Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 67 (2015) 314 – 319

Physics Procedia

25th International Cryogenic Engineering Conference and the International Cryogenic Materials Conference in 2014, ICEC 25–ICMC 2014

Thermal and mechanical analysis of the radiation shield design for HiLumi LHC crab cavity cryomodule

Andrew May[a,b], Thomas Jones[a], Niklas Templeton[a] and Shrikant Pattalwar[a,]*

[a]*STFC Daresbury Laboratory, Keckwick Lane, Warrington, WA4 4AD, United Kingdom*
[b]*School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom*

Abstract

A prototype cryomodule to test the performance of the crab cavities for the HiLumi LHC is currently being designed and scheduled to be installed on SPS at CERN prior to LS2 (long shut down). The cryomodule design consists of a unique open access structure, facilitating loading of the cavity string from the sides. It also provides access to internal components quickly and easily, even after installation. Design of the radiation shield and the cooling scheme for introducing thermal intercepts at intermediate temperatures, particularly for the high power RF couplers, is critical to achieving a desired stability at the cavity operating temperature of 2 K, as well as keeping the cooling power within the limits of the cryoplant available in the SPS test area at CERN. This paper describes the results of the thermal and mechanical analysis of the design for the radiation shield and thermal intercepts developed in the process.

Peer-review under responsibility of the organizing committee of ICEC 25-ICMC 2014

Keywords: Thermal shield; Cryomodule; Crab cavity; HiLumi LHC

1. Introduction

A prototype cryomodule to test the performance of the crab cavities for the HiLumi LHC is currently being designed and scheduled to be installed on SPS at CERN in 2016-17 prior to LS2 (long shut down). A series of complex boundary conditions [1] arising from the layout of SPS has made the design of the cryomodule with two

---

* Corresponding author. Tel.: +44 (0) 1925 603 209.
E-mail address: shrikant.pattalwar@stfc.ac.uk

Peer-review under responsibility of the organizing committee of ICEC 25-ICMC 2014
doi:10.1016/j.phpro.2015.06.093

dressed crab cavities an extremely challenging task. A preliminary analysis was undertaken to establish a design approach for the development of a cryomodule [2]. Design of the radiation shield and the cooling scheme for introducing thermal intercepts at intermediate temperatures, particularly for the high power RF couplers, is critical to achieving a desired stability at the cavity operating temperature of 2 K, as well as keeping the cooling power within the limits of the cryoplant available in the SPS test area at CERN. A detailed study has been conducted to address the cooling power requirements at intermediate temperatures. The results of the thermal and mechanical analysis of the design for the radiation shield and thermal intercepts developed in the process are discussed in the forthcoming sections.

2. The design approach

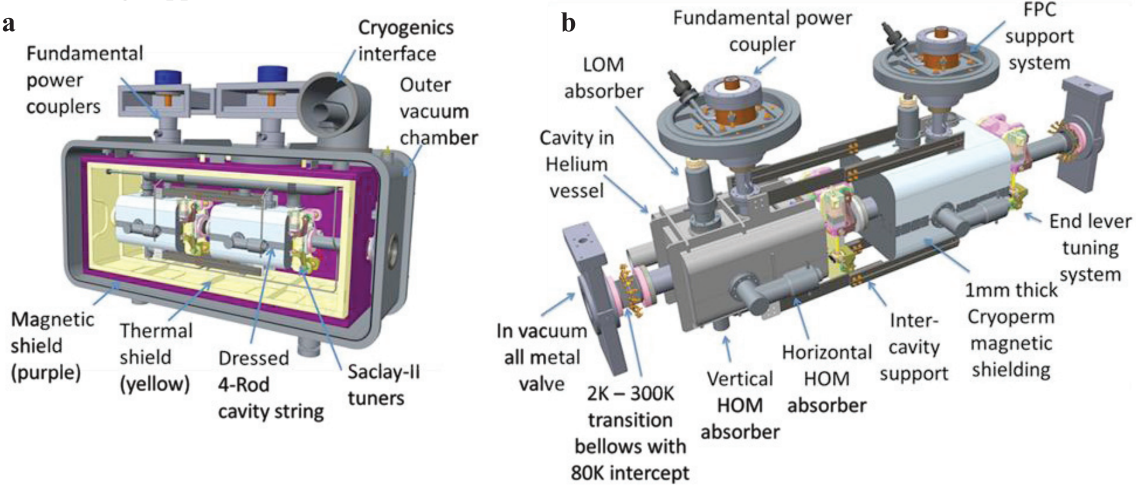

Fig. 1: (a) Open access cryomodule for 4-Rod crab cavities and (b) Dressed 4-Rod cavity string

