DUNE-ND LArTPC Cryostat Lid

2024-09

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U.S. DEPARTMENT OF ENERGY | Office of Science

BERKELEY LAB

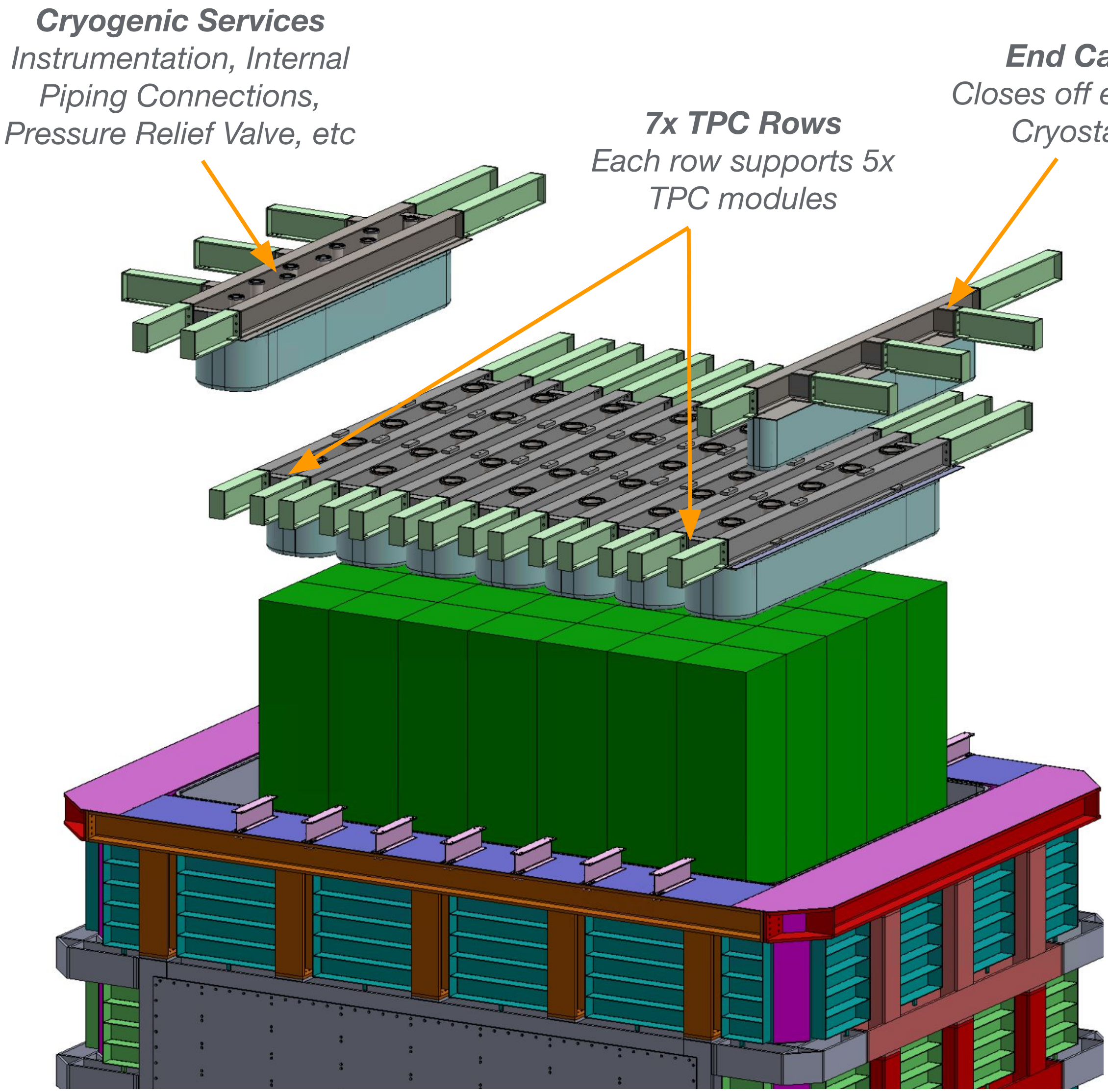
Requirements and Interfaces

Charge # 1, 6.e, 6.f

- FESHM 5031.7 Membrane Cryostats
  - Lid to meet AISC 360 Specification for Structural Steel Buildings
    - Design to safety factor >2 on yield strength as conservative simplification of 600+ page code
    - Licensed structural engineer to evaluate final design against AISC 360 code before release to fabrication
  - Skin panels to limit water vapor permeability into insulation layer to 0.5 g/m^2 per 24 hr
- ND-LAr TPC
  - Maximum TPC array displacement 10 mm under operational loads
  - TPC array position measurement accuracy ±5 mm
    - Array position relative to beam is not tightly controlled, but final position must be measured precisely to inform detector calibration

There are 3 unique lid designs and 9 total lid sections

- Lids are installed individually
- This presentation will focus on the TPC Row; other lids use similar construction
- Total envelope 8.8 x 7.8 x 1.2 m (L x W x H) outside dimensions
- Total mass 23.4 metric tons [25.8 US tons]
- S460ML steel for I beams and warm structure
    - 460 MPa [67 ksi] yield strength
        - Safety factors assume alternate A572-65 steel at 65 ksi [448 MPa]
    - 17% elongation at failure
- AISI 304 stainless steel for membrane, skin panel and feedthroughs
    - 31.2 to 140 ksi [215 to 965 MPa] yield depending upon work hardening
        - 38.5 ksi [265 MPa] yield assumed for analysis
- Manufacturing methods
    - I beams cut and machined
    - Plates cut and machined
    - Foam blocks cut and machined
    - Welding – structural and hermetic
    - Adhesive bonding
    - Painting



Charge # 2

Analysis Plan

Approach

- Preliminary design: cryostat team analyzes with ANSYS and hand calcs, targeting safety factor >2 on yield strength
- Final design: Illinois-licensed structural engineer evaluates against AISC 360 requirements

Thermal Heat Transfer Calculations

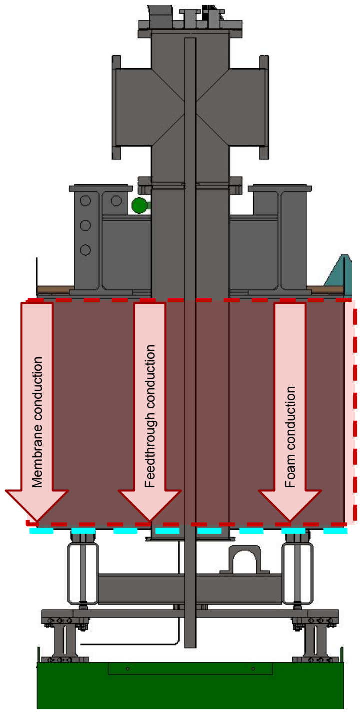
- 1D Conduction Model Spreadsheet
- Natural Convection Model Spreadsheet

Thermal-Structural Load cases

- Gravity: gravity, TPC weight without buoyancy, room temperature
- Cool down: gravity, TPC weight without buoyancy, cryogenic temperature
- Operational: gravity, TPC weight with buoyancy, cryogenic temperature, 350 mbar gas pressure

Requirements

- Safety factor >2 on yield strength (best practice to ensure we meet AISC 360)
- Maximum TPC array displacement 10 mm



1D Conduction Schematic

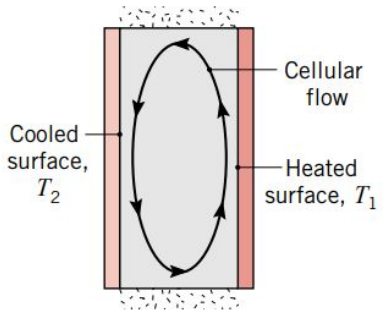
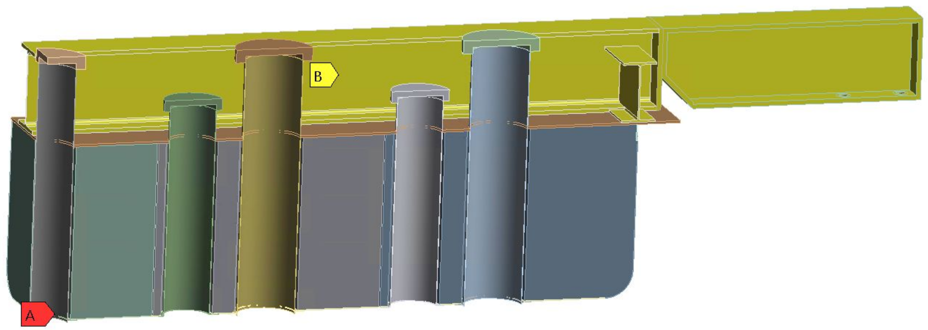


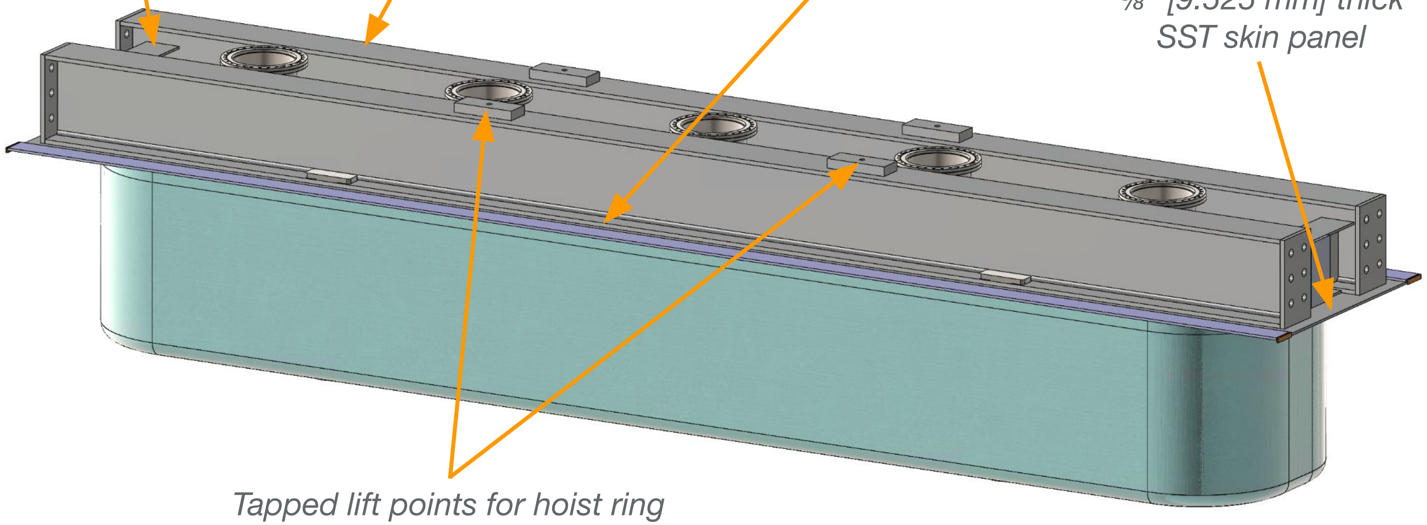
FIGURE 9.12 Cellular flow in a vertical cavity with different sidewall temperatures.

