

Design of horizontal test cryostat for testing two 650 MHz cavities: *cryogenic considerations*

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Abstract. Horizontal Test Cryostat has been designed for testing two 650 MHz “dressed” Superconducting Radio Frequency (SCRF) cavities in a single testing cycle at Raja Ramanna Centre for Advanced Technology, India (RRCAT) in collaboration with Fermi National Accelerator Laboratory, USA (FNAL). This cryostat will facilitate testing of two 5-cell 650 MHz SCRF cavities, in CW or pulsed regime, for upcoming High Intensity Superconducting Proton Accelerator projects at both countries. Two such HTS facilities are planned, one at RRCAT for Indian Spallation Neutron Source project (ISNS), which is on the horizon, and the other at FNAL, USA. A test cryostat, a part of horizontal test stand-2 (HTS-2) will be set up at RRCAT for Indian project. In order to maximize the utility of this facility, it can also be used to test two dressed 9-cell 1.3 GHz cavities and other similarly-sized devices. The facility assumes, as an input, the availability of liquid nitrogen at 80 K and liquid helium at 4.5 K and 2 K, with a refrigeration capacity of approximately 50 W at 2 K. Design work of cryostat has been completed and now procurement process is in progress. This paper discusses salient features of the cryostat. It also describes different design calculations and ANSYS analysis for cool down of few subsystems like cavity support system and liquid nitrogen cooled thermal radiation shield of horizontal test cryostat..

1. Introduction

All Superconducting radio frequency (SCRF) cavities have to be qualified in two test facilities prior to installation in cryomodels of a superconducting linear accelerator. First, the bare cavities are tested in a pool type cryostat with liquid helium under saturated condition, in a facility called as vertical test stand (VTS) [1]. After qualification of cavities in VTS, cavities are dressed with their auxiliary components, like welded helium vessel of cavity, HOM couplers, tuner and main coupler. These dressed cavities are then tested in HTS facility. The cryostat of this facility offers a possibility



to test fully equipped (dressed) superconducting RF cavities before final assembly in cryomodules of an accelerator [2]. In principle, this is a continuous flow type cryostat. Cavities are tested at temperature of about 2K with saturated liquid helium at sub atmospheric pressure in the helium vessel surrounding the cavity. Cavity performance tests like establishment of Q_0 v/s E_{acc} at 2 K with measurement of cryogenic heat load are carried out [1]. In this test cryostat, cold leak tightness of the helium vessel, the tuning range and performance of cold tuner are also get verified [2].

At present there is only one such a bi-cavity test facility called as **HoBiCaT**, at **Berliner Elektronenspeicherring-Gesellschaft f ü r Synchrotronstrahlung m. b. H. (BESSY)**, Germany, which is in operation. This facility can test a pair of dressed 9-cell TESLA cavities in CW mode for **BESSY FEL**. Another facility was installed recently (2014) at **Facility for REsearch Instrumentation & Accelerator development (FREIA)** laboratory, Uppsala University, Sweden for ESS cavities.

The cryostat for HTS-2 facility has been designed to satisfy the expected functional requirements [3, 4]. During design of HTS-2, an operational experience of existing horizontal test stand (for testing only one dressed 1.3 GHz or 3.9 GHz cavity in one cycle) at FNAL has been considered. RRCAT designed this HTS-2 cryostat under aegis of IIFC (Indian Institute Fermilab Collaboration). This paper briefly describes main features of cryostat. It also discusses different design considerations and different analyses of subsystems like cavity support system, liquid nitrogen cooled thermal shield and relief system requirements of cryostat with design. Design work of cryostat has been completed and now procurement is underway.

2. Major functional requirements of HTS-2

HTS-2 test facility will be primarily used for testing two dressed 650 MHz cavities (of PIP-II of USA and future Indian high intensity proton accelerator) in CW or pulsed regime. Two cavities will be loaded in the cryostat at a time but will not be powered simultaneously. In order to maximize the utility of this facility, 9-cell 1.3 GHz cavities & other similarly-sized devices can also be tested in the future if need arises [3,4]. For testing of 650 MHz cavities ‘design point’ accelerating gradient of 19.2 MV/m and quality factor Q_0 of 2×10^{10} with expected dynamic heat load of 31 watt/cavity [3, 4]. At a maximum test gradient of 25 MV/m and a Q_0 as low as 5×10^9 , dynamic heat load would be too high (211 W). In that case, one would switch to operating scenario with a 10% RF duty factor to reduce the heat load by a factor of 10. The facility assumes, as an input, the availability of liquid nitrogen at 80 K, and liquid helium at 4.5 K. A vacuum system will pump helium down to super fluid temperatures to provide a refrigeration capacity of 50 W at a nominal operating temperature of 2 K. Magnetic shielding is provided by a low carbon steel (ASTM 516 Grade 60 or equivalent) cryostat vacuum vessel and a 1mm thick layer of cavity specific cryogenic magnetic shield (Cryoperm10) around the cavity helium vessel.

