Design of Horizontal Test Cryostat for Testing Two 650 MHz SCRF Cavities: Cryogenic Considerations

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Outline

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2. Technical requirements of Horizontal Test Stand (HTS-2)
3. Glimpses of 3-D model of cryostat
4. Main sub-systems of HTS-2
   A. Vacuum Vessel of Cryostat
   B. 80 K Thermal shield
   C. Cavity support system
   D. Feed can of HTS-2 cryostat
   E. Cryogenic distribution scheme
5. Summary
1. Introduction

- Horizontal Test Cryostat is a continuous flow type cryostat for testing two 650 MHz dressed SCRF cavities at 2 K, individually, but in single test cycle to qualify them for assembly into cryomodule.

- RRCAT & Fermi Lab. (USA) have jointly designed the cryostat keeping operating experience of Horizontal Test Stand -1 in mind.

- Design was reviewed by expert committee constituted for the purpose.

Part of infrastructure for upcoming “Indian Spallation Neutron Source Project”.

HOBICAT, BESSY

Operational Bi-Cavity Horizontal Test Facility
March 07-11, 2016

FREIA
Facility for REsearch Instrumentation & Accelerator Development, Sweden
Uppsala University, Sweden, installed in 2014

RRCAT
Will be Third such facility in world
1. Introduction

From Cavity to Accelerator

Cavity Fabrication \(\rightarrow\) Surface Processing \(\rightarrow\) Vertical Testing

Fail! \(\rightarrow\) Fail! \(\rightarrow\) Pass!

Horizontal Testing \(\rightarrow\) High-pressure water rinse \(\rightarrow\) Attach He Vessel

Pass! \(\rightarrow\) Fail! \(\rightarrow\) Pass!

Discussing about cryostat of this testing

Cold String Assembly in Cryomodules

Cryomodule – an accelerator’s building block
1. Introduction

- HTS-2 will be a relatively stand-alone facility.
- Two horizontal test cryostats are being fabricated as the main part of HTS-2 facility. One cryostat for RRCAT and other for FNAL.
- The major interface of the cryostats will be to the upgraded cryogenic facilities at both institutions.
2. Technical requirements from HTS-2 facility

Major requirements and assumptions.

- The system should be able to test, two 5-cell 650 MHz SRF cavities in one cycle. Both CW & pulsed regime testing should be possible. However main operating mode is CW testing up to gradients of ~ 25 MV/m at 2 K. The cavities will not be powered simultaneously.

- With minimum modifications, cryostat should be able to test 9-cell 1.3 GHz cavities & other similarly-sized devices also.

- The facility requires, as an input, the availability of LN2 at 80 K and LHe at 4.5 K. A refrigeration capacity of approximately **50 W at 2 K** has to be in place. A vacuum system capable of pumping helium down to superfluid temperatures is required.

- CW testing of ($\beta=0.61$) 650 MHz cavities with “design point” gradient and $Q_o$ (19.2 MV/m & $2 \times 10^{10}$), will result into dynamic heat load of 31 W. It may see ~211 W, if a gradient of 25 MV/m and $Q_o$ of $5 \times 10^{9}$, is encountered. Then we switch to 10% RF duty factor to reduce heat load to 10%.
2. Technical requirements from HTS-2 facility

Requirements (Some points based on operational experience of HTS-1)

- The cavity/cryostat system should come to thermal equilibrium within 24hrs of start of cool down.

- The system should provide a throughput of 4 cavities tested every 6 weeks.

- Magnetic shielding is provided by low carbon steel (ASTM 516 Grade 60) vacuum vessel & 1mm thick layer of cavity specific magnetic shield (Cryoperm10) around the cavity helium vessel.

- Thermal shields to be physically well-separated so as to prevent any chance of a thermal short.

- Coupler port should have provision for different sized coupler.

- HTS- 2 should have actively cooled cavity support system as the presently used conductively cooled system of HTS-1 takes very long time to cool down resulting in longer turn around time.
3. Glimpses of 3-D model

3-D MODEL OF HORIZONTAL TEST CRYOSTAT -2 WITH FEEDCAN
3. Glimpses of 3-D model

3-D MODEL OF HORIZONTAL TEST CRYOSTAT WITH FEEDCAN
(With sliding sleeve moved upward showing pipe/tubing connections in interface)
3. Glimpses of 3-D model

3-D MODEL OF INNER PIPING AND 650 MHz SCRF CAVITIES
(Without 80K Shield and vacuum vessel)
4. Major subsystems of HTS-2

