DESIGN OF THE THERMAL AND MAGNETIC SHIELDING FOR THE LHC HIGH LUMINOSITY CRAB-CAVITY UPGRADE

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Abstract

Before the High Luminosity (Hi-Lumi) upgrade of the Large Hadron Collider (LHC), two pairs of superconducting compact Crab Cavities are to be tested within separate cryomodules, on the Super Proton Synchrotron (SPS) at CERN in 2018 prior to Long Shutdown 2 [1]. Two novel side-loaded cryomodules, which allow ease of access for assembly, inspection and maintenance, have been developed for the prototype tests. The cryomodule shielding includes a thermal shield and double layer magnetic shield, consisting of a warm-outer shield, and two cold-inner shields (one per cavity). Various constraints and considerations have led to unique cold shielding, mounted inside the cavity helium vessels, resulting in several design challenges. The shielding adopts and utilises the module's side-loaded configuration, for continuity and accessibility, while satisfying tight spatial constraints and requirements to meet the functional specification. This paper outlines the design, analysis, manufacture and assembly of the Hi-Lumi SPS test cryomodule's thermal and magnetic shielding, which are critical to achieving the operational stability [2].

INTRODUCTION

The Double Quarter Wave (DQW) and RF Dipole (RFD) cavities, shown in fig. 1 below, are superconducting compact crab cavities for ultra-precise beam rotation, developed by Brookhaven National Laboratory and Old Dominion University respectively [1].

Figure 1: DQW (left) and RFD (right) prototype crab cavity models.

The cavities feature several ports for the input coupler and High Order Mode (HOM) absorbers, as well as tuner and helium vessel interfaces. A dummy beampipe has been included on SPS tests for compatibility with LHC. The RFD cavity also features stiffening ribs to reduce pressure sensitivity [3]. These features all impact the cold magnetic shield design which is assembled around the cavities.

Two of each cavity will be installed on the SPS ring within separate cryomodules for commission and cold testing prior to the Hi-Lumi LHC upgrade [1]. Figure 2 shows a model of the DQW cryomodule in section, the thermal and outer magnetic shields are represented blue and grey respectively, while the cold magnetic shields are shown within the cavity helium vessel. The image shows a number of cryomodule and cavity string systems which impact on the shield designs [4].

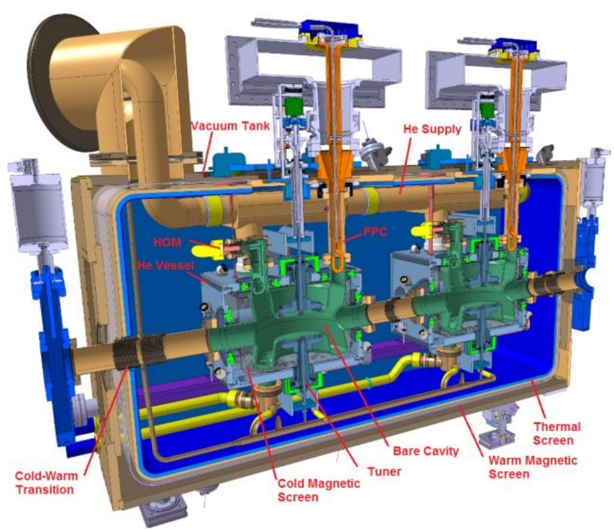

Figure 2: DQW cryomodule section.

The thermal shield serves as a radiative heat barrier and also recycles gaseous helium to intercept and thermalise critical components, such as the fundamental power coupler, ensuring minimal heat leak to the cavities, since there is limited cooling capacity at super-fluid helium level [4]. The design of the magnetic shielding prevents field of more than 1 μT reaching the niobium cavity surface as not to increase the surface resistivity through magnetic field trapping which would limit cavity performance [5].

MAGNETIC SHIELDING

A magnetic survey in the SPS area concluded that an external field of no more than 200 µT is to be expected during operation [6]. This estimate includes the earth's magnetic field and local sources, such as electrical busbars, which are to be individually isolated and shielded.

