# 952MHz Nb3Sn Cryostat Design and Thermal Management

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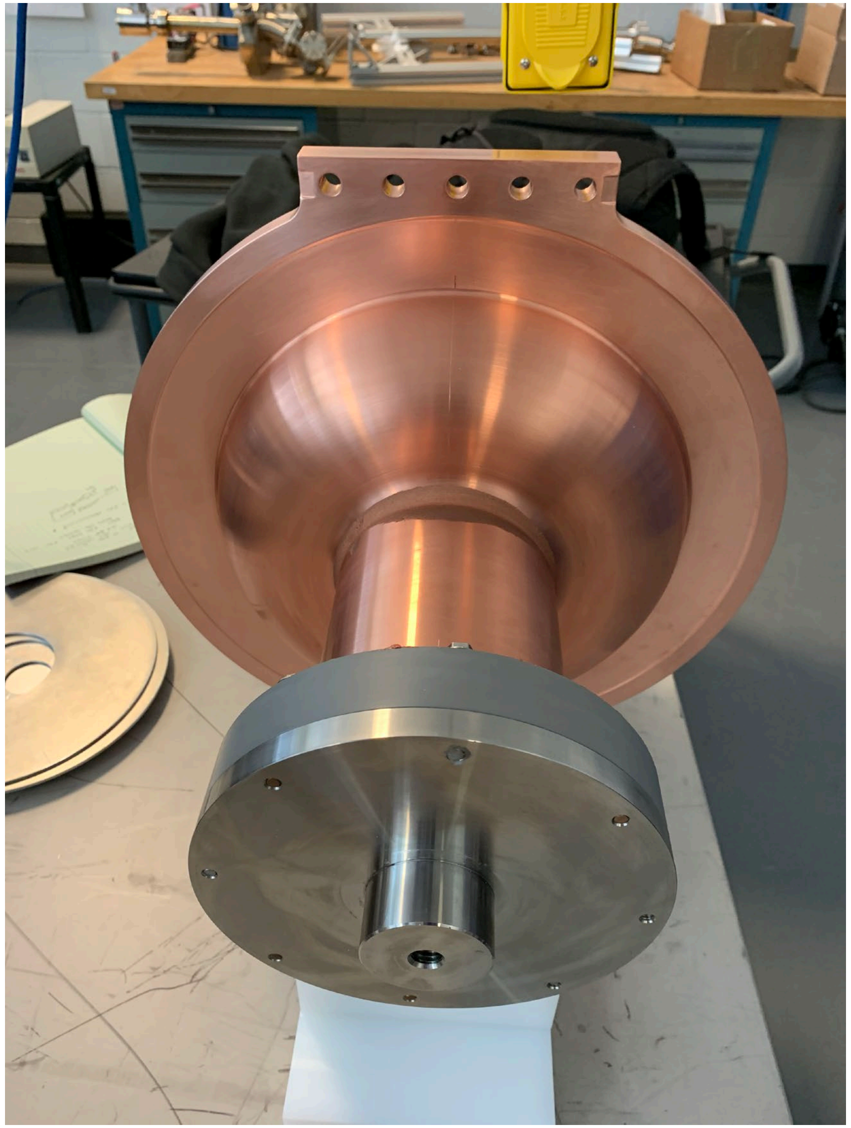
# Overview

- A US DOE stewardship project titled “Design, prototype and testing of an SRF cavity for a low-cost, compact SRF accelerator for environmental applications” is awarded to Jefferson Lab back in 2019.
- The proposed project is based on a previous research project that concluded with the design of a compact, low-cost, megawatt-class SRF accelerator design using a single-cell cavity. This project aims to demonstrate a coated single-cell cavity that may be used in such a  compact accelerator.
- A 952 MHz niobium cavity is selected to be coated with Nb3Sn on its interior, for high Q0 at 4K, and copper on its exterior to improve thermal conduction.
- To test the coated cavity, a compact cryostat is designed and built. It is featured with three cryocoolers, a vacuum vessel with bolted-on end caps, thermal shield, magnetic shields and the insulated 952 MHz cavity.
- The following slides will go over the mechanical design and thermal aspects of the 952 MHz cavity cryostat





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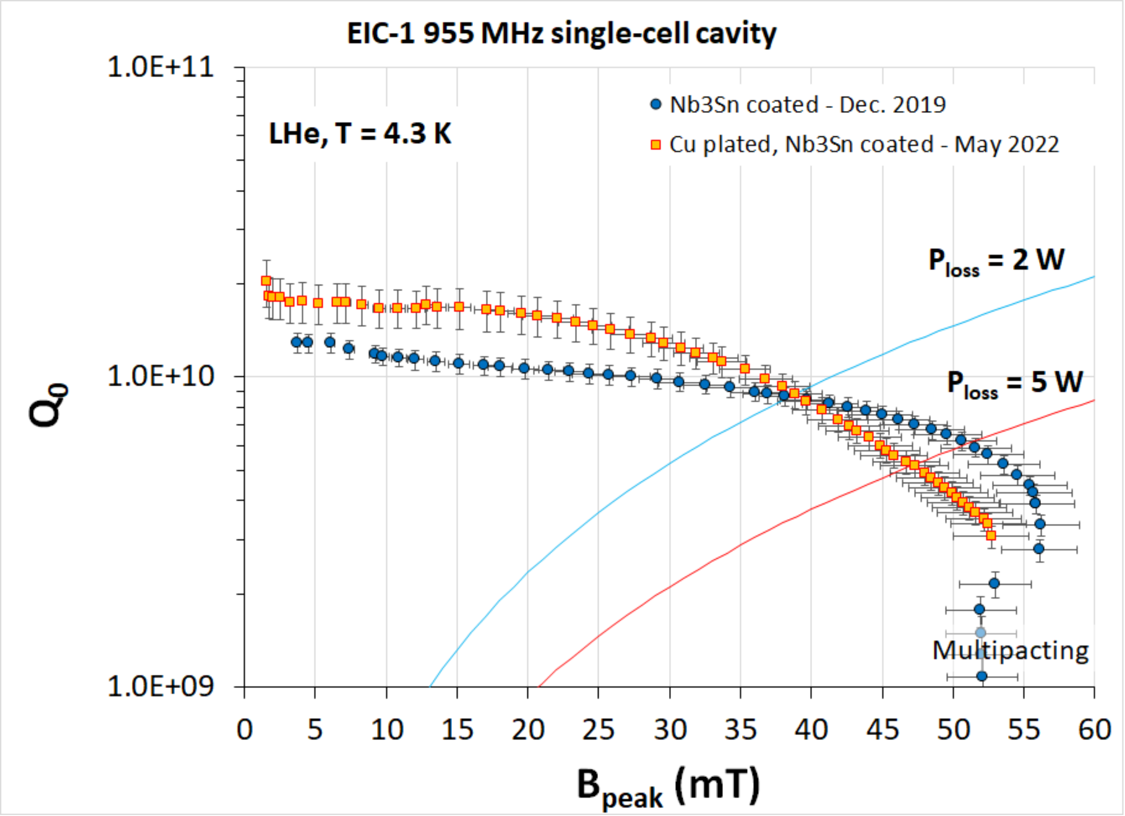
# Nb3Sn and Copper Coated 952 MHz Cavity

