QCM Accelerator Structure ESRF CDR Contribution

21 April 2026

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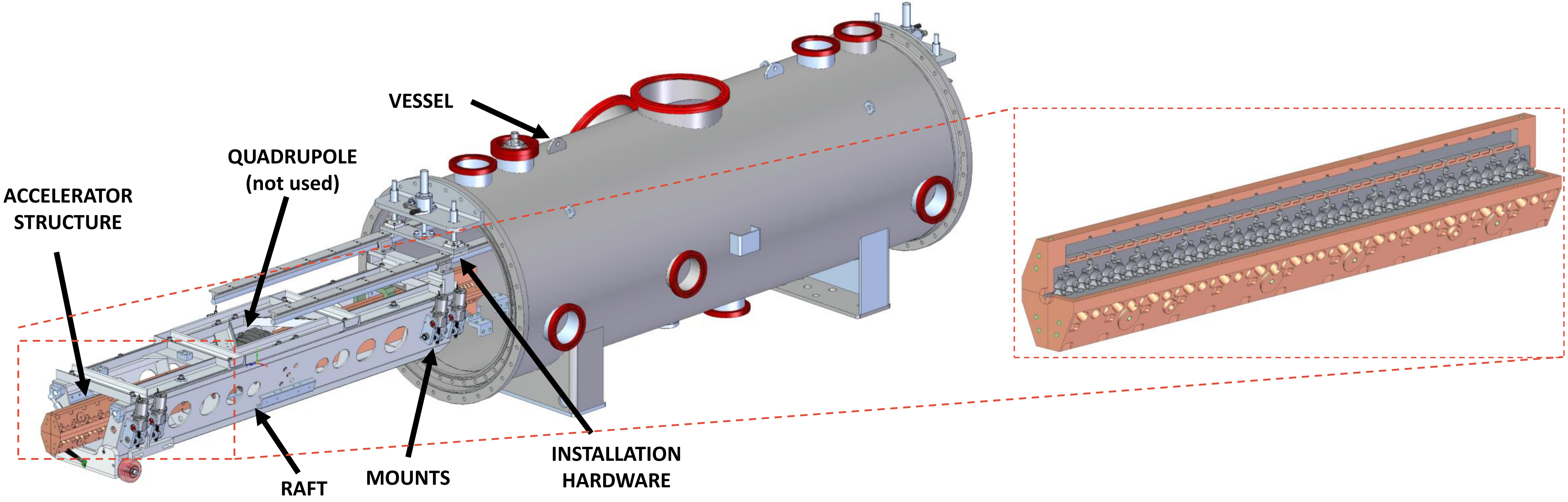
Stanford University | U.S. DEPARTMENT OF ENERGY

Agenda

1. QCM Overview
2. Schedule
3. Accelerator RF Design
4. QCM Design and Build Status
5. Alignment Requirements
6. External Mounts
7. Cryogenic Requirements
8. Vacuum Requirements

QCM Overview

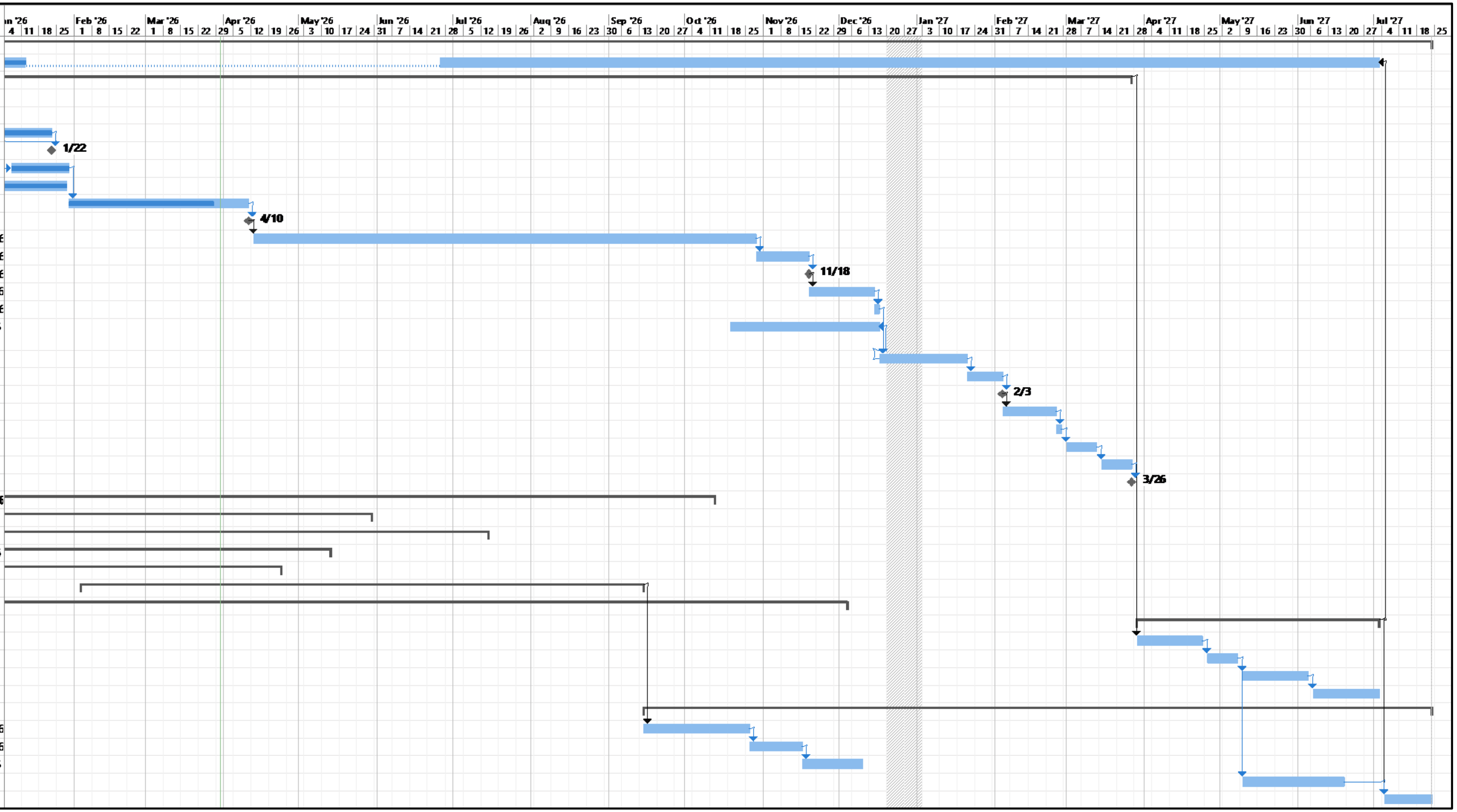
- Original goal: demonstrator for C^3
- Additional goal: provide QCM to ESRF
    - The full C^3 design works for ESRF, but ESRF has less stringent requirements



Proposed Schedule

- Mechanical assembly of the QCM to start by Nov 2026, allowing testing before shipment to ESRF by July 2027

Task Name	Duration	Start	Finish
QCM	**430 days**	**Fri 10/17/25**	**Fri 7/23/27**
PM	279 days	Fri 10/24/25	Fri 7/2/27
C-Band Accelerator Structure	**345 days**	**Fri 10/17/25**	**Fri 3/26/27**
Concept Design	15 days	Fri 10/17/25	Thu 11/6/25
PDR	0 days	Thu 11/6/25	Thu 11/6/25
Detailed Design	41 days	Fri 11/7/25	Thu 1/22/26
FDR	0 days	Thu 1/22/26	Thu 1/22/26
Detailed Drawings	16 days	Wed 1/7/26	Thu 1/29/26
Quote	20 days	Wed 12/17/25	Wed 1/28/26
Procurement Process	50 days	Fri 1/30/26	Fri 4/10/26
Order Placed	0 days	Fri 4/10/26	Fri 4/10/26
Procurement/Manufacturing	28 wks	Mon 4/13/26	Wed 10/28/26
Receipt & QC	15 days	Thu 10/29/26	Wed 11/18/26
2 Sets Received	0 days	Wed 11/18/26	Wed 11/18/26
Braze Setup & QC (set 1)	15 days	Thu 11/19/26	Mon 12/14/26
Braze (set 1)	2 days	Tue 12/15/26	Wed 12/16/26
Handling Cold Test Fixture Design/Procurement	40 days	Mon 10/19/26	Thu 12/17/26
Straighten & QC (set 1)	15 days	Thu 12/17/26	Wed 1/20/27
RF tuning	10 days	Thu 1/21/27	Wed 2/3/27
1st Set Built	0 days	Wed 2/3/27	Wed 2/3/27
Braze Setup & QC (set 2)	15 days	Thu 2/4/27	Wed 2/24/27
Braze (set 2)	2 days	Thu 2/25/27	Fri 2/26/27
Straighten & QC (set 2)	10 days	Mon 3/1/27	Fri 3/12/27
RF tuning	10 days	Mon 3/15/27	Fri 3/26/27
2nd Set Built	0 days	Fri 3/26/27	Fri 3/26/27
C-Band Waveguide	**239 days**	**Fri 10/17/25**	**Mon 10/12/26**
Cryostat Prep	**124 days**	**Mon 11/17/25**	**Fri 5/29/26**
Cold Boxes	**176 days**	**Fri 10/17/25**	**Tue 7/14/26**
Installation Fixture	**122.5 days**	**Mon 11/3/25**	**Wed 5/13/26**
Raft	**120 days**	**Fri 10/17/25**	**Thu 4/23/26**
Supports	**155 days**	**Tue 2/3/26**	**Mon 9/14/26**
Heater Test	**238.5 days**	**Thu 12/11/25**	**Fri 12/4/26**
QCM Assembly	**70 days**	**Mon 3/29/27**	**Fri 7/2/27**
Install Accelerator in Raft	20 days	Mon 3/29/27	Fri 4/23/27
Installation of Raft in QCM	10 days	Mon 4/26/27	Fri 5/7/27
Cold testing	20 days	Mon 5/10/27	Fri 6/4/27
Alignment testing	20 days	Mon 6/7/27	Fri 7/2/27
QCM Shipment	**211.5 days**	**Mon 9/14/26**	**Fri 7/23/27**
Design shipping configuration	30 days	Mon 9/14/26	Mon 10/26/26
Draw shipping container	15 days	Mon 10/26/26	Mon 11/16/26
Quote shipping container	15 days	Mon 11/16/26	Thu 12/10/26
Procure shipping container	30 days	Mon 5/10/27	Fri 6/18/27
Package QCM	15 days	Mon 7/5/27	Fri 7/23/27



