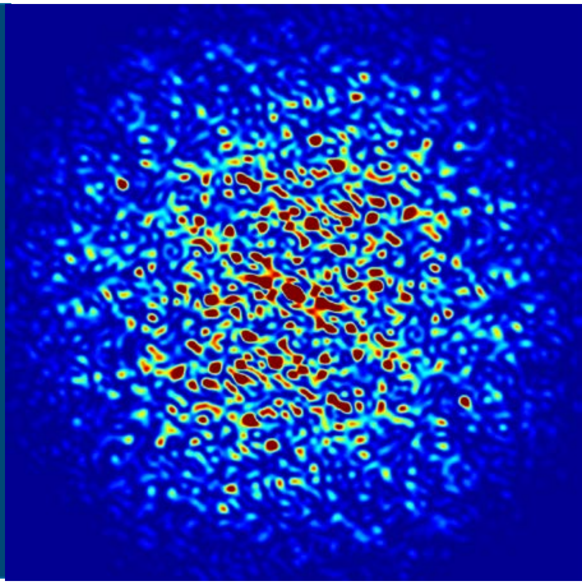
Cryostat Design for the APS-U SCUs



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ASD Seminar October 3, 2018

Abstract

- The APS Upgrade will include eight new planar SCU sources and will re-use one existing planar SCU source.
- New SCUs are packaged into four 4.8-m long cryostats (2 SCUs each).
- A new cryostat based on the HSCU is being developed to meet the cryogenic and mechanical requirements and fit the available space.
- Lessons learned from the first-article cryostat will be applied to the remaining three units.
- I will describe the evolution/status of the new cryostat design, highlighting aspects of the chamber, cryogenic cooling, magnet support/alignment, and vacuum vessel systems – all driven by APS-U requirements.
- I will discuss the maturation of SCU activities and processes as part of the APS Upgrade.

SCU scope for the APS Upgrade

- The APS Upgrade includes four full-ID-length SCUs, each with two 1.8-m planar SCU magnets. Two contain in-line sources and two contain canted sources.
- The Upgrade also re-uses one existing SCU.
- New SCU cryostats will be modeled on the HSCU 2nd-generation design.

Parameter	Value	Unit
Cryostat maximum length	4.5	m
Insertion device maximum length	1.8	m
Vertical magnetic gap	8.0	mm
ID chamber vertical aperture	6.3 +0.1/-0.3	mm
Vacuum chamber straightness in plane with small magnetic gap	+/- 50	μm
ID rms phase error for any operational current	~3	degree

Primary requirements

- ***The SCU cryostat supports the magnets and the beam vacuum chamber – both <u>physically</u> and <u>thermally</u>.***

  - Magnets:
    - Must meet alignment and position measurement tolerances.
    - Must be cooled to stable operating temperature (<4.5 K).
    - Must use self-contained, stand-alone refrigeration system.

  - Beam vacuum chamber:
    - Must meet alignment and position measurement tolerances.
    - Must reach UHV and be thermally isolated from the magnets.

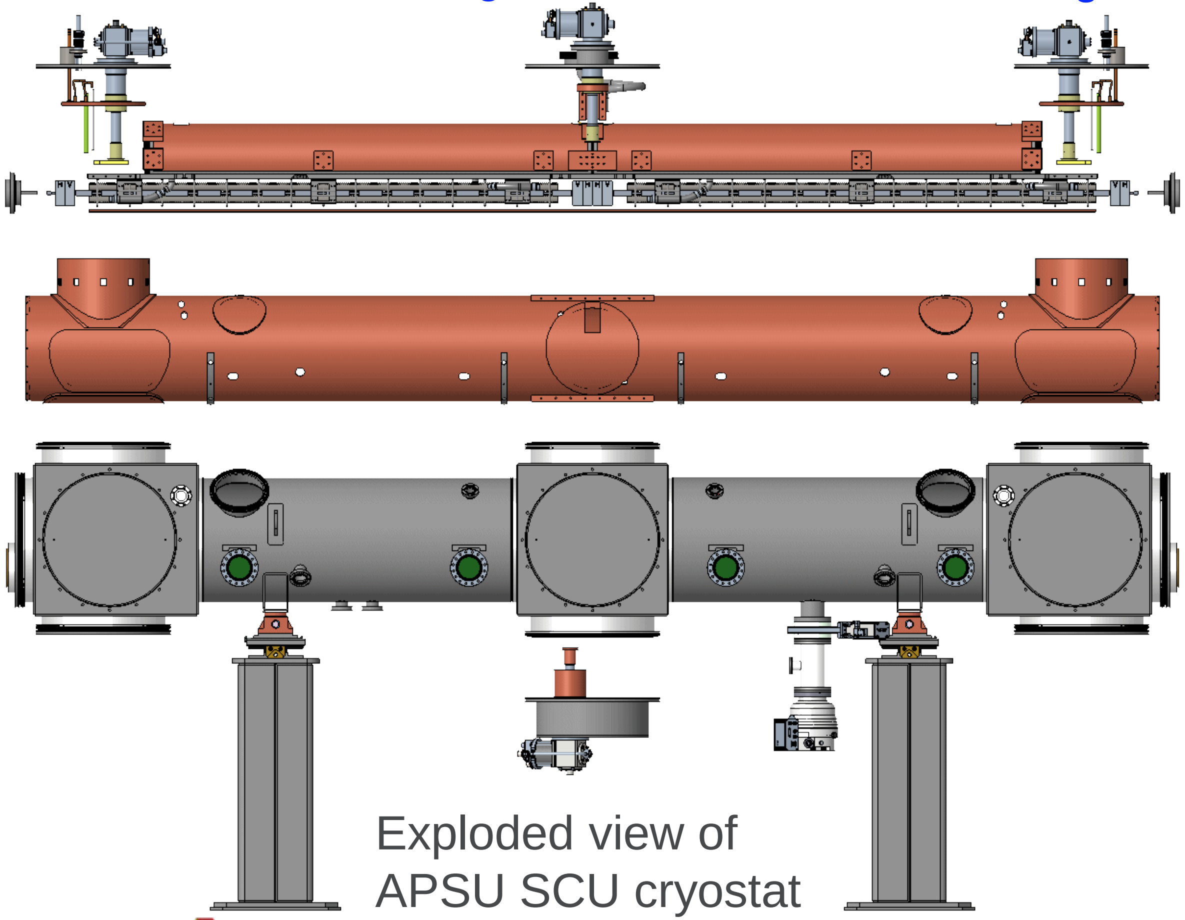
Secondary requirements

- Thermal:
  - Cryocooler-based refrigeration system (capacity limits).
  - Appropriate heat load management:
    - Minimize magnet load by intercepting beam-induced heat at elevated (but cryopump-effective) chamber temperature.
    - Minimize static heat load (cold mass support system).
  - Provide refrigeration storage for enhanced reliability (LHe).
  - Provide required quench response (< 1 hr recovery time).

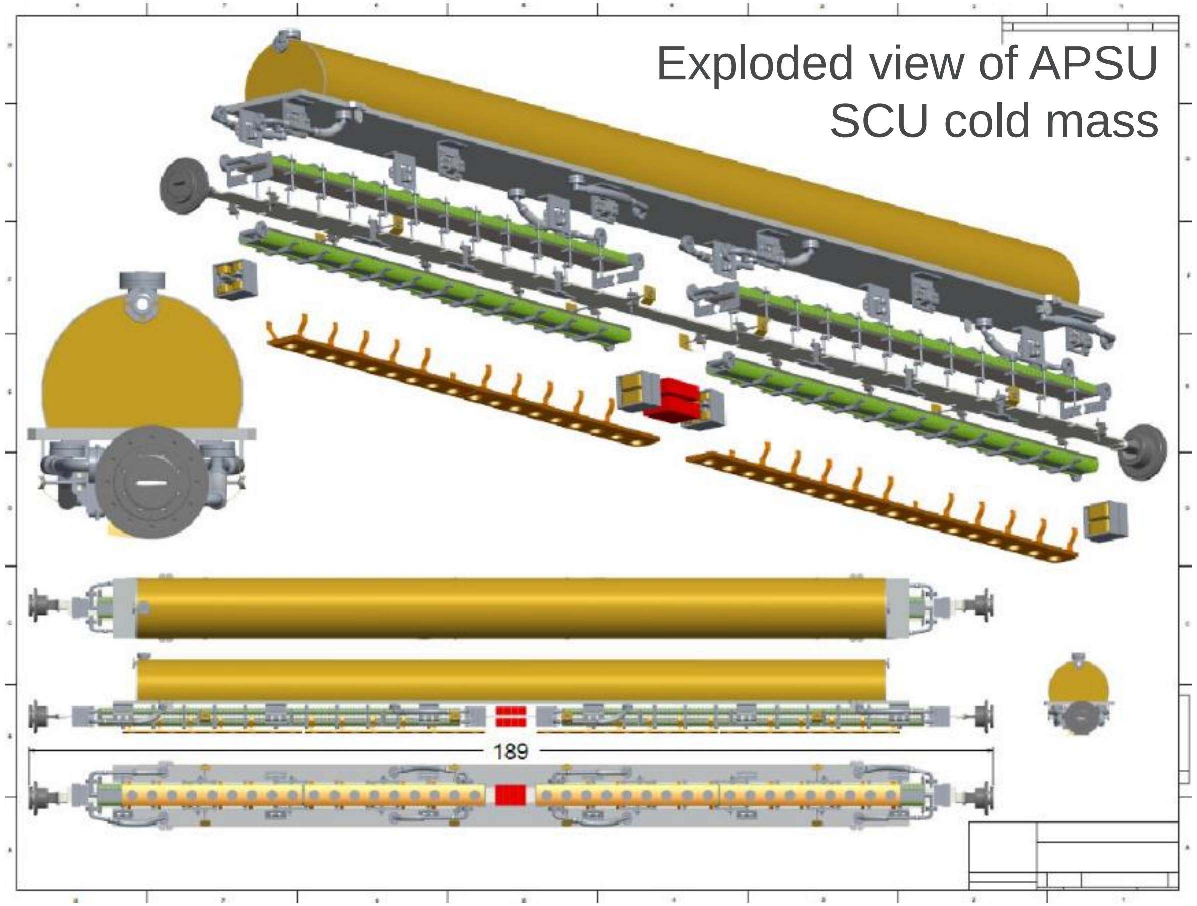
- Mechanical:
  - Alignment requires a rigid cold mass platform with a high-precision, externally adjustable support system.
  - Position measurement requires externally visible targets and an associated high-precision readout system.

SCU cryogenic engineering requirements

1. Support magnet operation:
    - Magnet support/alignment
    - Manage heat loads
    - Provide refrigeration
2. Ensure ebeam transparency:
    - Chamber vacuum
    - Field correction
    - Alignment
3. Ensure safe operation:
    - Pressure system safety
    - Cryogenic system safety
    - Mechanical safety



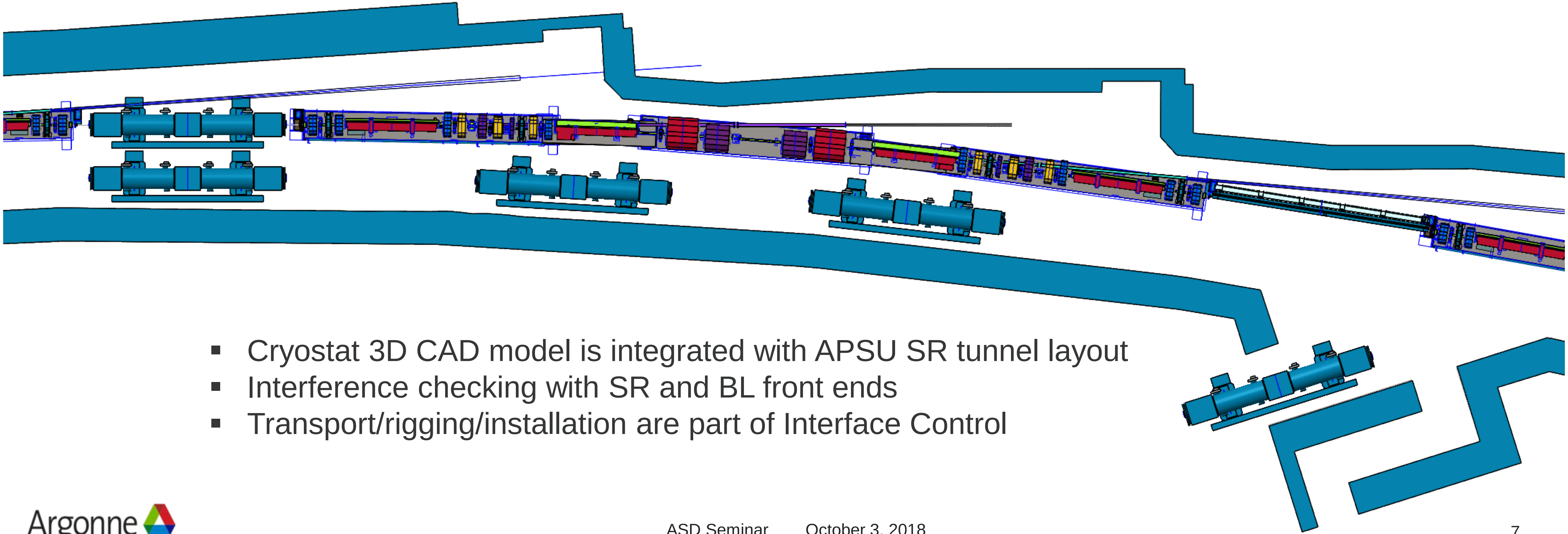
Exploded view of APSU SCU cryostat



Exploded view of APSU SCU cold mass

Cryostat integration with storage ring tunnel

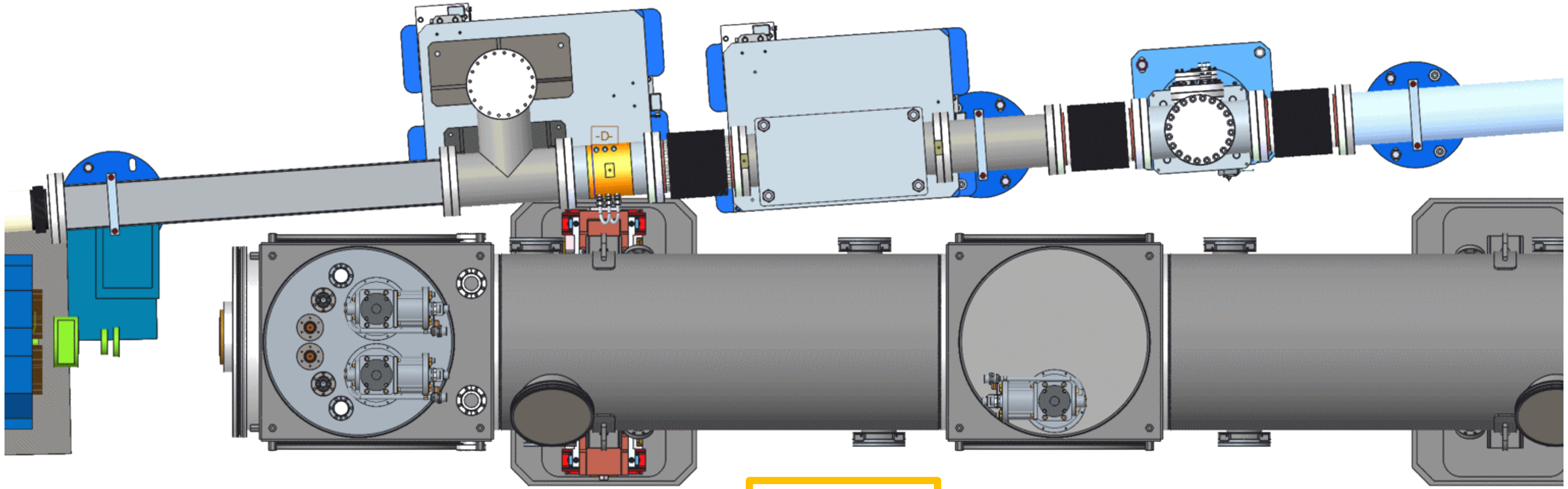
- ***Longitudinal (z):*** must fit within the Insertion Device (ID) straight.
- ***Transverse (x):*** must clear the x-ray BL front end and preserve tunnel aisle clearance.
- ***Vertical (y):*** must allow overhead clearance for cryocooler maintenance.



