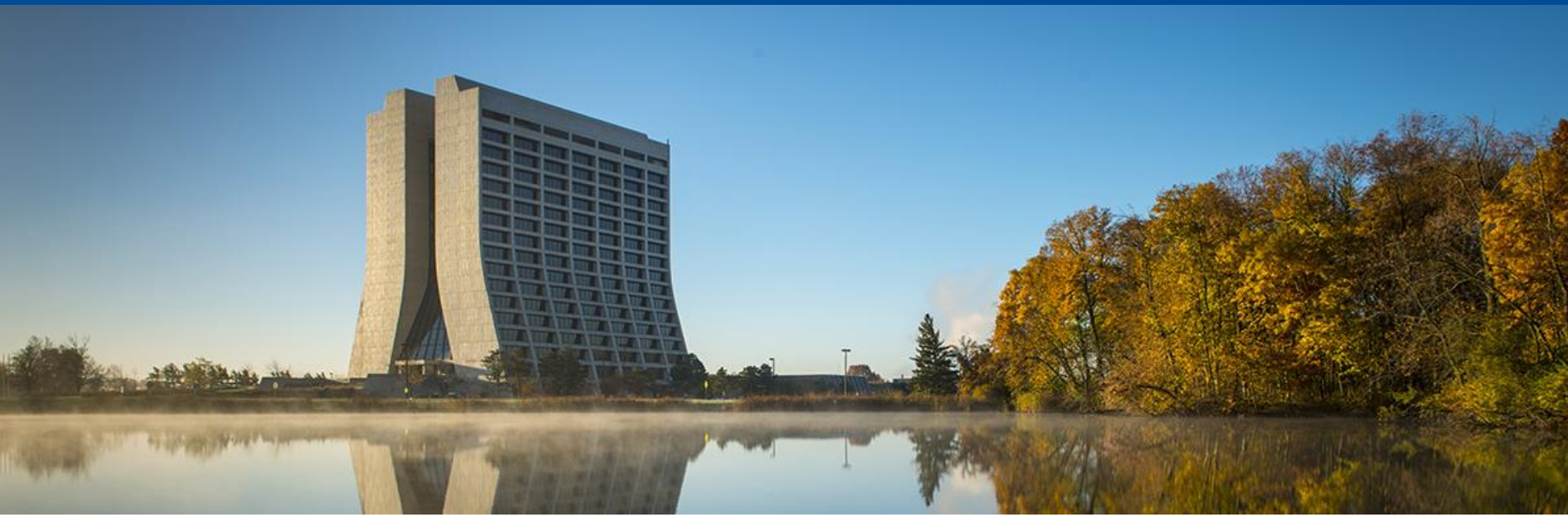


# Low Heat Leak Couplers and the Path Towards Higher Powers

Josh Helsper

WWFPC 2024

3 July 2024

# About Me

- First time to WWFPC (Thanks Eric and all!!)

- **Mechanical** Engineer
  - Please forgive my limited RF knowledge ☺

- Full Time at Fermilab 4 years + 2 years Master's Degree
  - 3 years as PIP-II coupler engineer w/ Sergey Kazakov
  - 1 year as engineer for IARC

- Slides – slightly 'not formal' – similar to meeting ☺

# What is IARC?

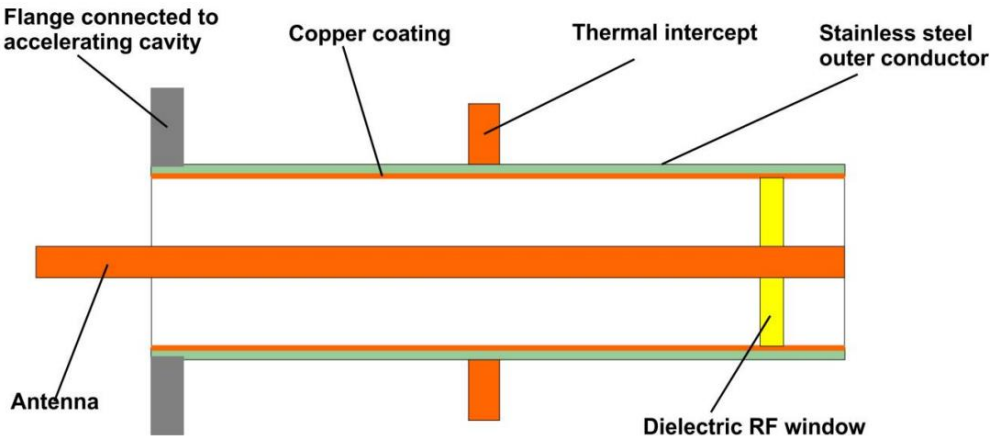
- Illinois Accelerator Research Center
  - We seek to help accelerator science and technology breakthrough to mainstream industry
  - We work with industrial partners to understand their needs

# IARC Goals

- Develop conduction cooled cryomodules for industry
  - ≤10MeV
  - Long term, >300 kW CW
  - Minimize energy consumption
  - Maximize reliability
  - No liquid helium system

# Conceptual Design of Low Leak Coupler

## Conventional Coupler




## Low Heat Leak Coupler

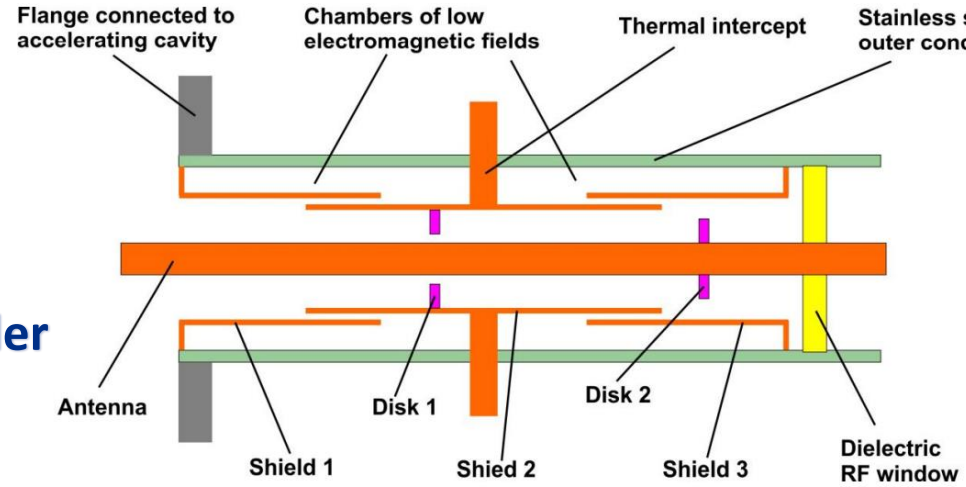


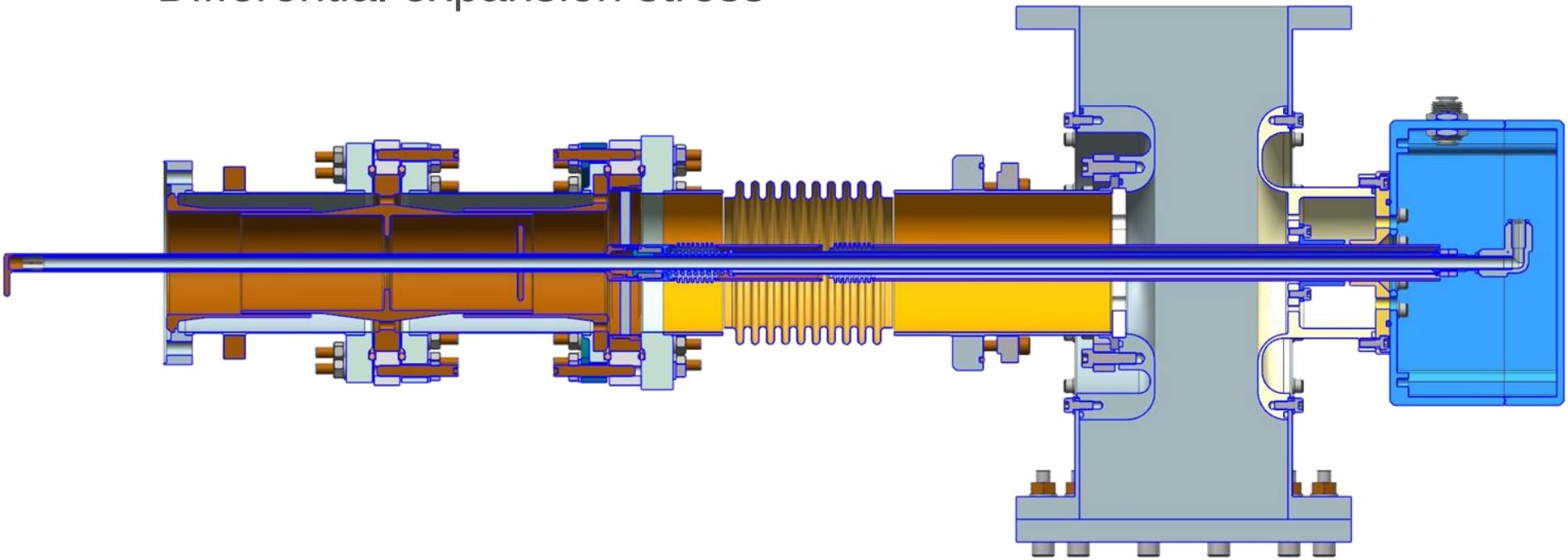

Figure courtesy of S. Kazakov



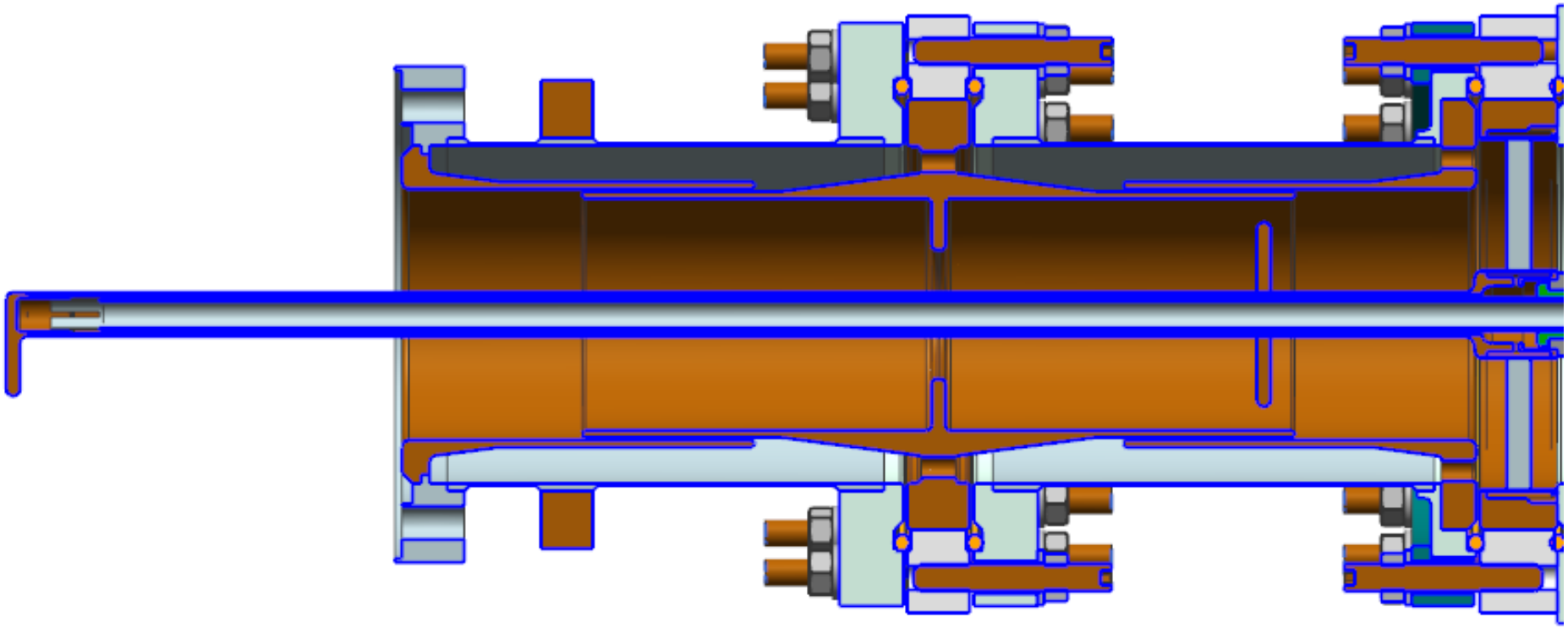
Fermilab

# 650 MHz Low Heat Leak Coupler

- 20 kW CW operation
- Air Cooled
- Limited to ≈80 kW due to ceramic temperature
  - Differential expansion stress

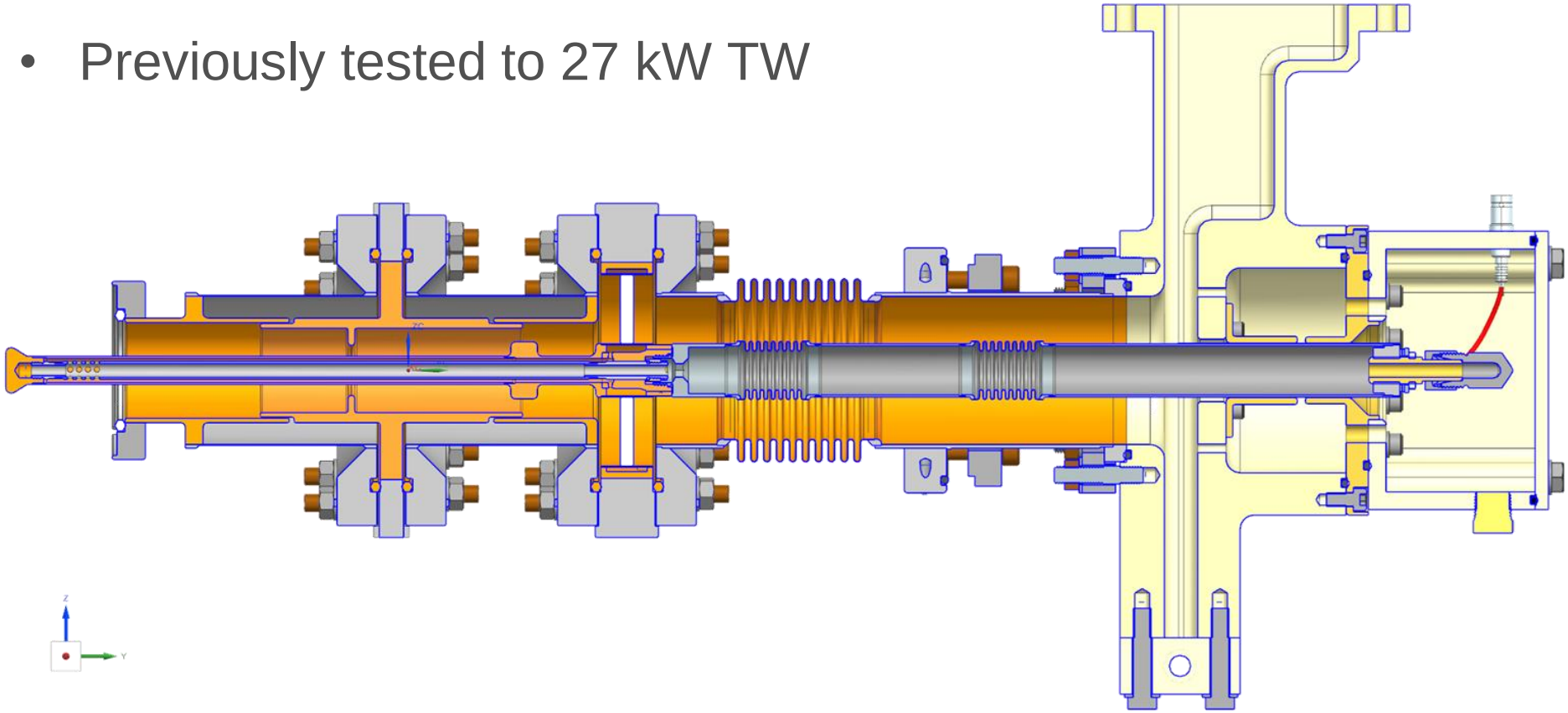


# 650 MHz Low Heat Leak Coupler

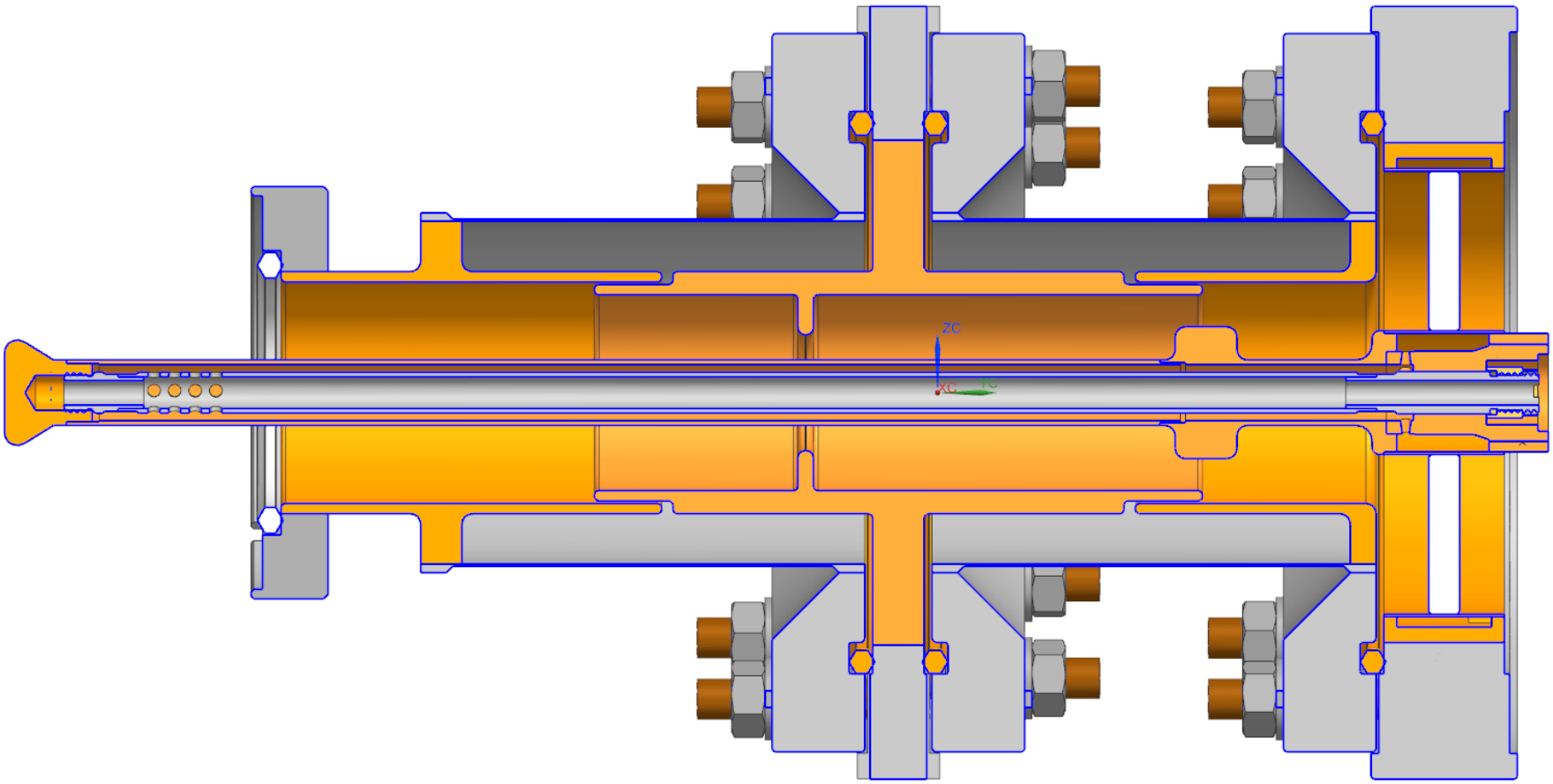


# 1.3 GHz Low Heat Leak Coupler

- 20 kW CW operation
- Air cooled
- Previously tested to 27 kW TW

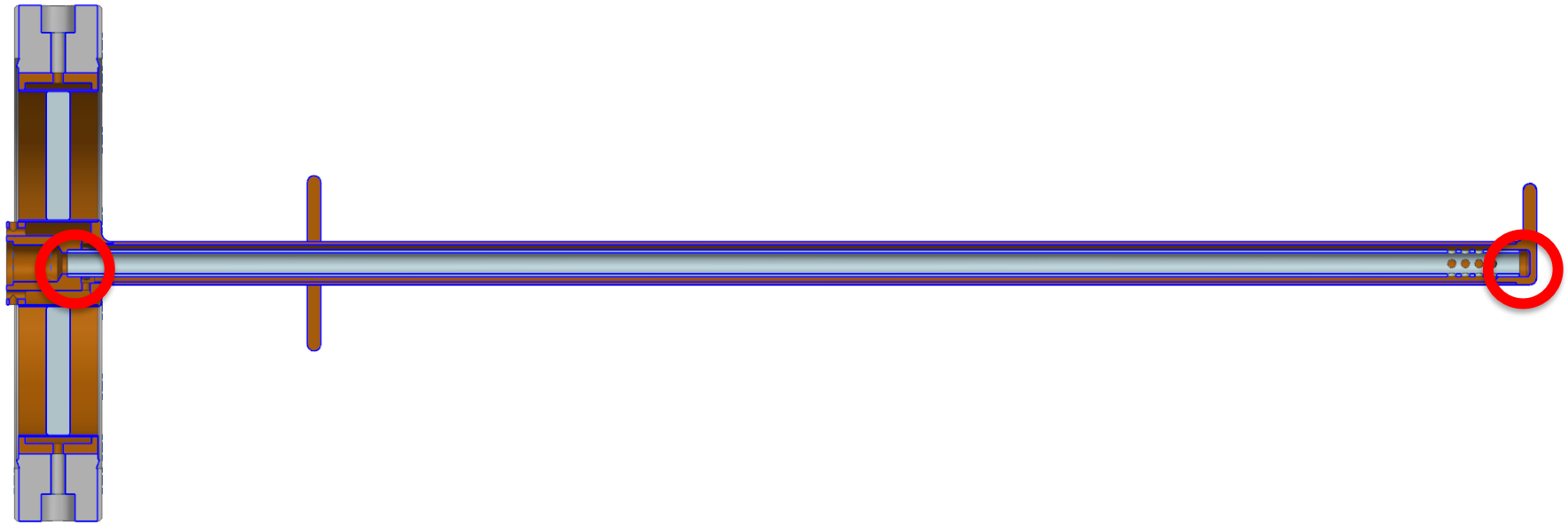


# 1.3 GHz Low Heat Leak Coupler



# Issue for PIP-II Couplers

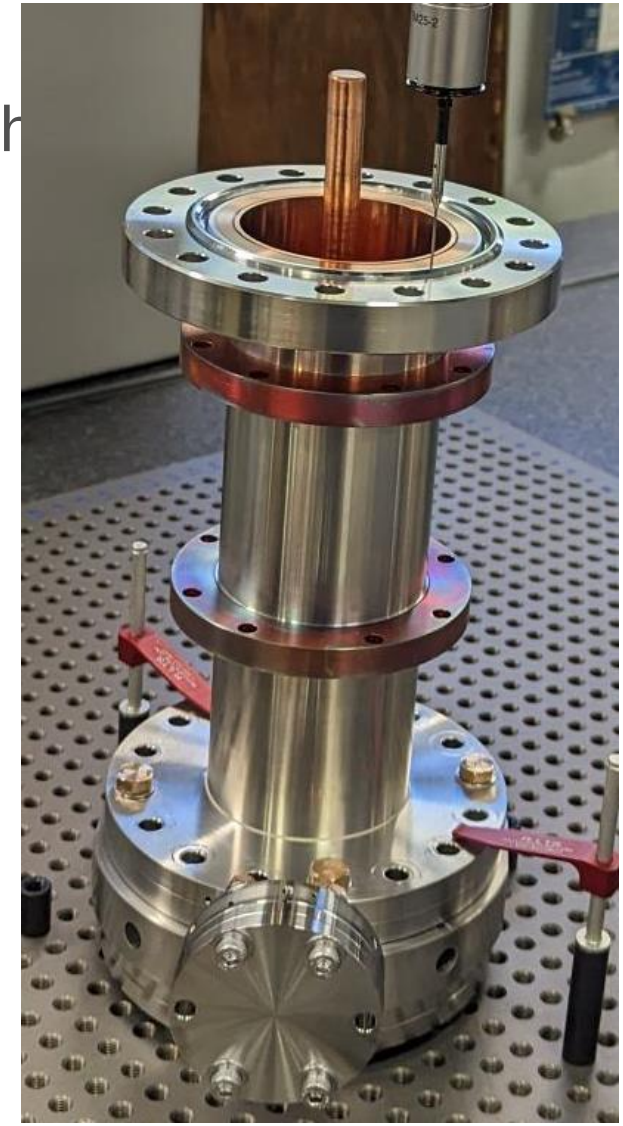
- Previous, similar antennas used the design below, with brazed joints at both sides of the SS air cooling tube
  - Buckling upon cooldown
- Stiffness required for transportation