- Why 952 MHz? The 1 MW accelerator design was scaled to 915 MHz, which is the frequency of industrial magnetrons. 952 MHz was a cavity that was already built with close-enough frequency for another project (JEIC).
- The targeted Bp is 47 mT. This is because it is the Bp-value corresponding to an Eacc that would give 1 MeV energy gain in the 750 MHz cavity for the 1 MW accelerator.
- The Nb3Sn coating on the interior surface raises the transition temperature to ~ 18K hence the Nb3Sn coated cavity can have a high $Q_0$ at an 4K-ish temperature.
- The copper coating on the exterior of the cavity enhances thermal conduction from the cavity to cryocoolers. This coating also stiffens the cavity mechanically.




$Q_0$ vs. Eacc measured at 4.3 K



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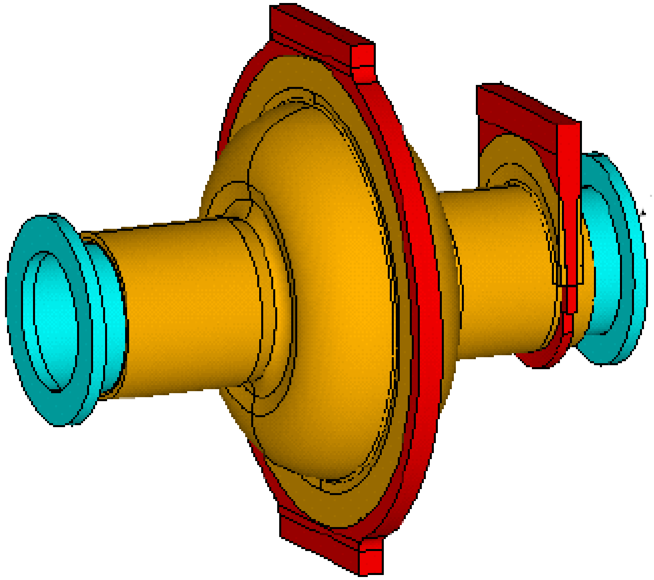
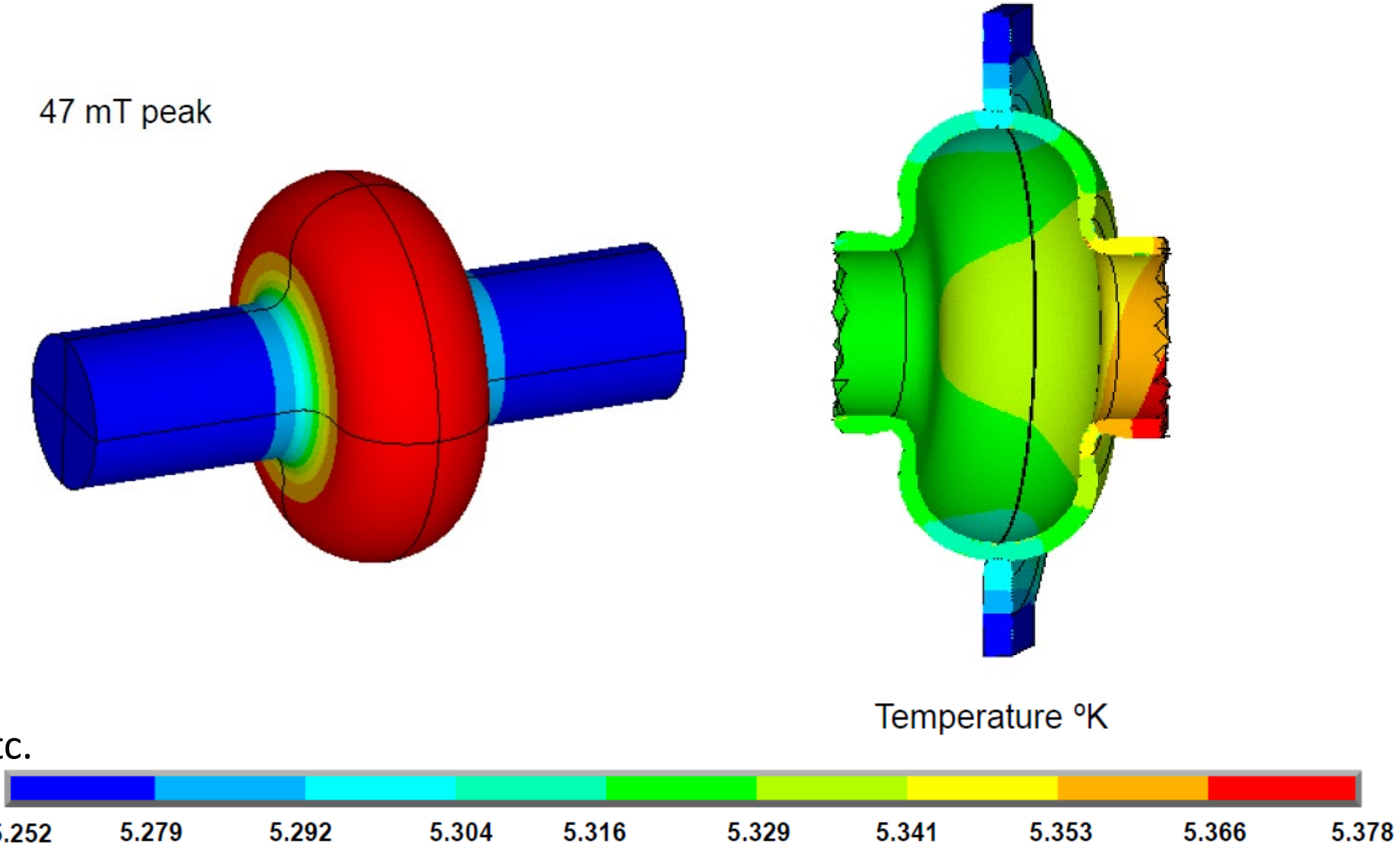
# Cryostat Design – Coated Cavity

Target Bp = 47 mT, corresponding to Eacc = 11.75 MV/m.