- Vacuum Vessel
- LN$_2$ Cooled 80K Thermal Shield
- Rolling Cart
- Framebridge
- 650 MHz Cavity
- Cryogenic Support Post

END VIEW OF HORIZONTAL TEST CRYOSTAT
(Shows major sub-systems in cryostat)
4a. Vacuum Vessel - Cryostat

3-D MODEL OF HORIZONTAL TEST CRYOSTAT -2 VACUUM VESSEL WITH RELIEF STACK

Designed as per provisions of ASME B&PV code Section VIII Div I

<table>
<thead>
<tr>
<th>Vacuum vessel of HTS-2 Cryostat</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside Diameter of Cryostat</td>
<td>1.17 m (46 inch)</td>
</tr>
<tr>
<td>Vessel made up of Carbon Steel *</td>
<td></td>
</tr>
<tr>
<td>Overall Length of Vessel</td>
<td>3.5 m (137.7 inch)</td>
</tr>
<tr>
<td>Nominal Thickness of Vessel</td>
<td>9.5 mm (0.375 inch)</td>
</tr>
</tbody>
</table>
4b. 80 K Thermal Shield

3-D MODEL OF HORIZONTAL TEST CRYOSTAT-2 (HTS-2)
80 K THERMAL SHIELD
ANSYS analysis for 80K Shield

**Transient thermal analysis**

- Liquid nitrogen cooled shield
- Thermal properties of shield material (OFE Cu 101) are averaged over the temperature range as variation is nearly linear
- No 5K shield
- Constant thermal radiation flux of ~ 1.5 W/m^2 from 300 K vacuum vessel. A steady conductive load thru' support post ~ 3.3 w thorough out cool down.
- Assumed linear cool down of 10 hrs.
- Max. Temperature difference during cool-down is < 30 K
- steady state (≤ ΔT~10K assumed a steady state) is reached after ~ 14hrs.
4c. Supporting structure (Frame bridge) of SS for cavities

An actively cooled supporting structure mounted on cryogenic support post (frame bridge) of SS having “v” shaped rail on one side & plain rail on the other side for rolling cart.
Design of supporting structure for restrictions of longitudinal movement of cavity mounted on rolling cart at coupler end in HTS-2

- Frame bridge of SS with “v” shaped rail on one side & plain rail on the other side for rolling cart
- Invar Rod fixed to 2 K flange of cryogenic support post and rigidly connected to cavity cart at other end
- Estimated contraction of Invar ~ 0.22 mm

- Fixed support (movement constrained)
Assumptions:

- Framebridge is made of SS 304L
- Conservative value of heat transfer coefficient was taken. Convection heat transfer coefficient 200 watt/m²·K was taken (corresponding to 2 g/s flow of He)
- Temperature variation along the cooling pipe was ignored.

Boundary Condition:

- 0.06 watt/m² of radiation load was taken on frame bridge.
- 0.1 watt of total static heat in leak was taken per support post

- Result: Cool down time was found to be ~ 11 Hrs.
  (assuming contact of cooling tube with supporting structure framebridge over full length of structure)
**Principle:**

Disc Initially at Interference with G11 Tube at 300K.

Disc cooled by LN2 & Placed within G11 with Ring in Position and Allowed to warm Up.

After Shrinkfitting Disc-Tube-Ring Assembly behaves as Structurally Single Component.

Contact pressure Depends on Interference between G11 Tube and Disc/Ring Set

Disc and Ring, Support the Axial Load due to Contact Pressure and Friction at the Interfaces

Support Post modelled as Three Component Compound Cylinder
4.c Design of Cryogenic Support Post

- No Fastener or Adhesive Used in Support Post Assembly
- Supports Axial Load because of Contact Pressure and Friction at the Interface with G11 Tube and Metal Disc/Ring

- Bottom of Support Posts rests on Vacuum Vessel at 300K with Cold Mass at 2K attached on Top
- Each Post Made in Two Part for Ease of Assembly of Cold Mass inside Cryostat
- Cold End and Room Temp End of Support Post 275 mm Apart
- Each Post Withstands 1000 kg Load and Permits 9 mW Static Heat Inleak at 2K
Static Heat Calculation Through Support Posts

- 2K Cold Mass: 9.36E-03 W, 0.39 W, 0.57 W
- 4K Support Post: 2.78 W, 5KHe
- 80K Thermal Shield + Support Post: 17.61 W, 7.50 W, 1.19 W, 22.96 W
- 300K Vacuum Vessel
4 d. Feedcan of Cryostat