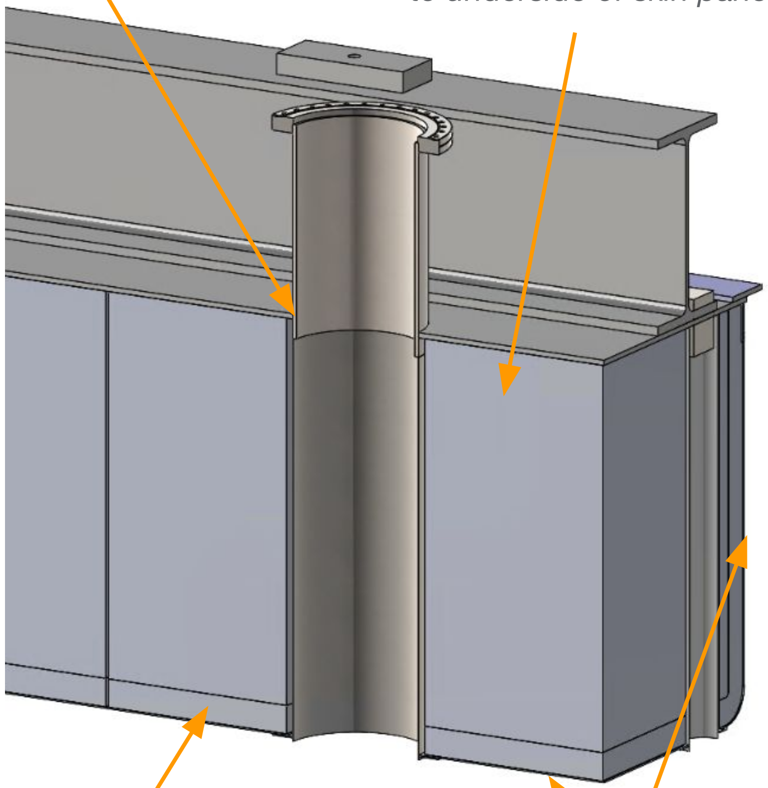
Natural Convection Schematic



ANSYS Quarter Symmetry Thermal-Structural Model

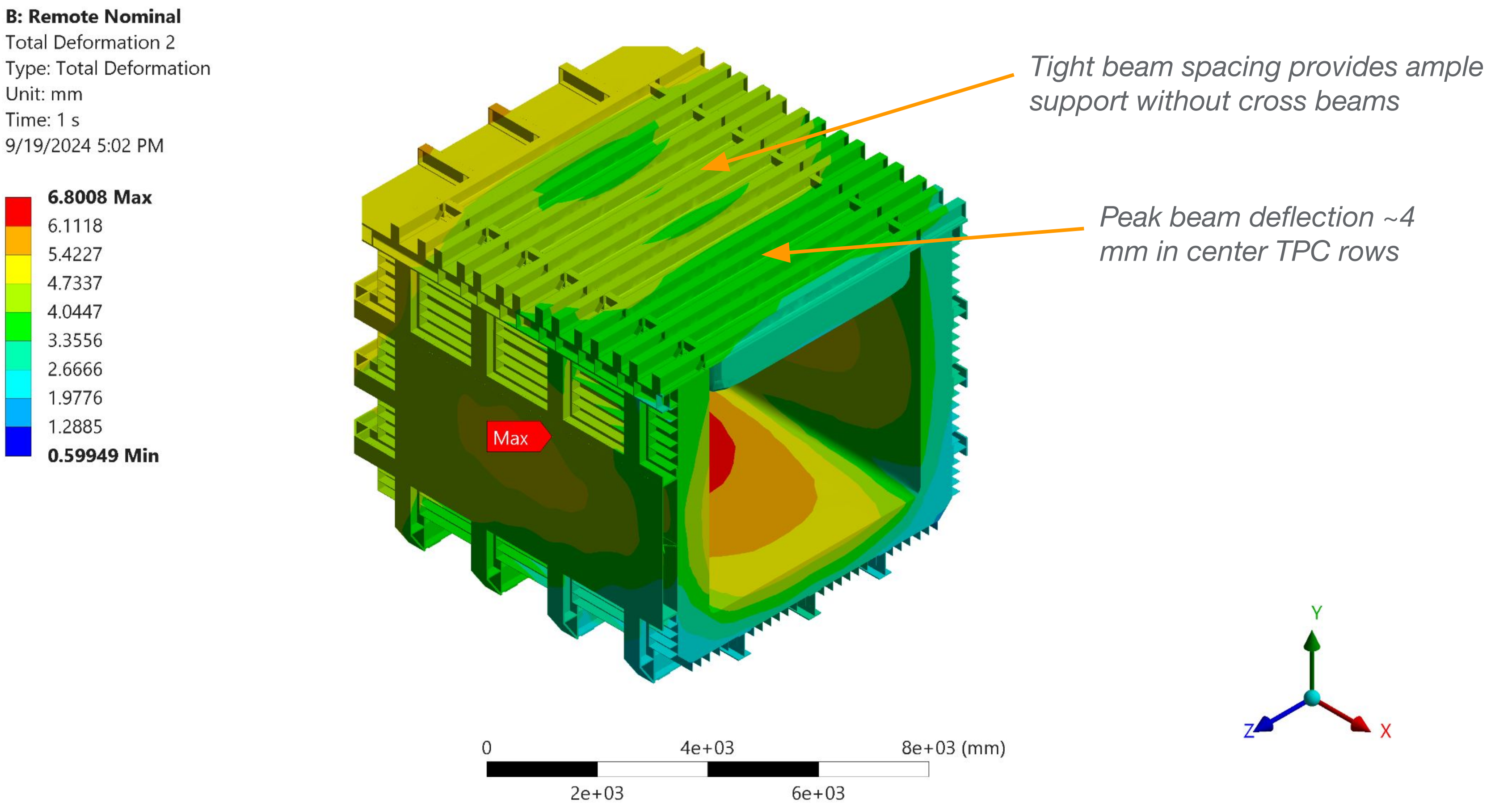
Lid structure is an I beam frame and skin panel, similar to warm structure





- Carbon steel I beams welded to SST skin panel form basic structure
- Small cross beams at ends provide torsional stiffness for handling
- No cross beam connections from lid to lid (analysis results in next slide)

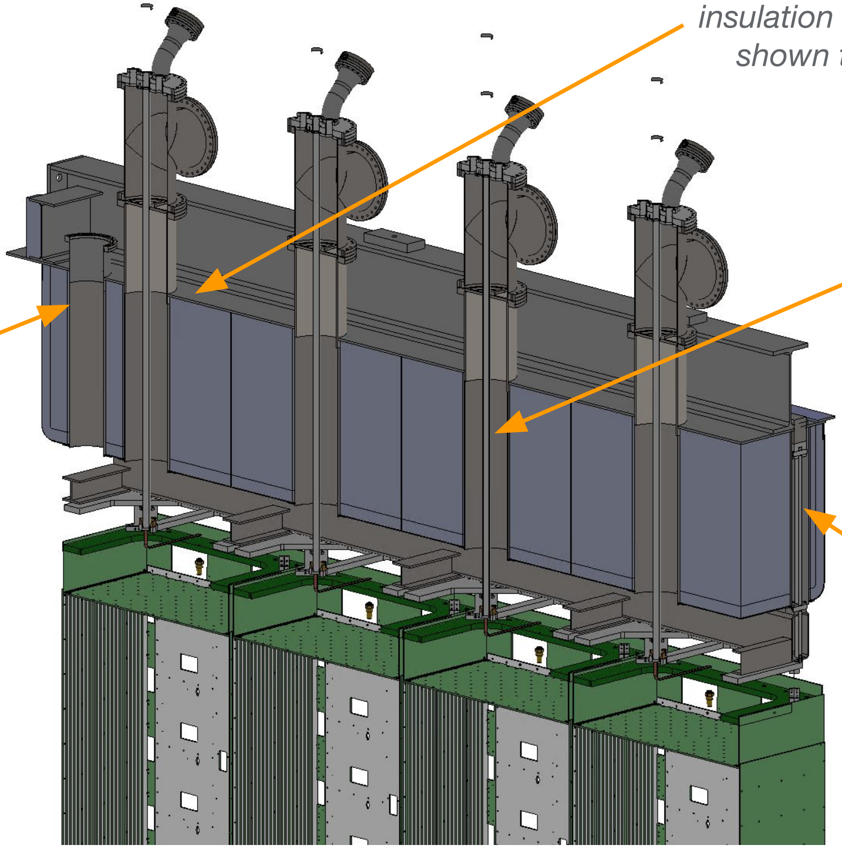
Analysis Results: Upsizing lid beams to W14x53 allows cross beams to be removed

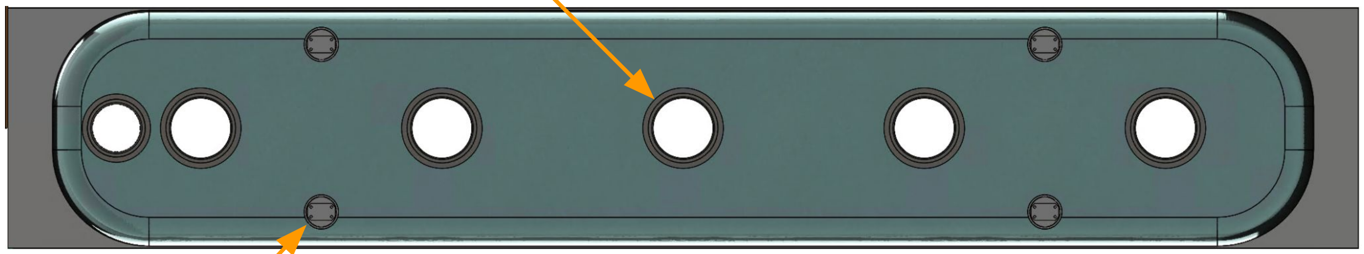


- <60 MPa beam stress (safety factor >7)
- ~4 mm deflection well under 10 mm TPC array displacement limit
- Larger beams add 2 tons but save complexity of connecting cross beam segments across lid sections

Charge # 2, 6.a

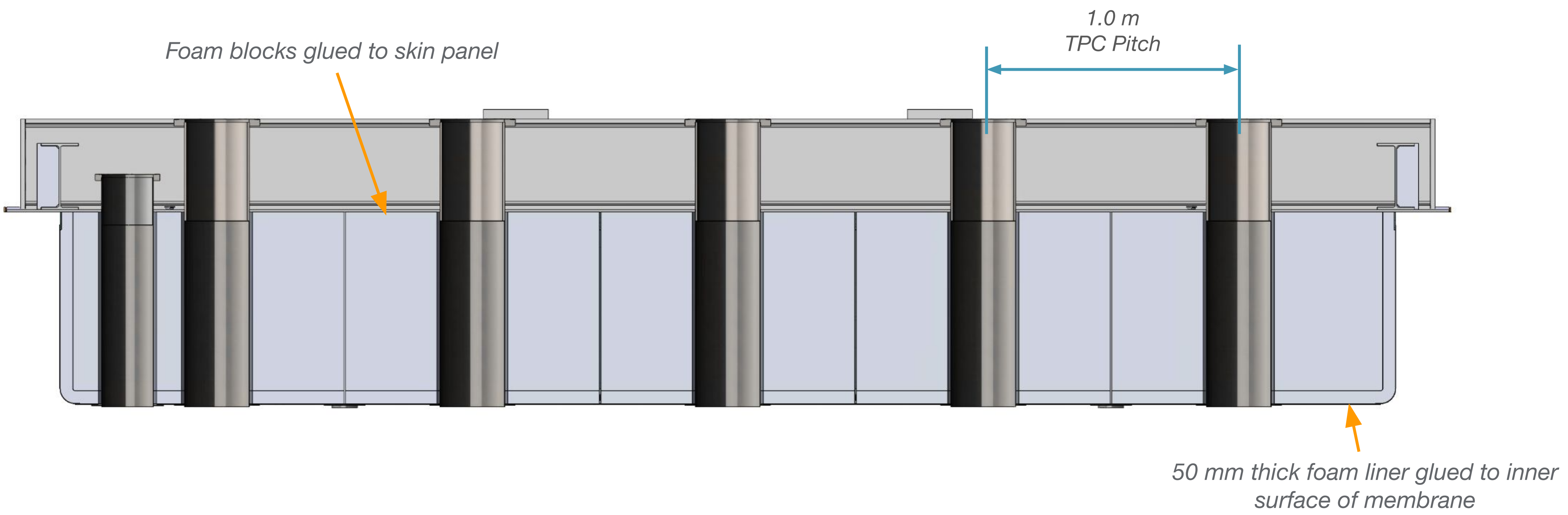
Feedthroughs for TPC cabling, LAr supply, TPC row support and N_2 Purge