3. Design of main subsystems of cryostat with analysis

HTS-2 cryostat mainly consists of subsystems like vacuum vessel, cavity support system; liquid nitrogen cooled thermal shield, cryogenic distribution scheme, feedcan and relief venting stack of helium, required in case of accidental situation like cavity or insulating vacuum loss. The vacuum vessel of cryostat is of low carbon steel and designed for an overall diameter of 1.2 meter and length of 4.3 meter. The vacuum vessel of the feedcan which sits above the test cryostat is of stainless steel SS 304L. Both vacuum vessels have been designed to comply with provisions in ASME Boiler & Pressure Vessel code section VIII, Div. I. Vessel has two bottom ports for cryogenic support posts. Two ports for main RF couplers at two ends and two ports for individual cavity pumping are also

provided. Each cavity will be RF powered and tested individually. Figure 1 depicts an image for 3 D model (made in UGNX) of a cryostat with feedcan.

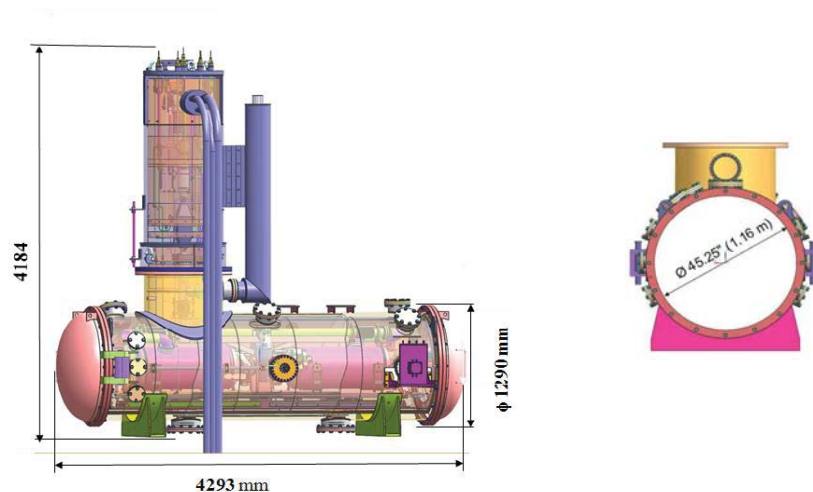


Figure 1. A 3 D model image of cryostat for Horizontal test stand-2.

3.1. Cavity support system

A dressed 650 MHz cavity (viz. a cavity with own helium vessel, tuner, magnetic shielding on helium vessel, and a cold part of RF coupler) will be mounted on the rolling cart of stainless steel, outside the vacuum vessel. Then two such cavities with their rolling carts will be rolled inside the vessel, from openings at each end. These rolling carts will be supported on rails attached to the both sides of supporting table called “frame bridge” (made of stainless steel). Frame bridge itself is supported on two cryogenic support posts. The cryogenic support post transferring the load of cold mass on the vacuum vessel, has two thermal intercept, one at 80 K and one at 4.5 K to minimize the conducted heat in-leak from 300 K to cavities at 2 K. The frame bridge and rolling cart have been designed considering their relative movements due to shrinkage during cool down. Design of cavity rolling cart is such that the cart movement is restricted on coupler end by attaching it with Invar rod to 2 K flange of cryogenic support post but the cart is allowed to move in axial direction at end opposite to that of RF coupler. Due to V type rail on one side of frame bridge, transverse movement of cart is restricted. Frame bridge is fixed on cryogenic support post at one end of vessel where feedcan is located but at the other end, it is allowed to move axially during cool down. Frame bridge and carts are actively cooled with 4.5 K helium flowing through SS tube welded on both sides of frame bridge. Figure 2 shows 3-D model image of cavity support system.