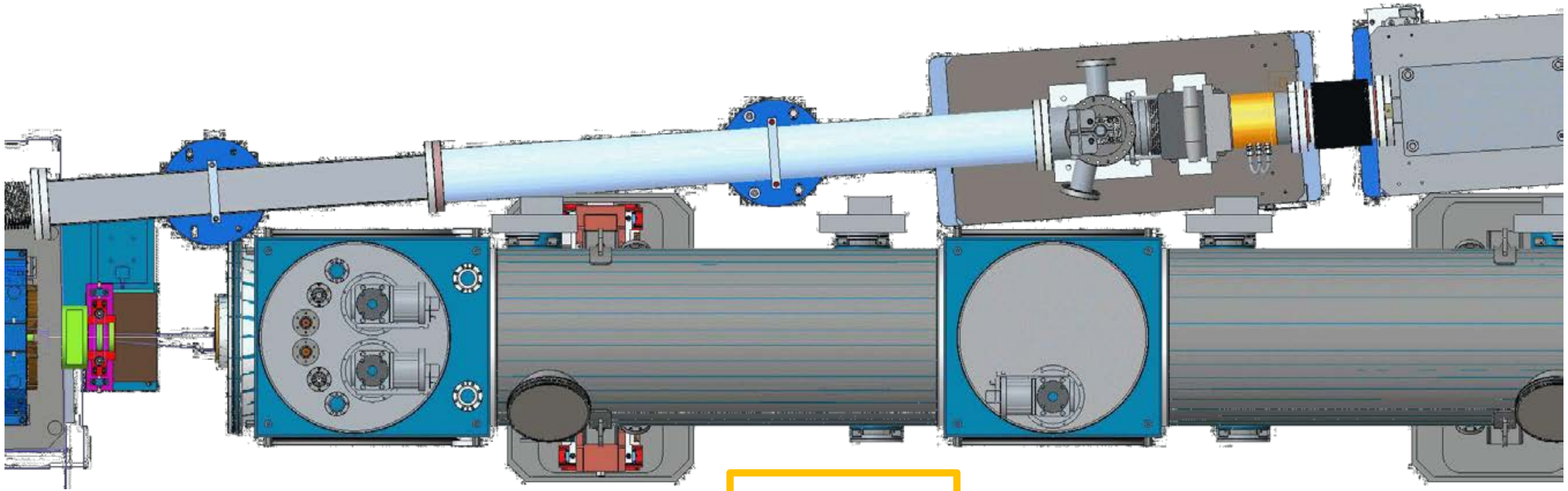
- Cryostat 3D CAD model is integrated with APSU SR tunnel layout
- Interference checking with SR and BL front ends
- Transport/rigging/installation are part of Interface Control

Integration with front end

- SCU model is integrated with front end model (a work in progress)
- At present no interference is detected
- SCU team collaborates with front end designers to avoid collisions.

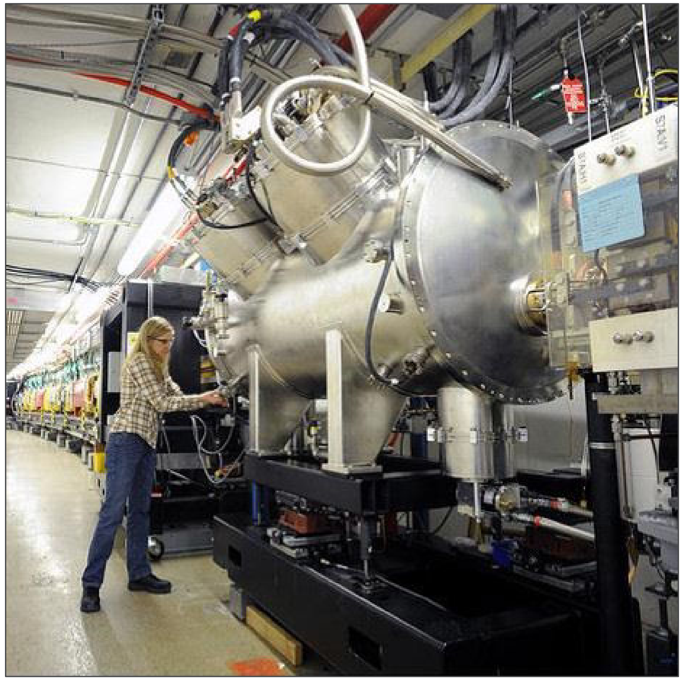


INITIAL

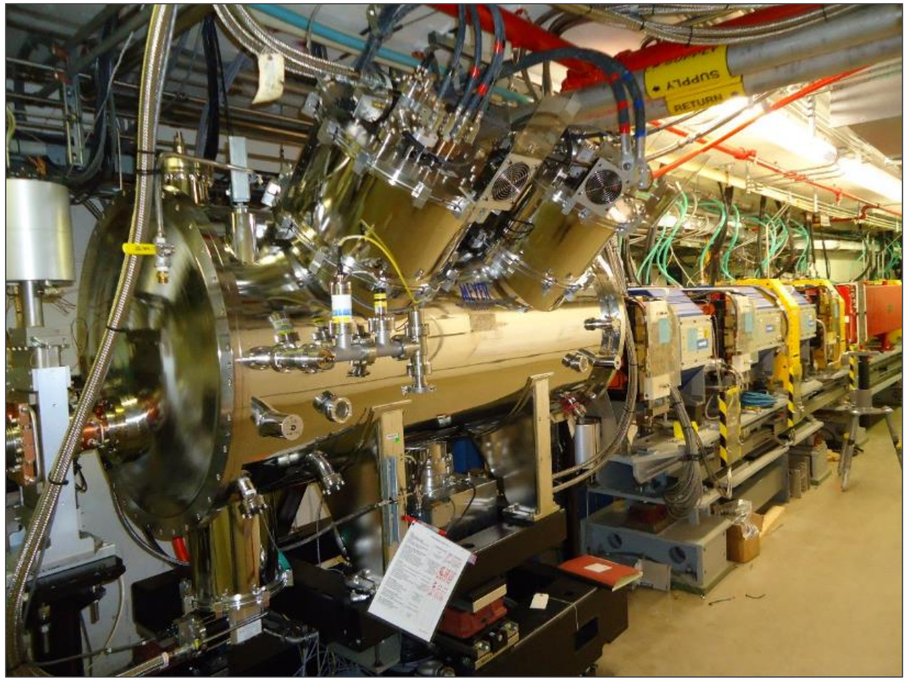


REVISED

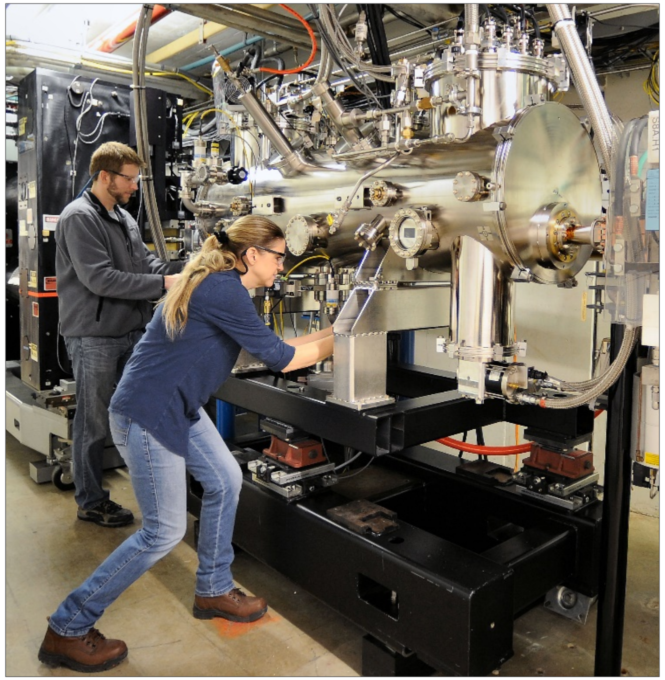
Evolution of SCU Cryogenic Design at APS



Sector 6



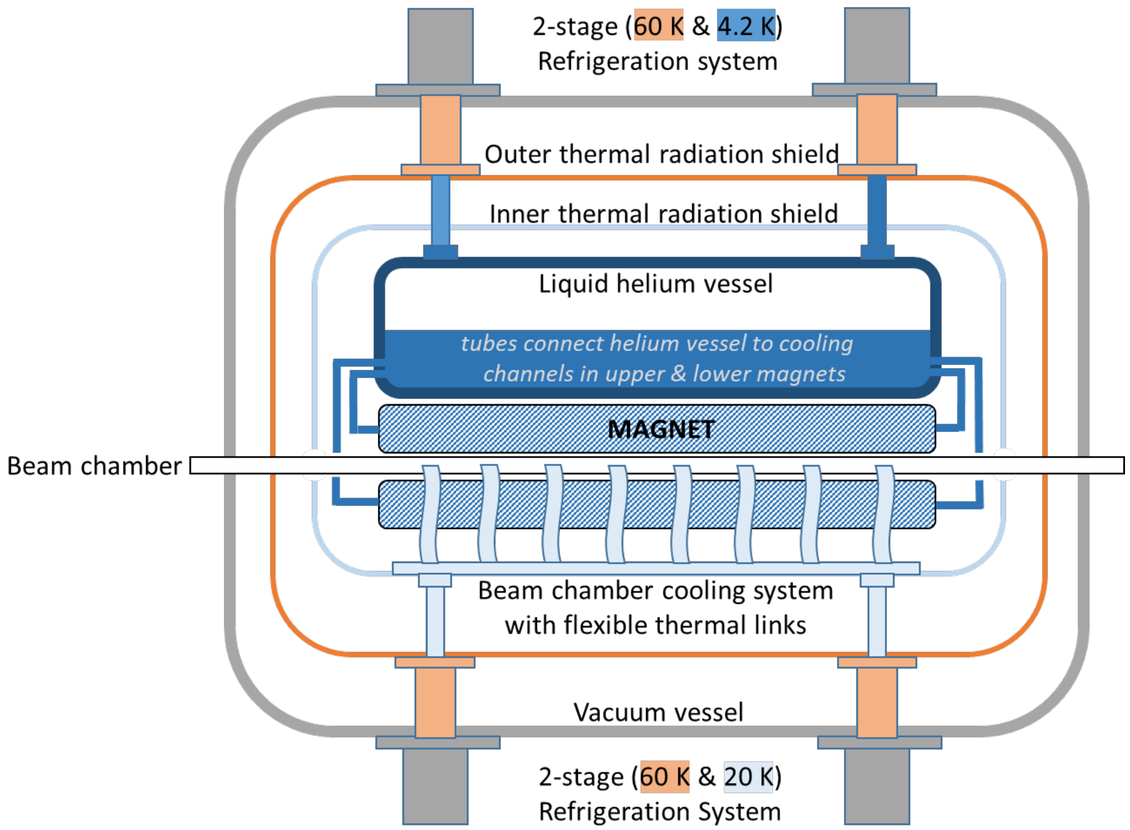
Sector 1



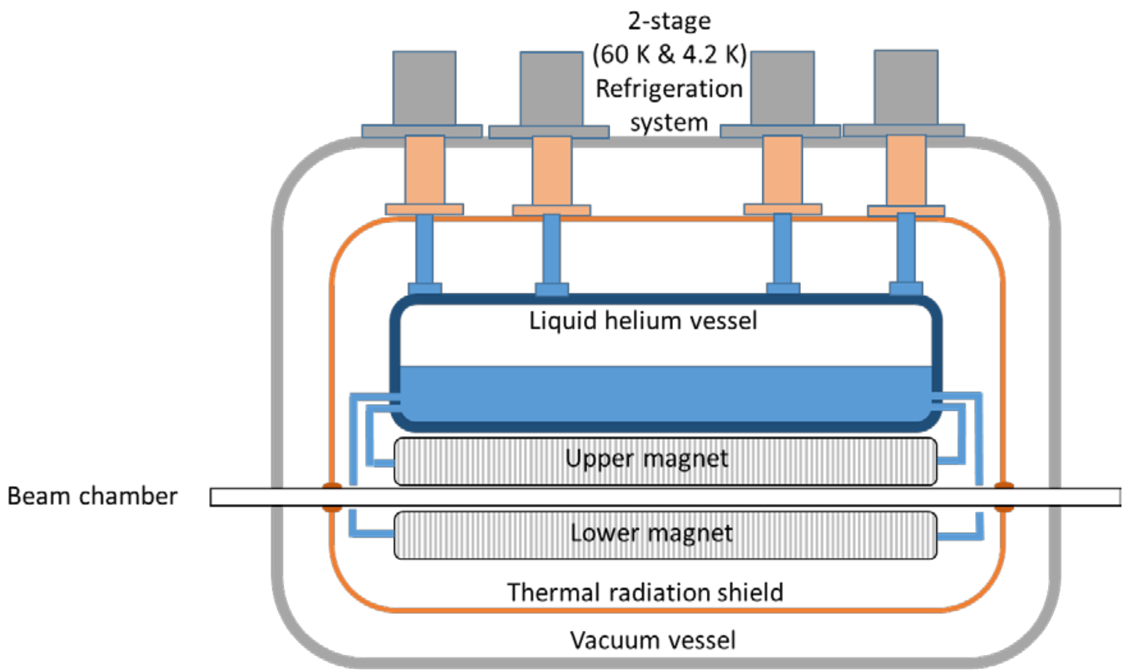
Sector 7

- 1^{st}-Generation cryostat designed by BINP (2009-2012) – two in operation
- 2^{nd}-Generation cryostat designed by APS – (2015-2017) – one in operation