# Issue for PIP-II Couplers

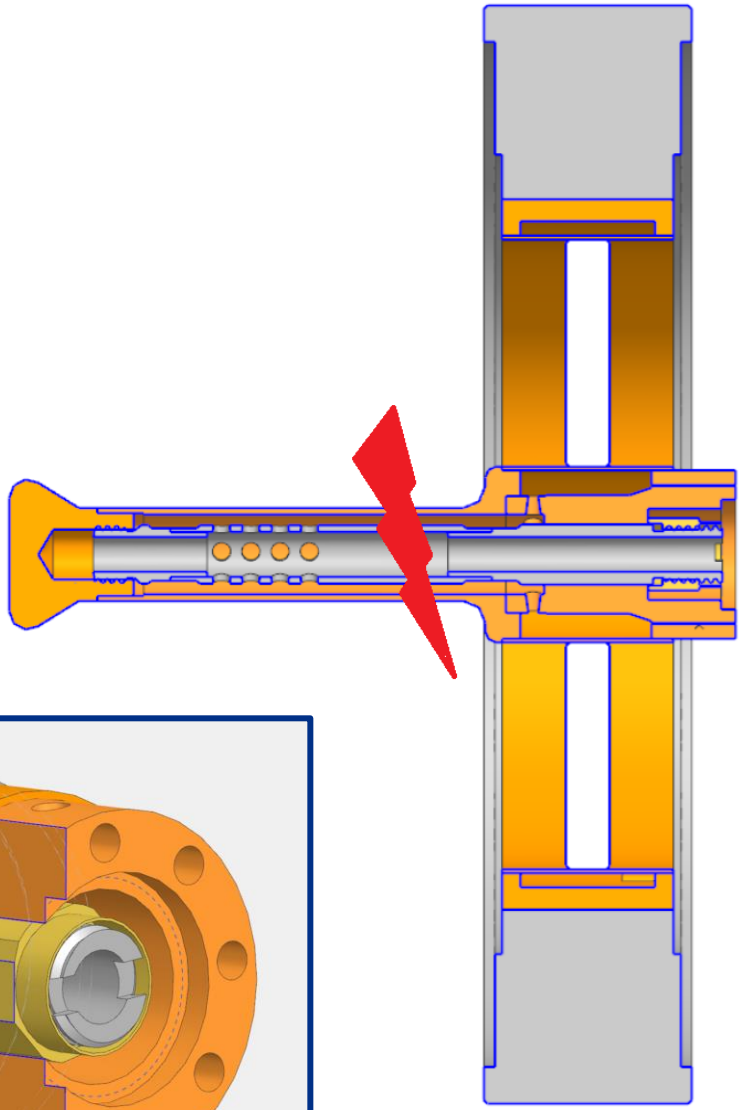
- Long antenna – SS + Cu – Brazed at both ends
  - Instability due to dissimilar contraction rate- bending
- Here: worst case of PIP-II bent antennas
  - 325 MHz cavity agnostic

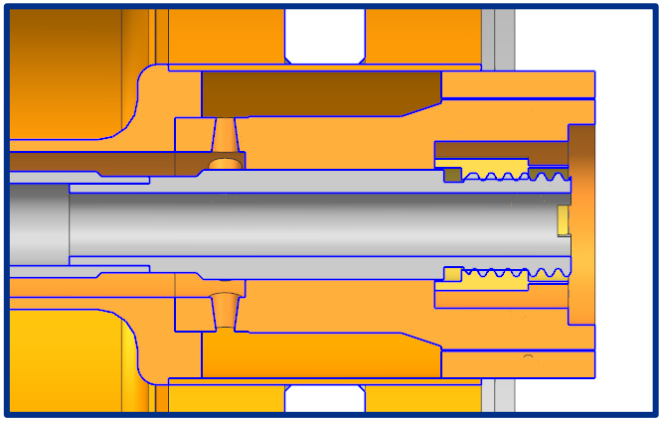
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Pc | PART NAME : josh sample | | | | April 18, 2023 | 08:50 | |
| | REV NUMBER : | | SER NUMBER : | | STATS COUNT : 1 | | |
| MM | POSITON OF COPPER PIN - CIR1 | | | | | | |
| AX | NOMINAL | +TOL | -TOL | MEAS | DEV | OUTTOL | BONUS |
| X | 0.000 | | | -2.735 | -2.735 | | |
| Y | 0.000 | | | -1.530 | -1.530 | | |
| DF | 11.447 | 0.010 | 0.010 | 11.447 | 0.000 | 0.000 | 0.000 |
| TP | RFS | 0.010 | | 6.268 | 6.268 | 6.258 | 0.000 |
| | Tip off center by 6.26 mm | | | | | | |
| MM | TOP OF COPPER PIN - PLN2 | | | | | | |
| AX | NOMINAL | +TOL | -TOL | MEAS | DEV | OUTTOL | |
| Z | 53.684 | 0.050 | 0.050 | 53.684 | 0.000 | 0.000 | |
| MM | DEPTH OF O RING - PLN2 TO PLN3 (ZAXIS) | | | | | | |
| AX | NOMINAL | +TOL | -TOL | MEAS | DEV | OUTTOL | |
| M | 56.071 | 0.010 | 0.010 | 56.071 | 0.000 | 0.000 | |

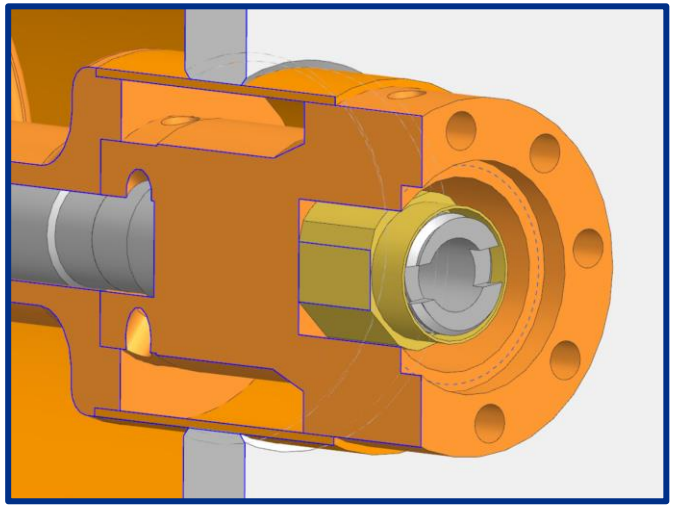


# Novel Antenna Joint

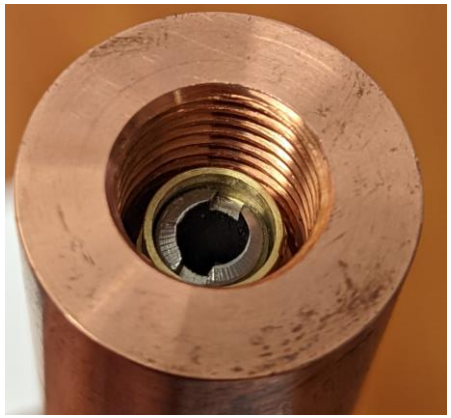
- Solution
  - 0.0005” slip joint between SS tube and Copper piece
  - Custom ‘crimp nut’ installed after brazing
  - Same stiffness as previous
  - This was prototyped successfully

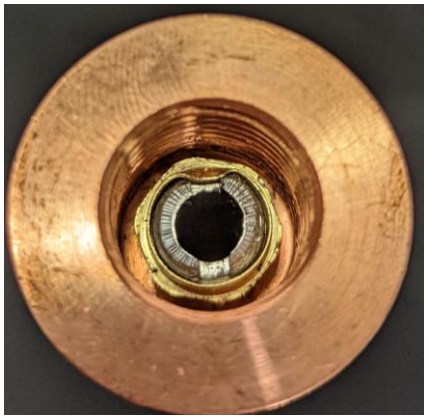






# Novel Antenna Joint





# The desire for higher RF power

- High RF Power = ability to treat more industrial material
  - More viable to ‘really be useful’

- Current powers: 50-60 kW CW max at Fermi
  - Air cooled, 650 MHz coaxial + doorknob + waveguide

- Target power: 300 kW -1MW CW
  - Water cooled
  - Single 650 MHz cavity, multi-cell

# Design Change Ideas

- Water Cooling for antenna, inner conductor, outer conductor, possibly waveguide
- Shift the RF window to be outside the vacuum vessel envelope – easy access to water channels
  - Example: BNL – Wencan Xu

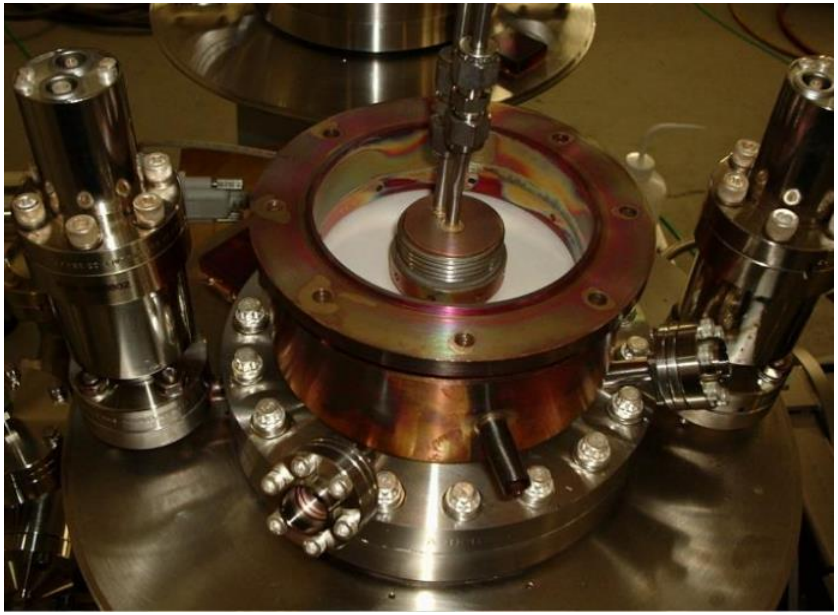


Image source: WWFPC 2019, Wencan Xu

# Design Change Ideas

- Multiple couplers
  - System must be reliable. At a certain point, it will be better to use more lower power couplers that are 'stable'.

- Special RF compatible gaskets or RF shielding will be needed

# Design Change Ideas / Questions

- Water-cooling for antenna
  - Connection methods?
    - Is there something more low-profile than compression fittings without brazing?
  - How to prevent long-term leaking?
    - Are brazes reliable after 20+ years?
    - Lower flow rate = less erosion? Does it make a difference?

# Design Change Ideas / Questions

- Is there a way to prevent thermal short circuit for inlet / outlet?
  - Double wall / something else?
  - Does it even matter?

- Most reliable antenna design for water cooling?

- Coolant other than water?

# Design Change Ideas / Questions

- Water Cooling
  - Leak detection?
  - Leak effects?
  - Pre-cooled liquid?
    - Could use anti-freeze cooled low. Condensation issues?
  - How to cool outer conductor? What path?
    - Ex- copper tube wrapped around, brazed, water through tube
  - Other advice? I have no experience in water cooling.

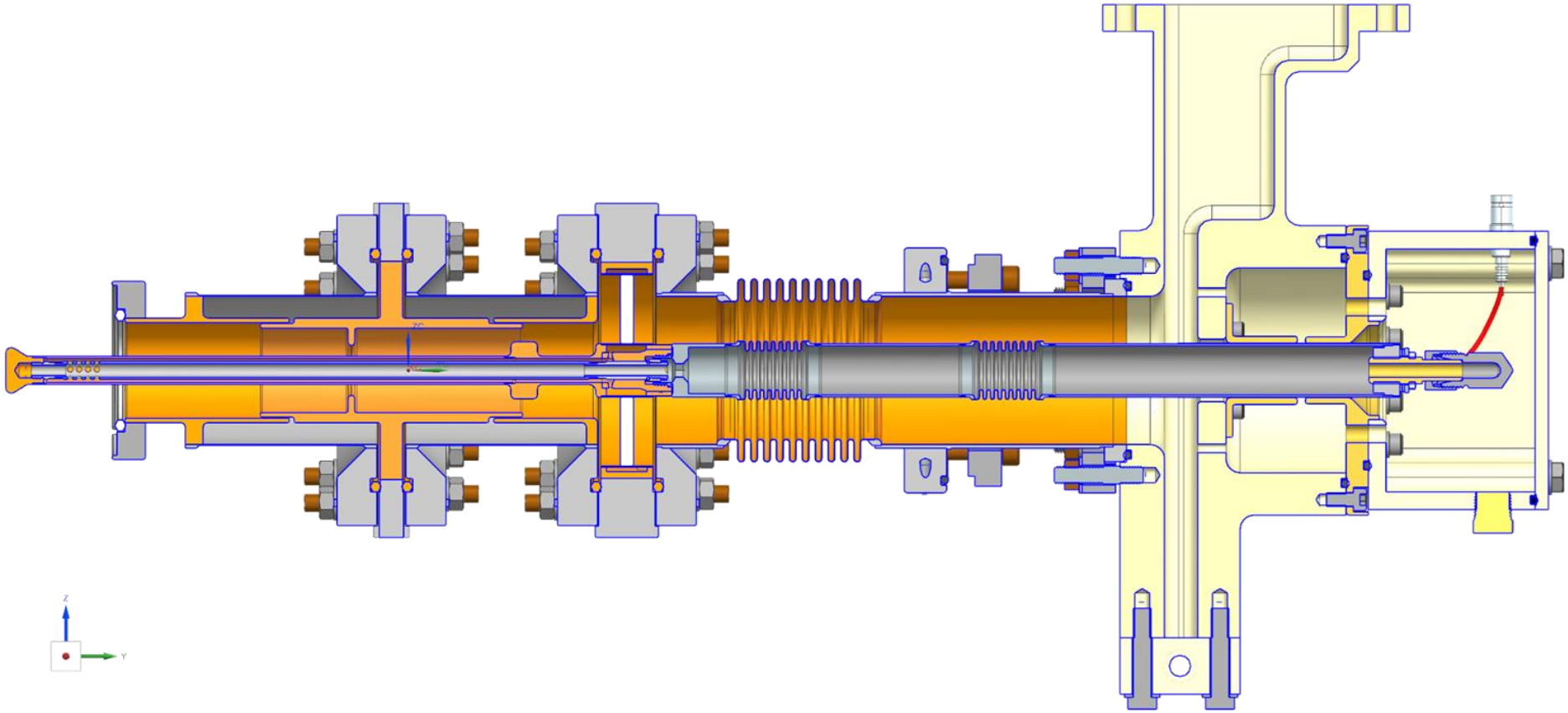
# Design Change Ideas / Questions

- Waveguide fed cavity?
  - Static heat loss may beat coaxial couplers if several coaxial couplers are needed to meet power target
  - Not so common, and likely more difficult due to 'lack of knowledge / experience'

- What power level can be achieved at 650 MHz for good reliability and low-moderate complexity? One coupler.
  - Water cooling will be needed for certain
  - Waveguides – special features?
    - N2, cooling, etc…

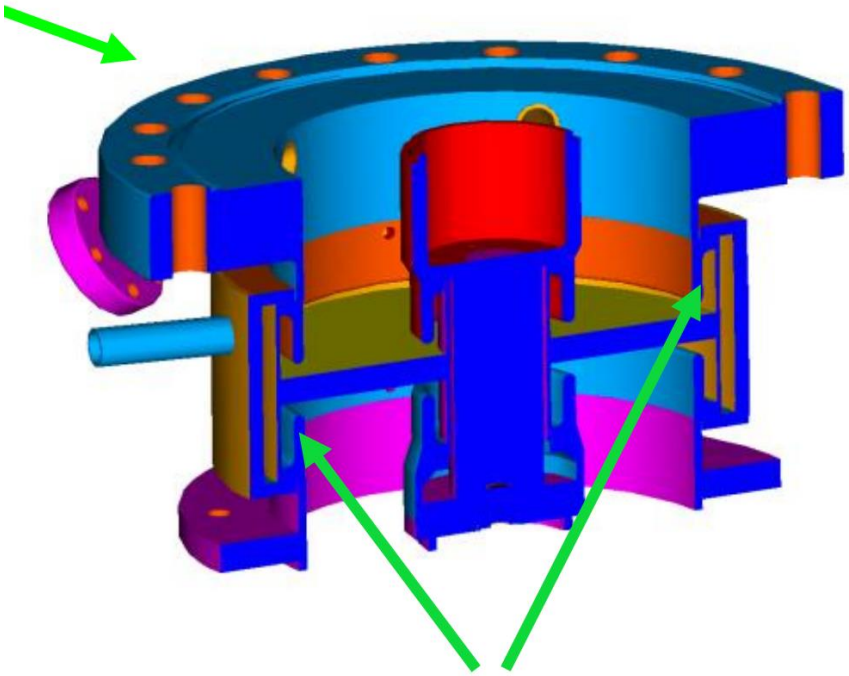
# Design Change Ideas / Questions

- How to go about removing bellows from inner conductor?
  - Spring finger contact required at window?



# Design Change Ideas / Questions

- If we <u>always</u> use HV Bias, is hiding the triple joints needed?
  - Is it just up to simulations, or should it be a ‘given’?




Source: Lectures for mechanical engineers: Lecture 3

Fundamental power couplers for Superconducting cavity

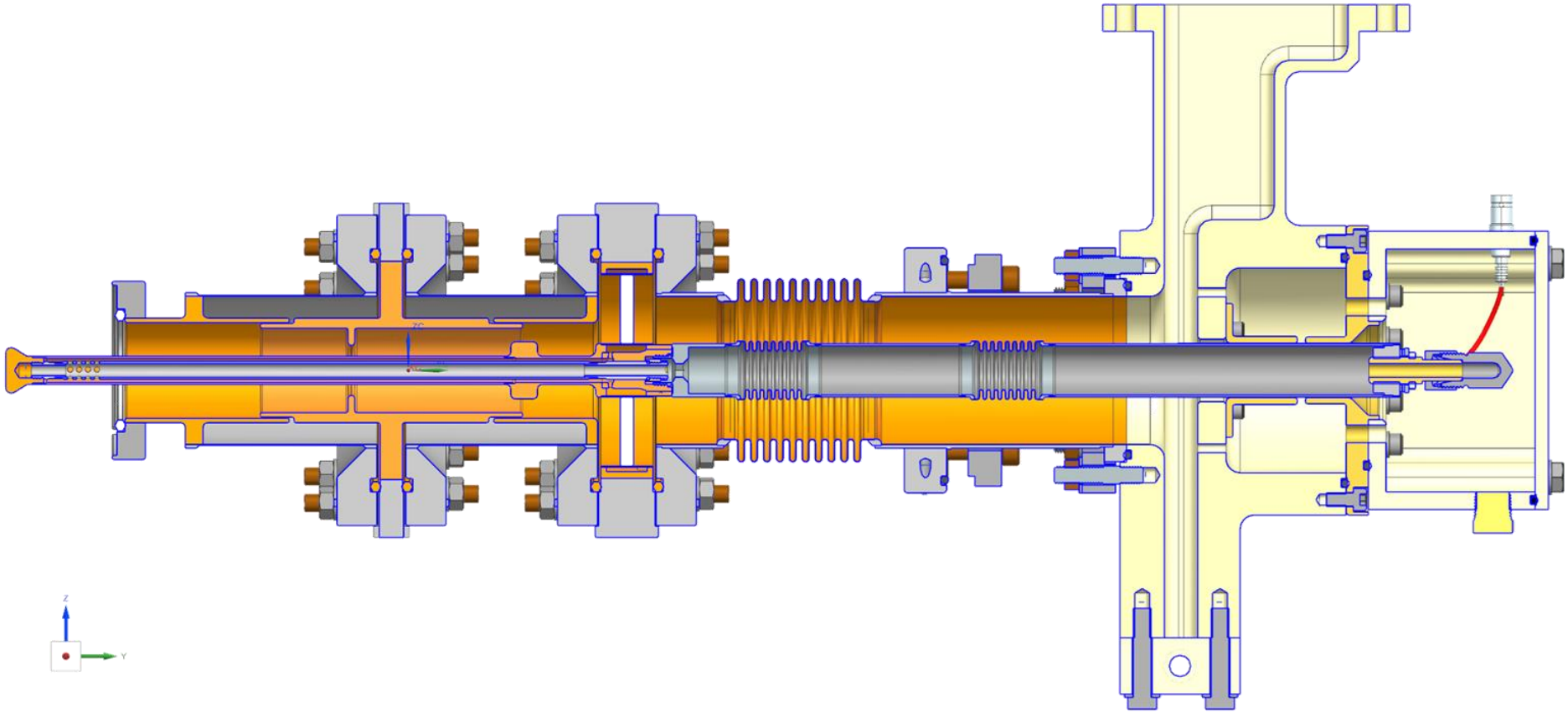
Wencan Xu
Brookhaven National Lab
April 28, 2011

# Other

- Who used conflats at cold connections for couplers? Anyone here?
  - European style has better history per FRIB
  - In use at FRIB with cold window
- Has anyone incorporated 3D printing to couplers / processes?
  - Tooling, metal parts, etc….
- Has anyone used laser welding for UHV coupler parts?
- A strong need for a vacuum gauge for a 4.5K system?

