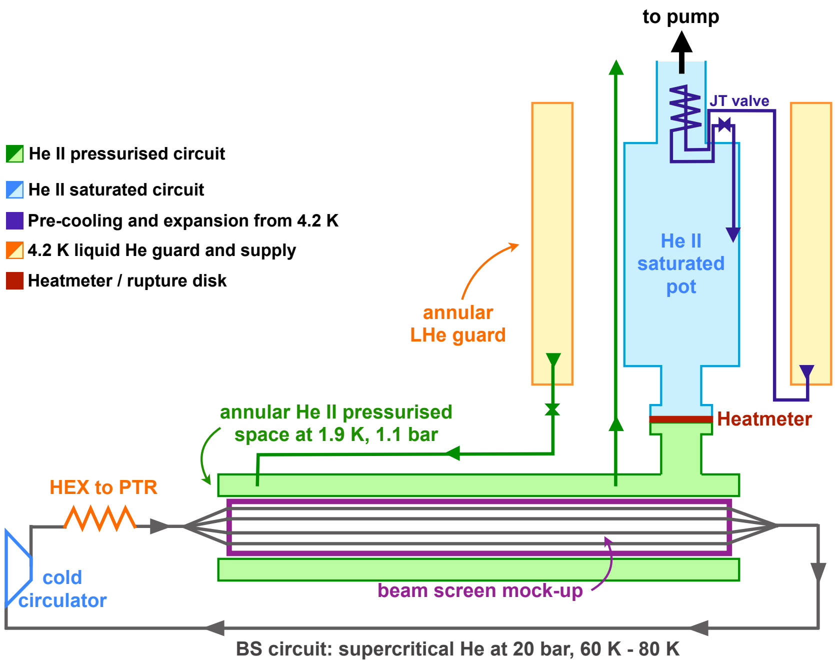

Figure 2. Cooling scheme of the beam tube emulating HL-LHC conditions and of the beam screen cooling circuit. The beam tube annular space is filled with He II at 1.9 K and 1.1 bar and conducts the incoming heat to the heatmeter; heat is absorbed by evaporation of the saturated He II that is constantly pumped and kept at a stable pressure.

He II bath whose temperature is controlled so that the pressurised side remains constant at 1.9 K. Incoming heat loads from the beam screen to the beam tube are conducted through the pressurised He II to the heatmeter, and heat extraction is achieved by evaporation of the saturated bath.

3. Results and discussion

The first measurement run consisted in a parametric study of a D1-type beam screen in which the base temperature was varied between 40 K and 80 K while the heat load applied on the tungsten blocks was varied between 0 and 20 W m^{-1}. Different heating options such as homogeneous vs. uneven heating, or step-wise changes from 0 W m^{-1} to 15 W m^{-1} were applied. The temperature distribution of the different components of the beam screen was measured, as was the heat load to the 1.9 K bath. For this run, the baseline configuration was chosen for the beam screen, using 32 of the available 64 sets of springs+spheres, which were positioned on the bottom-half of the screen to support it on the 0.8 m beam tube of the 1.9 K cold mass.

Figure 3 and figure 4 show the average beam screen temperatures as a function of heat load for different base temperatures. These are steady-state results where the heat loads were homogeneously distributed over the four quadrants, and the base temperature of the supercritical He circulation loop was varied by changing the temperature of the PTR. The pressurised He II bath was actively controlled at 1.900 ± 0.001 K.

The plot in figure 3 shows the temperature difference between the inner surface of the beam screen and the base temperature (*i.e.* helium gas) as a function of applied heat load for the base temperature range 40 K to 88 K. The ΔT was calculated as the difference between the highest temperature measured on the inner surface of the beam screen and the minimum temperature recorded on the cooling tubes; error bars are the combined standard deviation. For the investigated range, the temperature difference between the inner surface of the beam screen

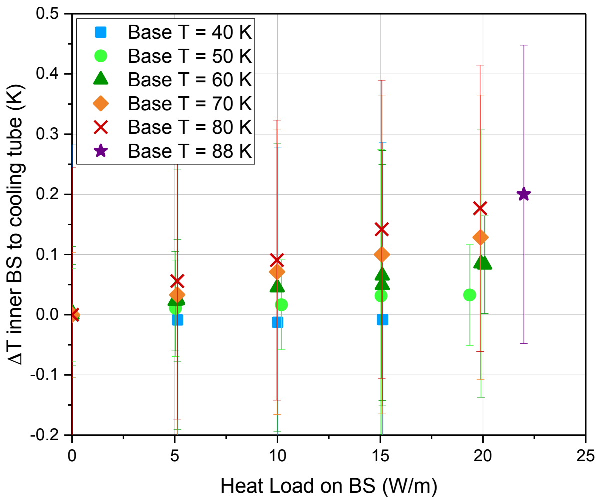

Figure 3. Temperature difference between the inner surface of the beam screen and the base (helium) temperature as a function of applied heat load for different base temperatures.

