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

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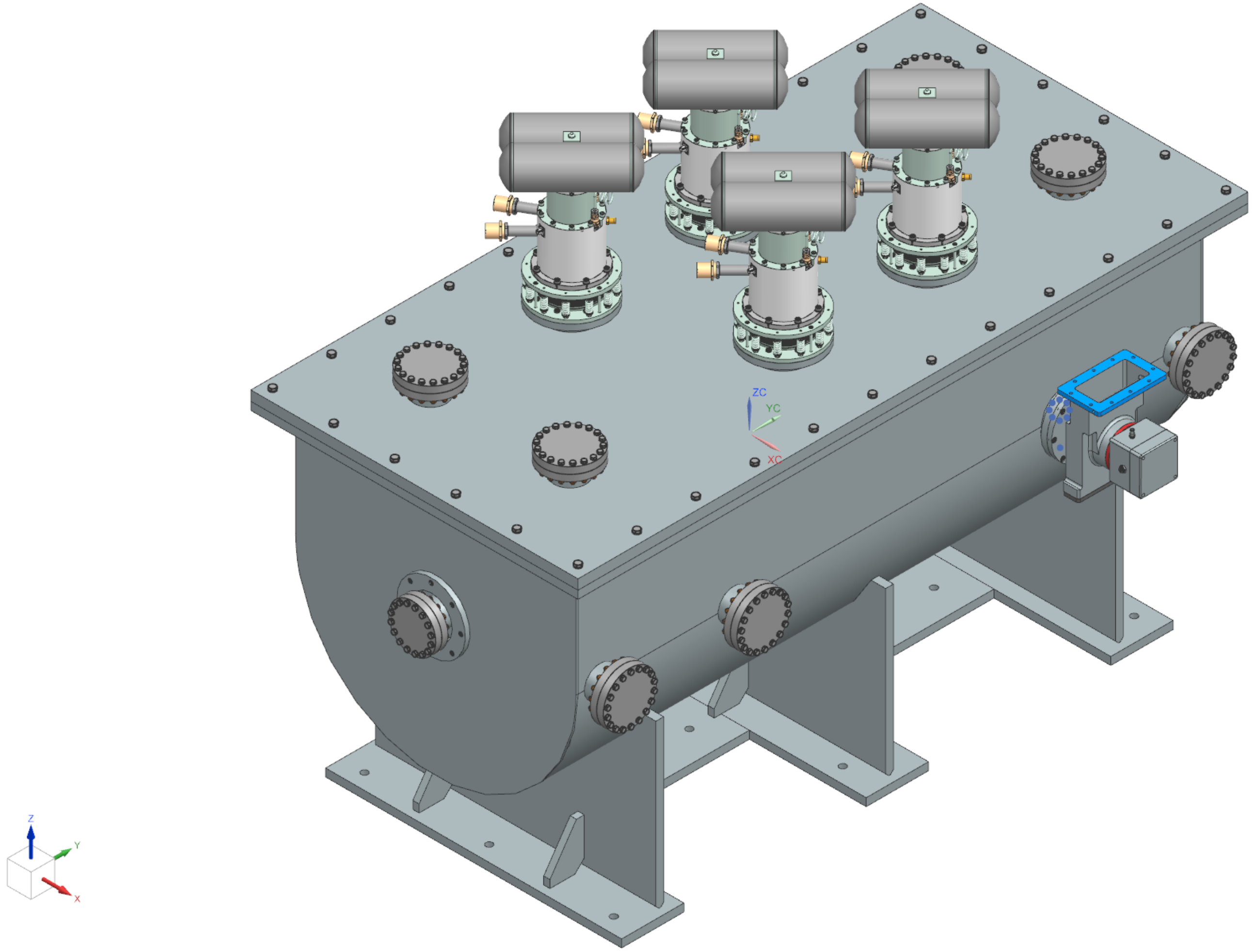
Introduction