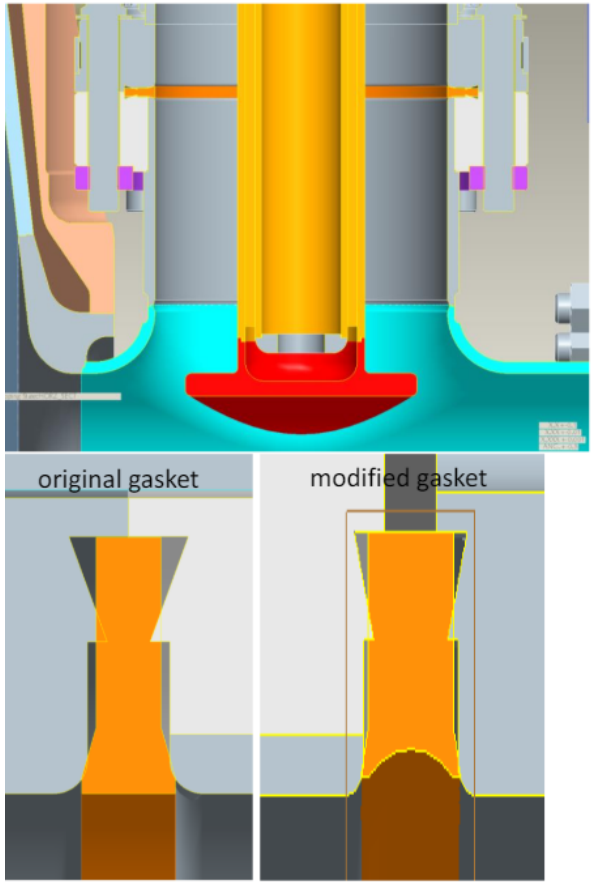
# End of IARC Slides

Thank you all!!!

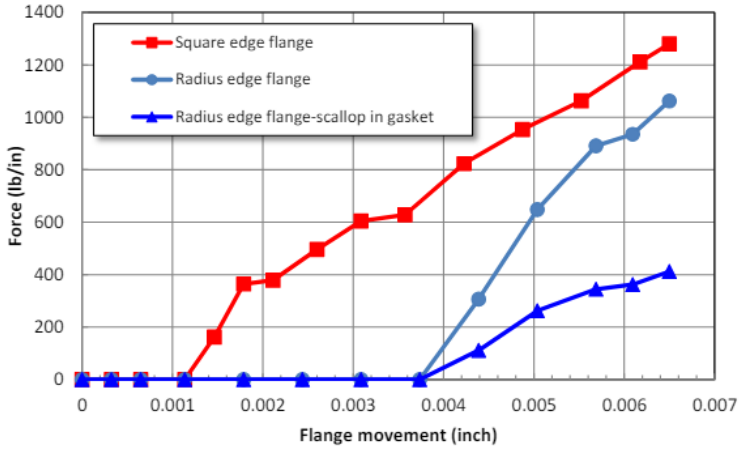


# Back Up – BNL Gasket Example

## Conflat gasket with RF seal




- A custom Conflat gasket with RF seal is used between the FPC and the SRF gun cavity.
- We have found that the original gasket was difficult to seal as the flanges had to crush the gasket in two places, which required very high force.
- A modification was proposed to alleviate the problem. It is used now on the SRF gun cavity/FPC interface.
- We may use similar gaskets in the future for beam pipe seals.




## Source:

High power coupler at BNL

Wencan Xu
Brookhaven National Lab

# Many ‘Random’ things – i.e. no linear story

# PIP-II Transportation Tests for Couplers

Goal:

Validate ANSYS models and other predictions so we can confidently transport couplers (and cryomodule)

Motivation:

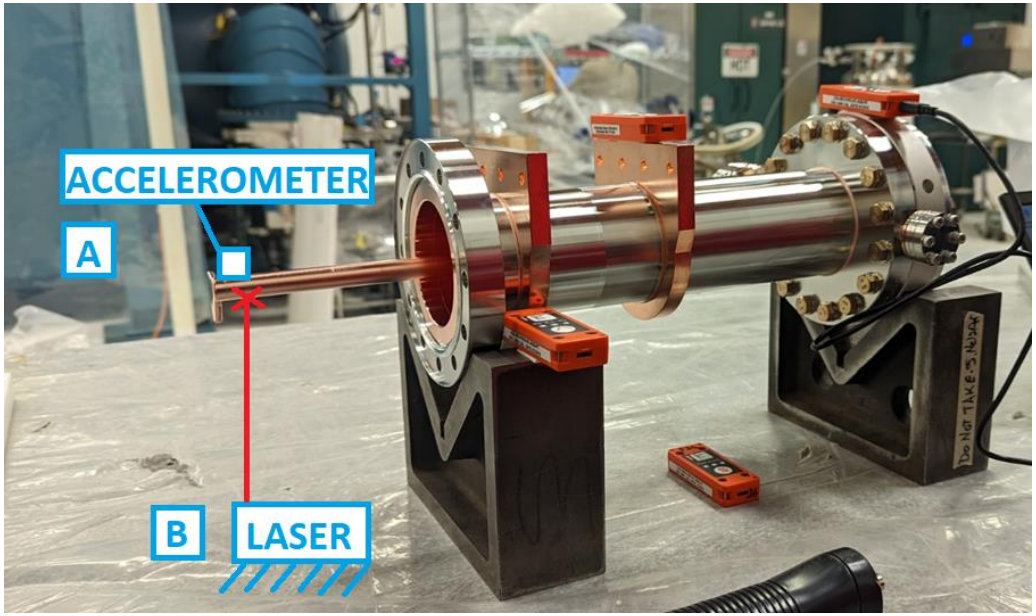
- Breaking a cryomodule expensive
- Two cryomodules in the last 5 years have broken, due to….Couplers!

Methods:

- Check vibration behavior meets expectations
- Perform transportation fatigue test

# PIP-II Resonance Testing – with laser

- Test:
  - Use accelerometer and laser to verify resonance of antenna
- Expected results:
  - 37 Hz first mode

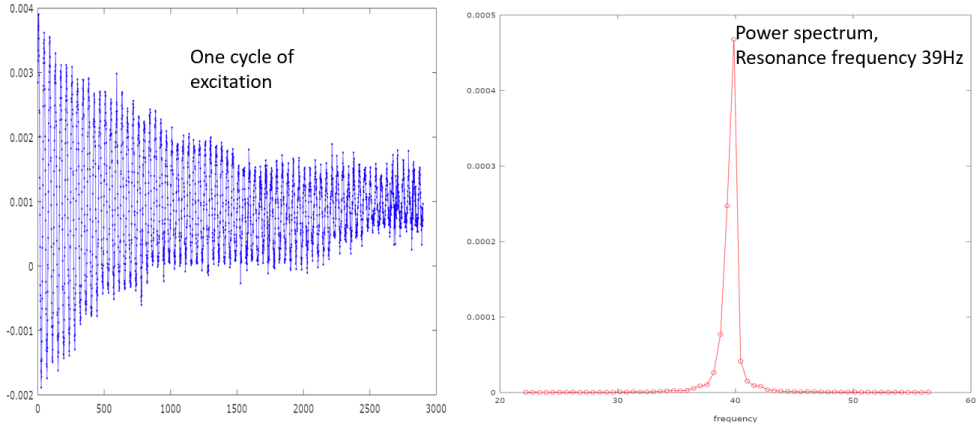


# PIP-II Resonance Testing – with laser

- Plan:
  - Use distance measurement laser and data logger to verify resonance of antenna

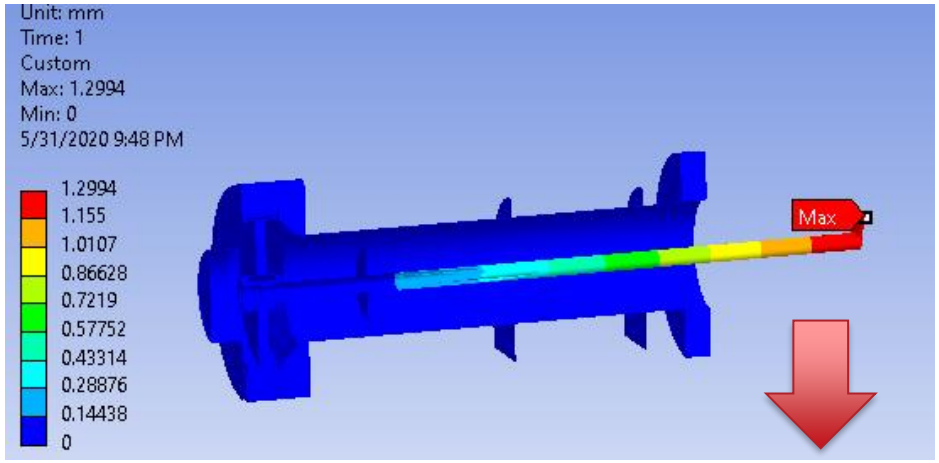
- **Actual results:**
  - **39 Hz first mode**
  - **Matches trend from accelerometer which shows slightly stiffer**
  - **<10% error satisfied**

One cycle of oscillation and power spectrum

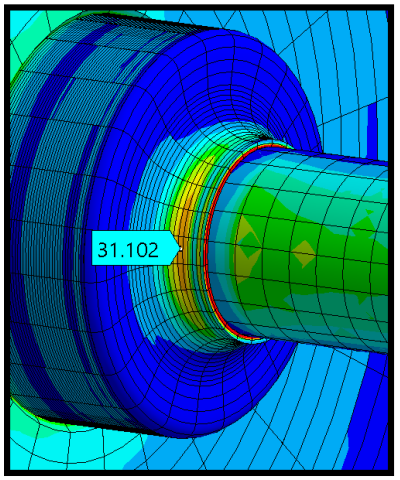


# PIP-II Coupler Fatigue Test – Main Principles

- Couplers transported installed in cryomodule.
- 6G perpendicular to antenna max. accel. Spec.
- Acceleration induces deformation and stress on antenna
- Recreating the deformation recreates the stress.




6G Deformation

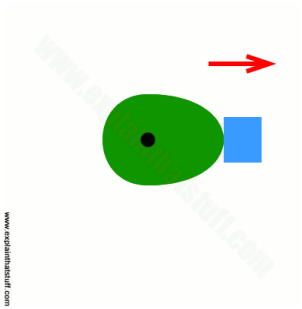


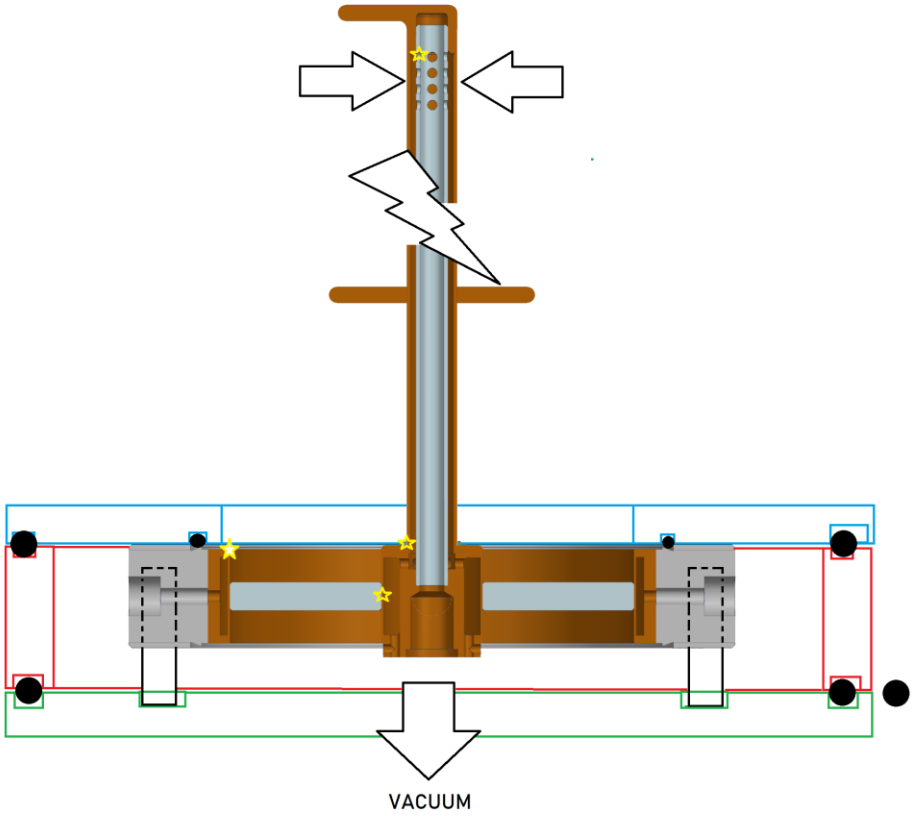

Connector Stress

# PIP-II Coupler Fatigue Test – Conceptual Design

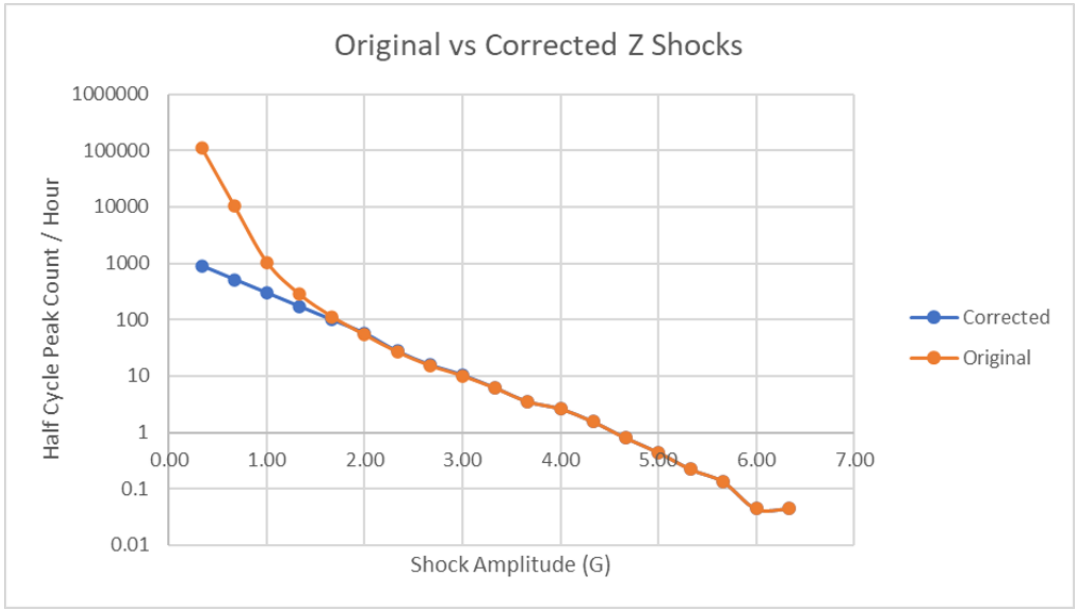
- Can’t manipulate antenna if the normal part is under vacuum, so let's reverse it (stress nearly the same)

- Let’s use a cam lobe for controlled displacement
  - Blue square is antenna

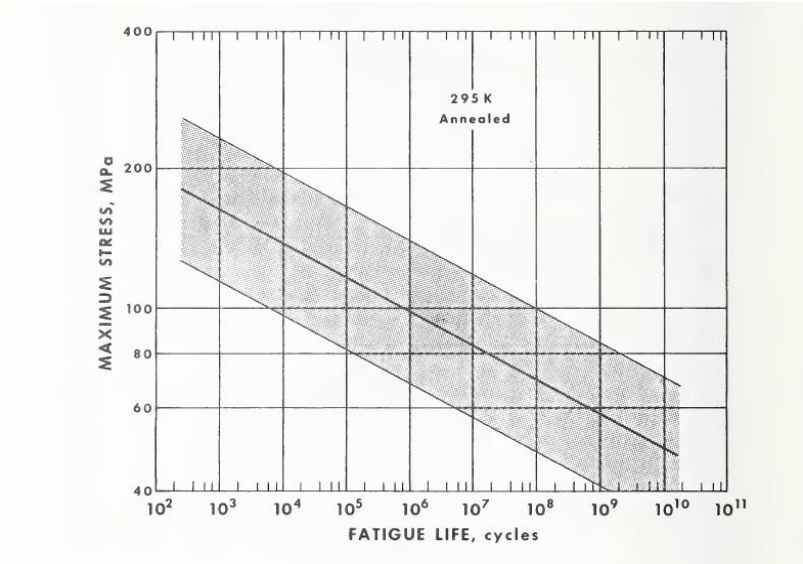




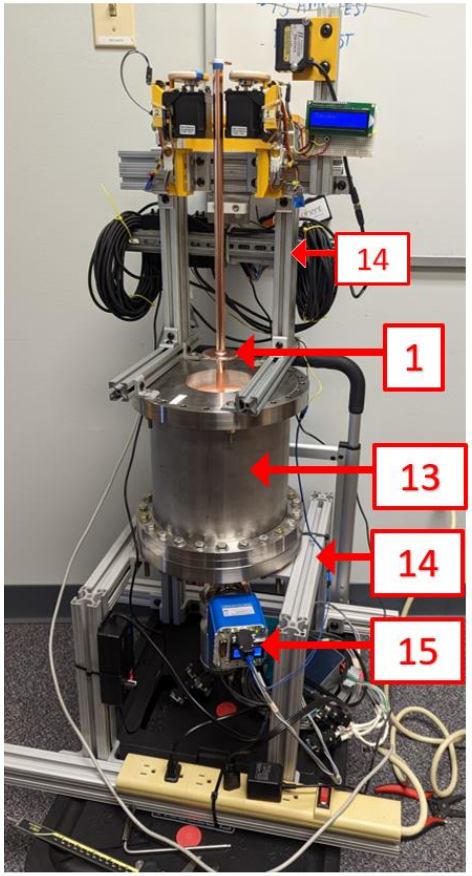
# PIP-II Coupler Fatigue Test – Cycle Estimation



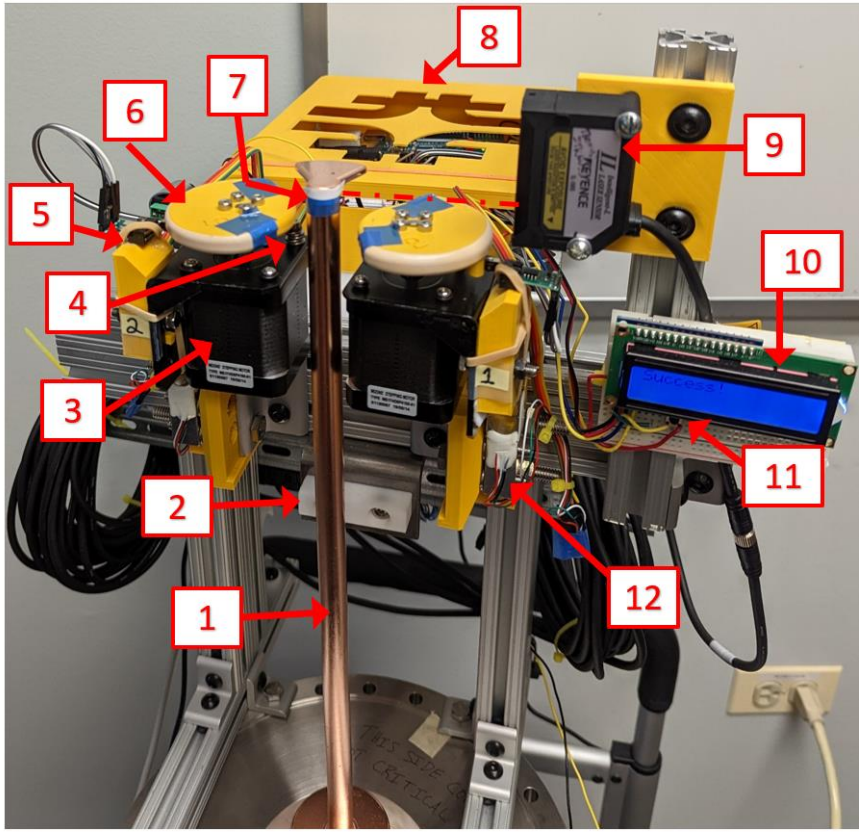

| Shock Level, G | Oa, max Stress, Mpa | Fully Rev. Cycles to Failure | Damage per cycle | Number of cycles predicted | Total damage |
|---|---|---|---|---|---|
| 0.33 | 7.6 | 5.65E+08 | 1.77E-09 | 3.58E+06 | 6.33E-03 |
| 0.67 | 9.5 | 2.28E+08 | 4.39E-09 | 1.38E+06 | 6.04E-03 |
| 1.00 | 11.4 | 1.08E+08 | 9.23E-09 | 5.53E+05 | 5.11E-03 |
| 1.33 | 13.2 | 5.78E+07 | 1.73E-08 | 2.36E+05 | 4.08E-03 |
| 1.67 | 15.1 | 3.35E+07 | 2.98E-08 | 1.07E+05 | 3.19E-03 |
| 2.00 | 17.0 | 2.07E+07 | 4.82E-08 | 4.99E+04 | 2.41E-03 |
| 2.33 | 18.9 | 1.35E+07 | 7.41E-08 | 1.98E+04 | 1.47E-03 |
| 2.67 | 20.8 | 9.14E+06 | 1.09E-07 | 1.14E+04 | 1.24E-03 |
| 3.00 | 22.7 | 6.41E+06 | 1.56E-07 | 7.51E+03 | 1.17E-03 |
| 3.33 | 24.6 | 4.62E+06 | 2.16E-07 | 3.95E+03 | 8.54E-04 |
| 3.67 | 26.5 | 3.42E+06 | 2.93E-07 | 2.11E+03 | 6.17E-04 |
| 4.00 | 28.3 | 2.58E+06 | 3.88E-07 | 1.57E+03 | 6.11E-04 |
| 4.33 | 30.2 | 1.98E+06 | 5.05E-07 | 9.33E+02 | 4.71E-04 |
| 4.67 | 32.1 | 1.55E+06 | 6.47E-07 | 4.80E+02 | 3.11E-04 |
| 5.00 | 34.0 | 1.22E+06 | 8.17E-07 | 2.67E+02 | 2.18E-04 |
| 5.33 | 36.5 | 9.14E+05 | 1.09E-06 | 1.33E+02 | 1.46E-04 |
| 5.67 | 39.0 | 6.96E+05 | 1.44E-06 | 8.00E+01 | 1.15E-04 |
| 6.00 | 41.5 | 5.39E+05 | 1.85E-06 | 2.67E+01 | 4.95E-05 |
| 6.33 | 44.1 | 4.24E+05 | 2.36E-06 | 2.67E+01 | 6.29E-05 |
| | | | | | |
| | 5G+1G Equivalent | | **4.22E+04** | Total Damage | **3%** |