Initial OPERA analysis determined that a double layer magnetic shield is the preferred solution for ensuring minimal field at the cavity surface [7]. The double layer consists of a warm MuMetal outer shield and cold Cryophy inner shields. While it is just possible to achieve the required shielding factor with either one of the shield layers, it was determined that incorporating both cold and warm options would serve as the most effective and reliable shielding. Given the known discrepancies between simulation and operation, a solution which meets and exceeds the specification is desired for operating confidence.

A magnetic field analysis was performed using simplified shield models in OPERA 3D (Tosca). Basic geometries were substituted for greater element quality, as meshing proved to be difficult given the large aspect ratios of the thin walled shields. The same overall dimensions, penetrations and material properties were used for the Mu-metal and Cryophy layers, while non-magnetic components, not relevant to shielding performance, were omitted form the simulations.

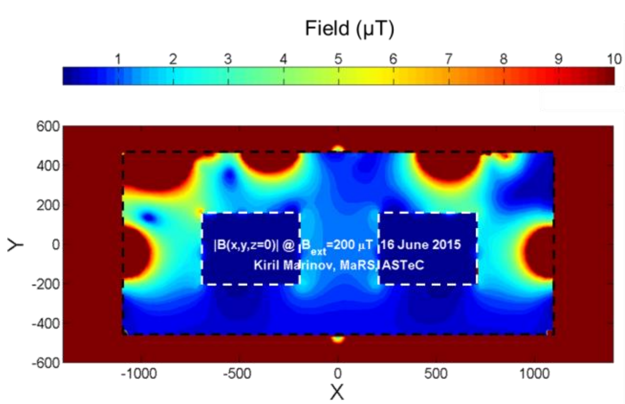

Figure 3: OPERA shielding analysis.

An external field of 200 µT was applied, in what was determined to be the worst case orientation, longitudinally to the shield (z direction). Figure 3 shows the simulations results, with the warm shield outlined in black, the cold shield outlined in white and areas within the magnetic field specification shown in blue. Since the Cavity is located within the cold shield it was concluded that the solution satisfies the shielding requirements with some allowance for additional penetrations or higher ambient fields. It should also be noted that these models do not include shield curvature and branch tube covers which enhance field containment and attenuation respectively.

Cold Magnetic Shield

After various design iterations of the cold shield and helium vessel it was decided that the shields are to be suspended within the 2 K liquid helium bath in order to reduce size and cost while enhancing performance, since shielding factor is inversely proportional to size (diameter). An internal shield also benefits from improving shield reliability as the helium vessel acts as a protective barrier to the shield, preventing any random damage during installation and testing which can reduce permeability [8]. Suspending the shield in the helium baths also ensures an optimal working temperature without the need for thermalisation. Other advantages include minimising the size and number of penetrations and having minimal impact on other dressed cavity systems.

The cold shields, shown in fig. 4, are assembled around the crab cavities and dummy beampipes. They are mounted internally to the helium vessel using thin Grade 2 Titanium brackets which eliminate the risk of thermal stresses damaging the shield on cool down. The shield panels and cover strips are manufactured from APERAM Cryophy; a nickel-iron soft magnetic alloy proven to provide greatest magnetic shielding at liquid helium temperatures for a given thickness [8].

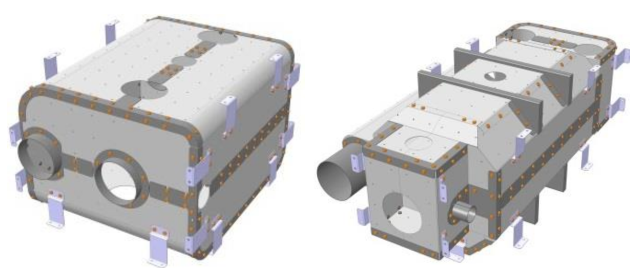

Figure 4: cold magnetic shields DQW (left) and RFD (right).

