Cryomodule Design and Fabrication Status

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On Behalf of the ANL Physics Division Accelerator R&D Group
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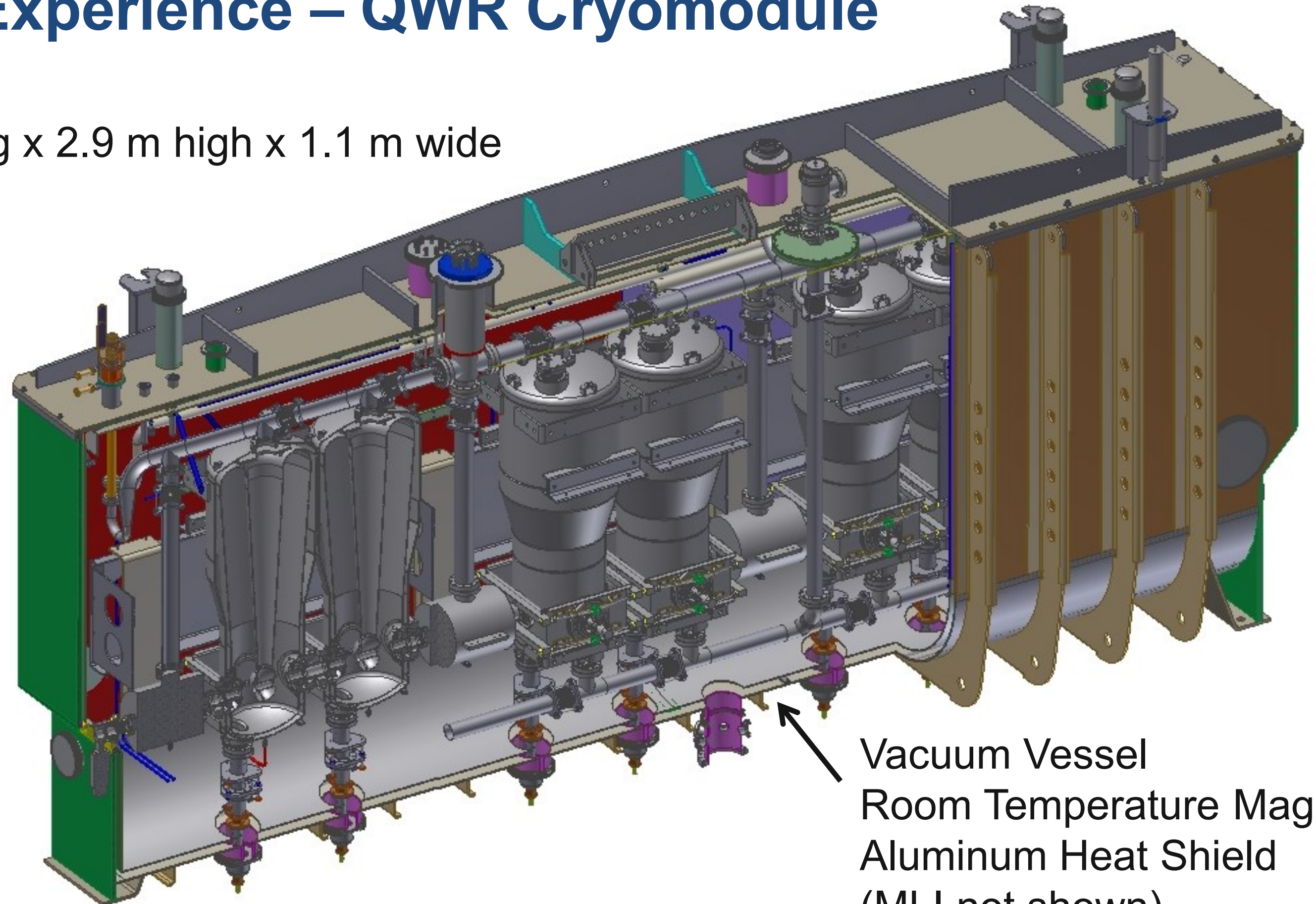
Overview

- Recent experience.
- Review of the cryomodule design:
  - Component layout.
  - Alignment.
  - BPM status.
- Safety and engineering analyses:
  - Half-wave resonator design and safety analysis.
  - Vacuum vessel safety analysis.
    - With a brief aside with design impact.
- Interface considerations will be addressed in a presentation later today.
  - Will the cryomodule fit?
  - Cryogenics.
  - Instrumentation.
  - Alignment.
  - Etc.

Recent Experience – QWR Cryomodule

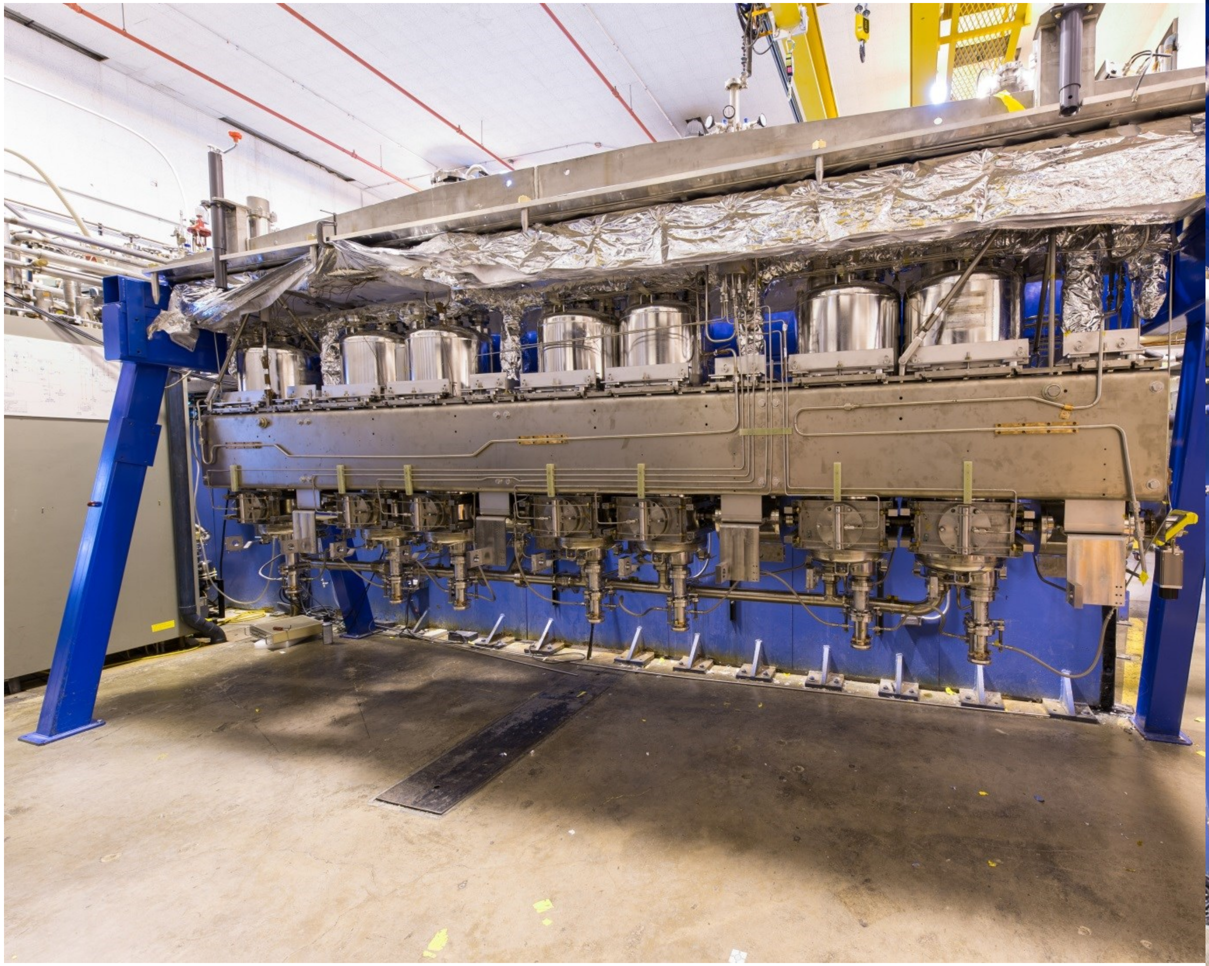
5.2 m long x 2.9 m high x 1.1 m wide

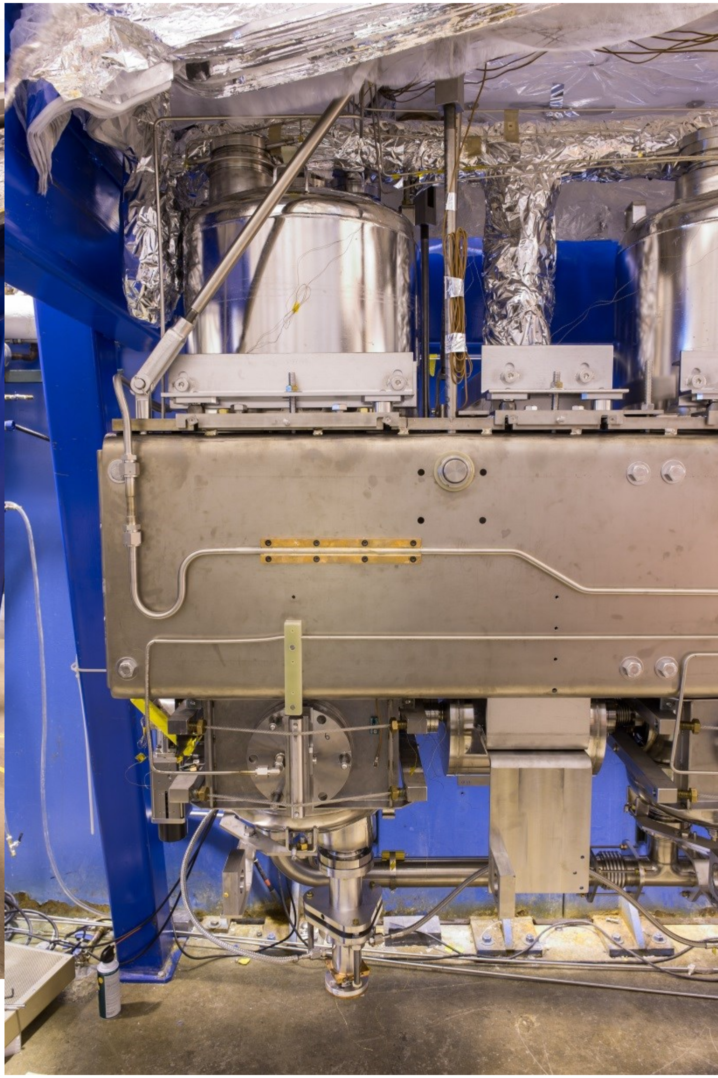


Vacuum Vessel
Room Temperature Magnetic Shield
Aluminum Heat Shield
(MLI not shown)

- Highly optimized SRF cavities and solenoids.
- Solenoid fields shielded with return coils.
- First Argonne SRF cryomodule designed to comply with the D.O.E. vacuum and pressure vessel safety guidelines.
  - Focus of this presentation.
- Reduced 4 and 80 K loads relative to previous energy upgrade cryomodule.