- 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

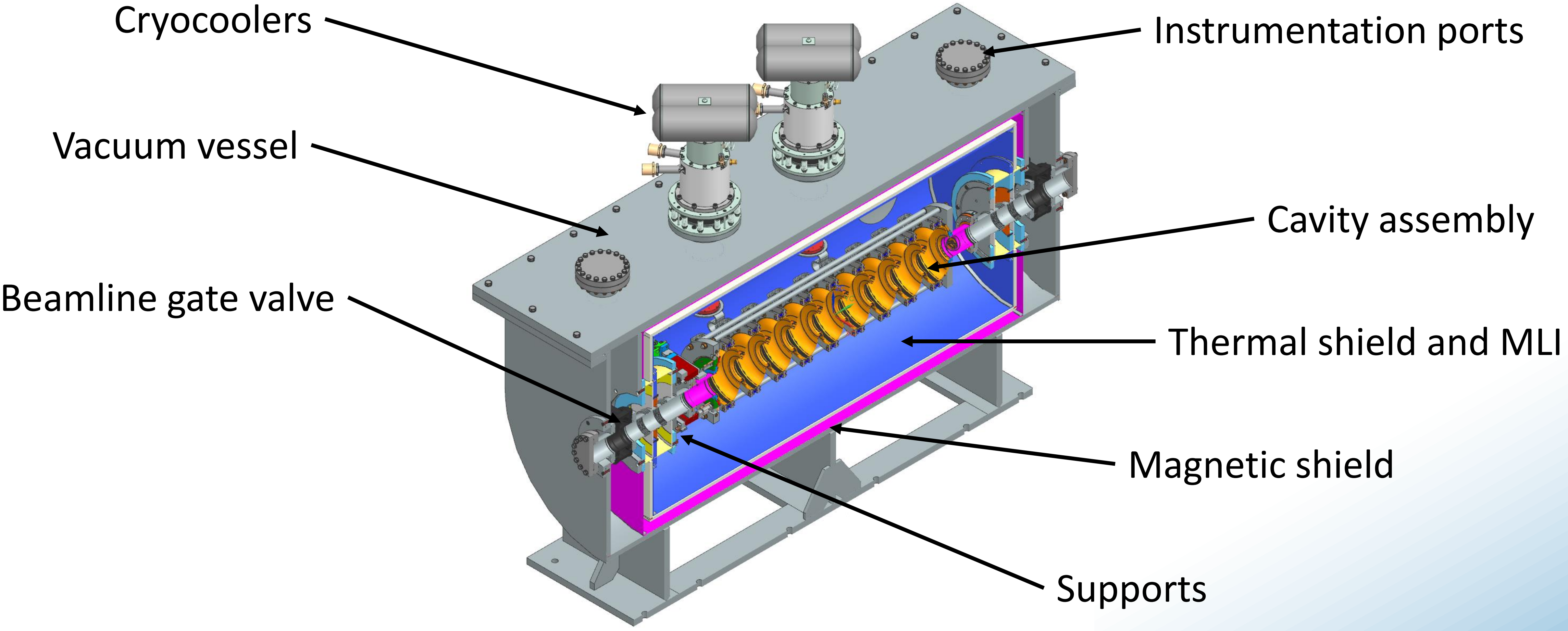
Cryostat assembly



<u>Approximate size</u>

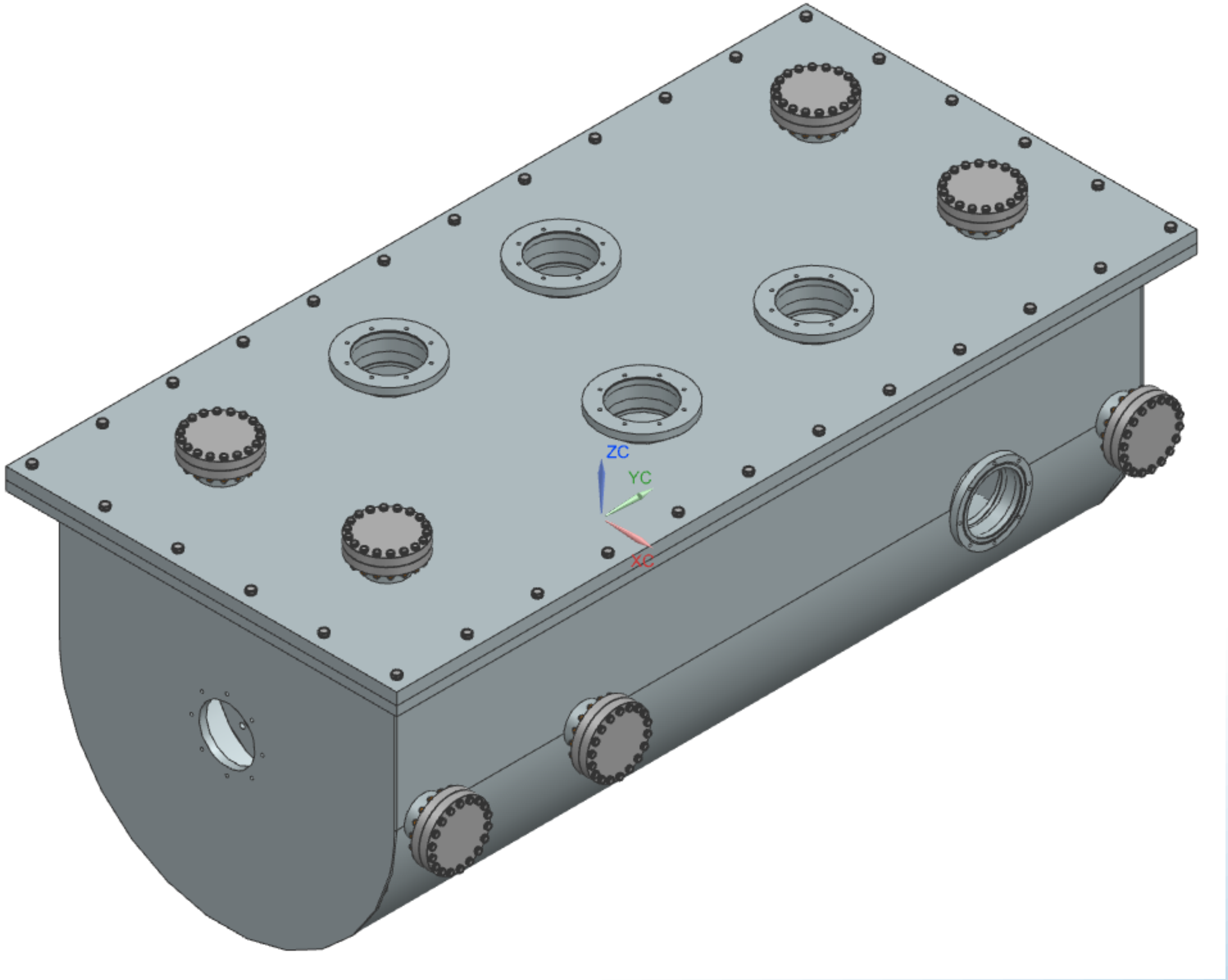
2.2 m long
1.3 m wide
2 m high

Cryostat assembly



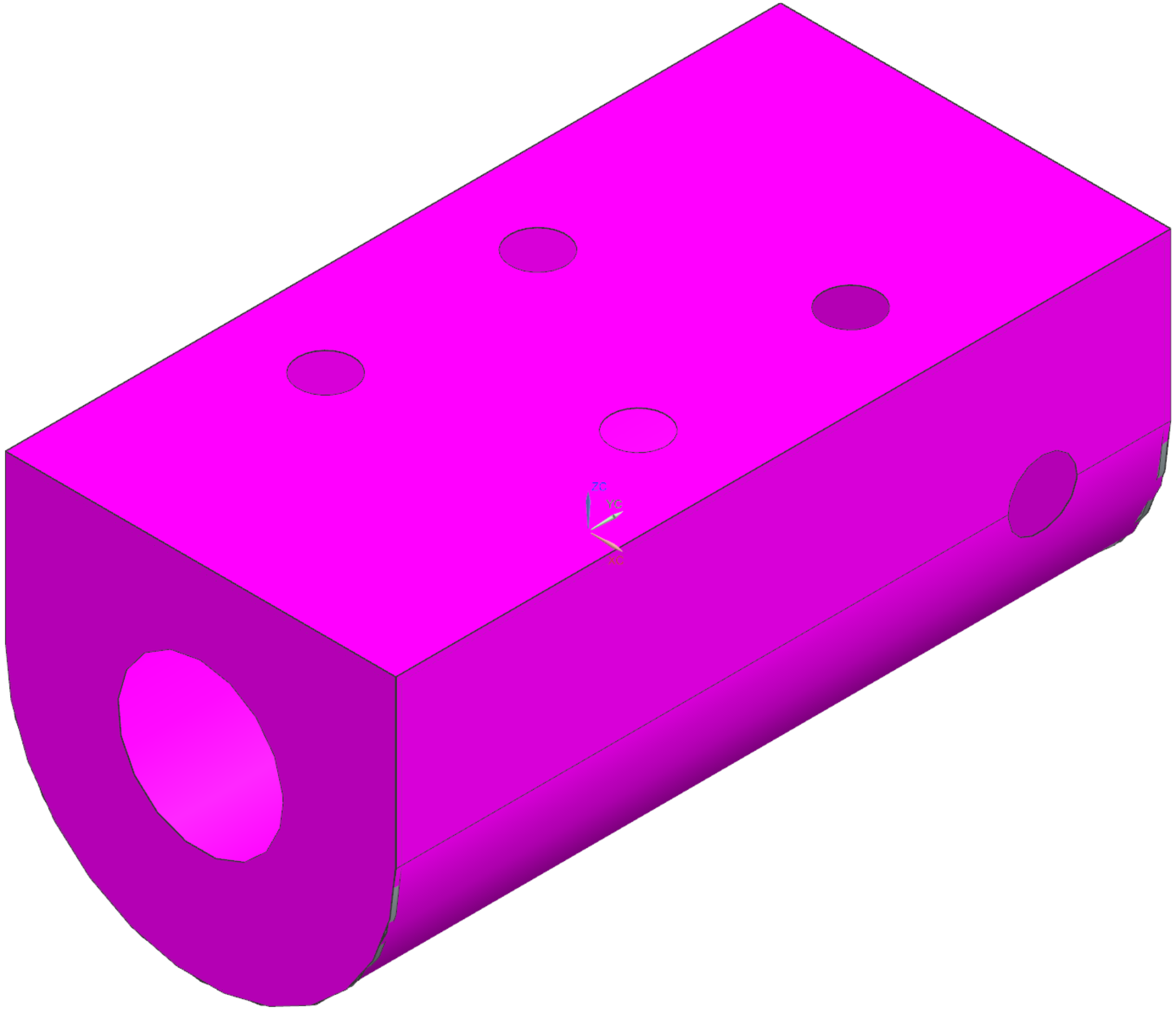
Vacuum vessel

- 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



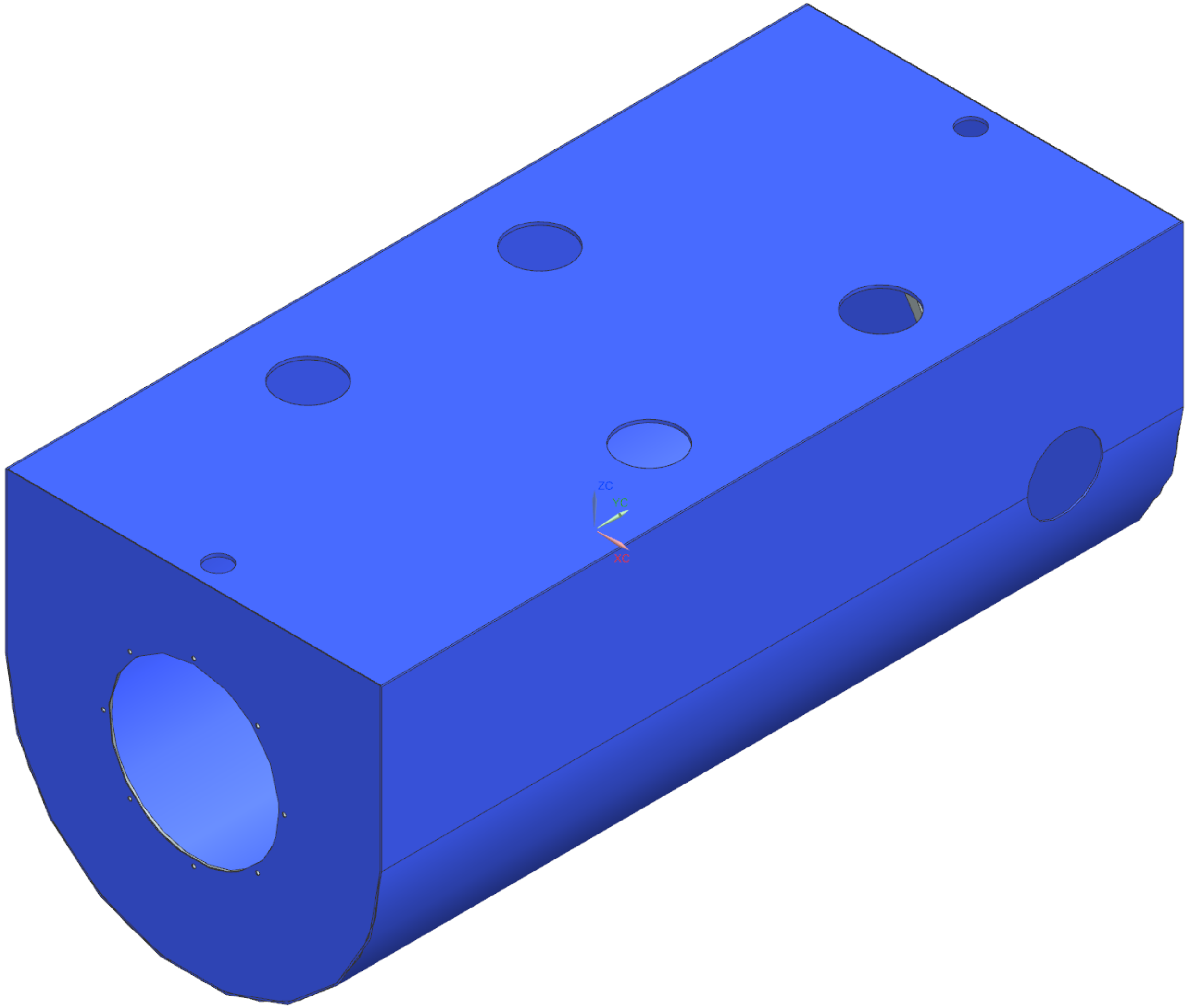
Magnetic shield