The shield designs are dictated largely by the complex cavity and helium vessel geometries; ports, thick walled plates and dummy beampipe creating strict spatial constraints and assembly procedure. Furthermore, it has been specified that the shield should not come in contact with the cavity and that a minimum layer of 3 mm liquid helium is required around the cavity for heat extraction [2]. To ensure a heat flow of at least 1 W/cm^2 the shields have been perforated with ø3 mm helium transfer holes. A design approach to minimise shield panels and maximise curvature was adopted for cost effectiveness, ease of assembly and to maximise the rigidity of the thin walled structures, in order to reduce self-weight deformation (sagging).

The shield parts are bent, folded, and tig welded, as required, before being preassembled and inspected, they are then heat treated in a pure dry hydrogen environment up to 1150°C for operation at liquid helium temperatures. The shield panels are to be pre-assembled with self-clinching nuts for connections. All fasteners are specified as non-magnetic Grade A4 Stainless Steel.

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Magnetic Shield Assembly

Since the shield is located inside and supported from thick walled helium vessel, the assembly procedure for both shield and tank must be carefully considered in parallel. Figure 5 shows some of the assembly stages for the cold DQW shield within the helium vessel. Firstly, the split bottom panels are assembled around the cavity then mounted to the helium vessel base plate. Thereafter, the remaining shield panels can be assembled around the cavity along with the connection parts and branch tube covers. Once the shield assembly is complete, the front, rear and top vessel plates can be assembled so that the remaining support brackets can be connected. The helium vessel assembly is completed as the side plates are added before the weld operations take place, making the vessel leak tight with seam welds and thin walled bolt hole cover plates.

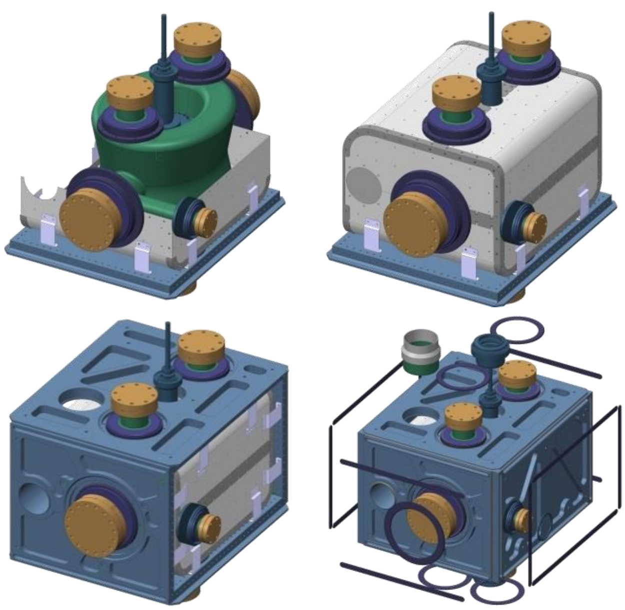

Figure 5: Assembly of DQW shield and helium vessel.

Cold Shield Mechanical Analysis

The magnetization of both shielding materials is adversely affected by high stresses above yield [8]. Hence degradation of the shielding material during assembly and handling should be carefully studied and monitored. Effects of self-weight and thermal contraction were modelled in finite element analysis solver ANSYS.

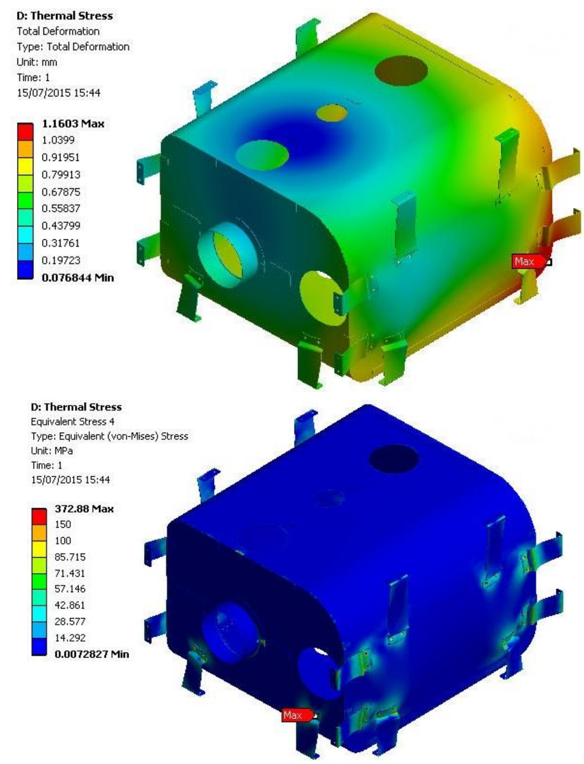

Figure 6: Thermal deformation (top) and stress (bottom) of DQW magnetic shield at 2 K.