ANL ATLAS Intensity Upgrade Cryomodule – Part 3

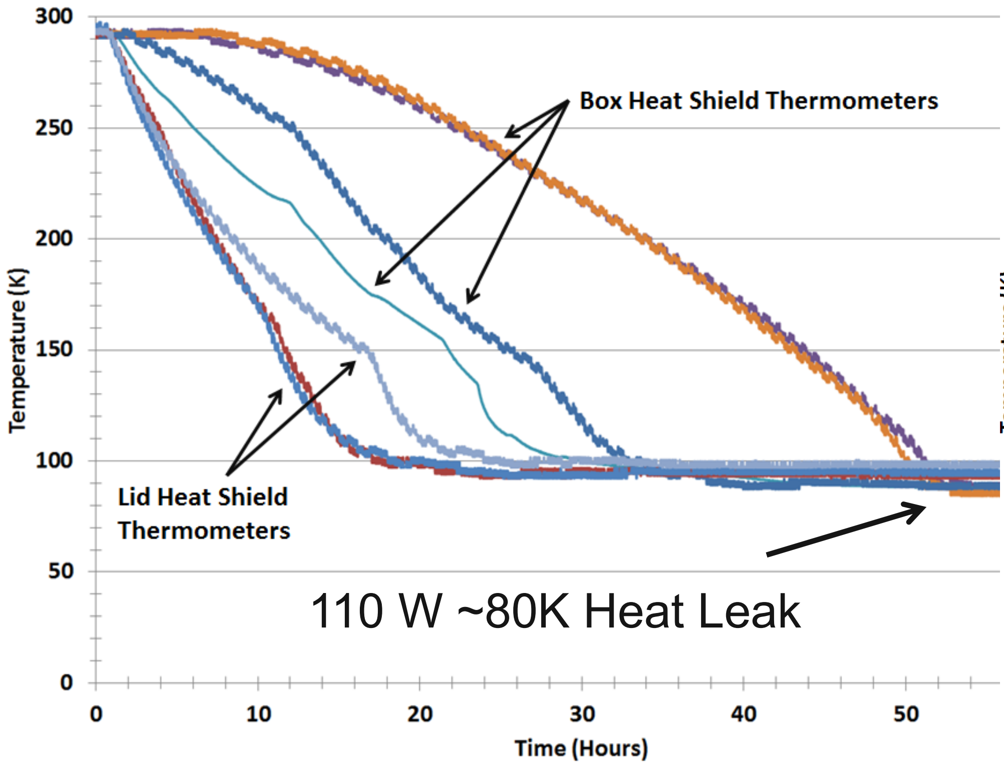




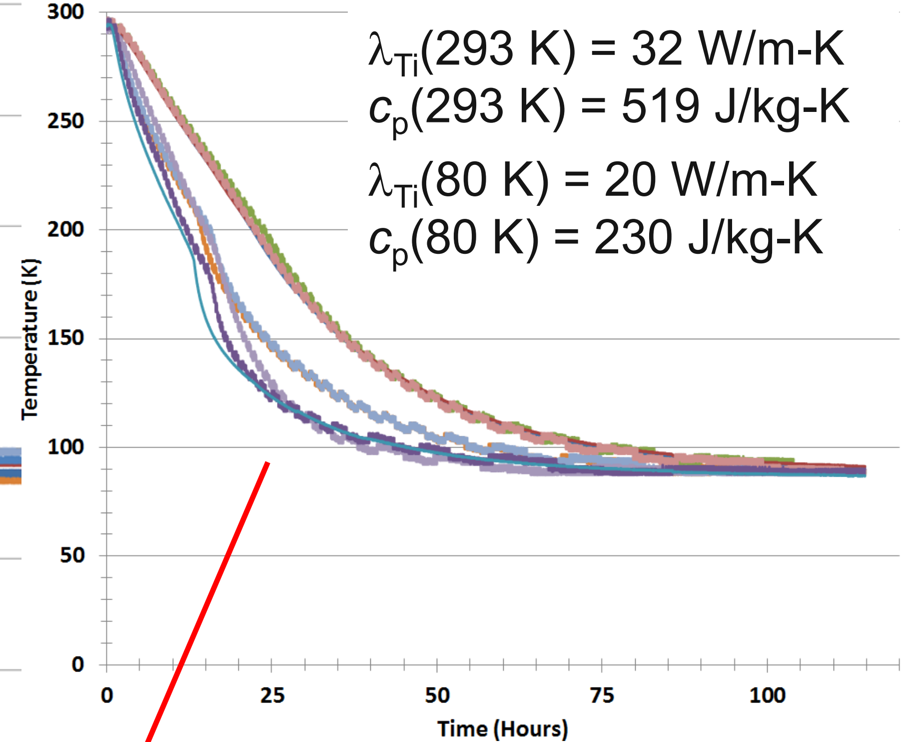
Final Assembly

First Cooldown to 80 K

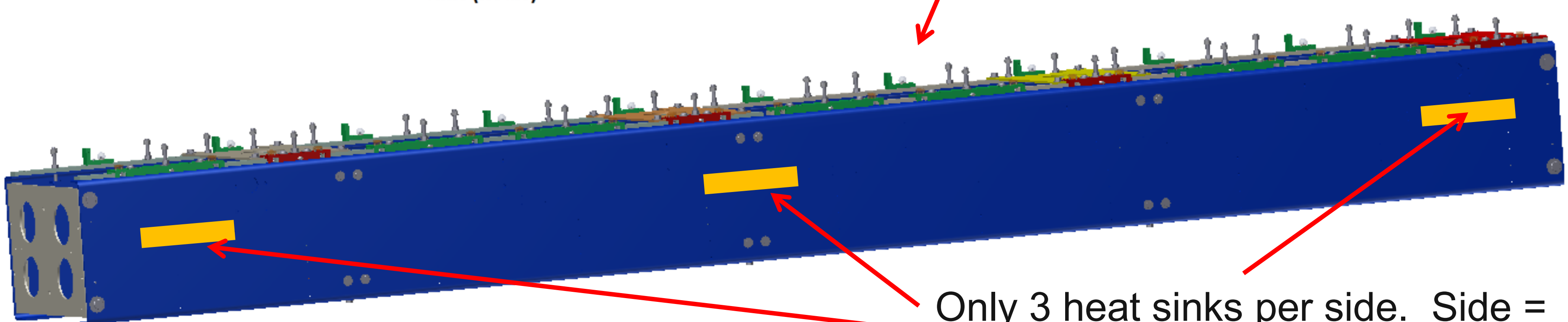
80 K Heat Shield Cooldown



Titanium Strong-Back Cooldown

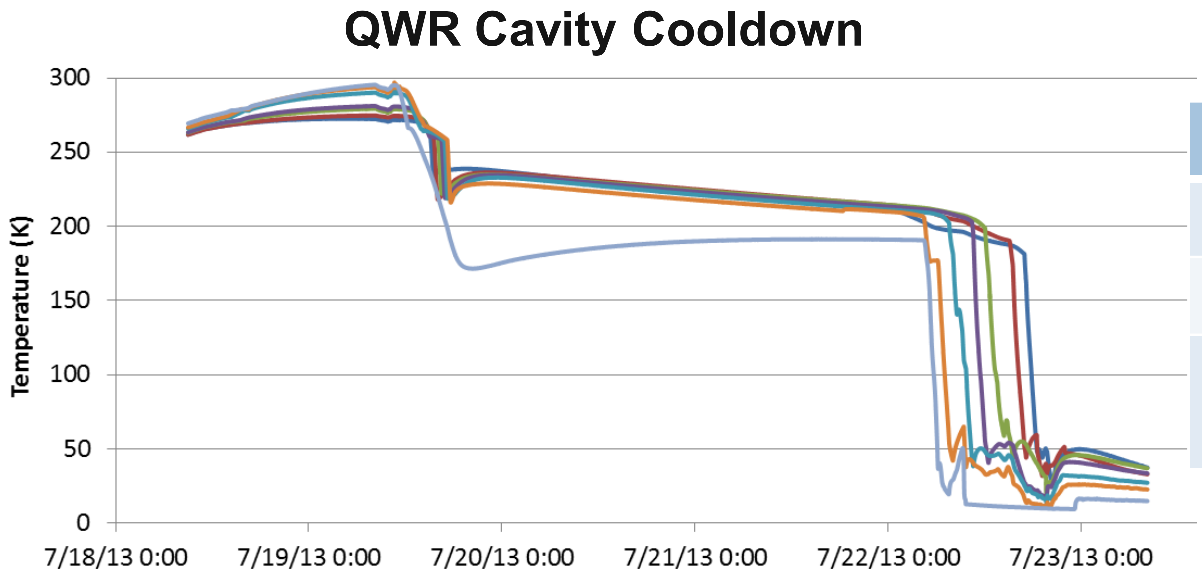


λ_{Ti}(293 K) = 32 W/m-K
c_p(293 K) = 519 J/kg-K
λ_{Ti}(80 K) = 20 W/m-K
c_p(80 K) = 230 J/kg-K

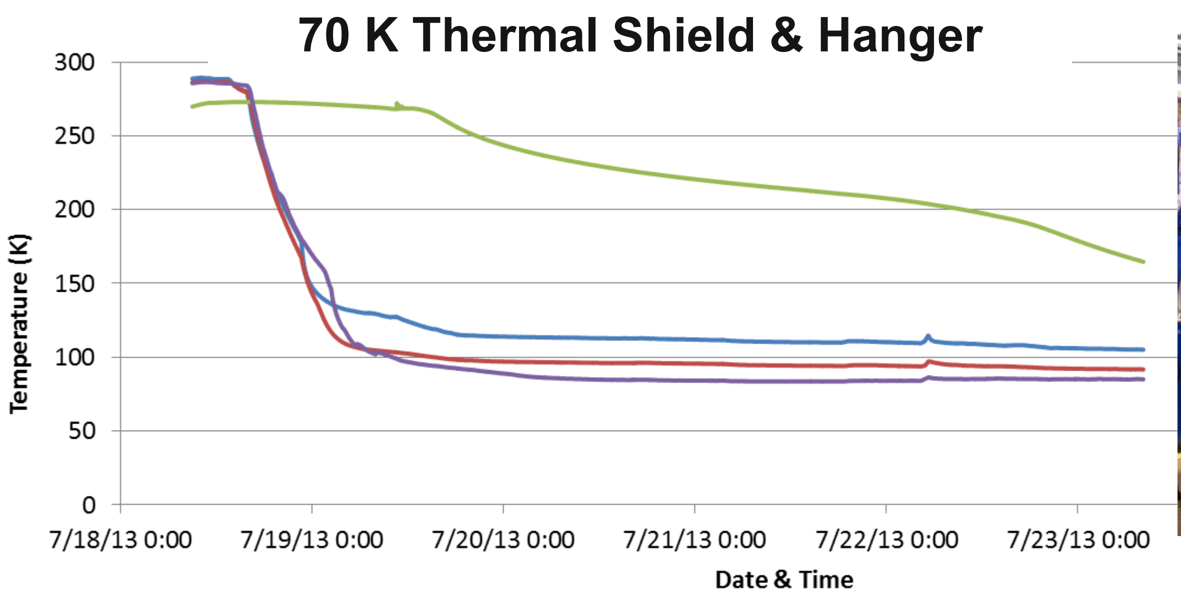


Only 3 heat sinks per side. Side = 190" Length.

First Cooldown to 4 K



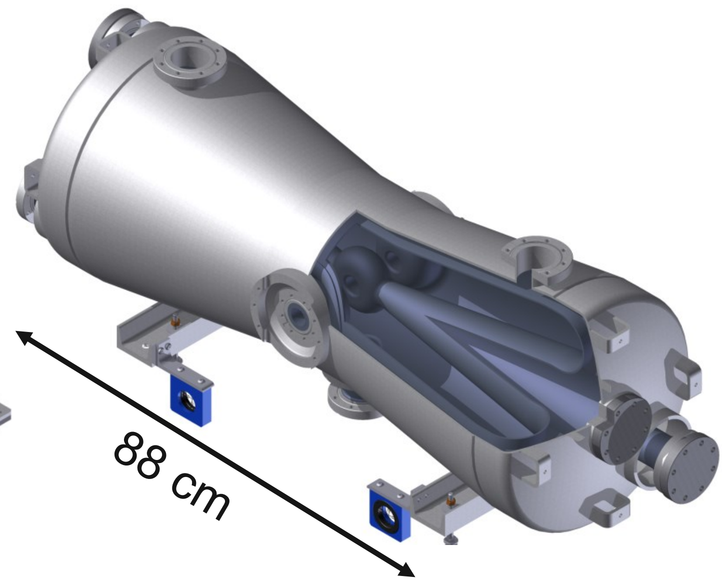
Load	Measurement
80 K (static)	160 W
4 K (static)	12 W
Hanger Heat Leak	<0.1 W