- 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



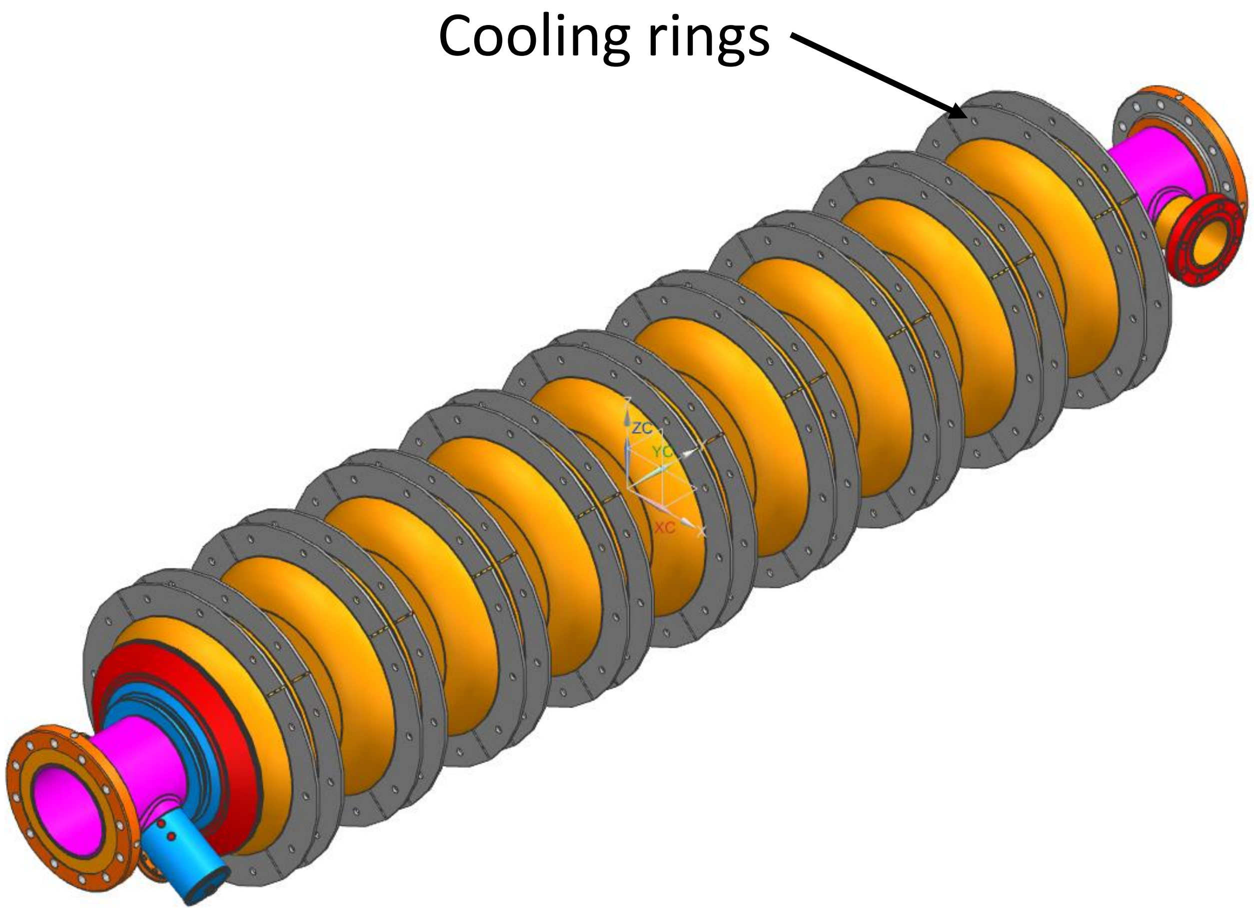
Thermal shield

- 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



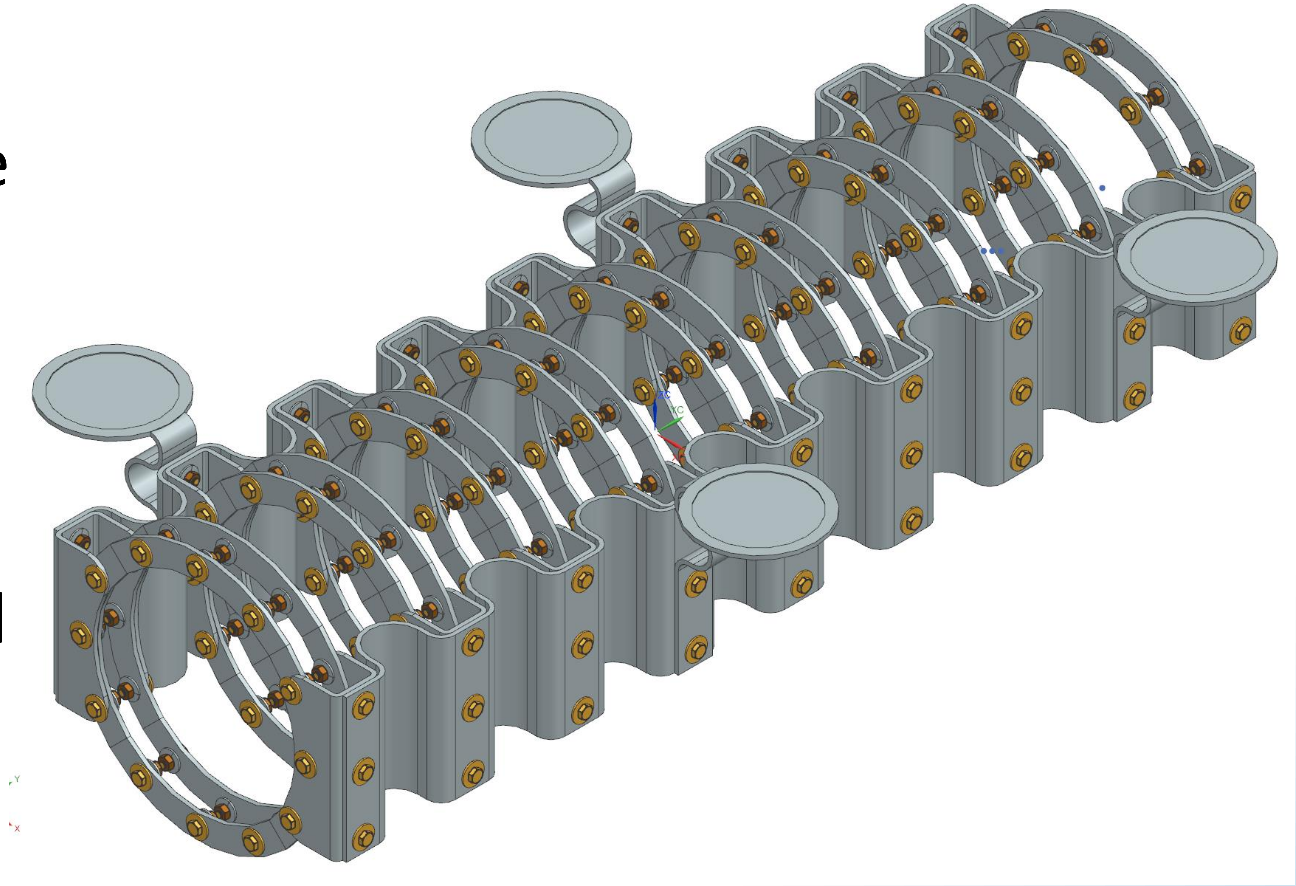
Cavity assembly

- 1.3 GHz nine-cell elliptical cavity
- Same design as that used in LCLS-II cryomodules
- Nb_3Sn coated to ensure high-Q and to increase operating temperature margin
- Cooling rings welded at two places on each cell equator