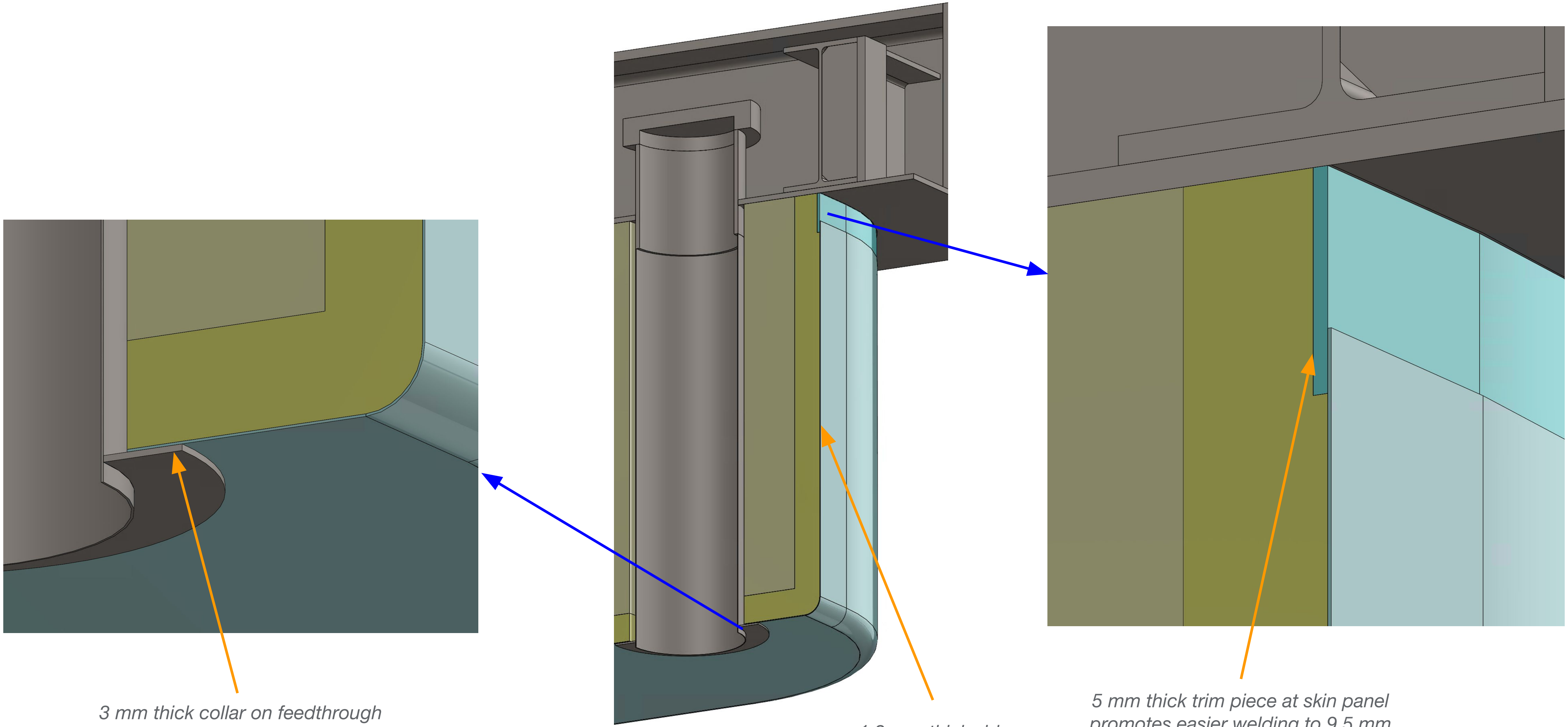
Foam Insulation Block Layout

Charge # 2, 6.a



- Foam cut into 1 x 1 m size pieces for easier fabrication and handling
- Liner supports thin membrane panels under pressure loads
- Clearances accommodate fabrication tolerances and differential thermal contraction
  - 6 mm clearance between blocks
  - 12 mm radial clearance to feedthroughs

Variable Membrane Thickness

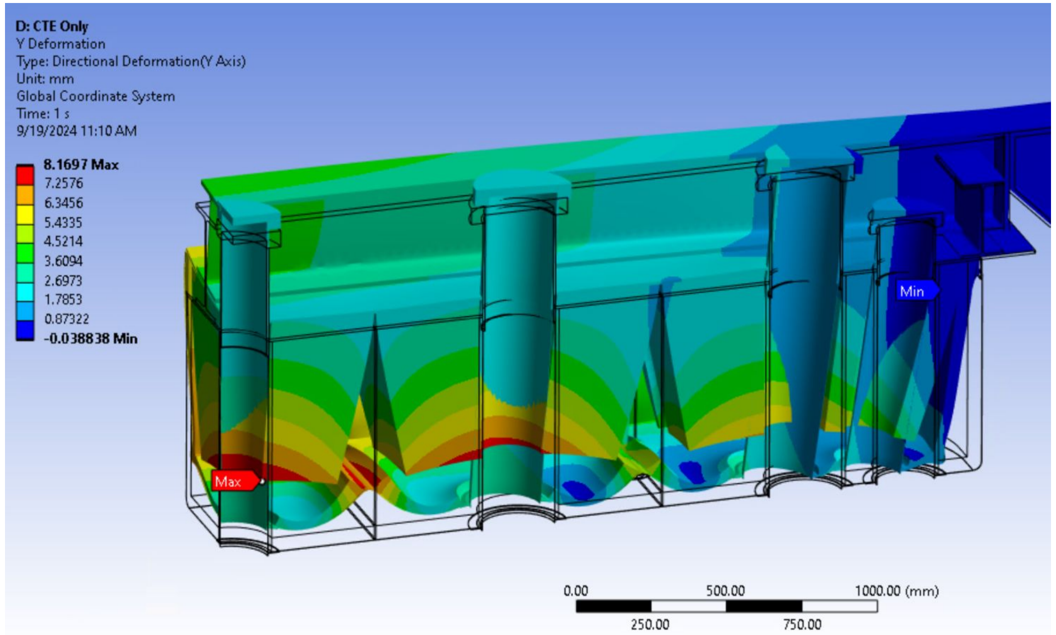


3 mm thick collar on feedthrough allows for lap joint and reduces stress at feedthrough interfaces

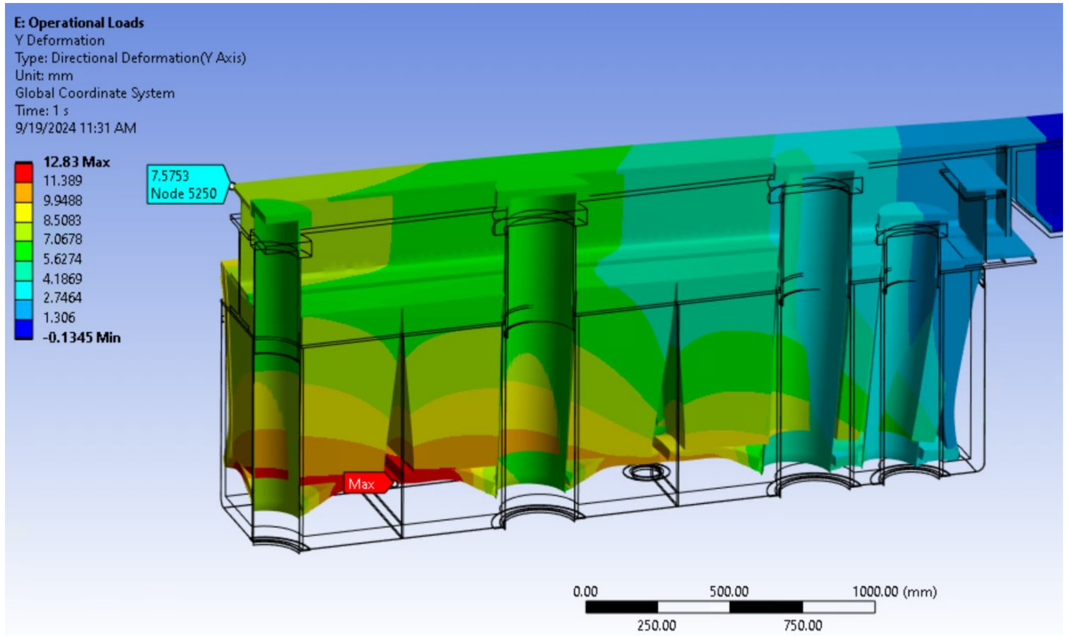
1.2 mm thick side walls reduce heat leak

5 mm thick trim piece at skin panel promotes easier welding to 9.5 mm skin panel

Structural-thermal analysis results show that more deflection occurs from cool down than pressure loads