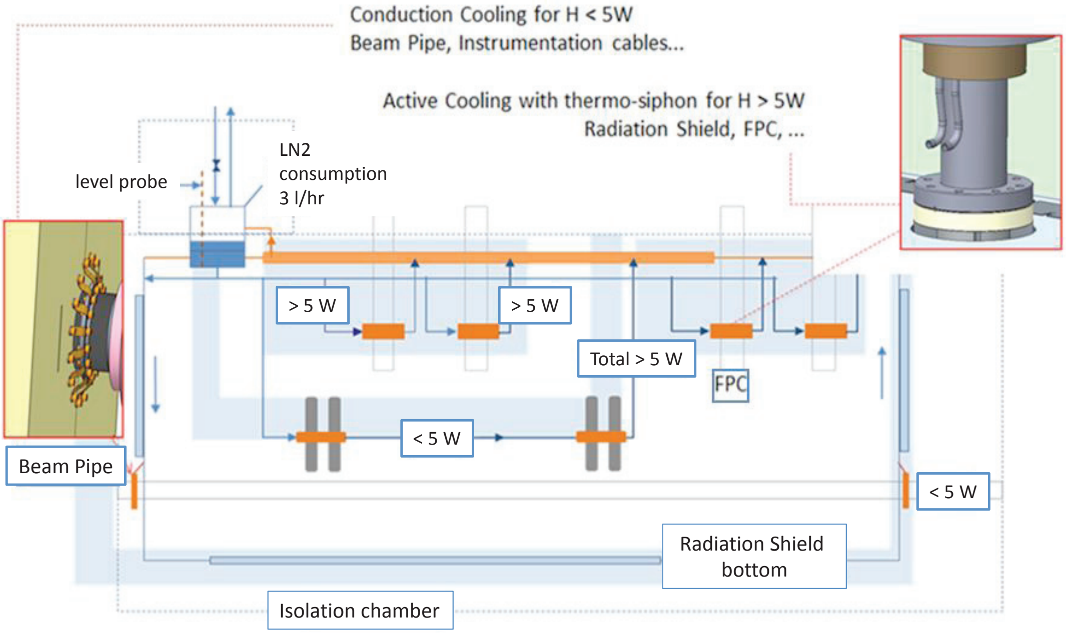

Fig. 2: Schematic for 80K cooling scheme

The cryomodule design for 4-Rod crab cavities [3] as shown in Fig. 1(a) comprises an Outer Vacuum Chamber (OVC), Mu Metal magnetic shield and Aluminum thermal shield surrounding a dressed cavity string (Fig. 1(b)). The dynamic heat loads for the cryomodules are estimated to be 30 W and 200 W at 2 K and 80 K respectively. The thermal shield, the thermal intercepts on the RF couplers and the beam pipes are cooled with liquid nitrogen as per the proposed cooling scheme shown in Fig. 2. LN_2 is supplied to a small reservoir inside the cryomodule and then distributed to various individual components. The thermal intercepts on the RF couplers are actively cooled using thermo-siphon technique. Copper laminated shunts are used as thermal links between the beam pipe and the shield providing passive cooling.

2.1. Assembly

An outline of the assembly sequence is given in Fig. 3(a). The dressed cavity string is assembled in the clean room, aligned inside the OVC and mounted. The thermal shield, which consists of two welded ‘window frame’ sections (including pipes) and four side panel sections is assembled around the cavity string as shown in Fig. 3(b), and then suspended by flexure mounts from the OVC (see Fig. 4(a)). The LN_2 lines are then connected to the cryogenic services port. Each side panel can be removed independently, allowing access to internal components.

2.2. Material selection and welding scheme

The shield panels and the pipes are fabricated from Al 6061-T6. The shield is subject to higher stresses during cooldown (see Section 4.2) and hence 6061-T6 has been chosen for its significantly higher yield stress and increased weldability, instead of Al 1050 as utilised by Pagani et al. [4]. The shield is suspended from 6 flexure mounts attached to the inside of the OVC. The mounts are arranged (see Fig. 4) such that they create a fixed point at the centre of the shield [5]. The results of the thermal and mechanical analysis presented in Section 3 show how the flexures are allowed to deform as the shield cools. Ti-6Al-4V has been selected for the flexure mounts as used on the SPICE instrumentation support. The cooling pipes are welded directly to the shield. Al 5356 is used as the filler for welding Al 6061 to itself. By staggering the welds and only welding longitudinally the pipes are allowed to flex during cooldown, reducing stresses in the shield. The pipes are welded through slots in the panels.