Procurement Status

Long Lead Items

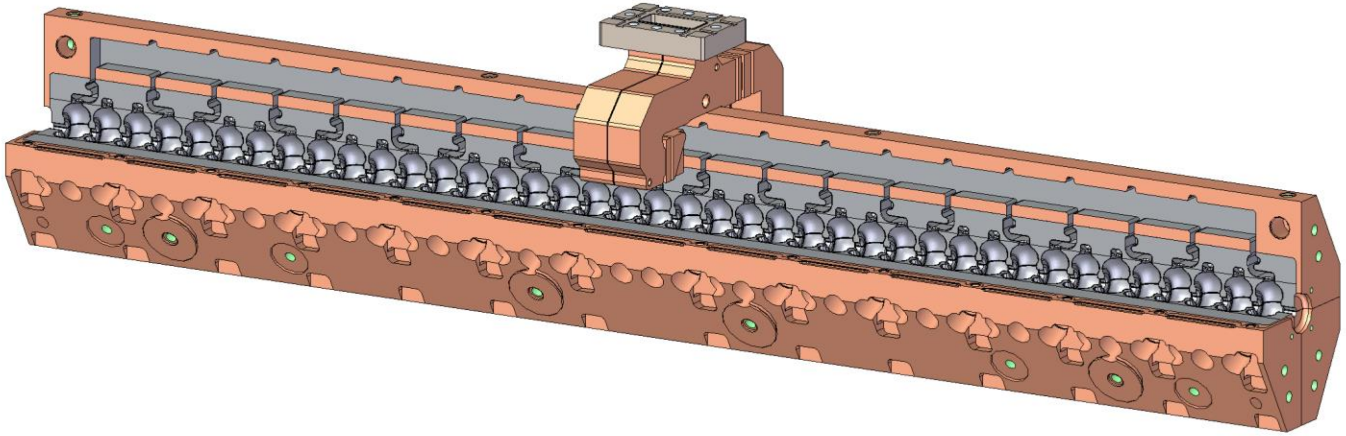
Accelerator Structure

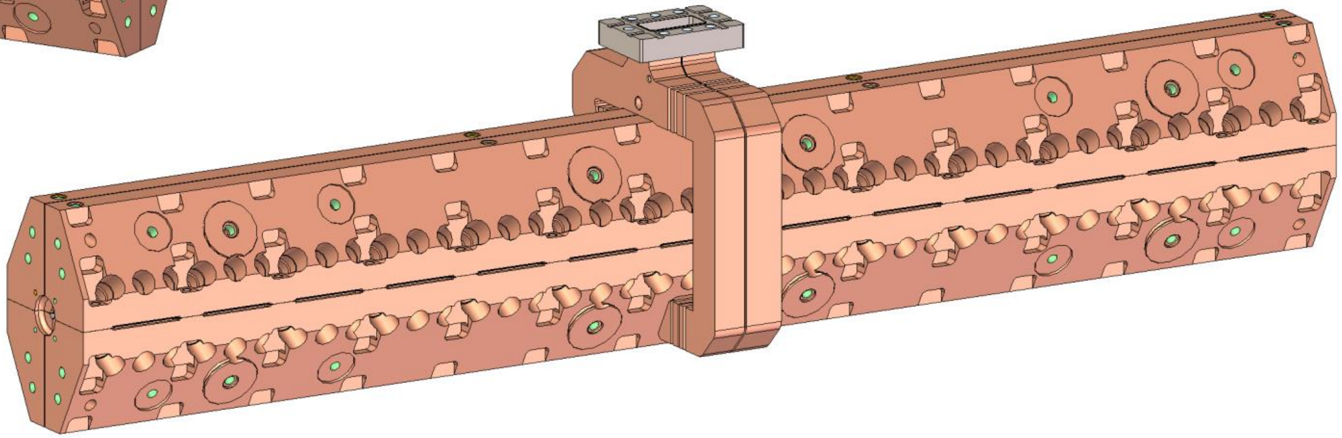
- Request for Proposal process completed via Sam.gov website – received 8 bids
- A vendor has been identified, but paperwork and contracts are still in process
- Lead time for the first set of parts is 28 weeks and for the complete two sets of parts is 34 weeks.
    - Receive at SLAC in November 2026

Cryomodule

- Received at SLAC in 2025

Design and Build Status – Accelerator Structure

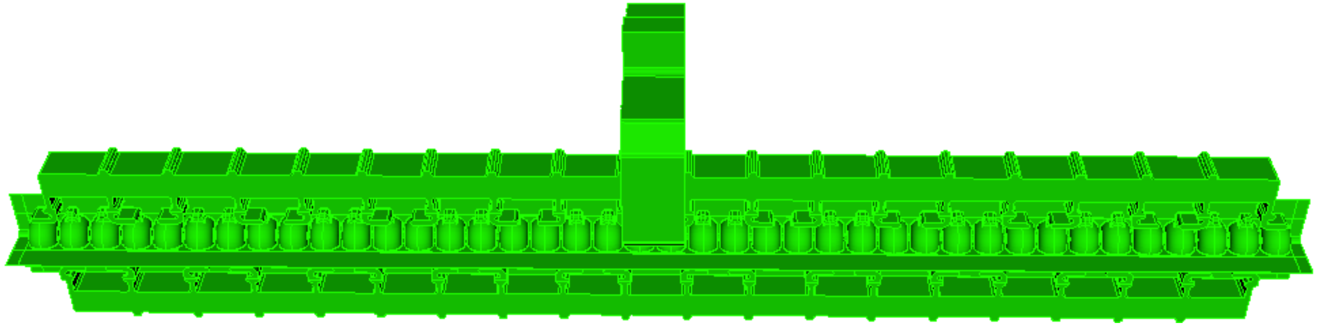




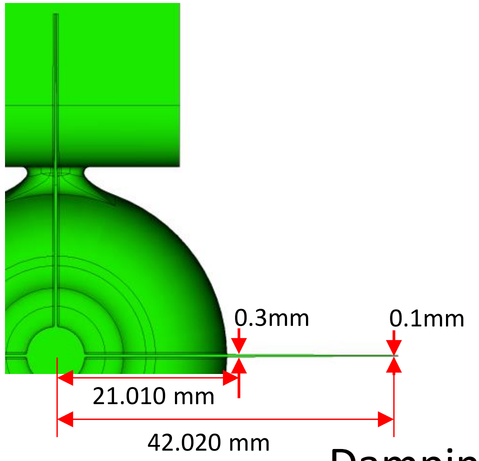
Final RF Geometry

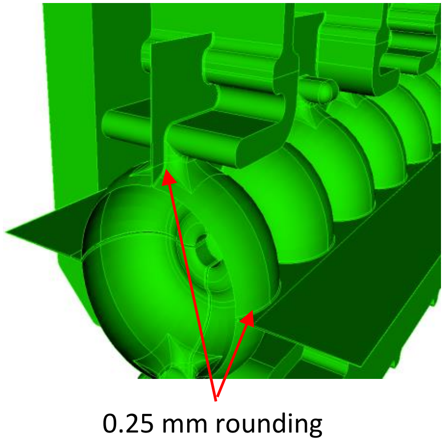
Features

- *40 cells with pair wise side to side distributed coupling*
- *Cell Balancing features*
- *4 damping slots extending to the beam center line (4 part open cells and iris)*
- *Structures to be spaced so that cell center to center distance is (N+.5)*26.242 at operating temperature*

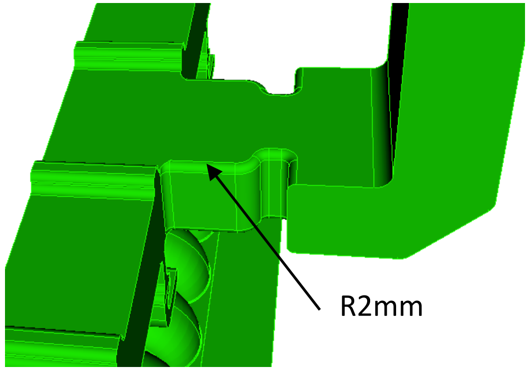


1-m structure: 40-cell with damping slots





Damping slot



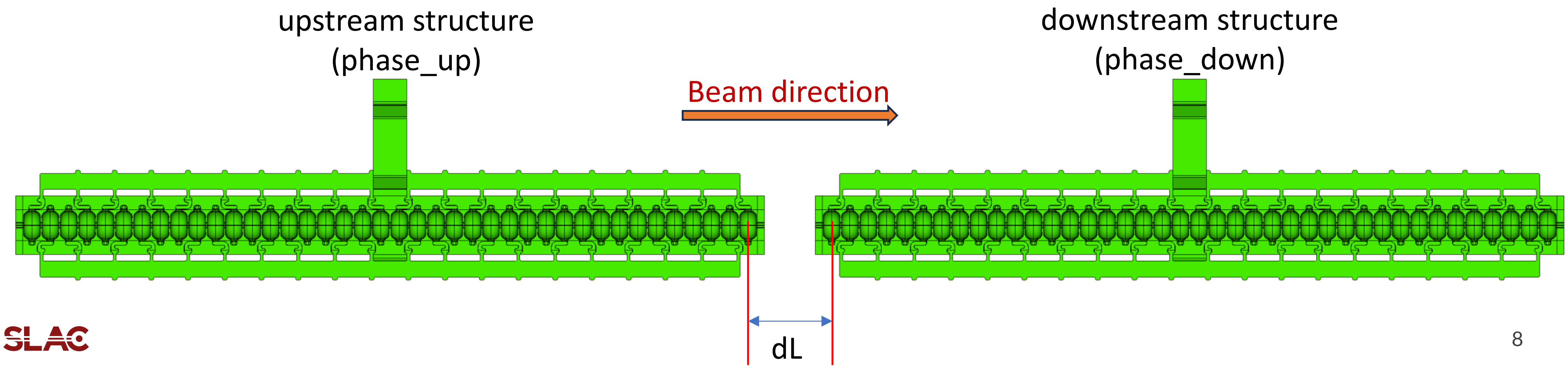
Waveguide corner rounding

Final RF Geometry

Position and RF Phasing Two or More C-Band Structures to Cancel Backward Acceleration

- C-Band PI-mode cell length L_{cell} = 26.242 mm
- Separation required to cancel acceleration: dL
  - Measured from center to center of two end cells
  - dL = (n + 1 + 0.5)*L_{cell}
  - n = 0, 1, …
- Structure RF phase
  - phase_down – phase_up = -(n+0.5)*180 degree

- Note: all dimension measured at operating temperature
  applies to more than two structures



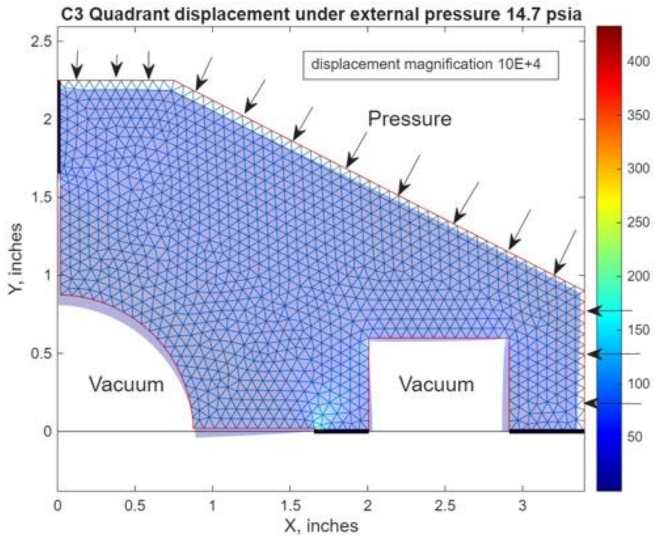
SLAC

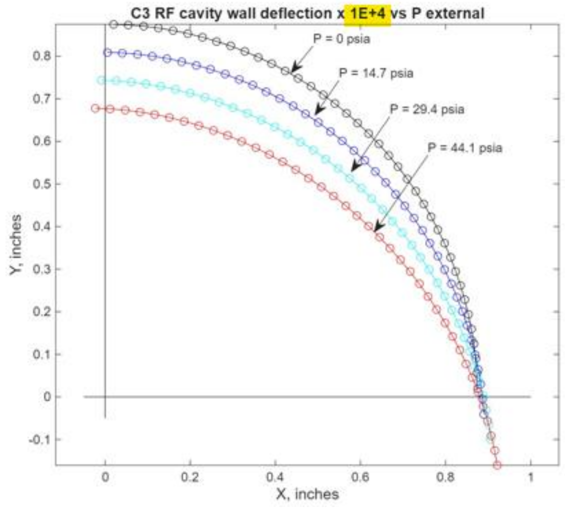
FEA: Deflection Under Pressure, 2D

The “2r” wide damping slots create continuous vacuum space that must be supported to prevent excessive displacement of the cell surfaces. Small predictable elastic deformation can be compensated for during structure tuning.

