DUNE-ND LArTPC Cryostat Warm Structure

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U.S. DEPARTMENT OF ENERGY | Office of Science

BERKELEY LAB

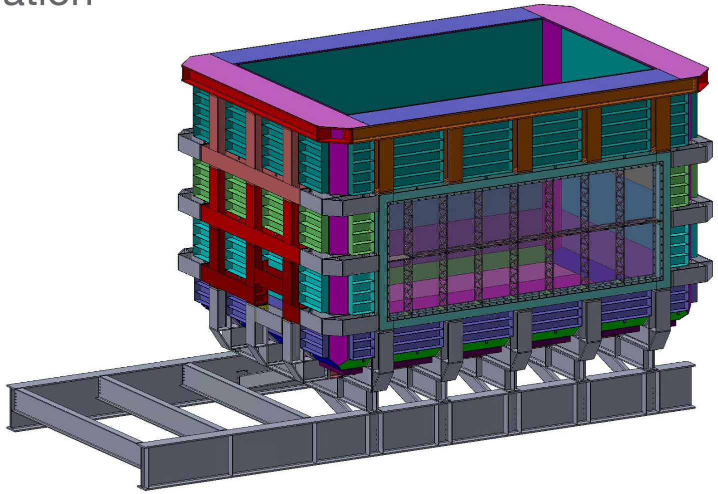
Requirements and Interfaces

Charge # 1, 6.a, 6e, 6.f

- FESHM 5031.7 Membrane Cryostats
    - Warm structure 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
    - Pressure test of final assembly (250 mbar pneumatic)