Analyses are run to determine the number of cryocoolers and Cu coat thickness






Considerations in the cavity model:
Cryocooler capacity map, Rs (Bp,T), Kxx(T),
Interface conductance, strap conductance, etc.

# Cryostat Design – Cryocooler

- The Sumitomo RDE-418D4 is selected because its 2nd stage removes 2.0 Watts heat load. Refer to the heat capacity map for details. Cavity thermal analyses concluded with the minimum number of cryocoolers required.
- It is found that three cryocoolers are required. Two of them are upright and the third one is inverted (98% capacity). Two cryocoolers connect to the equator. The 3rd cooler is mounted on the FPC side beampipe.
- Heat capacity map is hard wired into the simulation code. Mechanical loads at the 1st and 2nd stages are checked against the limits by conducting a cool down analysis.

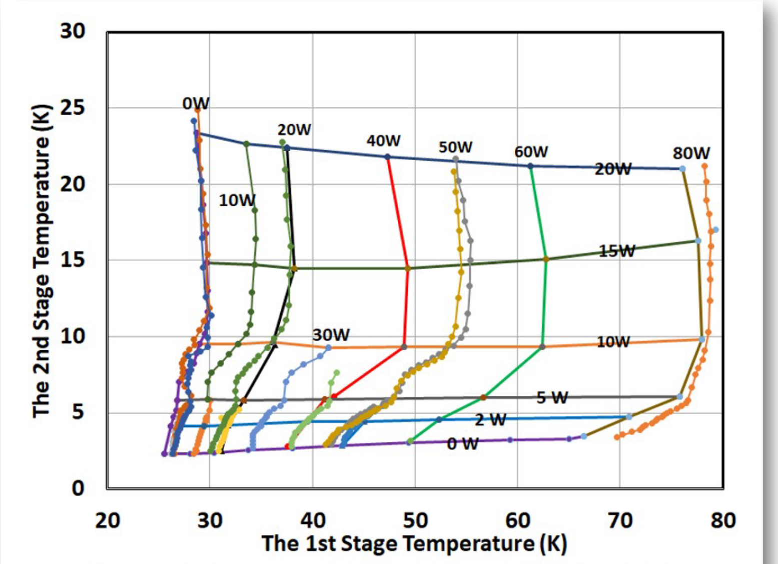
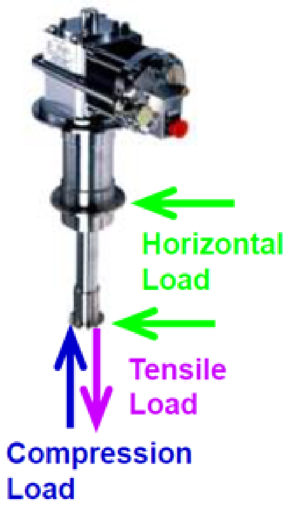


**Figure 7**. The measured capacity map of RDE-418D4

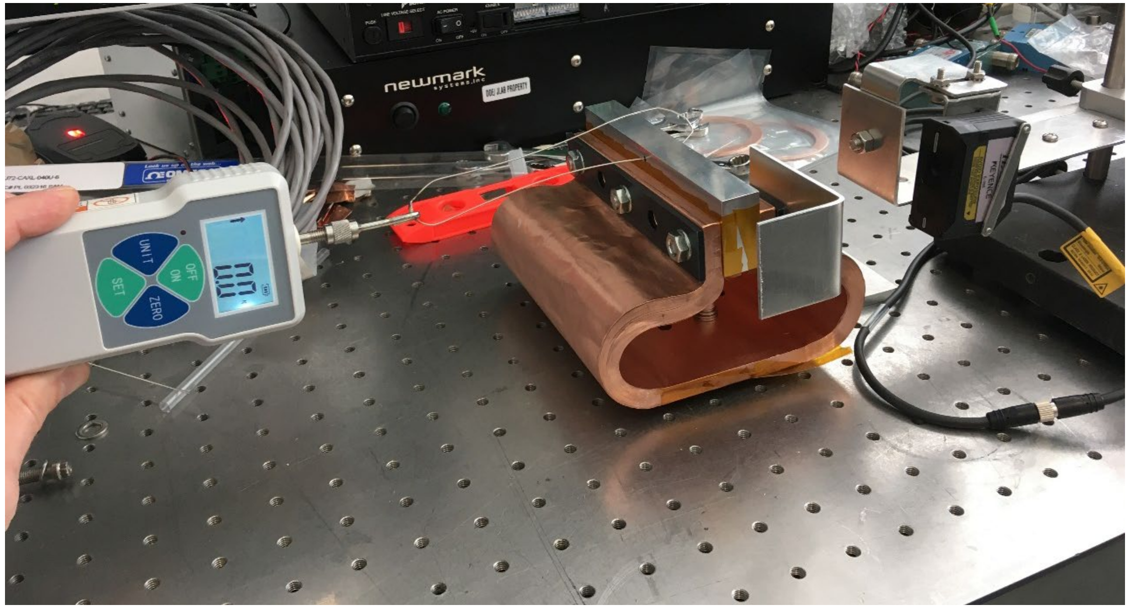



| Type | Horizontal Load (unit: kgf) | | Vertical Load (unit: kgf) | | | |
|---|---|---|---|---|---|---|
| | | | Compression Load | | Tensile Load | |
| | 1st | 2nd | 1st | 2nd | 1st | 2nd |
| RDK-415D | 10 | 5 | 200 | 100 | 30 | 30 |
| RDK-408D | 10 | 3 | 200 | 100 | 30 | 30 |
| RDK-305D | 8 | 2 | 200 | 100 | 30 | 30 |
| RDK-205D | 7 | 1 | 200 | 100 | 30 | 30 |
| RDK-101D | 5 | 0.5 | 200 | 100 | 30 | 30 |
| RDK-400B | 10 | - | 200 | - | 30 | - |

Sumitomo commented that the load limits for RDE-418D4 are the same as for RDK-415D

# Cryostat Design – Thermal Straps

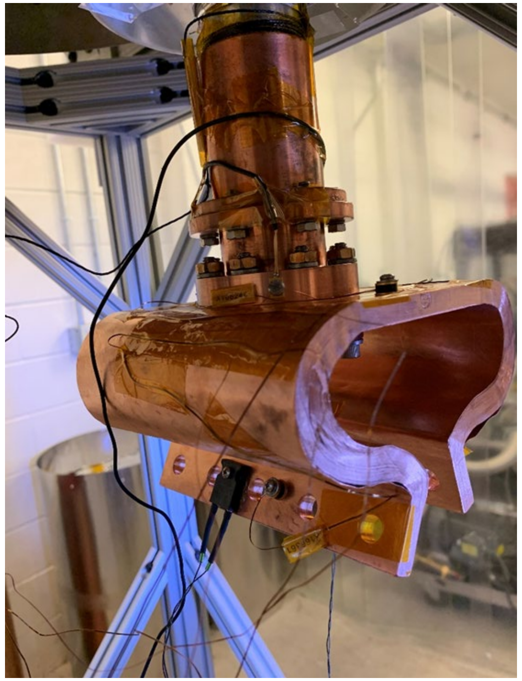
- Considered braided copper wire strap, rope strap. Thermal conductance is insufficient.
- Foil type thermal strap can yield high conductance. But end block resistance reduces overall conductance.
- Project finally turned to the foil type straps with ends press-welded
- Strap stiffness and thermal conductance are measured. Both satisfy design requirements