This was initially reviewed with simplified geometry in 2D to determine if the span would need support within the damping slots or if the full span could be supported by the structure.

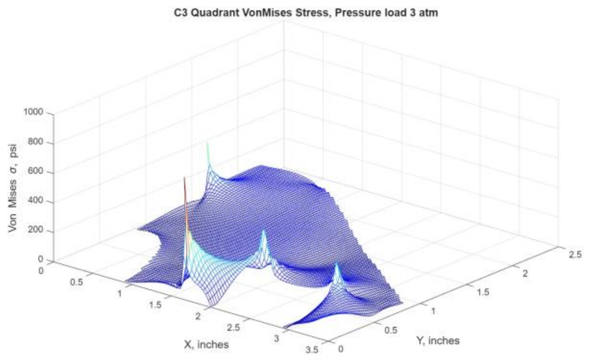
With distortion in the range of .3µm conclusion is that the damping slots can remain continuous without interruption for support as long as the inner WG joint is well connected.





- The motion of the upper end of the cavity wall under external pressure in microns is:

P	Ux	Uy	|U|
14.7	-.036	-.167	.171
29.4	-.073	-.334	.341
44.1	-.109	-.500	.513



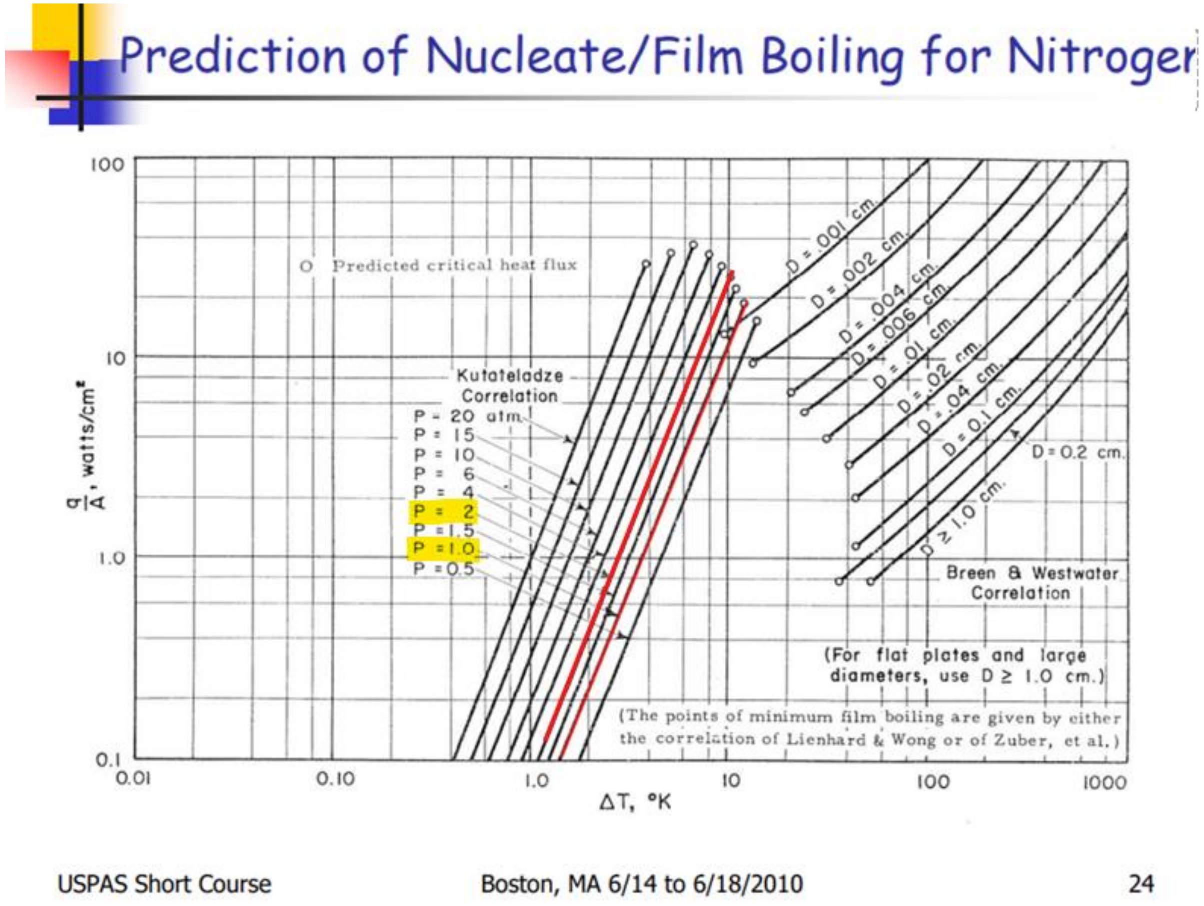
FEA: LN Pool Boiling

Chart shows heat transfer coefficient in nucleate and film boiling regimes as well as transition temperatures. **The design goal is to avoid film boiling, staying in nucleate boiling**.

To remain in nucleate boiling (at nitrogen pressures between 1 and 2 atm) the **surface/bulk temperature difference must remain below ~10 K.**

In nucleate boiling the heat transfer coefficient will vary from ~.1 to 10 W/cm^2 as the surface/bulk temperature difference ranges from ~1 to 10K. (.1 to 1 W/cm^2/K)

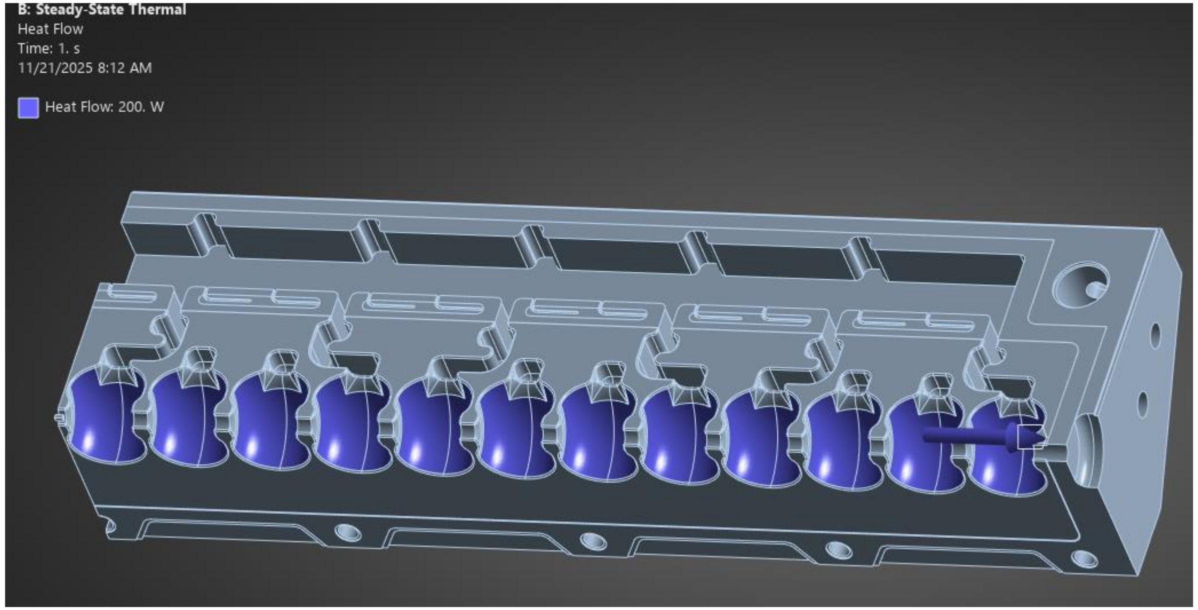
Other sources were checked with similar coefficients. **Simulations indicate that this is not critical as the surface heat flux is well below onset of film boiling.**

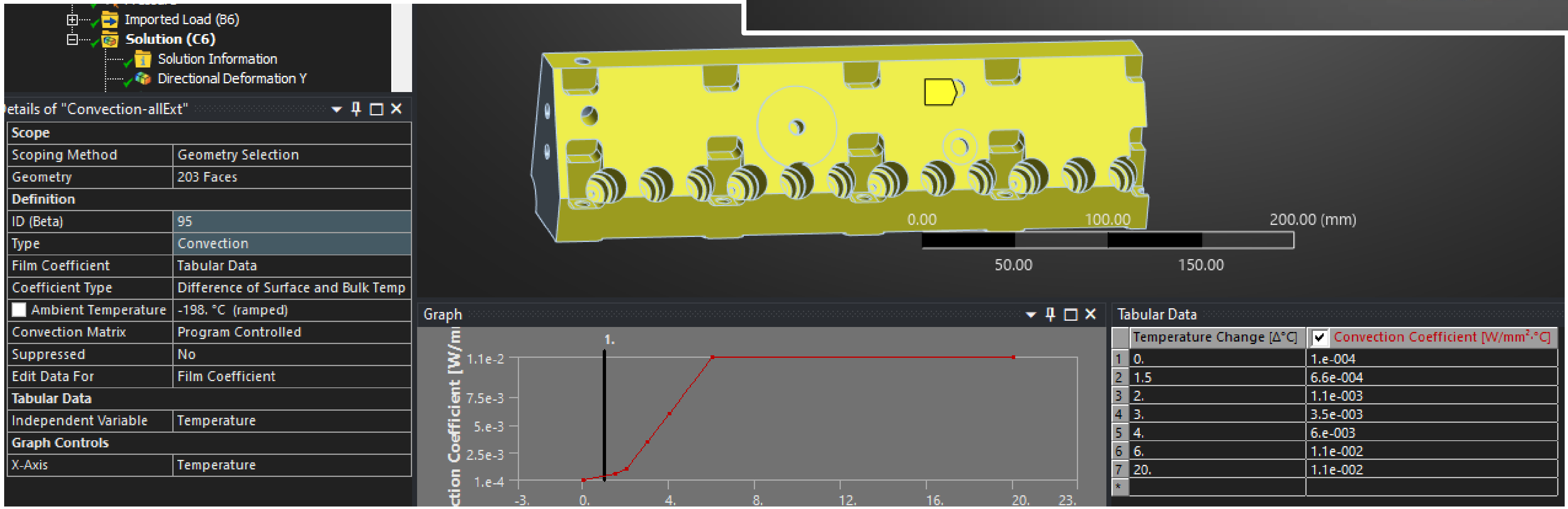


FEA: Structure Cooling

Our typical (and proposed) tuning features create 2 potentially problematic conditions.