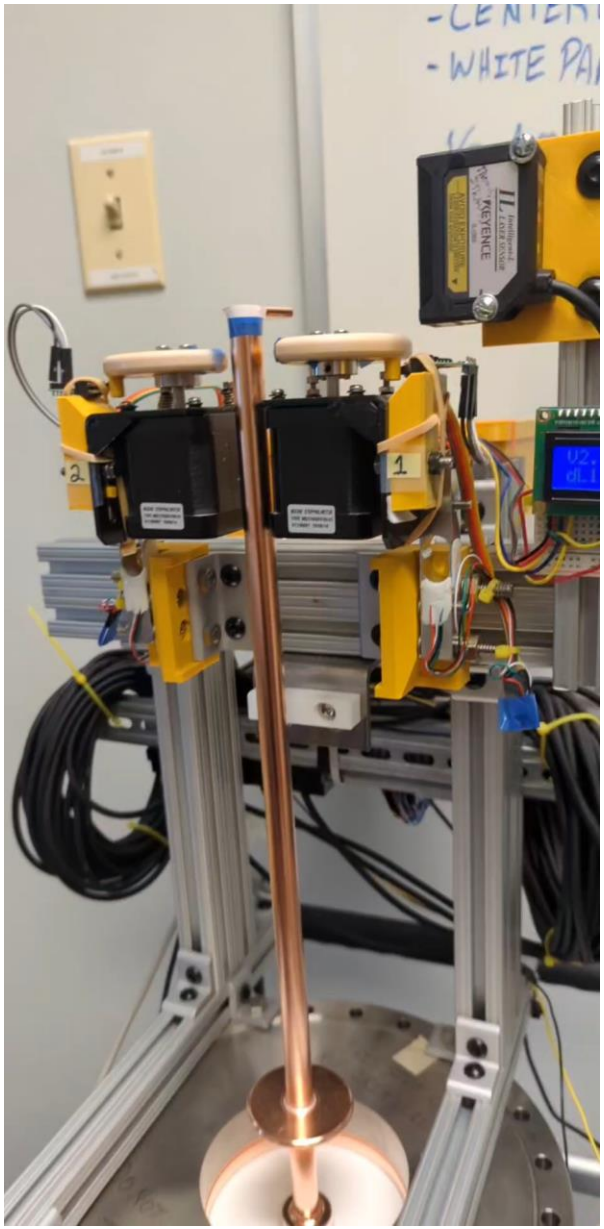
# PIP-II Coupler Fatigue Test



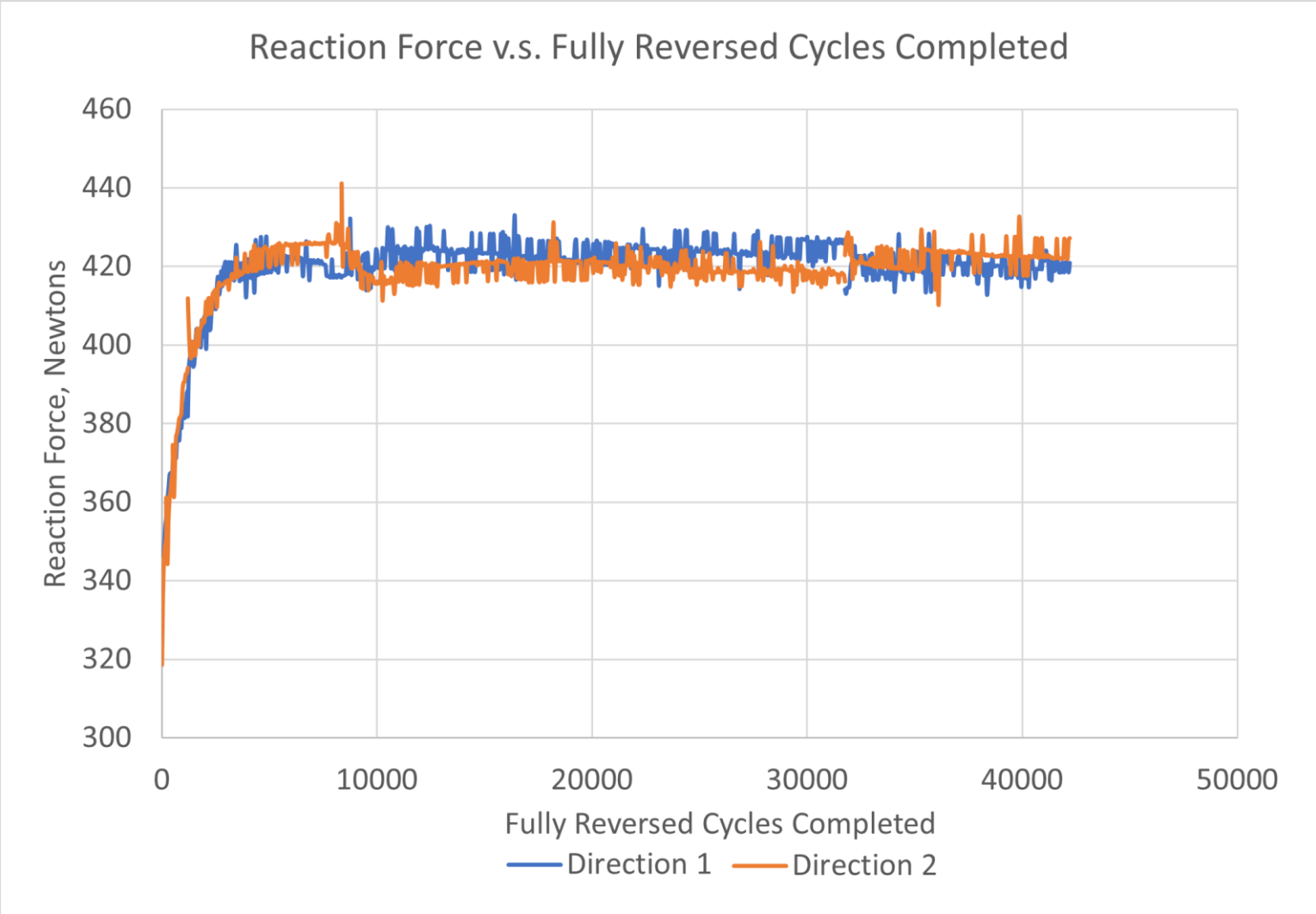

| Item | Description |
|---|---|
| 1 | pHB650 Antenna |
| 2 | PTFE Slider Support Bar |
| 3 | Stepper Motor |
| 4 | Cam Safety Stop |
| 5 | Roller Limit Switch |
| 6 | Cam Lobe, Snail Shape |
| 7 | Non-Reflective Covering |
| 8 | Controls Housing |
| 9 | High Precision Laser |
| 10 | LCD Readout |
| 11 | User Interface |
| 12 | Load Cell |
| 13 | Vacuum Chamber |
| 14 | Framing |
| 15 | Vacuum Gauge |



# Video



# PIP-II Coupler Fatigue Test - Results

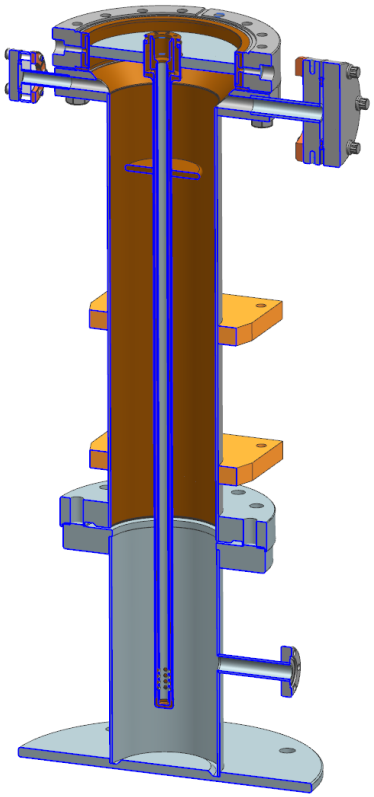


# Proof Test

- We performed 2x proof test a coupler to approx. 130 PSIG
  - This certified coupler for pressure boundary safety per BVPC
  - Analysis finds that we may see some plastic yield, but no failure should occur
  - This pressure level has enough margin to certify all units of a production run with a single test
  - We still plan to test all couplers to 60 PSIG or more.

# Test Configuration

- Hydrostatic test
  - Better for safety
  - We will do it before FDR is closed
- To be performed on coupler after fatigue test
  - Conservative



# PIP-II Coupler Pressure Test





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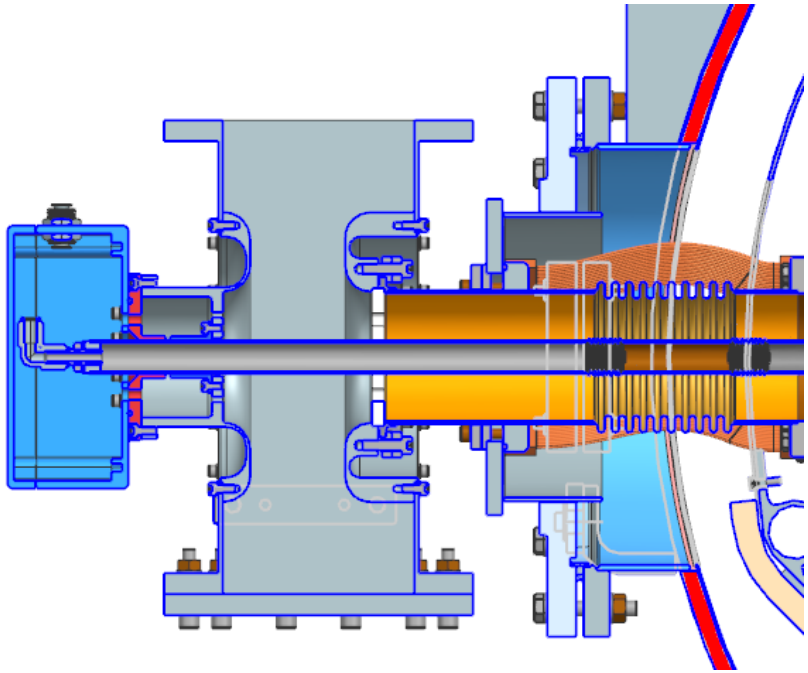
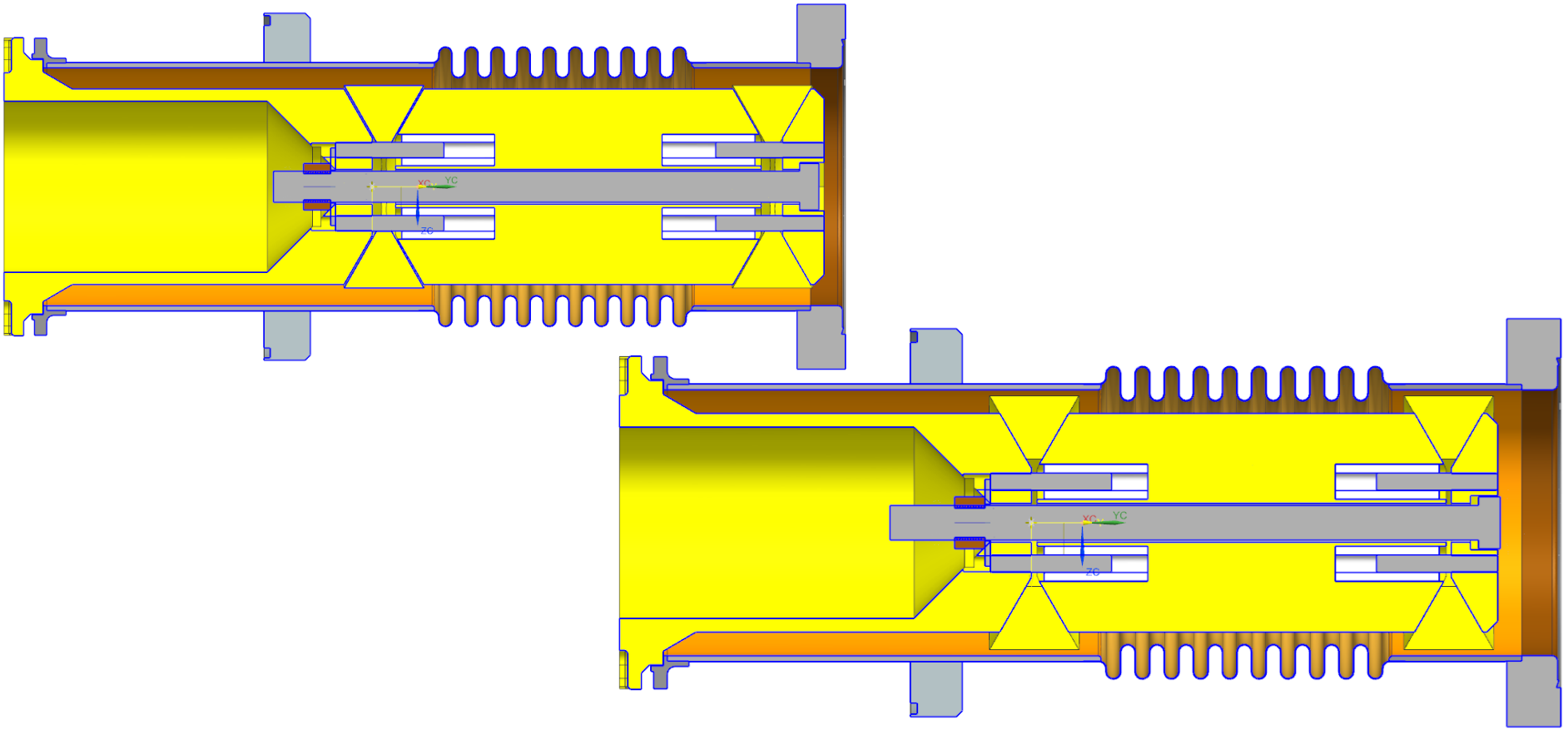
# PIP-II Coupler Installation Tool

- Air side assembly – tooling for air outer conductor complete
  - Purpose: hold sections straight during assembly to prevent deflection in bellows during custom fit-up with vessel flanges



# PIP-II Coupler Installation Tool



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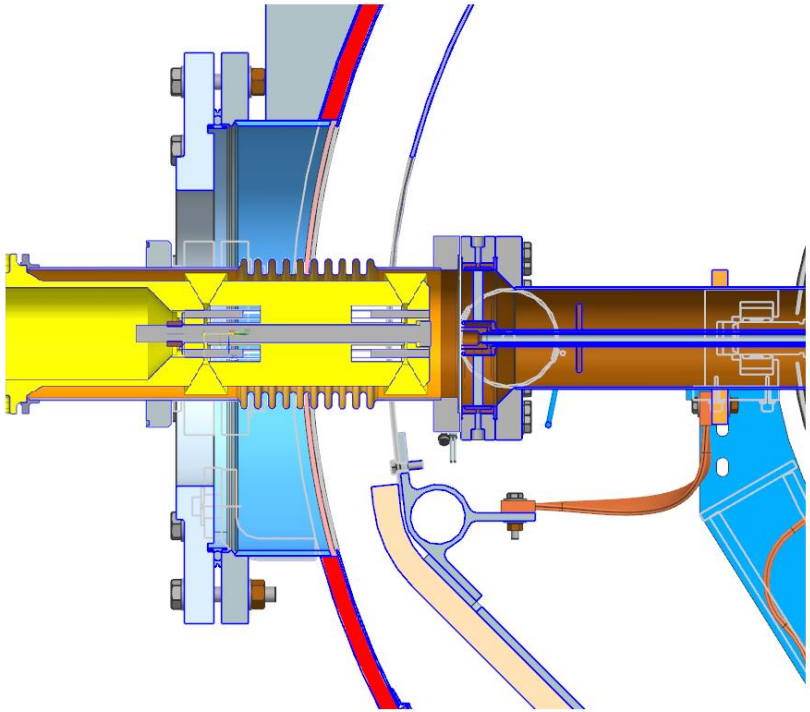
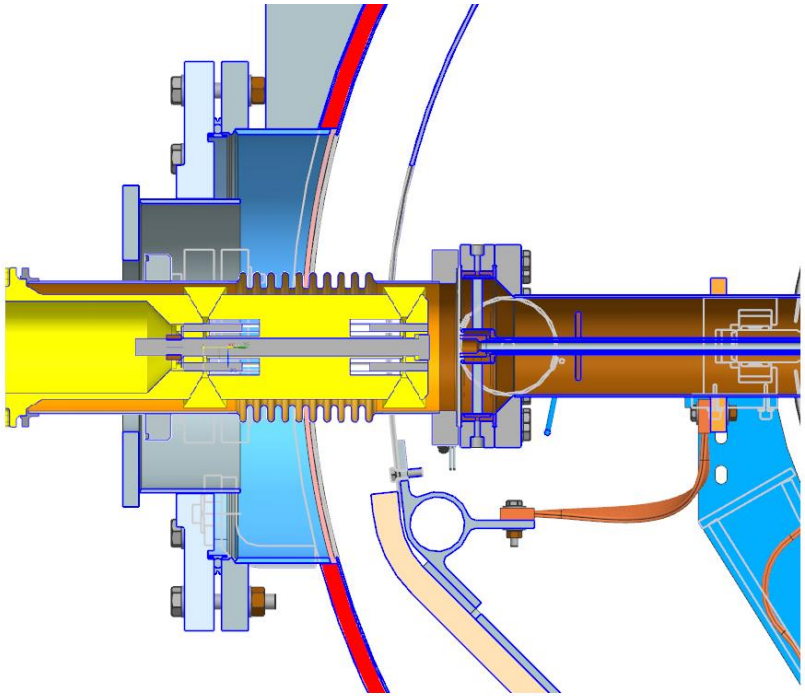
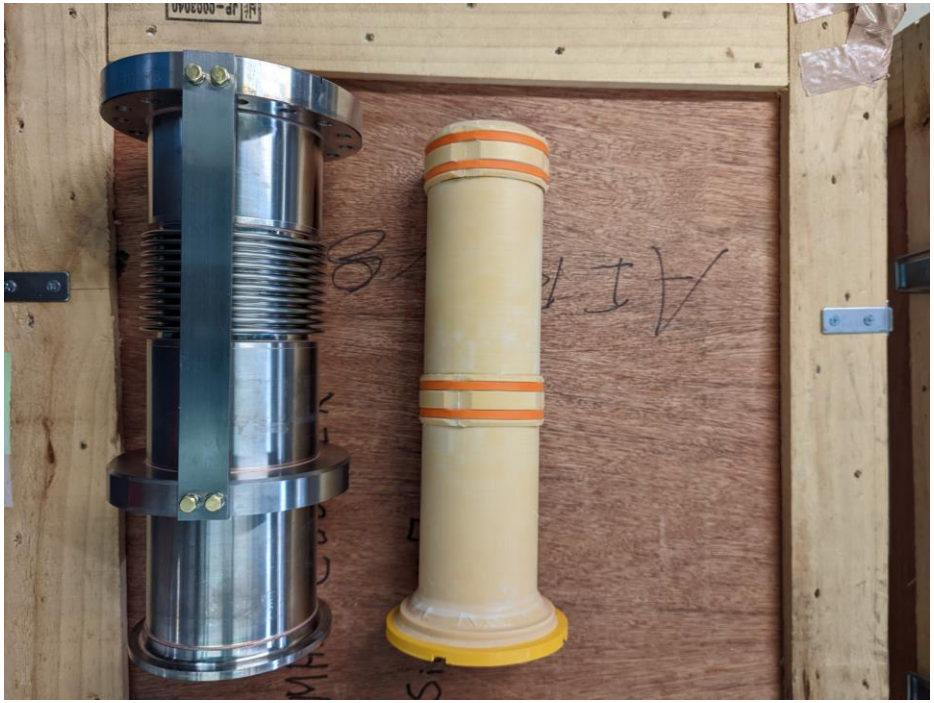
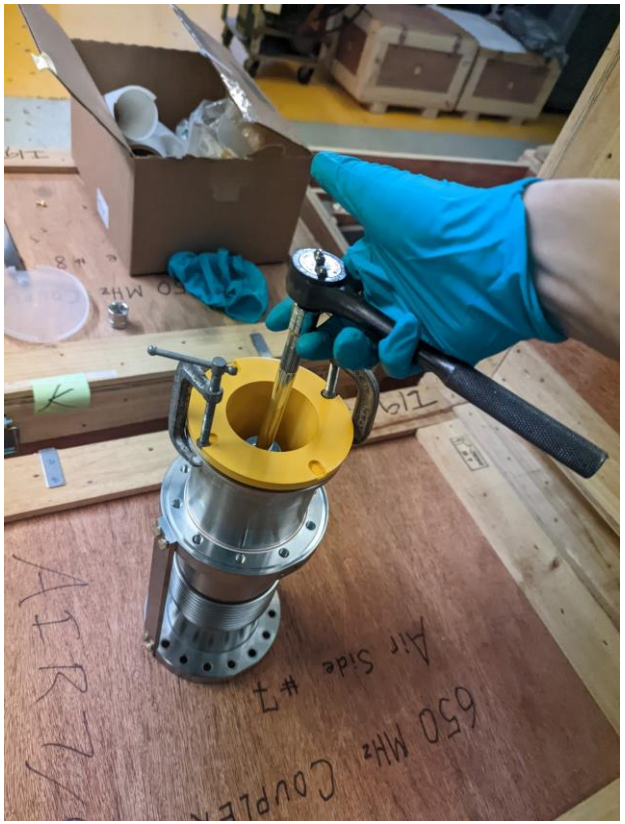
# PIP-II Coupler Installation Tool





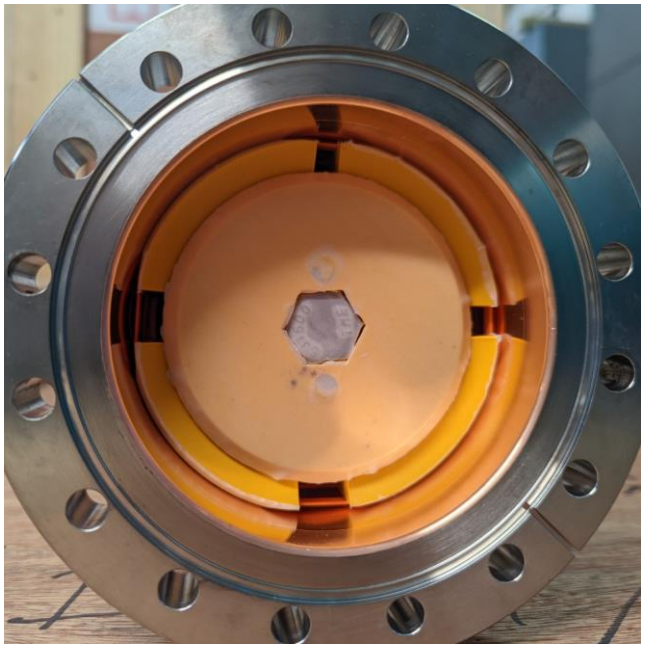
# PIP-II Coupler Installation Tool





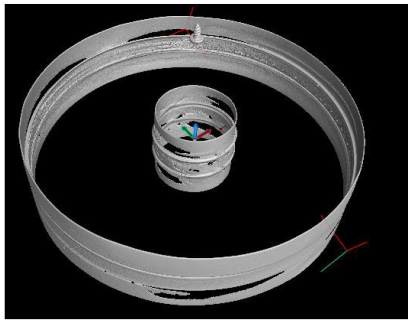

Lesson learned – cover with plastic bag to prevent rubber-copper contact

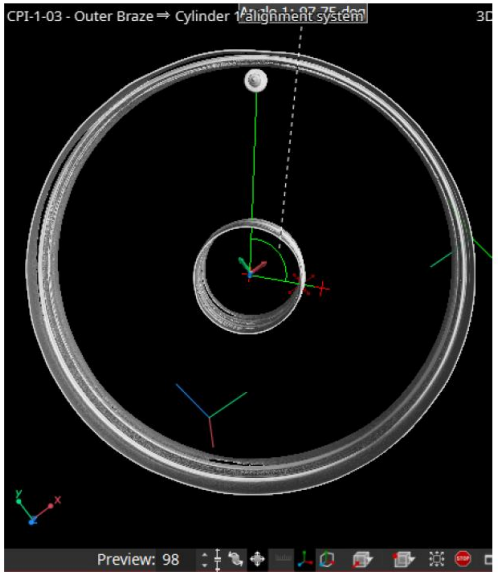
# PIP-II Coupler Installation Tool



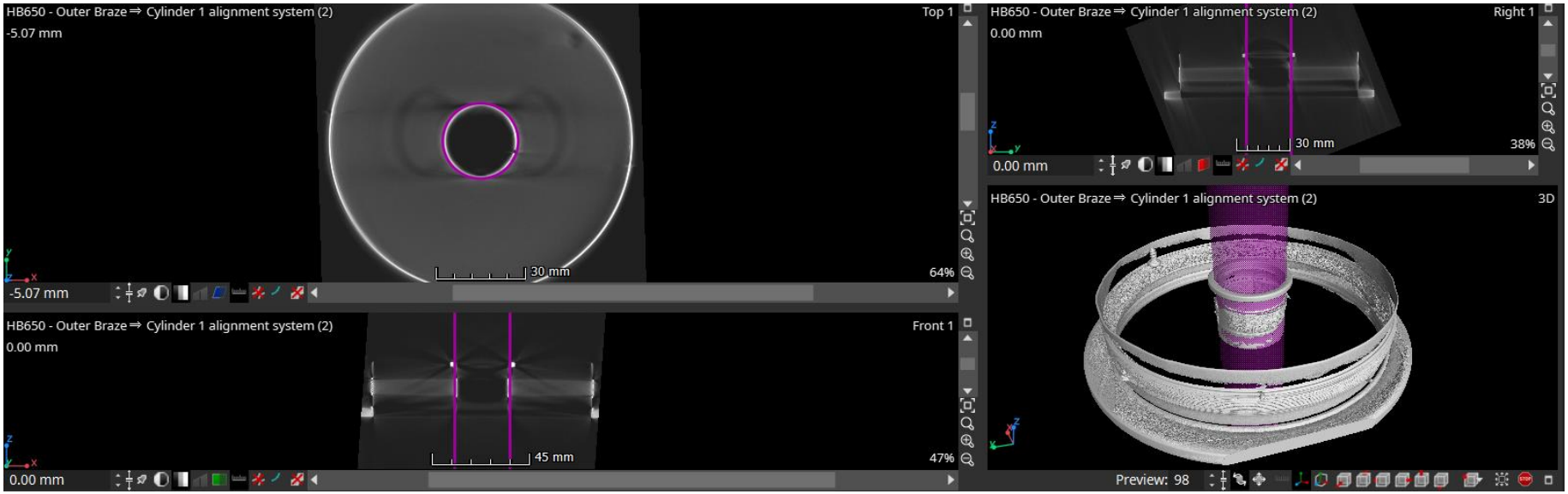
# PIP-II CT Scanning

- We used CT Scanning to identify (potential) voids in the ceramic-copper brazing
  - Resolution: approx. 60 um
  - Cost: approx. $300-500 USD per window
  - Vendor: Jesse Garant Metrology, Toronto Canada
  - Data format: 3D + unrolled braze images