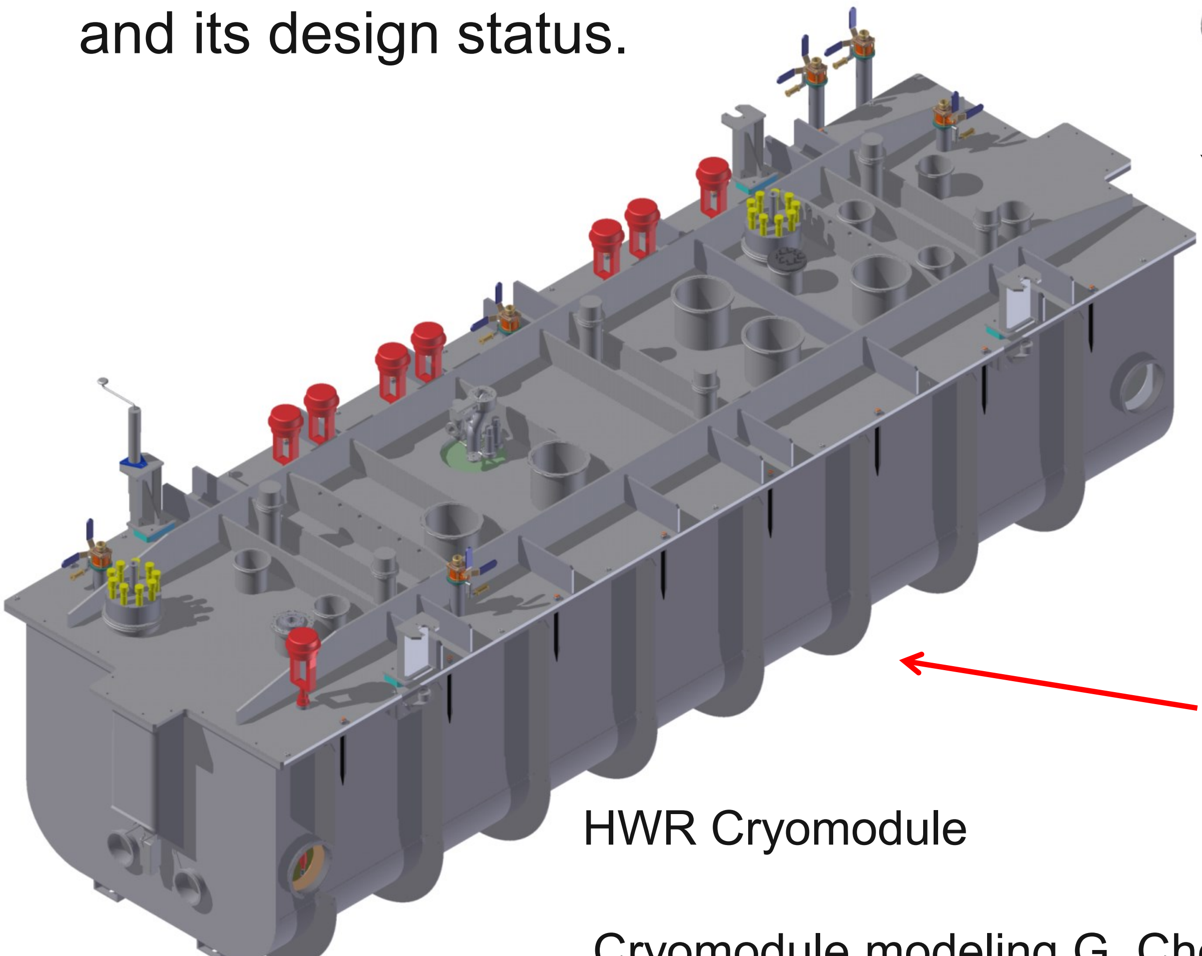


HWR Cryomodule

- 8 SC HWR & 8 SC Solenoids with integral return and steering coils.
- Here the focus will be on the hardware and its design status.

HWR Cut-Away View





HWR Cryomodule

Parameter	Value
Length (beam ports)	5.9 m
Length (overall)	6.3 m
Width	2.1 m
Height	2.2 m

Cryomodule modeling G. Cherry (ANL-NE)

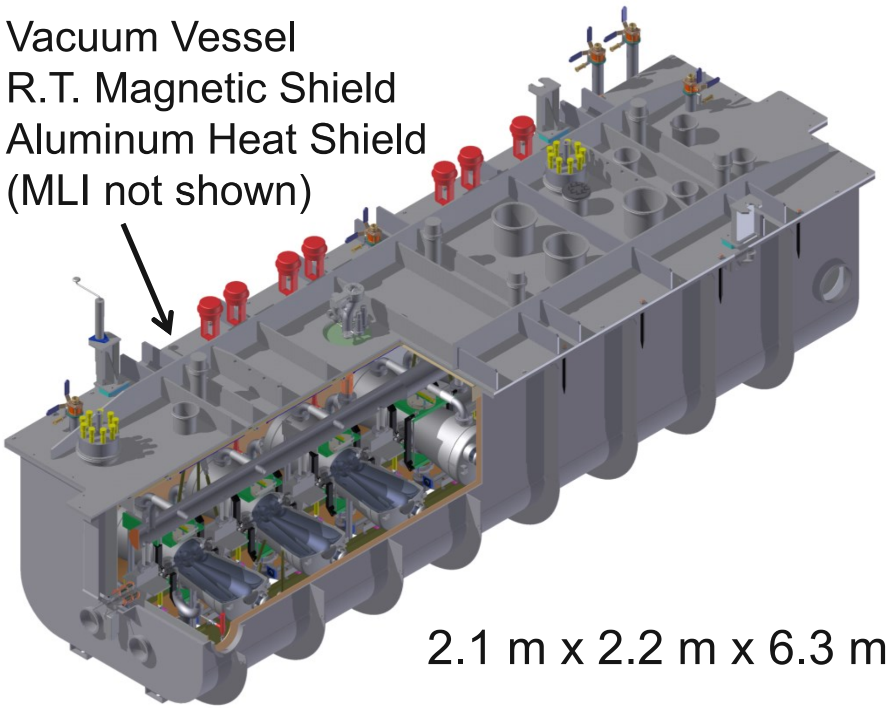
HWR Cryomodule Requirements

- Interfaces:
  - Bayonet connections for Helium supply/return.
  - Cryogenic valve control system & connections.
  - Pumping/pressure relief connections.
  - Cryomodule positioning and alignment.
  - Beam ports terminated with a low-particulate vacuum valve.
  - RF inputs to power couplers and pick-up probes.
  - Instrumentation connections (including BPM signals).
  - Magnet lead connectors (solenoids & correctors).
  - Alignment fiducials on the cryomodule referenced to cavities.
- Instrumentation:
  - Beam position monitors (BPM).
  - Temperature sensors (couplers, magnets, cavities, etc.).
  - Heaters (magnets, cavities, etc.).
  - Helium system (pressure taps, liquid level probes, temperature sensors and heater).
  - Vacuum monitoring for both cavity/cryomodule systems.

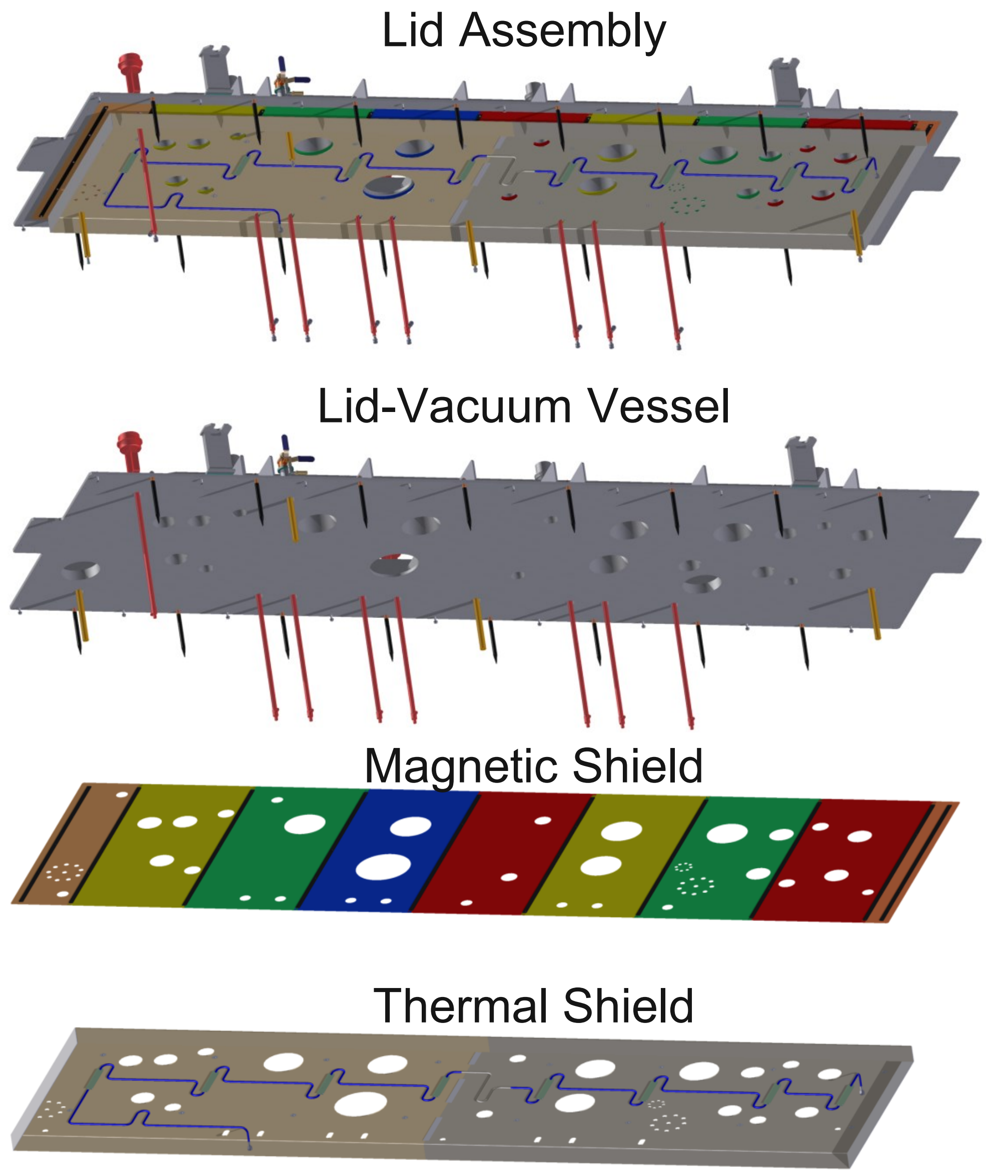
Layout

Cryomodule: Vacuum Vessel & Magnetic Shields

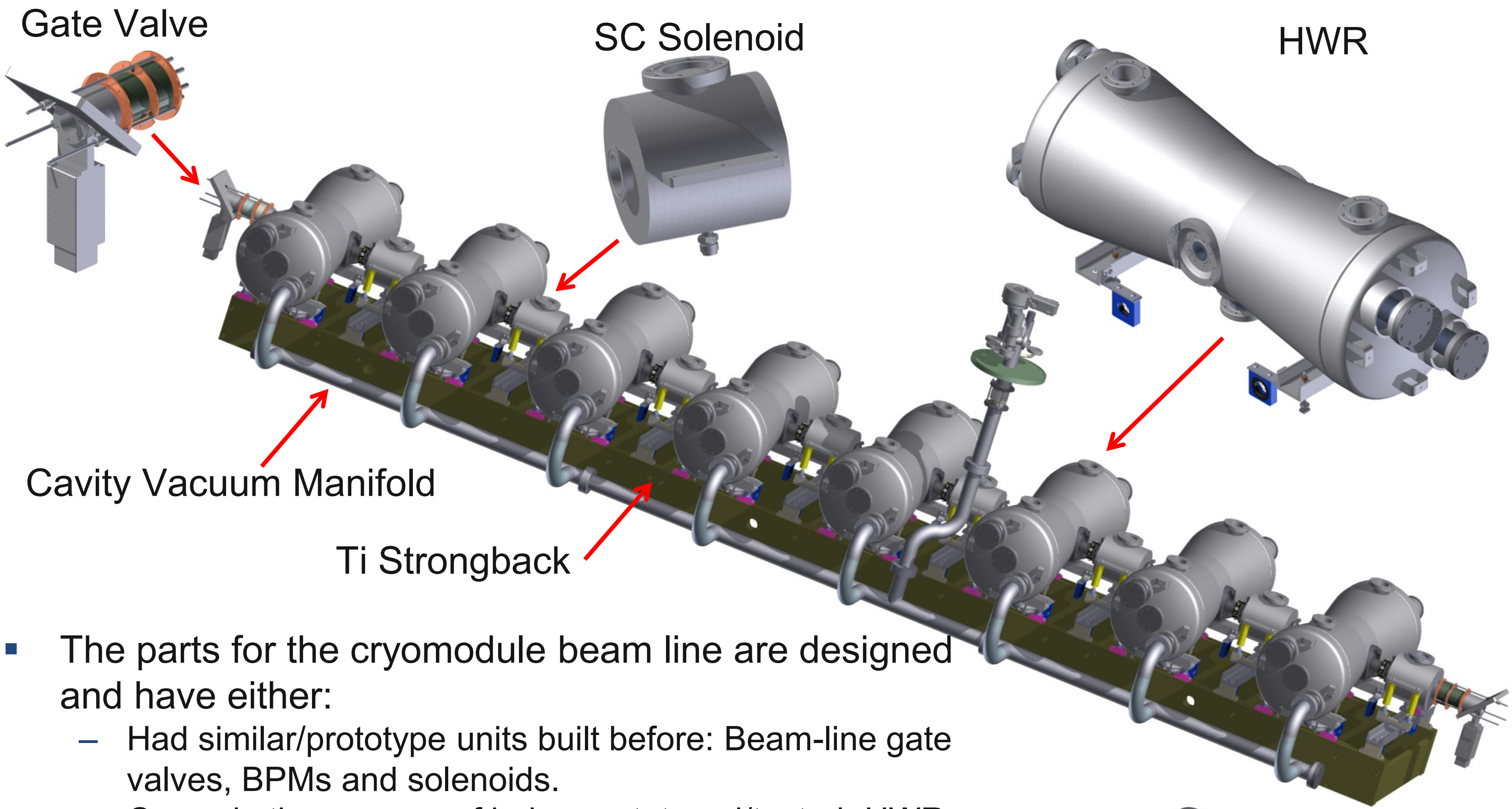
- The 2 K cold mass will be enclosed within a 70 K thermal shield and a 1 mm thick MuMetal enclosure.
- This is functionally identical to our previous box cryomodules.