- GTT Interfaces
    - As built interior dimensions
        - Flatness 4mm / m at I beams, 15mm overall
        - Corner perpendicularity 5mm over first 500mm
    - Deflection under load
        - Flatness 4mm / m at I beams
        - Corner perpendicularity 0.5 degrees

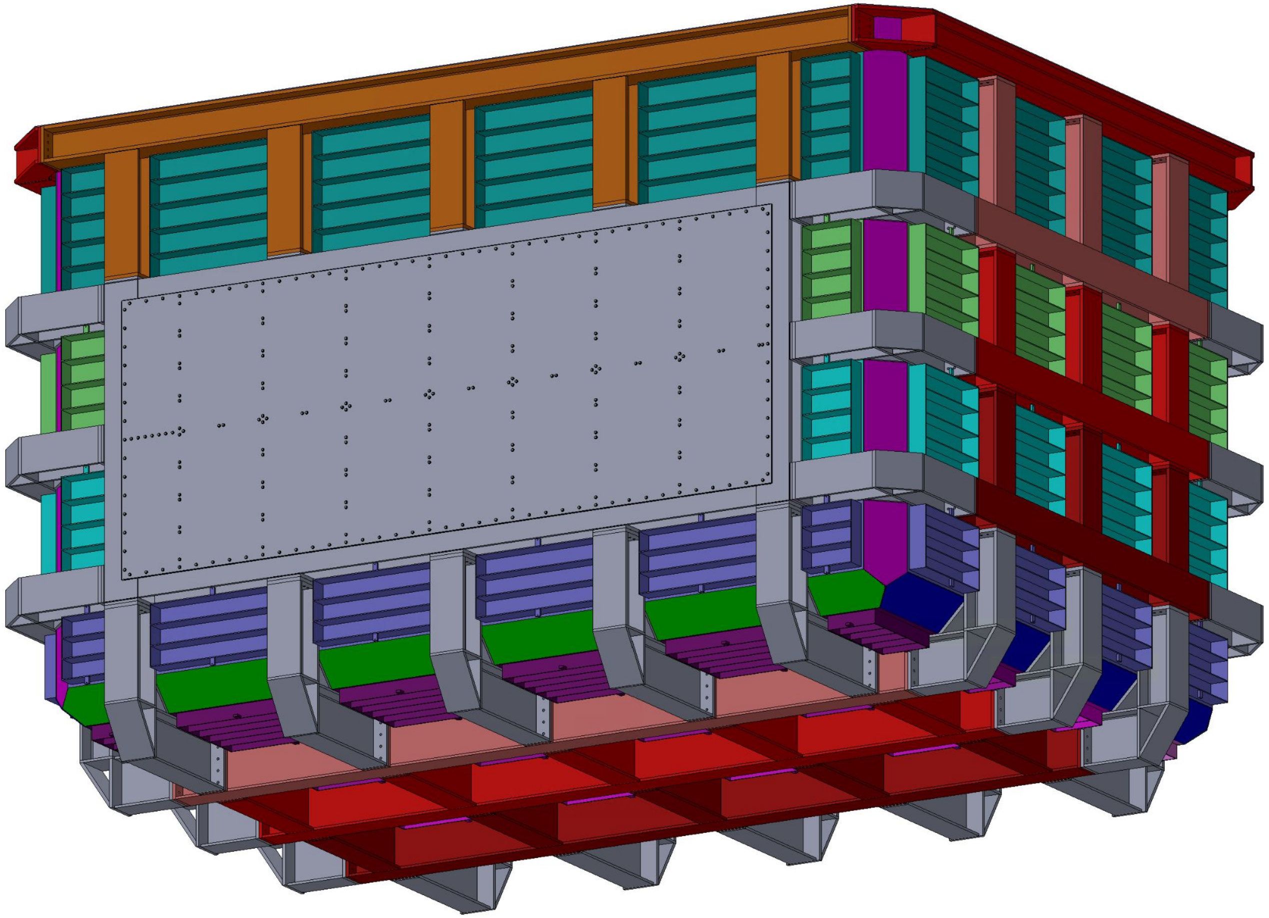
Interfaces and Boundary Conditions with PRISM Subframe