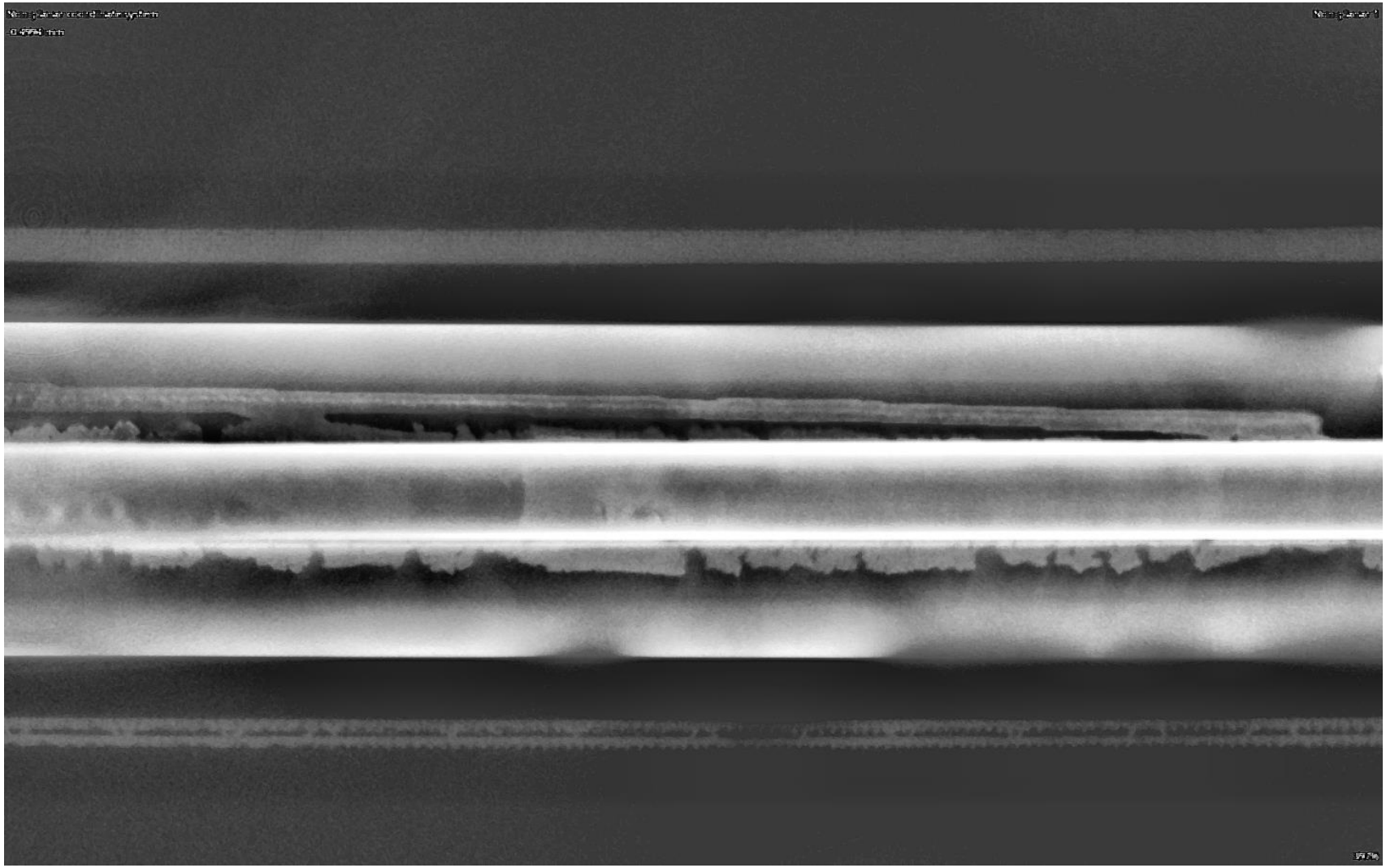




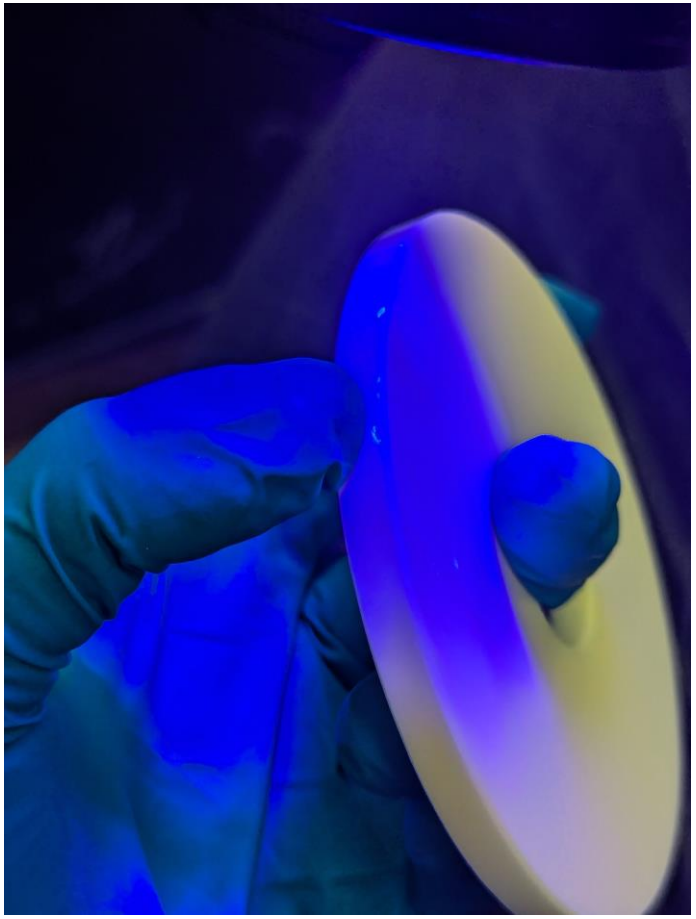
# PIP-II CT Scanning



# PIP-II CT Scanning



# Dye Penetrant Testing



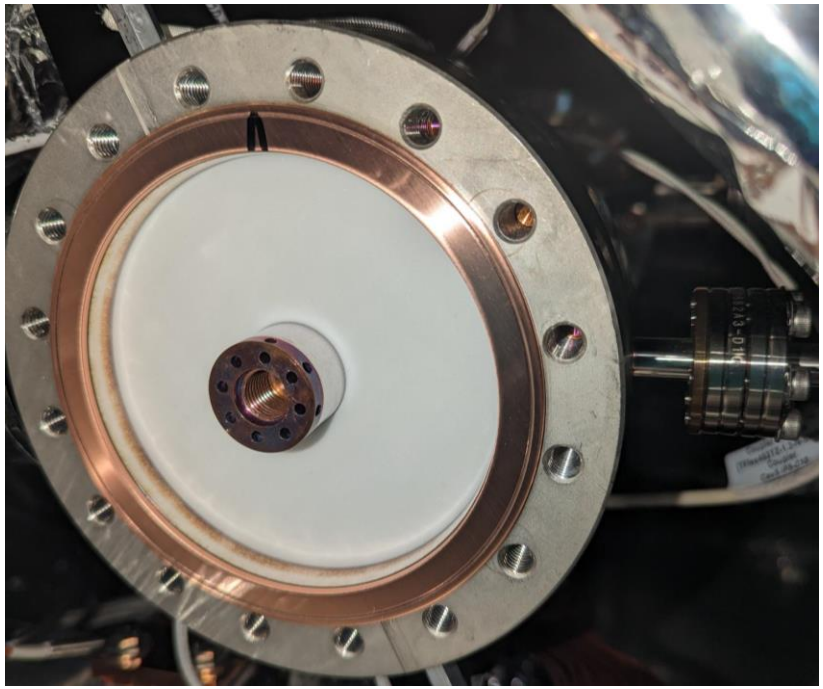
MAGNAFLUX ® ZL-4C water-based dye penetrant, with ZP-4D powder developer – thanks to CEA for this information.

# PIP-II Couplers – Operational Challenges

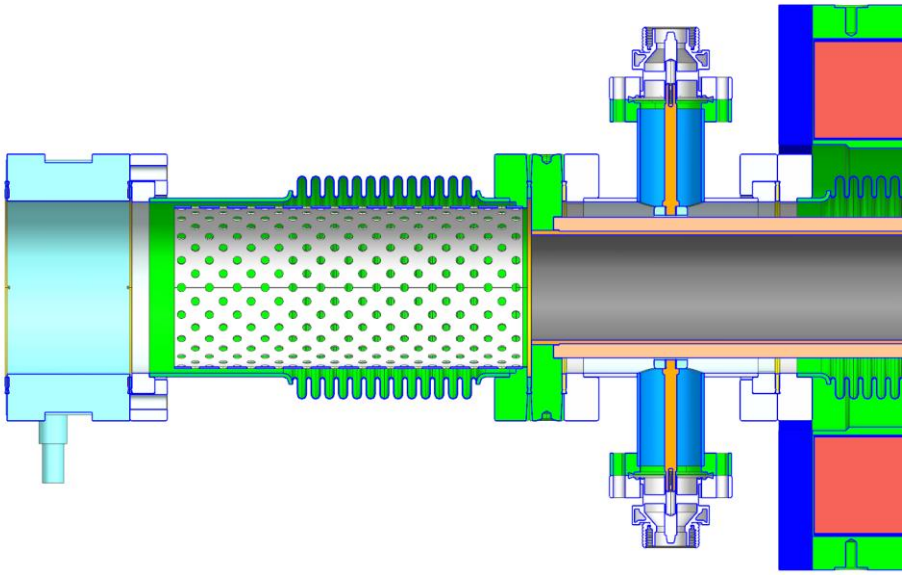
- We have some CCG – Pfeifer
- Vacuum gauges are IN insulating vacuum.
- Over many months with very good beamline vacuum (10-9 or less) vacuum gauges ‘go to sleep’
- We think it is just a ‘feature’ of the CCG – impossible to stay at such low vacuum levels.
- Others have experience with this?

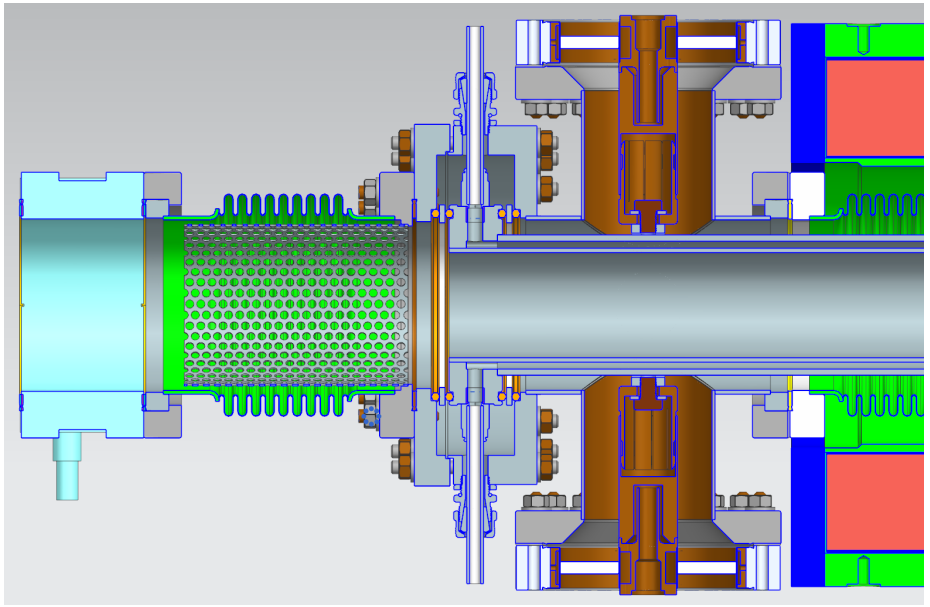
# PIP-II Lesson Learned – Machining CF pockets

- We made the CF pockets ‘just’ slightly too small
  - It lead to impossible sealing if the sharp edge of the seal was inserted
  - It made it very difficult to remove the seal



# BNL RF GUN





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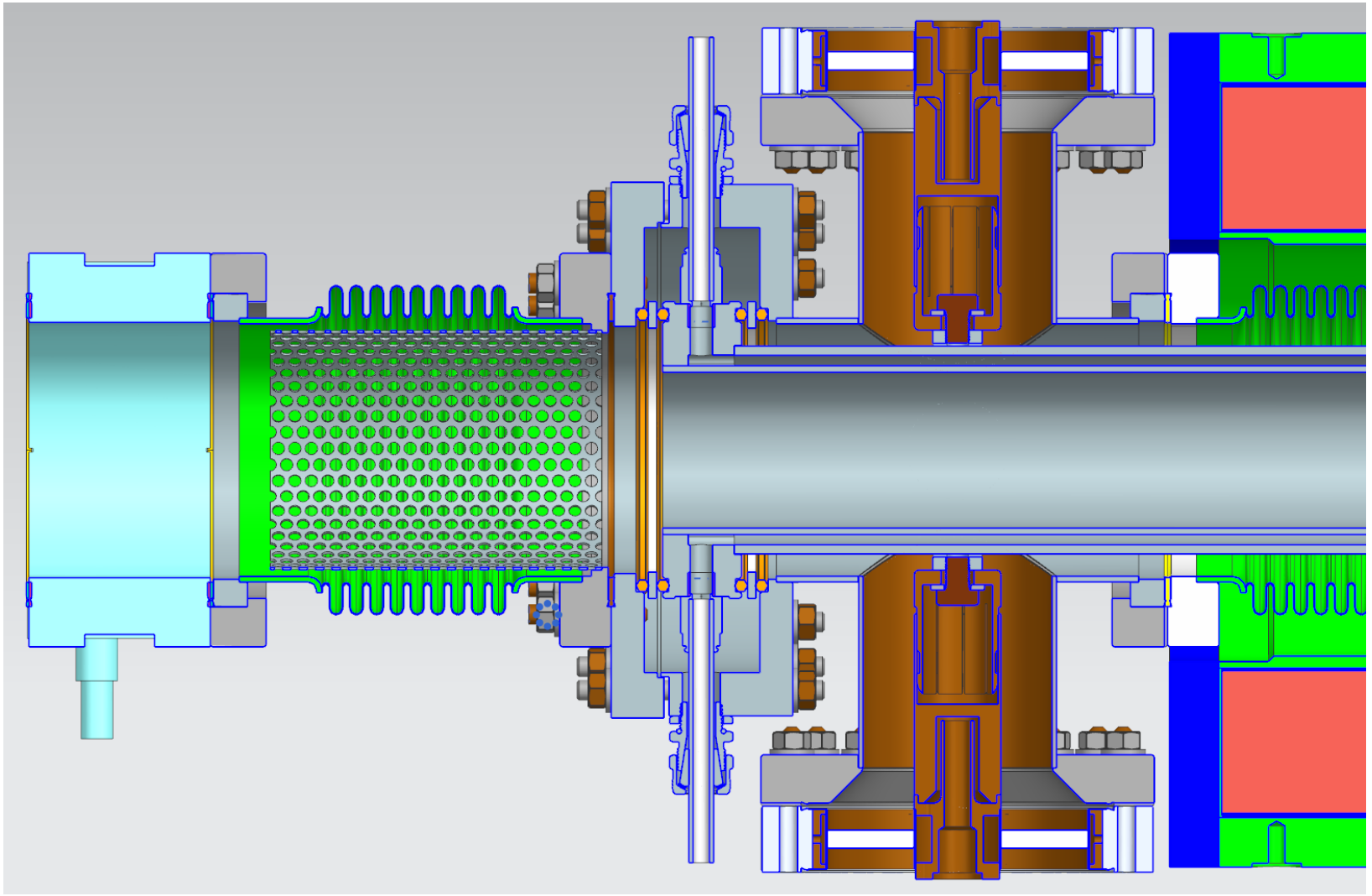
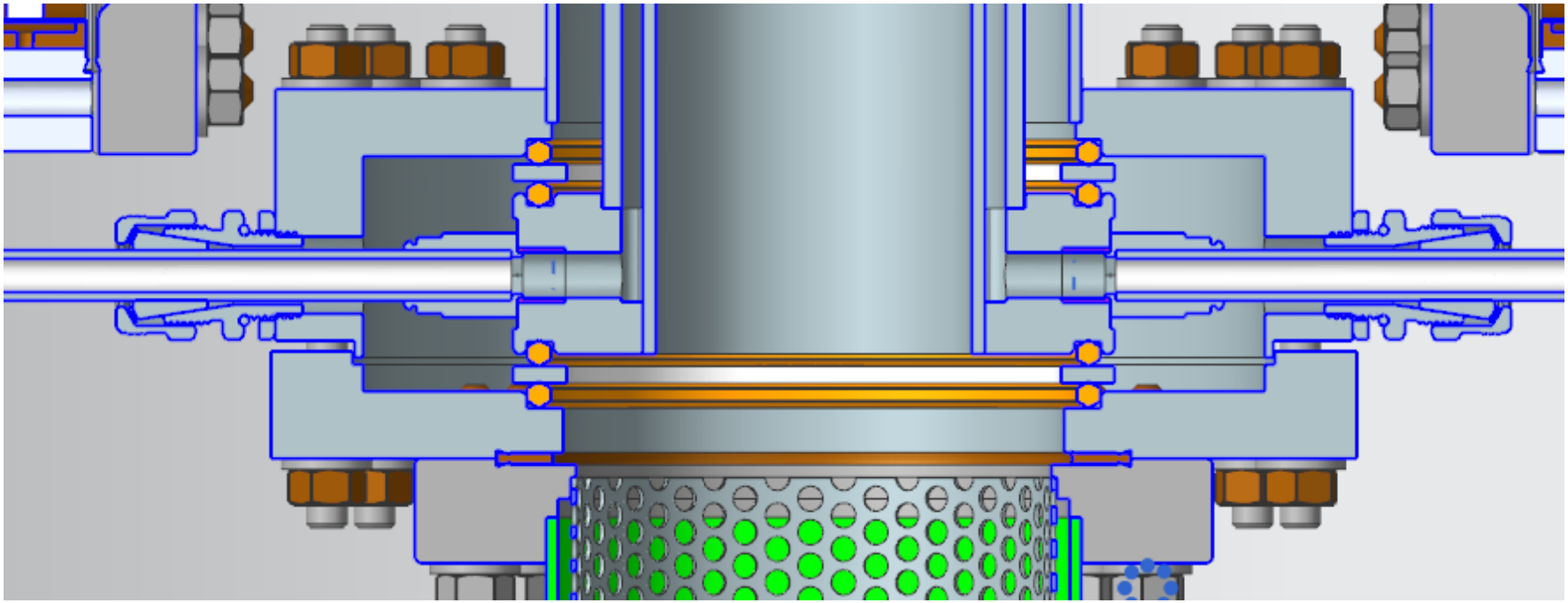
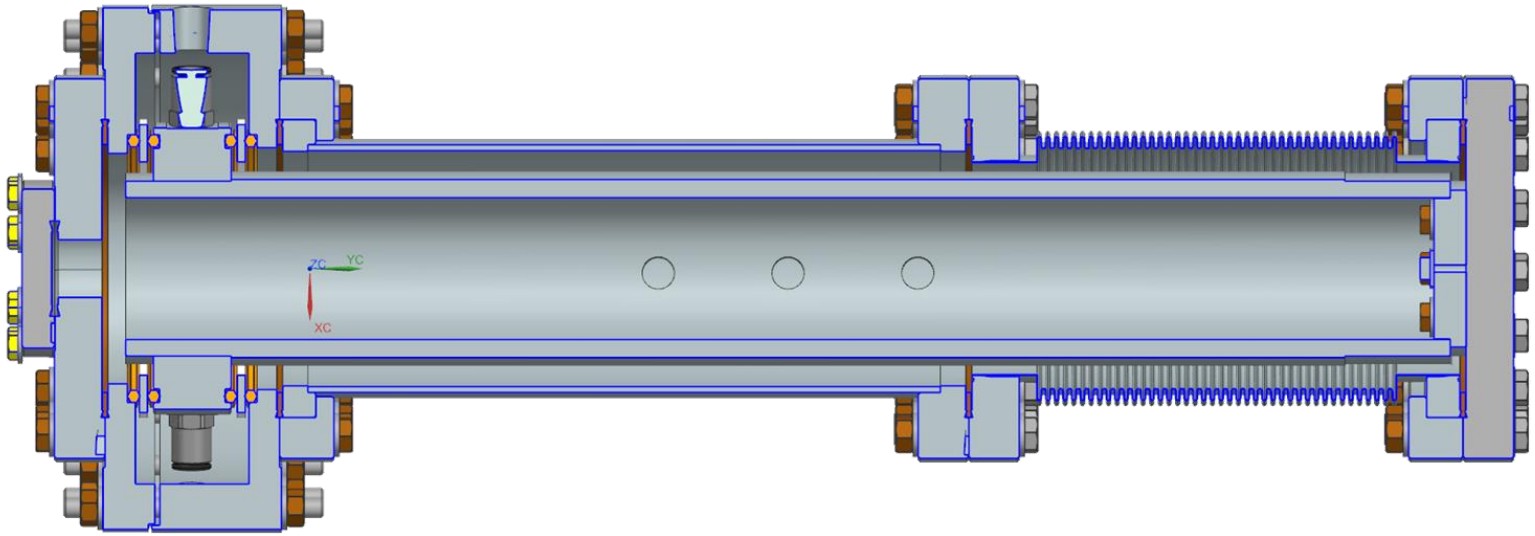