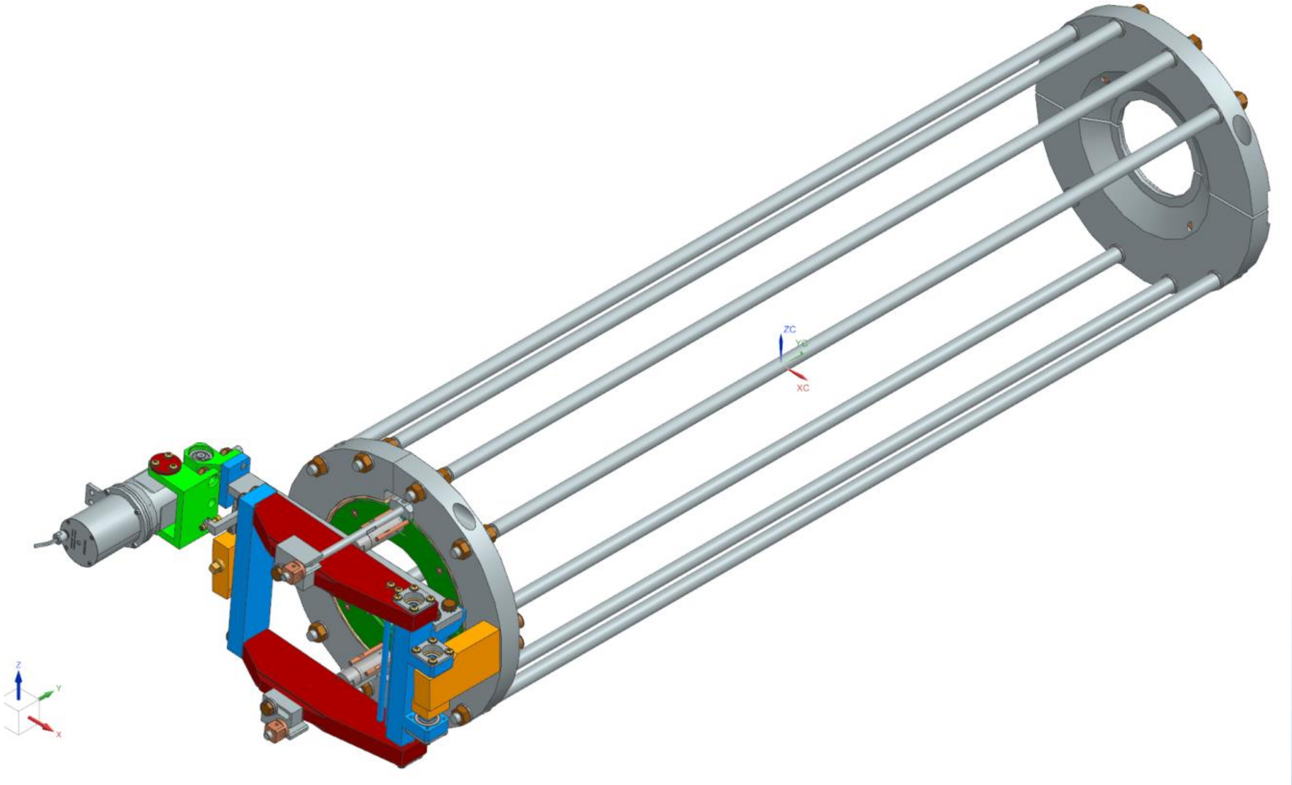
Cooling structure

- 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

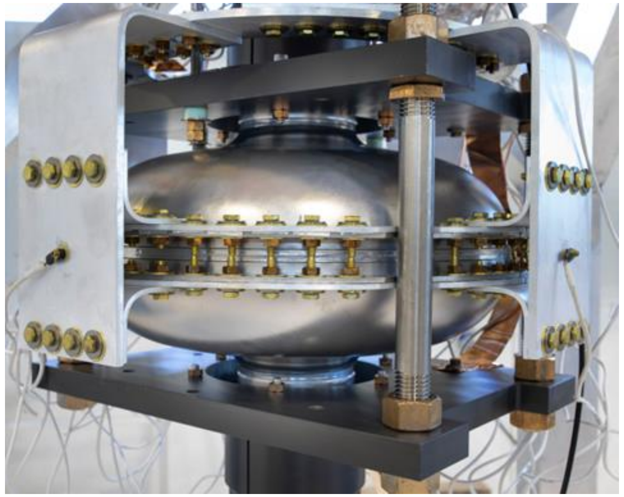


Cavity tuner and frame

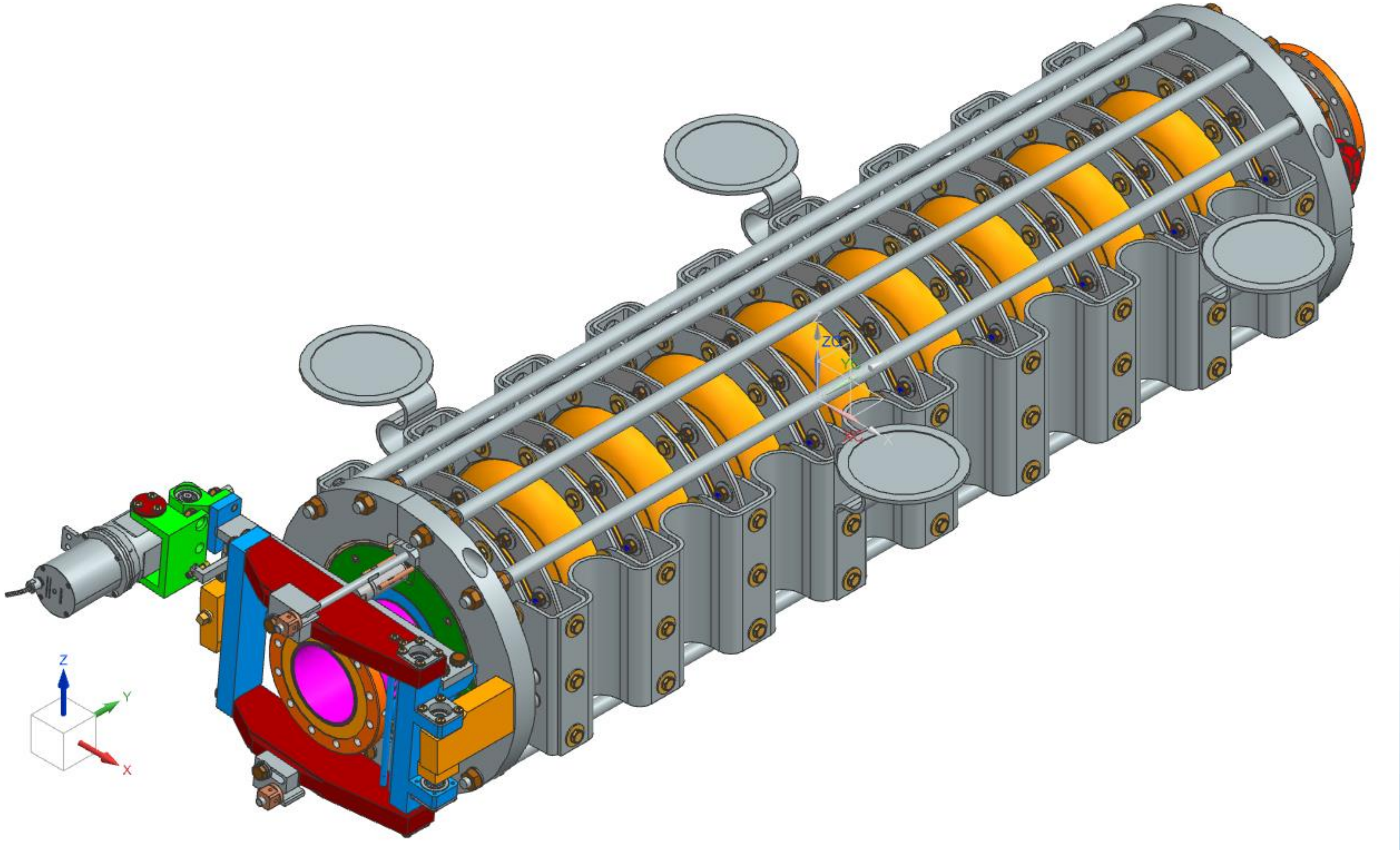
- Eight-bar Grade 2 titanium frame replaces conventional helium vessel to react tuner forces
- Piezo tuner adapted from the LCLS-II design