- Mechanical interface
  - This is a key difference with SBND (warm structure mounted on steel subframe instead of concrete)
  - Metrology and shimming plans are designed to provide appropriate flatness for installation
  - Analysis shows it is not a problem (see EDMS 3161162 report and later slides)
- Dynamic effect
  - Lateral acceleration on the order of a few 1e^{-3} g
    - Negligible effect on structural deformations
    - Negligible effects on liquid argon sloshing
    - To be verified by testing, but preliminary analysis suggests significant margin
  - Natural frequencies
    - Targeting suspension modes in the 2-10 Hz range, both horizontal and vertical directions
    - Mostly driven by the requirements of the rollers (need lateral and vertical compliance to accommodate rail imperfections)
    - The isolation provided will be beneficial to the detectors
    - Modes should be close to critically damped, and therefore will not couple with payload modes
    - Tilt-horizontal coupling is negligible with modes in this frequency range

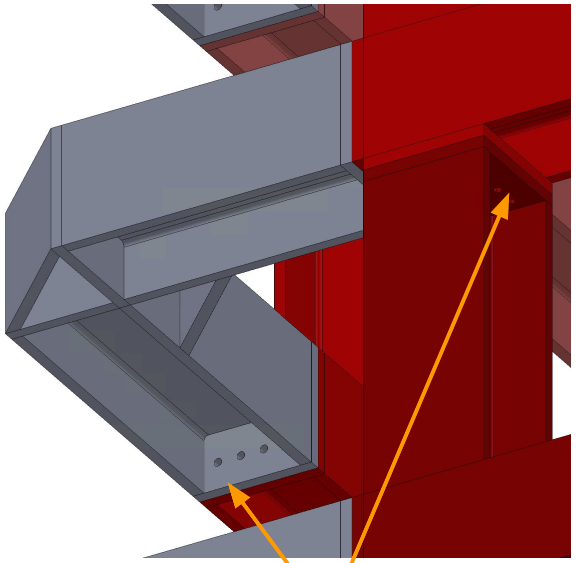


Design Overview

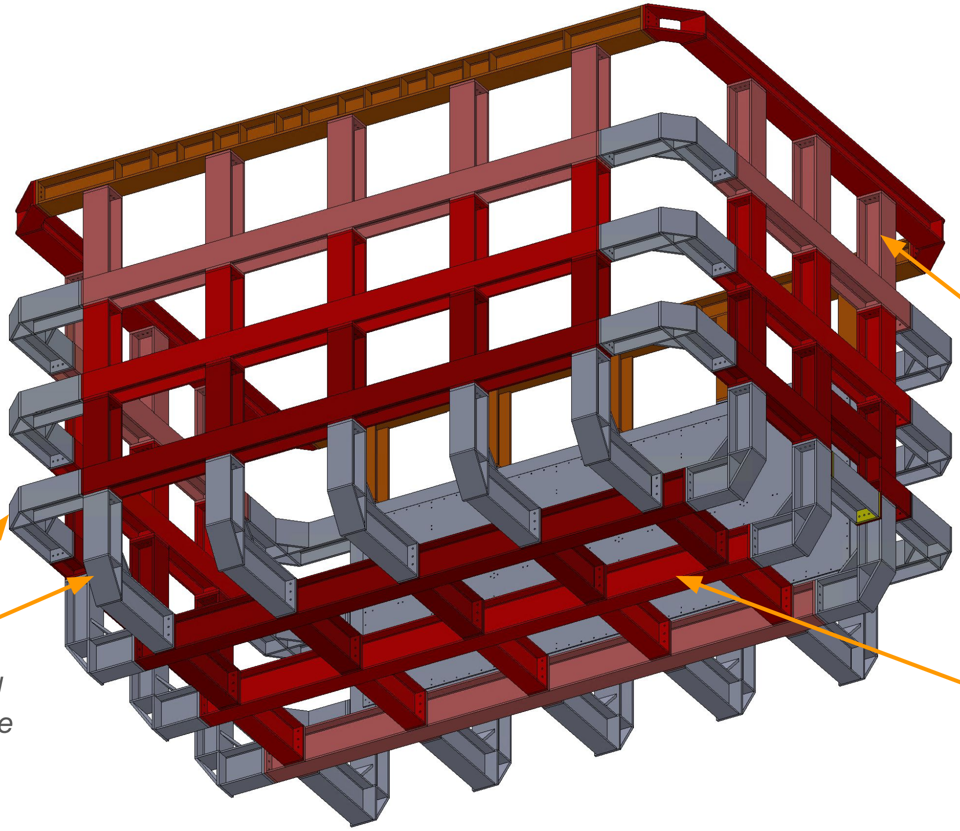
- 11.0 x 7.8 x 6.9 m (L x W x H) outside dimensions
- 117 metric tons [129 US tons] of steel weldments
- S460ML steel
  - 460 MPa [67 ksi] yield strength
    - Safety factors assume alternate A572-65 steel at 65 ksi [448 MPa]
  - 17% elongation at failure
- Manufacturing methods
  - I beams cut and machined
  - Plates cut and machined
  - Welded subassemblies
  - Bolted final assembly
  - Painting
- Part count
  - 43 I beam frames
  - 35 Warm membrane panels
  - 1 Muon Window



I Beam Frame Assemblies



Weldments connected by bolt plates on ends of I beams



Custom shapes at edges and other reinforcements are made from cut and welded plates