***Cool Down**: 4.1 mm beam deflection (8.2 mm at foam), 25x scale*

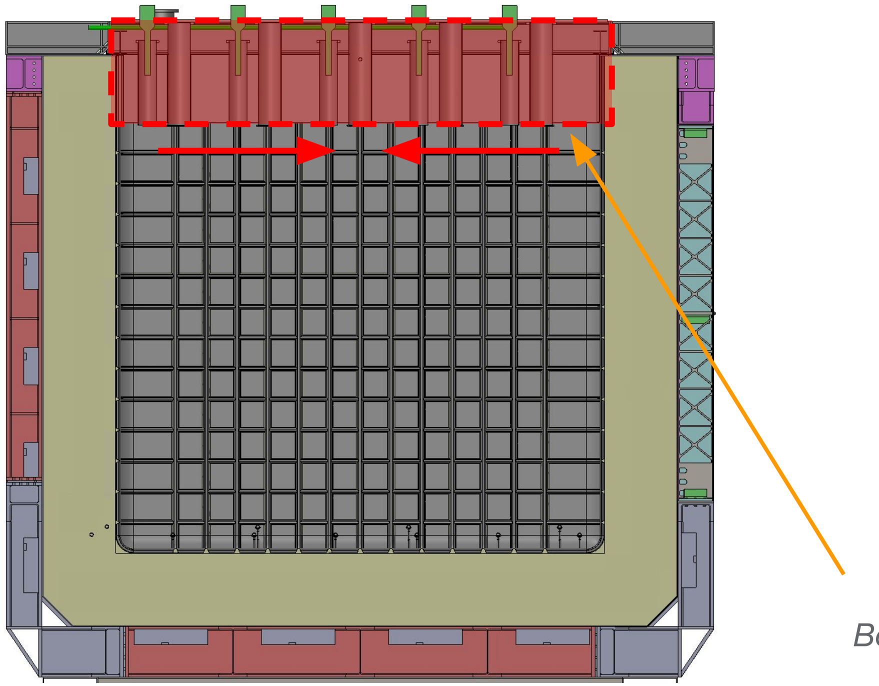


***Operation**: 7.6 mm beam deflection (12.8 mm at foam), 16x scale*

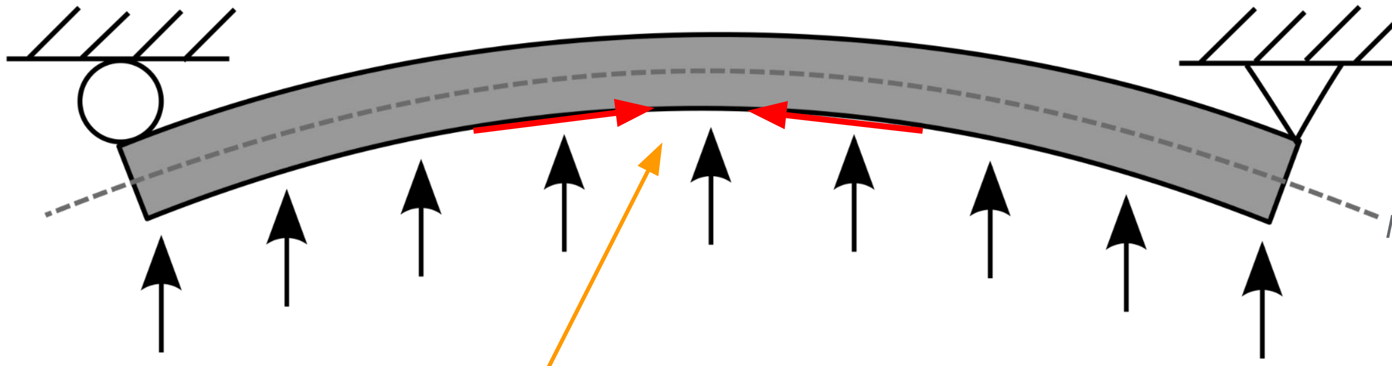
- Membrane acts as an extension of beam, increasing moment of inertia
  - Less deflection from pressure load than I beams alone
  - But membrane thermal contraction compresses bottom of beam, deflecting the center upwards
- Peak membrane stress currently falls between yield and ultimate strength using linear elastic material model
  - Need to reevaluate considering strain hardening and non-linear behavior
  - Evaluate using alternative criteria based on plastic strain limit rather than yield strength

Charge # 2

CTE-driven Beam Bending: Contraction below neutral axis imposes beam deflection similar to pressure load



Cross Section of Cryostat tub and TPC Row Lid Section (TPCs hidden for clarity)

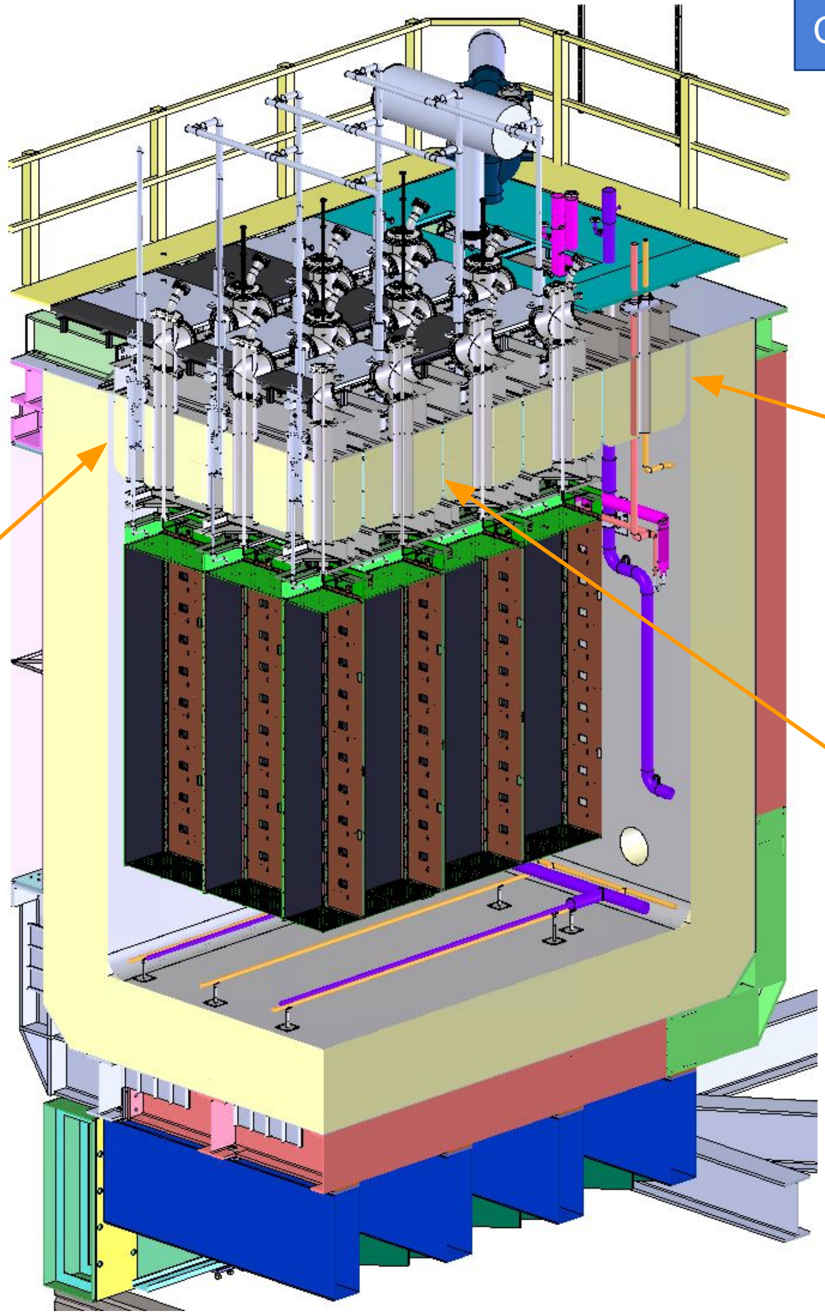


Bottom of lid is coldest and contracts the most, driving deflection of the beam similar to a distributed (pressure) load

Charge # 2

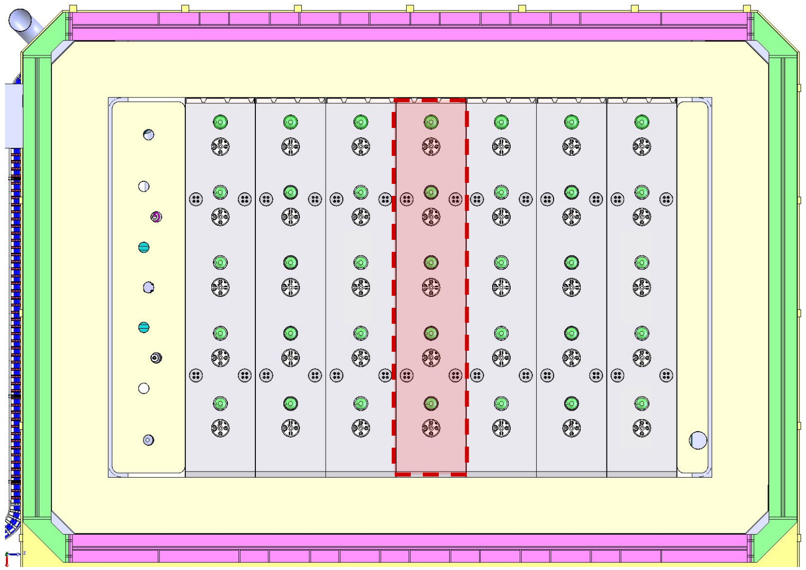
Natural convection analysis results allow for generous gaps between membranes

- Convection and conduction in the gaseous argon gaps have minimal impact on overall heat leak
    - Estimated **82 W total**, <1% of 10.7 kW cooling system target
- Minimizes chance of membrane damage during lid installation
- TPC to TPC gaps remain much smaller at 4 mm nominal



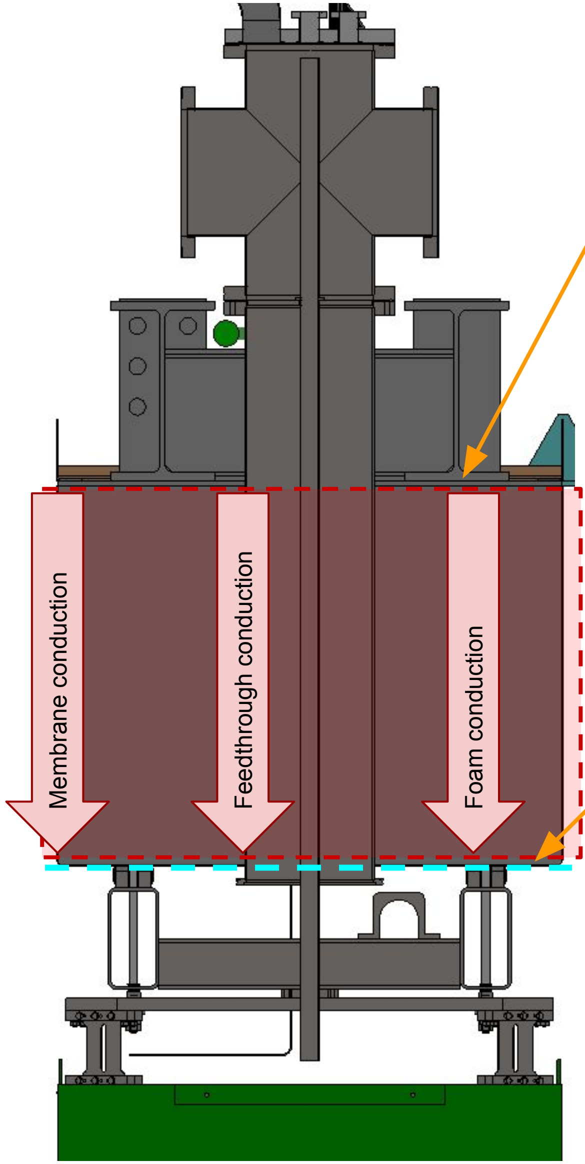
1D Conduction Heat Transfer Model Methodology

Charge # 2



Assume TPC row is representative and multiply by 9 for total lid estimate. Likely conservative given extra feedthroughs on TPC rows.