3-D MODEL (SECTIONAL VIEW) OF FEEDCAN OF HORIZONTAL TEST CRYOSTAT
(Showing vacuum vessel, internal cryogenic pipings, control valves, a heat exchanger)
4 e. Cryogen Distribution Scheme
4 e. Cryogen Distribution Scheme

Internal Cryogenic Piping of Cryostat

3-D Model showing internal piping
FIRST 1.3 GHz LASER WELDED SCRF CAVITY

1. No necessity of vacuum environment
2. Capital cost 25 times Less
3. Operational cost 6-7 times less
4. Production rate (5-6 times more)
5. Intricate joints easily welded
6. Provides flexibility for cavity designers.
7. Low HAZ (0.5mm).
8. Low shrinkage & distortion

And Still

\[ E_{\text{acc}} \text{ 31.6 MV/m at } Q_0 1.0 \times 10^{10} \text{ at 2 K} \]
Summary

- A Horizontal Test Stand facility is being established to test dressed 650MHz superconducting RF cavities at 2 K temperatures. The cryostat for this facility has been designed.

- The facility will have the capacity to test two SCRF cavities in one test cycles although cavities will not be powered simultaneously.

- The cryogenic systems are being upgraded to provide a refrigeration capacity of approximately 50 W at 2 K.

- The design has been reviewed and cleared for fabrication by an expert committee constituted for the purpose.

- The cryostat is now under procurement process from Indian industry. After fabrication at industry, testing & installation of one cryostat will be done at RRCAT.

- Subsequently one cryostat will be shipped to FermiLab for installation and commissioning there.
Thank You
BACK-UP SLIDES
Cooldown analysis of thermal shield of HTS-2

3-D Model:
- 3-D model of thermal shield is prepared to perform analysis.
- The model is slightly simplified to carry out analysis so, cooling pipe is not considered in analysis and convection loads are applied to the corresponding areas in the shell of thermal shield.

*Reference.*

1. "Advances in Cryomodule Design and New Approaches", Carlo Pagani, INFN Milano-LASA and University of Milano, Via Fratelli Cervi, 201, 20090 Segrate (MI), Italy

2. "THERMAL AND STRUCTURAL MODELING OF THE TTF CRYOMODULE COOLDOWN AND COMPARISON WITH EXPERIMENTAL DATA"
   S. Barbanotti, P. Pierini, INFN Milano, Segrate (MI), Italy  K. Jensch, R Lange, W. Maschmann, DESY, Hamburg, Germany

Material:
- Material of shield is OFE Cu10100
SOLID 87 element in ANSYS:

- SOLID87 is well suited to model irregular meshes
- SOLID87 is 3-D 10-Node Tetrahedral Thermal Solid element.
- The element has one degree of freedom, temperature, at each node.
- The element is applicable to a three-dimensional, steady-state or transient thermal analysis.
- If the model containing this element is also to be analyzed structurally, the element should be replaced by the equivalent structural element (such as SOLID92). A 20-node thermal solid element, SOLID90, is also available.
- Convections or heat fluxes (but not both) may be input as surface loads at the element faces.

Output Data:

The solution output associated with the element is in two forms:

- Nodal temperatures included in the overall nodal solution

*ANSYS Theory Reference
Assumptions and Restrictions:

• The element must not have a zero volume.
• An edge with a removed midside node implies that the temperature varies linearly, rather than parabolically, along that edge.
• The specific heat and enthalpy are evaluated at each integration point to allow for abrupt changes (such as melting) within a coarse grid of elements.
• A free surface of the element (i.e., not adjacent to another element and not subjected to a boundary constraint) is assumed to be adiabatic.
• Thermal transients having a fine integration time step and a severe...
Meshing thermal shield

• The model is then meshed using 10 node tetrahedron element.
• 10 node tetrahedron is higher order element and will lead to more accurate results than lower order ones.
• Figure shows the meshed model of thermal shield.
Results of 10 Hrs linear cooldown analysis of thermal shield

After 3 Hrs

After 6.3 Hrs

After 10 Hrs

After 11.3 Hrs

Max. temp. diff. over time
Boundary & Initial conditions:

• Heat inleak from coupler port : 2 Watts
• Heat inleak from support post port : 3.3 Watts
• Radiation heat flux : 1.5 W/m²
• Initial temperature of shield : 300K
• Convection heat loads :
  • Temperature varies linearly from 300K to 80K for 10 Hrs (10 Hrs linear cooldown*).
  • Heat transfer coefficient values corresponding to temperature at different times is taken.
## Cryogen Distribution Scheme