SCU cryogenic system diagrams

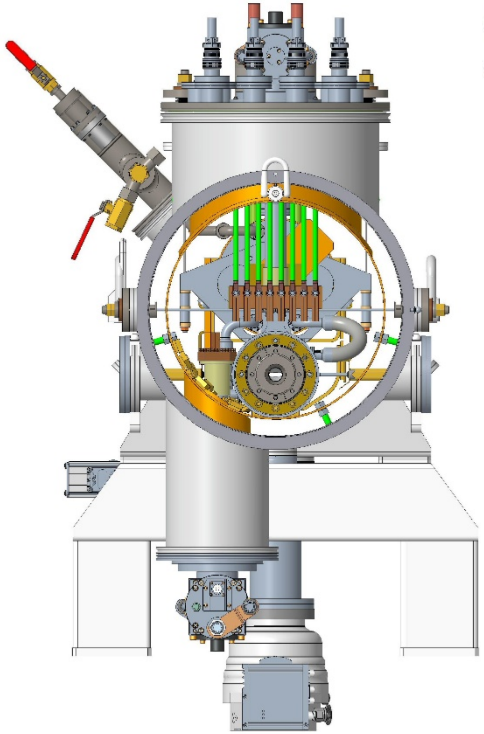


1st-Generation - BINP

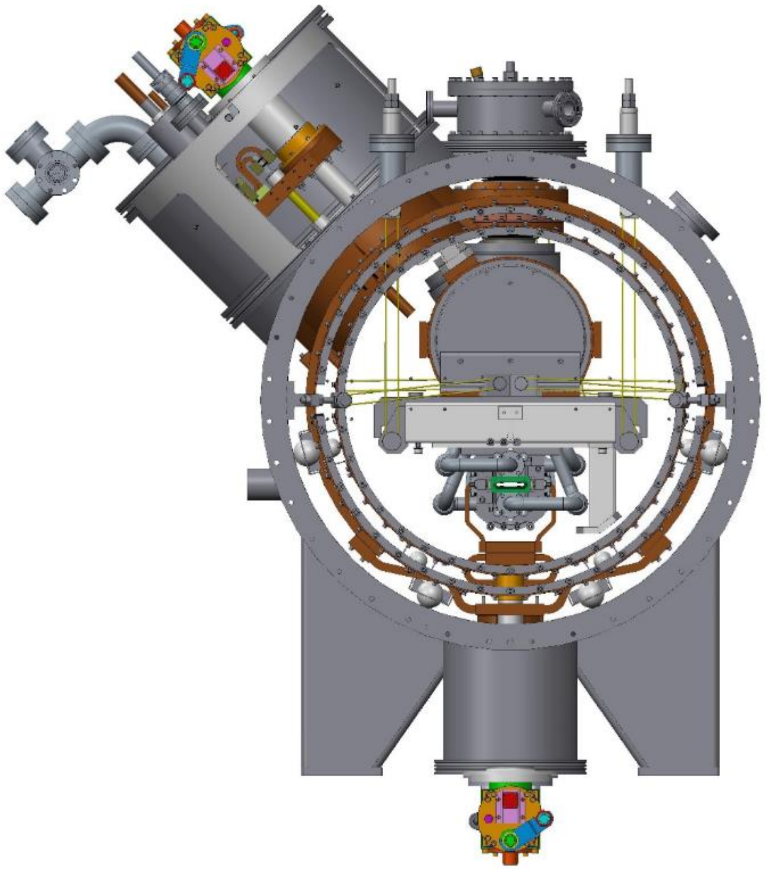


2nd-Generation - APS

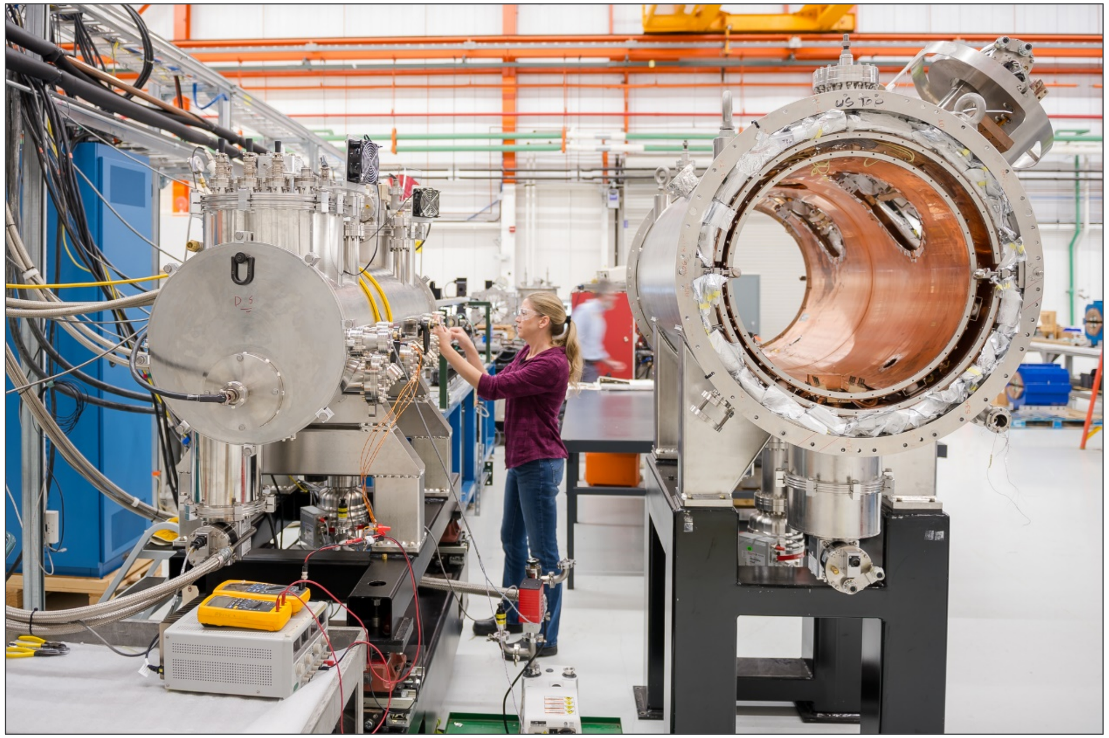
Cryostat design comparison



2^{nd}-Generation



1^{st}-Generation



- Design revisions include:
  - Single thermal shield
  - Re-configured cryocooler layout for improved 4.2 K cooling margin
  - Improved alignment capability
  - Value engineered for simplicity, ease of assembly & low cost

Cryostat heat load overview – thermal shield & chamber

APSU full-length SCU	Static [W]		With electron beam [W]		With beam and 450 A magnet current [W]	
	each	total	each	total	each	total
THERMAL SHIELD						
Beam chamber warm-cold transition:	2.9	5.8				
Main current Lead (300K to shield):	9.9	40				
Correction current leads (300K to shield):	4	24				
Joule heat through main current lead:					4.7	19
Joule heat through correction/phase shifter current leads:					0.78	12
Cold mass support vert (300K to shield):	0.50	2.0				
Cold mass support horiz (300K to shield):	0.83	3.3				
Thermal radiation from RT:		9.5				
LHe & relief piping (300K to 40K):	1.2	2.4				
Instrumentation:		0.25				
Total 1st stage load:		87		87		**118**
BEAM VACUUM CHAMBER						
Electron beam heating				7		7
Beam chamber warm-cold transition	0.40	0.80	0.30	0.60	0.35	0.70
Total <20 K load:						**7.7**

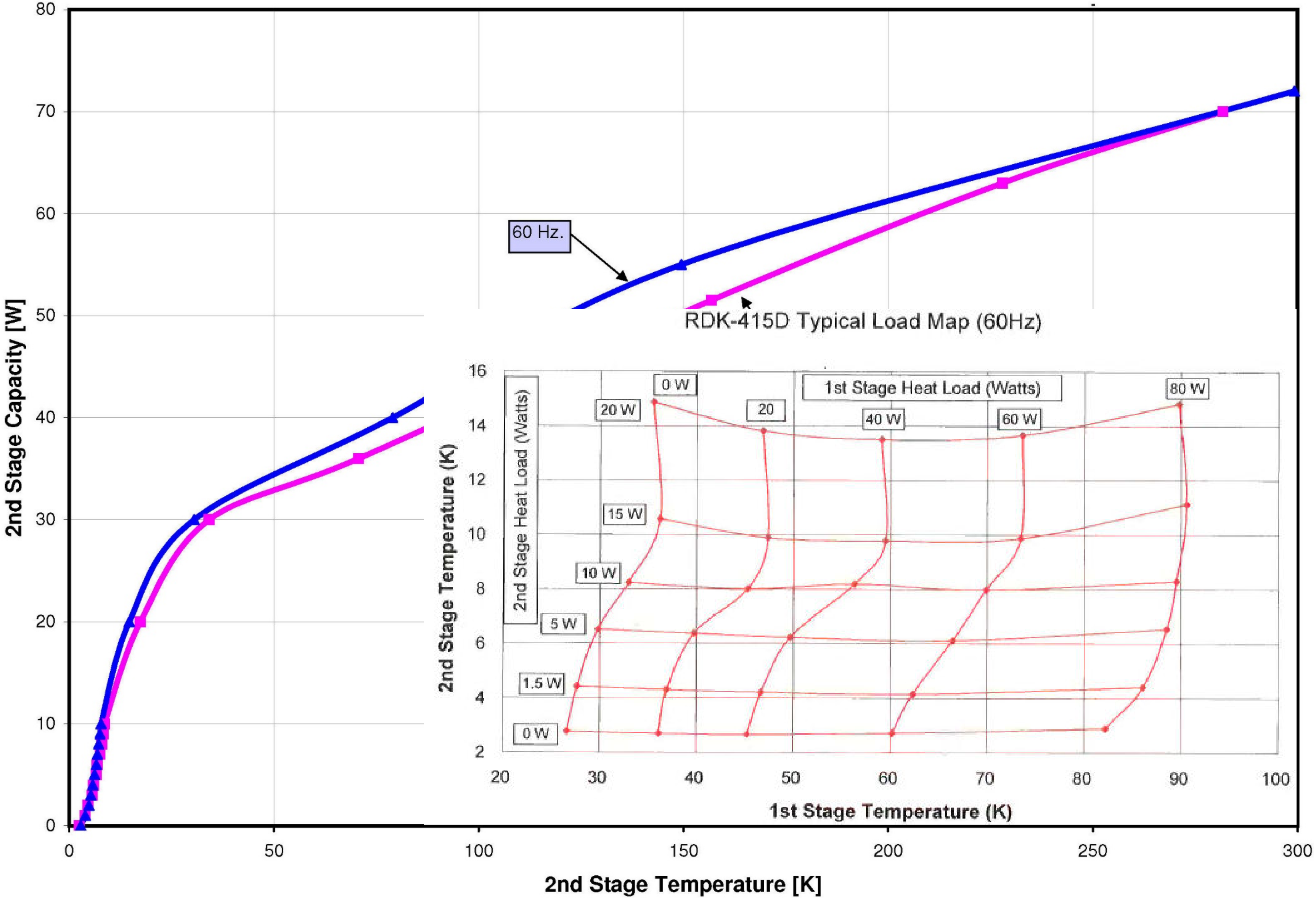
Cryostat heat load overview – 4.2 K cold mass

APSU full-length SCU	Static [W]		With electron beam [W]		With beam and 450 A magnet current [W]	
	each	total	each	total	each	total
Conduction HTS main lead pairs:	0.212	0.42				
Conduction HTS corr/phase shifter leads:	0.032	0.19				
Cold mass vertical support:	0.003	0.012				
Cold mass horizontal support:	0.004	0.018				
Thermal Radiation from shield:		0.054				0.016
Beam Chamber supports:		0.010		0.020		
Main current lead resistive joints:						0.21
Instrumentation:		0.02				
LHe & Relief Piping:	0.02	0.04				
Total 2nd stages load:		0.76		0.78		**1.0**

Refrigeration capacity – installed cooling power (1)

Cryocooler requirements:

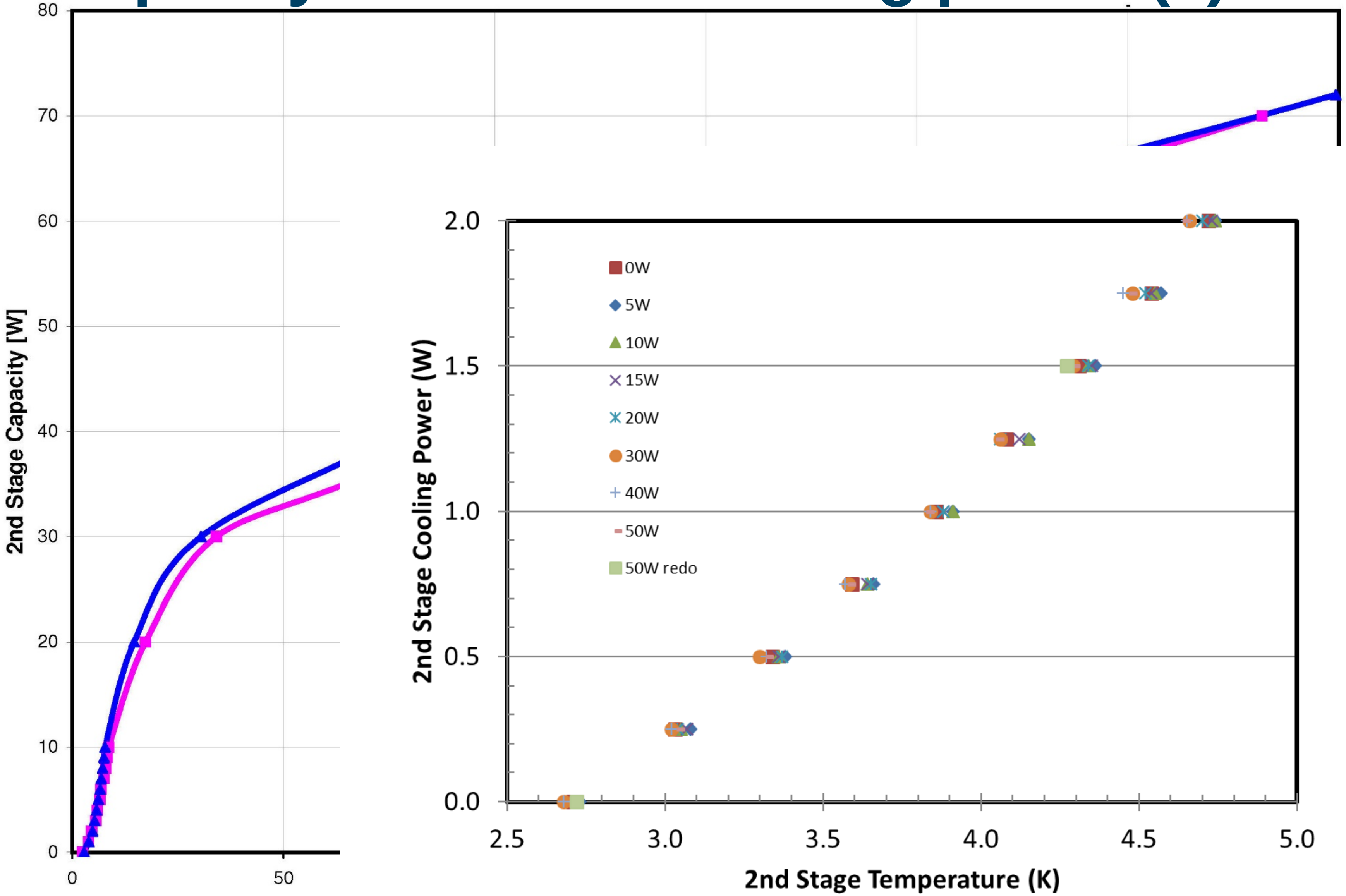
- Design heat load
- Desired operating margin
- Vendor-supplied performance data



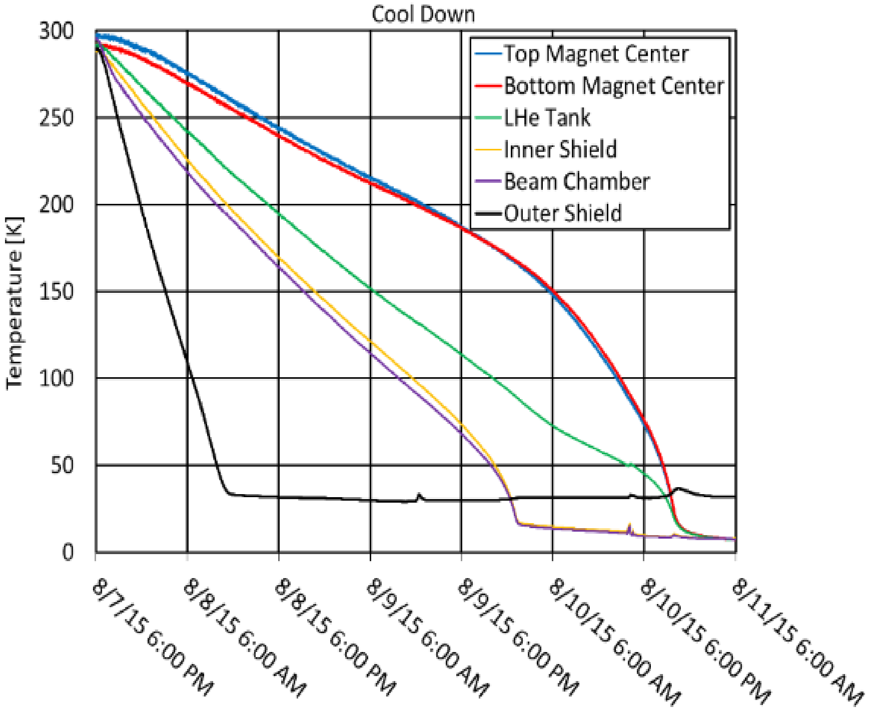
Refrigeration capacity – installed cooling power (2)