Cavity, cooling structure, tuner, and frame assembly

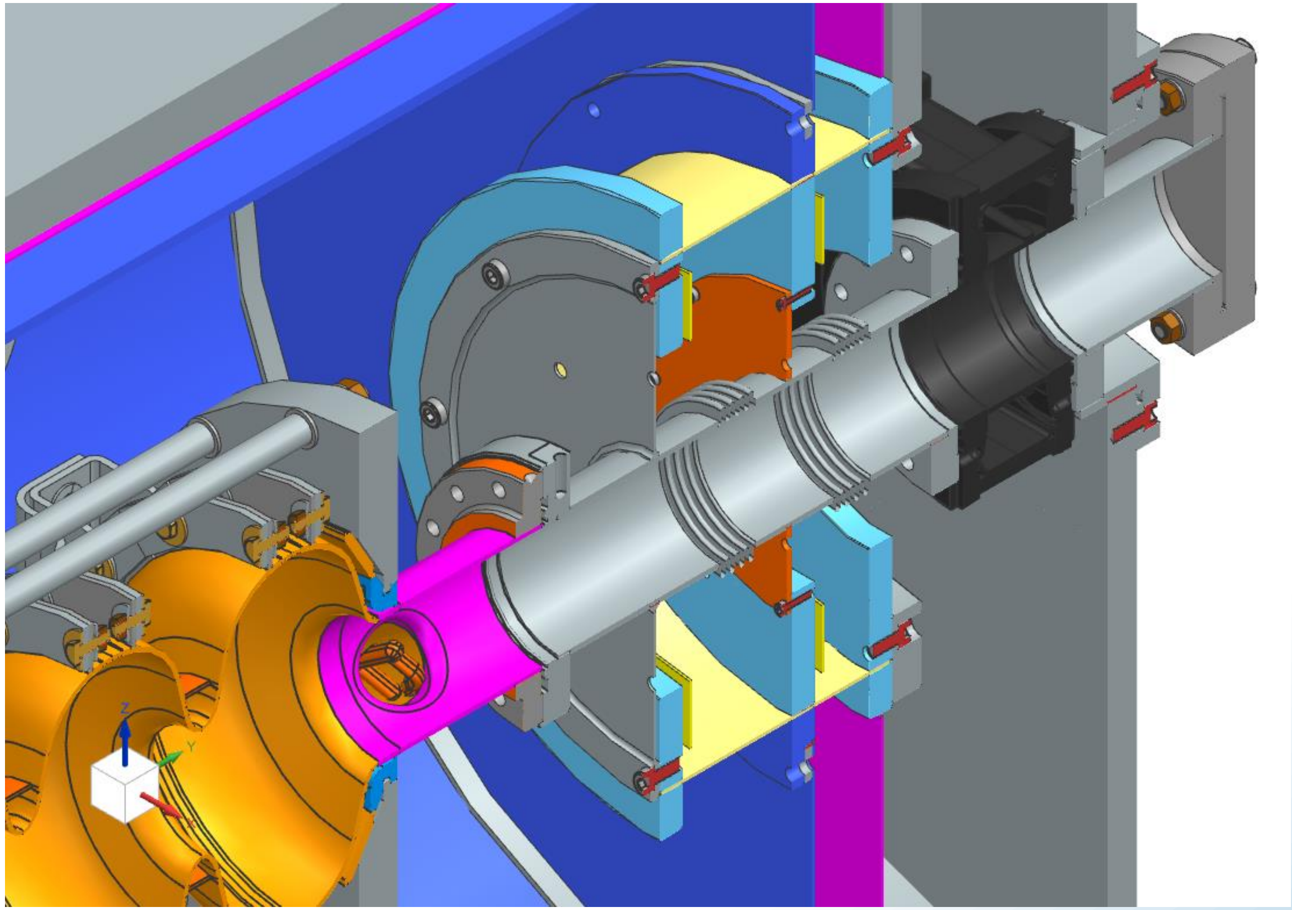


Nb$_3$Sn-coated 650 MHz cavity with welded Nb rings for attaching cooling links



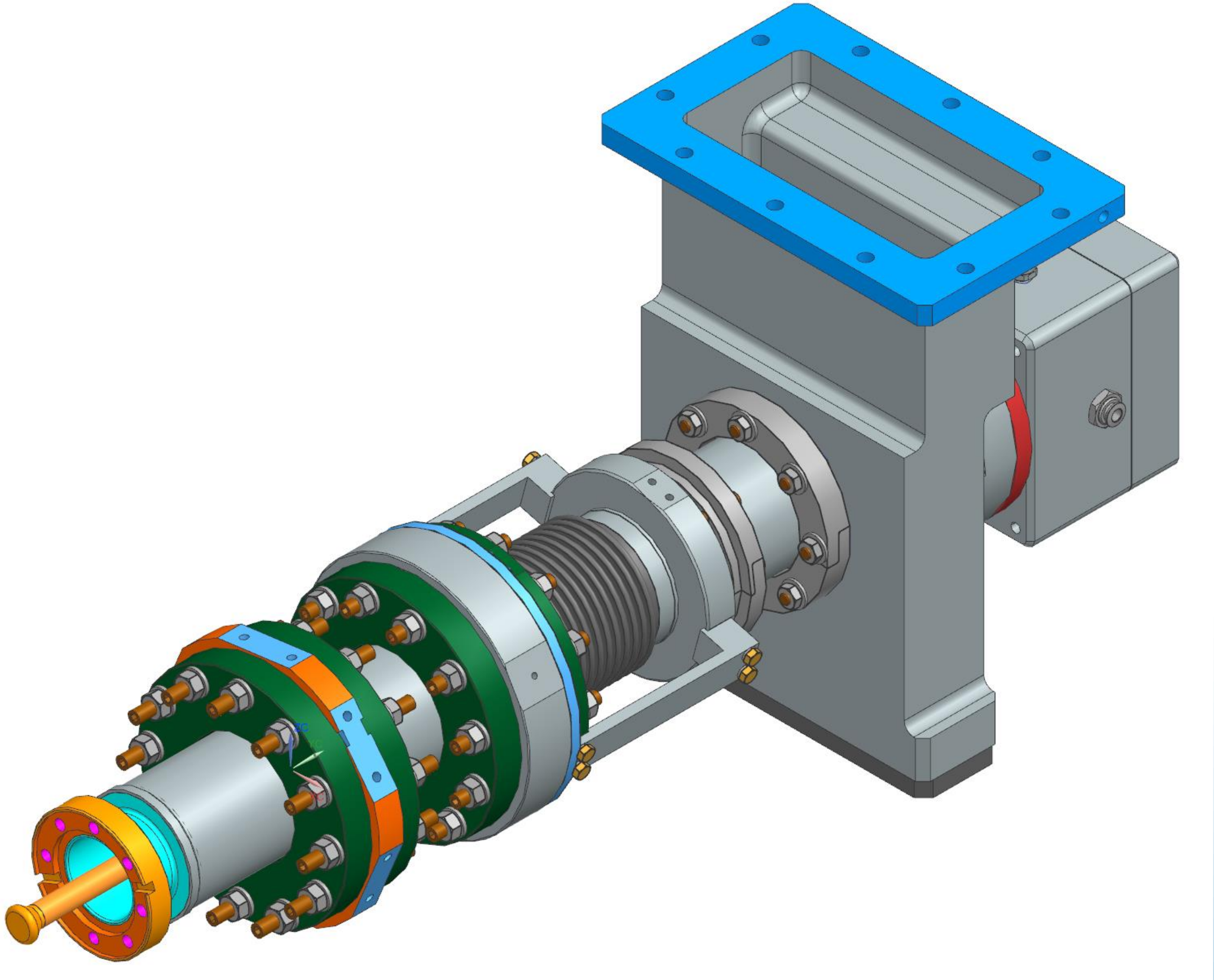
Cavity supports

- 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



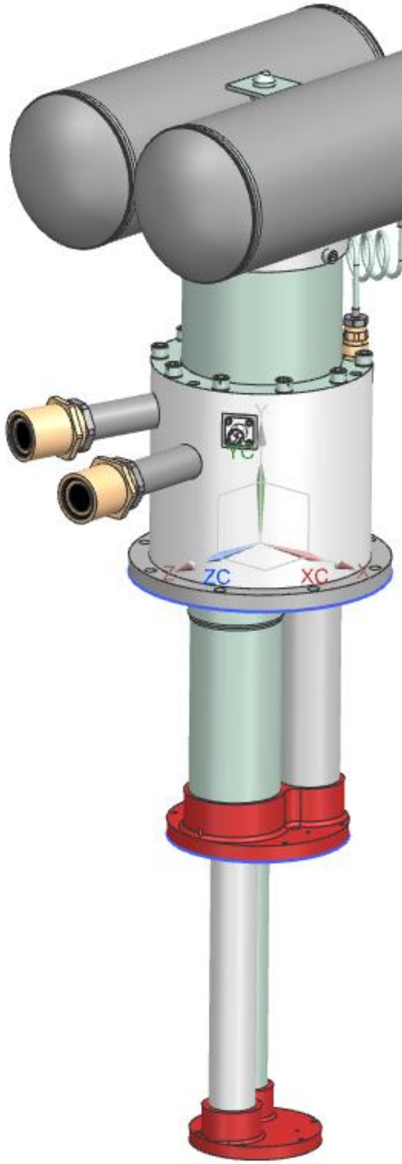
Coupler

- 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



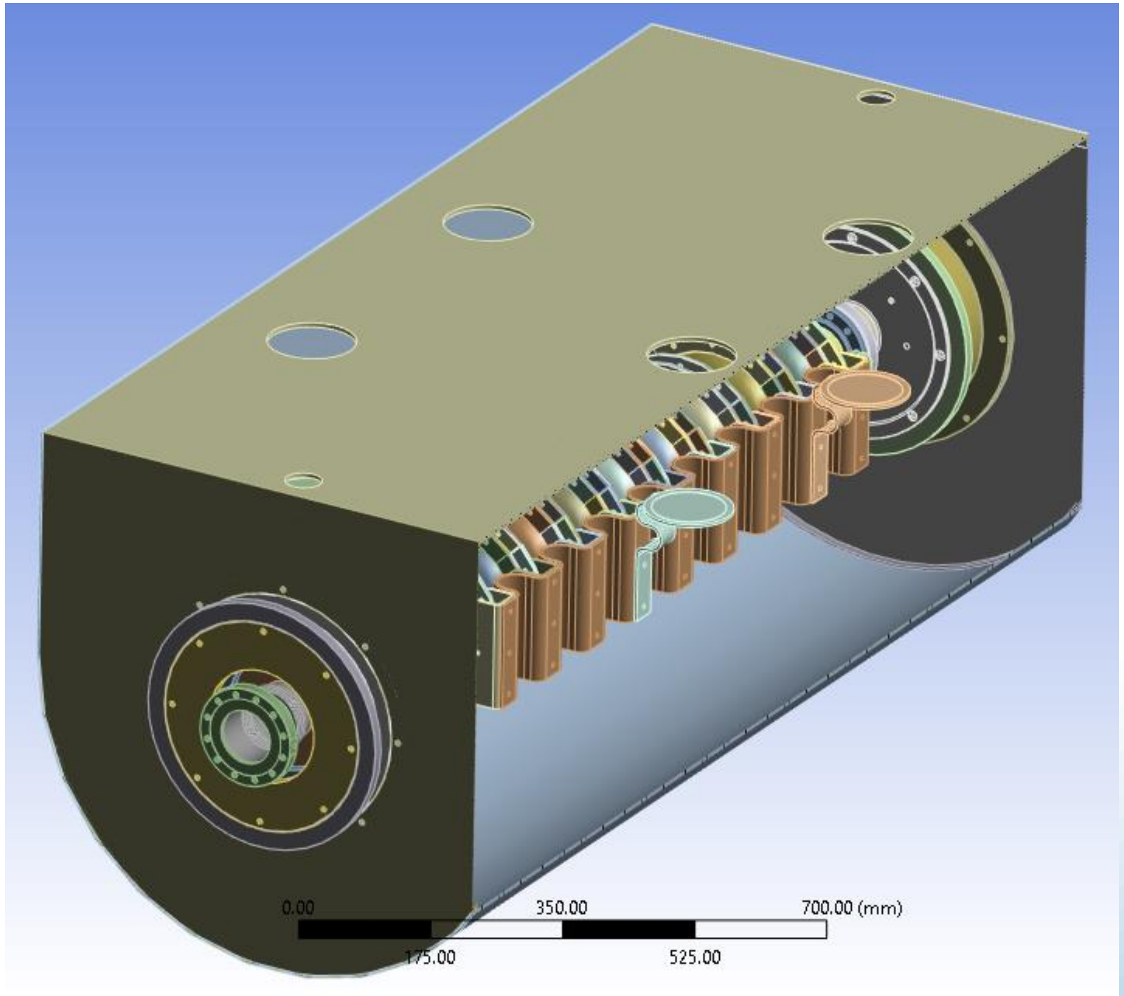
Cryocoolers