### Pipe Sizes for different circuits

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Pipeline or Component Identified</th>
<th>Material</th>
<th>Design Pressure (psia)</th>
<th>O.D. inch</th>
<th>O. D. mm</th>
<th>I.D. mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Liquid nitrogen supply and return line</td>
<td>SS 316 L</td>
<td>80</td>
<td>0.5</td>
<td>12.7</td>
<td>10.2</td>
</tr>
<tr>
<td>2</td>
<td>5 K intercept &amp; frame bridge Inlet line</td>
<td>SS 316 L</td>
<td>80</td>
<td>0.5</td>
<td>12.7</td>
<td>10.2</td>
</tr>
<tr>
<td>3</td>
<td>5 K helium intercept and frame bridge outlet/return line</td>
<td>SS 316 L</td>
<td>80</td>
<td>0.5</td>
<td>19.05</td>
<td>15.75</td>
</tr>
<tr>
<td>4</td>
<td>Cool down/warm-up line for cavity and LL dewar</td>
<td>SS 316 L</td>
<td>80</td>
<td>0.5</td>
<td>12.7</td>
<td>10.2</td>
</tr>
<tr>
<td>5</td>
<td>Capillary (from cooldown/warmup line to Liquid level dewar)</td>
<td>SS 316 L</td>
<td>80</td>
<td>0.25</td>
<td>6.35</td>
<td>3.86</td>
</tr>
<tr>
<td>6</td>
<td>2 K helium supply pipeline from JT valve and HX</td>
<td>SS 316 L</td>
<td>80</td>
<td>0.5</td>
<td>12.7</td>
<td>10.2</td>
</tr>
<tr>
<td>7</td>
<td>2 K 2 phase helium line or manifold</td>
<td>SS 316 L</td>
<td>80</td>
<td>4</td>
<td>101.6</td>
<td>95.5</td>
</tr>
<tr>
<td>8</td>
<td>2 K helium pumping from 2 K 2 ø helium manifold</td>
<td>SS 316 L</td>
<td>80</td>
<td>4.5</td>
<td>114.3</td>
<td>108.2</td>
</tr>
<tr>
<td>9</td>
<td>Gaseous helium p relief line /venting line</td>
<td>SS 316 L</td>
<td>80</td>
<td>4.5</td>
<td>114.3</td>
<td>108.2</td>
</tr>
<tr>
<td>10</td>
<td>Liquid nitrogen trace tubing on 80 K thermal shield</td>
<td>OFE copper</td>
<td>80</td>
<td>0.5</td>
<td>12.7</td>
<td>10.2</td>
</tr>
<tr>
<td>11</td>
<td>Liquid Level dewar</td>
<td>SS 316 L</td>
<td>80</td>
<td>4.5</td>
<td>114.3</td>
<td>108.2</td>
</tr>
</tbody>
</table>
### Cool down estimates of 80 K Shield

#### Cool-down estimate of different liquid nitrogen cooled subsystems based on heat capacity for given flow rate

<table>
<thead>
<tr>
<th>Liquid Nitrogen</th>
<th>LN2 Shield</th>
<th>Feedcan shield interface</th>
<th>Support post flange/piping etc.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>OFE Copper</td>
<td>OFE Copper</td>
<td>SS</td>
<td></td>
</tr>
<tr>
<td>Density; Kg/m3</td>
<td>8960</td>
<td>8960</td>
<td>7900</td>
<td></td>
</tr>
<tr>
<td>Total weight of parts; Kg</td>
<td>380</td>
<td>20</td>
<td>15</td>
<td>415 Kg</td>
</tr>
<tr>
<td>Comments</td>
<td>Weight with 2 end covers of shield</td>
<td>Shield inside feedcan at interface region</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Int Cp 80 -300 K; j/kg</td>
<td>7.00E+04</td>
<td>7.00E+04</td>
<td>1.36E+05</td>
<td></td>
</tr>
<tr>
<td>Enthalpy to be removed; j</td>
<td>2.66E+07</td>
<td>1.40E+06</td>
<td>2.04E+06</td>
<td></td>
</tr>
<tr>
<td>Mass of LN2 per Kg of material; Kg/Kg</td>
<td>0.27</td>
<td>0.27</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>Corresponding mass of L N2; Kg</td>
<td>102.6</td>
<td>5.4</td>
<td>4.05</td>
<td></td>
</tr>
<tr>
<td>Cooldown times at 2 g/s; hours</td>
<td><strong>14.3</strong></td>
<td><strong>0.8</strong></td>
<td><strong>0.6</strong></td>
<td><strong>15.6 Hrs.</strong></td>
</tr>
<tr>
<td>Comments</td>
<td>flow of 2 g/s considered</td>
<td>flow of 2 g/s considered</td>
<td>flow of 2 g/s considered</td>
<td></td>
</tr>
</tbody>
</table>
Prototyping to validate the Design

• As of now there is no necessity of developing a full scale prototype as other details of the system are being developed.