Analyze single TPC row



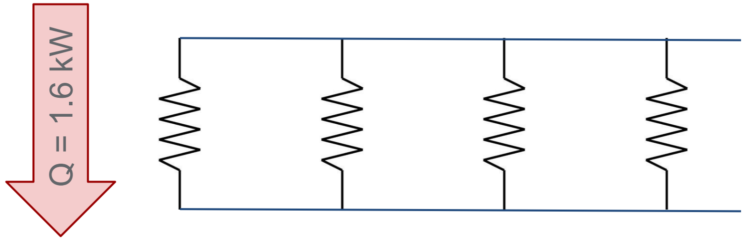
Neglect conduction resistance through warm membrane SST panel, convection resistance to ambient air

Warm membrane panel at 295 K [22 °C]

Neglect convection resistance from GAr to membrane and conduction resistance through membrane thickness

Membrane at 86 K, conservative assumption of LAr temp even though membrane is in GAr

1D Thermal Resistance Model



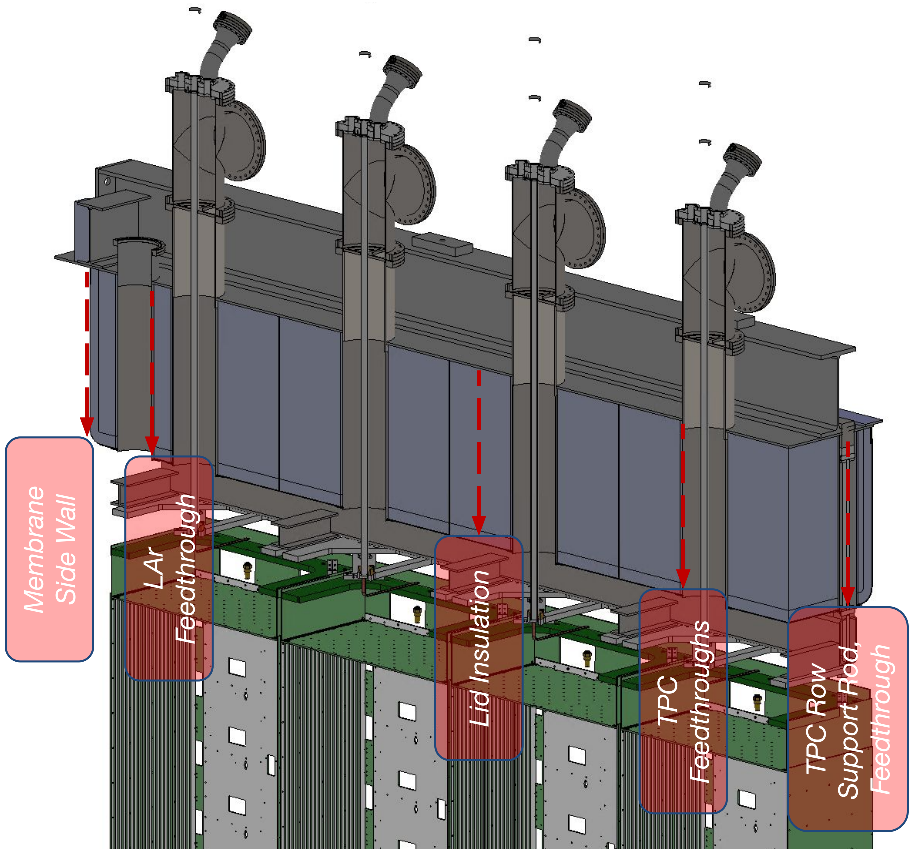
$T_{ambient}$ = 295 K

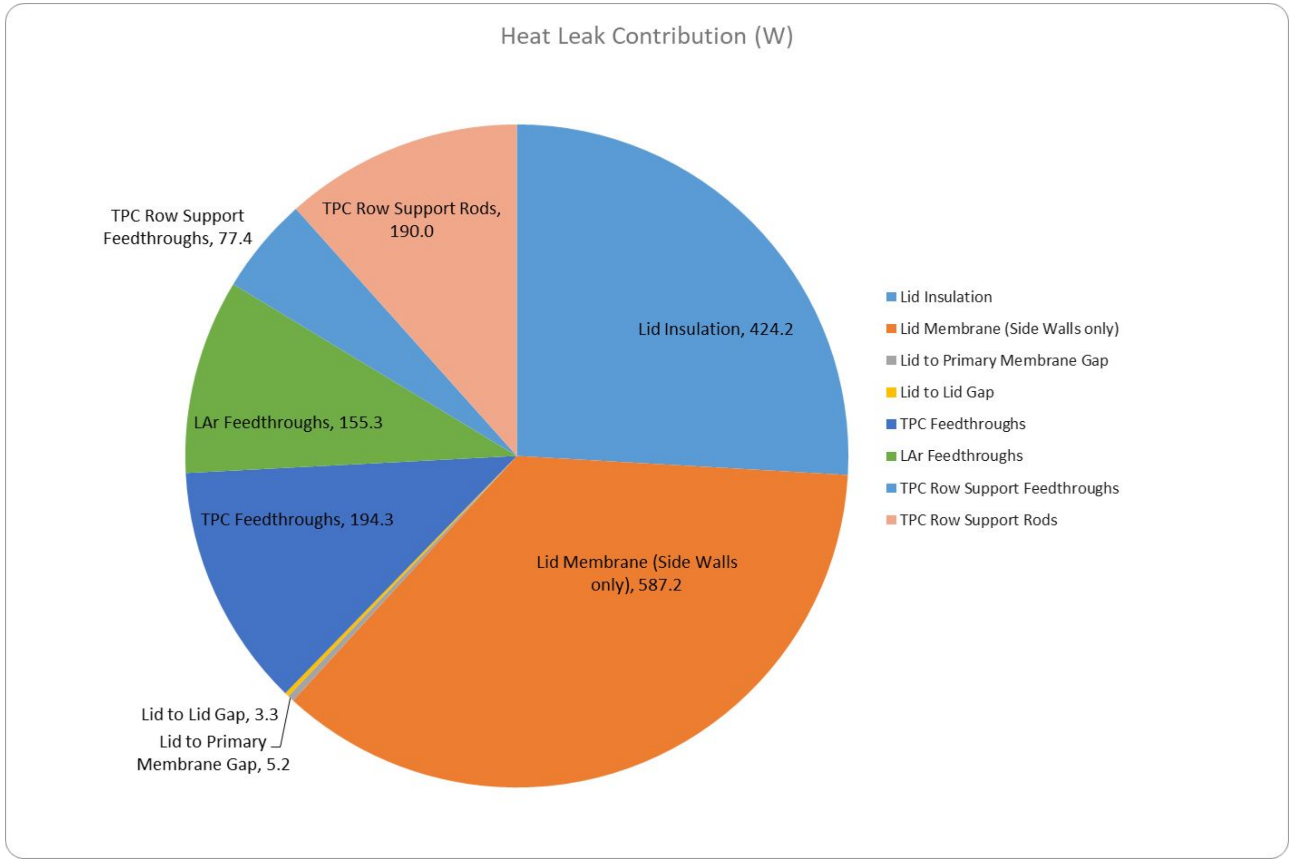
T_{LAr} = 86 K

$R_{conduction} = L/kA$

$Q = \Delta T/R$

1D conduction analysis indicates roughly equal heat leak from membrane side walls, insulation foam and feedthroughs (all combined)

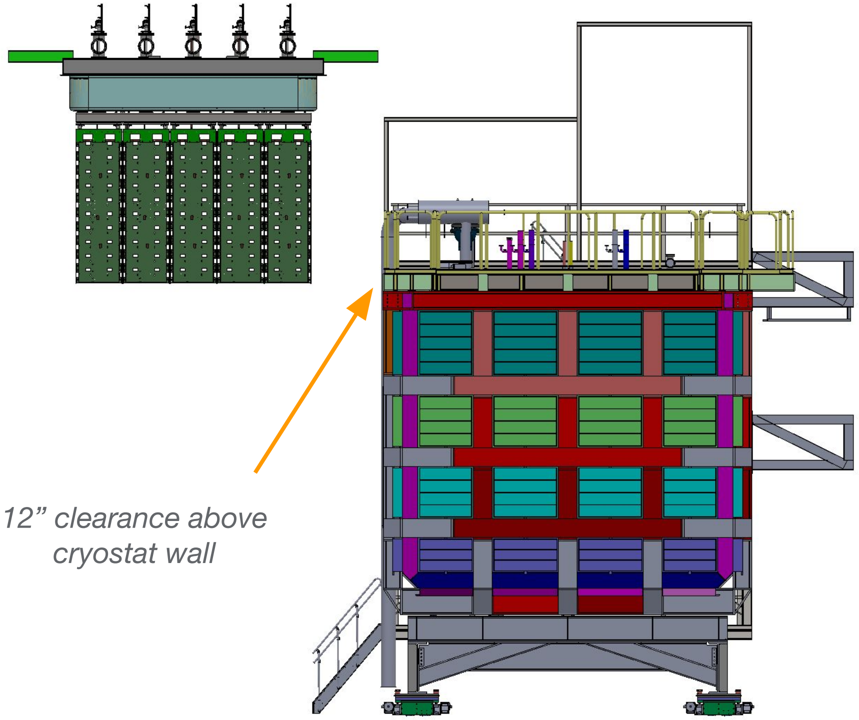


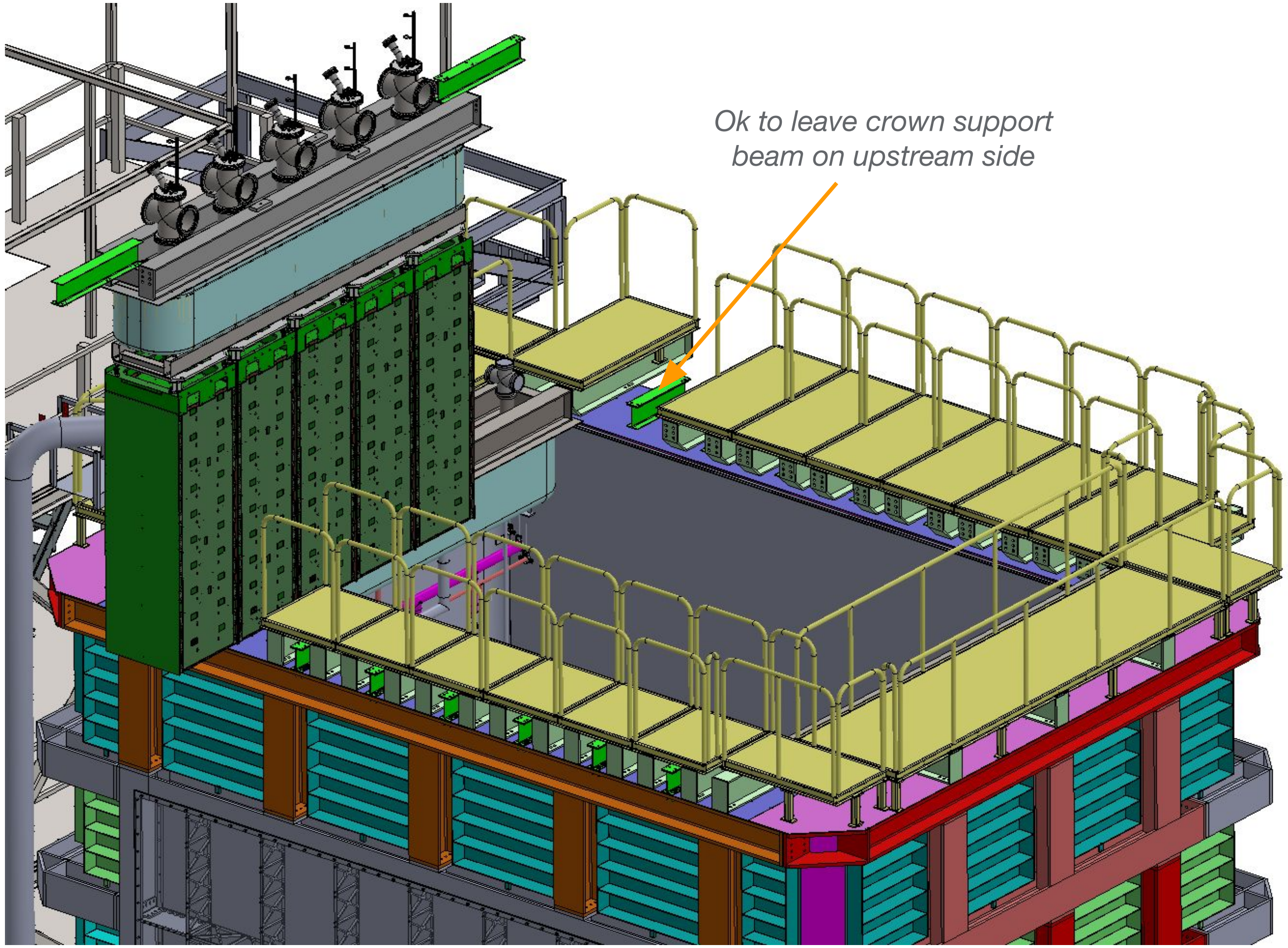


- These three majors sources each contribute roughly 500 W each to the **1640 W estimated total**
- Area specific lid heat leak 36 W/m^2 vs GTT cold membrane limit 10 W/m^2
- Worth optimizing membrane and feedthrough wall thickness to reduce heat leak