3.1.1. Thermal and structural analysis of cavity support system. ANSYS analysis for cool down of frame bridge (SS304L) from 300 K to 4.5K has been carried out. Analysis has been carried out by breaking whole temperature range from 300 K to 4.5K in four steps and assuming instantaneous cool down of sink to average temperature during each step. Steady state temperature profile in each step was taken as initial condition for the next step. An average value of heat transfer coefficient of 200

watts/ m² K (corresponding to maximum 3 g/s of helium flow) was assumed and applied to nodes in areas where cooling tube is attached to *frame bridge*. Total cool down time is about 11 hours which is sum of cool down times of all steps. A thermal coupled structural analysis of cavity cart has been done, applying 180 Kg weight of 650 MHz cavity (equally distributed) on four brackets of cart. After cool down of cart from 300 to 80 K, maximum directional deformation observed near coupler end is up to 0.5 mm along axis of cryostat (X-direction) and is below 1 mm vertically (Z -direction) by additional thick ribs in bracket on cart. Equivalent Von Mises stresses in structure are also well below 20 MPa.

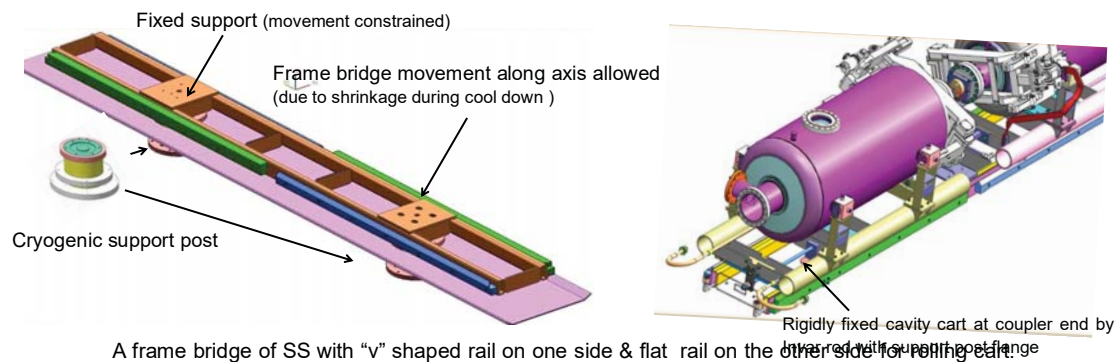
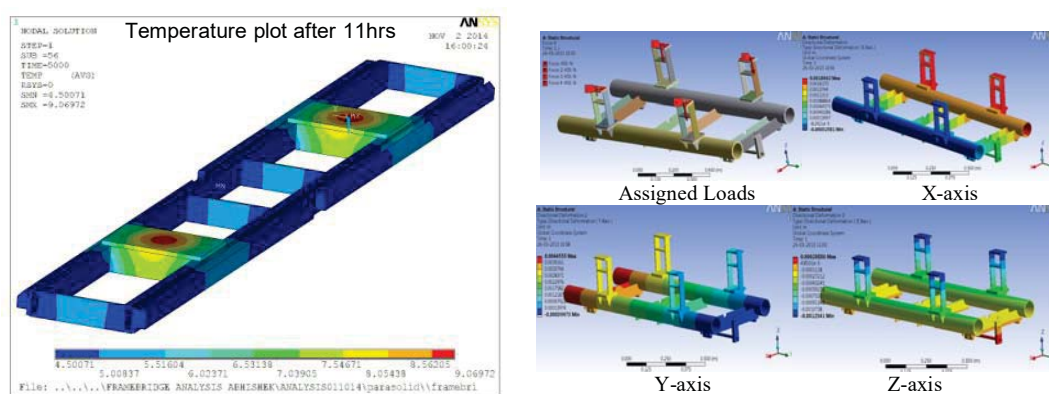


Figure 2. A 3 D model image of cavity support system with cryogenic support post



(a) Cool down ANSYS analysis of frame bridge

(b) Thermal and structural analysis of cavity cart

Figure 3. ANSYS analysis of cavity support system

3.2. 80 K liquid nitrogen cooled thermal shield

The cryostat has only one thermal radiation shield of 80K which is cooled by flow of liquid nitrogen. Thermal shield consists of an upper part of 1.6 mm thick OFE copper sheet and a 6 mm thick bottom part of OFE copper. Thermal shield has diameter of 1.07 m and 4 m of overall length. The doors/end domes will be bolted to the main cylindrical shell of shield after installation of the cavities, and are cooled by thermal contact. The total weight of shield assembly is about 380 kg. The cryostat shield is mounted on cryogenic support post. Thermal shield will be cooled by liquid nitrogen flowing at mass flow rate of 2 g/s in a copper tubing of diameter 10 mm soldered to the shield. This cryostat has 30 layers of MLI on 80 K shield. Figure 4 describes 3-D model of shield showing a layout of copper cooling tube on it.