- Gas trapped areas that will not be well cooled
- Areas close to the cell walls that may flash to film boiling





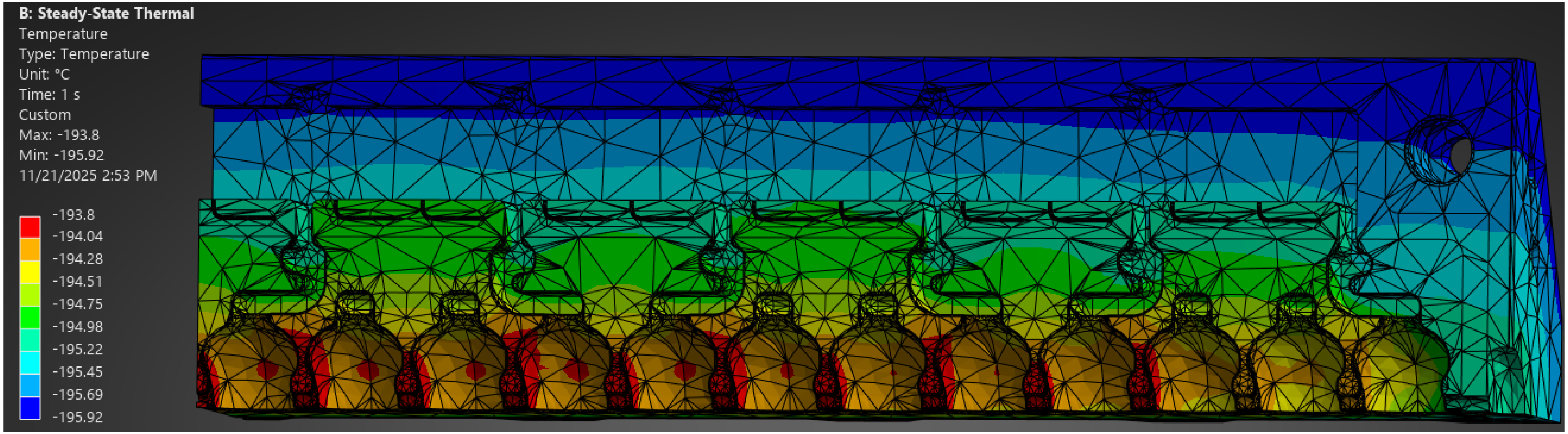
- Used 12 cells and included "end effect"
- Loss then 2500/40*12/4=187 > round up to 200 W
- Cooling ranged from all exterior to just the main faces
- Used convection coeff from ~relevant sources

FEA: Pool Boiling Temperatures

Case with no cooling at the tuner surfaces indicates inside temperatures at approximately 4° above the LN bulk temperature.

As this is "well below" the film transition temperature of ~10°, no modification of the tuning features is thought essential.

- This also shows the extent of the additional end cooling which is discussed on subsequent slides.



FEA: Heat Transfer, Pressure, & End Effects

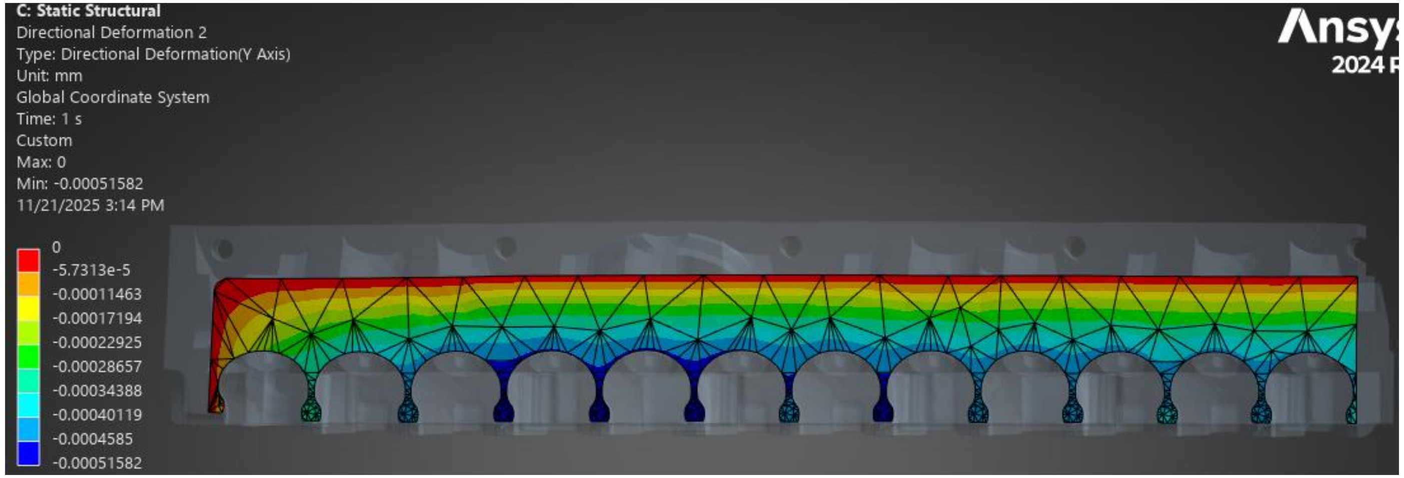
Deformation normal to the damping slot

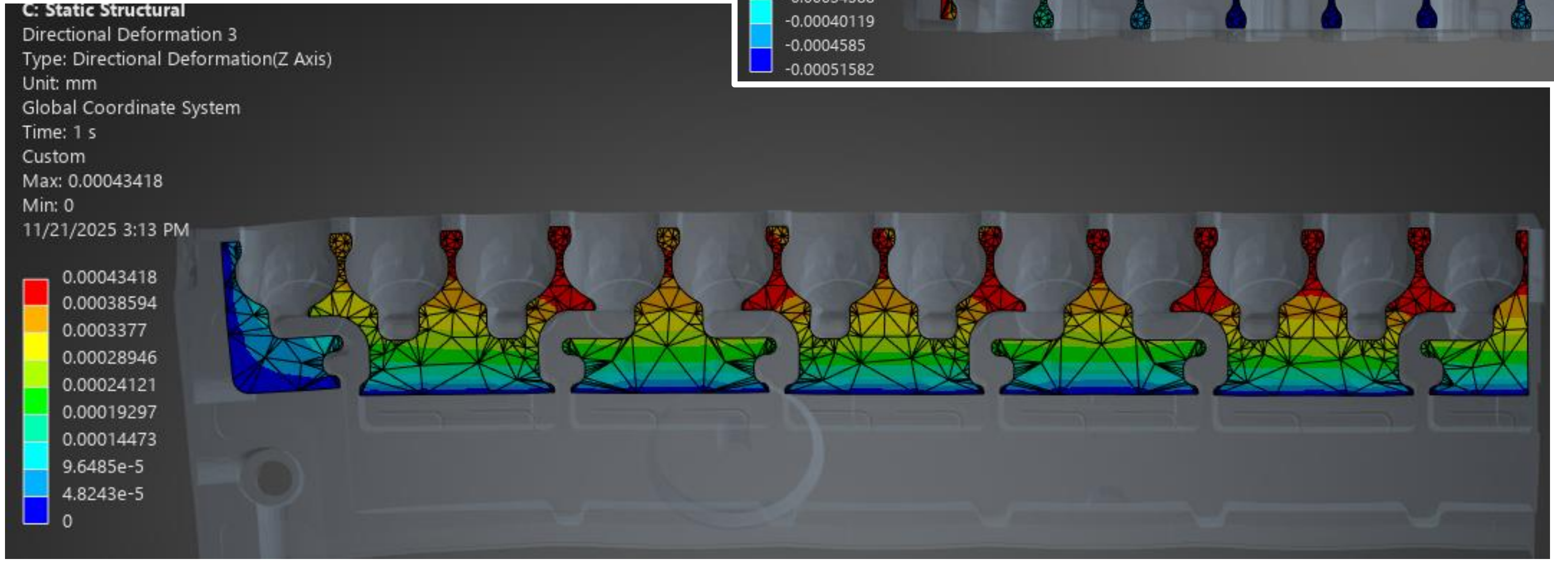
Distortion from RF heating and 3 atm pressure (1.5x design)

Case without any tuner surface heat transfer

Displacement of less than 0.5 µm is acceptable

Some tuning offsets to compensate for end effects may be incorporated.





Temperature (C)	Thermal Conductivity (W m^-1 C^-1)
-200	580
-100	413
23	397

Temperature (C)	Coefficient of Thermal Expansion (C^-1)
-200	7.4E-06
-100	1.44E-05
23	1.674E-05

Temperature (C)	Young's Modulus (Pa)
-200	138000000000
-100	133000000000
23	126000000000

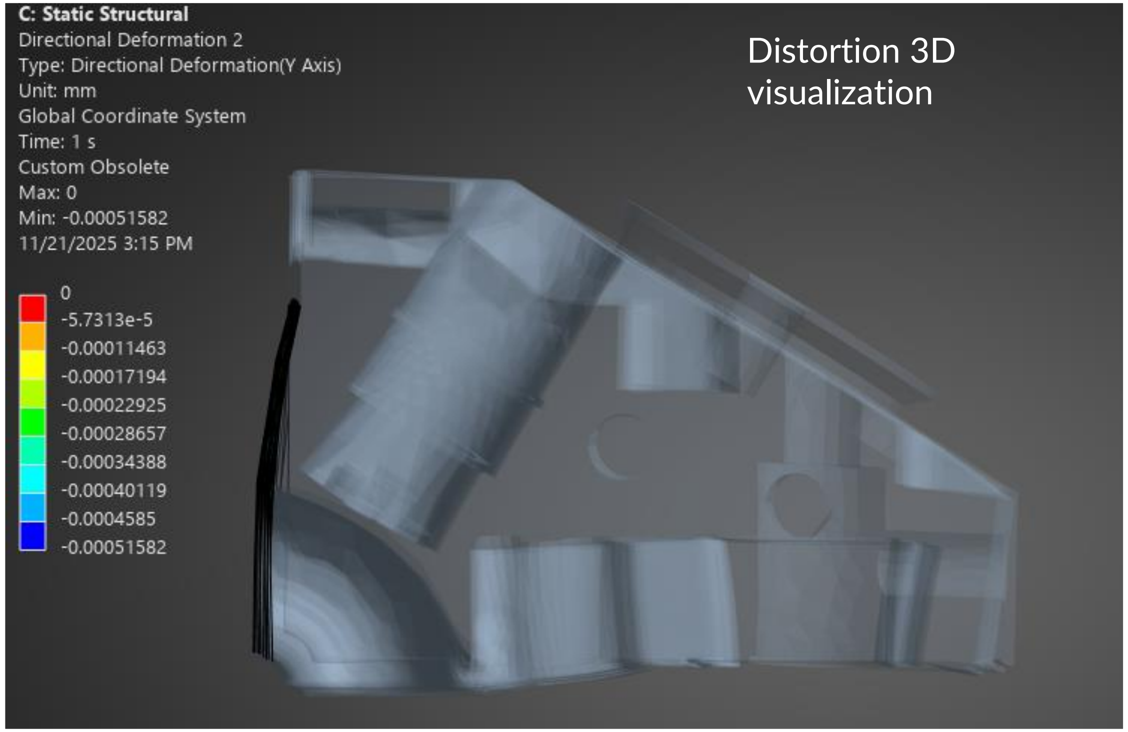
Temperature (C)	Poisson's Ratio
-200	0.338
-100	0.341
23	0.345