Installation Process

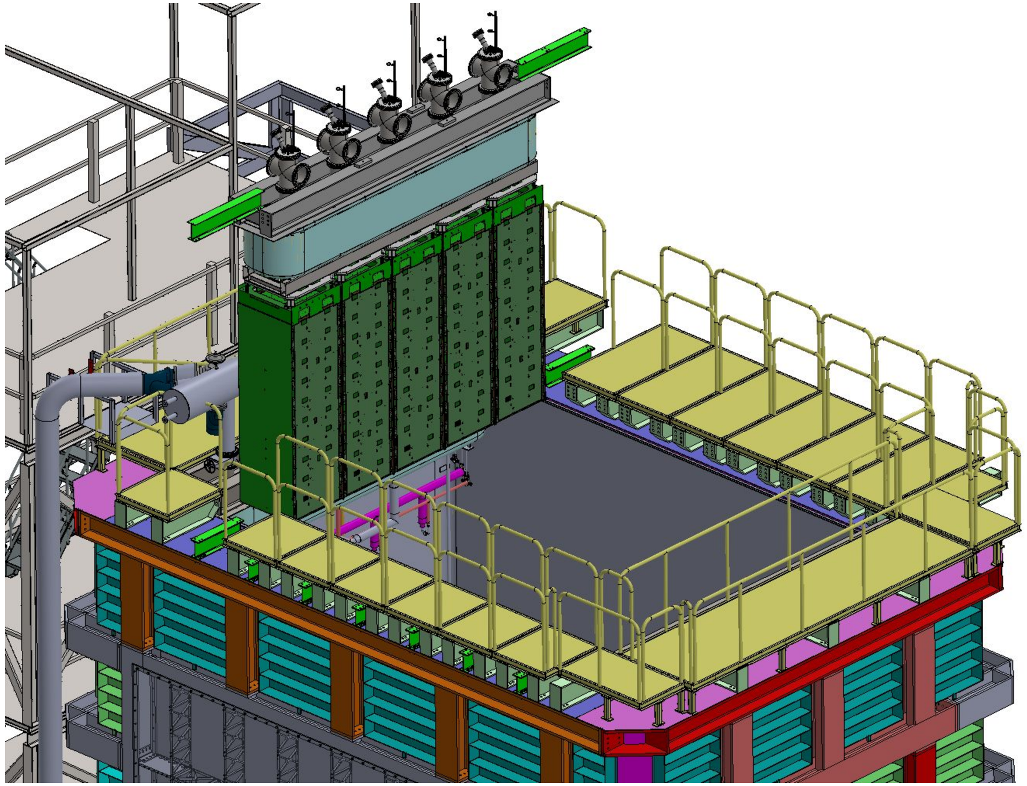
- Expected vertical clearance just 12” [30 cm]
  - Need to remove perimeter mezzanine panels (techs use fall protection harnesses during lid placement)
  - Need to remove crown support beam on downstream side
- Guides on ends of nearby mezzanine panels to be designed

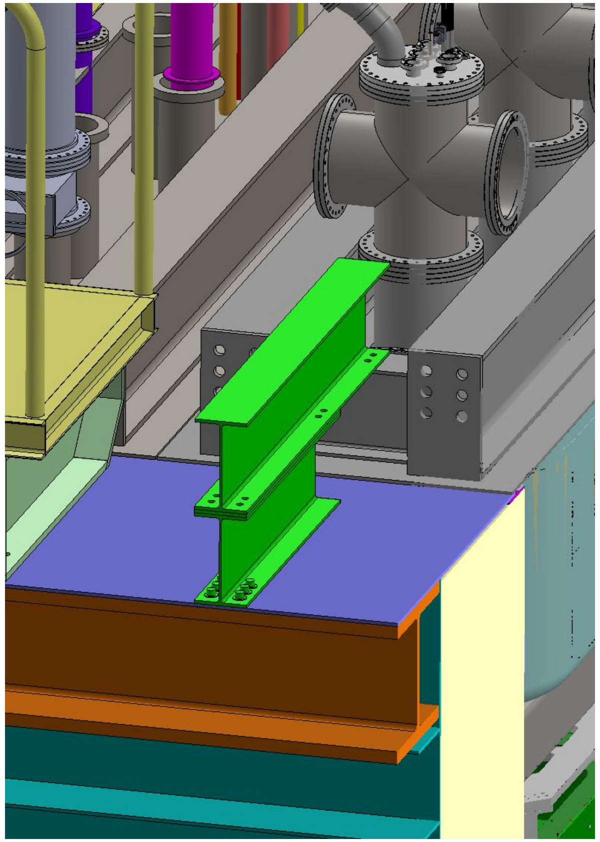


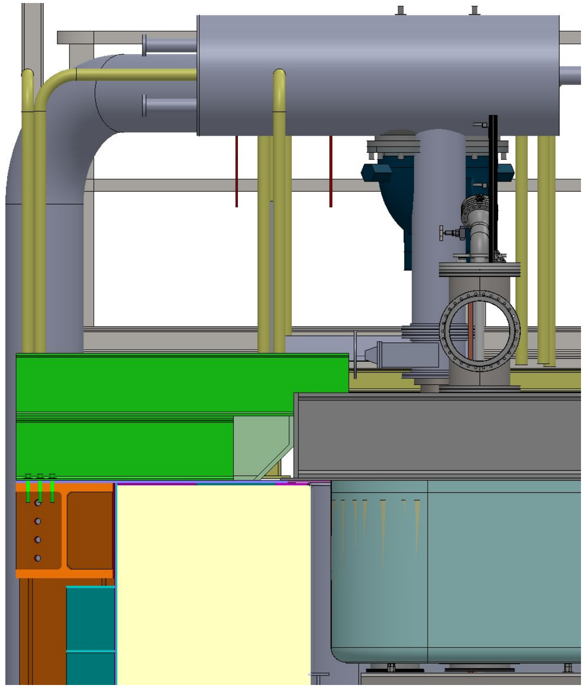


Installation Process

- Reinstall crown support beam
- Lower lid into place
- Horizontal guides (to be designed) key off of lid bracket mount holes