Thermal strap stiffness measurement

Conductance spec'ed:
17.5 W/K @ 4K

Measured:
21 W/K @ 4.5K





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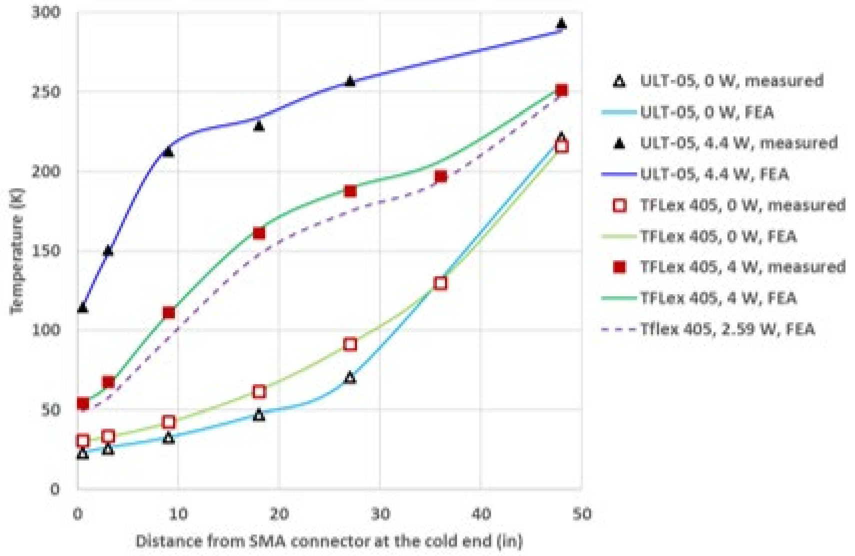
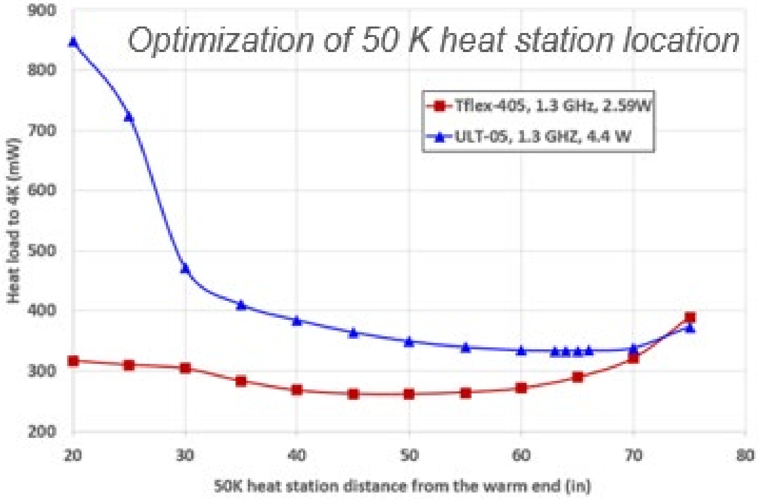
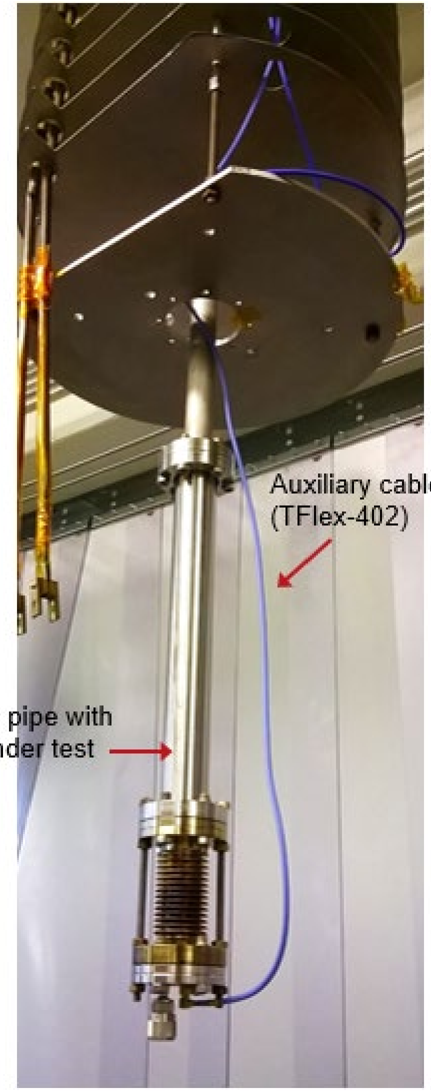
# Cryostat Design – RF Cables

- A series of RF cables are evaluated, final choice is made to use TFLex-405 as the power input cable and ULT-05 as the pick-up cable. See SRF 2019 article THP068 for details.
- JLAB is considering to build a cryocooler based test stand that can be adapted to measure RF cable losses.