The simulations shown in fig. 6 indicate that the maximum stress is 373 MPa in the support brackets, which is within the acceptable limits for Grade 2 Titanium at 2 K. The stress on the shield is minimal and well below the shield elastic limit of Cryophy (~280 MPa). The supports are designed to provide sufficient flexibility in order to eliminate any thermal stresses on the shield; at worst, stress zones are equivalent to a penetration in the affected area, as such it is vital that the difference in thermal contraction between the helium vessel and shield is compensated by the support brackets. The maximum stress in the supports is localised at the fastener connection and is likely to be lower since the model is somewhat over-constrained in the simulation as best practice for conservative results.

THERMAL SHIELD

Each cryomodule will be equipped with a thermal shield which acts as a radiative barrier as well as an intermediate cooling stage between the cold cavity and outer vacuum chamber in order to reduce the thermal load on the cavity helium vessels. The shield will be actively cooled using a series of tubes which also provide a structural skeleton. Thermalisation of cavity string components can be achieved using active or passive cooling from this screen. Intercepts are actively cooled using thermo-siphon technique. Passive cooling is achieved using thermal links such as copper laminated shunts between the beam pipe and the shield.

Initially the thermal shield and intercepts were to be cooled with liquid nitrogen due to the unavailability of cold helium gas at intermediate temperatures at SPS, however a new cryoplant is being installed which will overcome this limitation but requiring the shields to be reconfigured to work with gaseous helium. Despite the alteration in cooling fluid, the thermal analysis shown below is still accurate for design validation since the majority of thermal contraction occurs in the room temperature to liquid nitrogen range.

The shield panels and the tubes, shown in fig. 7, are fabricated from Aluminium Alloy 6061-T6 which has been selected for its high yield stress and increased weldability. The cooling tubes are welded directly to the shield through slots in the panels. By staggering the welds and orientating them longitudinally the tubes are allowed to flex during cool down, reducing stresses in the shield. The outside of the shield will be covered with 30 layers of cryogenic multi-layer insulation (MLI) in order to ensure a radiative barrier [9].

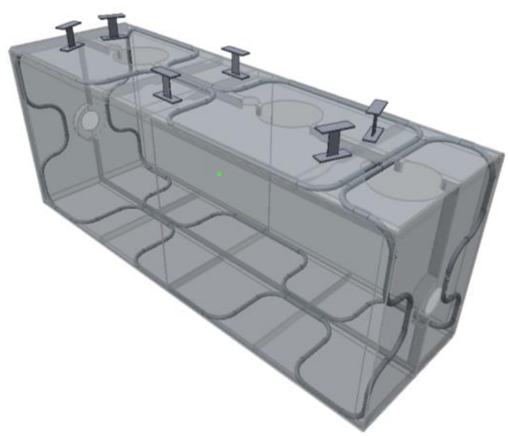

Figure 7: Assembled thermal shield.

The assembly is supported from six flexure mounts, made from Grade 5 Titanium, which are arranged so that they create a fixed point at the centre of the shield, which is the focal point for thermal contraction.

Thermal Shield Analysis

A thermal-mechanical study was undertaken using ANSYS to validate the shield design. The shield flexure mounts were optimized to be 2 mm thick and 40 mm wide to support the suspended mass of the thermal shield (~116 kg) whilst providing sufficient flexibility to minimise thermal stress between the shield and OVC [9]. The flexure profile also minimise the thermal path to reduce unnecessary heat leak to the system at the intermediate stage.