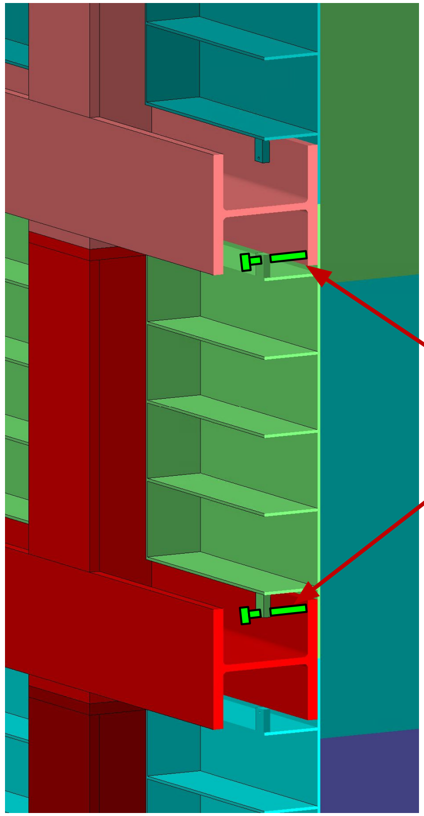
W14x193 I beams on side walls

W21x132 I beams on bottom panel

- Weldments to be fabricated in place during test build at factory
  - Earlier weldments essentially act as fixtures for later ones
- Tolerances applied to final assembly, not parts
  - Part tolerances and non-critical assembly tolerances governed by ANSI/AISC 360-22

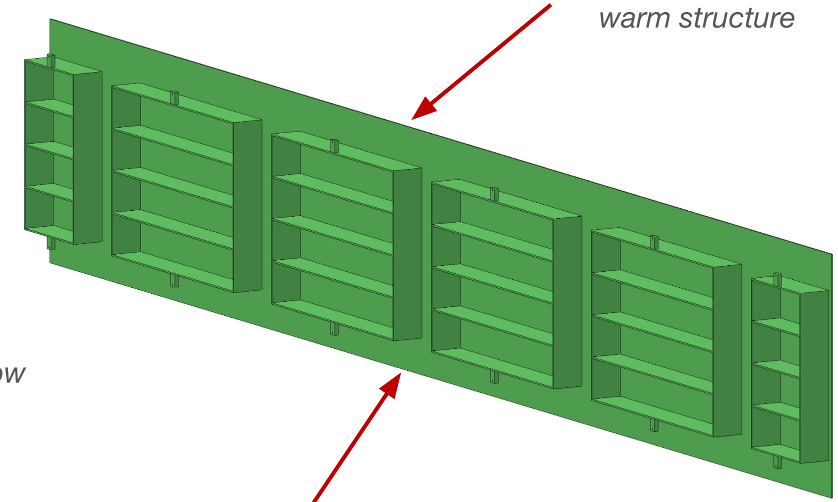
Charge # 2

Skin Panels (Vapor Barrier)

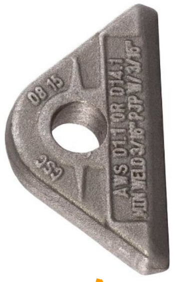


Threaded blocks allow for panels to be clamped to I beams

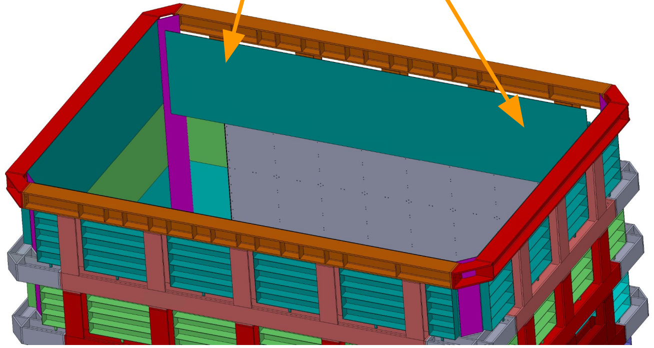
⅜” [9.525 mm] panels line entire interior surface of warm structure



Perimeter to be welded to neighboring panels to seal insulation volume from ambient air