2.1 m x 2.2 m x 6.3 m



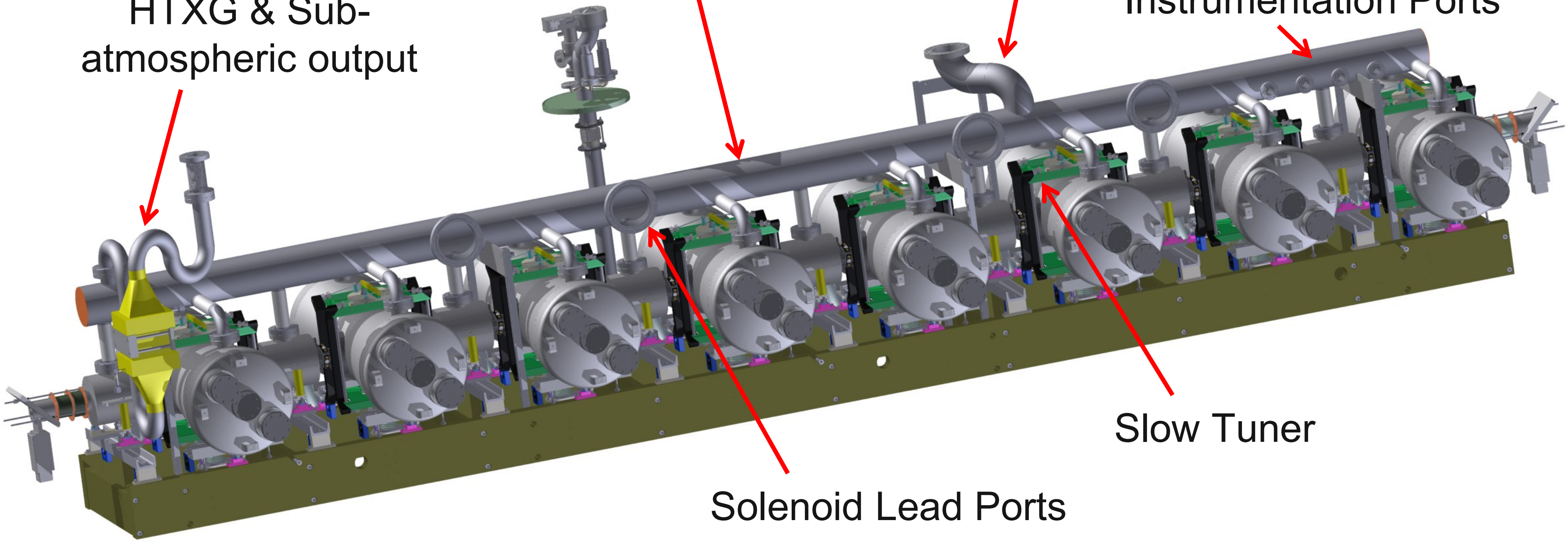
Cryomodule Components – Beam Line



- The parts for the cryomodule beam line are designed and have either:
  - Had similar/prototype units built before: Beam-line gate valves, BPMs and solenoids.
  - Or are in the process of being prototyped/tested: HWRs and beam line interconnects.
- This assembly is done in the cleanroom and does not leave the cleanroom until after a hermetic seal is made.

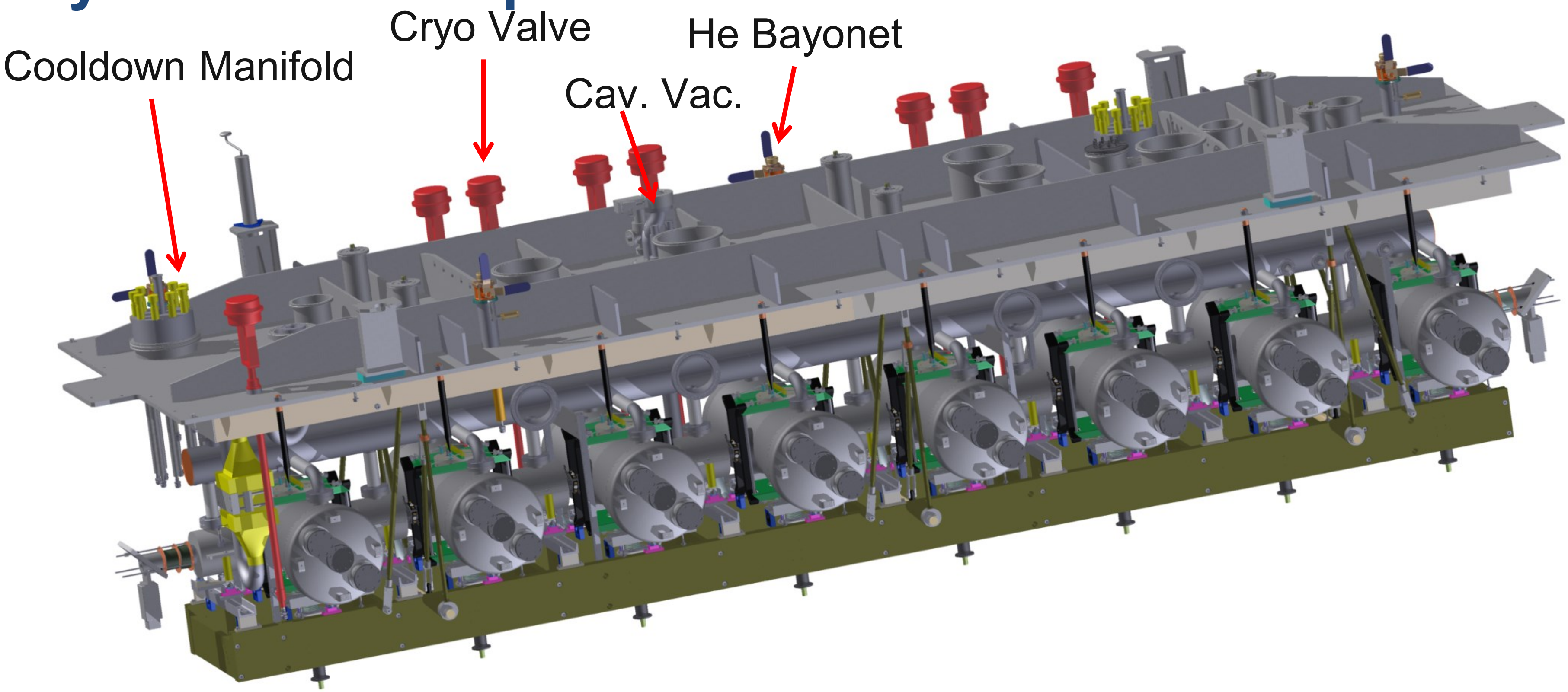

BPM & Interconnect

Cryomodule Components – Helium Manifold/HTXG



- On the bottom of the helium manifold there are connections for each cavity (2 per) and solenoid (one).
- The 2-phase helium input and sub-atmospheric output are located on the top of the manifold.
- There are 4 6" ports for the 48 solenoid leads.
- There are 4 1.5" ports for instrumentation: LHe level probes, measurement lines and thermometry.
- Each cavity/solenoid has a VCR-8 (1/2") fitting for cooldown.

Cryomodule Components – Lid & Coldmass



- The lid/coldmass assembly is done outside of the clean-room and after the hermetic sealing of the low-particulate clean vacuum system.
- The layout and designs used here are functionally identical to what we have done for our previous cryomodules.
- The lid interfaces will be discussed later today.

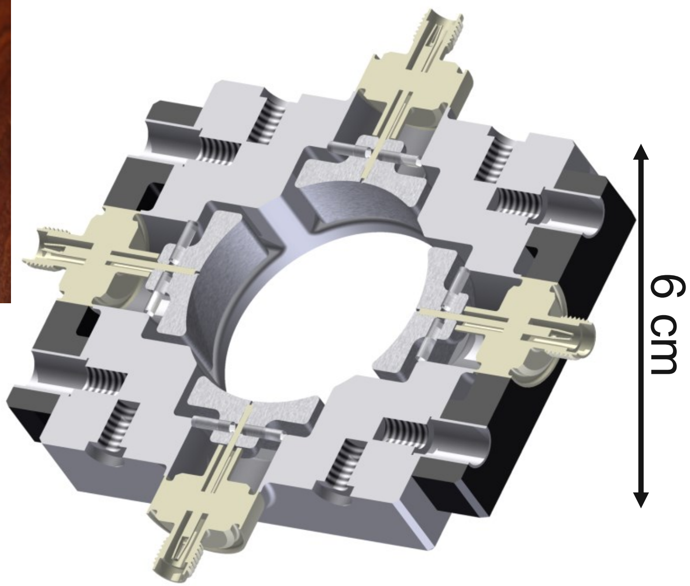
Beam Position Monitors

- Prototype fabrication finished.
- Bench-top tests agree well with CST simulation.
- Planning to test with beam @ SARAF in coming months.

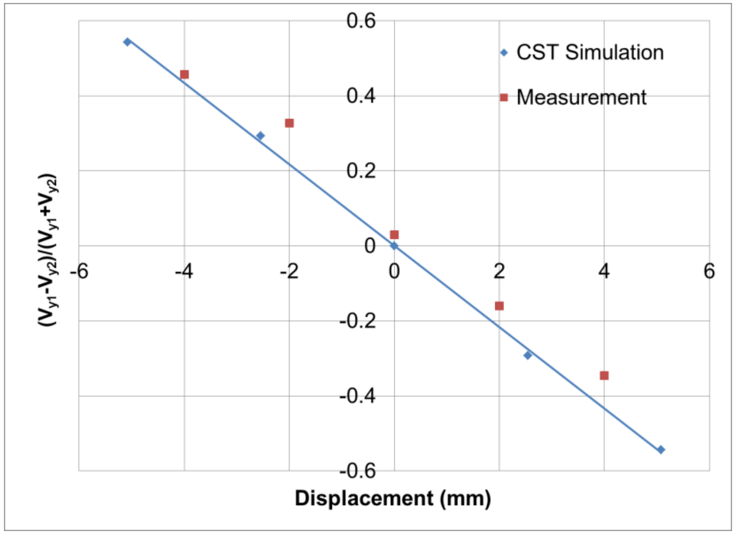
BPM

BPM Electrode

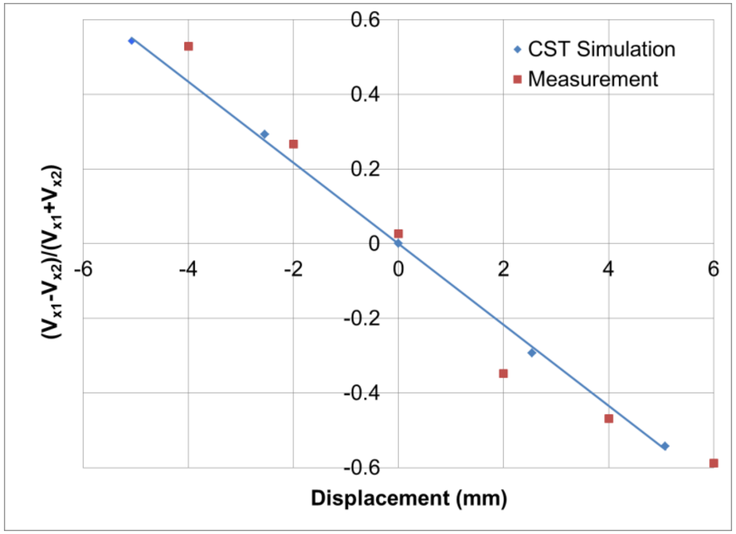
BPM Cross Section



Vertical Displacement Sensitivity



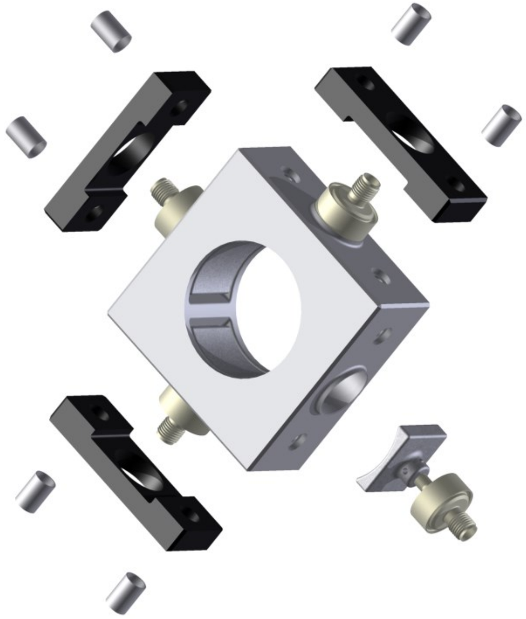
Horizontal Displacement Sensitivity



BPM Fabrication

- Typical BPM gaps are too small to enable SRF type cleaning. So we enlarged them.
- The BPM is fabricated from 304 SST and is made using sinker EDM, conventional milling, laser welding and electron beam welding.