Figure 8 shows the thermal stress in the flexure mounts with shield cooled to 77 K and the OVC at room temperature. The results show a maximum stress in the flexure mounts of 258 MPa which is well below the yield stress of Grade 5 Titanium at room temperature (868 MPa). It is also known that the yield stress will increase further at cryogenic temperatures allowing additional assurance in the design.

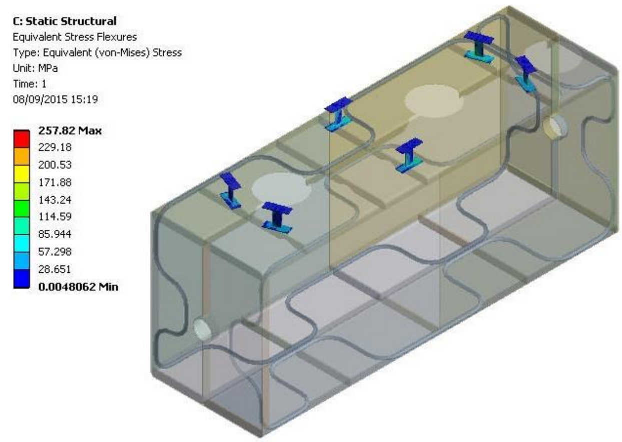

Figure 8: Cool down stress on flexure mounts.

Thermal Shield Assembly

The thermal shield consists of two window frame sections (including tubes) and four side panels which can be removed independently, allowing access to internal components. The shield is assembled around the cavity string as shown in fig. 9; the sections are inserted laterally to the cryomodule and suspended by the flexure mounts to the OVC. The cooling tubes are connected to the cryogenic services port before the side panels close the shield.

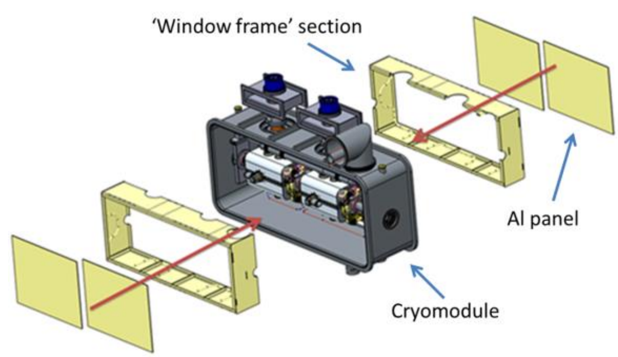

Figure 9: Thermal shield assembly.

CONCLUSION

The Crab Cavity cryomodule shielding is critical to achieving operational stability required for Hi-Lumi LHC. A double layer magnetic shielding solution, consisting of a warm outer shield and two cold inner shields, has been developed by for the SPS prototype cryomodules. The magnetic shields have been deigned to ensure that no more than 1 µT reaches the cavity surface, with an external field of 200 µT in the worst case orientation. The thermal shield is designed provide a radiative heat barrier and also act as a thermal intercept to minimise heat load to the superfluid helium vessels.

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OPERA simulations of various shielding options determined that, due to the expected field and number of necessary penetrations, a double layer shield is the most effective and reliable solution. The warm outer shield, fabricated from 3mm Mu-metal, is mounted internally from the OVC and surrounds the cavity string. The design features several penetrations for cavity supports, power couplers, cryolines, etc. The cold inner shields, fabricated from 1 mm thick Cryophy, are mounted internally to the cavity helium vessels. Various constraints and considerations contributed to the internal design which brings with it many advantages but also manufacture and assembly challenges. The cold shields will be manufactured by Magnetic Shields LTD and delivered to CERN for dressed cavity assembly.

The thermal shield consists of split sections, reinforced with a cooling tube skeleton, and four removable side panels. The shield is covered in MLI, to minimise emissivity, and suspended from six flexure mounts on the OVC. The shield acts as an intermediate cooling stage in order to minimise heat leak to the crab cavity helium vessels. Cavity string components can be actively pre-cooled by thermo-siphoning or passively cooled using thermal-links.

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