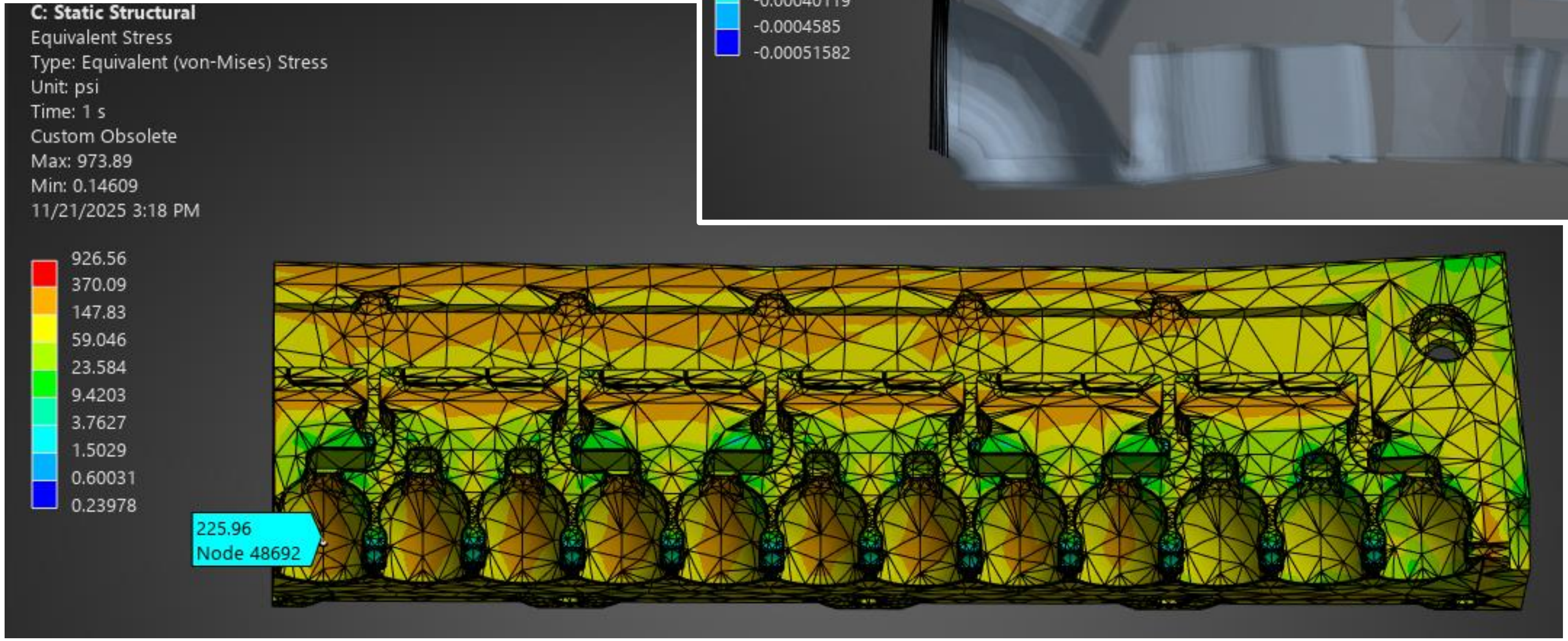
FEA: Heat Transfer, Pressure, & End Effects

Conditions from previous slide

Von-Mises stress below 1 kpsi. Annealed copper yields at >3 kpsi.

Yielding is not expected



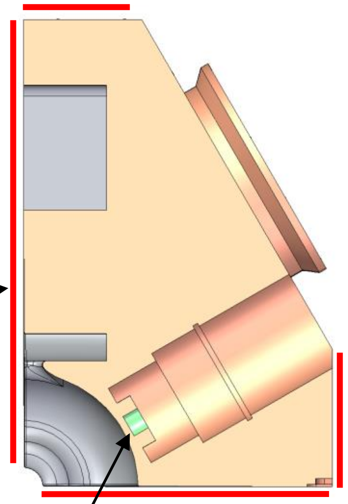


Mechanical Features - External

Part handling feature for machining – TBD by vendor

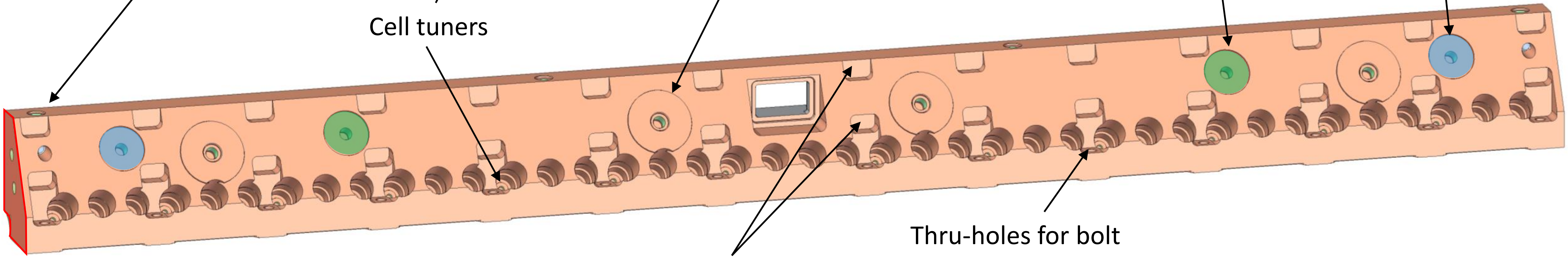
Mounts for **Rasnik or laser nests**

Alignment **surfaces** to be machined in one pass at the final step, checked/recorded