• This prototyping work is being done in order to
  - Validate our calculations
    - These calculations are necessary if some change has to be made in the CSP

• As we are thinking of removing 4K shield we wanted to calculate what is the additional heat leak in.

• We can also think about simplifying the assembly process for this CSP hence this prototyping is being done

• OFF COURSE full scale prototyping will also be done.
3-D model showing prototype of frame bridge for HTS in CCTR
Cool-down Study of Thermal Shield in CCTR

Data acquisition from temperature sensors during cool-down of liquid nitrogen cooled thermal shield
Material assign are S.S. and Invar for rod
Cool down from 300 K to 80 K
End of Invar Rod is attached to fixed support.
Cavity Load acted upon columns = \( \frac{180}{4} = 45 \text{ Kg} \) i.e., 450N
Boundary conditions: One side of cart is allowed to slide along Y axis i.e. longitudinally, whereas other side is fixed only in Z-direction. Support post end of Invar Rod is attached to fixed support.
Cool down to 80 K from 300 K
Max. 42 Mpa stresses are showing at joints otherwise stresses are well below 20 Mpa
Static structural FEA analysis of cavity cart

X-axis

- Directional deformation sof supporting frame/bracket on cart
  - Near coupler = up to 0.5 mm along axis of HTS-2 (X-direction)
  - < 1 mm in vertically at column (Z-direction) so additional thick ribs introduced to increase stiffness of bracket.
Ideal shape of cool down curve from 300K to 80 K

Ideal cool down curves for different mass of copper shield from 300 to 80 K
Load bearing Capacity of Prototype

Poisson's Ratio Al 6061T6c Disc $\mu_1 = 0.33$
Poisson's Ratio G11 Tube $\mu_2 = 0.2$
Poisson's Ratio Al 6061T6c Ring $\mu_3 = 0.33$

Young's Modulus Al 6061T6 Disc, $E_1 = 70\text{ Gpa}$
Young's Modulus G11 Tube, $E_2 = 28\text{ Gpa}$
Young's Modulus Al 6061T6 Ring, $E_3 = 70\text{ Gpa}$

Friction Coeff b/w Al 6061T6 Disc/Ring and G11 Tube $0.3$

Max Axial Load taken by Inner Joint $F_i = 2700\text{ Kg}$
Max Axial Load taken by Outer Joint $F_o = 2361\text{ Kg}$

Contact pressure at Inner Joint $P_i = 32.8\text{ MPa}$
Contact Pressure at Outer Joint $P_o = 26\text{ MPa}$
Stresses Developed due to Shrink Fitting
Radial and Circumferential Stresses Developed at ID & OD of Disc, Tube and Ring material

<table>
<thead>
<tr>
<th>Material</th>
<th>Stresses at Disc ID</th>
<th>Stresses at Disc OD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Disc Al 6061T6</td>
<td>Radial: 0MPa, Circumferential: -67.7MPa</td>
<td>Radial: -32.8MPa, Circumferential: -35MPa</td>
</tr>
<tr>
<td>Tube G11</td>
<td>Radial: -32.8MPa, Circumferential: 42.7MPa</td>
<td>Radial: -26MPa, Circumferential: 36MPa</td>
</tr>
<tr>
<td>Outer Ring Al 6061T6</td>
<td>Radial: -26MPa, Circumferential: 70MPa</td>
<td>Radial: 0MPa, Circumferential: 46MPa</td>
</tr>
</tbody>
</table>

Allowable Stress G11: 62Mpa
Allowable Stress Al6061 T6: 70MPa
Allowable Stress SS304: 130Mpa
Prototype Developed

ID of G11Tube: 57mm
OD of G11Tube: 63mm

Material of Inner Disc and Outer Ring: Al6061 T6

Single Joint

Single Joint-Top View

Double Joint
Prototype Testing
Prototype Test Result

Load Testing of Inner Joint

Calculated Max Load Bearing capacity 2700 kg
Max Load before Slippage 2750 kg