# BNL RF GUN



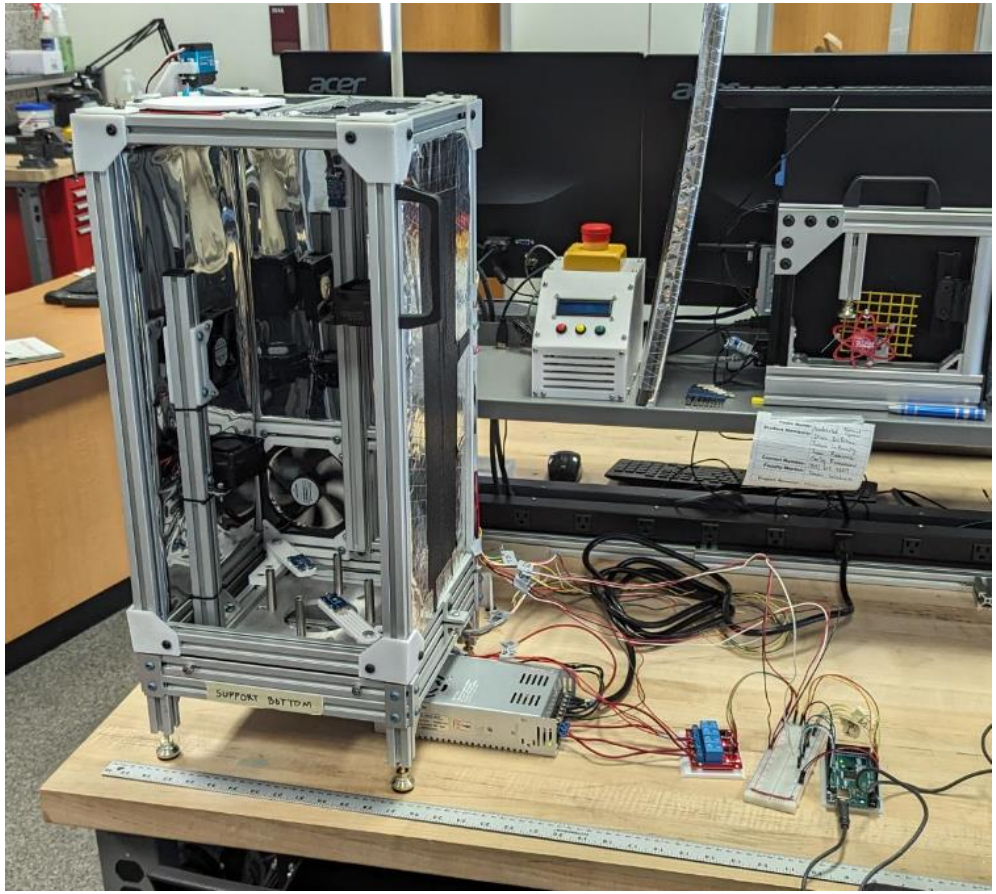
# BNL RF GUN

- Due to the unique design (ceramic-diamond sealing) – it's necessary to perform a test of the antenna prior to production
- A mock antenna, flanges, and accessories have had drawings made, and the items are procured
- Ran out of money to perform test



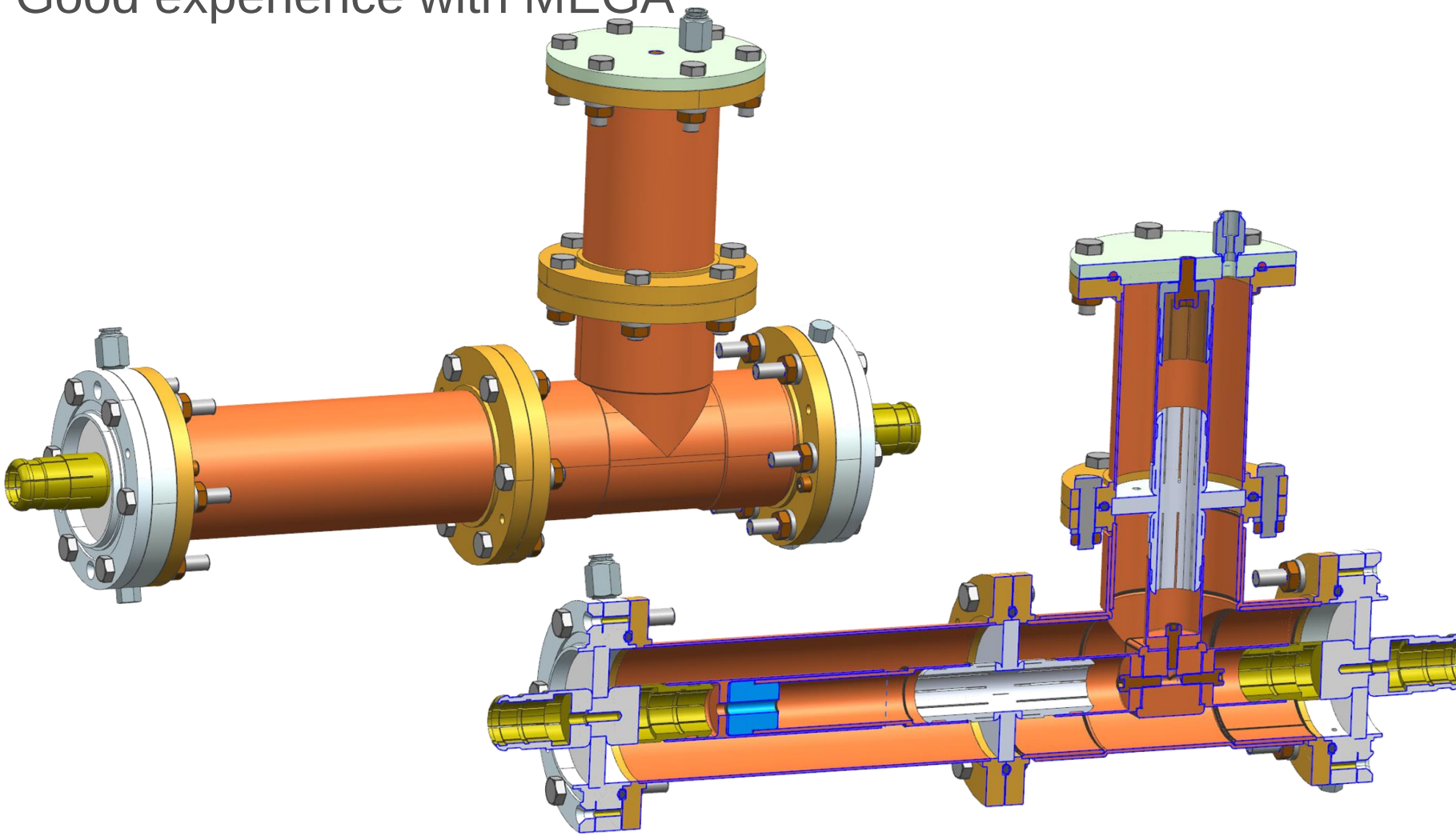
# Accelerated Thermal Cycler

- I had some students time for free, and for $1,000 they built me a thermal cycler for an antenna

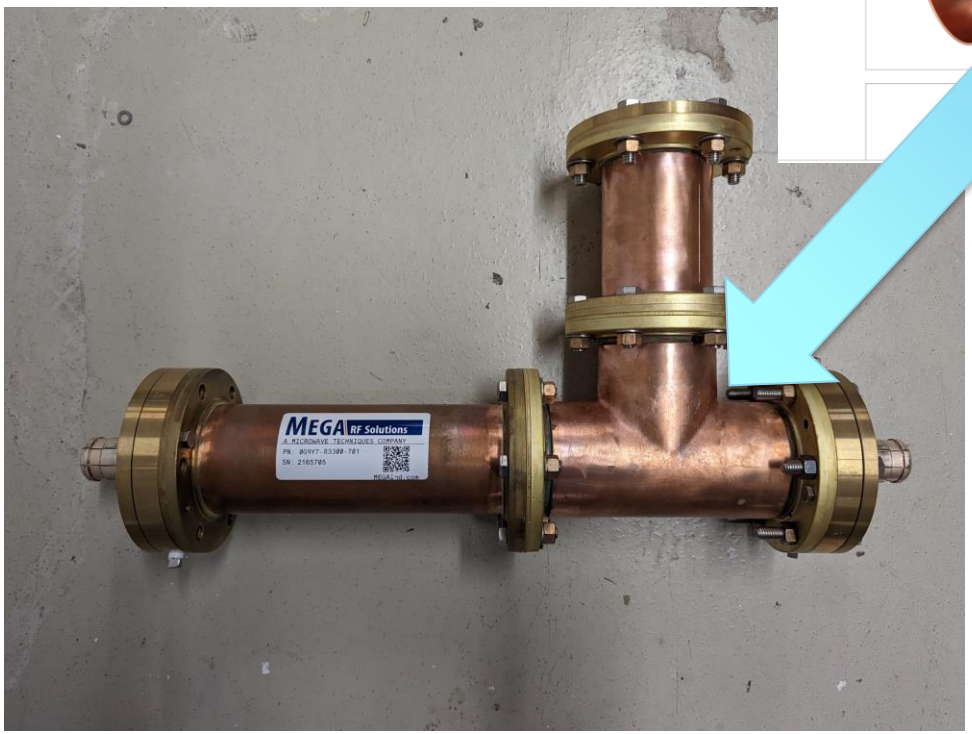


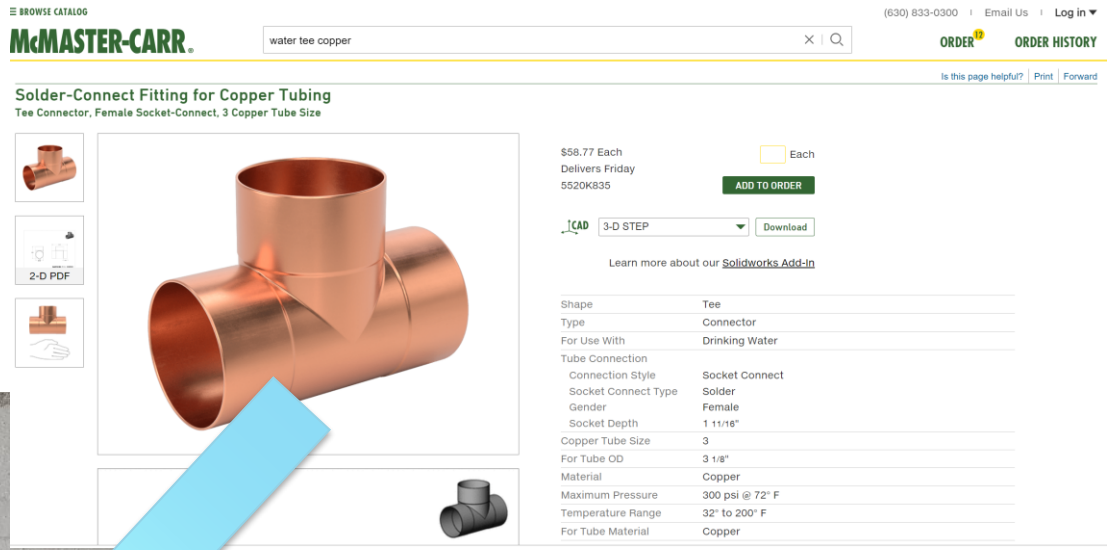
# PIP-II 325 MHz DC Block

- Good experience with MEGA



# PIP-II 325 MHz DC Block

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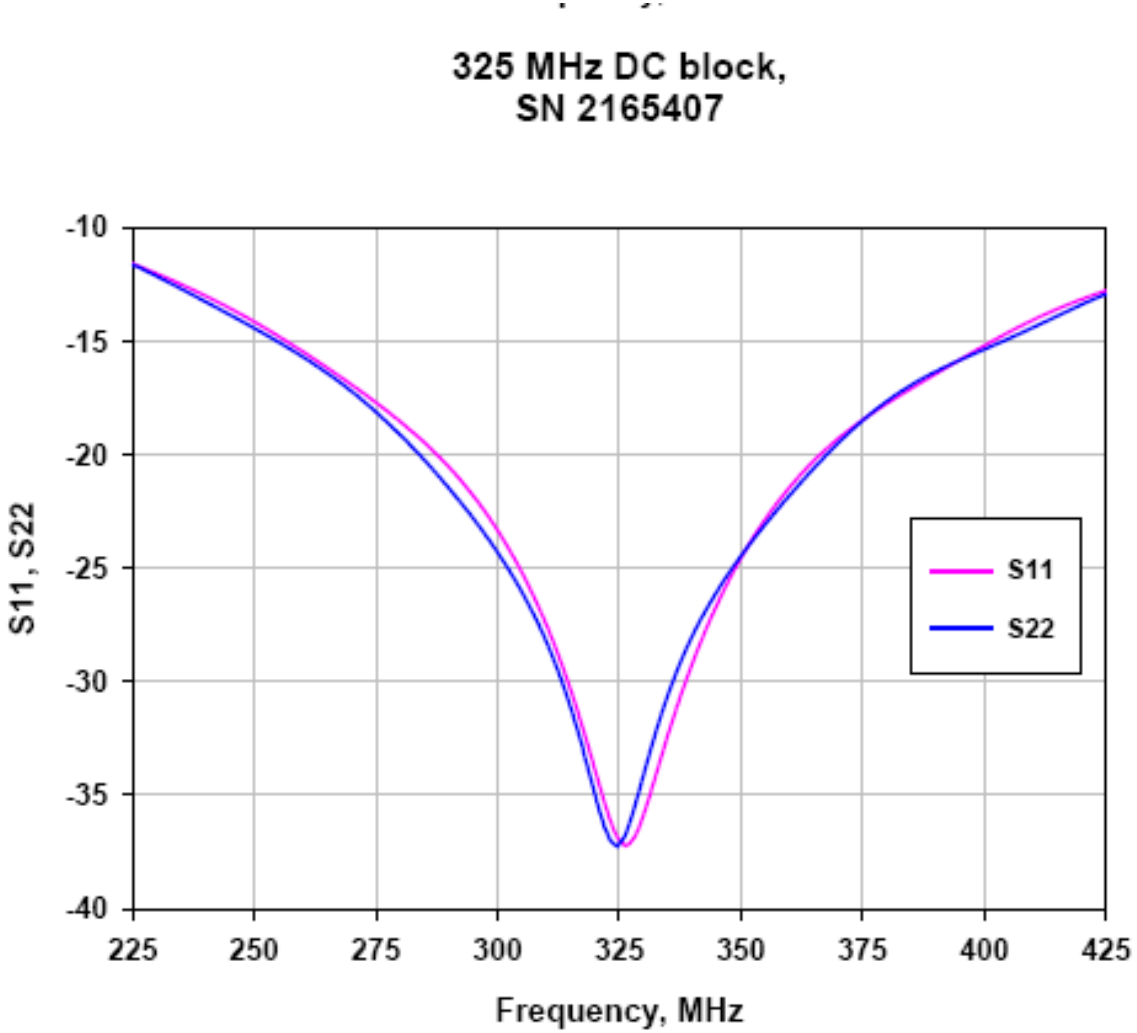
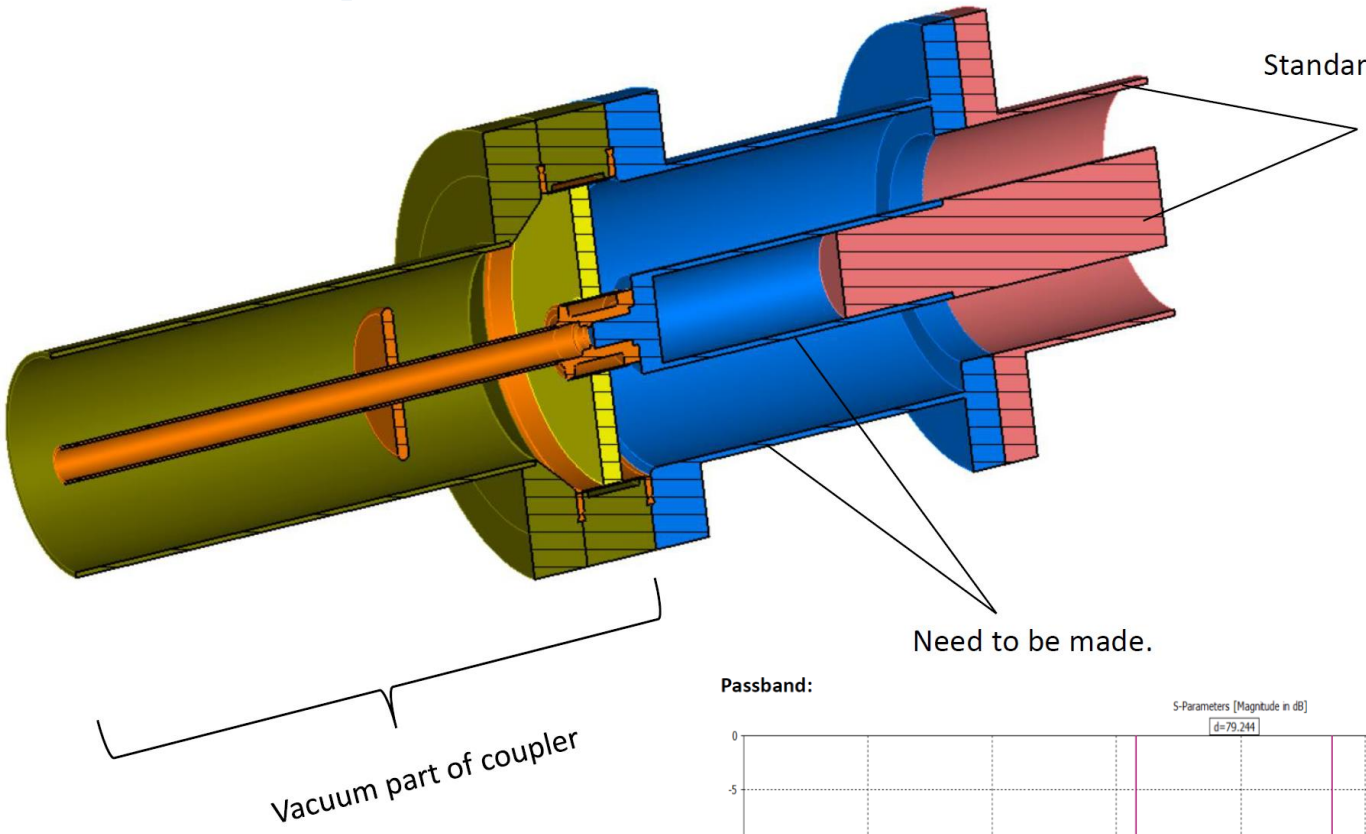
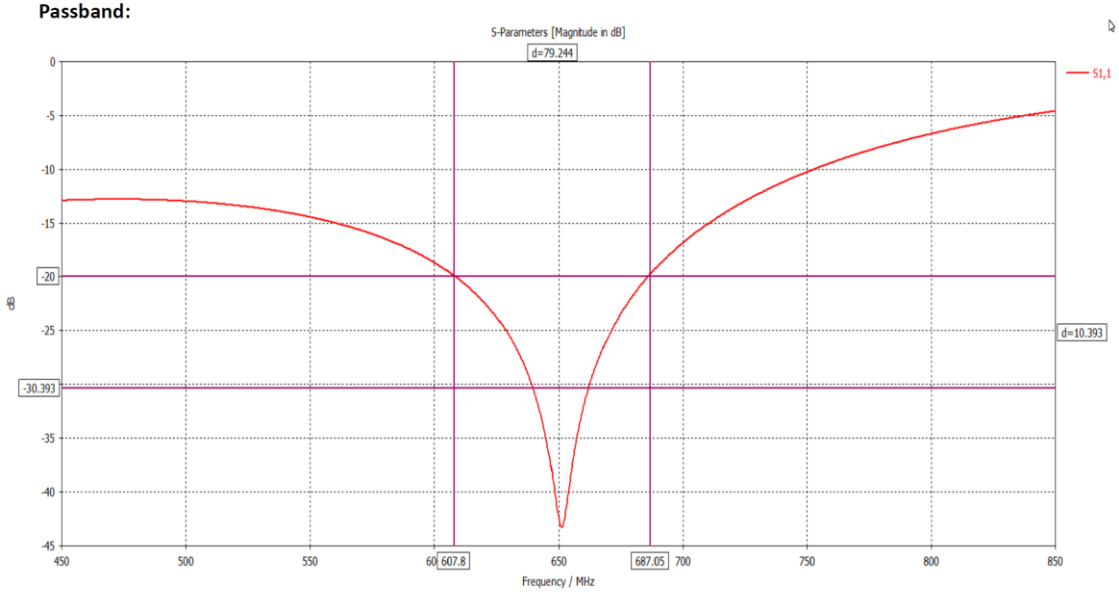
# PIP-II 325 MHz DC Block



# “Fake Coupler Air Side”




**Passband:**



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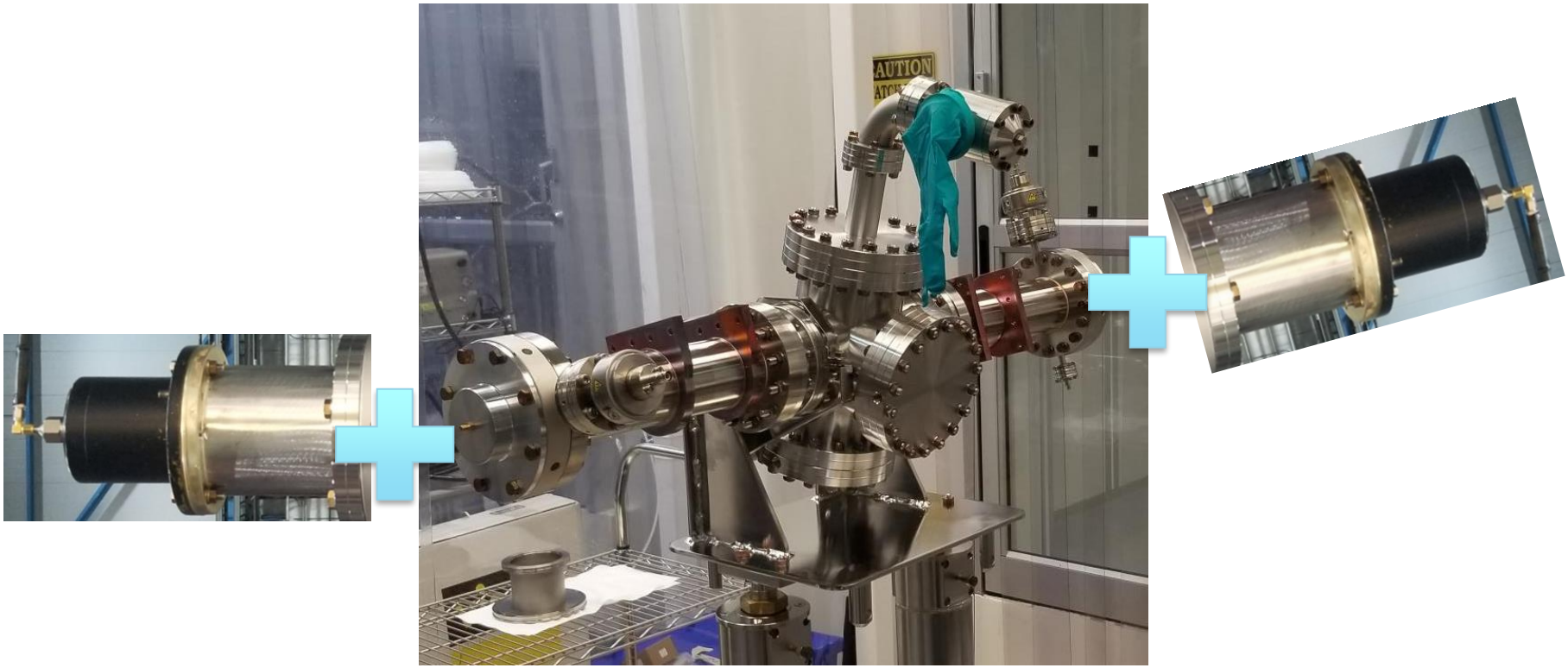
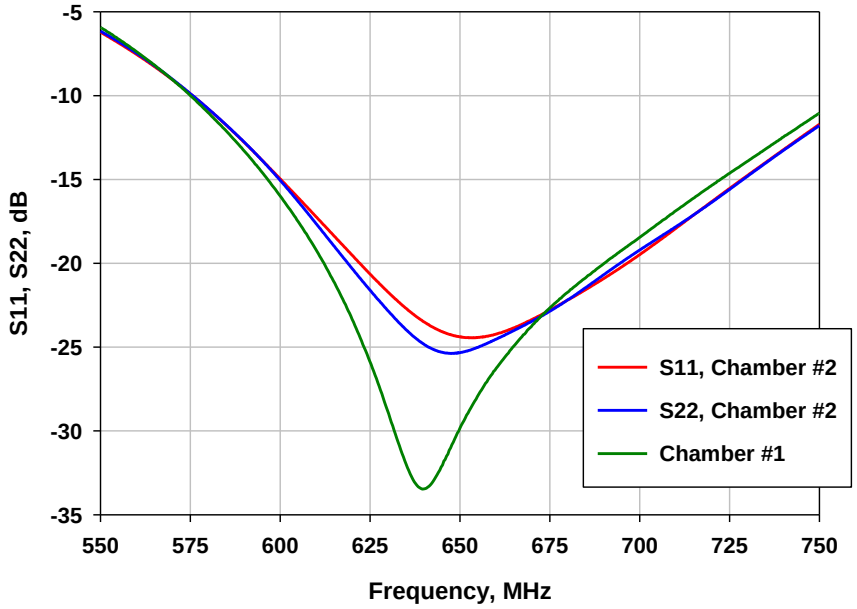