- 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



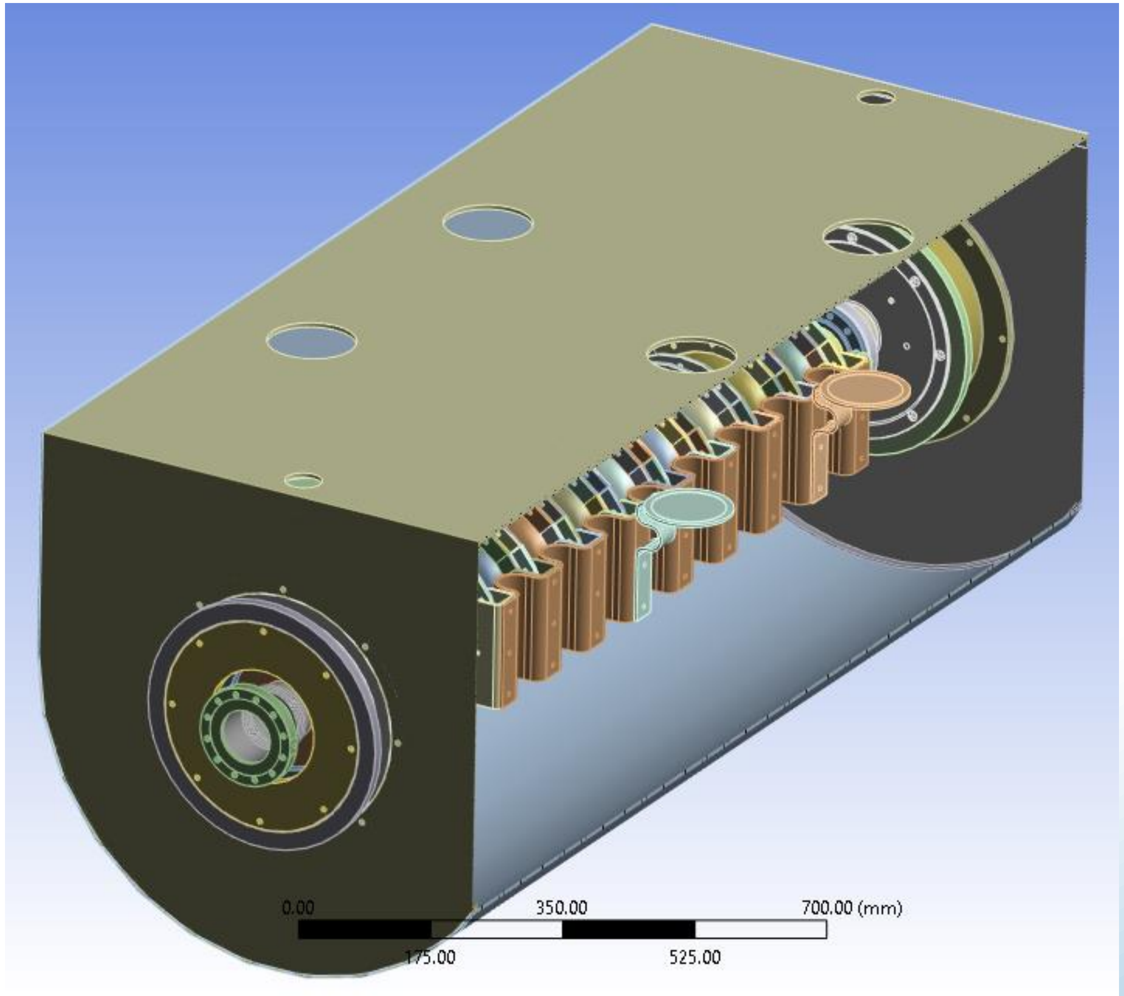
Thermal and structural analysis

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



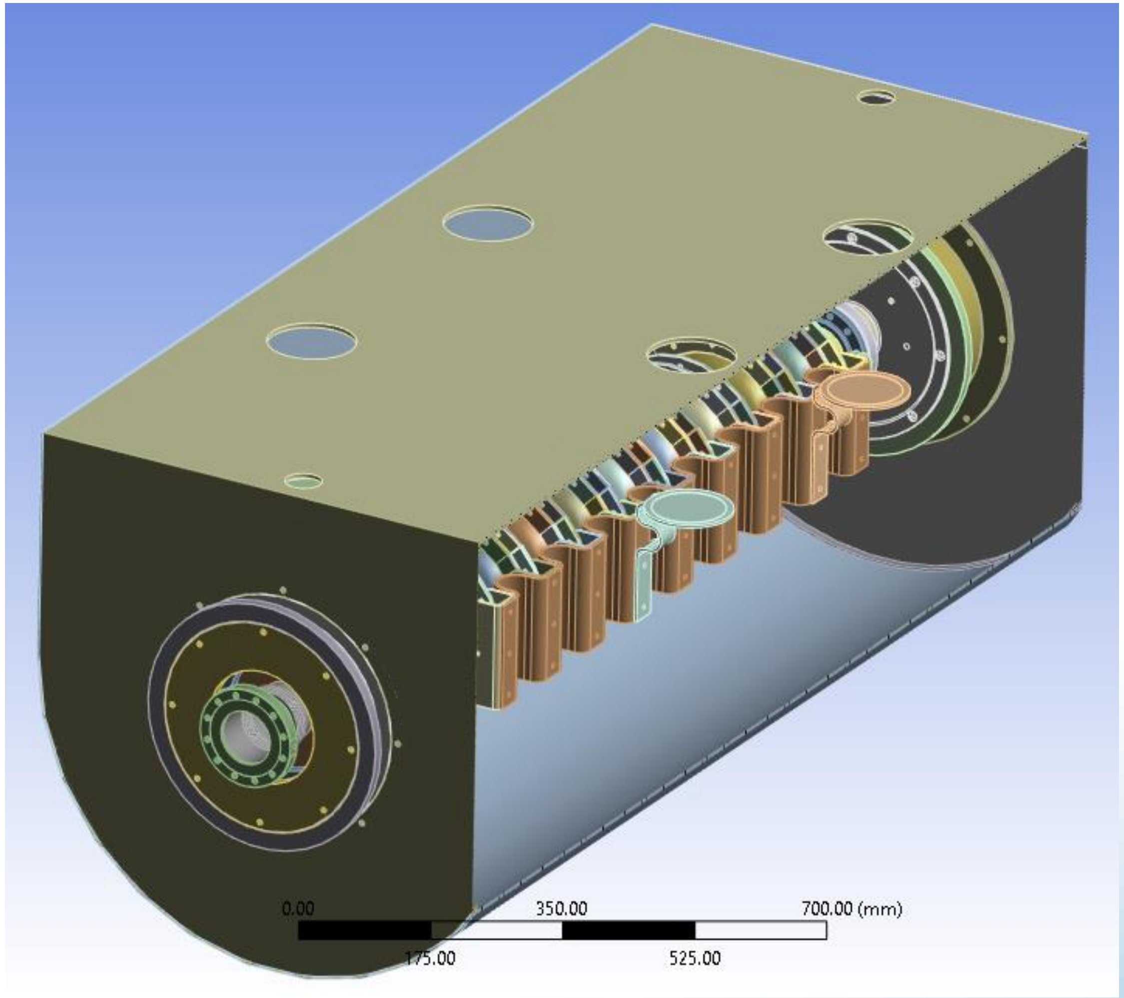
Thermal boundary conditions

- 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/m^2 heat flux: Thermal shield
- 0.15 W/m^2 heat flux: Cavity assembly
- 1 W/cm^2-K conductance at bolted thermal contacts
- 1 W: Coupler connection
- 14 W: RF cavity load