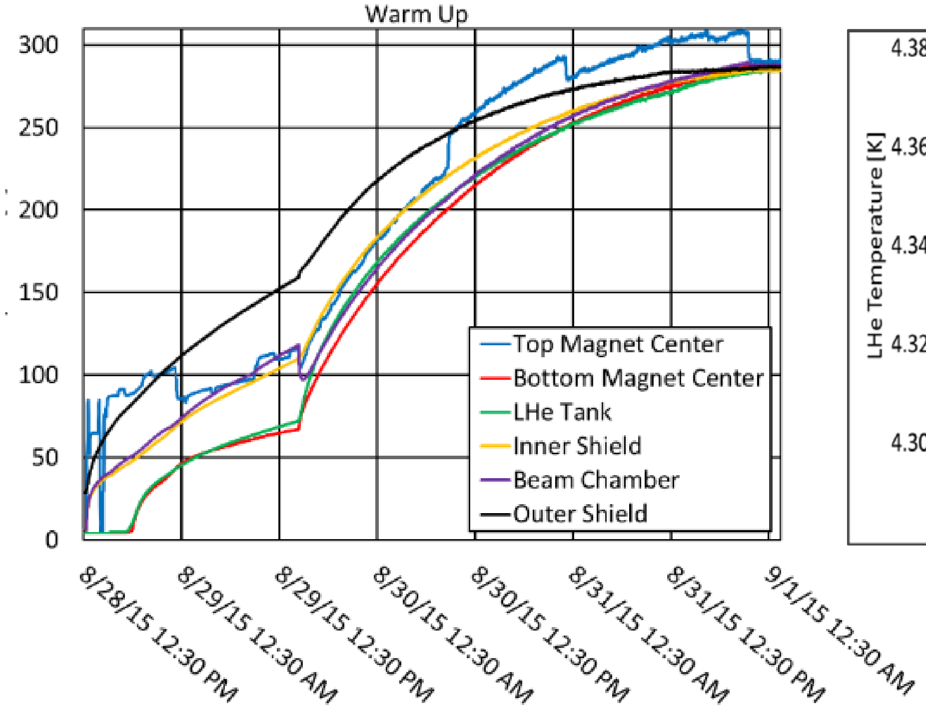
Cryocooler requirements:
- Design heat load
- Desired operating margin
- Vendor-supplied performance data

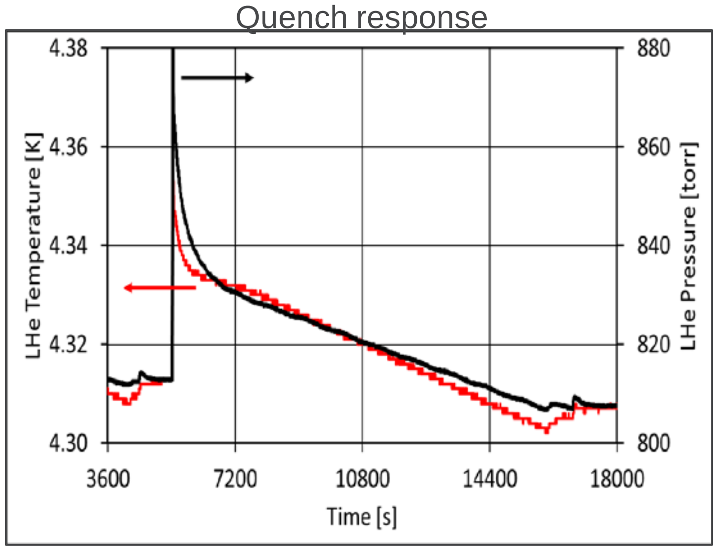
- ***Cryocooler base temp at operating Q***



Cryogenic performance - 1st-gen cryostat with planar SCU







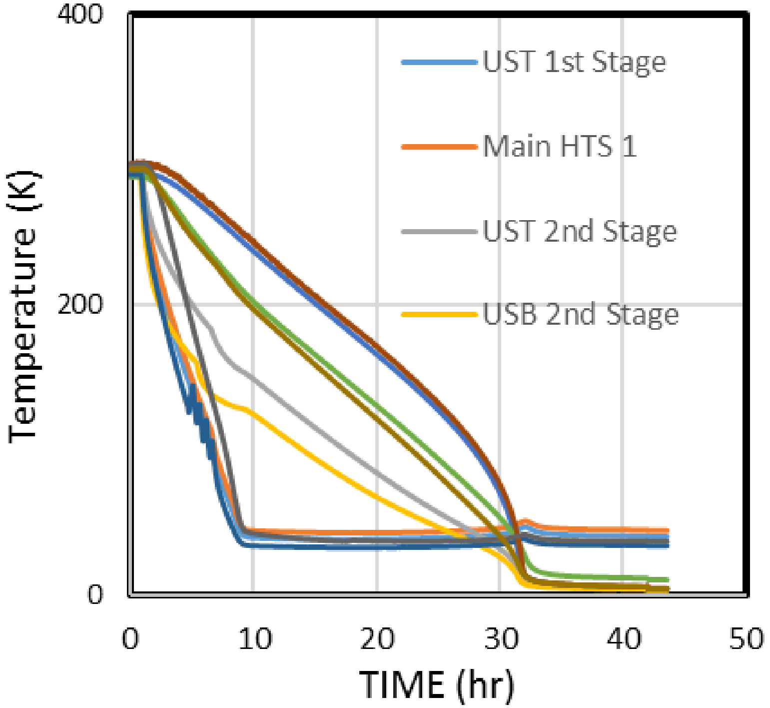
- Cooldown/fill takes 4 days
- Takes advantage of increased cryocooler capacity at higher temperatures

- Warmup takes ~4 days
- Heaters and intentionally "spoiled" insulating vacuum speed the process

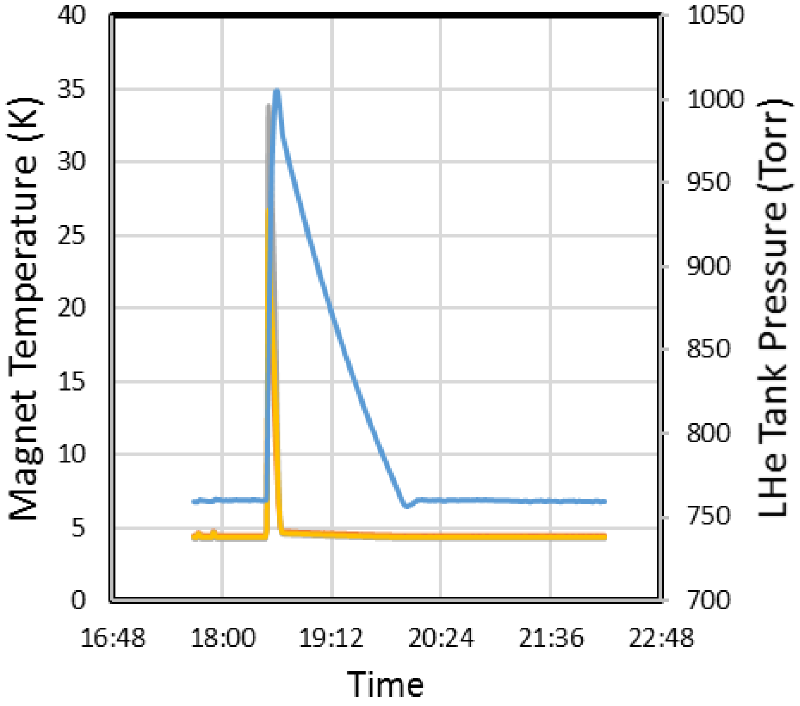
- Magnet quench is the primary system perturbation during operation.

Cryogenic performance - 2nd-gen cryostat with helical SCU

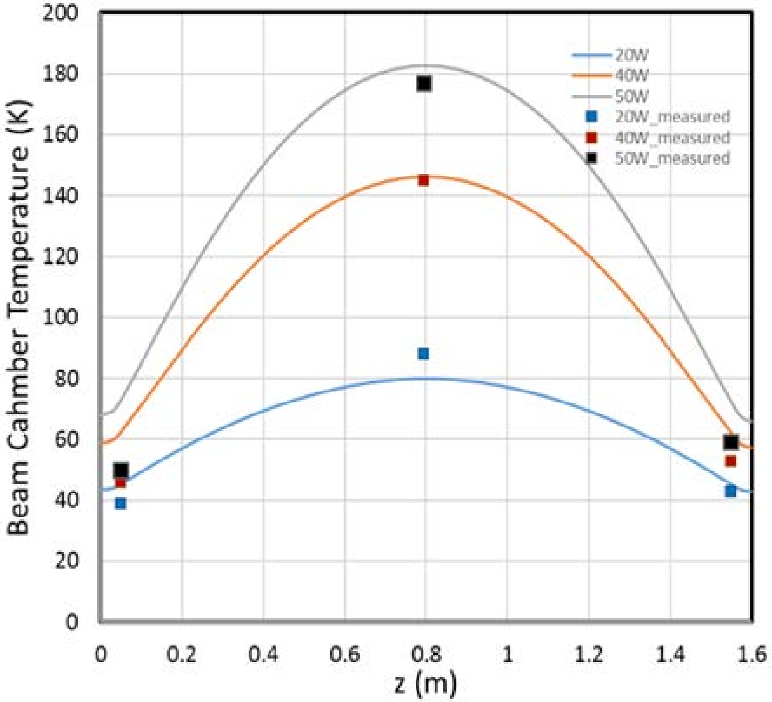
Cooldown



Quench recovery

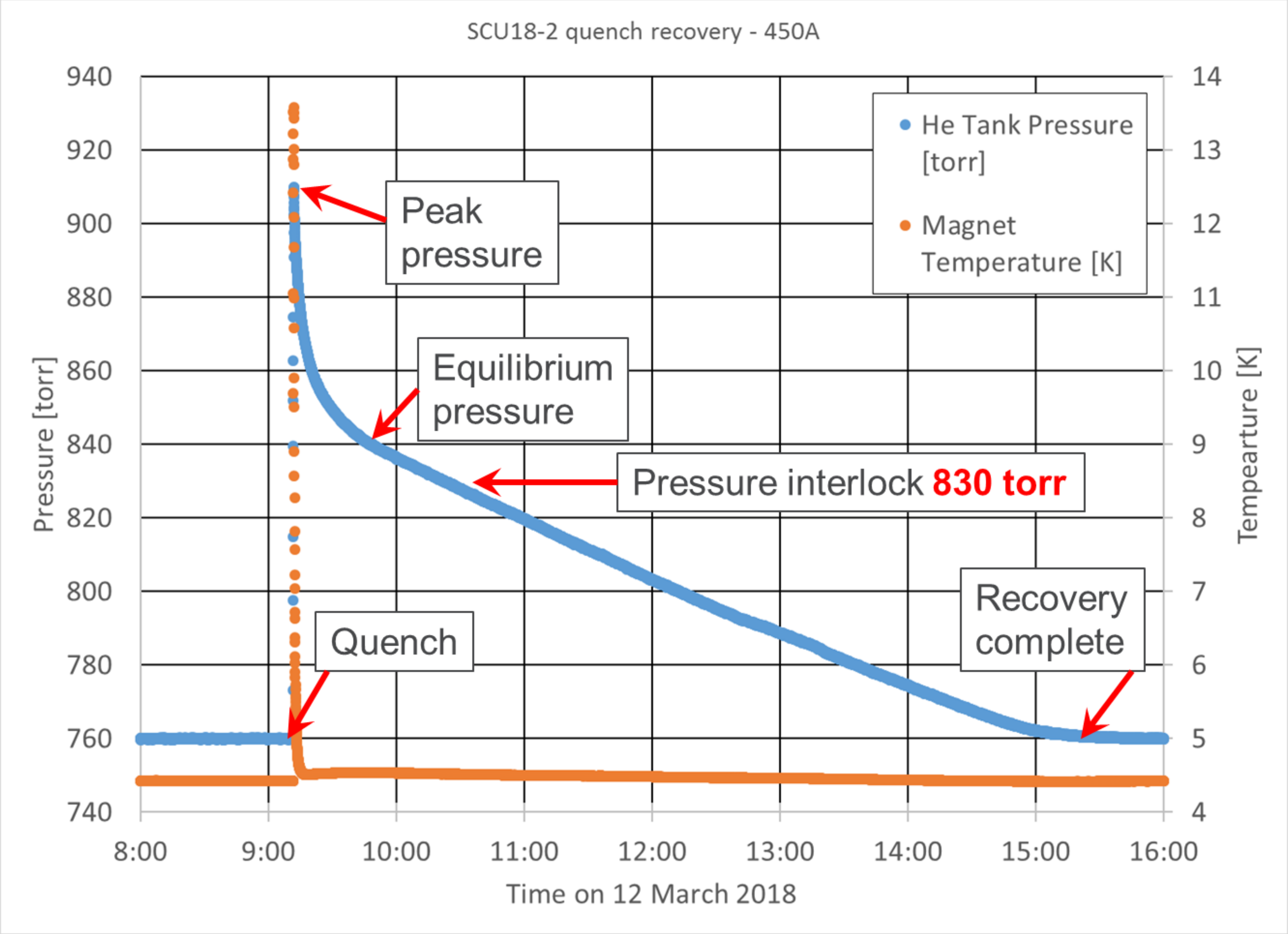


Beam chamber temperature profile with different applied heat



- Cool down time is about 1.5 days.
- Quench recovery time (ready for beam) is ~1hr.
- Data confirm the predicted beam chamber temperature profile associated with cooling only at the chamber ends (chamber is inaccessible inside the magnet bore).