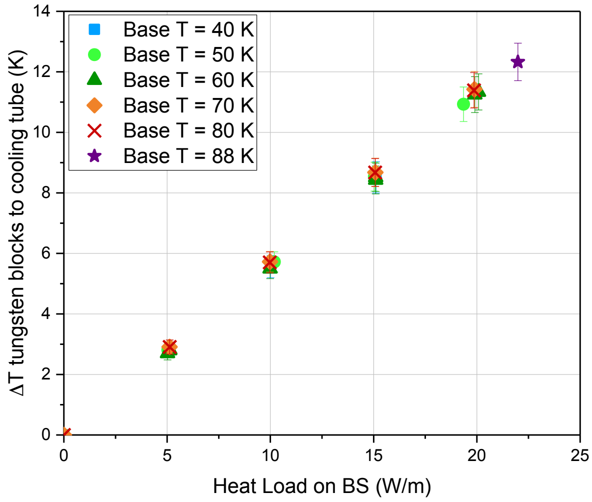

Figure 4. Temperature difference between the tungsten blocks and the base (helium) temperature as a function of applied heat load for different base temperatures.

and the circulating helium stays below 0.5 K, well within the maximum allowed temperature increase of 5 K. Although small, there is an increase of the temperature difference with increasing heat load as expected, more pronounced towards higher base temperatures.

Figure 4 shows the temperature difference between the heated tungsten blocks and the base temperature (*i.e.* helium gas) as a function of applied heat load for the base temperature range 40 K to 88 K. The ΔT was calculated as the difference between the mean tungsten block temperature and the mean cooling tube temperature; error bars are the combined standard deviation. The ΔT between the blocks and the cooling circuit increases linearly with increasing heat load, having a value of $\Delta T = 9\,\mathrm{K}$ at nominal heat load ($15\,\mathrm{W\,m^{-1}}$), which is reasonably low considering the amount of heat being deposited onto the blocks. Heat transfer from the tungsten blocks to the helium gas is independent of base temperature, even as the properties of constituent materials change. This was previously observed in measurements of small beam screen samples [2], and now verified in a full-scale mock-up: the material and contact thermal conductance between the tungsten blocks and the cooling circuit are of the same magnitude over the measured temperature range.

The heat load deposited onto the He II bath, which is cooling the beam tube, was determined by measuring the Kapitza resistance-induced ΔT across a thin metallic disc separating the two He II baths (labelled as "heatmeter" in figure 2), and then calibrating the set-up to work as a precise heat meter below T_λ; this technique was successfully used before in the Cryolab [5]. Figure 5 shows the heat load deposited on the beam tube by the beam screen as a function of tungsten block temperature, comprising several heat loads and base temperatures. The axis on the left-hand side shows the absolute measured heat load, *i.e.* including the static heat loads inherent to the cryostat; the right-hand side shows the heat load in HL-LHC conditions, *i.e.* without the static heat load offset. Considering nominal operating conditions, the temperature of the tungsten blocks should be between 60 K (minimum operating temperature) and 90 K (maximum base temperature of 80 K + 10 K increase due to $15\,\mathrm{W\,m^{-1}}$ heat load), the heat load transferred to the beam tube varies between $200\,\mathrm{mW\,m^{-1}}$ and $375\,\mathrm{mW\,m^{-1}}$, staying below the allowed $500\,\mathrm{mW\,m^{-1}}$. The lines in figure 5 show a model that considers radiation and conduction heat transfer; previous measurements of springs+sphere conductance as a function of temperature were used [2]. For nominal operating conditions, *i.e.* for the 60 K to 90 K range,