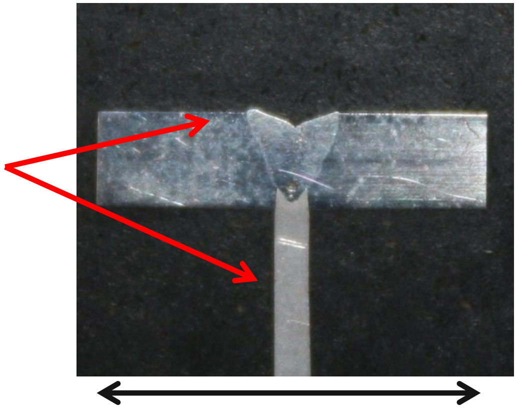
BPM Parts



BPM Parts Before Welding

Micrograph of EBW of Electrode

Center conductor 0.020” from this end before weld.



0.438”

Cavity & Solenoid Alignment

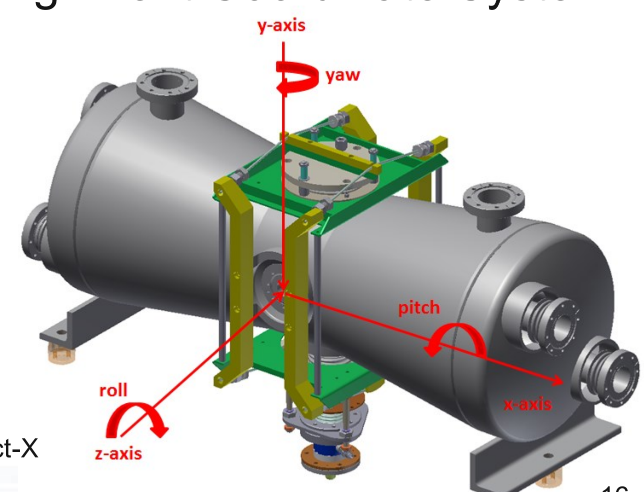
- We are using three point kinematic mounts to independently control the position of each component.
- We have experience with similar hardware.
- The hardware which bolts onto the cavities/solenoids is all commercially available.

Dimension	Intensity Upgrade Sol (Cav)	PXIE HWR
x (mm_{rms})	±0.12(±0.50)	±0.50(±0.50)
y (mm_{rms})	±0.19(±0.28)	±0.50(±0.50)
z (mm_{rms})	N.M.	±0.50(±0.50)
Pitch	$\pm 0.03^0$	$\pm 0.06^0(\pm 0.14^0)$
Yaw	$\pm 0.08^0$	$\pm 0.06^0(\pm 0.14^0)$
Roll	N.M.	$\pm 0.06^0(\pm 0.14^0)$

See S.H. Kim's presentation.

Alignment Hardware Examples

Alignment Coordinate System



Safety and Engineering Analyses

Analysis Overview

- Detailed engineering and safety analyses have been performed for the half-wave resonator Nb/SST structure and the cryomodule.
- Design considerations:
  - Preserve the cavity RF properties.
  - Comply with ANL and FNAL safety requirements.
  - Ensure manufacturability.
  - Substantiate performance:
    - Cavity: slow tuner range, df/dP, no structural failure.
    - Cryomodule: validate alignment plan, cryogenic efficiency, structural integrity.
- All ANSYS Multiphysics modeling and analyses done by R. Fischer (ANL-NE).
- Design/drafting done by G. Cherry (ANL-NE).

Safety Analyses

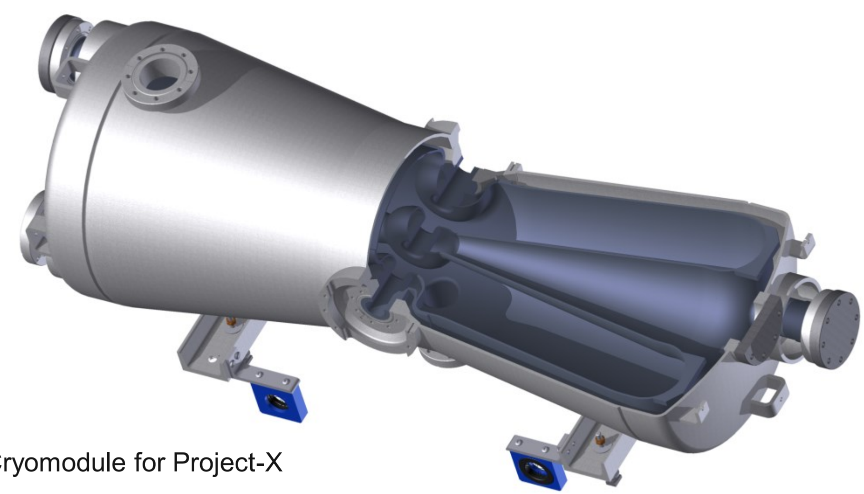
- The safety analyses for the HWR and the cryomodule simply follow the ASME BPVC (2010, Sec. VIII, Div. 2 Part 5) to ensure the design is:
  - Protected against plastic collapse (5.2).
  - Protected against local failure (5.3).
  - Protected against buckling (5.4).
  - Protected against failure due to cyclic loading (5.5).
    - Fatigue failure (Not required due to small number of loading cycles, < a few hundred, 5.5.2.3).
    - Ratcheting failure (5.5.6).
- The HWR safety analysis, reviewed on 17 May 2012 = passed.
- The cryomodule safety analysis, reviewed on 16 May 2013 = passed.

HWR162 Requirements

- Requirements set by FNAL cryogenic system.
  - The cavity cooling circuit will be supplied with 2 Bar helium gas for cooldown.
  - In the event of a cryogenic system failure when @ 2 K the pressure would rise to 4 Bar.
  - Pressure reliefs, not presented here, will be in the system to ensure these conditions are met.
- The modeling constraints were chosen to mimic:
  - The appurtenance loading in the cryomodule.
  - The fabrication tolerances we expect.
  - Slow tuner action (10 kN & -260 kHz).
- The model represents the worst case for loading.

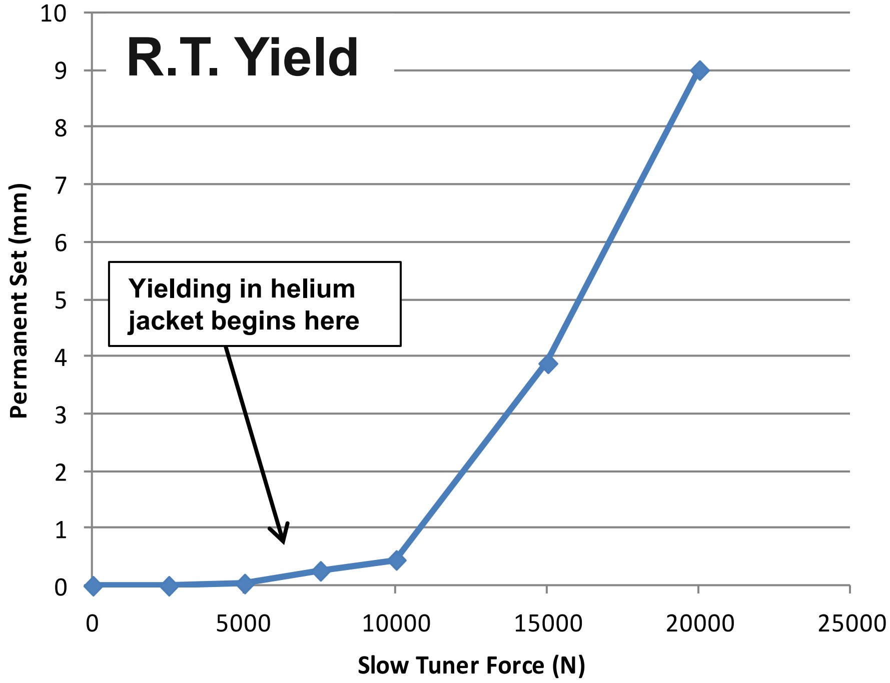
Parameter	Value
$T_{operation}$	2 K – 293 K
MAWP	2 Bar (@ 293 K) 4 Bar (@ 2 K)

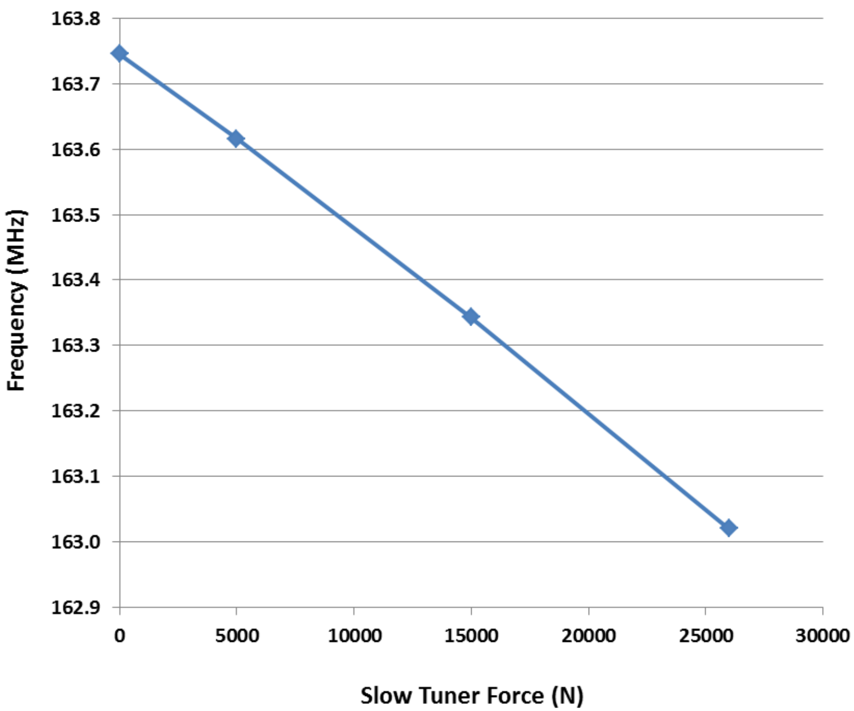
Cavity Type	HWR
Freq. (MHz)	162.5
β	0.11
l_{eff} (cm, $\beta\lambda$)	20.7
Operating Voltage (MV)	1.5/2.0
E_{pk}/E_{acc}	4.6
B_{pk}/E_{acc} (mT/(MV/m))	5.4
QR_s (Ω)	48
R_{sh}/Q (Ω)	262
df/dP (Hz/mbar)	+6
Slow Tuner Sensitivity (kHz/kN)	-26
# of Cavities Required	8