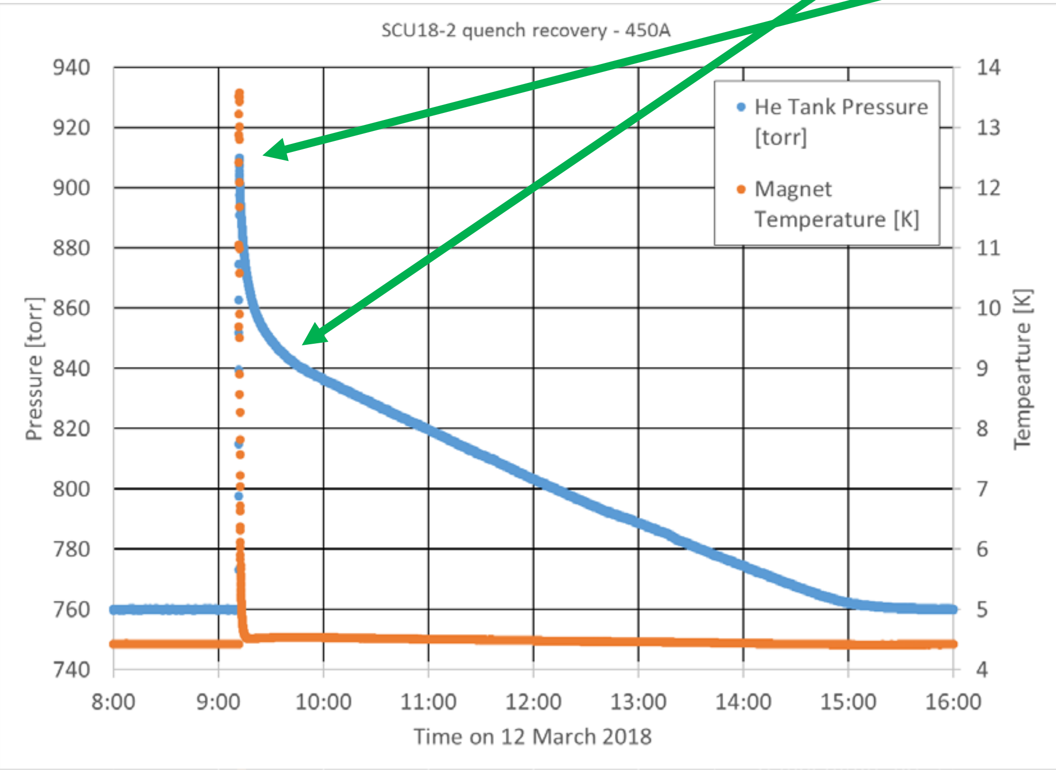
Quench recovery (1)- anatomy of a quench



Quench recovery (2) – pressure calculation in MSExcel

	Quench Energy [J]	Temp of Liq. [K]	Sat. Temp [K]	Press [Pa]	Density Liq. [kg/m3]	Density Sat. Vapor [kg/m3]	Internal E Liq. [J/kg]	Internal E Sat. Vapor [J/kg]	Vol. Liq. [L]	Vol. Sat. Vapor [L]	Total Vol. [L]	Mass Liq. [kg]	Mass of Sat. Vapor [kg]	Total Mass [kg]	Energy of Liq. [J]	Energy of Sat. Vapor [J]	Total Energy [J]	Press [psia]	Press [psig]	Press [Torr]
			4.22	1E+05	124.95	16.844	9207	24724	**30**	**70**	100	3.748	1.179	4.93	34514	29152	63665	14.7	-0	760
Equilibrated pressure	**4000**		4.33	1E+05	122.75	18.725	9708	24701	29.4	70.63	100	3.605	1.323	4.93	34996	32669	67665	16.25	1.554	**840.6**
Peak pressure	**4000**	4.222	4.41	1E+05	126.15	20.243	9090	24657	27.4	72.59	100	3.458	1.469	4.93	31434	36231	67665	17.46	2.762	**903**

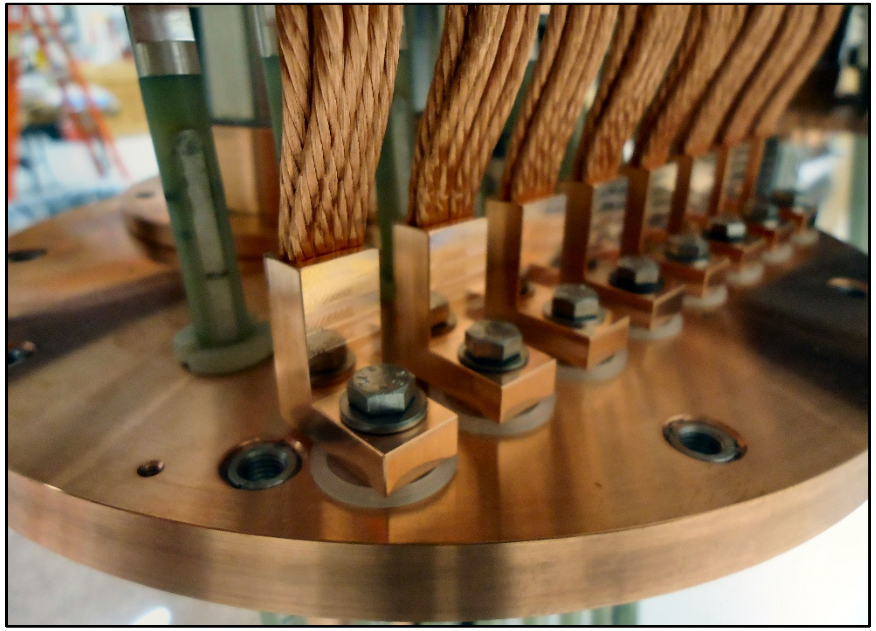
- Inputs: Initial pressure, vol He liquid, vol He vapor, quench energy
- *SOLVER* iterates to find the final pressure due to added quench energy.
- System total mass and volume are const.
- **Peak** pressure keeps the liquid temp constant and allows superheated vapor.
- **Equilibrium** pressure maintains saturated conditions.

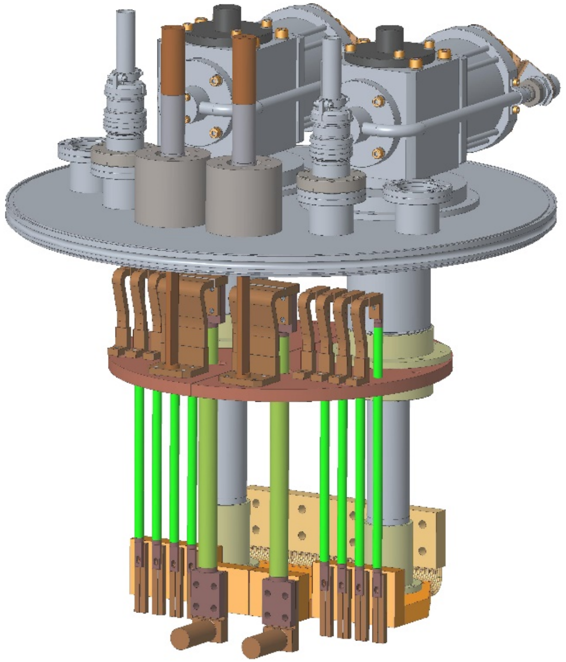


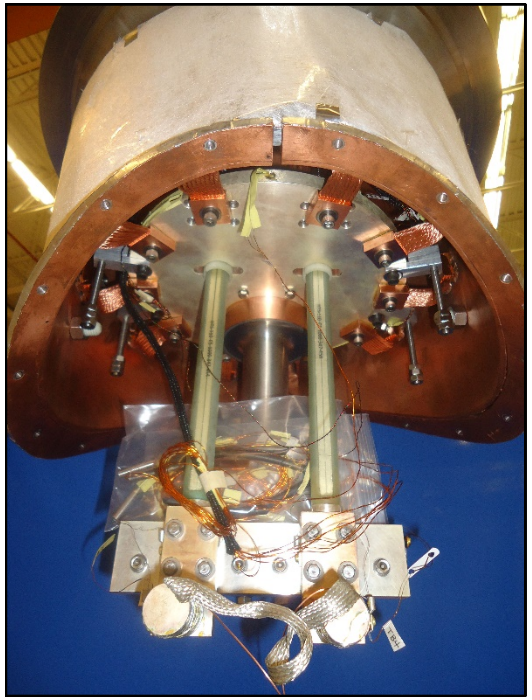
Fabrication strategy

- For the vacuum vessel, thermal radiation shield, and LHe tank we have migrated to a build-to-spec strategy:
  - Vendor is provided with a detailed SOW/Technical Spec and the 3D CAD models.
  - Vendor scope includes production of detail drawings, to be approved by APS-U prior to fabrication.
- Some subcomponents are also excellent candidates for design/build.
- For other subcomponents (such as the current lead turrets) a complete detail drawing packages are produced internally for “build-to-print” vendor fabrication.
- Final assembly documentation has evolved – currently described by the SCU18-2 technology licensing package.

APS-U SCU turret CAD model with photos of HSCU turrets for comparison.

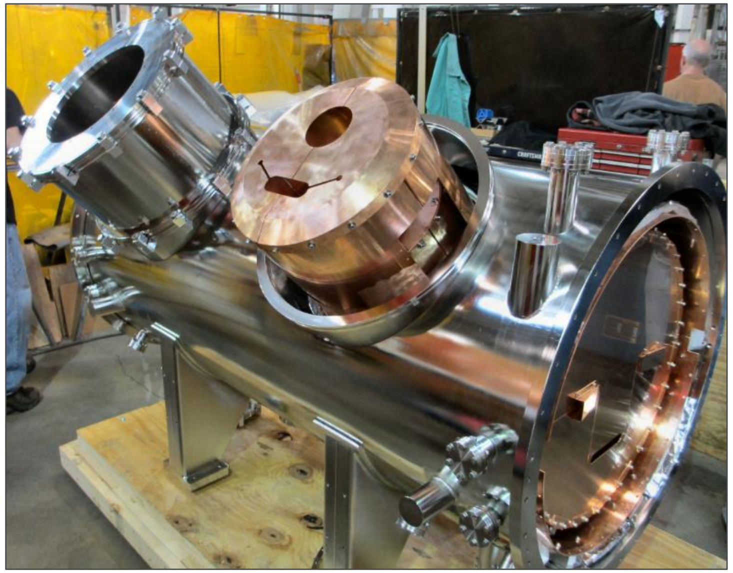




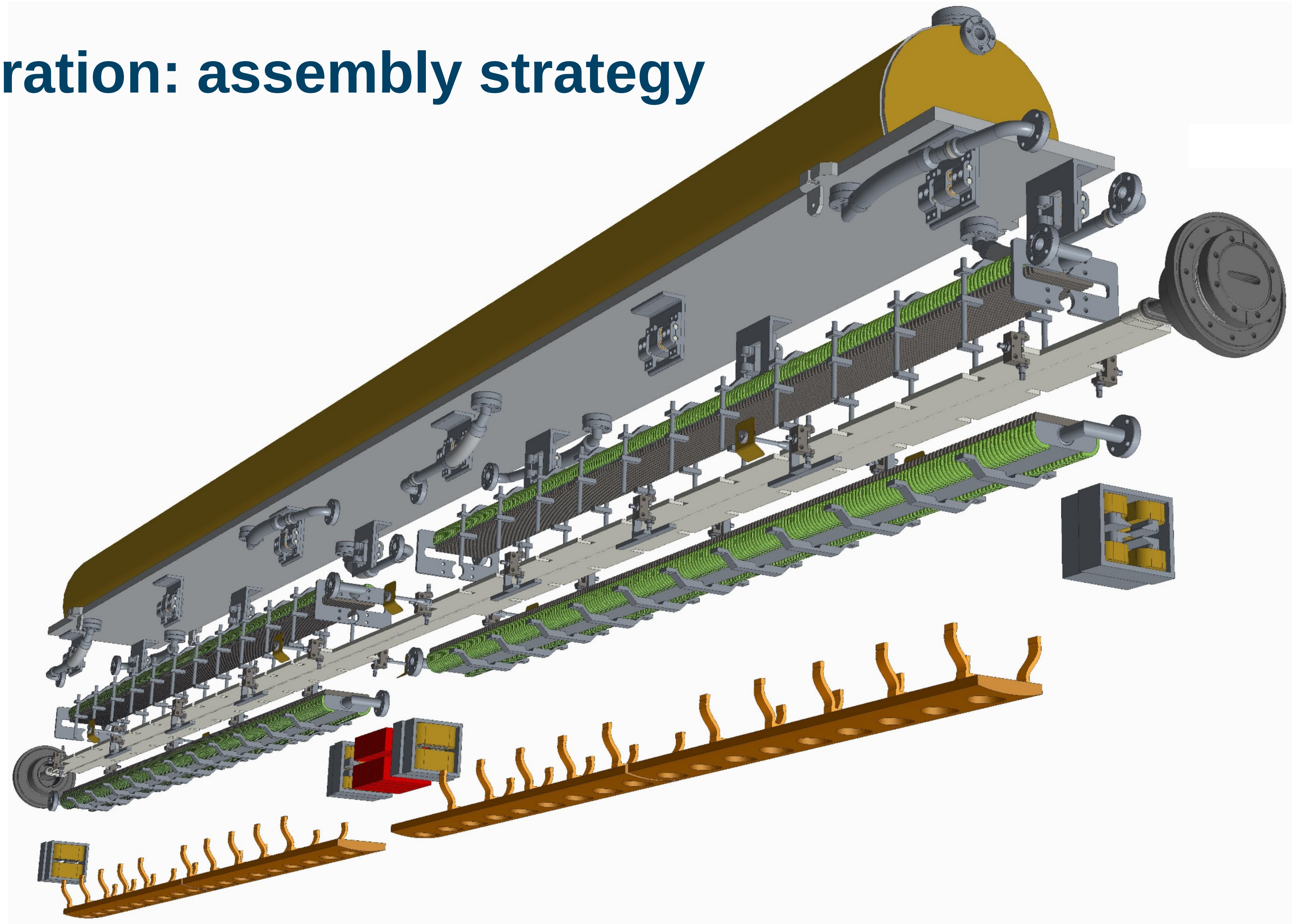


Transition of production to industry

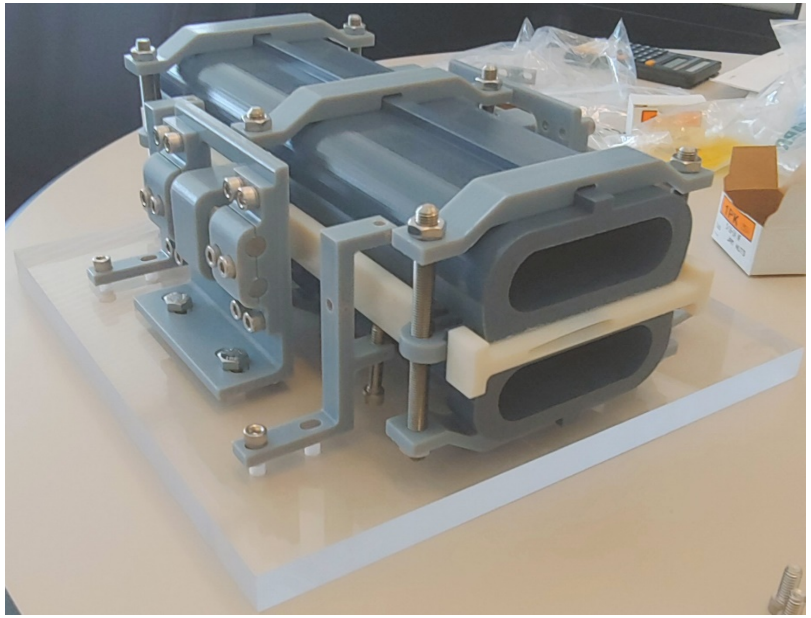
- Subsystems are fabricated in industry from ANL designs:
  - Vacuum vessel
  - Thermal shields
  - Liquid helium reservoir
  - Magnet cores
- Long-term goal is to develop vendors for “turn-key” SCU production:
  - Magnetic design & analysis
  - Hardware design & fabrication
  - Magnet winding, full cryostat assembly
  - Could include ANL collaboration for measurement & test
- APS SCU technology is available for license