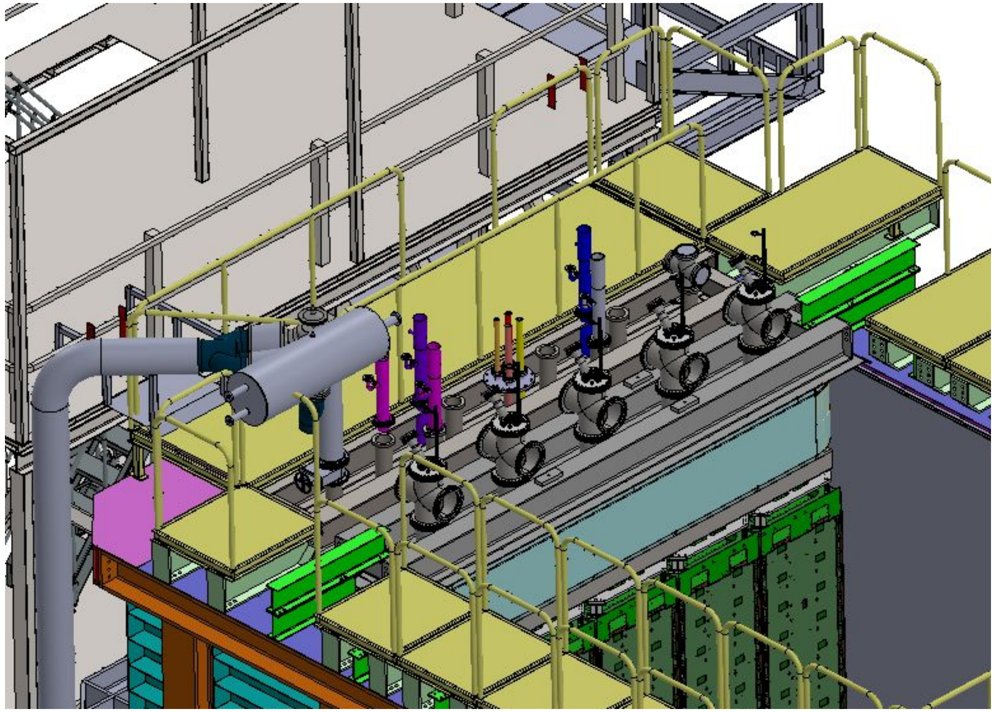


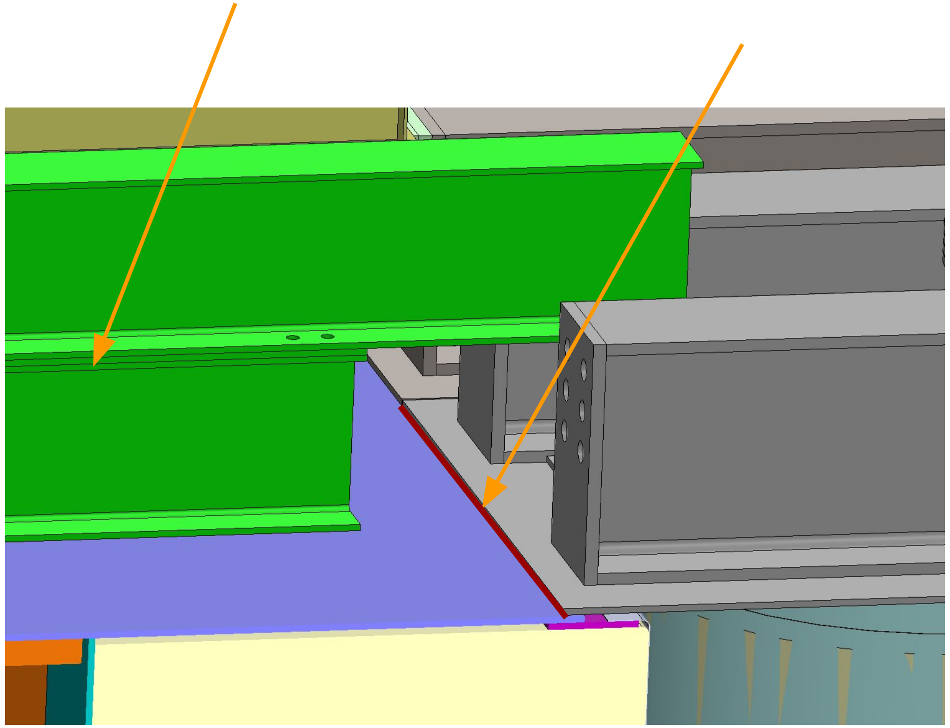




Installation Process

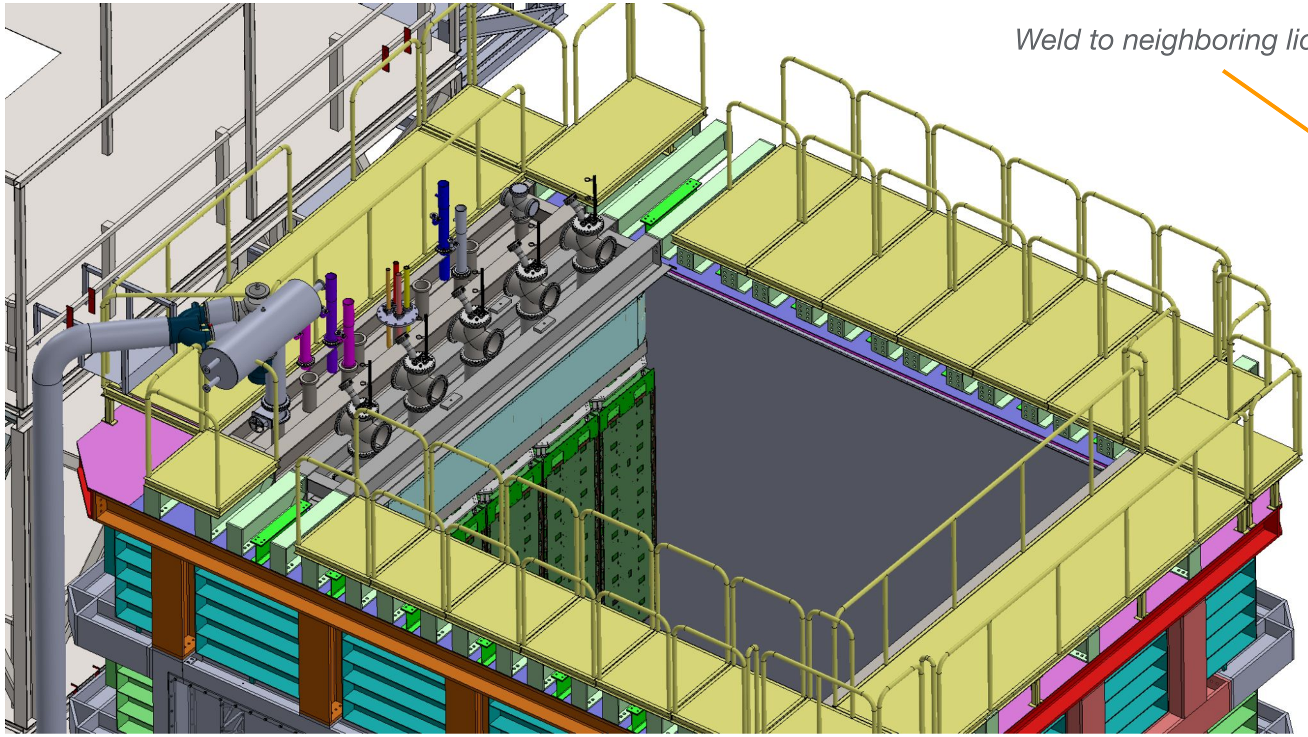
- Shims on crown support beams set height of lid
- Install temporary center support beams
    - Unlike final lid brackets, these offer significant clearance around the welds
- Weld ends (no people or equipment allowed on lid yet)
    - 250 x 250 mm envelope around weld

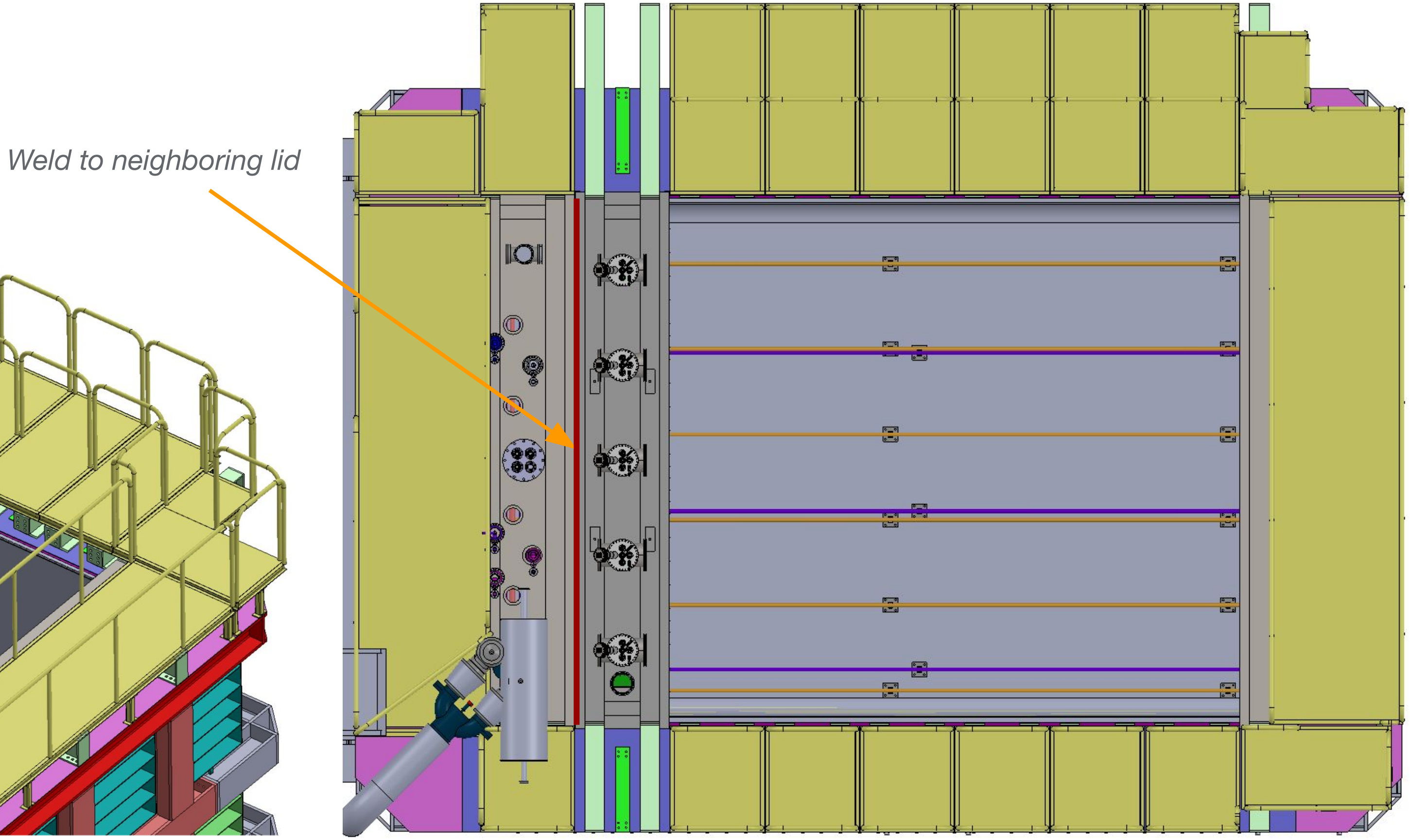




Installation Process

- Install all four final lid brackets
  - Large clearance holes ensure lid position is still set by shims
- Remove temporary center support beam
- Install internal mezzanine panels (ok to walk on lid and install equipment now that brackets take torsional load)
- Weld to neighboring lid

