Conduction Cooled Cryostat for Small-scale Superconducting Radio Frequency Accelerator Applications

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Introduction

• Fermilab’s Illinois Accelerator Research Center (IARC) is designing several small-scale ~10 MeV conduction cooled accelerators

• Applications include
  • Destruction of PFAS (forever chemicals)
  • Medical device sterilization
  • Wastewater and ballast water treatment
  • Curing roadway pavement

• One such project for the U.S. Army Engineer Research Development Center (ERDC) consists of a single 1.3 GHz nine-cell cavity

• This report introduces the preliminary design of the cryostat for that conduction cooled cavity
Outline

• Cryostat design
  • Vacuum vessel
  • Magnetic shield
  • Thermal shield and MLI
  • Cavity assembly
  • Cavity supports
  • Coupler
  • Cryocoolers

• Thermal and structural analysis

• Summary
Cryostat assembly

Approximate size
2.2 m long
1.3 m wide
2 m high
Cryostat assembly

- Cryocoolers
- Vacuum vessel
- Beamline gate valve
- Instrumentation ports
- Cavity assembly
- Thermal shield and MLI
- Magnetic shield
- Supports
Vacuum vessel

• Contains the insulating vacuum and secures all other cryostat components to the floor
• “Bathtub” style
• 300 series stainless steel
• Top plate thickness of 31.75 mm and shell and end thickness of 19.05 mm for vacuum loading
• Top plate is bolted and O-ring-sealed to the lower shell
Magnetic shield

• Shields cavity assembly from Earth’s magnetic field and local magnetic sources

• Material is room temperature, 1.5 mm thick, mu-metal – low temperature alloy not required
Thermal shield

• Intercepts thermal radiation from the vacuum vessel and magnetic shield and provides heat sinks for supports, tuner, etc.
• Material is 6061 aluminum, but copper is an option
• Cooled by the cryocooler first stage and operates nominally from 30 to 50 K
• MLI will cover the thermal shield and cavity assembly
Cavity assembly

• 1.3 GHz nine-cell elliptical cavity
• Same design as that used in LCLS-II cryomodules
• Nb$_3$Sn coated to ensure high-Q and to increase operating temperature margin
• Cooling rings welded at two places on each cell equator
Cooling structure

• Provides the connection between the cryocoolers and the cavity
• Material is 5N aluminum (99.999%)
• Attachments are via brass fasteners, Belleville washers, and Indium foil
Cavity tuner and frame

• Eight-bar Grade 2 titanium frame replaces conventional helium vessel to react tuner forces
• Piezo tuner adapted from the LCLS-II design
Cavity, cooling structure, tuner, and frame assembly

\( \text{Nb}_3\text{Sn}-\text{coated 650 MHz cavity with welded Nb rings for attaching cooling links} \)
Cavity supports

- Two shrink-fit glass-reinforced composite support assemblies
- Similar in design to other superconducting magnet and SRF cryomodule supports
- Novel design orients supports horizontally with the cold-to-warm transition passing through the center
- Cavity to support attachment via a thin flange to provide lateral stiffness and axial flexibility
Coupler

• Design adapted from 325 and 650 MHz couplers for PIP-II at Fermilab
• 20 kW coaxial design with room temperature waveguide connection
• One ceramic window at room temperature
• Air-cooled center conductor
Cryocoolers

• Initial cryostat design was based on Cryomech PT425 pulse-tube cryocoolers (~2.7 W @ 4.2 K / 55 W @45K)

• Larger capacity PT450 has been announced (~5 W @ 4.2 K) *(see C2Or3A-03 for more details)*

• Current plan is to adopt the PT450s and utilize four for our sub-20 W 4.5 K heat load
Thermal and structural analysis

• Model consists of the
  • Thermal shield
  • Cold-to-warm transition
  • Supports
  • Cavity
  • Cooling structure
  • Cavity to support connection flange
Thermal boundary conditions

• 300 K: Support base and cold-to-warm transition warm end
• 50 K: Thermal shield to cryocooler connections
• 4.5 K: Cryocooler cold head connections
• 1.5 W/m² heat flux: Thermal shield
• 0.15 W/m² heat flux: Cavity assembly
• 1 W/m²-K conductance at bolted thermal contacts
• 1 W: Coupler connection
• 14 W: RF cavity load
Structural boundary conditions

• Fixed support: Support post base and cold-to-warm transition warm end
• Gravity load: Entire model
## Thermal analysis results

<table>
<thead>
<tr>
<th>Load case</th>
<th>50 K heat load (W)</th>
<th>4.5 K heat load (W)</th>
<th>Cavity cell $T_{\text{max}}$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>21.3</td>
<td>1.1</td>
<td>4.6</td>
</tr>
<tr>
<td>Dynamic (14 W)</td>
<td>21.3</td>
<td>16.1</td>
<td>5.9</td>
</tr>
</tbody>
</table>
Thermal analysis results

Maximum temperature in the cell structure ~5.9 K

Maximum thermal shield temperature ~55K
Structural analysis results

Maximum vertical deflection ~1.5 mm

Maximum axial cavity to support flange deflection ~0.65 mm
Summary

• Preliminary design for the ERDC cryostat is complete

• Still need to:
  • Integrate newest line of cryocoolers
  • Minimize temperature rise across bolted connections in the cooling structure
  • Complete magnetic shield simulations
  • Further optimize structural performance to reduce stresses and deformations
  • Begin transport analysis

• See C2Po1B-10, Ram Dhuley et al, for a design overview of a 650 MHz conduction cooled cavity cryostat
Thank you.