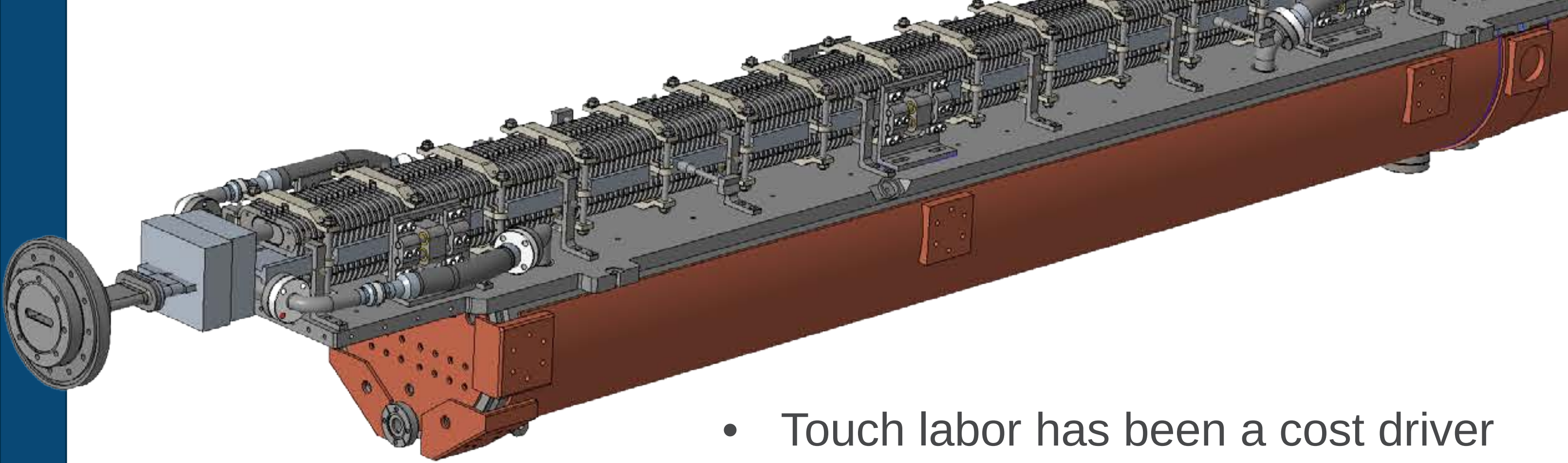


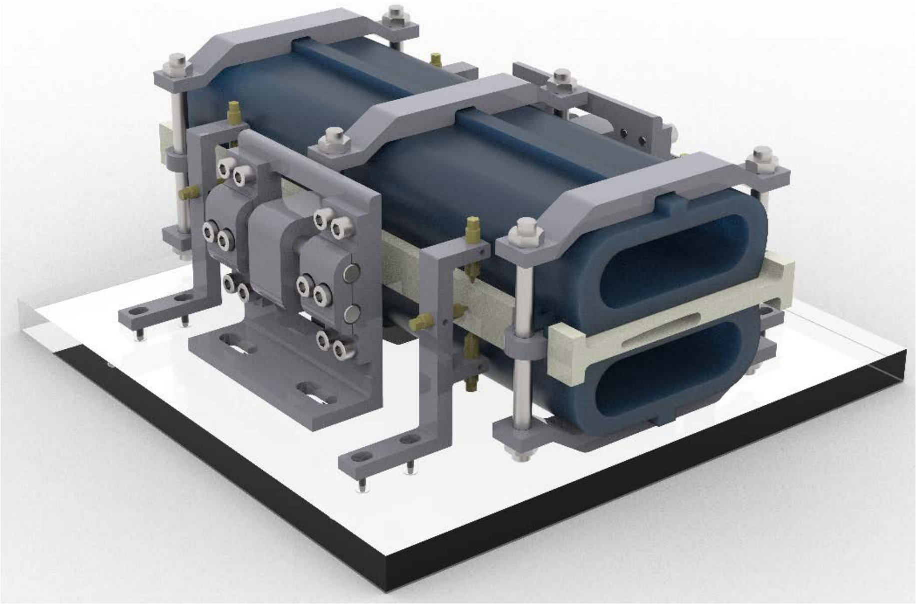
Integration: assembly strategy



Cold mass build-out



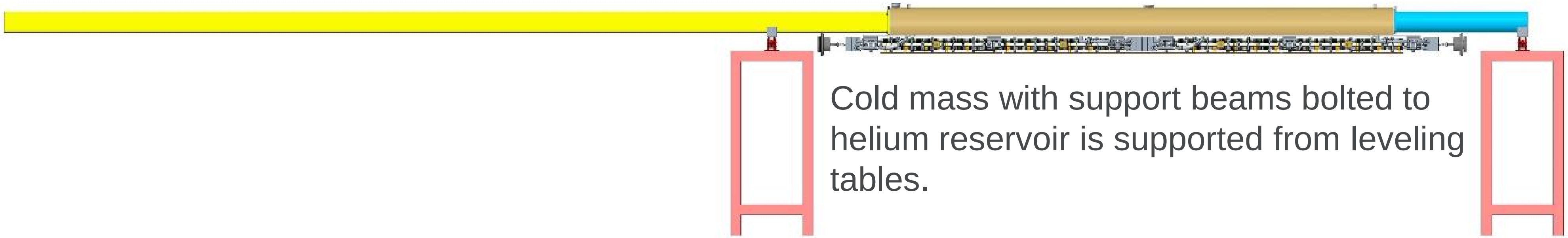




- Touch labor has been a cost driver
- New cold mass design represents a departure from past planar SCUs
- Although designed for accessibility, part count is high (2x SCUs)

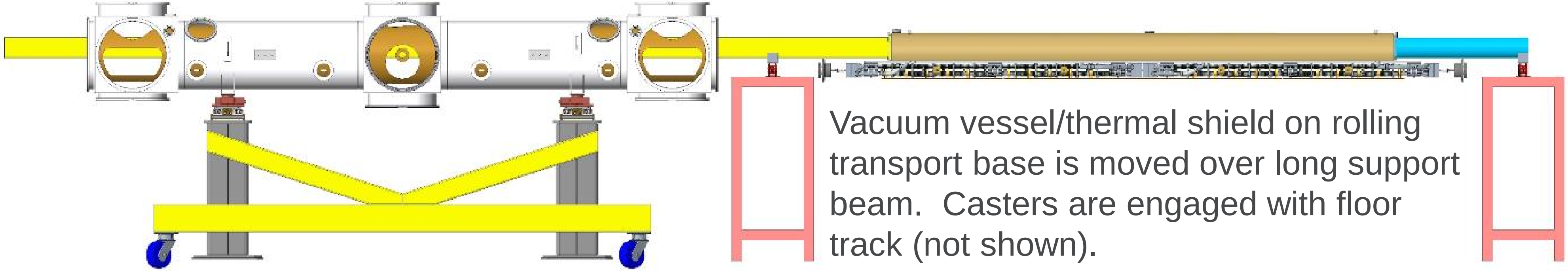
End-loading assembly (1)

1



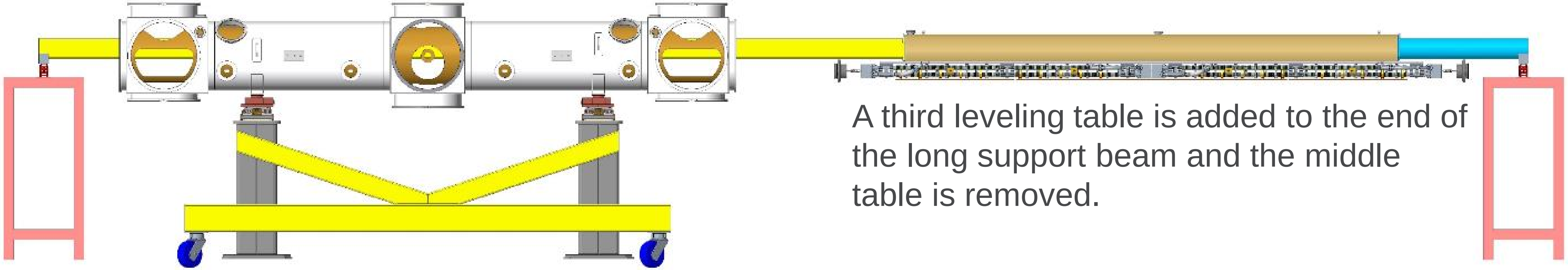
Cold mass with support beams bolted to helium reservoir is supported from leveling tables.

2



Vacuum vessel/thermal shield on rolling transport base is moved over long support beam. Casters are engaged with floor track (not shown).

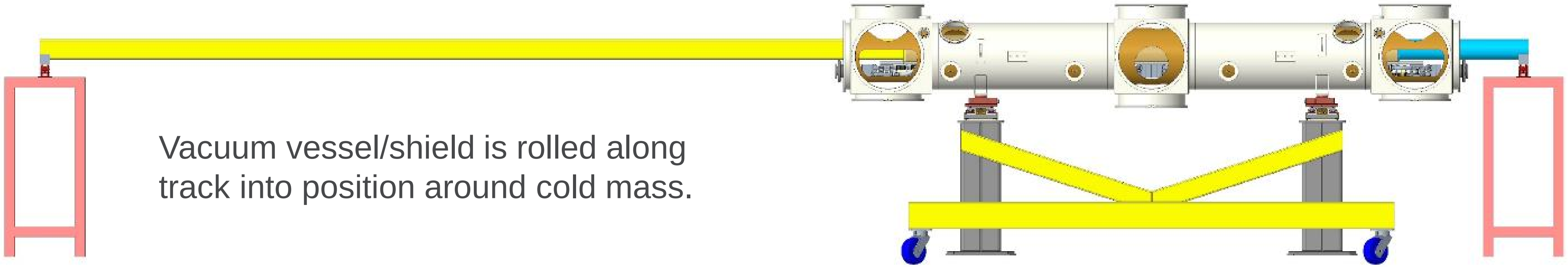
3



A third leveling table is added to the end of the long support beam and the middle table is removed.

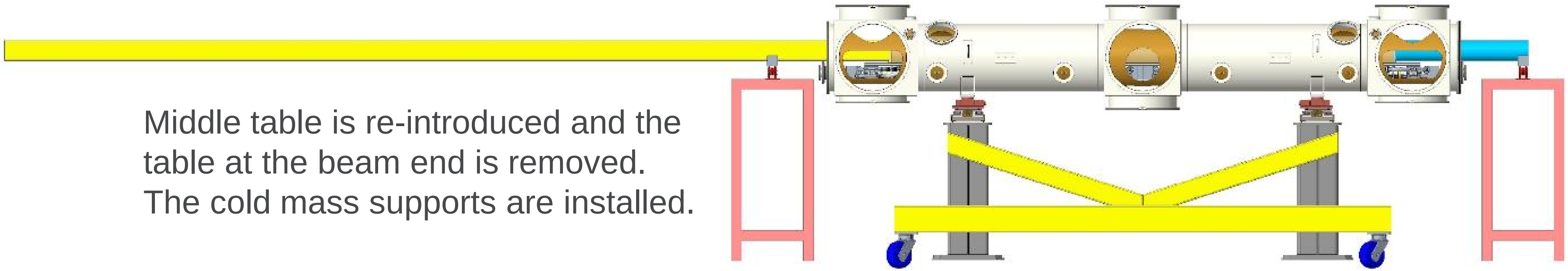
End-loading assembly (2)

4



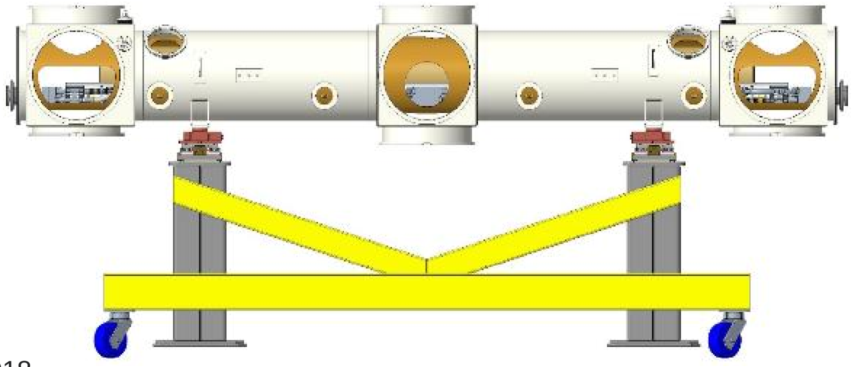
Vacuum vessel/shield is rolled along track into position around cold mass.

5



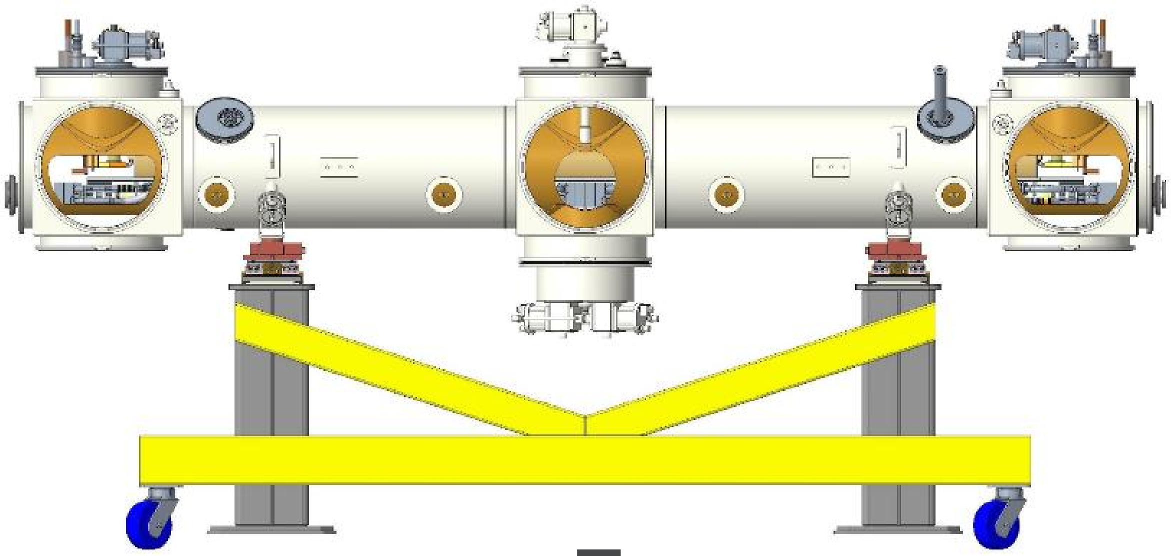
Middle table is re-introduced and the table at the beam end is removed. The cold mass supports are installed.

6



Cold mass weight is transferred from tables to cold mass supports. Beams are removed.

End-loading assembly (3)



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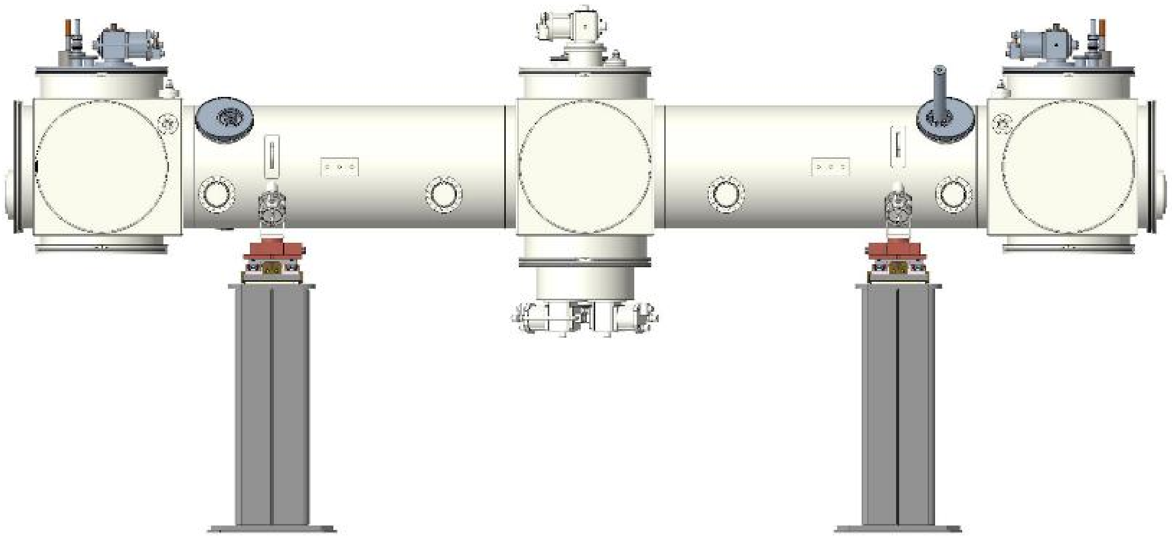
Cryostat assembly continues: shipping supports, cryocooler turrets, helium fill/relief ports, current lead wiring, instrumentation. Rolling transport fixtures remain attached to the pedestal supports.



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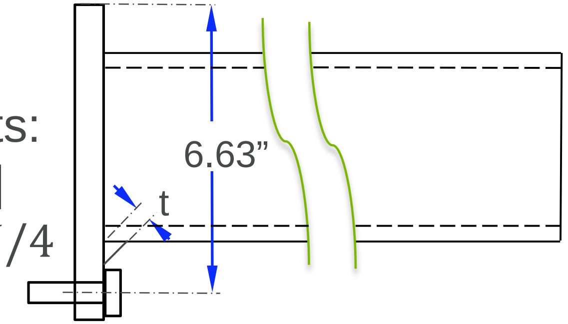
After transport to SR and positioning in the ID straight, cryostat is transitioned from casters to pedestal bases and bolted down. Rolling transport fixtures are removed.