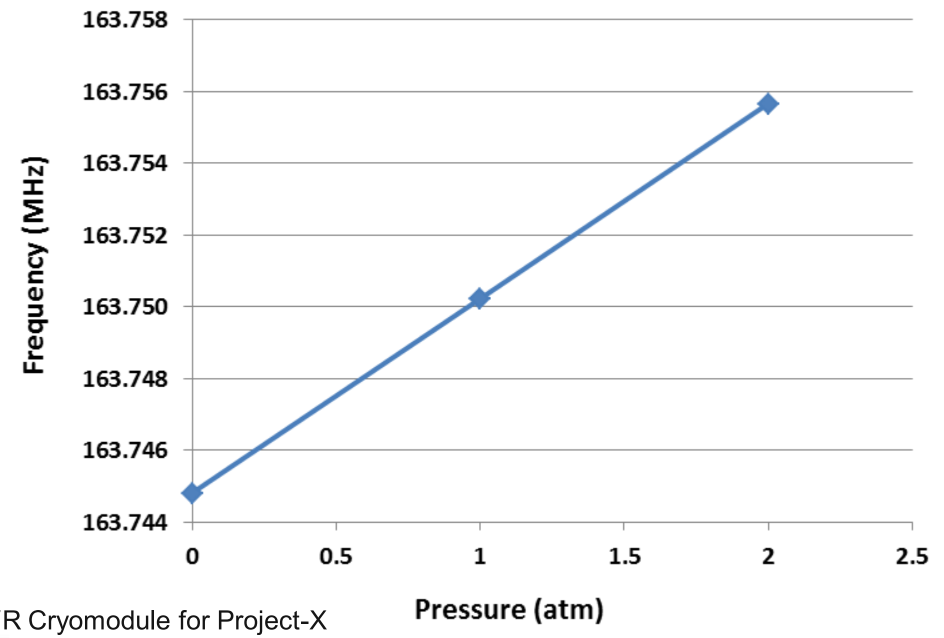


HWR df/dP and Slow Tuner

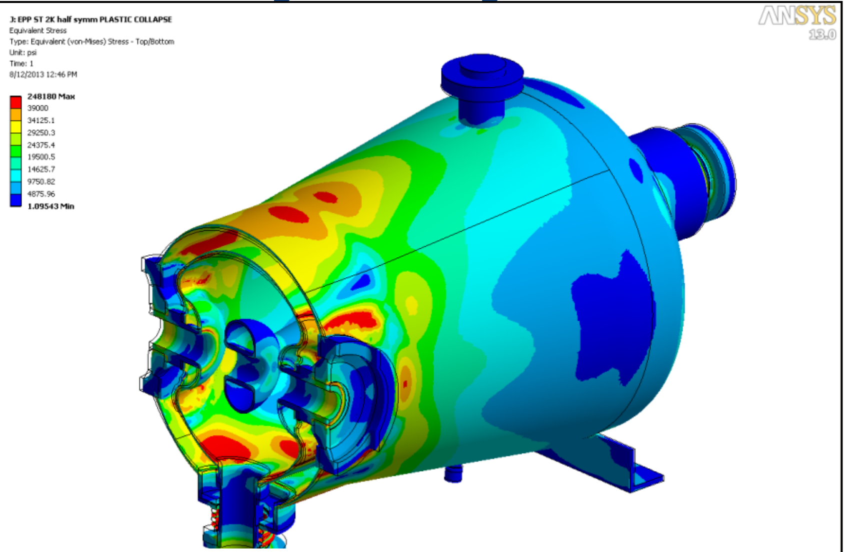
- Nb thickness = 0.125”.
- SST jacket Thickness = 0.125”.
- To avoid plastic deformation at R.T. the slow tuner range needs to be limited to 5 kN or 130 kHz.



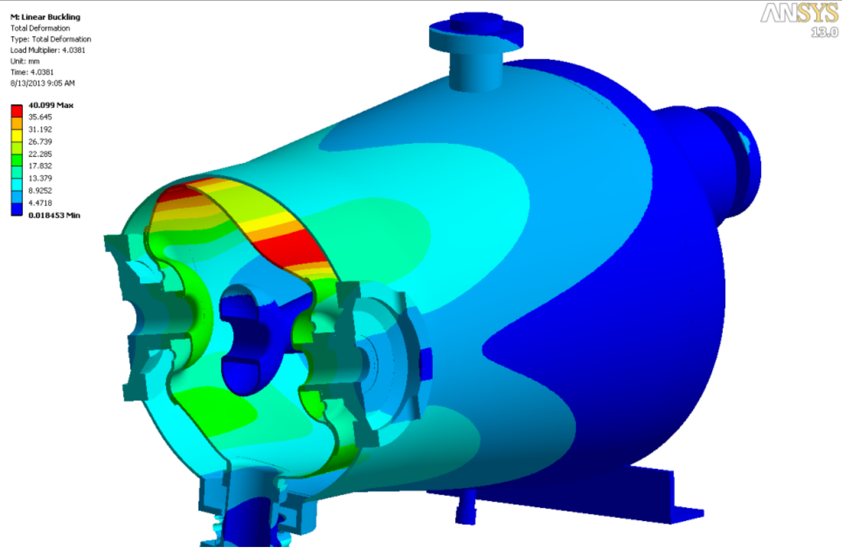




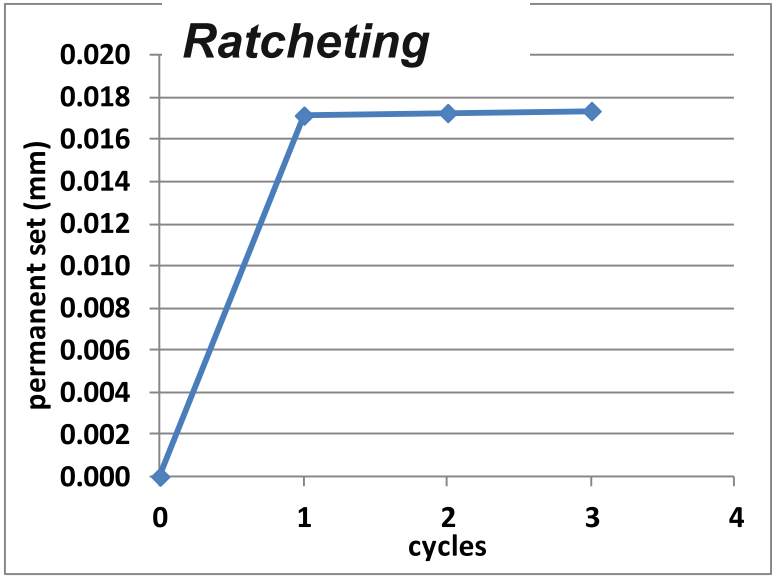
HWR: Safety Analyses

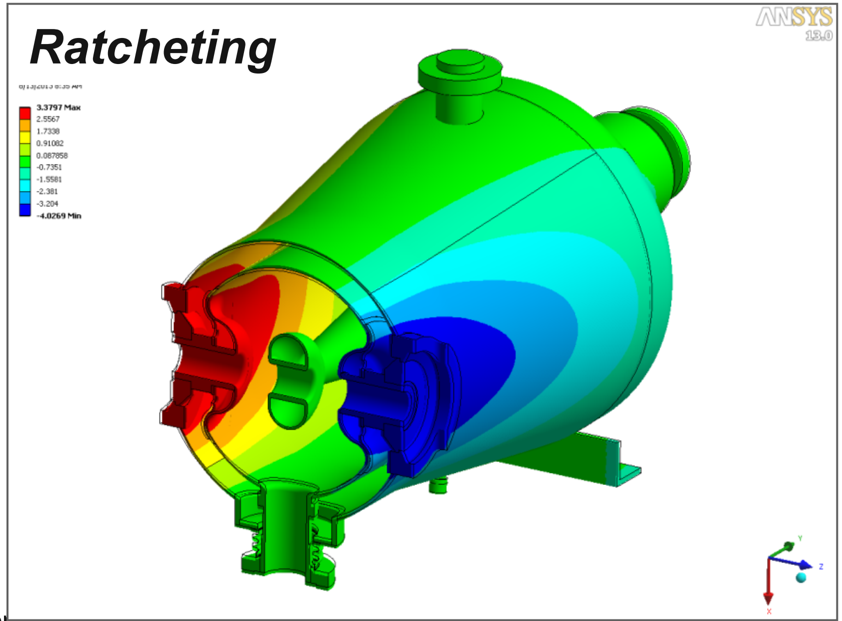


Material stress:& Passes Analysis



Buckling Load Factor = 4.06 (> 2.5)