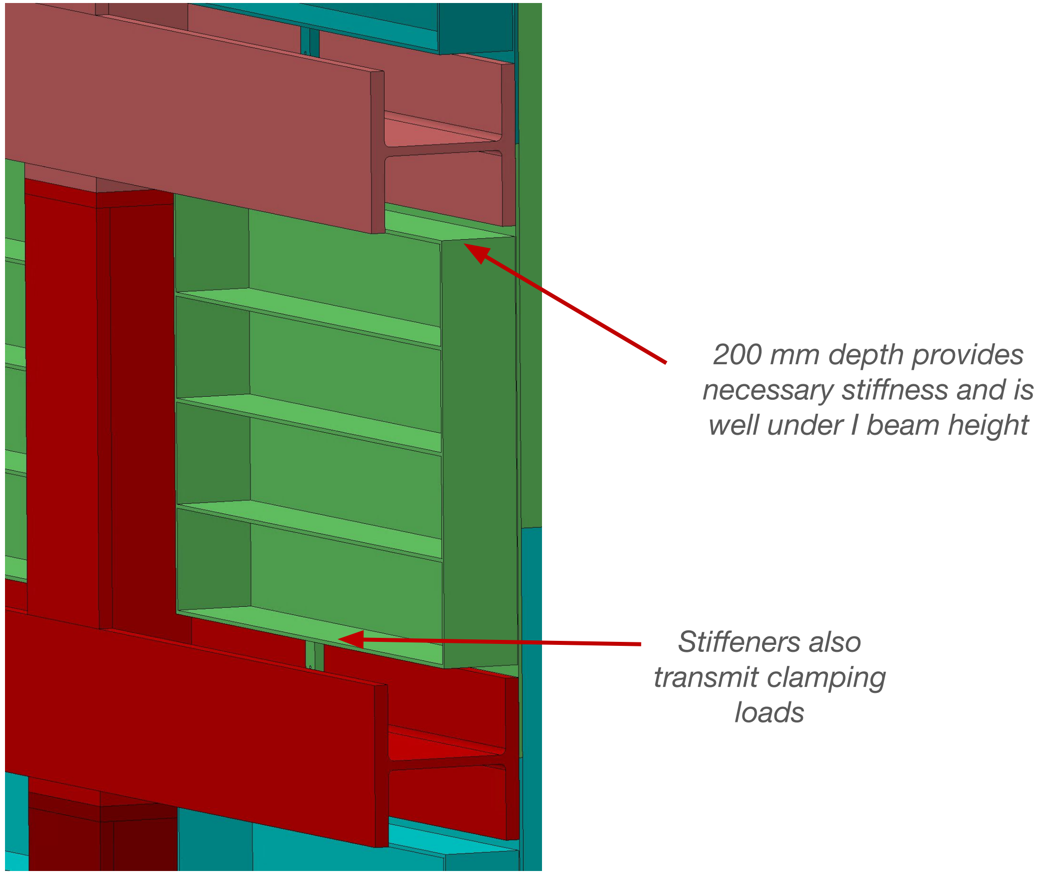


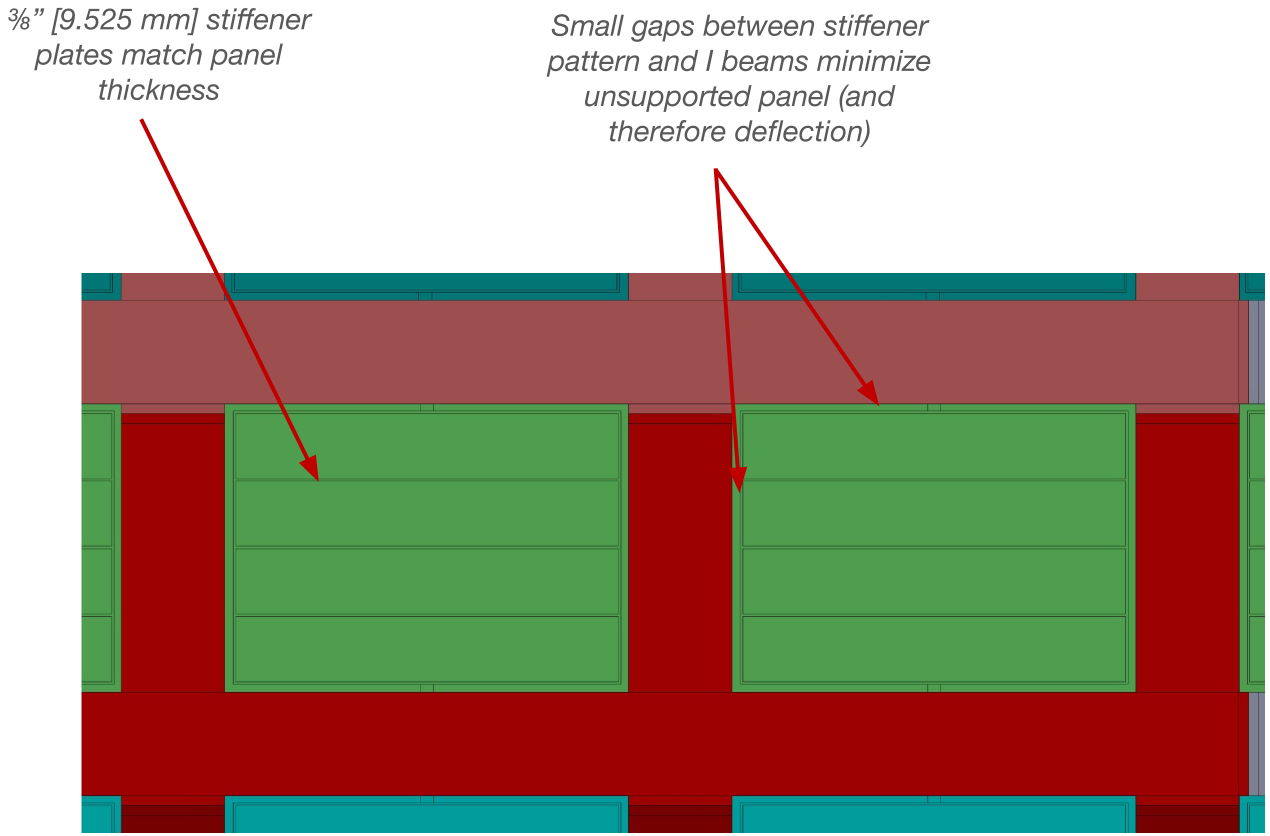
Temporary padeyes welded to inside surface for lifting, ground off after clamping



- Skin panels are clamped to I beams, not welded
  - Limits weld distortion
  - Preserves adjustability when positioning against neighboring panels
- Skin panels welded to each other to provide vapor barrier that separates insulation volume from ambient air
  - All welds are leak checked twice
    - First dye penetrant or magnetic particle
    - Then bubble test under vacuum