*Simulated (FEA) vs. measured temperatures on the ULT-05 and TFlex-405 cables.*



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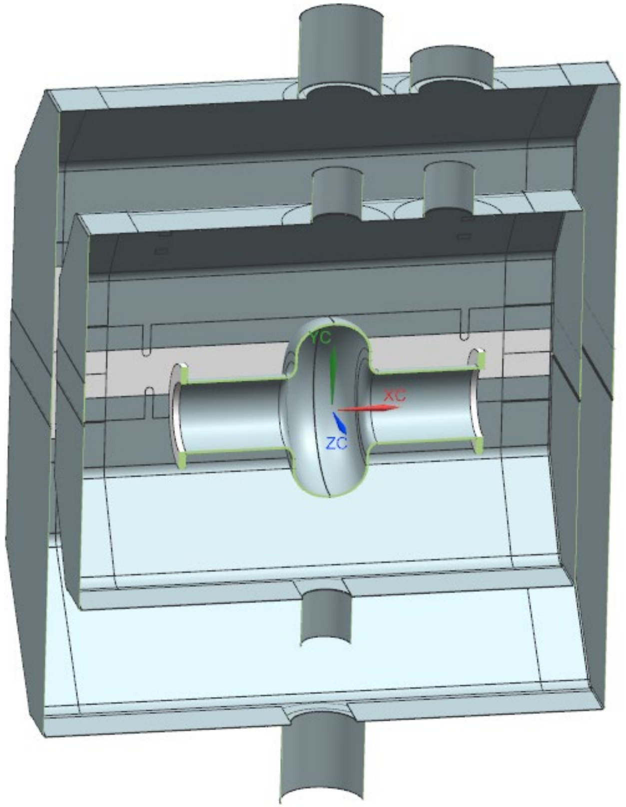
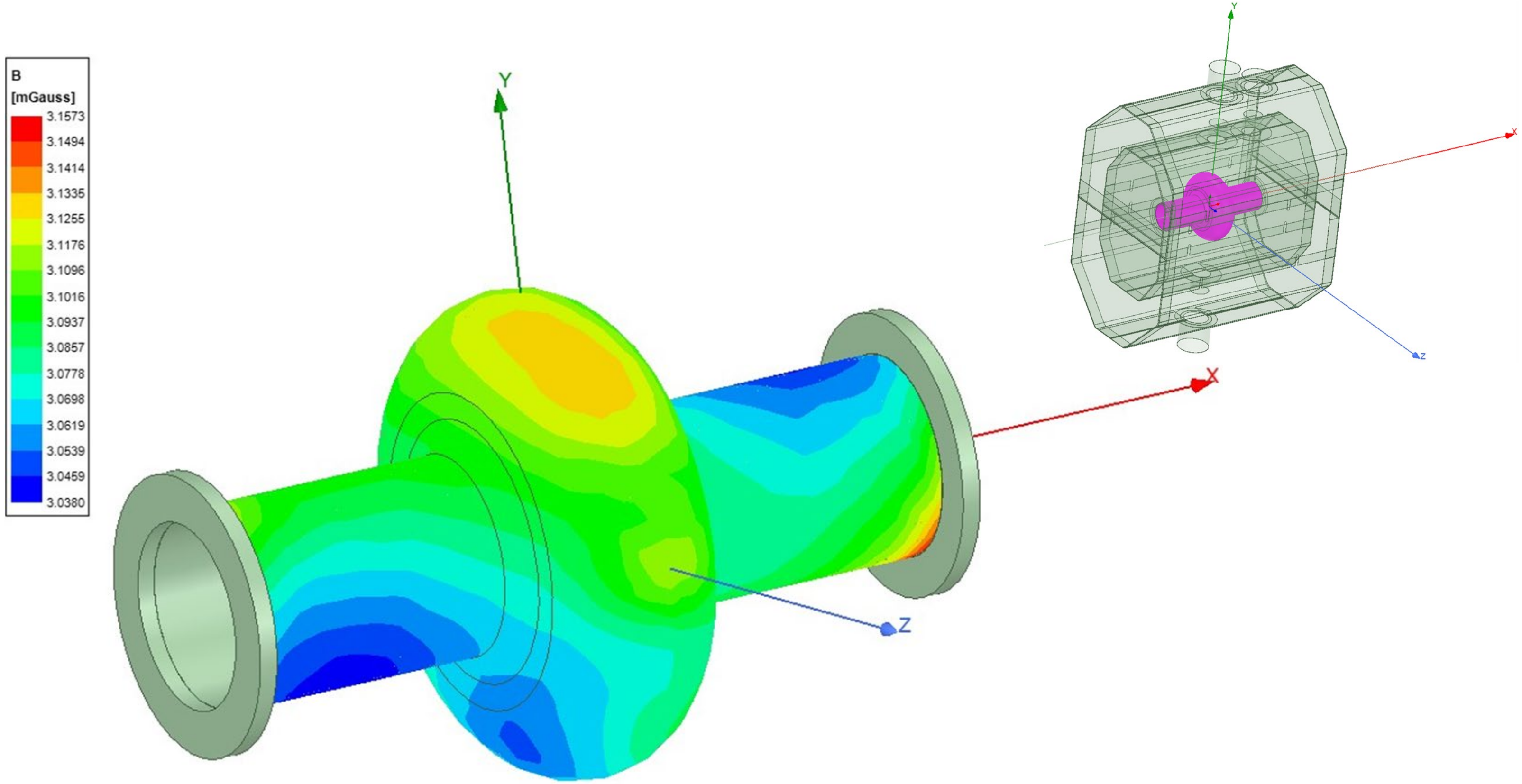
# Cryostat Design – Magnetic Shields

- Double layer magnetic shields. Both layers of shields have end caps.
- A preliminary assembly of the cryostat w/o cavity was completed and cooled down. Magnetic field at the cavity location is measured to be ~1 mG. At warm, there is ~ 5.7 mG field.



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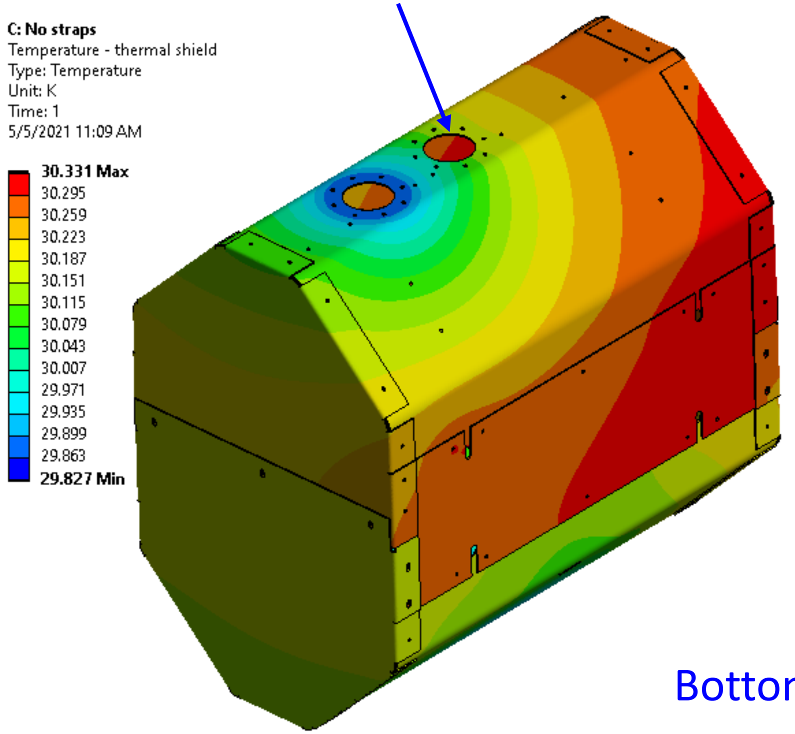
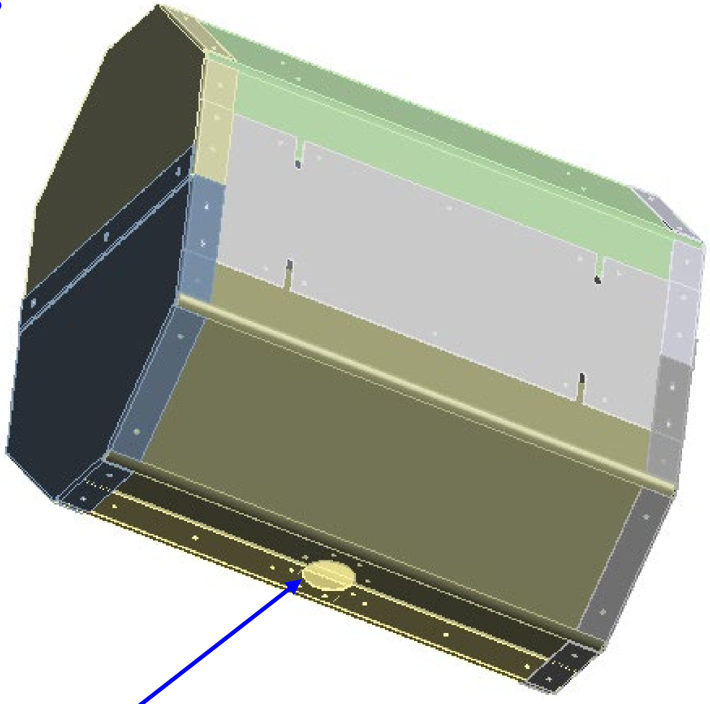
# Cryostat Design – Thermal Shield