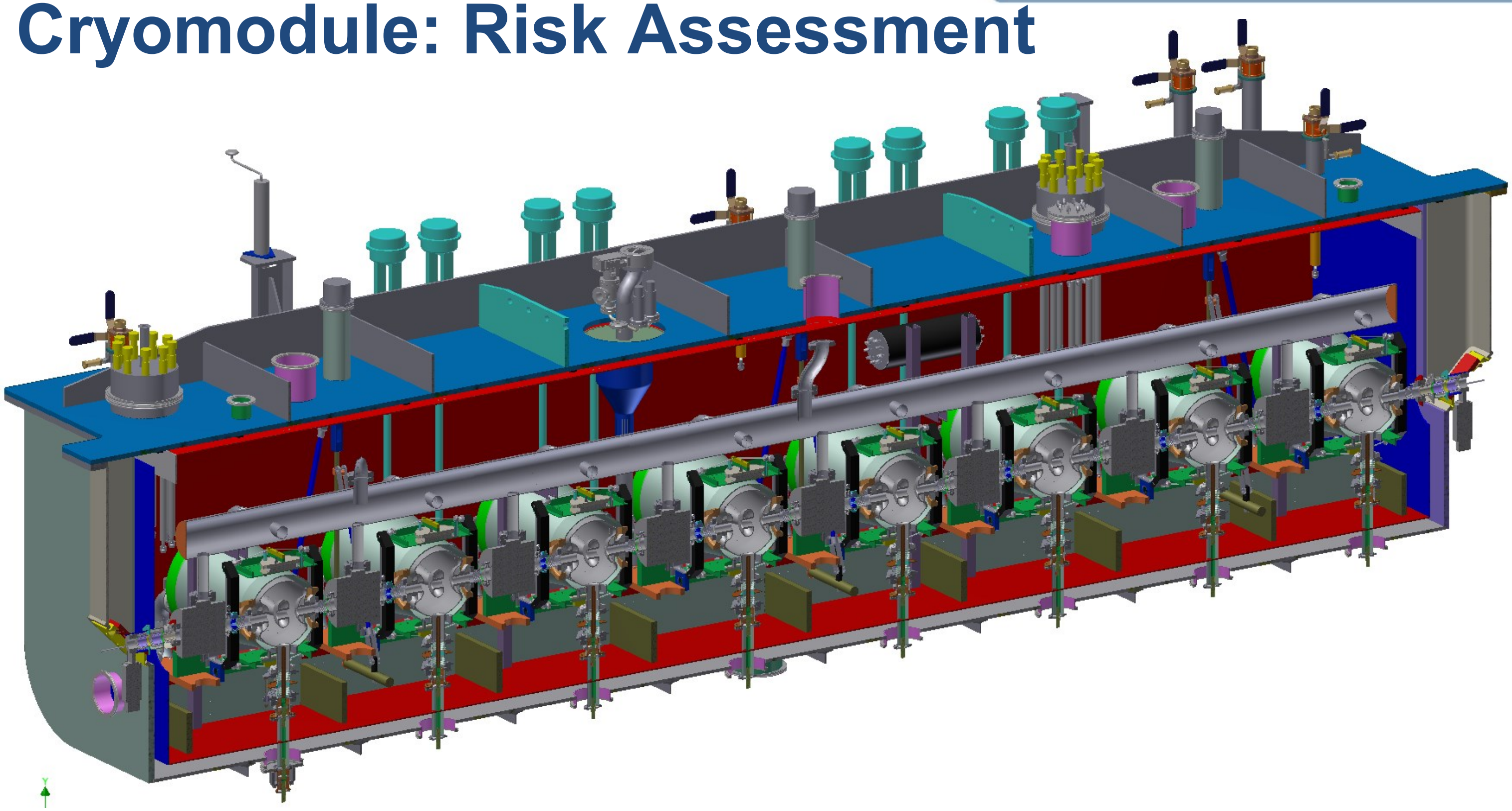


Cryomodule Vacuum Vessel

Operating Conditions

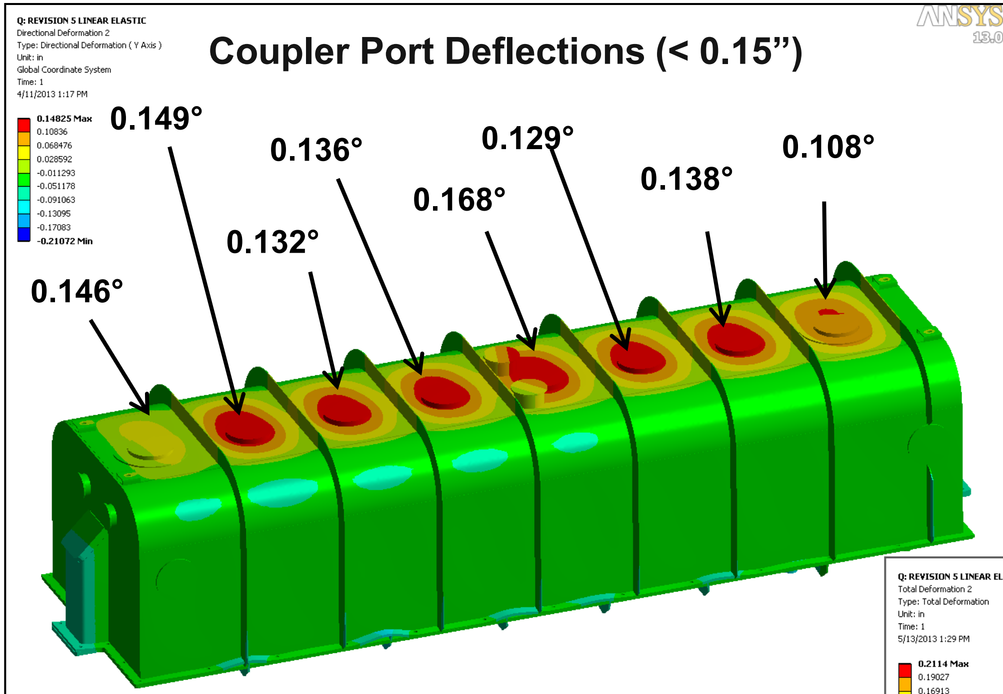
- There is only one operating condition for the cryomodule.
  - The cryomodule interior is evacuated to < 1e-6 bar.
  - The load hanging from the lid is 8,000 lbs.
  - The entire assembly is supported in a kinematic mount.
- At various operating times the helium system will have liquid helium.
  - A failure may occur which would result in rapid helium boil-off.
  - The entire helium system is treated as a pressure system with its own independent reliefs.
- The vessel has been analyzed using the ASME Boiler and Pressure Vessel Code (BPVC) Section VIII, Division 2, Part 5.
  - We have verified that relief requirements satisfying UG-125 of Div 1 exist for operation.
- To satisfy all of this the FEA analysis certifies that the vacuum vessel has a MAWP of 15 psiv (vacuum) and I certify that redundant safety pressure relief devices will be installed to limit the internal pressure to < 10% above atmosphere.

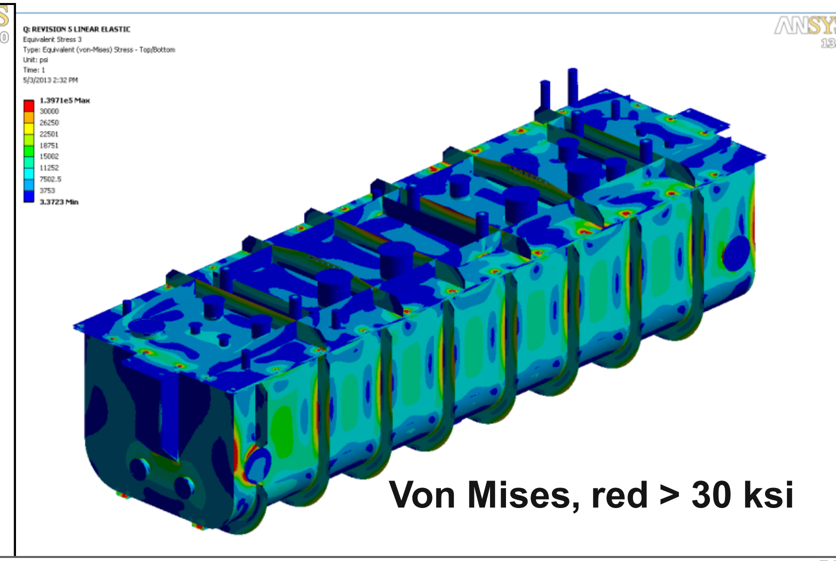
HWR Cryomodule: Risk Assessment

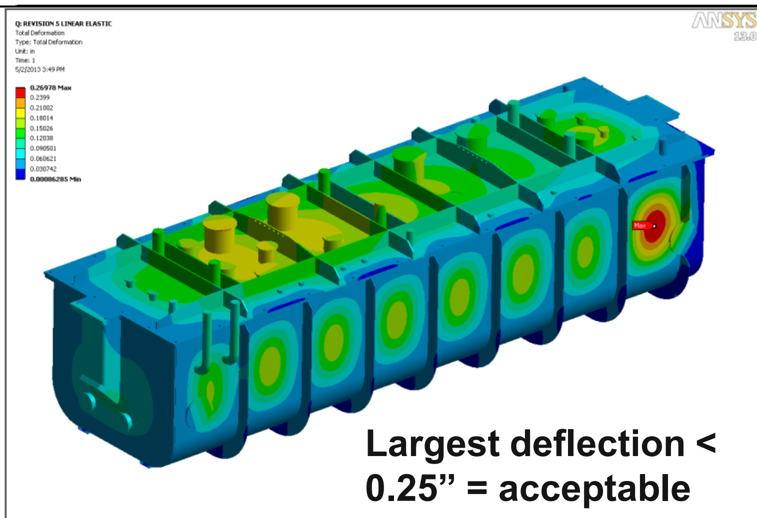


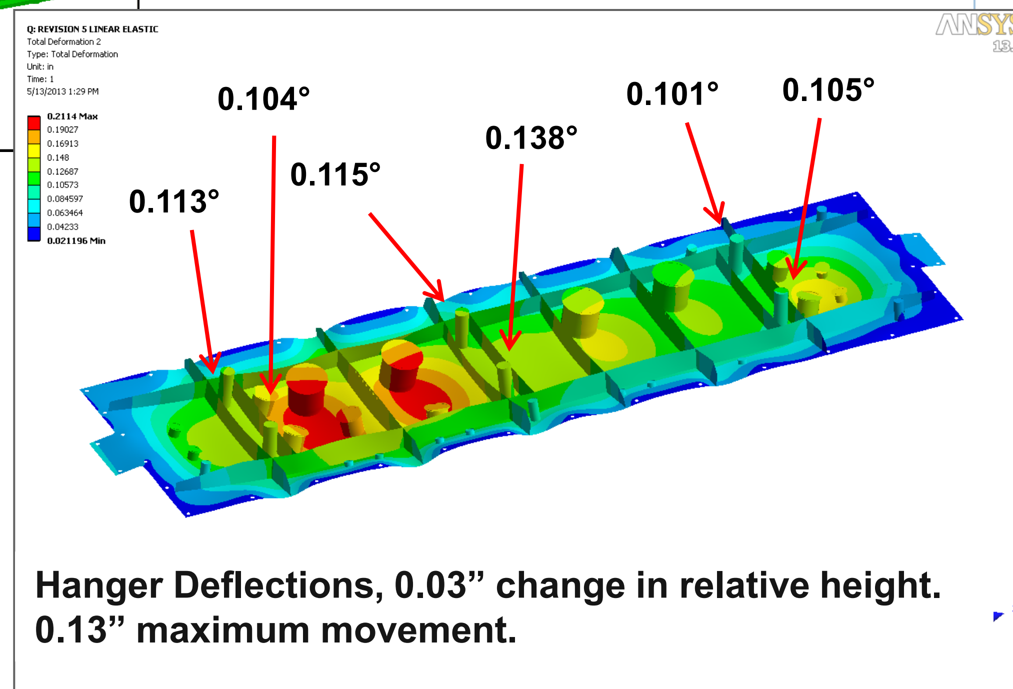
- What are credible failure modes of this device?
  - Superfluid helium leak to insulating vacuum.
    - Protection = redundant engineering controls to limit pressurization to less than 10% above atmosphere.
    - Superfluid goes away after very little warming.
  - A He line breaks
    - Protection = redundant engineering controls to limit pressurization to less than 10% above atmosphere.

HWR Cryomodule: Deformation/Plastic Collapse



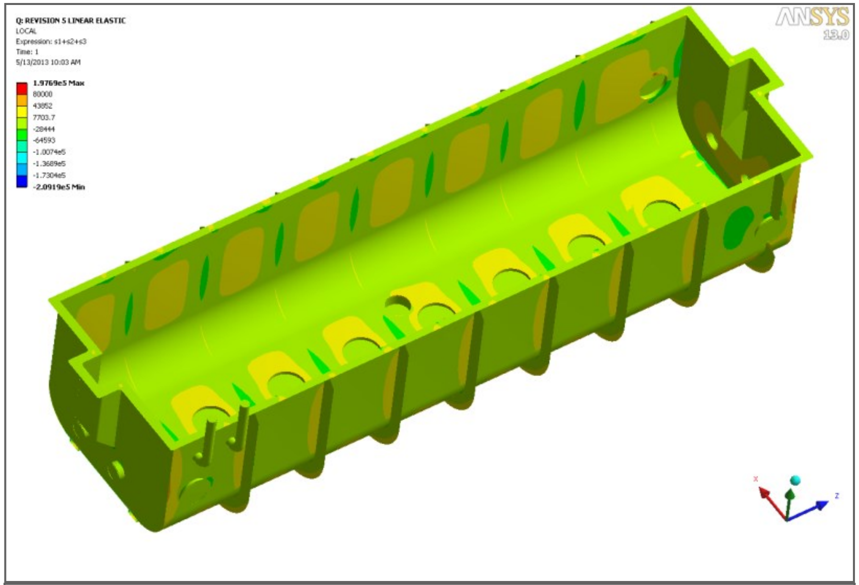


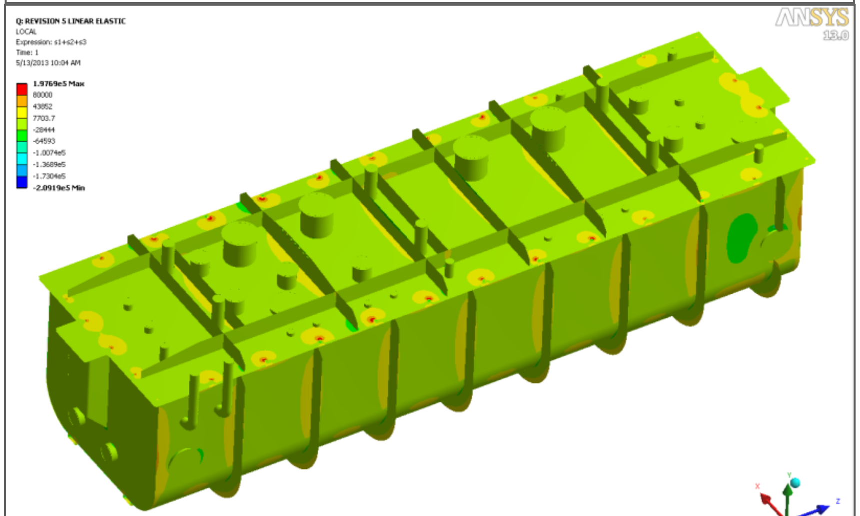




HWR Cryomodule: Local Failure and Ratcheting

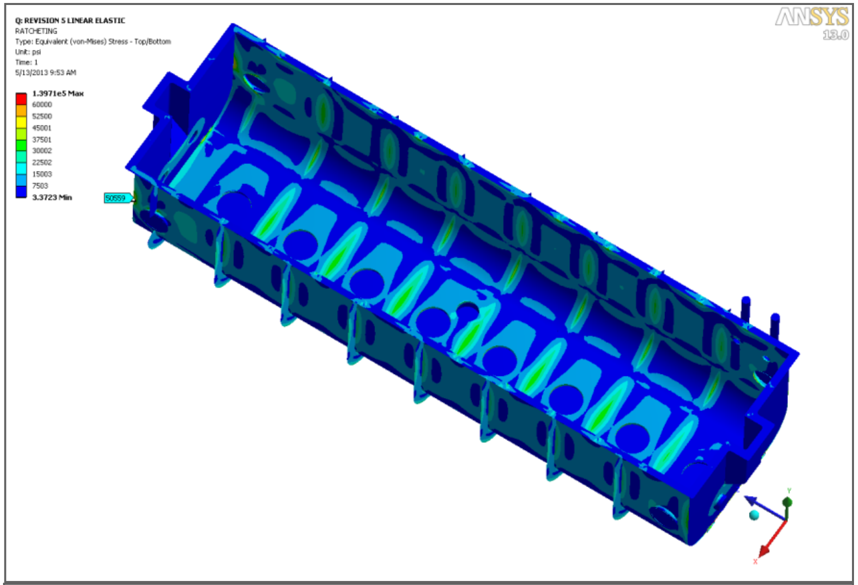
Local Failure

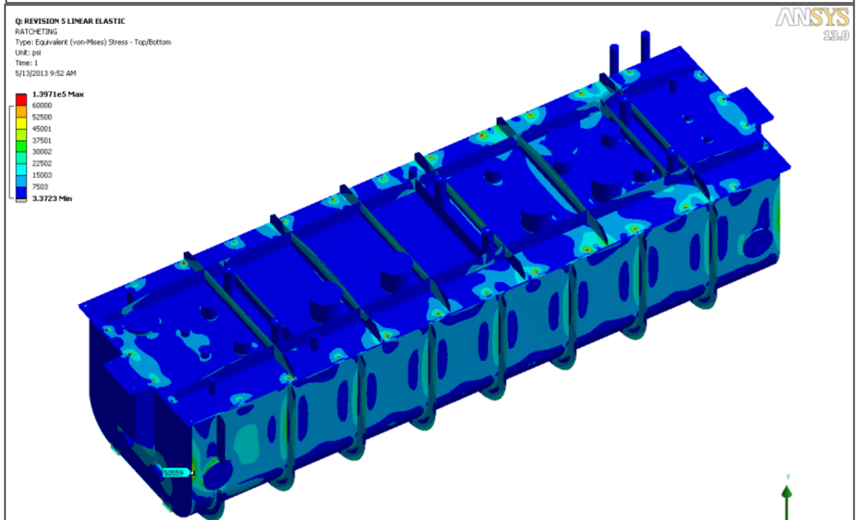




S1+S2+S3 < 4S = 80 ksi (red > 4S)