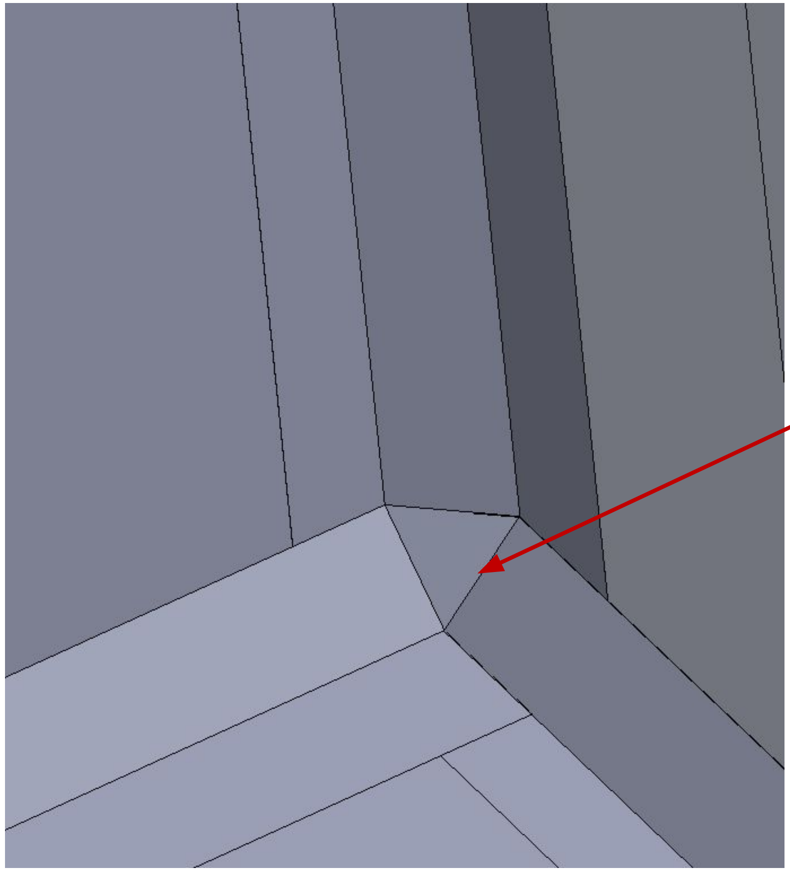
Skin Panel Stiffeners



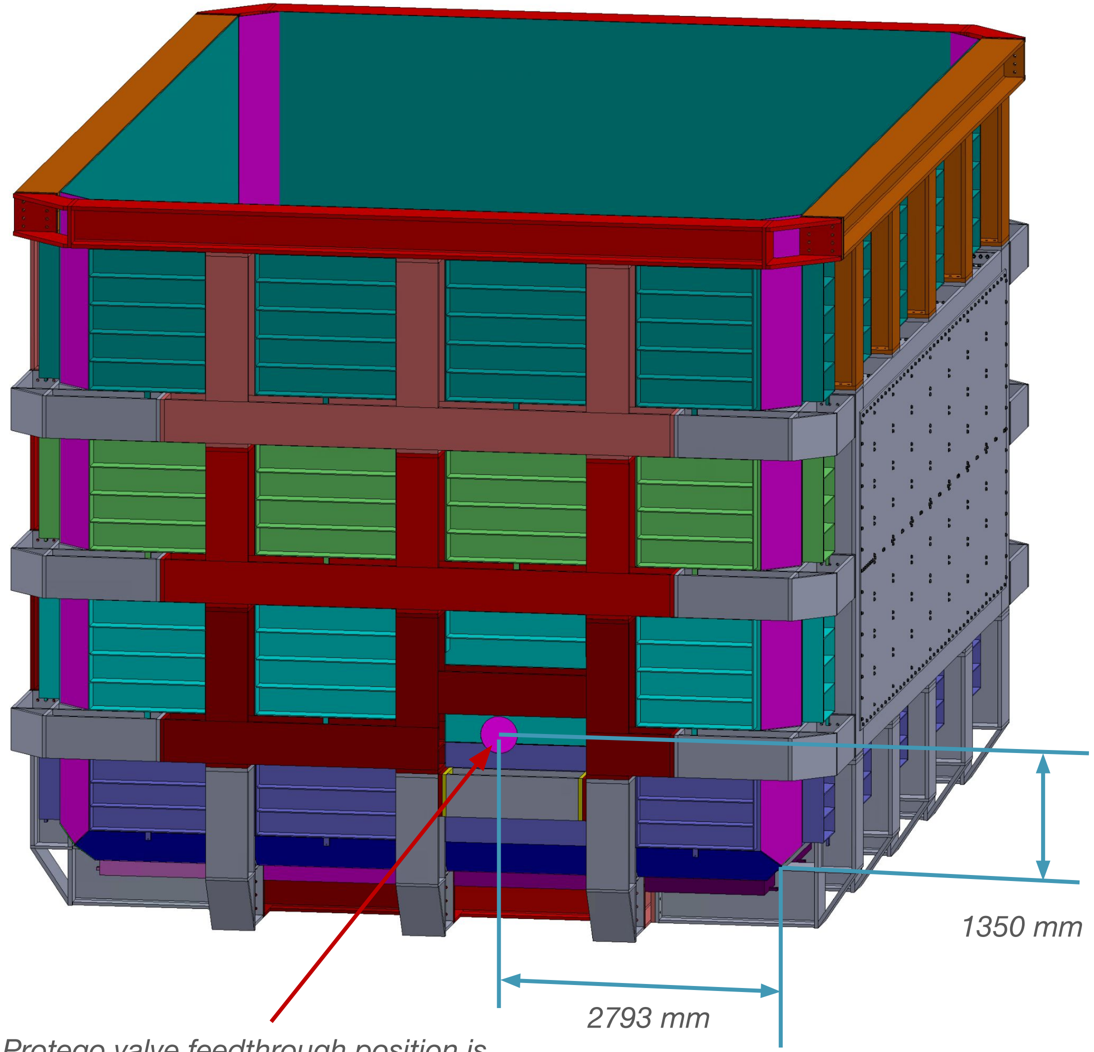


- Stiffeners prevent excessive panel deflection between I beams
- Stiffeners provide mounting point for clamps and transmit clamp loads to push panels against I beams from the inside (same direction as hydrostatic pressure)

Edges and Feedthrough Match SBND to Minimize Cost and Risk



Identical 330 mm edge chamfers required to prevent re-engineering costs