- The cryostat's copper thermal shield is split into upper and lower sections. Upper and lower shields are allowed to slide w.r.t. each other to mitigate the force exerted to the cryocoolers
- Two cryocoolers are thermally connected to the upper and lower shields, respectively
- Looked into the benefit of connecting the two shield sections with straps. Decide not to link shields with straps.
- Preliminary cool down of cryostat w/o cavity shows each shield (not insulated) generates ~ 50 Watts. Decide not to wrap MLI on t-shield for final testing.

One of the two upper cryocoolers is not anchored to t-shield



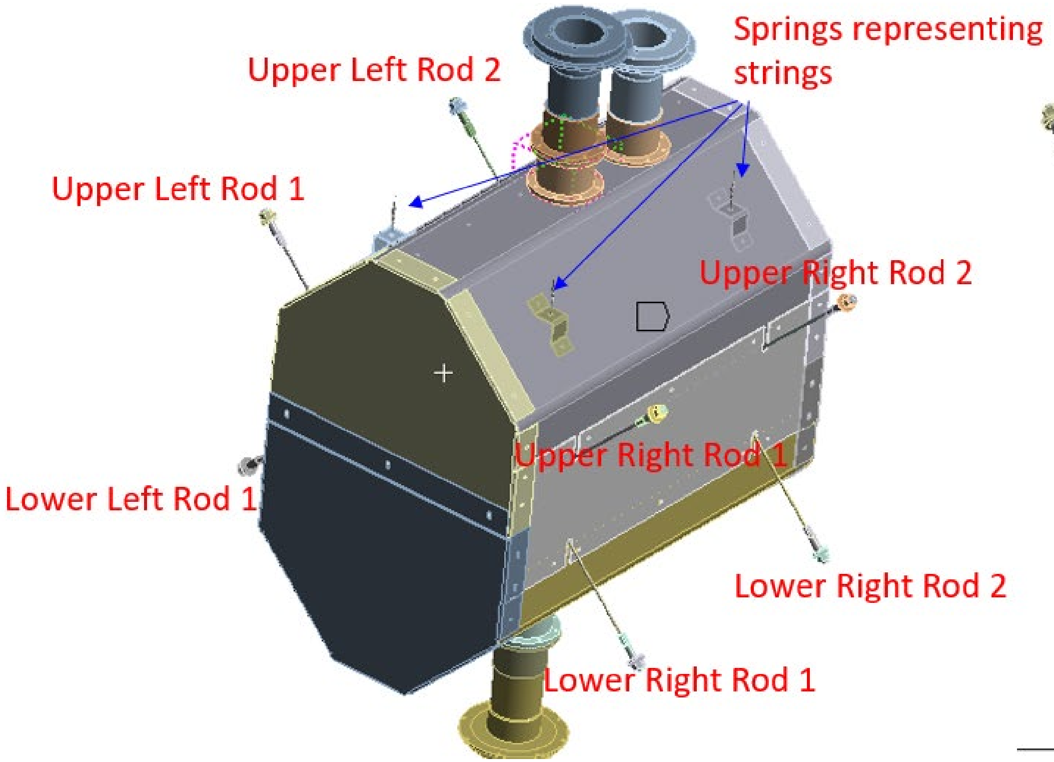



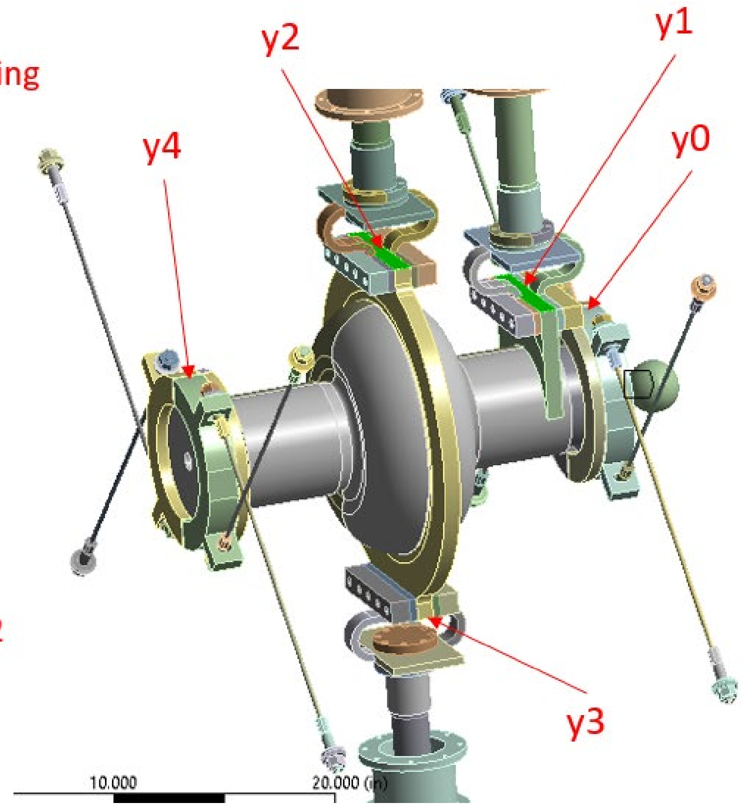
Bottom cryocooler is anchored to t-shield