Mounts for **struts** to support raft

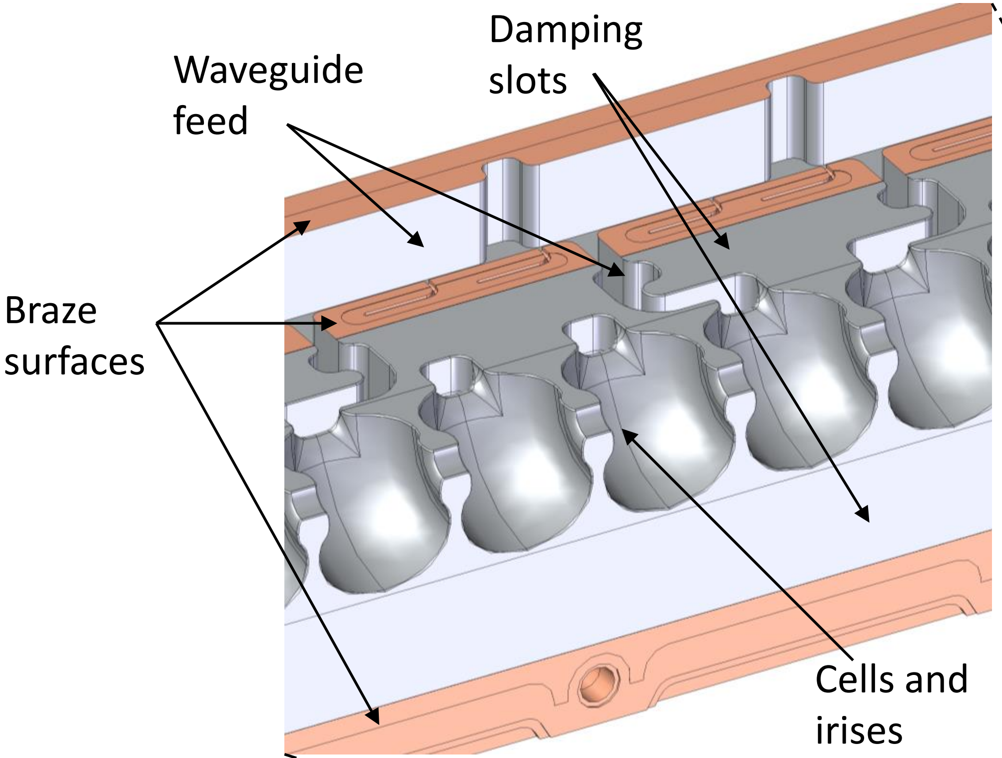
Cell tuners

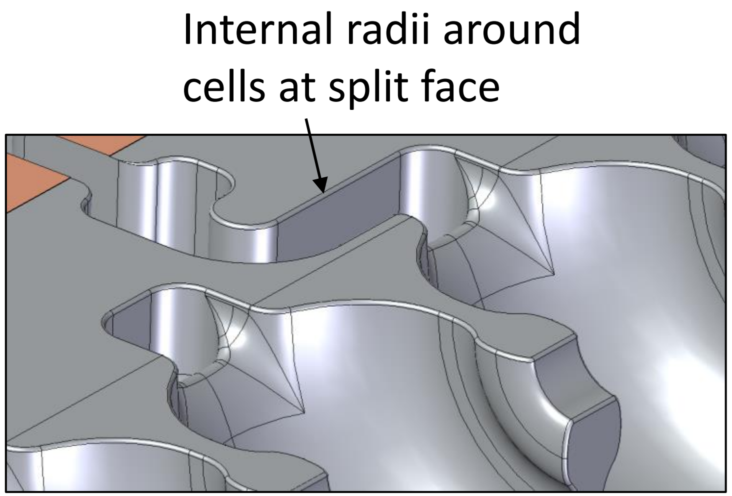


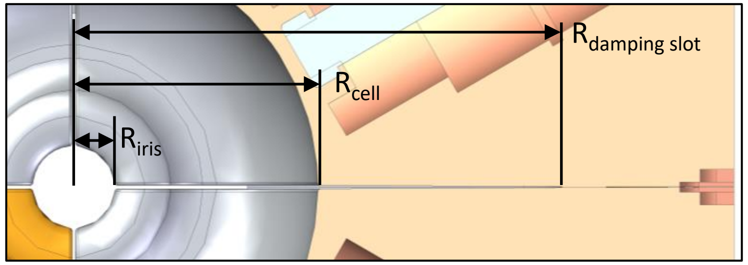
Braze clamping pads

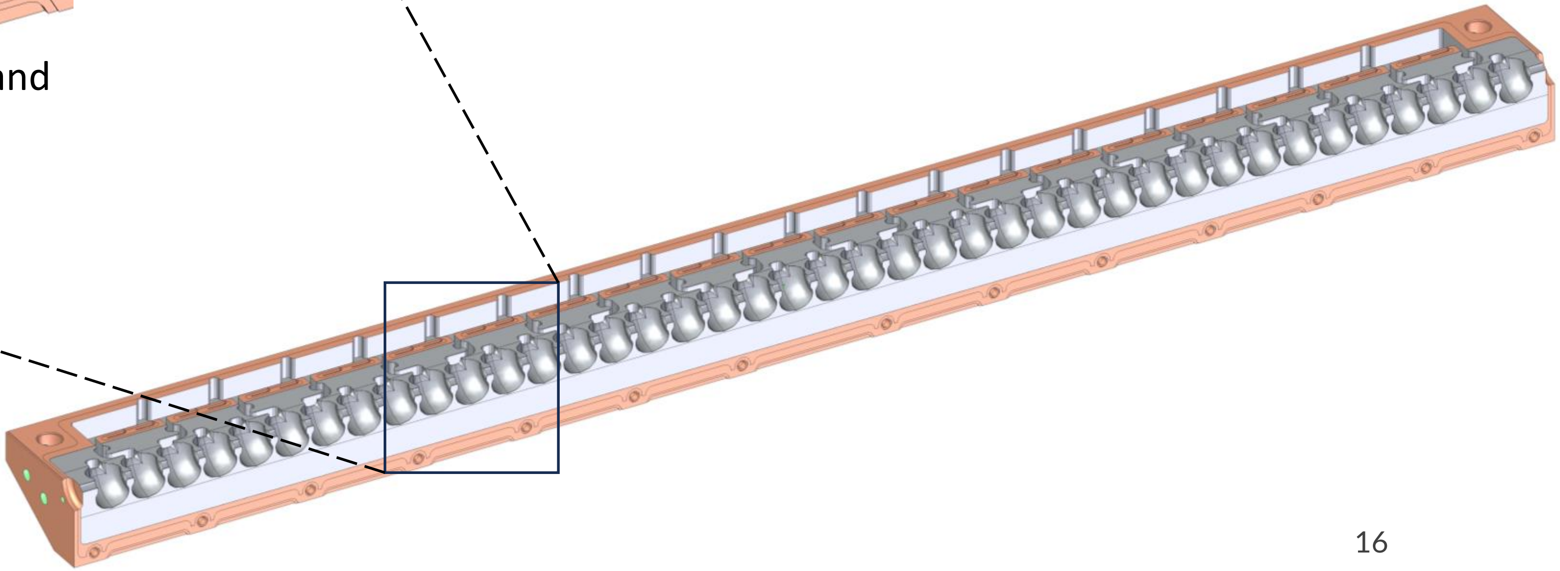
Thru-holes for bolt clamping at braze

Mechanical Features - Internal







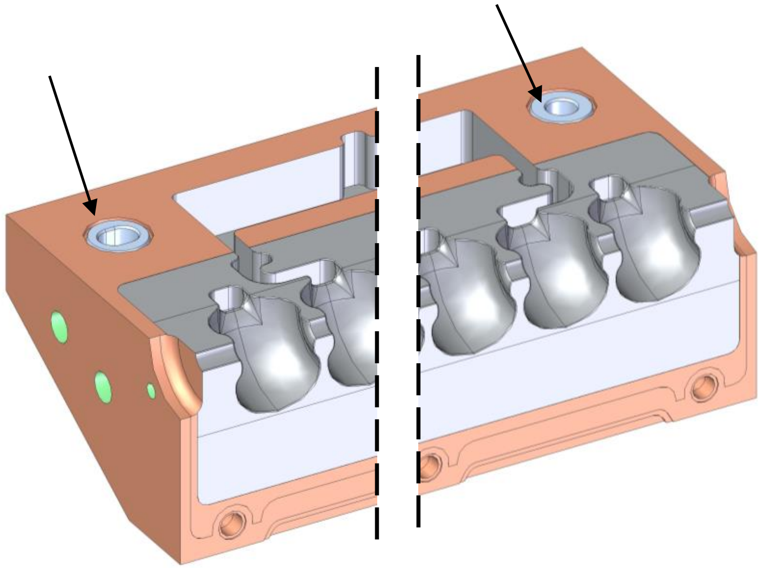


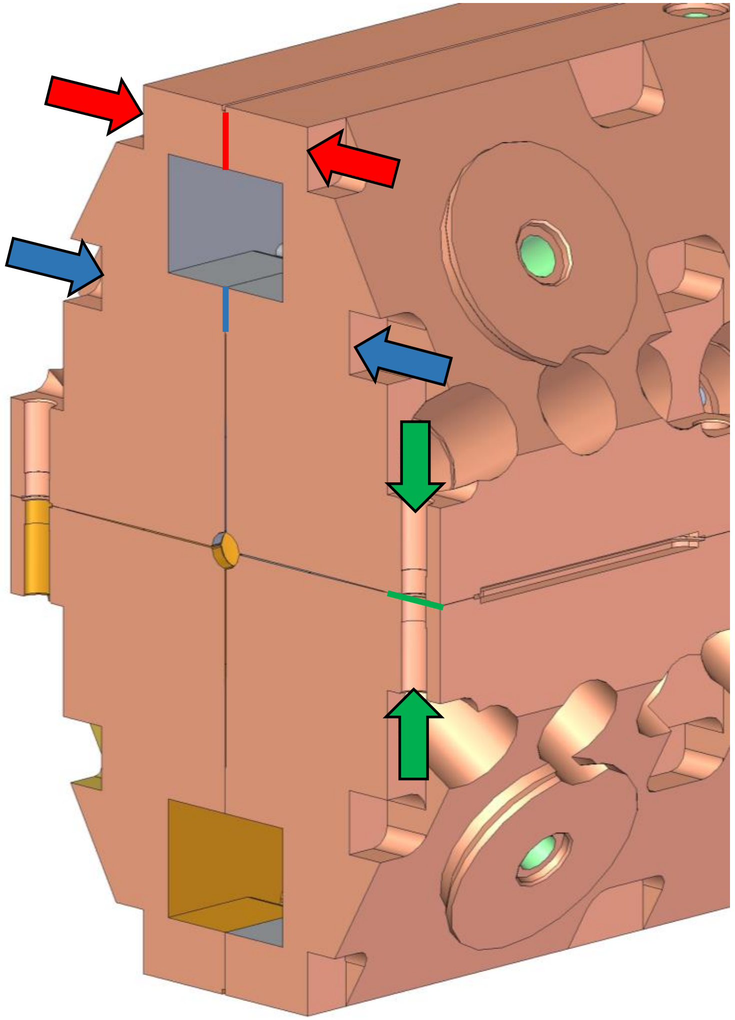
Braze Steps and Features

3 critical "perimeter" joints (2 vacuum, 1 mechanical)

During braze, the braze joints are held by external clamps and compression bolts.

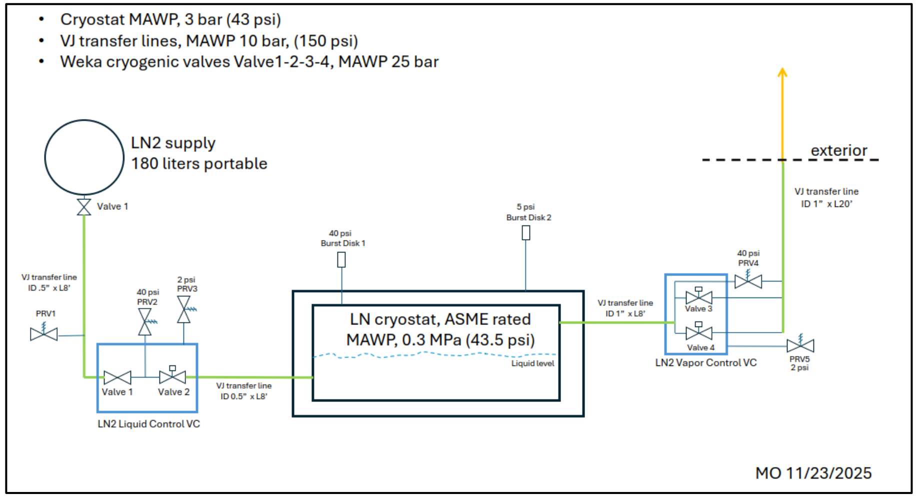
At assembly, alignment is achieved with a pin and slot arrangement, using stainless steel inserts to prevent deformation of the hole and slot (exterior flat surfaces may also be used)

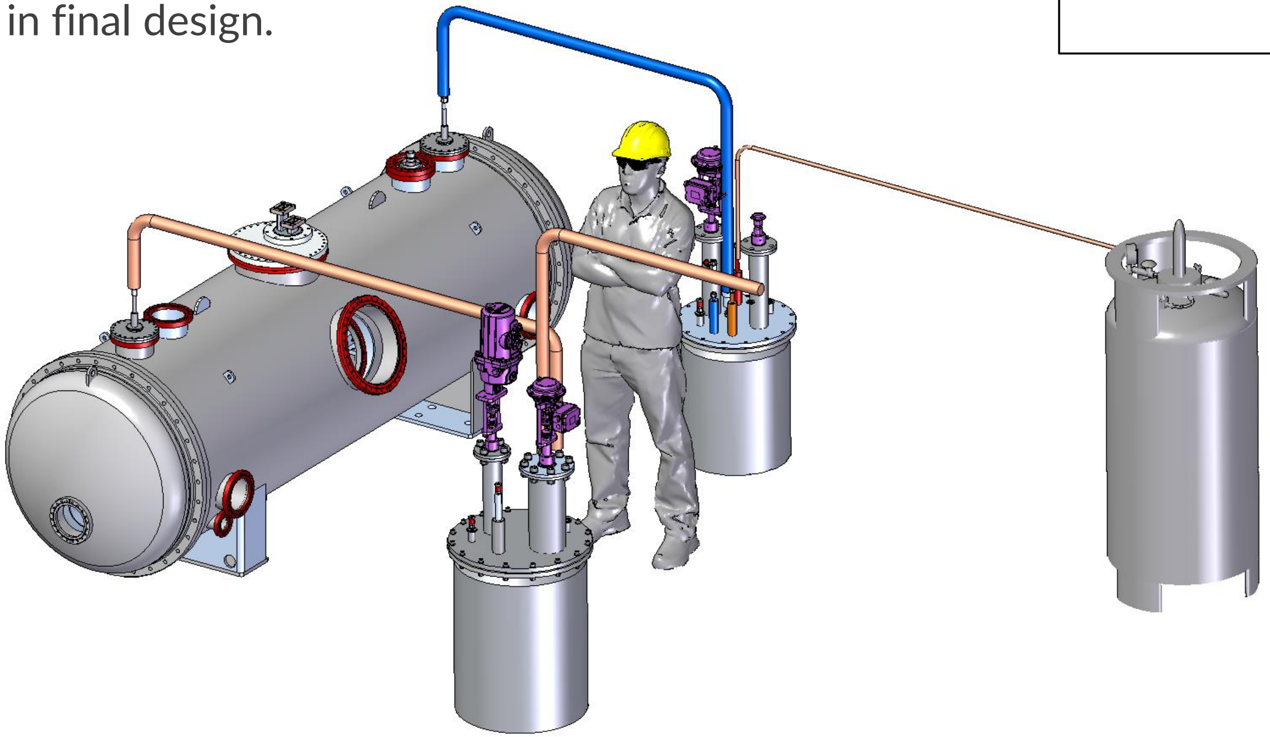




Design and Build Status – Cold Box/Fill Lines

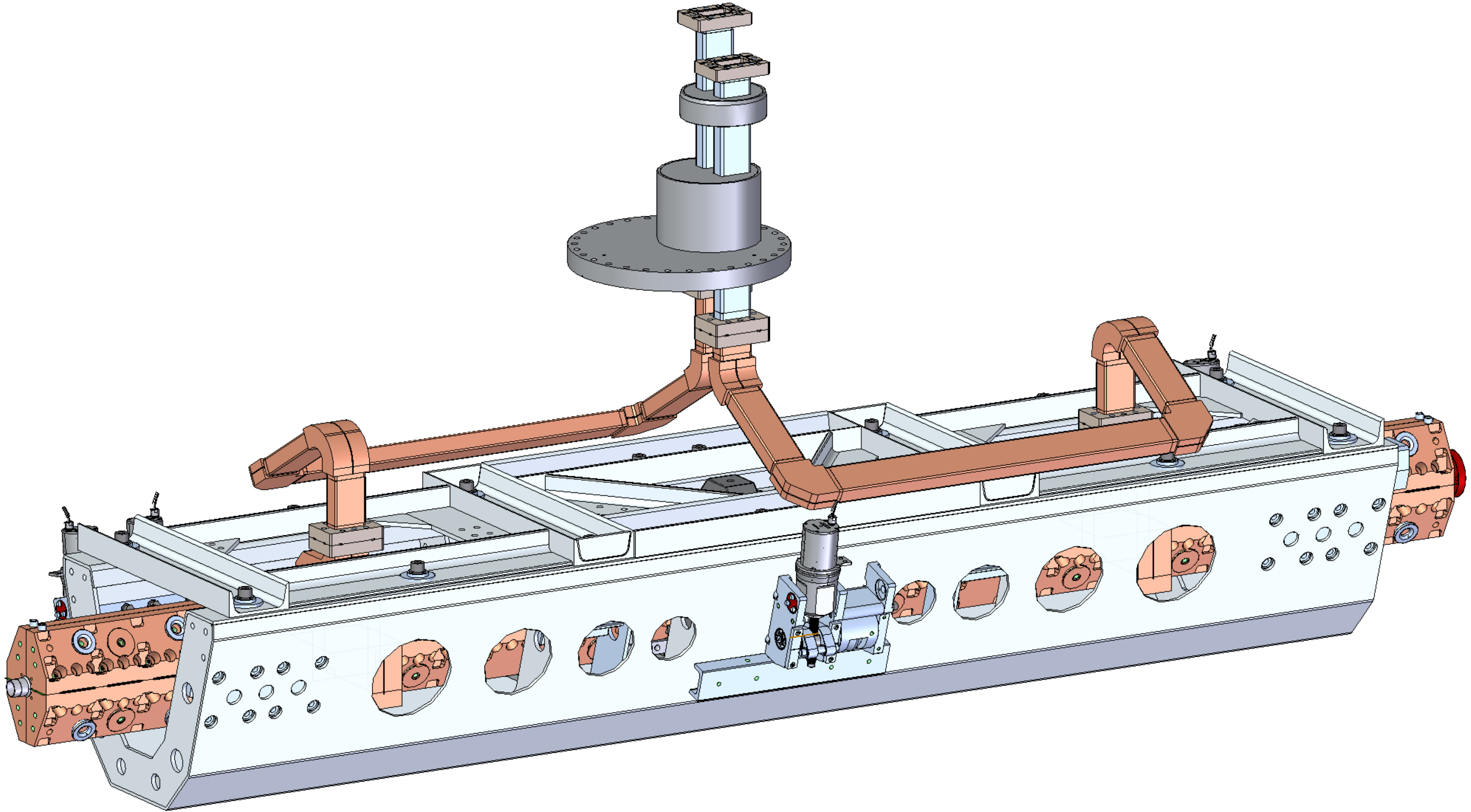
- Cold boxes designed to enable controlled filling/venting of cryomodule.
- P&ID agreed upon with SLAC pressure vessel safety team.
- Valves are already received at SLAC.
- Half of the transfer lines and bayonets are received at SLAC, but will require additional components or modification.
- Boxes and lids are in final design.