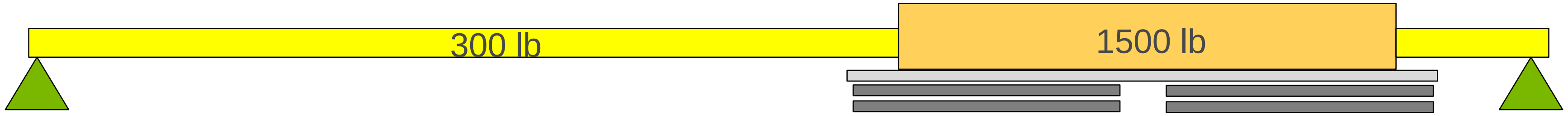
Assembly support beam analysis

- 6”x4”x0.25” wall
- 6.6 m (258”) long
- 1 m (39”) long
- ASTM A36
- QTY6 5/8-11 Grade 8 fasteners

Total load on bolts:
$F = M/6.63$ [lb]
Load per bolt = $M/4$



- Bending moment M:
  - Long beam: 560lb(258”) = 144 kip-in
  - Short beam: 1240lb(39”) = 48 kip-in
- Fasteners on long beam see higher load



Long Beam:
Bolt load = (560lb)(258”)/6.63” = 21,800lb = 5450lb/bolt (QTY4).
For 5/8-11 bolt (stress area 0.226in^2) the stress = **24.1 ksi**
Gr 8 σ_T = 150 ksi, so F.S.=**6.2**

Weld throat t = 1/4”, A = 1in^2, σ = **21.8ksi**
For ASTM A36: σ_T = 58 ksi minimum, so F.S.= **2.7**

Stress & deflection - cantilever beam:

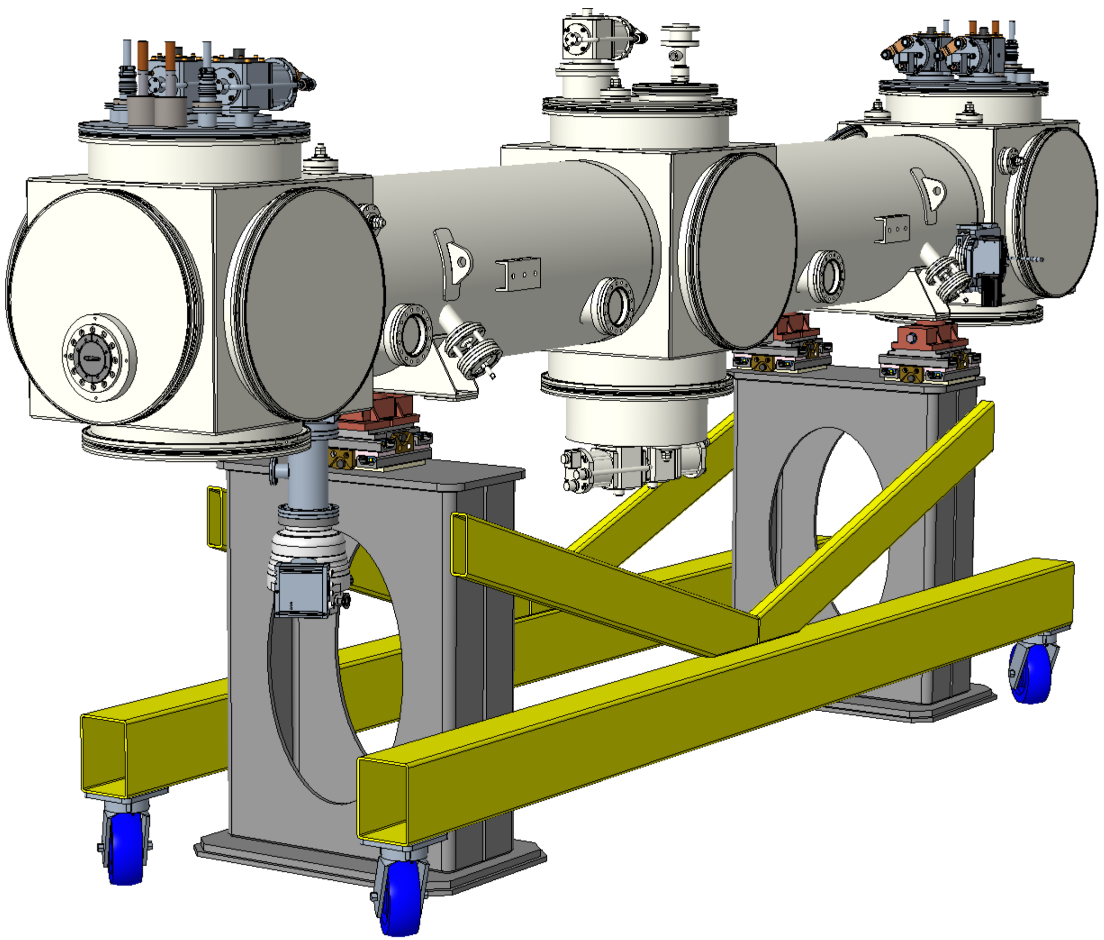
$$\delta = \frac{FL^3}{3EI} = 4.9”$$

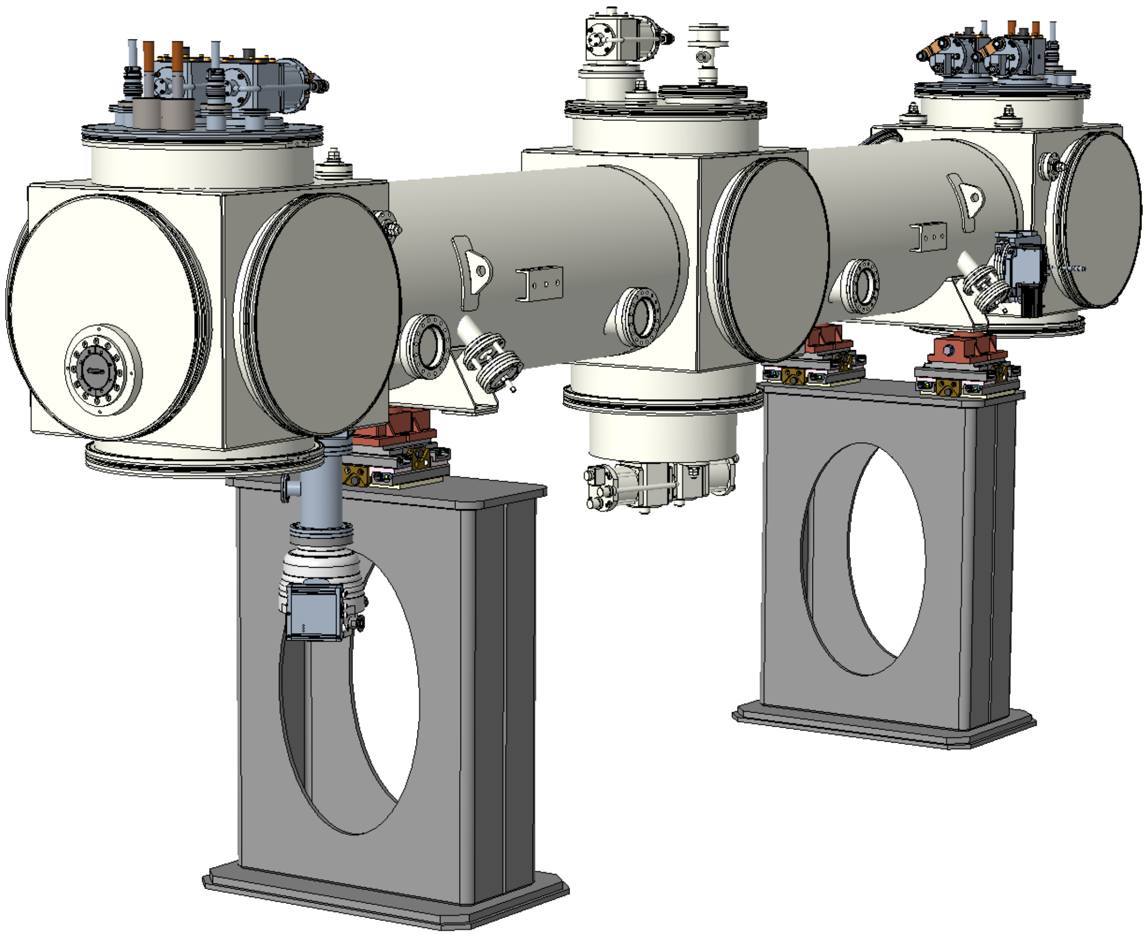
$$\sigma = \frac{FLc}{I} = 18.4 \text{ ksi}$$

For ASTM A36: F.S. = **3.2** w.r.t. σ_T

Where:
F = load = 560lb
L = length = 258”
E = Young’s modulus = 28E6 psi
I = moment of inertia = (1/12)(b)(h^3) = 23.5 in^4
C = distance to neutral axis = 3”

Support Stand Design



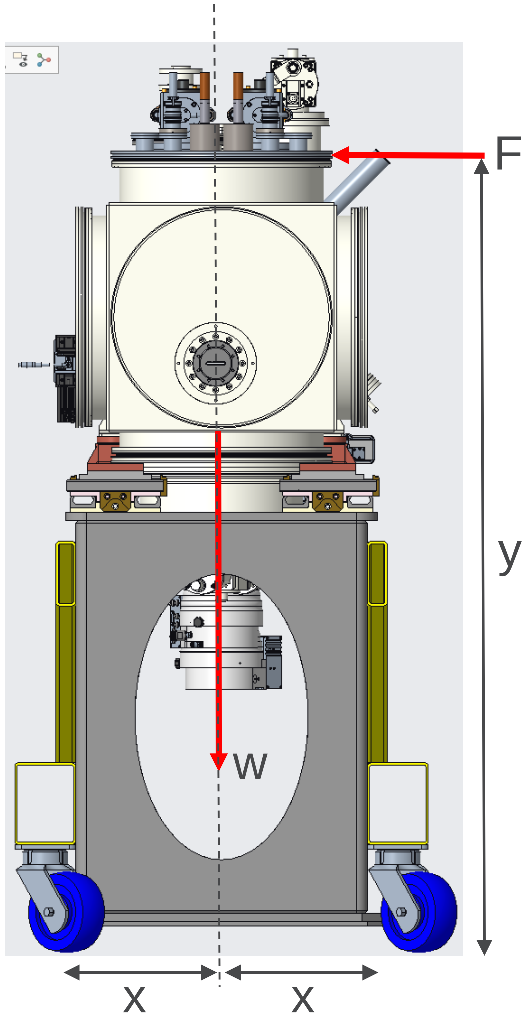


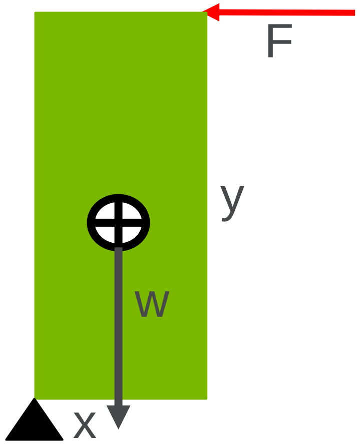
- With stiffener/wheel system installed (this config. throughout assy/transport)
- Stiffener/wheel system removed after installation in SR

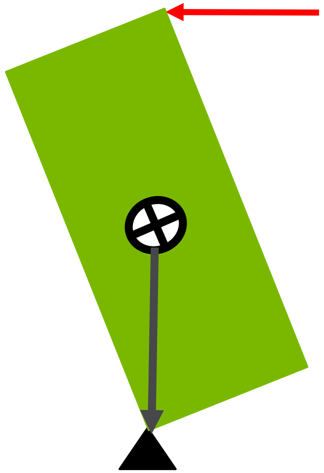
Rigging & transport

- Removable shipping supports for the cold mass are designed to withstand +/- 3g vertical, longitudinal & transverse and to allow 15 degree tilt about longitudinal axis.
- Base + stiffener/wheel system will be designed with designated forklift pockets and for compatibility with motorized crawler transport (*Hilman Traksporter* or similar).

Stability analysis – side load





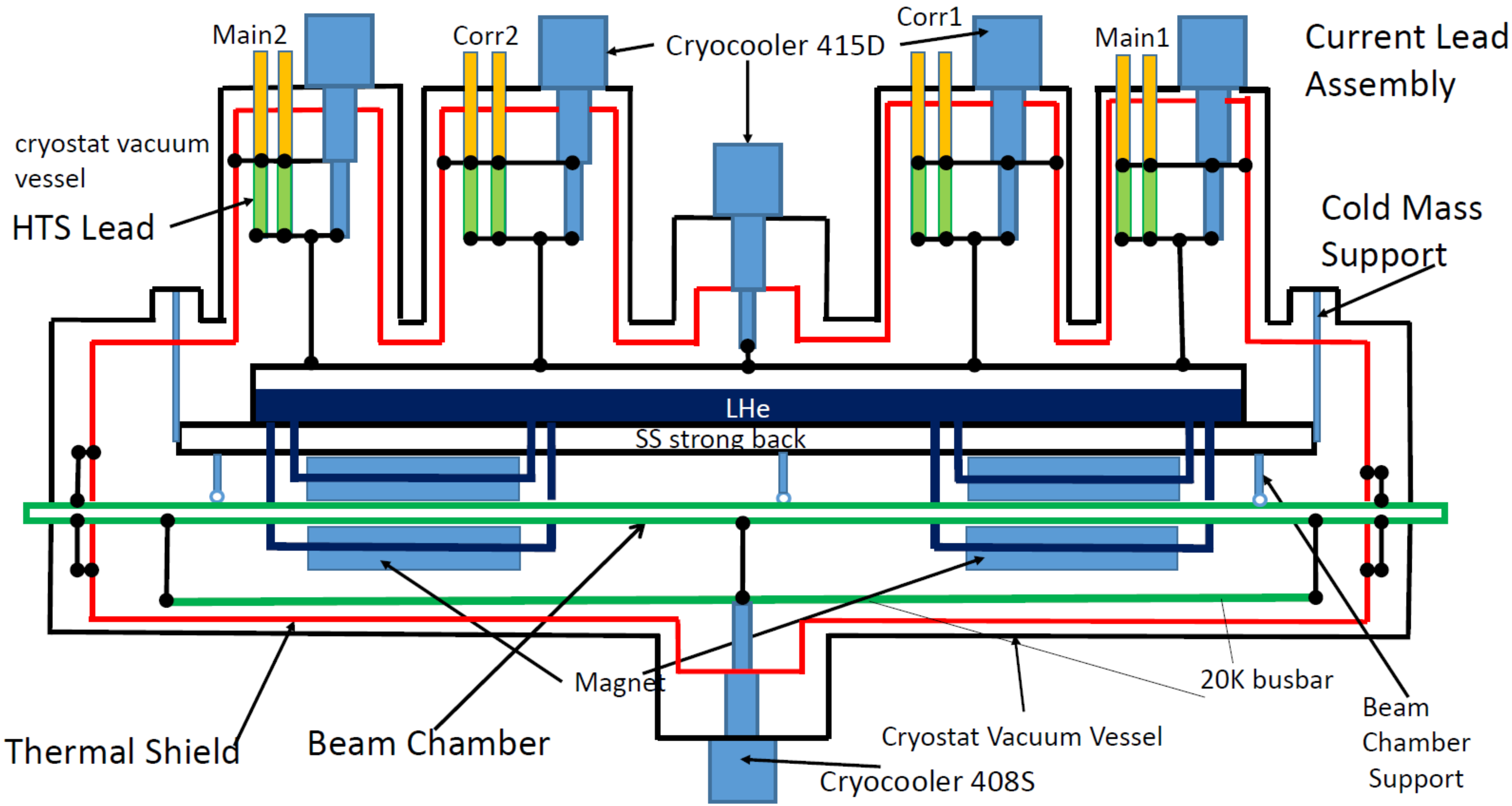


- Static: how much force to tip?
  - Force F is applied at the worst-case location (maximum lever arm). Tipping moment Fy must exceed restoring moment wx to initiate tip.
  - For y = 78”, x = 12”, and w = 6880 lb:
    - F = **1060 lb**
- Dynamic: how fast to trip?
  - Center of gravity (CG) is 53” above floor.
  - Assume simplified block model of cryostat where b = 2x and h = 2(CG):
    - $v = 2\sqrt{\frac{g}{3}\left(1+\frac{b^2}{h^2}\right)\left(\sqrt{(h^2+b^2)}-h\right)}$