| Shield temperature | heat flux | heat to 4K (mW) |
|---|---|---|
| 28 | 0.007111 | 5.33 |
| 29 | 0.008183 | 6.14 |
| 30 | 0.009372 | 7.03 |
| 31 | 0.010686 | 8.01 |
| 32 | 0.012134 | 9.10 |
| 33 | 0.013723 | 10.29 |
| 34 | 0.015464 | 11.60 |
| 35 | 0.017366 | 13.02 |
| 36 | 0.019437 | 14.58 |
| 37 | 0.021689 | 16.27 |
| 38 | 0.024131 | 18.10 |
| 39 | 0.026774 | 20.08 |
| 40 | 0.029627 | 22.22 |
| 50 | 0.072336 | 54.25 |
| 60 | 0.15 | 112.50 |
| 70 | 0.277896 | 208.42 |
| 80 | 0.47408 | 355.56 |

# Cryostat Design – Suspensions

- Cavity is lifted by 8 nitronic rods; Inner magnetic shield is hung from the thermal shield; Thermal shield is hung from the outer magnetic shield using steel wires; Outer magnetic shield is anchored to the vacuum vessel.
- Suspensions that will experience transition temperatures are designed to be flexible in transverse direction



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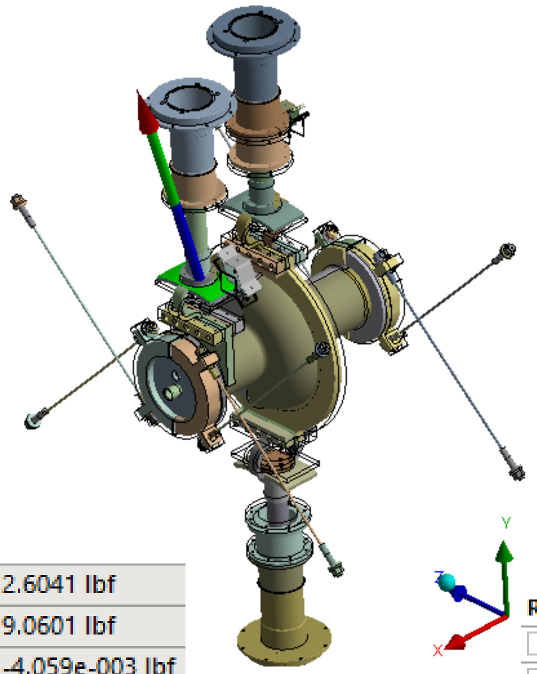
# Cryostat Design – Forces from Cool Down

- The crycooler's 1st and 2nd stages can only take a small amount of lateral load without affecting normal operation, that is 22 lbs and 11 lbs, respectively.
- Cool down analysis is conducted to check the loads. With the measures taken into suspension design, both 1st and 2nd stages are found to have loads within their limits.

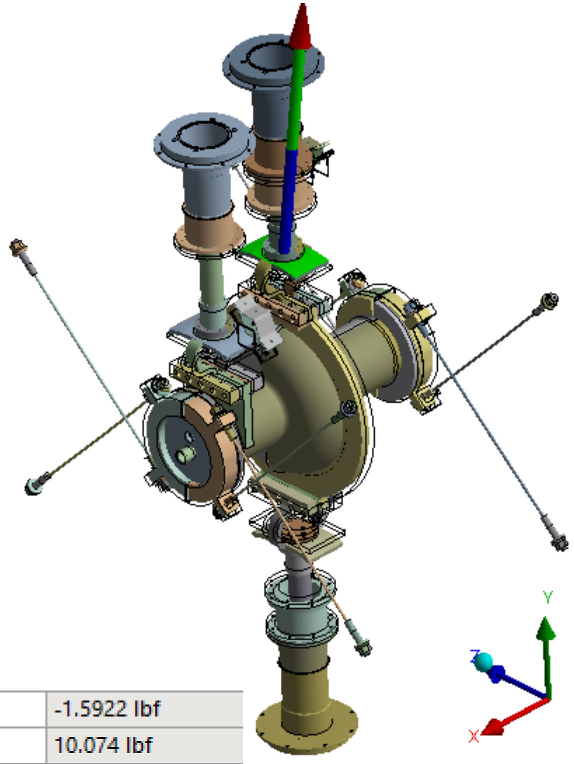
Cooler 1



**Results**

| | |
|---|---|
| X Axis | 2.6041 lbf |
| Y Axis | 9.0601 lbf |
| Z Axis | -4.059e-003 lbf |

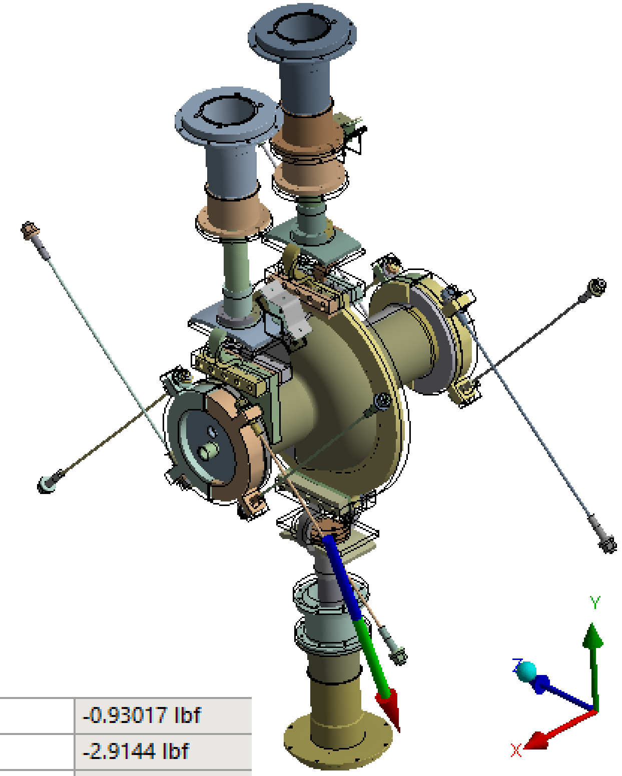
Cooler 2



**Results**

| | |
|---|---|
| X Axis | -1.5922 lbf |
| Y Axis | 10.074 lbf |
| Z Axis | -1.4782e-002 lbf |