3.2.1. Thermal Analysis of nitrogen cooled 80K shield. Thermal & structural analyses of 80 K thermal shield have been carried out. Variation of thermal properties (specific heat and thermal conductivity) of shield material, OFE Cu 101 over whole temperature range is considered. Heat transfer of 80 K shield with 2 K & 4.5 K cold mass is not considered. A constant steady state thermal radiation flux of $\sim 1.5 \text{ W/m}^2$ from 300 K vacuum vessel is applied on 80K shield with 30 layers of MLI. A steady conductive heat in-leak of 3.5 W is assumed from 300 K to 80 K through each support post during cool down period. Heat transfer coefficient average value of $150 \text{ W/m}^2 \text{ K}$ is assumed, corresponding to given mass flow rate of 2 g/s of nitrogen. In order to limit maximum temperature difference across the shield below 40K during cool down and thus avoid undue deformation in the shield, iterations were carried out with numbers of linear cool down periods. Finally a linear cool down period of 10 hours is considered where maximum temperature difference during cool-down is below 30 K. A steady state (for temperature difference $\leq \Delta T \sim 10\text{K}$ across shield) is reached after about 50000 sec. In structural analysis, after considering weights of pipe for cavity vacuum line anchored to shield, couplers and shield interface in feedcan port, it is seen that deflection is below 4 mm over the length of shield and stresses are within limits.

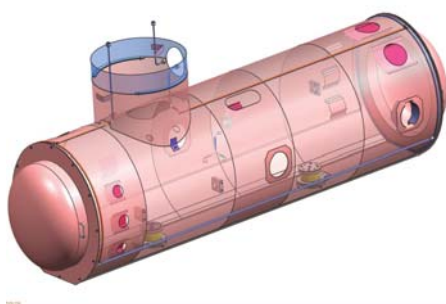


Figure 4. A 3 D model image of liquid nitrogen cooled 80K thermal shield of cryostat

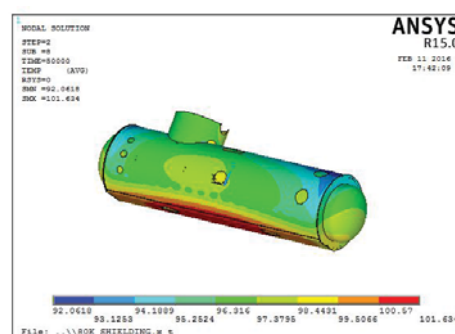


Figure 5. Transient thermal analysis of 80K thermal shield showing temperature profile after 50000 sec

3.3. Feedcan for cryostat

Vacuum vessel of feedcan (for distribution of cryogen to cryostat) is of stainless steel SS 304L. feedcan vacuum vessel shell has diameter of about 812 mm and shell thickness 7.9 mm. This vessel is also designed to ensure that allowable stresses are not exceeded and that the vessel is resistant to

buckling. The vacuum vessel of feedcan has a flanged connection to the cryostat vacuum vessel. This flanged connection is designed to allow part of the vacuum vessel to slide up and expose the interface piping connections. Feedcan houses different cryogenic control valves, check valves and 2 K heat exchanger with connected piping and instrumentation tubing supported from top plate. A 3-D model image of feedcan is shown in figure 6. Cryogenic distribution scheme is discussed in the next section of paper.

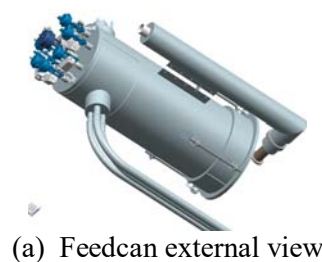


Figure 6. A 3-D model of feedcan

4. Cryogen distribution scheme

The cryostat is designed for refrigeration capacity of approximately 50 W at 2 K, assuming the availability of liquid nitrogen at 80 K and liquid helium at 4.5 K from cryogenic installation. As shown in figure 7 for P & I diagram cartoon, outer most line is liquid nitrogen line (LN₂ line) which fulfills the need of 80 K thermal shield and RF coupler and other 80 K intercepts. Maximum flow of liquid nitrogen available from facility will be @ 2 g/s at 45 psi. A 4.5 K liquid helium line from helium plant facility is divided in three streams. One stream supplies 4.5 K helium at 30 psi absolute to a low pressure heat exchanger (pre-cooling to 2.2 K) ahead of JT valve where it will get throttled to produce saturated helium at about 2 K and 31 mbar for cavity. This helium flow will be in action only after closing of cool down control valve achieving sufficient cool down of cavities and supporting structure below certain temperature. Second stream with control valve, supplies 4.5K helium for cool down to cavity and liquid level dewar from bottom side, required during cool down/warm-up phase of operation and third stream provides cooling of frame bridge, intercepts and cavity rolling cart. Figure 8 shows 3 D model for cryogenic piping of HTS-2. A common 2K liquid level dewar is used for controlling 2K liquid level in 2 K two phase pipe. This 2 K two phase helium manifold supplies super-fluid helium to helium vessels of both cavities as shown in figure 7. Figure 8 shows 2 K helium pumping line portion.