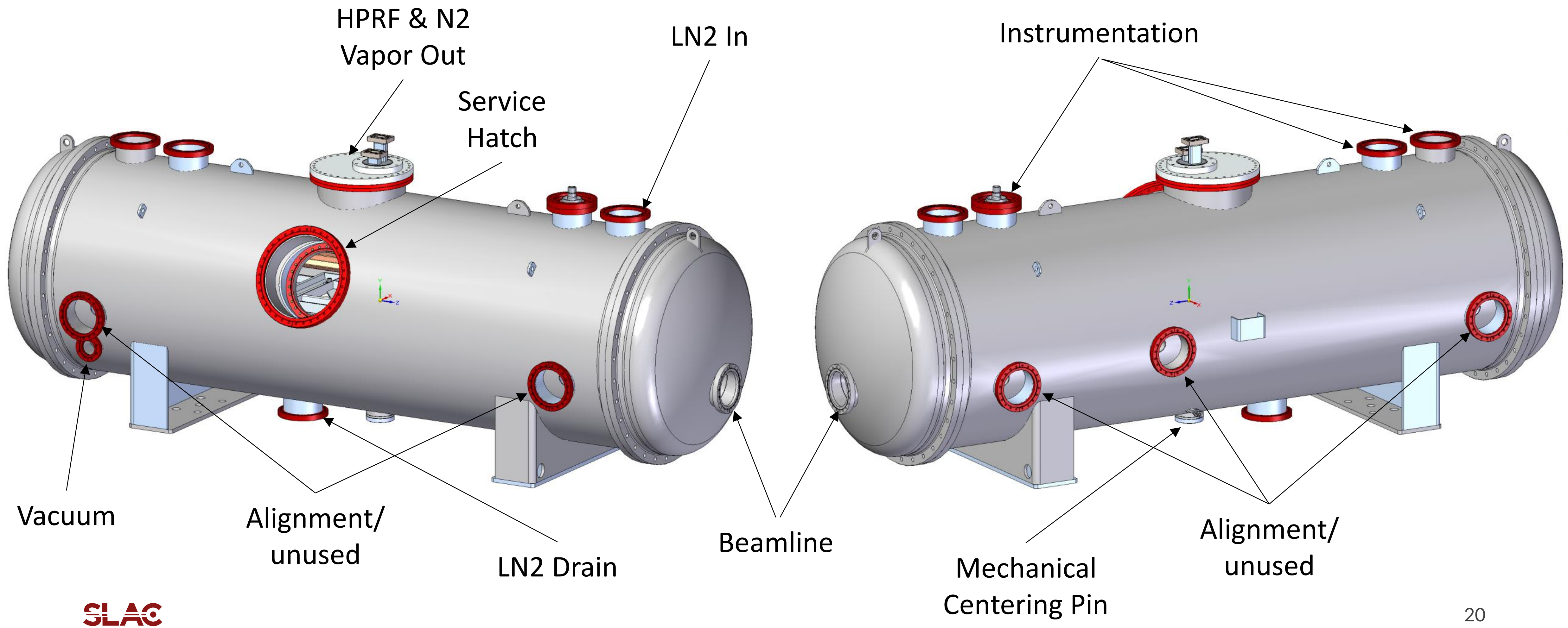
Design and Build Status – HPRF Waveguide

- Feedthrough into the QCM is via stainless steel waveguides bolted externally and internally.
- Internal waveguides are of copper and have an elongated path to make them flexible, allowing for mm-scale adjustments of the raft and accelerator while the feedthrough is fixed.



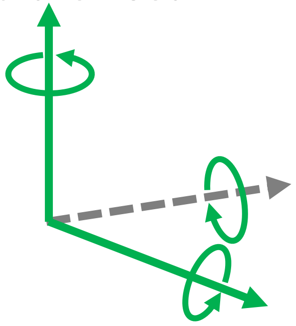
Design and Build Status - Feedthroughs

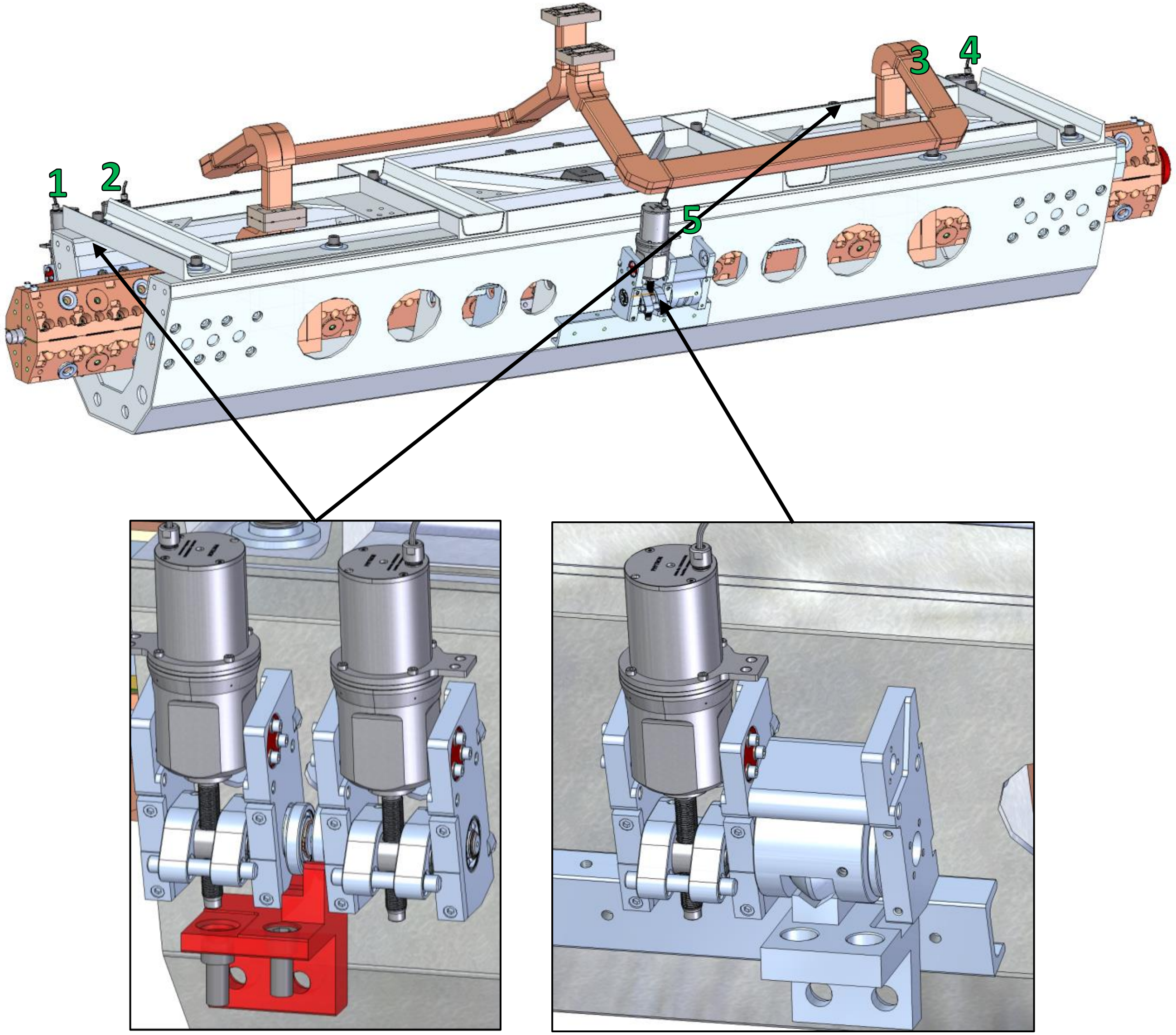
Proposed feedthrough locations

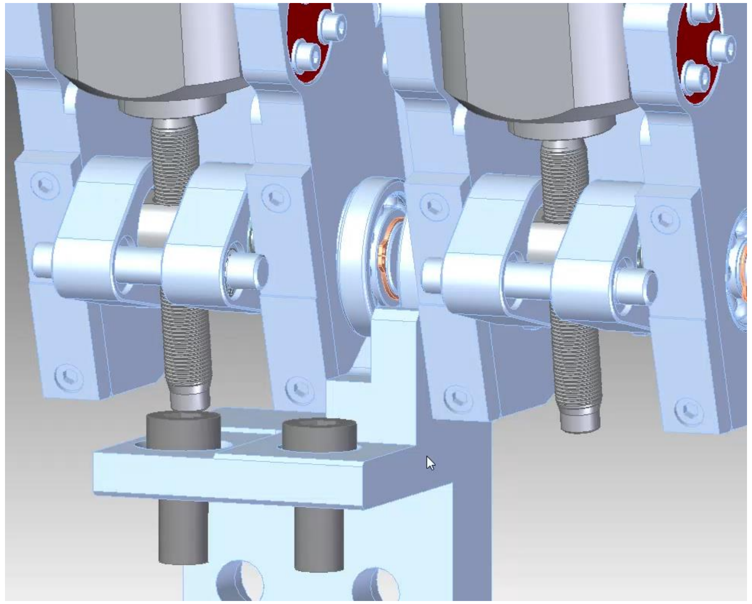


Design and Build Status – Mounts/Movers/Loaders

- 5 adjustable mounts for 5 degrees of freedom
- Adjustable range is mm-scale, with the exact limits to be agreed upon with ESRF and then set by SLAC.