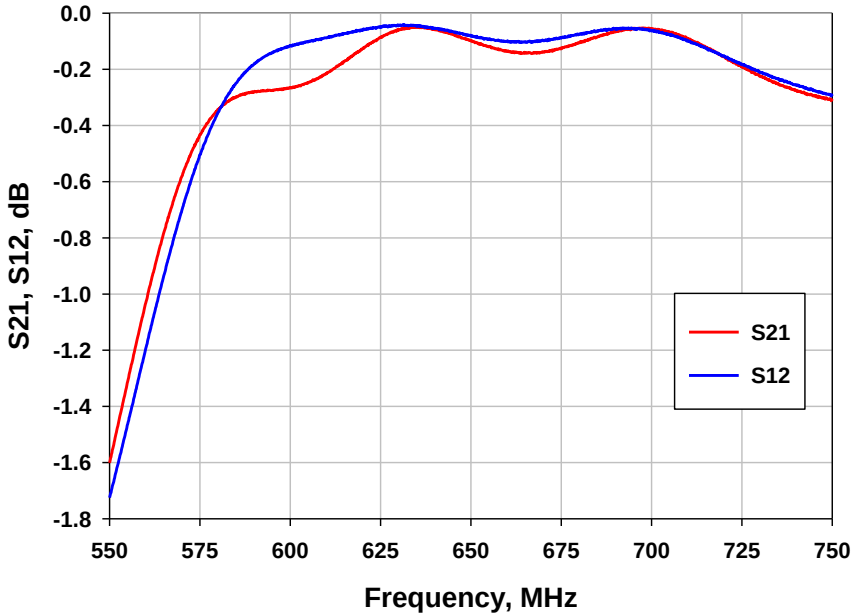
# Measurements of chamber #2.

S. Kazakov, 12/21/2021

Chamber #1 and Chamber #2.




Chember #2,
Transmission.



# Robot Assembly – Manual Control

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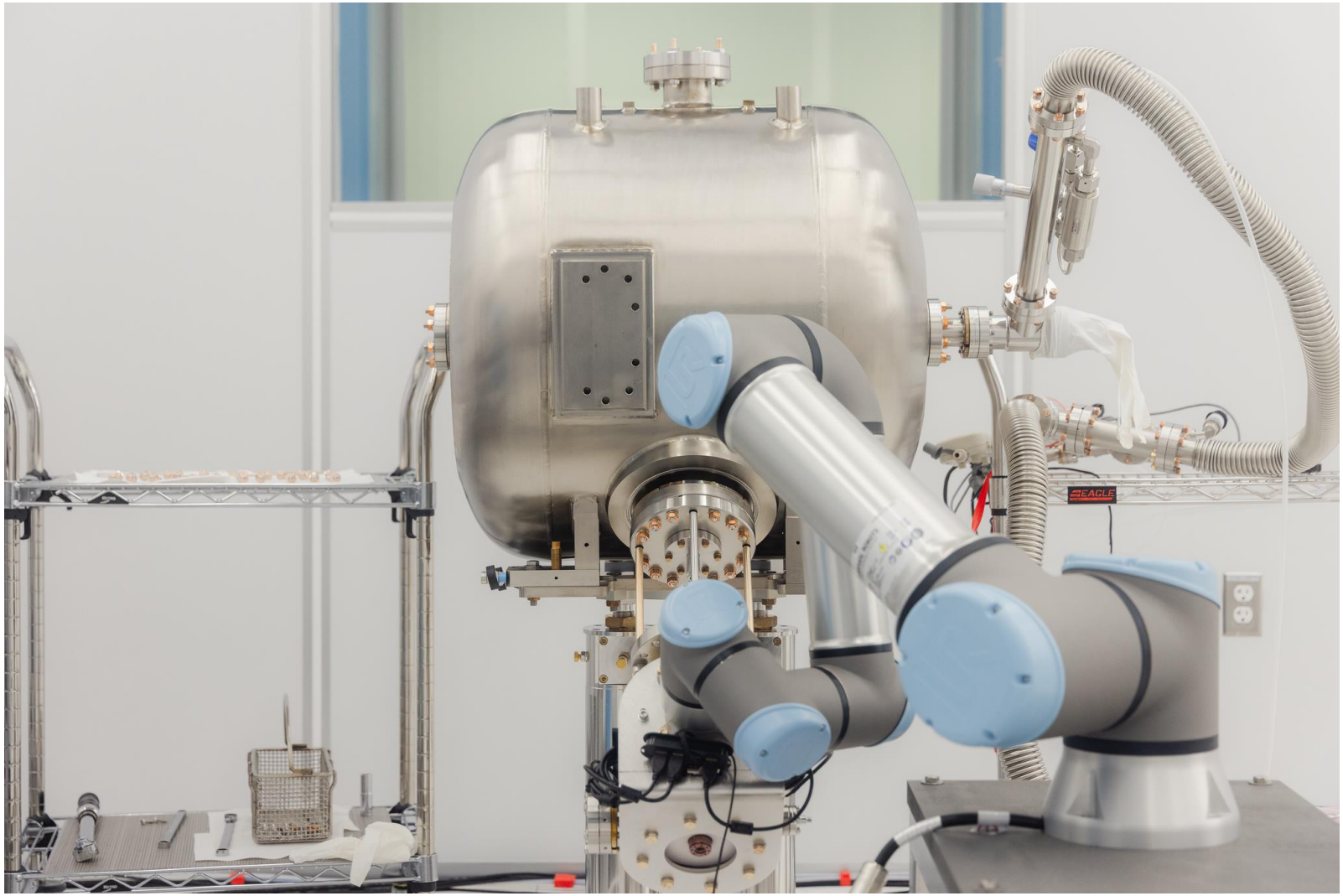
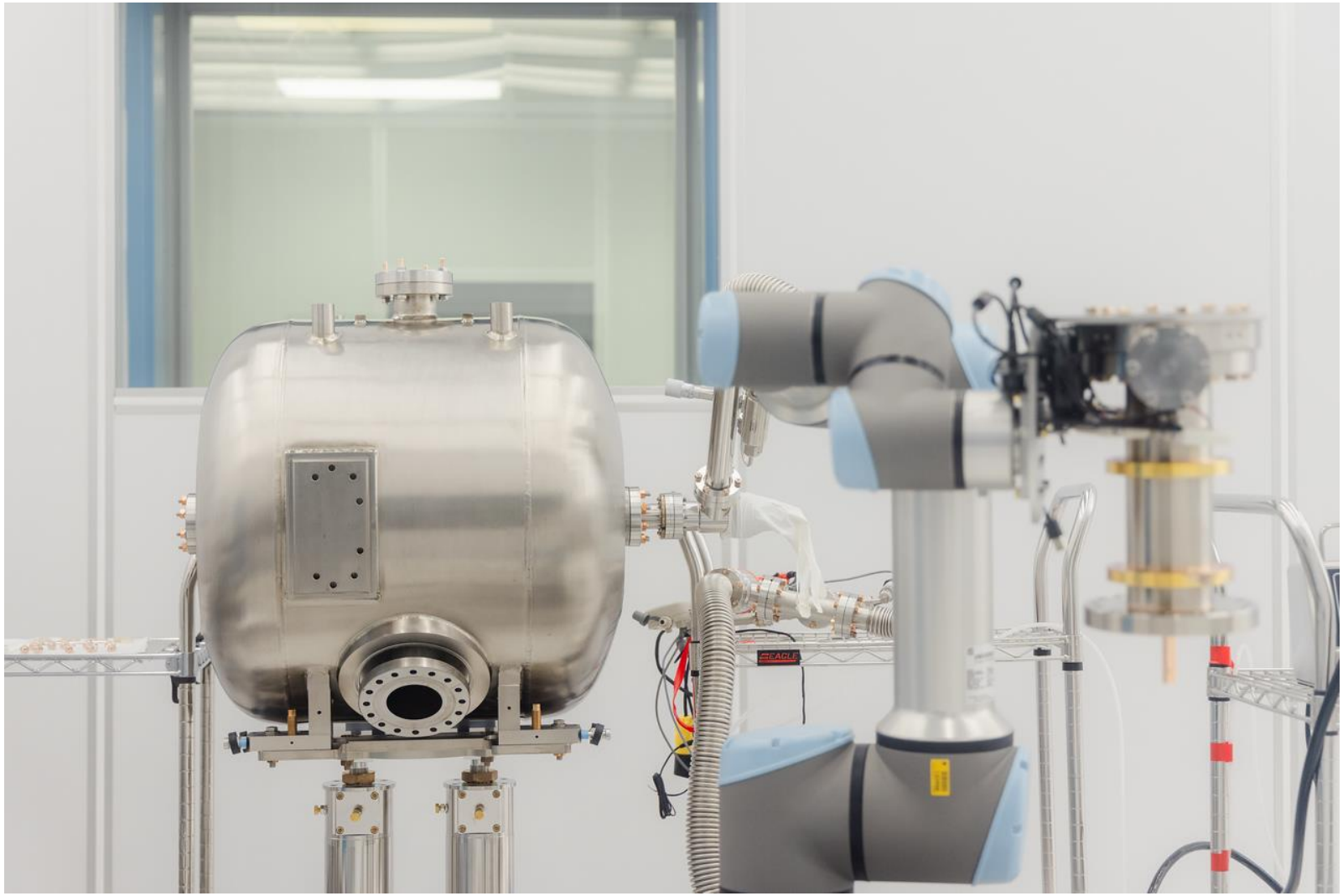
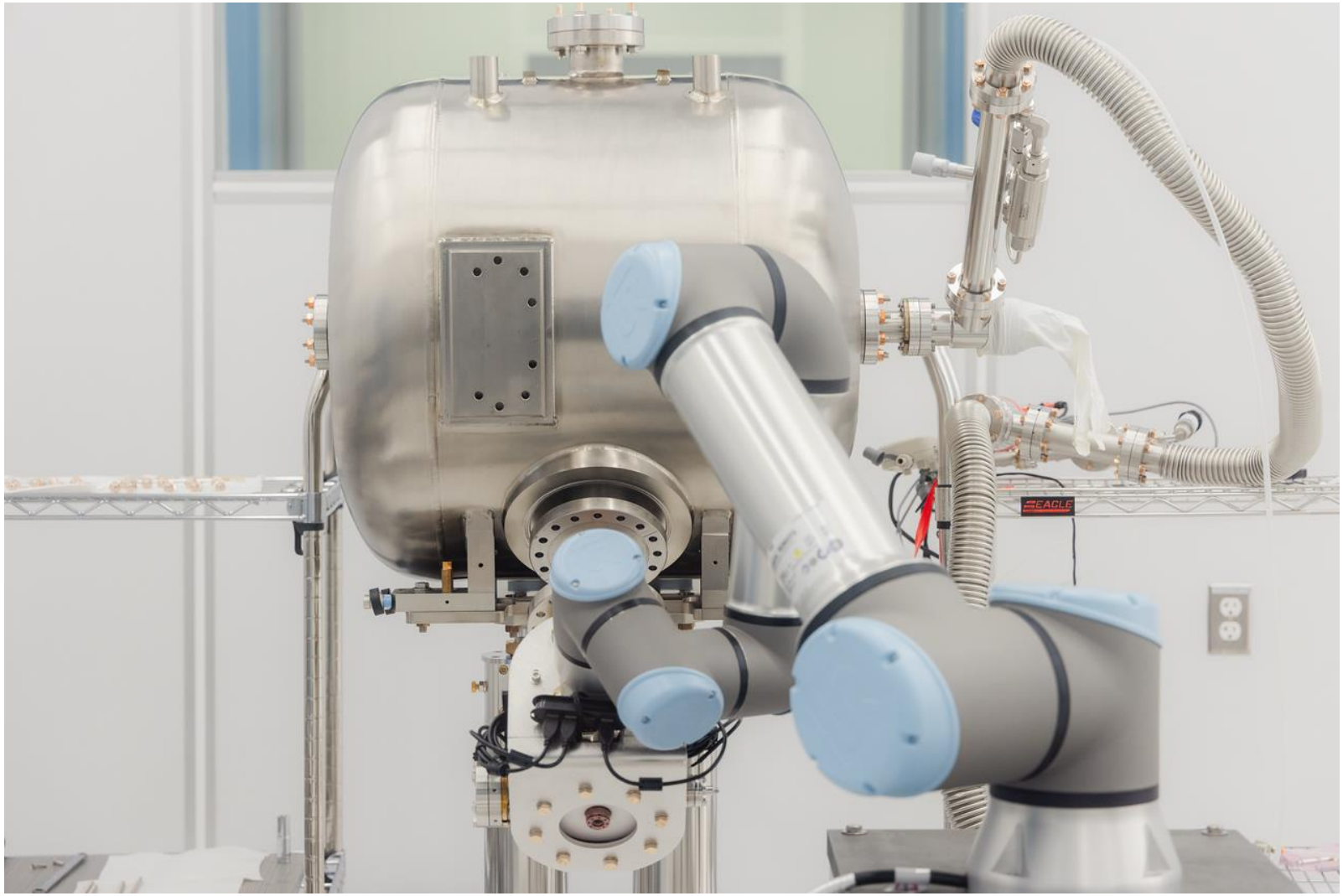