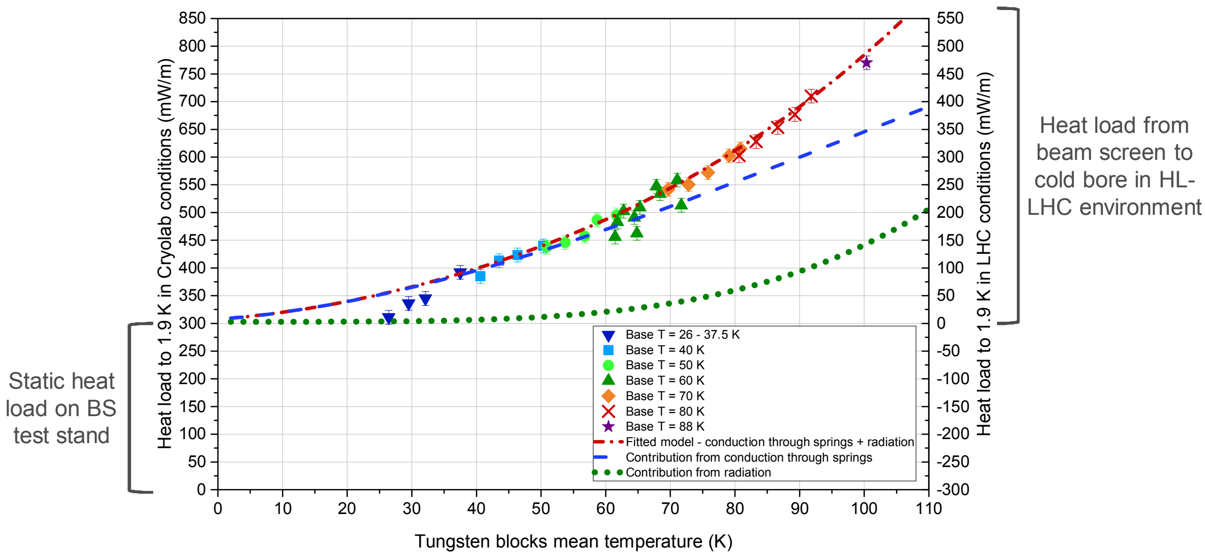

Figure 5. Total heat load transferred from the beam screen to the beam tube at 1.9 K as a function of tungsten block temperature. Symbols are experimental data points, lines a model that considers both radiation and solid conduction (including interface resistance).

the dominating heat transfer mechanism is the solid conduction through the springs and spheres that make up the mechanical supports. If the decision is made to use all of the available 64 springs to support and align the beam screen, the allowed heat load will likely be exceeded. Even if the top springs are subjected to lower forces (and as such should contribute less to the total heat load), they will increase the force on the bottom ones, further increasing heat transfer.

4. Final remarks

A fully operational test stand dedicated to the thermal validation of the new HL-LHC inner triplets beam screens has been designed, commissioned and put through its first measurement run. A full-scale mock-up of a D1-type beam screen was tested under nominal operating conditions with the baseline number of mechanical spring supports (32). First results show a maximum temperature rise on the inner beam screen of 0.5 K with respect to base temperature for the measured range, a factor 10 lower than the maximum allowed ΔT. A temperature rise of 10 K, independent of base temperature, was recorded in the tungsten blocks for the nominal heat load. The heat load transferred to the 1.9 K bath ranges from 200 mW m^{-1} to 375 mW m^{-1} under nominal operating conditions (60 K to 90 K on the tungsten blocks), keeping it below the maximum value of 500 mW m^{-1}. Overall, the design of the D1-type beam screen has been validated from a thermal standpoint, having complied with all predetermined requirements.

References

[1] CERN 2018 The High-Luminosity LHC URL `https://home.cern/topics/high-luminosity-lhc`
[2] Borges de Sousa P, Morrone M, Hovenga N, Garion C, van Weelderen R, Koettig T and Bremer J 2017 *IOP Conference Series: Materials Science and Engineering* **278** 012053
[3] Kersevan R, Garion C and Kos N 2014 Preliminary Design of the HiLumi-LHC Triplet Area Beam Screen Tech. Rep. CERN-ACC-2014-0268
[4] Lebrun P and Tavian L 2014 453–476. 24 p comments: 24 pages, contribution to the CAS-CERN Accelerator School: Superconductivity for Accelerators, Erice, Italy, 24 April - 4 May 2013, edited by R. Bailey
[5] Bzaguet A A, Dufay L, Ferlin G, Losserand-Madoux R, Perin A, Vandoni G and Van Weelderen R 1999 A Facility for Accurate Heat Load and Mass Leak Measurements on Superfluid Helium Valves Tech. Rep. LHC-Project-Report-319. CERN-LHC-Project-Report-319 CERN Geneva