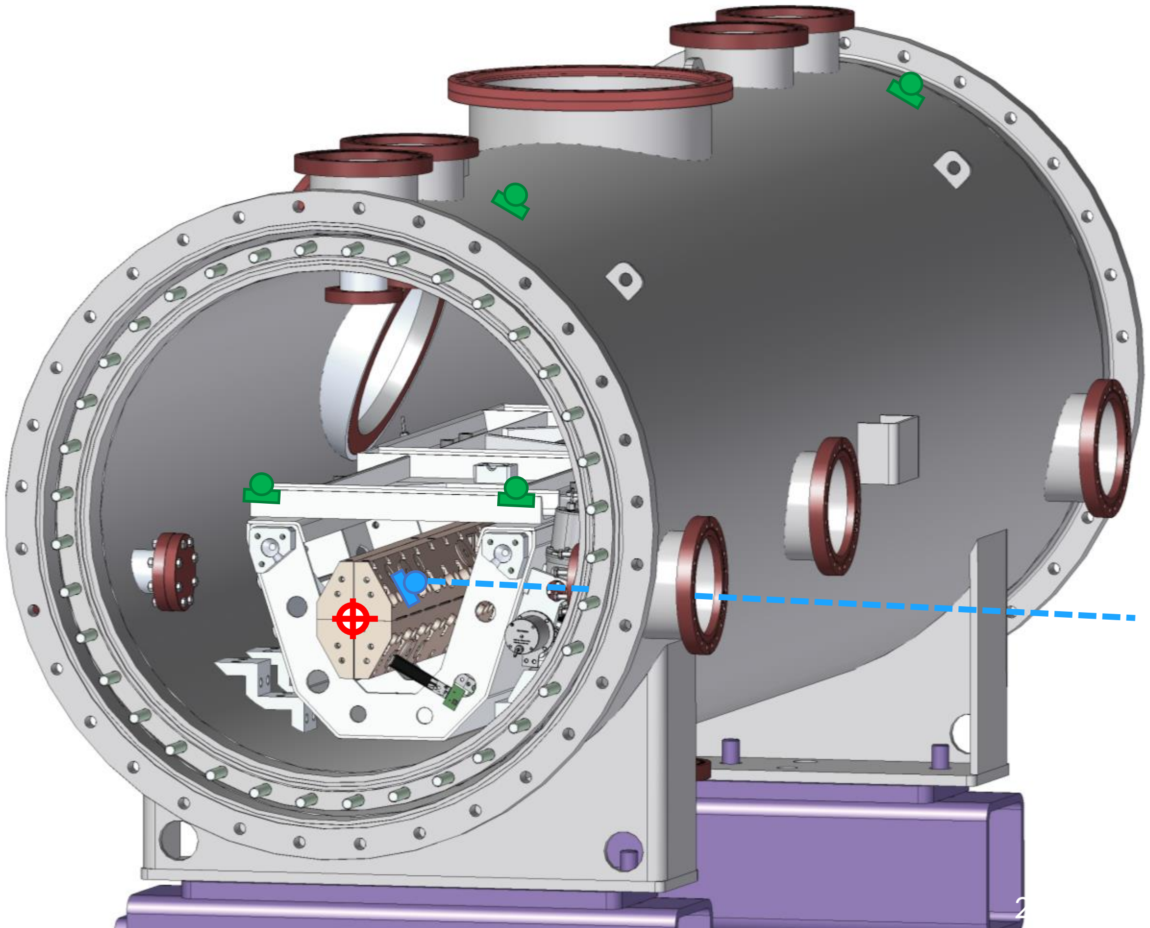
Animation showing various movements for one pair of movers

Mechanical Features – Alignment and Fiducials

ESRF needs: Precision alignment of the structures in the QCM to the machine coordinates (beam tunnel/mating components) and a means of verification/adjustment.

- Will want to check alignment while warm with cryovessel open – confirm if any movement during shipping.
- Needs confidence of the location while cold, however that is established.

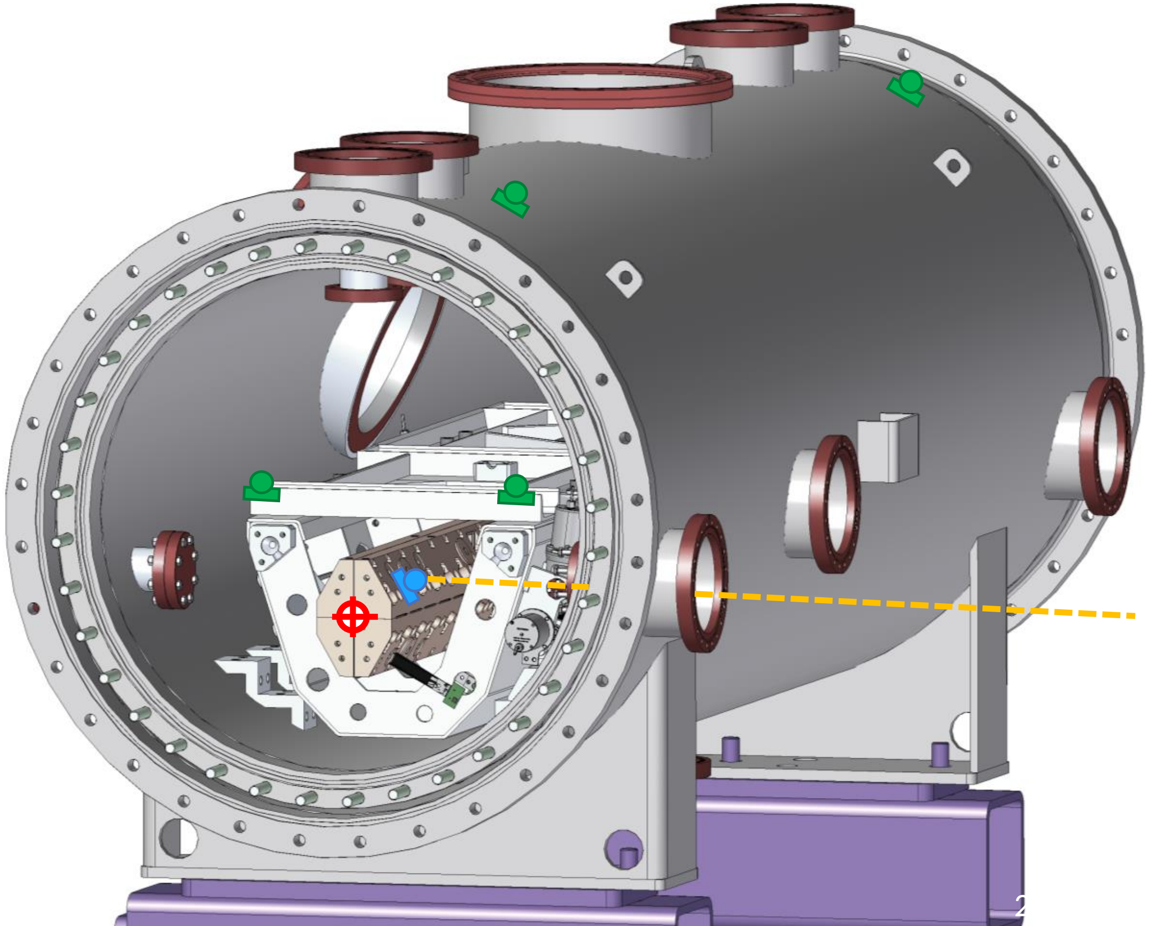
- **Option 1**: While warm, transfer datums to external fiducials and use a calculated or empirical "cold-warm" adjustment.
  - Need to qualify and ensure consistency in this adjustment factor.
- **Option 2**: Use the Rasnik alignment system to be installed and tested by SLAC.
- **Option 3**: Use optical viewports through vacuum and liquid nitrogen to directly measure fiducials on the accelerator.
  - Unclear if this is even possible and requires additional experimentation.



Mechanical Features – Alignment and Fiducials

Actions

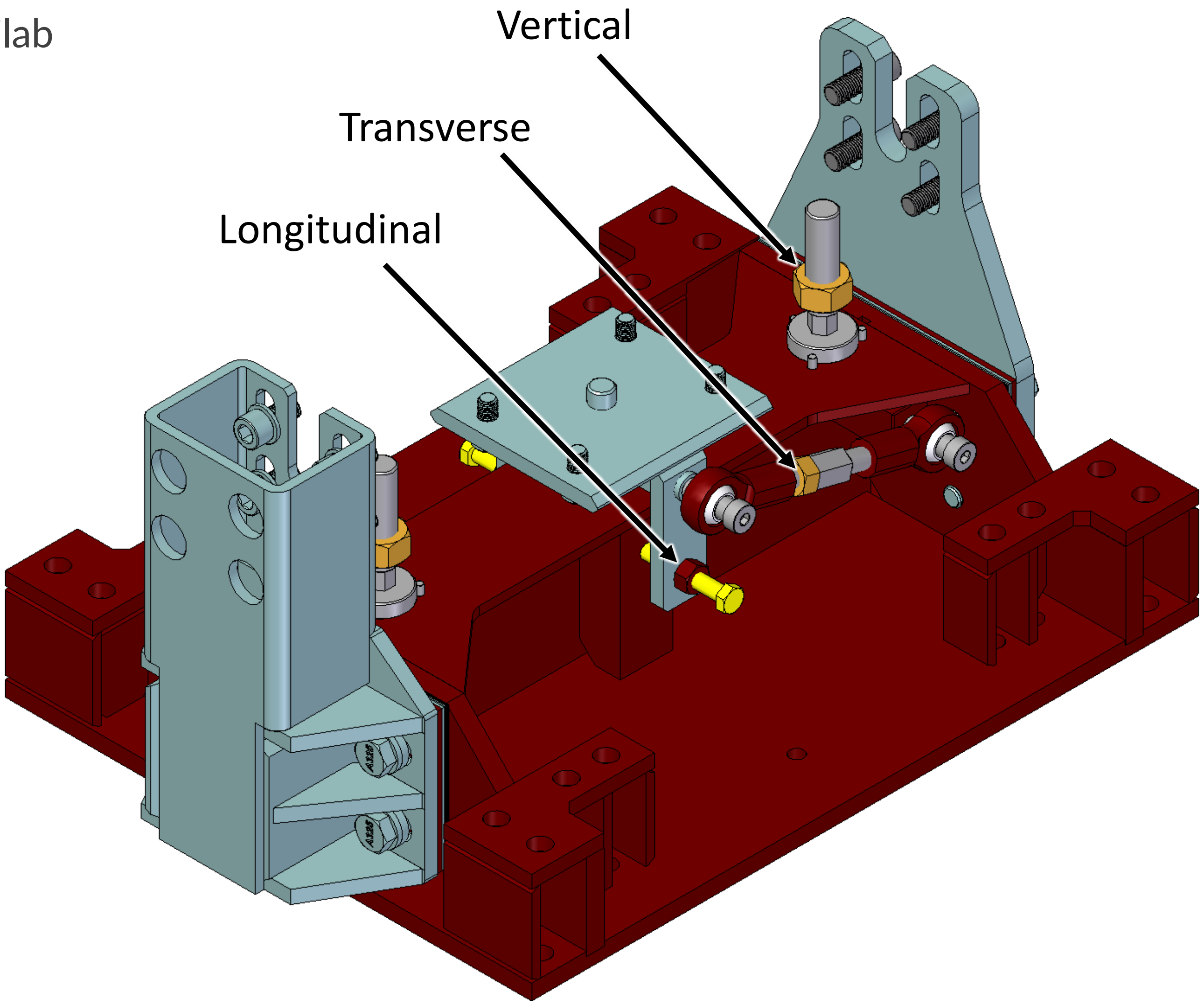
1. ESRF: Finalize mechanical alignment accuracy required before switching to beam-based alignment.
2. SLAC: Perform small-scale tests of measurement through windows and LN2.
3. SLAC: Investigate alternative alignment methods.
4. SLAC: Propose a plan for qualifying the alignment method chosen to ESRF's needs.



SLAC

External Mounts

- Adjustable mounts were originally designed by Fermilab for the LCLS-II LINAC cryomodules.
- Allow for vertical, transverse, and longitudinal adjustment.
- Include additional seismic restraints on the sides.



Cryogenic and Vacuum Requirements

- LN used on cooling fill: **1400 L**
  - Vessel volume: 550 L
  - Cooling the structure: ~720 L
  - Loss during fill: ~100 L (over 12 hours)
- Standby losses: **133 L/24 hr** for 286 W standby power loss
  - Radiation: ~247 W
  - Conduction: ~38 W
  - Convection: 0 W (assuming $<1\times10^{-5}$ torr vacuum)
- Operating losses will vary and be in addition to the above.
- Vacuum
  - Primary concern is to maintain vacuum $<5\times10^{-5}$ torr to ensure no convection heat loss.
  - This vacuum level requires turbo pumps (and appropriate backing pumps), but the exact size of pumps depends on system outgassing and leak rates, which will be determined during testing at SLAC.

Conclusion