*Merriam, J.L., **Engineering Mechanics: Statics and Dynamics**, John Wiley & Sons (1978) p. 398.*

- v = **5.4 ft/sec**

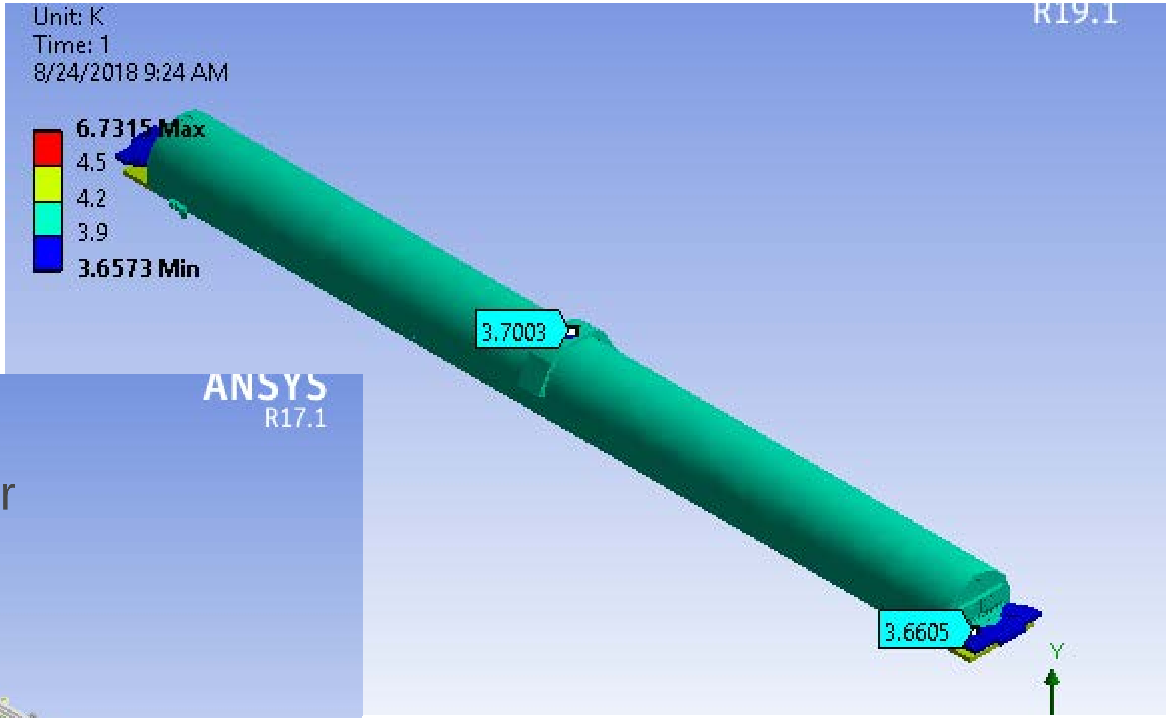
Thermal simulations (Y. Shiroyanagi)

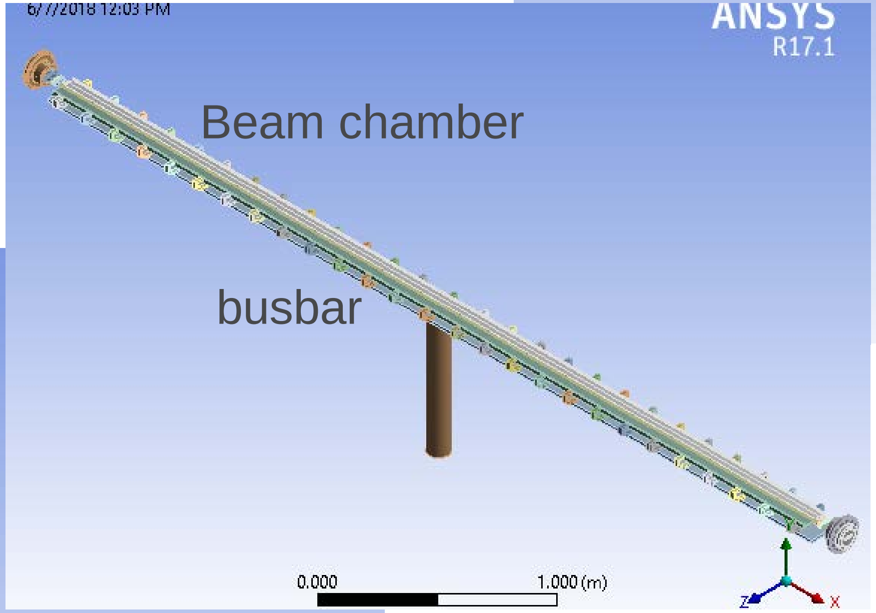


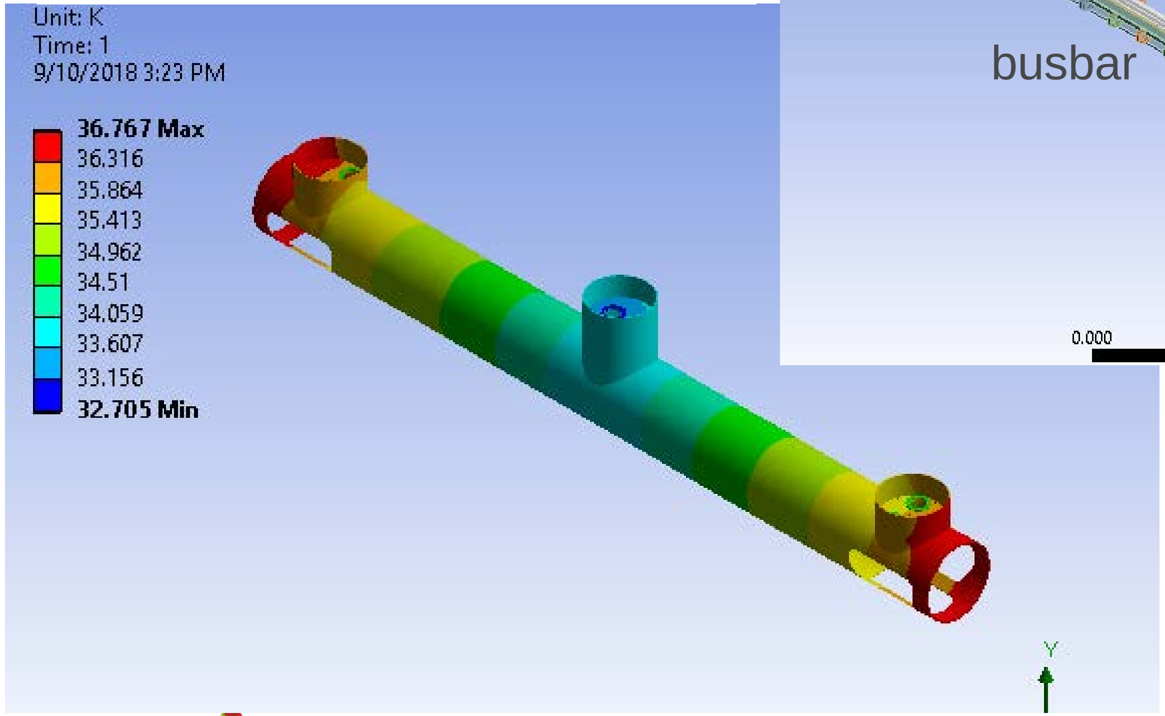
- A full thermal circuit model was created in ANSYS

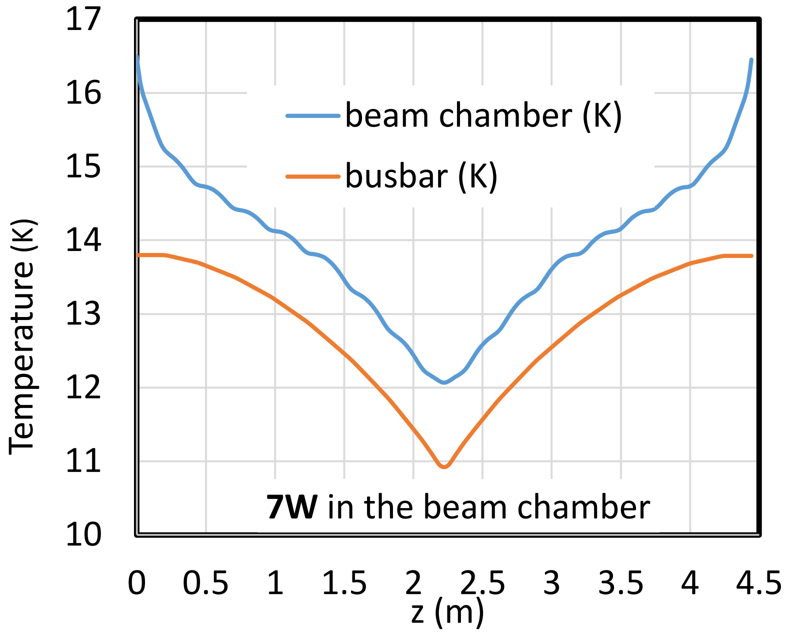
Simulation results

- ANSYS simulation solves all 3 temp levels simultaneously
- Further description in Yuko's seminar





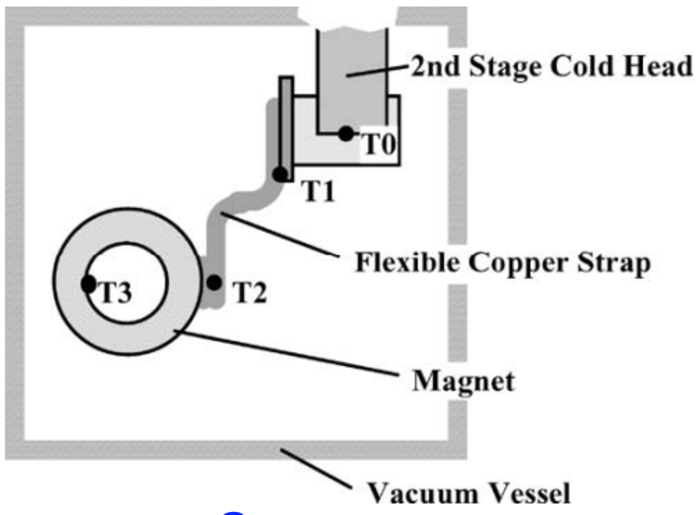




Cryogenic design alternatives – refrigeration

- We are inclined to reduce risk by retaining existing design strategies where they meet baseline requirements.
- However, we recognize areas for potential performance gains and/or cost savings that would merit investigation:

1. Cryomech PT420 pulse tube (shown) or new Sumitomo GM coolers provide ~2 W at 4.2 K and could provide an immediate 33% increase in available cooling power over the Sumitomo 415D GM units.
2. Greater cooling efficiency through revised coupling between load and cryocooler:
   a) Improve thermal link efficiency
   b) Replace flexible thermal links with helium vapor circulation/ liquid return ($\Delta T_{1\text{-}3}$ of 0.05 K is achievable)



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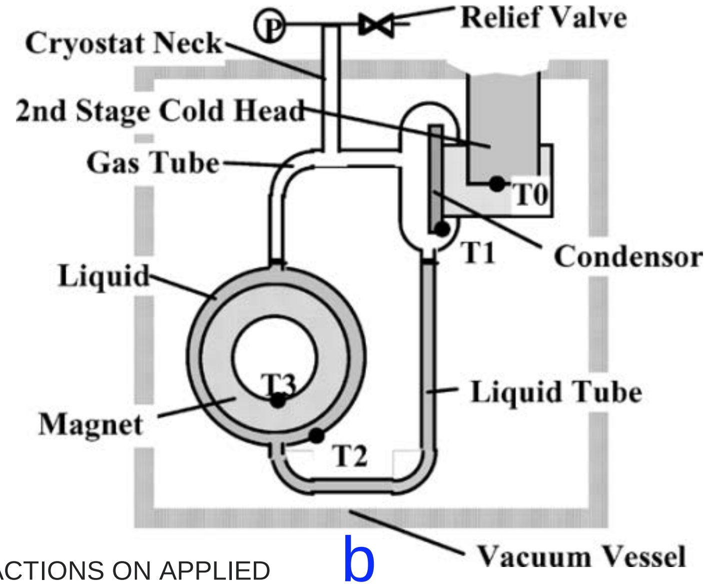

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M. A. Green, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 16, NO. 2, JUNE 2006

Installation, operations, maintenance

- Installation follows previous SCUs with revisions due to cryostat length and APS-U tunnel particulars and will be performed by dedicated installation personnel.
- 4.8 m cryostat will access the tunnel through existing superdoors.
- Aisle clearance is adequate, lateral translation into ID straight from the aisle is straightforward.
- Cryocooler compressors locate in the service corridor as with existing SCUs.
- Operations will be conducted in a manner very similar to existing SCUs – controls, instrumentation, interlocks all follow existing practice, subject to any APS-U control system upgrades/changes.
- Maintenance will be essentially identical to existing SCUs.
- Vacuum systems (both chamber and cryostat) are similar to existing installations and will follow similar maintenance protocols.

ES&H

- APSU Hazard Analysis Report addresses oxygen deficiency as well as vacuum and pressure system safety.
- Expectation is that the SR tunnel and EAA will be classed **ODH 0**
- Pressure systems will undergo Pressure System Evaluation (ANL-722) and be reviewed by the APS Pressure Systems Safety Committee (PSSC), pressure safety SMEs, and/or the ANL Pressure Technology & Safety Committee (PTSC).

QA processes

- Design tasks are managed with APS-U internal and external review processes.
- Vendor pre-qualification including audits of vendor QA programs etc. will occur depending on cost and risk to the project.
- Fabrication tasks (both “build-to-spec” and “build-to-print”) are managed through readiness reviews pre-award and close vendor oversight during contract performance. Vendor-supplied milestone schedules will be required where appropriate.
- Certain contracts will involve on-site inspections or witnessing of tests in addition to routine on-site status checks. Pre-ship inspections may be appropriate in some cases.
- Upon delivery items will be inspected depending on QA level. ~~Acceptance Criteria Lists (ACLs) may have been part of the contract~~. An electronic traveler system will be used.
- APS-U acceptance tests will be performed per the contract, according to the time schedule in the contract.

Risk mitigation

- The APS-U SCU cryostat design is an evolution of existing SCU technology.
- The design mitigates risk by retaining design features from earlier SCUs (for example current lead turrets and vacuum vessel/thermal shield/helium tank production strategy).
- In terms of performance in the APS SR we expect behavior similar to existing planar SCUs 18-1 and 18-2, with the relative simplicity of the 2nd-generation cryostat design demonstrated with the helical SCU.
- Thermal performance risks are mitigated through detailed numerical simulation of the shield and cold mass heat load and cooling power using actual CAD geometry.
- The design cooling power will include substantial excess capacity to mitigate the risk of unaccounted heat sources or lower than anticipated cooling power. Higher cooling power translates to faster quench recovery, so a refrigeration “excess” will play a role beyond risk mitigation.