Structural boundary conditions

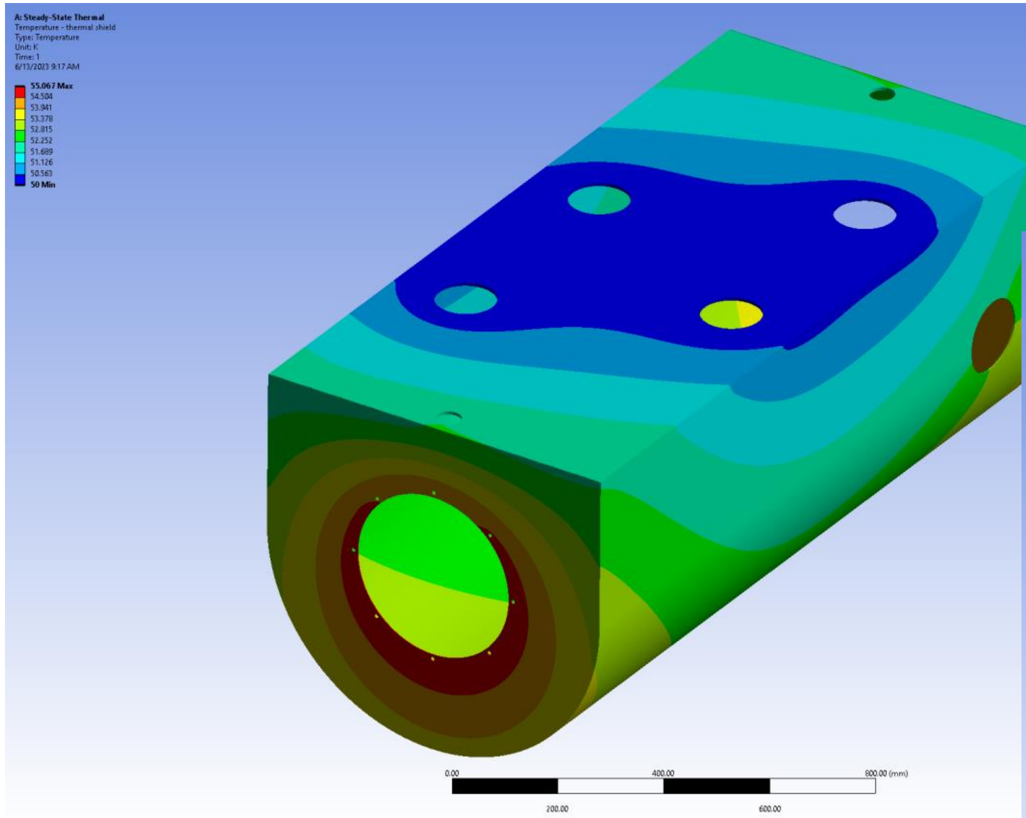
- Fixed support: Support post base and cold-to-warm transition warm end
- Gravity load: Entire model



Thermal analysis results

Load case	50 K heat load (W)	4.5 K heat load (W)	Cavity cell T_{max} (K)
Static	21.3	1.1	4.6
Dynamic (14 W)	21.3	16.1	5.9

Thermal analysis results

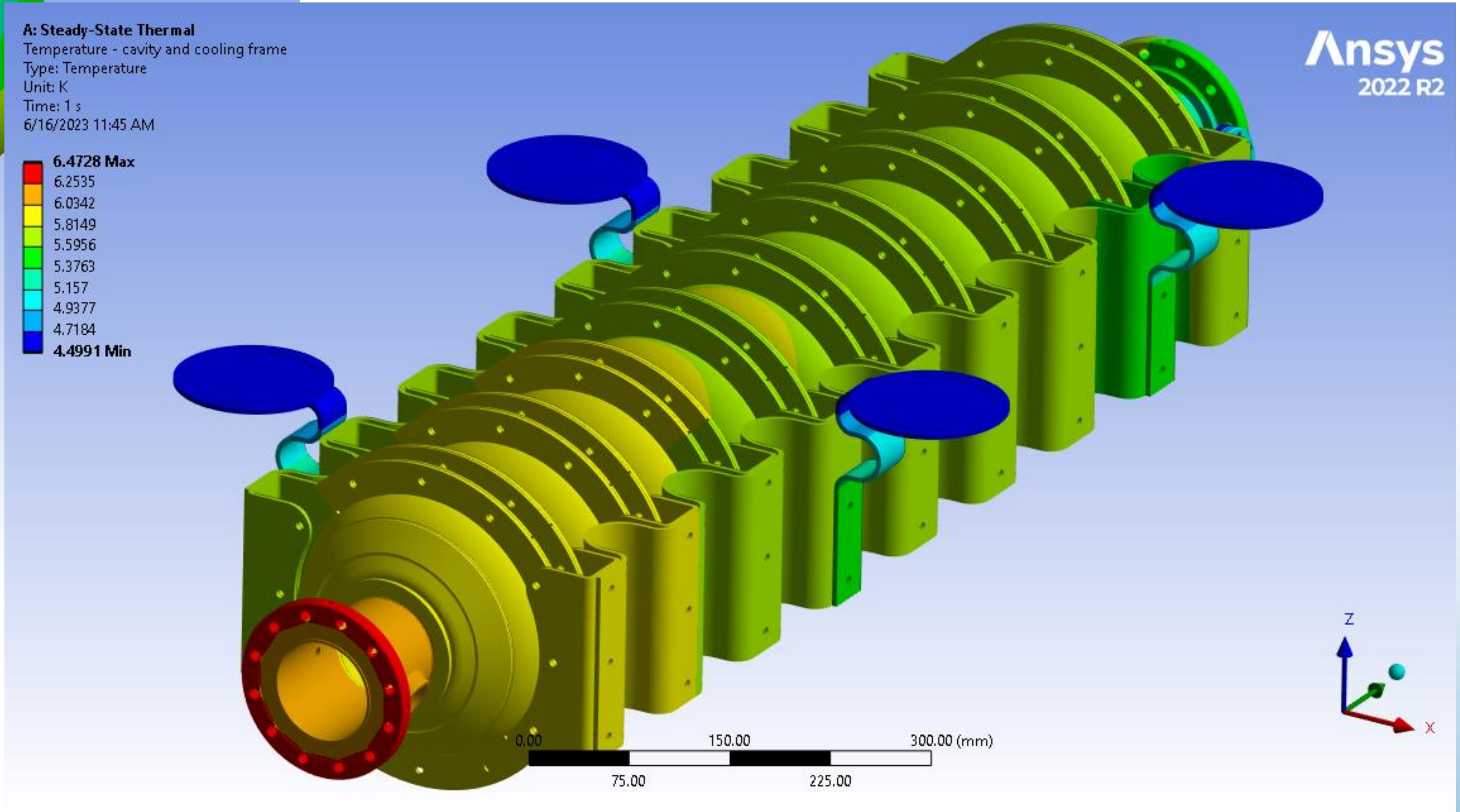


A: Steady-State Thermal
Temperature - thermal shield
Type: Temperature
Unit: K
Time: 1
6/13/2023 9:17 AM

55.067 Max
54.504
53.941
53.378
52.815
52.252
51.689
51.126
50.563
50 Min

Maximum thermal shield temperature ~55K

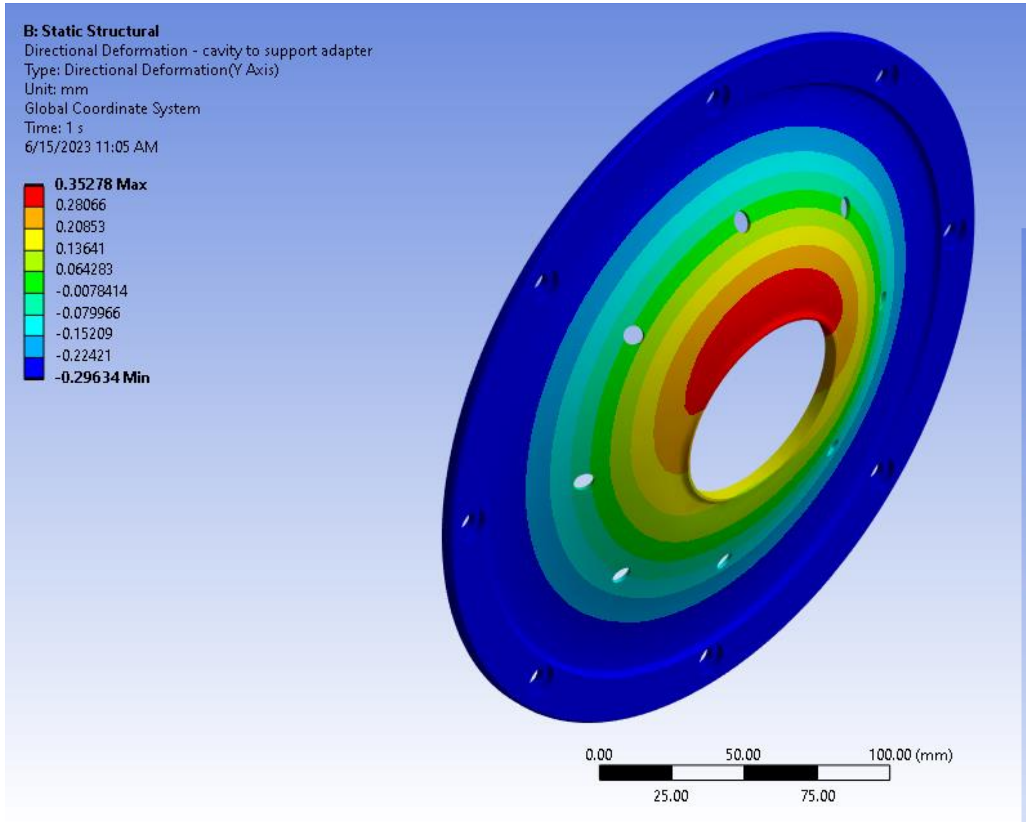
Maximum temperature in the cell structure ~5.9 K