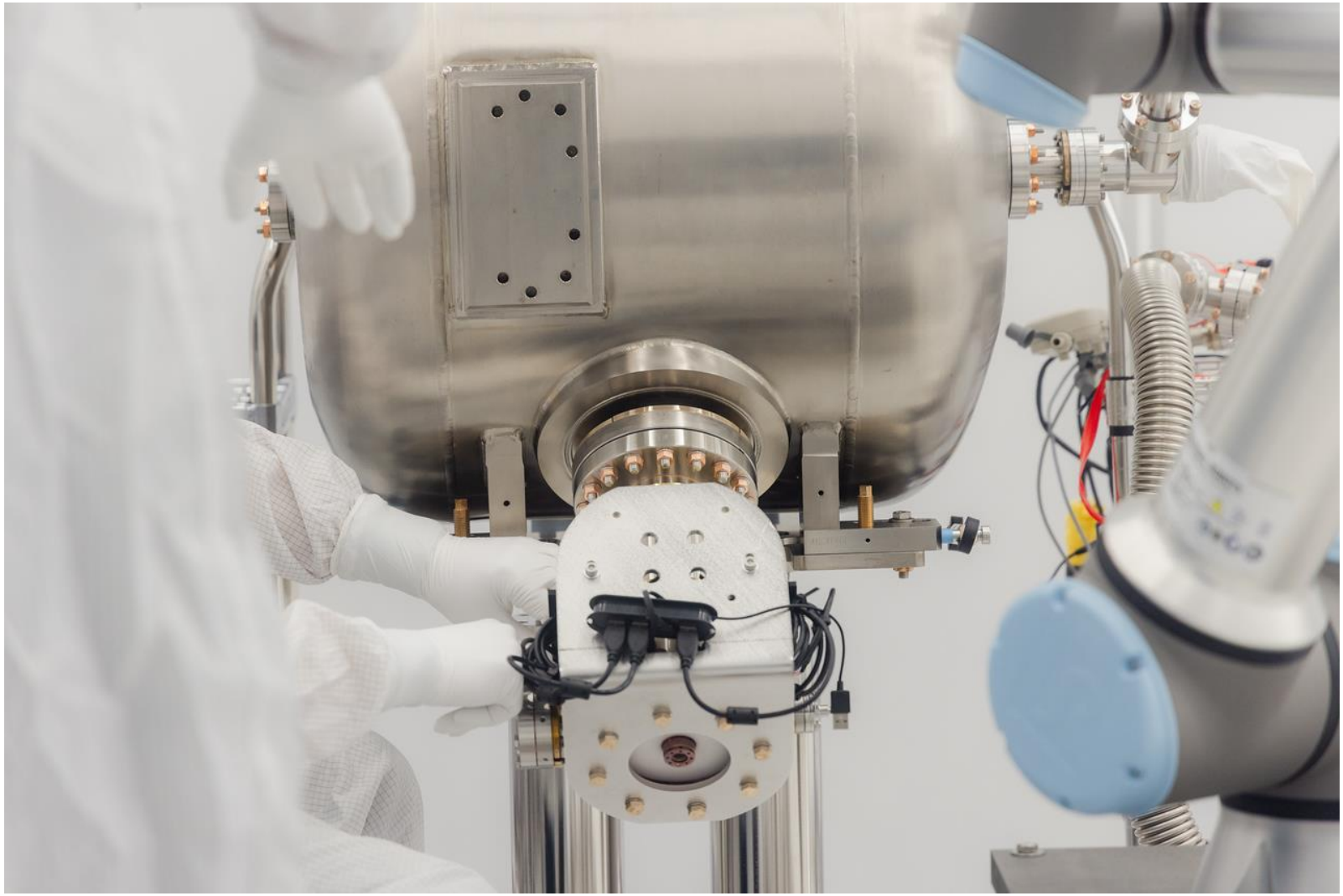
# Robot Assembly – Manual Control



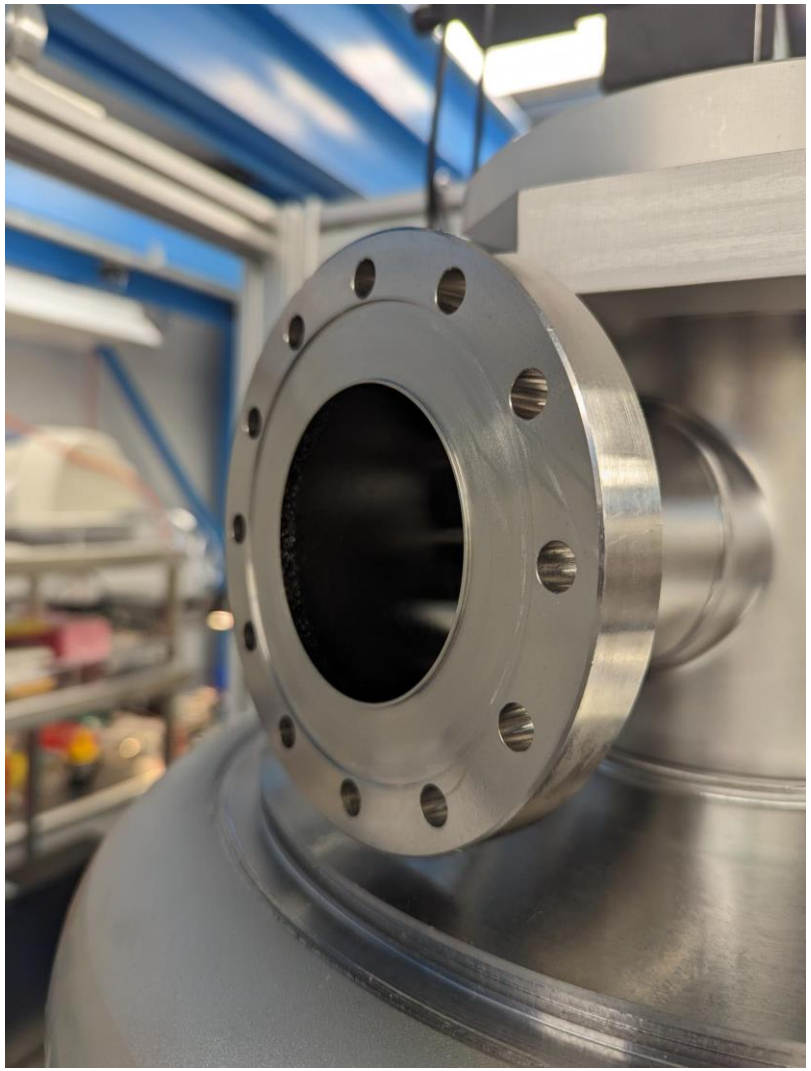
# Robot Assembly – Manual Control



# Robot Assembly – Manual Control

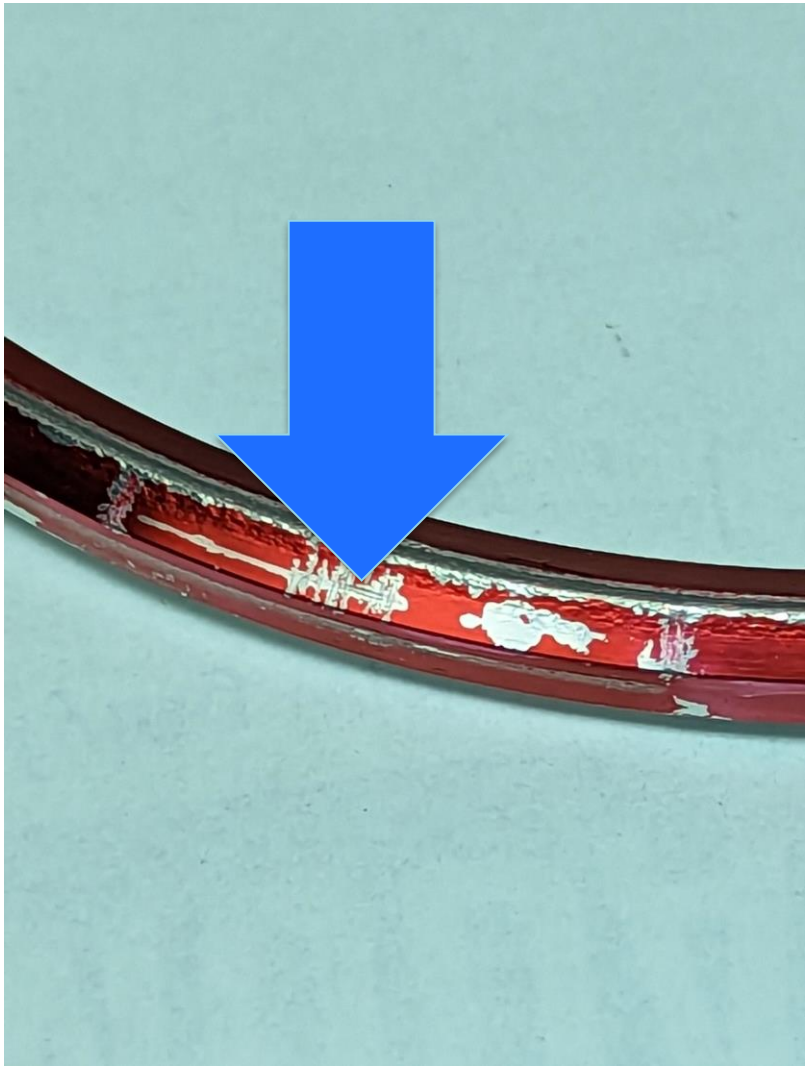


# Be Careful with Flange Lips



Flange + seal moved to extreme position

# Be Careful with Flange Lips



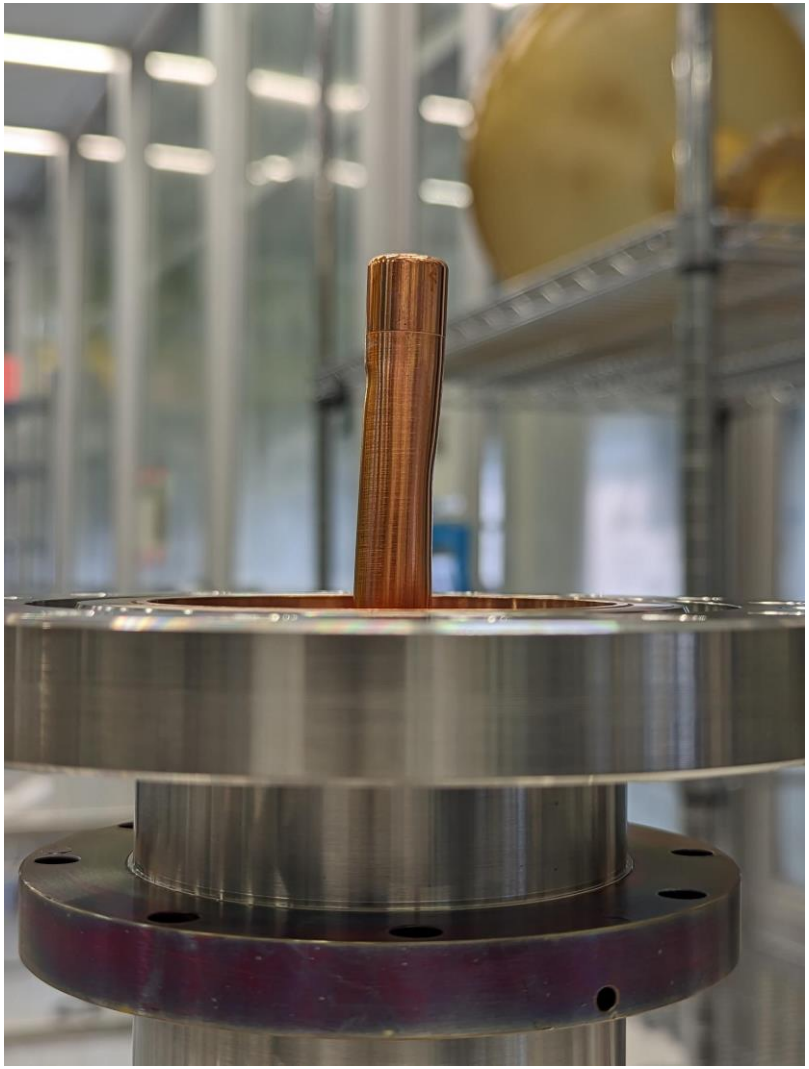
Seal coated in machinist fluid. 'Bent' in oval shape like technicians do, put in worst position

# Protect your antennas!

This is one example of manufacturing / delivery problem. I could give a full talk on only this. My best advice – see the parts yourselves – go to the vendors, go inside the clean room to inspect, etc… there is no substitute.

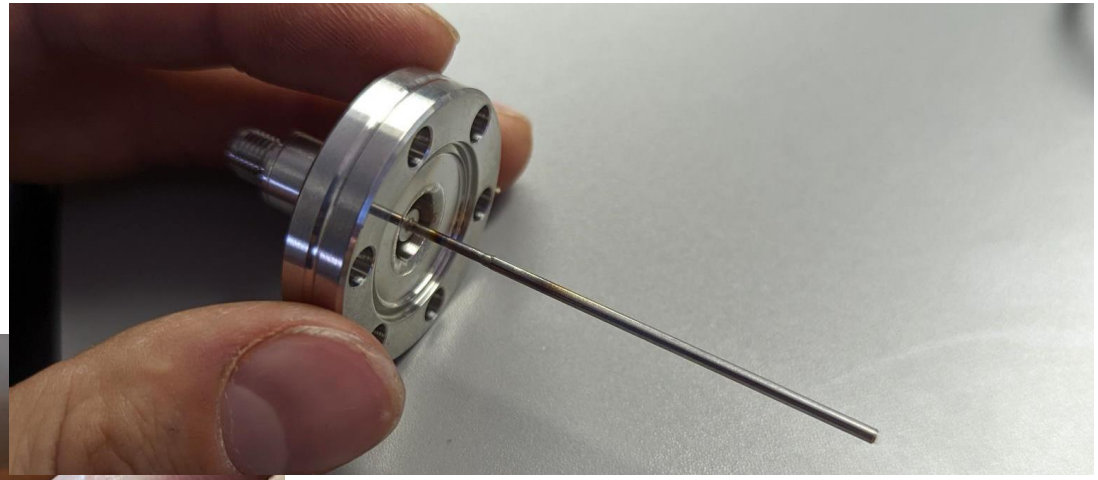
# Protect your antennas!

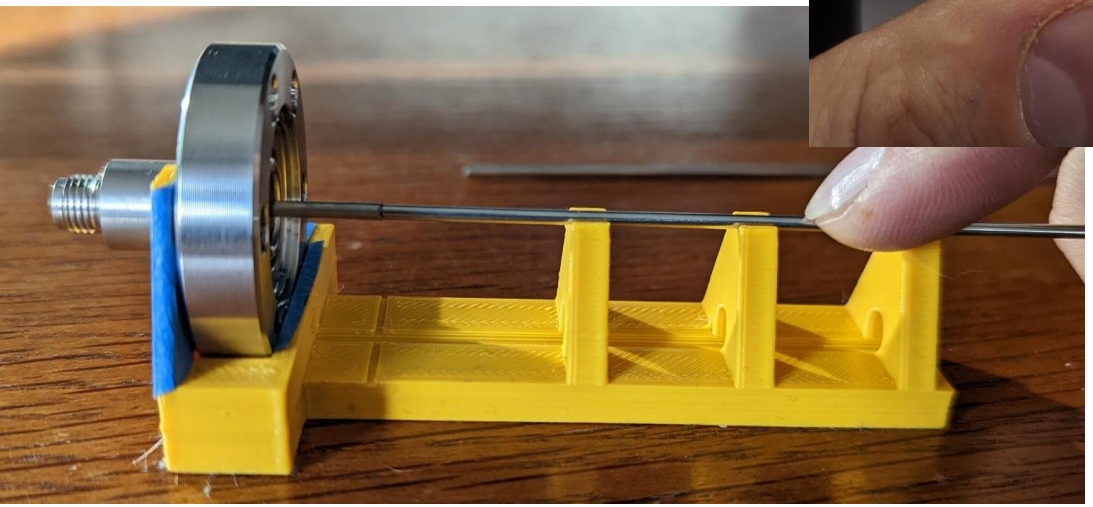
# Protect your antennas!



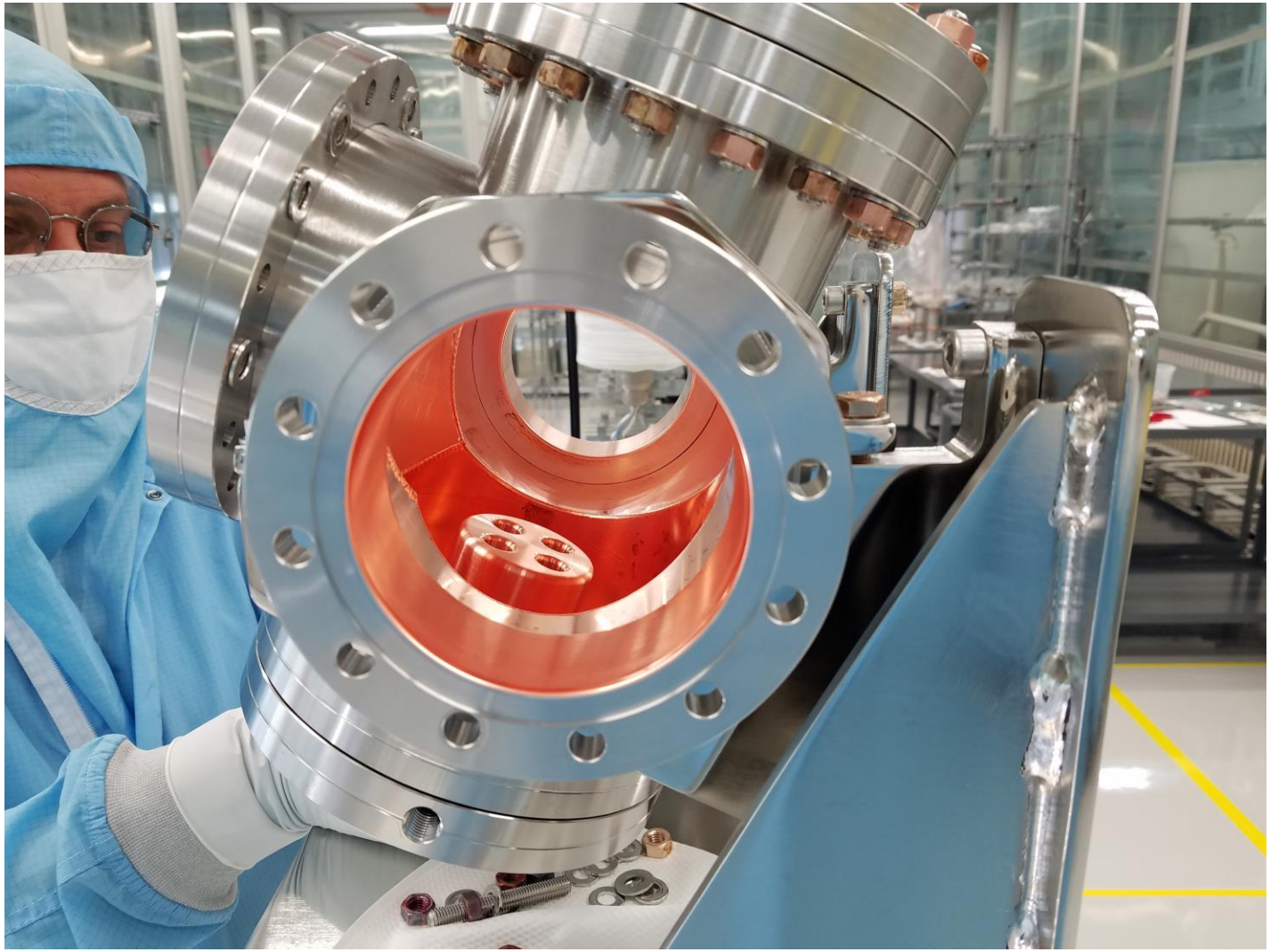
# E-Probe Length

- E-probes we had could measure nothing, we had to extend on short notice. Plasma welding worked nicely w/ 316ERL welding wire for an antenna extension





# Chamber Pictures



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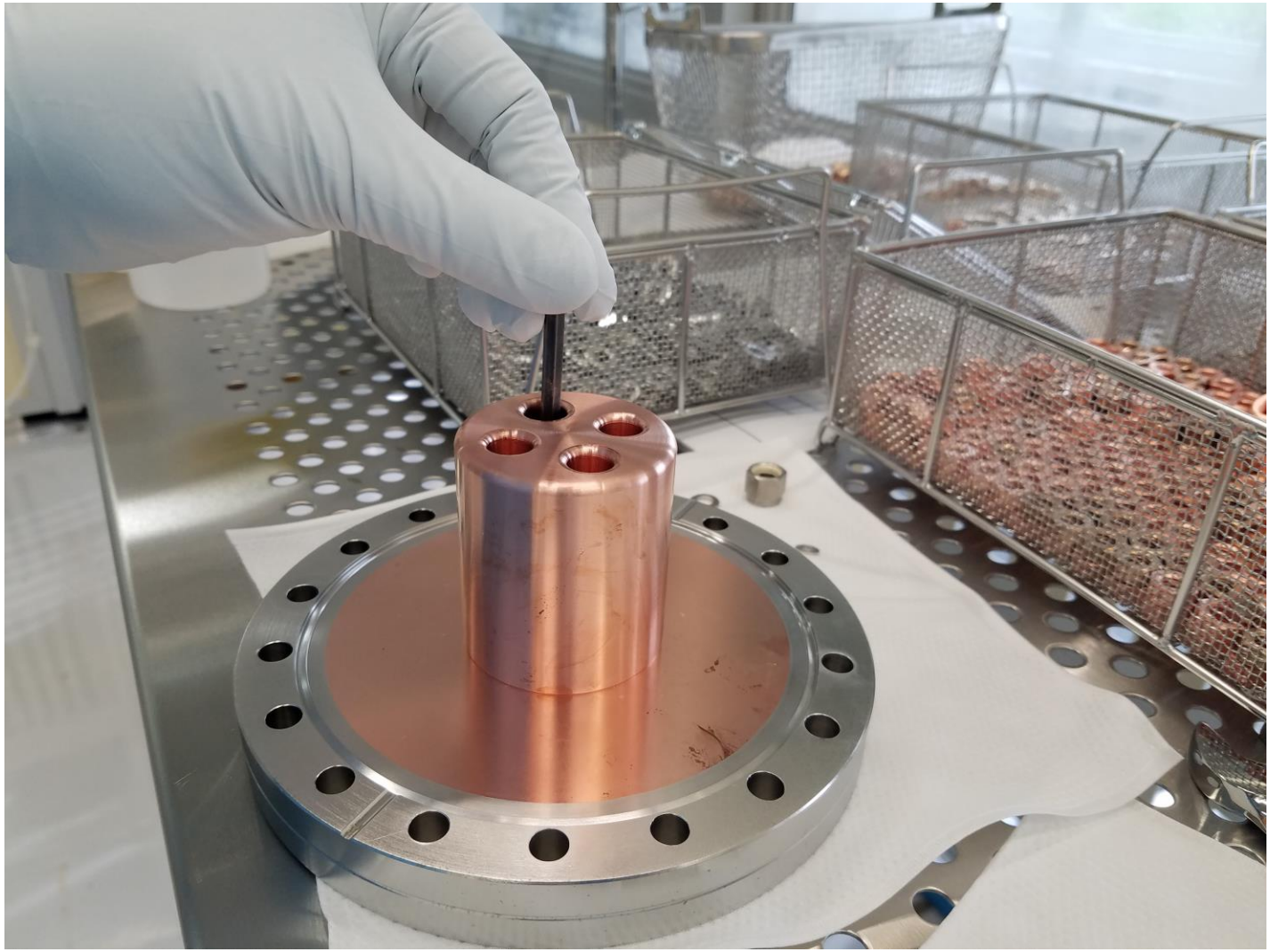

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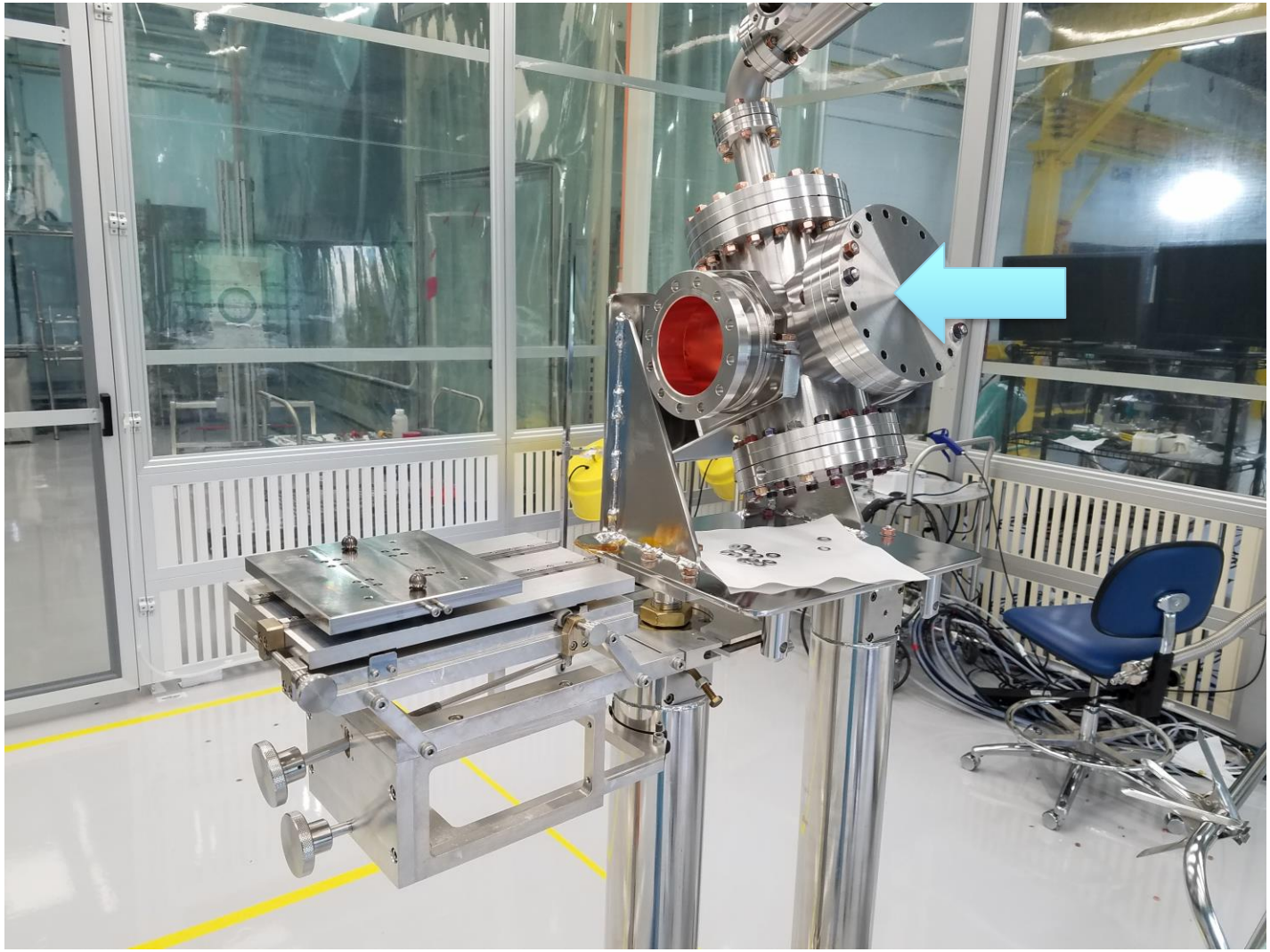

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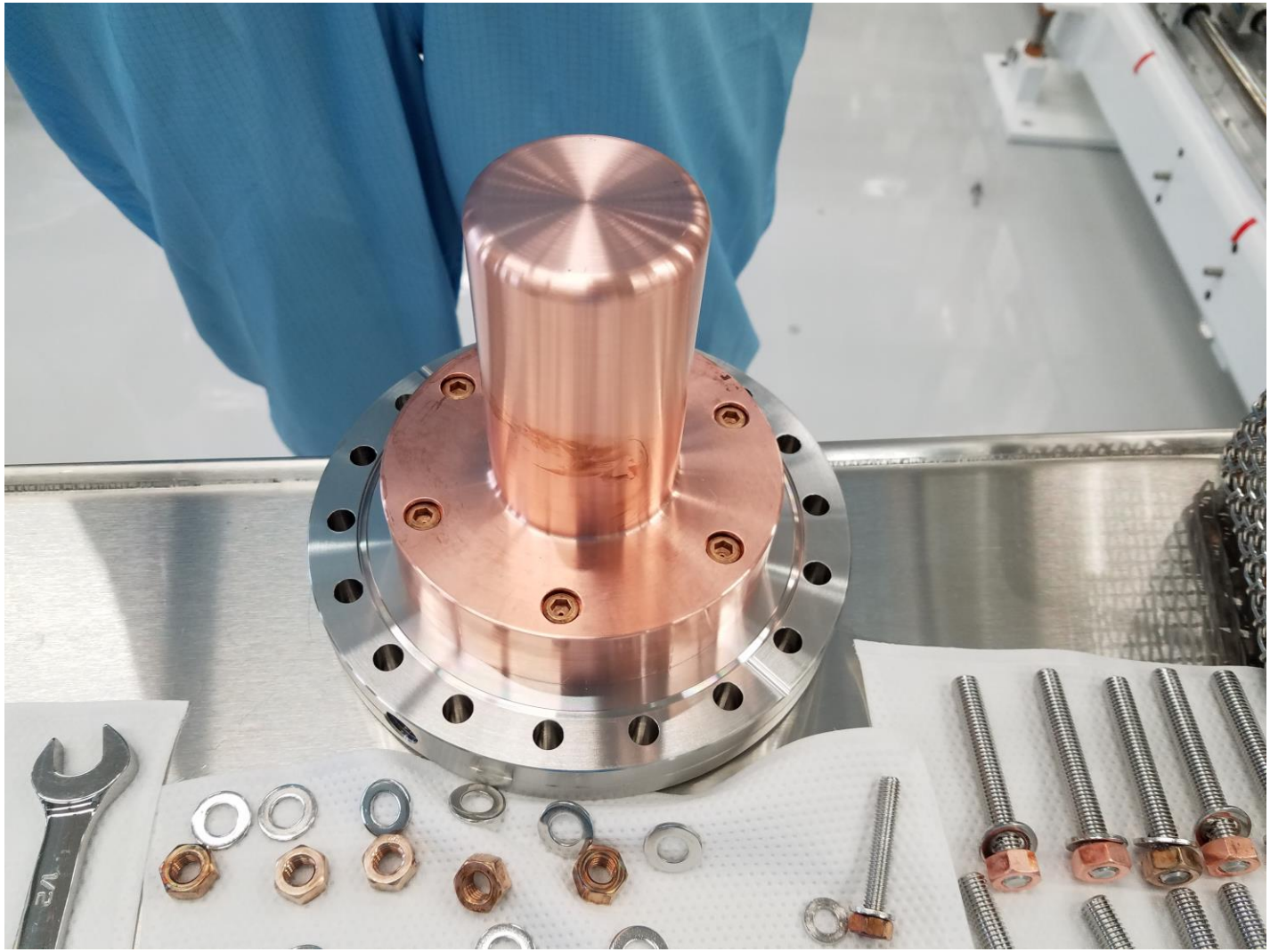

# Thanks!! Stay fun!!




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