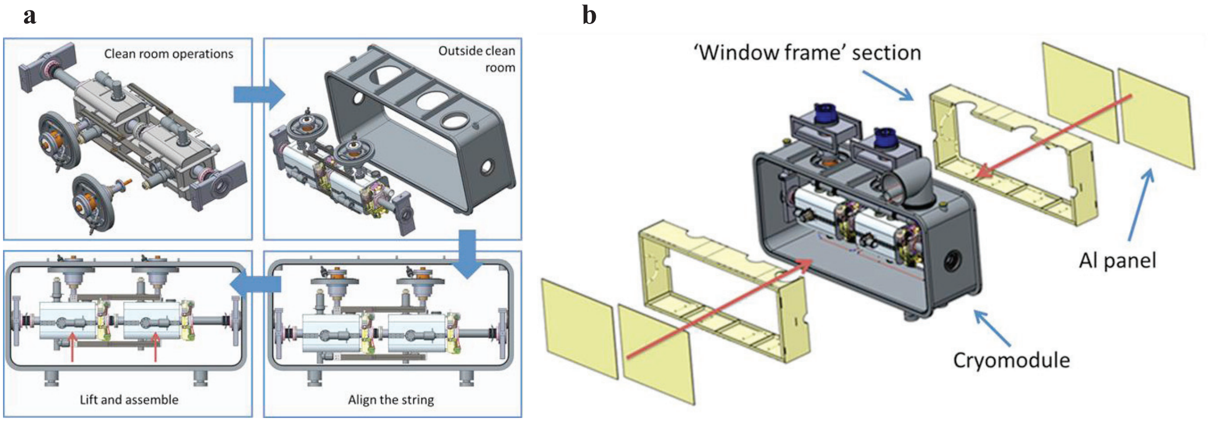

Fig. 3: (a) Assembly sequence for loading the cavity string in the cryomodule and (b) Assembly sequence for installing the thermal shields

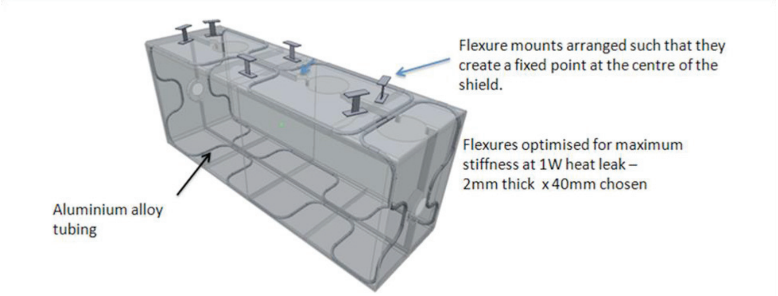

Fig. 4: Cooling pipes and flexure mounts.

3. Finite element analysis

Mechanical and thermal FEA has been carried out on the thermal shield model using ANSYS [6].

3.1. Thermal analysis

Transient thermal analysis was carried out assuming a fast cooldown (i.e. cooling pipes brought immediately to 77 K) using the boundary conditions given in Table 1. This is considered to be a reasonable assumption for the purposes of mechanical analysis as fast cooldown gives rise to higher thermal gradients (see Fig. 5(a)), and hence higher stresses, than will actually be seen by the shield in operation [7]. A margin of safety is therefore introduced into the design through this approach. Fig. 5 shows the temperature distribution at various times during fast cooldown of the shield. The flexure mounts are designed to allow heat leak of less than 1 W per flexure in the steady state condition.

Table 1: Transient thermal analysis boundary conditions

Boundary condition	Value(s)	Note
Pipe temperature	T = 77 K	Due to low Re, conduction will dominate heat transfer. Hence, set temperature is a reasonable approximation for the transient model where we assume fast cooldown
Radiation condition	$\varepsilon = 0.011$, T = 300 K	Based on heat flux of 5 Wm^{-2} for compressed MLI (worst case) and view factor consistent with surrounding magnetic shield
Convection to OVC	$h_f = 5\ Wm^{-2}K^{-1}$, T = 300 K	Convection coefficient consistent with free air flow over outer surface of OVC