A: Steady-State Thermal
Temperature - cavity and cooling frame
Type: Temperature
Unit: K
Time: 1 s
6/16/2023 11:45 AM

6.4728 Max
6.2535
6.0342
5.8149
5.5956
5.3763
5.157
4.9377
4.7184
4.4991 Min

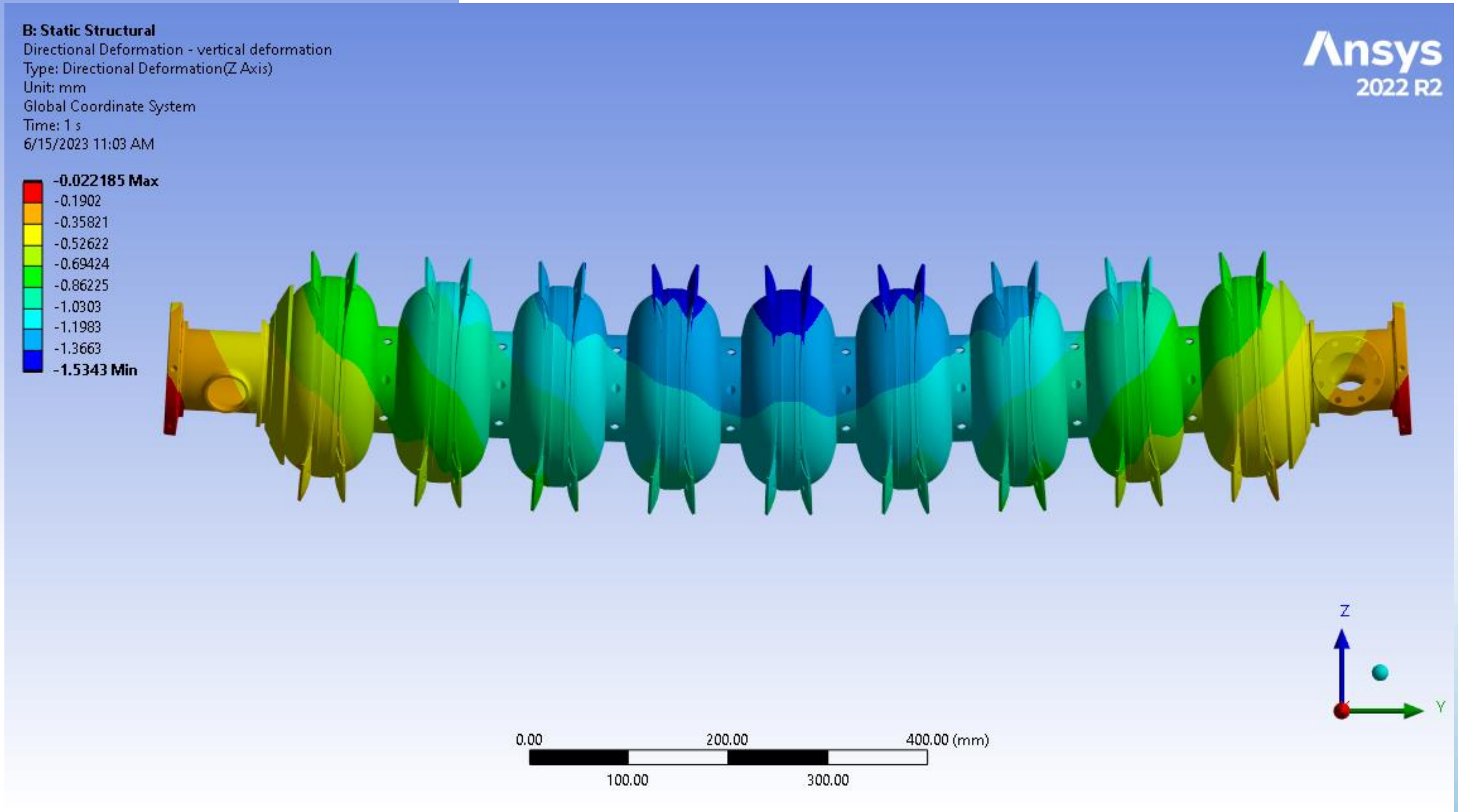
Structural analysis results



B: Static Structural
Directional Deformation - cavity to support adapter
Type: Directional Deformation(Y Axis)
Unit: mm
Global Coordinate System
Time: 1 s
6/15/2023 11:05 AM

Maximum axial cavity to support flange deflection ~0.65 mm

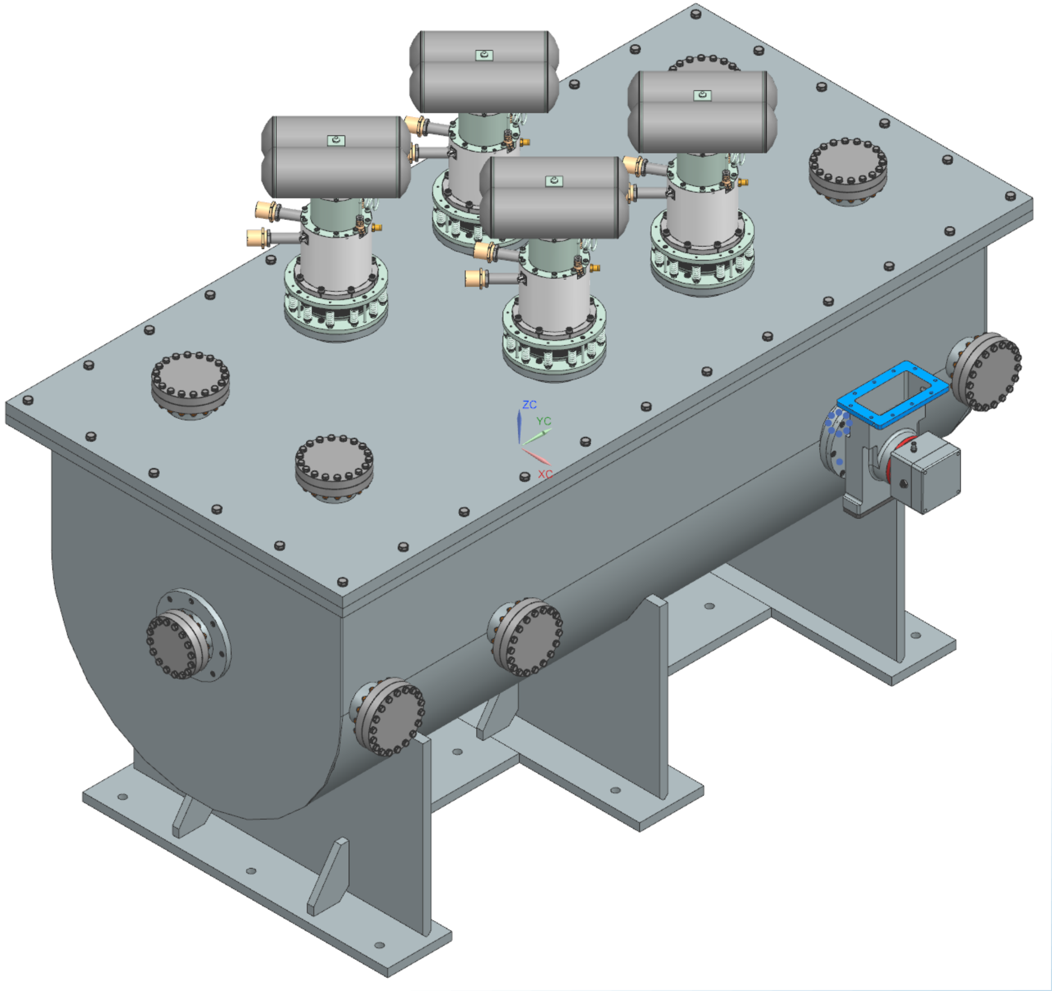
Maximum vertical deflection ~1.5 mm



B: Static Structural
Directional Deformation - vertical deformation
Type: Directional Deformation(Z Axis)
Unit: mm
Global Coordinate System
Time: 1 s
6/15/2023 11:03 AM

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.