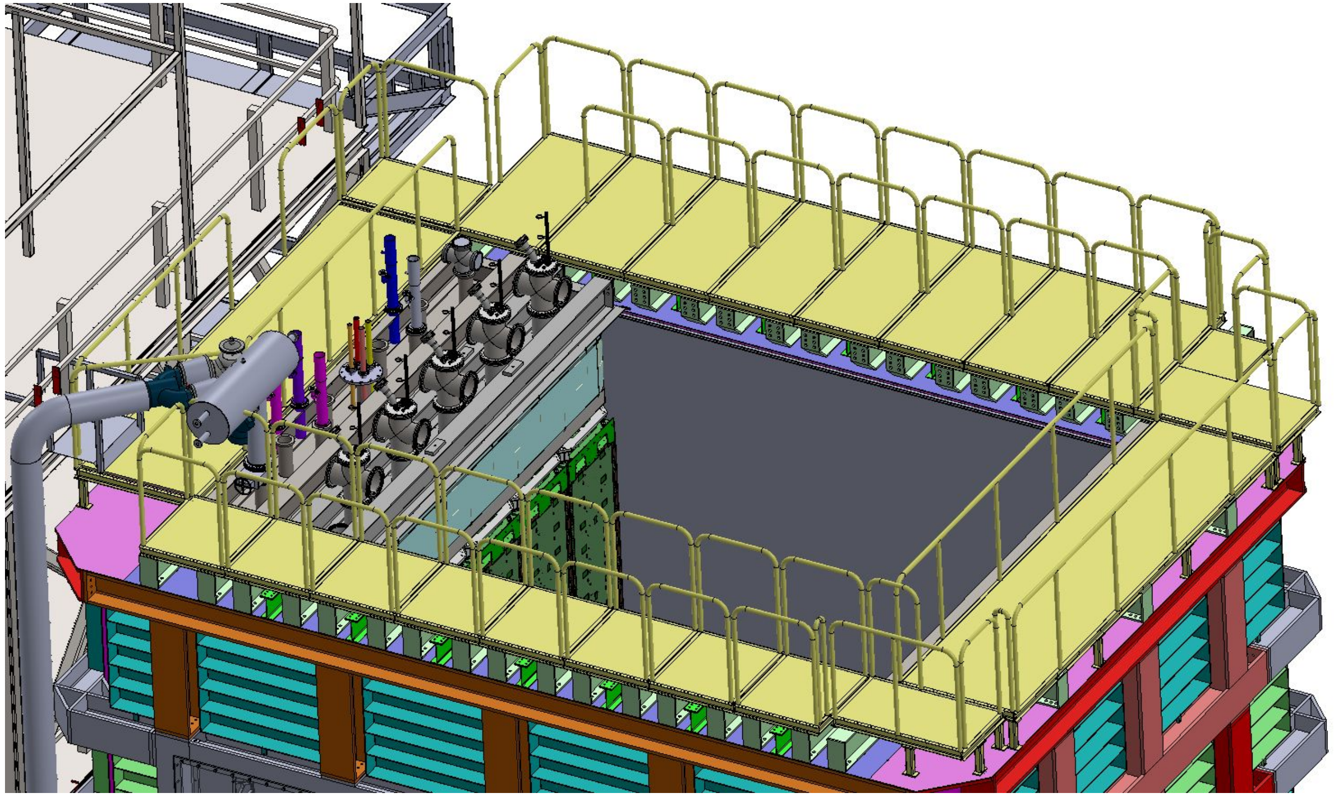




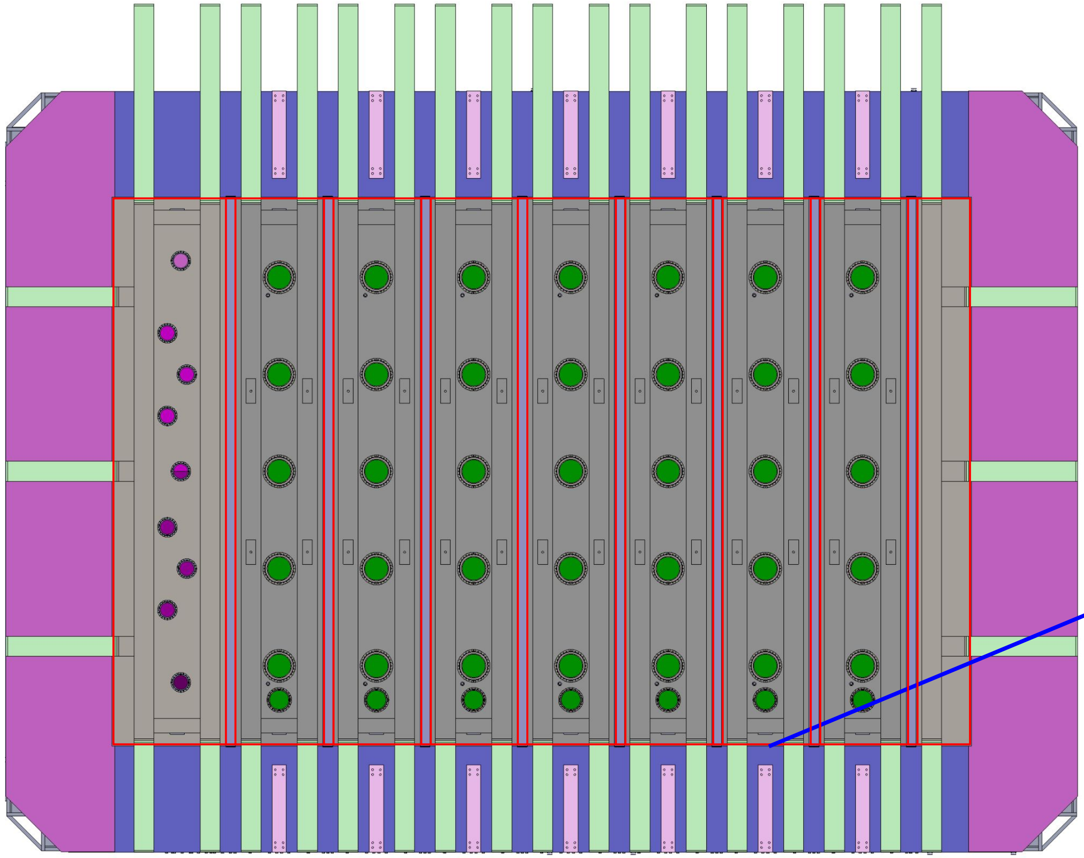
Charge # 6.b

Installation Process

- Reinstall perimeter mezzanine panels
- OK to walk around perimeter without fall protection harness
- Still need harness for accessing top of TPC row and installing ND-LAr components

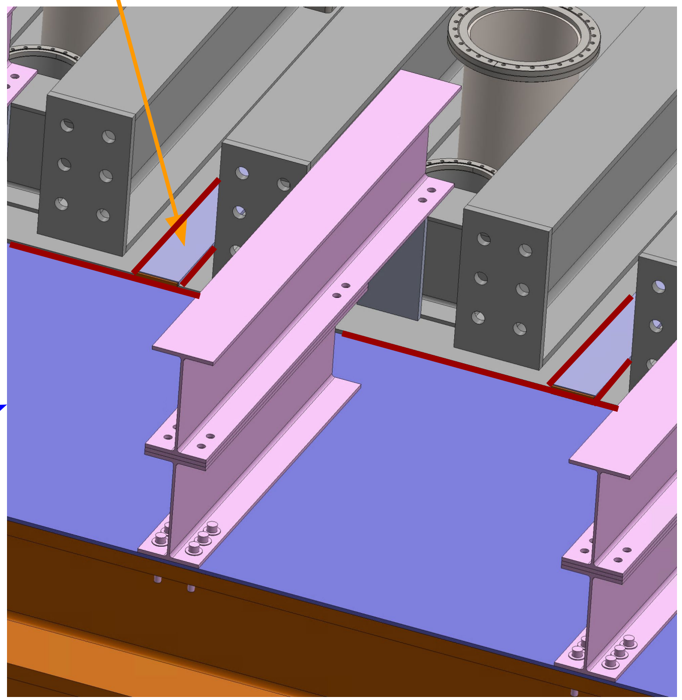


Lid hermetic welds



Top View
Field welds in red

⅜” thick bridge plates cover clearances between lids and serve as replaceable element



Lid to Lid

- Contamination risk is minimized because no welding or grinding operations happen directly over gaps between lid sections
- ⅜” bridge plates can be ground away and replaced without damaging lid sections

Manufacturing and Quality

Manufacturing

- Methods
  - I beams cut and machined
  - Plates cut and machined
  - Foam blocks cut and machined
  - Welding – structural and hermetic
  - Adhesive bonding
  - Painting
- Supplier pool
  - Experience with large assemblies such as rail, automotive, or aircraft components
  - Hoping to use same supplier as warm structure but not counting on it

Quality Assurance / Quality Control

- Dimensional inspection
  - Tie internal TPC fiducials to external lid section fiducials
  - Inspection points
    - After TPC Row integration
    - As-built after lid installation into Cryostat
    - Pressure test
- Fit check to warm structure using dummy lid

ND Hazard Analysis has informed lid design decisions

- Lid weld design minimizes chance of contamination
- Large clearances to primary cold membrane reduce risk of TPC and membrane damage
- Interior and exterior perimeter railings on mezzanine mitigate fall hazard

2. DUNE ND Hazard List — DUNE Near Detector Hazard List — DRAFT — Effective Date: 17-Dec-21 — Print Date: 13-Sep-24

Hazard Identification				Un-Mitigated Hazard and Risk Level					Mitigation Method / Updated Hazard and Risk Level						Verification	
#	Subsystem	Type	Title	Hazard Description	Severity	Probability	Risk Value	Risk Category	Mitigation Strategy	Mitigation Description	Severity	Probability	Risk Value	Risk Category	Verif Method	Verification Plan
3.01	NDLArCryoV	Mech	Fall from fully assembled cryostat	Cryostat work platforms are up to 30 ft above cavern floor; falls could result in serious injury or death.	1	D	8	Serious	Safety device	Use railings on stairways and elevated work platforms. If railings are removed for service procedures, use fall protection harnesses and anchor points on cryostat structure.	1	E	12	Medium	Audit	Verify railings and fall protection are compliant with relevant OSHA standards. Verify I&I process documents address fall protection.
3.02	NDLArCryoV	Mech	Fall from cryostat during construction	Cryostat work platforms are up to 30 ft above cavern floor; falls could result in serious injury or death.	1	D	8	Serious	Safety device	Use fall protection harnesses when working on scissor lifts, scaffolding and other elevated work platforms used to assemble cryostat.	1	E	12	Medium	Audit	Verify temporary work platforms and fall protection are compliant with relevant OSHA standards. Verify I&I process documents address fall protection.
3.03	NDLArCryoV	Env	Oxygen deficiency hazard inside of cryostat	Internal cryostat volume will be full of argon in operation. If volume is not adequately purged before personnel enter for service, ODH condition will exist.	1	C	4	High	Control hazard	All cryostat service to be performed from outside or after removing components from internal volume. No personnel access to inside of cryostat.	1	E	12	Medium	Audit	Verify no Cryostat elements require internal access for I&I or service. Verify no inspection, manufacturing and service documents reference accessing cryostat internals after lid is closed.
3.04	NDLArCryoV	Env	Confined space inside of assembled cryostat	Internal cryostat volume is a confined space with associated personnel extraction and access hazards.	3	C	11	Medium	Control hazard	All cryostat service to be performed from outside or after removing components from internal volume. No personnel access to inside of cryostat.	3	E	17	Medium	Audit	Verify no Cryostat elements require internal access for I&I or service. Verify no inspection, manufacturing and service documents reference accessing cryostat internals after lid is closed.
3.05	NDLArCryoV	Env	Confined space inside of cryostat during warm and cold structure installation	Internal cryostat volume is a confined space with associated personnel extraction and access hazards.	3	A	7	Serious	Safety feature	Use stair towers both inside and outside of cryostat when installing warm structure and cold structure into open tub.	4	A	13	Medium	Audit	Verify stair towers are compliant with relevant OSHA standards. Verify I&I process documents address confined space requirements.
3.06	NDLArCryoV	Env	Confined space under cryostat and between beams of PRISM frame	Area under cryostat and between PRISM frame is a confined space with associated personnel extraction and access hazards.	3	B	9	Serious	Control hazard	Limit PRISM frame assembly operations performed in cavern. Any ongoing inspection and service required on the PRISM frame to be performed from the outside.	3	D	14	Medium	Audit	Verify no PRISM frame elements require access underneath cryostat for inspection or service. Verify no inspection, manufacturing and service documents reference accessing area under cryostat after warm structure is built.
3.07	NDLArCryoV	Env	Confined space between cryostat and cavern wall	Area between cryostat upstream wall and cavern is a confined space with associated personnel extraction and access hazards.	3	B	9	Serious	Procedure, training	Limit cryostat upstream wall assembly operations performed in cavern. Lock out / tag out of energy chain while accessing area as energy chain passes through this area in operation.	3	D	14	Medium	Audit	Verify cryostat and PRISM I&I procedures require lock out / tag out when accessing area between cryostat and cavern wall. Verify no inspection, manufacturing and service documents reference accessing area between cryostat and cavern wall after warm structure is built.
3.08	NDLArCryoV	Press/ Vac	Cryostat overpressure leads to cryogen leak	Exceeding design pressure of cryostat may damage warm structure, resulting in cryogen leak into cavern and oxygen deficiency hazard.	1	C	4	High	Safety device	Dual pressure relief valves prevent cryostat gas pressure from exceeding design pressure. Structural safety factors and analysis draw upon accepted standards. Cavern moat contains potential argon spill so that ODH condition does not occur at cavern floor working level.	1	E	12	Medium	Test	Test pressure relief valve function during Cryostat I&I.

Excerpt of Cryostat entries from Hazard List (EDMS 3165698)

Charge # 3, 4

Lid risks to be mitigated by 5 Module Row Pre-production testing beginning in 2025

RI-ID	Title	Probability	Schedule Impact
RT-131-ND-257	ND Cryo: Cold membrane design fails downstream density requirement due to tech limitation	30%	6 -- 9 -- 12 months
RT-131-ND-295	ND Cryostat: Tight TPC alignment clearances drive tight Cryostat tolerances	50%	0 months
RT-131-ND-308	ND Cryostat: Revert Cryostat Muon Window to Composite Design	20%	12 months
RT-131-ND-294	ND Cryostat: Cryostat Cold Membrane Single Vendor	35%	3 -- 6 -- 9 months
RT-131-ND-330	ND-LAr: TPC modules damaged during installation into Cryostat	15%	3 months
RT-131-ND-327	ND Cryostat: Cryostat deflection during pressure test differs from analysis results	25%	1 -- 3 -- 6 months
RT-131-ND-328	ND Cryostat: Cryostat fails pressure test due to leak rate	5%	3 -- 6 months

- 5 Module Row Pre-production testing will reduce probability of (or retire) TPC alignment and installation risks
- FNAL risk registry

Path to Final Design

Charge # 2

- Perform structural-thermal analysis using strain based approach
- Bolted joint calculations and sizing
- Fabricate TPC Row lid section to support 5 Module Row Pre-production testing
- AISC 360 analysis by structural engineer
- Vendor selection
- Vendor quotes and feedback