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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]

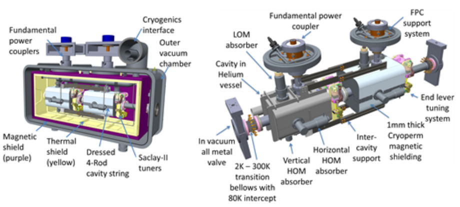
[a]STFC Daresbury Laboratory, Keckwick Lane, Warrington, WA4 4AD, UK

[b]School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Oxford Road, Manchester, M13 9PL, UK

Introduction

Preparations have begun to demonstrate the crabbing technique by evaluating the performance of the compact crab cavities with high intensity proton beams using SPS drive accelerator at CERN. A prototype cryomodule consisting of two identical crab cavities is scheduled to be installed before LS2 (2nd long shutdown in LHC operation).

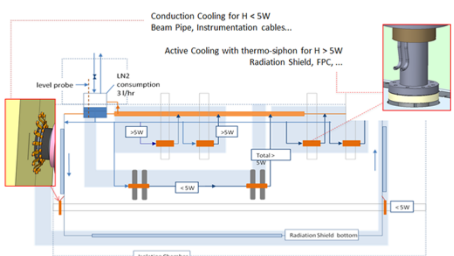
*Several cryomodule designs corresponding to three different cavity designs, **4-Rod, Double Quarter Wave (DQW) and RF Dipole (RFD)**, were considered*



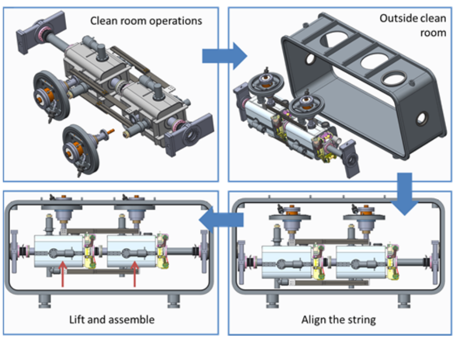
Side loaded cryomodule and the dressed cavity string

Design Approach for the 80K Circuit

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.



Schematic for cooling to 80K with LN2



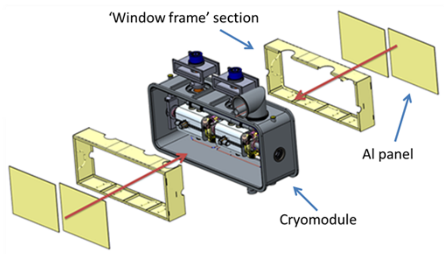
Cryomodule assembly sequence

Shield Mechanical Design

The shield is broken up into two 'window frame' sections with detachable side panels to facilitate access to the cavity string.

The panels and pipes are fabricated from Al 6061-T6 (chosen due to high stresses experienced during cooldown and weldability).

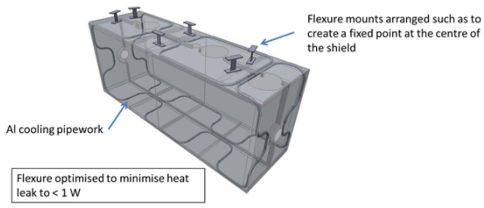
The cooling pipes are welded through slots in the panels directly to the shield. The welds are staggered longitudinally to allow the shield to flex during cooldown.



Thermal shield assembly sequence

The shield is suspended from the OVC by 6 flexure mounts arranged to create a fixed point in the centre of the shield.

The flexures, to be fabricated from Ti-6Al-4V (as used on the SPICE instrumentation) are allowed to deform as the shield cools.



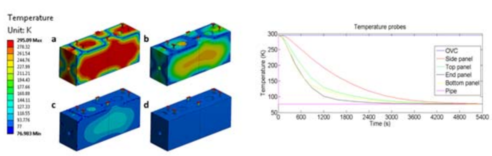
Thermal shield (including flexure mounts)

Thermal Analysis

Extensive FEA has been carried out on the thermal shield model using ANSYS. Transient thermal analysis was carried out according to the boundary conditions given in the table below. Results are also presented below.

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	ε = 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

Thermal FEA boundary conditions

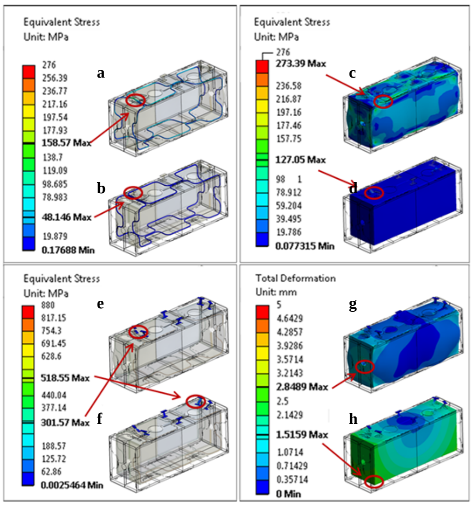


Temperature profile during fast cooldown at a) 72 s, b) 588 s, c) 2306 s and d) 5400 s (~steady state condition)

Structural Analysis

The maximum stress that occurs in the worst case is:

- 273.39 MPa in the panels (allowable limit of 276MPa)
- 158.57 MPa in the pipes (allowable limit of 276 MPa)
- 518.55 MPa in the flexures (allowable limit of 880 MPa)



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

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 material allocation 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 the development of crab cavities for LHC-HiLumi three cavity designs: 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. Due to the common design approach taken for each cryomodule, the thermal shield is compatible with all three.

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