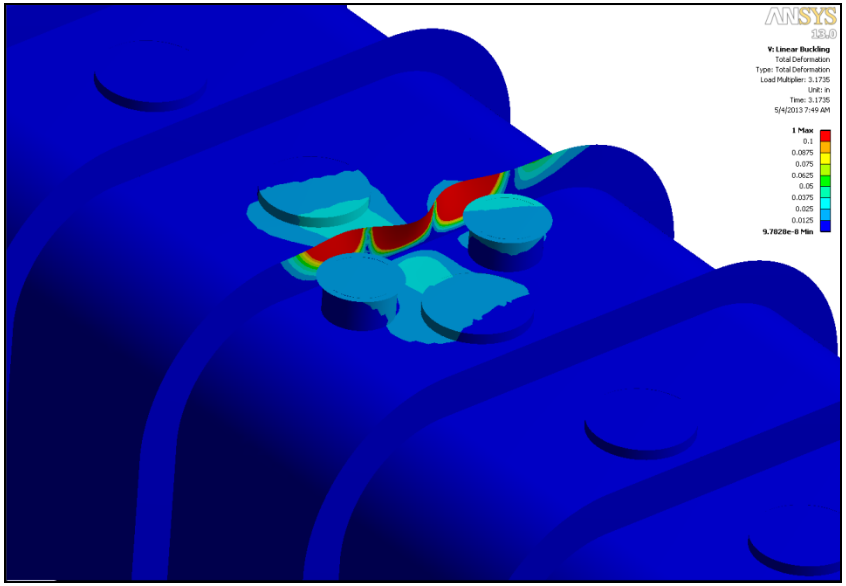
Ratcheting



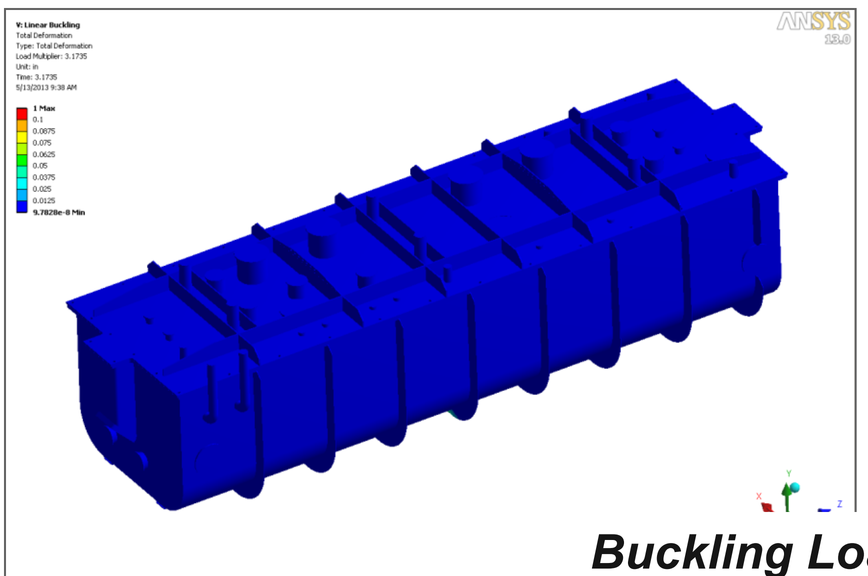


red > 3S = 2Sy = 60 ksi

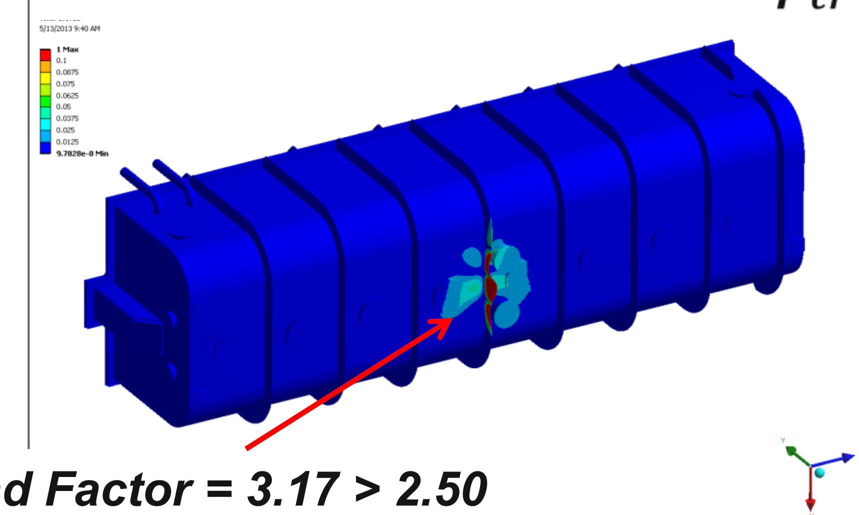
HWR Cryomodule: Buckling



- The lowest load factor buckling mode found was 3.17.
- This is larger than the minimum required value of 2.50.
- This completes this analysis.



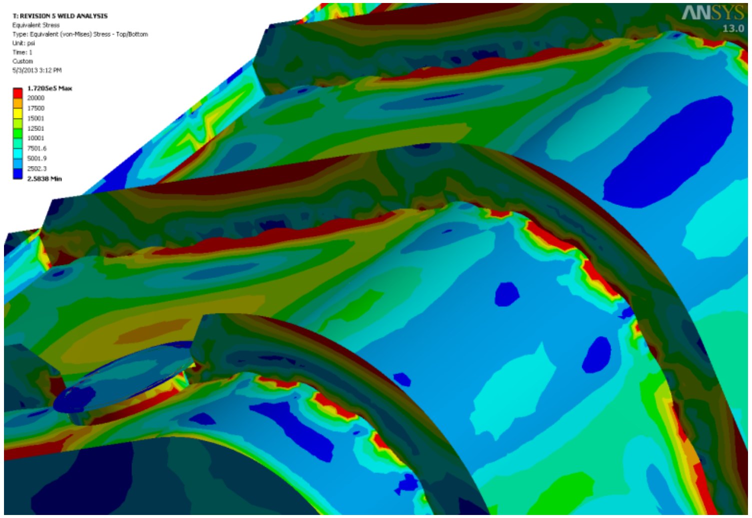
$$\textit{Buckling Load Factor} = \Phi_B = \frac{2}{\beta_{cr}}$$



Buckling Load Factor = 3.17 > 2.50

HWR Cryomodule: Select Analyses

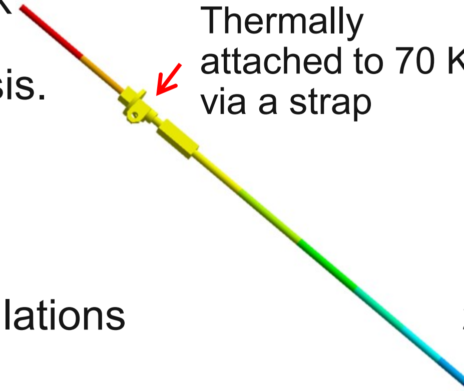
Stress at Welds

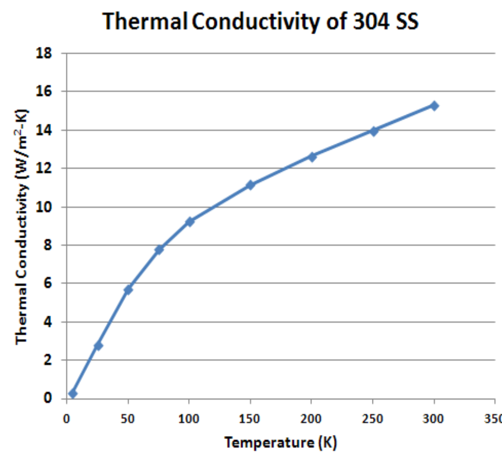


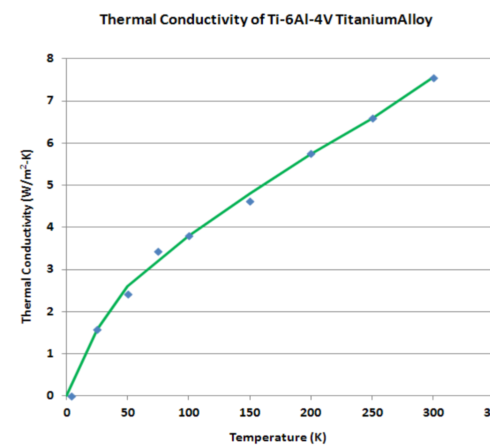
Weld analyses.

- The cryomodule welds are all over engineered.
- Design is good for static loads and lifting.

- Hanger Thermal analysis.
  - 70 K = 0.75 W.
  - 2 K = 0.050 W.
- No 5 K intercept.
- Agrees with hand calculations

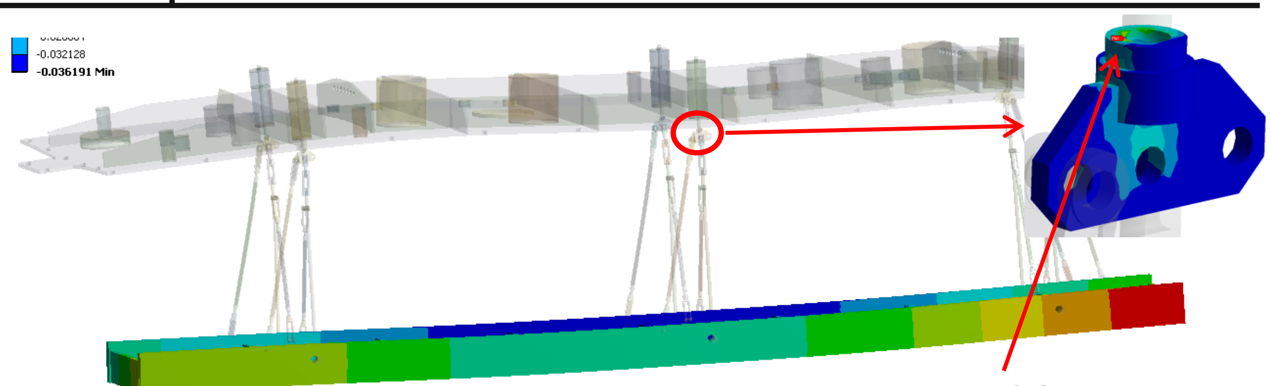






Lifting analysis.

- 0.007” beam-port deflection range when not supported by box.
- All hangers have factors of safety of 10 for the estimated loads.



10 ksi = max SST stress

Summary

- The cryomodule design is very mature and we are ready to start fabrication, especially for the long lead time items:
  - Cryomodule vacuum vessel.
  - Cryomodule lid.
  - Ti strong back.
  - Vacuum/cryogenic manifolds.
  - Etc.
- The designs satisfy all applicable safety requirements: ANL & FNAL and have been reviewed.
- More on the interfaces later today.
  - Cryogenic loads.
  - Cryogenic connections.
  - LHe reliefs.
  - Instrumentation.
  - Solenoid conduction cooled leads.