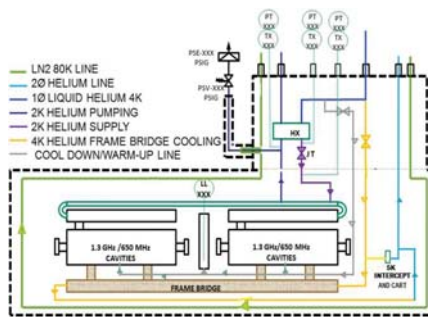


Figure 7. A Schematic illustrating cryogenic flow scheme for HTS2 cryostat

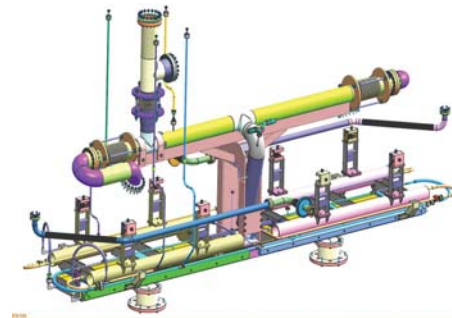


Figure 8. 3-D model showing internal cryogenic piping inside cryostat.

5. Relief System Requirements

HTS-2 design will permit easy connections of cavities to cryogenic system inside vacuum vessel. The relief devices are connected by piping to the helium (2K helium pumping line) return line as seen in figure 7 for P& I Diagram of HTS-2. Thus once the cavities are connected and ready for operation, there is assurance that the relief system will be in place. One cavity will be tested at a time in the HTS-2 [3, 4]. These both cavities will have a warm Maximum Allowable Working Pressure (MAWP) of 2.02 bar (absolute), in the temperature range of 80 K to 300 K and cold MAWP of 4 bar (absolute) for temperatures below 80 K. ASME-coded relief valve set at 15 psig is considered as main relief device for the system, backed by a 12 psig bursting disc, to protect cavities under both warm and cold conditions. There is also an operational relief valve set at 8 psig planned to relieve operational pressure transients. There will be a header downstream of the burst disc, to vent helium outside the cryostat radiation shielding cave particularly to take care of Oxygen Deficiency Hazard.

5.1. Relief System Calculations

Only two major worst cases or scenarios are considered: First one is 4 bar (absolute) cold operation with loss of beam tube vacuum and other one is 4 bar (absolute) operation with loss of insulating vacuum, with full system flow. Fire relief is not considered. Calculations have been carried out for required cryostat relief capacity in three steps. The first is an analysis of the inlet piping (up to relief device) pressure drop based on the relief line geometry. The second is a calculation of the relief valve capacity at allowed over pressurization (110% for non-fire) of MAWP with the inlet pressure derived from step one. The third is a check for the pressure drop in the relief header that vents the relief flow outside the test cryostat cave. In the case of accidental loss of insulating vacuum of cryostat, it was assumed that a uniform heat flux of 2 W/cm² would be applied to all cold piping leading to the relief valve. Heat flux of 3.8 W/cm² was considered for the case of loss of cavity beam tube vacuum [7]. Calculations were carried out for pressure drop in the inlet piping leading to the inlet relief device. The maximum flow rate evolved is about 5.7 Kg/s for an accidental scenario of insulation vacuum loss with insulated cavity helium vessel and un-insulated piping (with cold MAWP of 44.1 psig). The calculated pressure drop in the inlet header is about 12 psi, so inlet pressure to relief device is 51.2 psi@ (110%MAWP- inlet $\Delta p + 14.7$). The required inlet opening area or disk area with minimum diameter is about 3 inch. The work related to placing of relief valve with burst disk and consequent

design for relief header downstream of the burst disk will take place during installation and commissioning phase.

6. Present Status

The design of HTS-2 has been completed successfully and reviewed by Fermilab design review committee last year. Design review committee has given approval for fabrication of cryostat. Now procurement process is in progress for fabricating this cryostat from Indian industry.

7. References

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