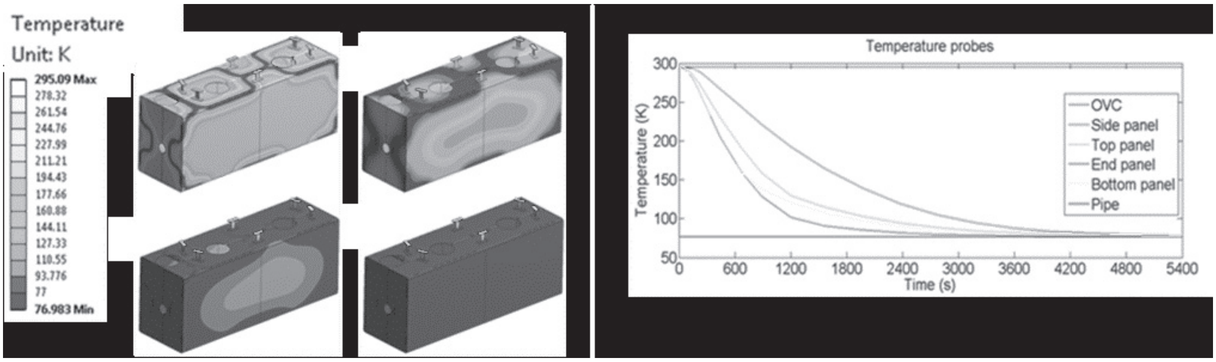

Fig. 5: Temperature distribution for fast cooldown at (a) t = 72 s, (b) t = 588 s, (c) t = 2306 s and (d) t = 5400 s (~steady state), (e) temperature profile of components during fast cooldown.