Cooler 3

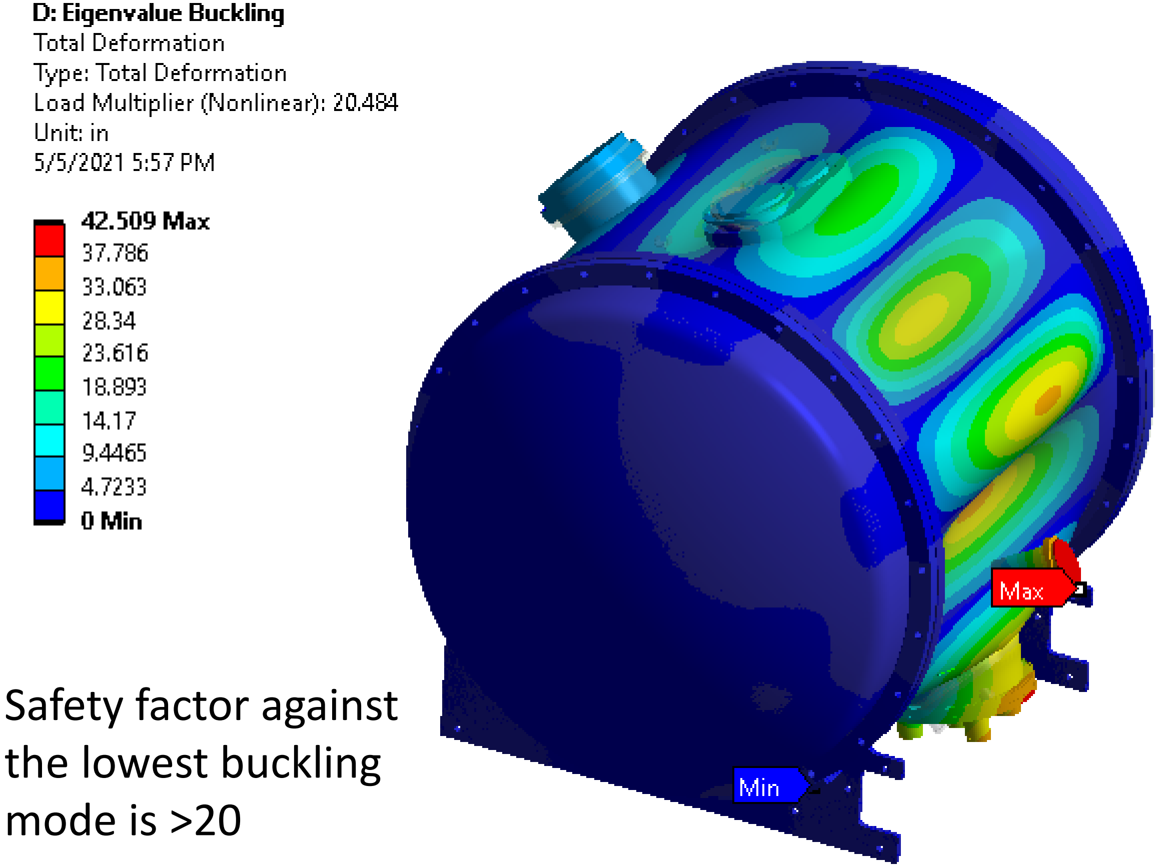


**Results**

| | |
|---|---|
| X Axis | -0.93017 lbf |
| Y Axis | -2.9144 lbf |
| Z Axis | -8.8159e-003 lbf |

# Cryostat Design – Buckling & Vibration

- Eigen value buckling analysis of the cryostat shows there is sufficient safety factor
- Vibration analysis indicates there are a few low frequency modes that might need to be mitigated. Since the vacuum vessel end caps are bolted on, it is feasible to add mechanical stops later on if vibration interferes with cryocooler operation.

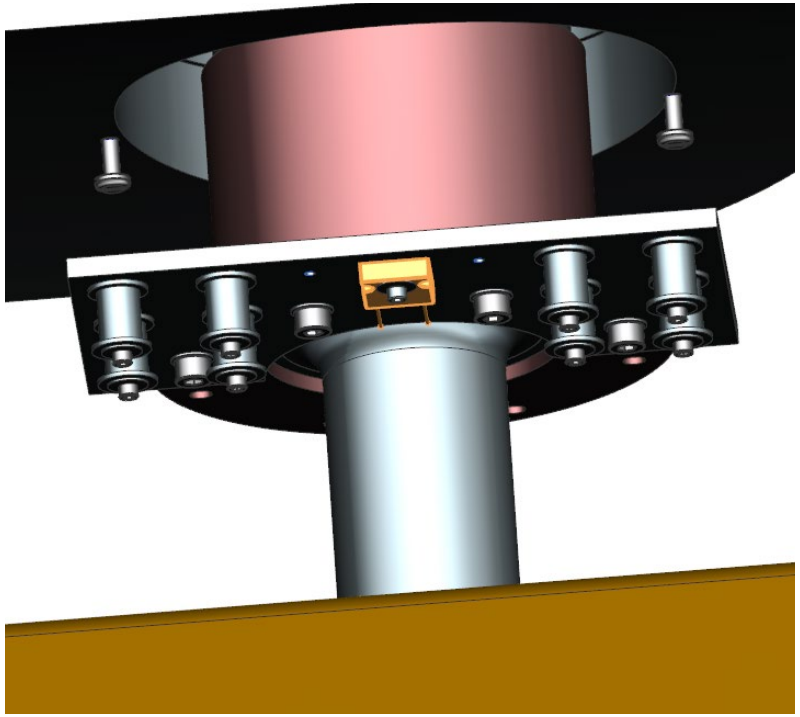



Safety factor against the lowest buckling mode is >20

# Thermal Management

- Estimated static heat loads to cavity is ~1.0 Watt
  - 8 rods 0.097 Watts
  - FPC cable 0.57 Watts (assume 10 Watts input)
  - Pickup cable 0.03 Watts
  - Radiation 0.1 Watts
  - Cryocooler conduction 0.29 Watts
- RF heat load to $Nb_3Sn$ coated cavity is 3.25 Watts
- Assumed fundamental power coupler heat load to beampipe is 6 Watts
- **Total heat load into the 2$^{nd}$ stage of cryocoolers is 10.25 watts**
- Simulation shows the cavity will be at < 5.5 K for Bp = 47 mT.

- Initial measurements show that the two crycoolers in contact with thermal shield removes approximately 50 Watts at each 1$^{st}$ stage
- We plan to use a heater to **maintain 50 Watts** to the cryocooler that is not in contact with t-shield.



# Questions/Comments/Suggestions?

The 952 MHz cavity cryostat is at its final assembly stage. Most of the cold mass assembly is complete.

Final testing is planned to happen in late Oct or early Nov.

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177