3.2. Structural analysis

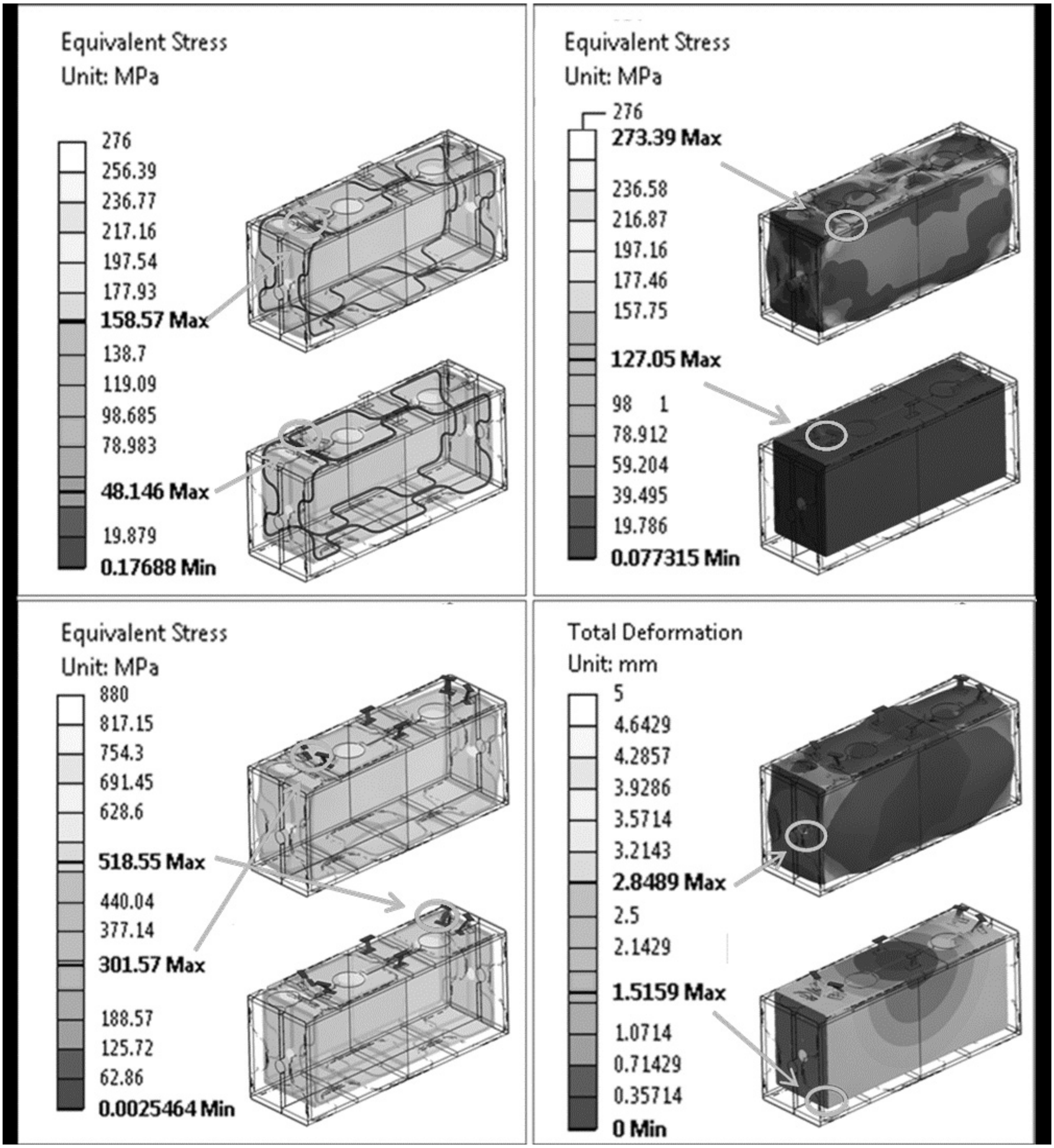

Fig. 6: Stress distribution in (a) cooling pipes for maximum thermal gradient across shield, (b) cooling pipes in steady state, (c) shield panels for maximum thermal gradient across shield, (d) the shield panels steady state, (e) flexure mounts for maximum thermal gradient across shield, (f) flexure mounts in steady state and (g) displacement field for shield for maximum thermal gradient, (h) displacement field for shield for steady state

In order to evaluate the worst case stress distribution, the temperature field at the time of highest thermal gradient across the shield was imported as a load into a static structural analysis. A gravitational load is included. Fig. 6(a)-(f) shows the Von Mises stress distributions for the greatest thermal gradient and steady state conditions. The maximum stress that occurs in the worst case is 158.57 MPa in the pipes (allowable limit of 276 MPa), 273.39 MPa in the panels (allowable limit of 276MPa) and 518.55 MPa in the flexures (allowable limit of 880 MPa). The displacements of all points on the shield were also analysed, in order to ensure compatibility with the geometric free space of the Cryomodule (Fig. 6(g)-(h)).

4. Conclusion and future plans

A mechanical and thermal analysis of the thermal shield for the HiLumi LHC crab cavity cryomodule has been studied in detail. Extensive thermal and mechanical finite element analysis has been carried out using ANSYS for the cryomodule considering the 4-Rod crab cavities. The design and the materials have been selected so that for a fast cooldown no stresses above the yield limit are present at any time. The simulation results show that shield is nearly isothermal at 77.4 K.

As a part of development of crab cavities for LHC-HiLumi three cavity topologies: 4-Rod, DQW (double quarter wave) and RFD (RF dipole), were under consideration. Considering the limited duration available for evaluation with SPS only DQW and RFD cavities are likely to be tested. The thermal shield design is conceptually compatible with the cryomodules for all three cavities. The design of the 80 K circuit will be extended to the cryomodules for DQW and RFD. The first cryomodule is scheduled to be installed on the SPS drive accelerator prior to the long shut-down period LS2 to evaluate performance with high-intensity proton beams.

Acknowledgements

This work has been undertaken as a part of The HiLumi LHC Design Study (a sub-system of HL-LHC) co-funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404. Authors wish to acknowledge all the members of the WP4 of the HiLumi Collaboration and US-LARP for their valuable inputs and discussions.

References

[1] P. Baudrenghien et al., “Functional Specifications of the LHC Prototype Crab Cavity System”, *CERN-ACC-NOTE-2013-003* (Feb 28, 2013).

[2] Pattalwar, S., et al., “Conceptual design of a cryomodule for compact crab cavities for Hi-Lumi LHC”. *Proceedings of SRF 2013* (2013)

[3] Burt, G. and Hall, B. “4-rod design and PoP test results”, *Crab cavity design review, BNL, USA* (2014)

[4] Pagani, C. et al., “Design of the thermal shields for the new improved version of the TESLA Test Facility (TTF) cryostat”, *Advances in Cryogenic Engineering*, Vol. 43, (1998)

[5] Jones, T., “ Side-loaded cryomodule for UK 4-rod tests on SPS”, *Crab cavity design review, BNL, USA* (2014)

[6] ANSYS is a registered trade mark of ANSYS, Inc.

[7] Barni, D. et al., “Cooldown simulations for the TESLA Test Facility (TTF) cryostats”, *Advances in Cryogenic Engineering*, Vol. 43, (1998).