Reusing Protego valve feedthrough position is not required but reduces execution risk and is compatible with ND design

Analysis Plan

Approach

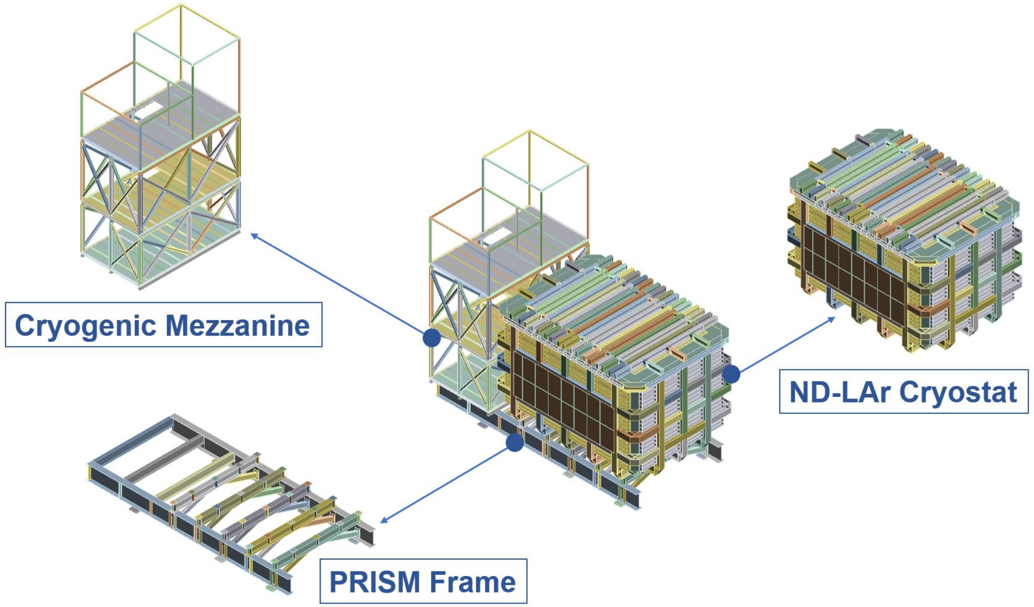
- Preliminary design: cryostat team analyzes with ANSYS and hand calcs, targeting safety factor >2 on yield strength
- Final design: Illinois-licensed structural engineer evaluates against AISC 360 requirements

Load cases

- Gravity only
- Gravity plus LAr hydrostatic pressure
- Gravity plus 350 mbar gas pressure
- Operational: gravity, LAr hydrostatic pressure, 350 mbar gas pressure

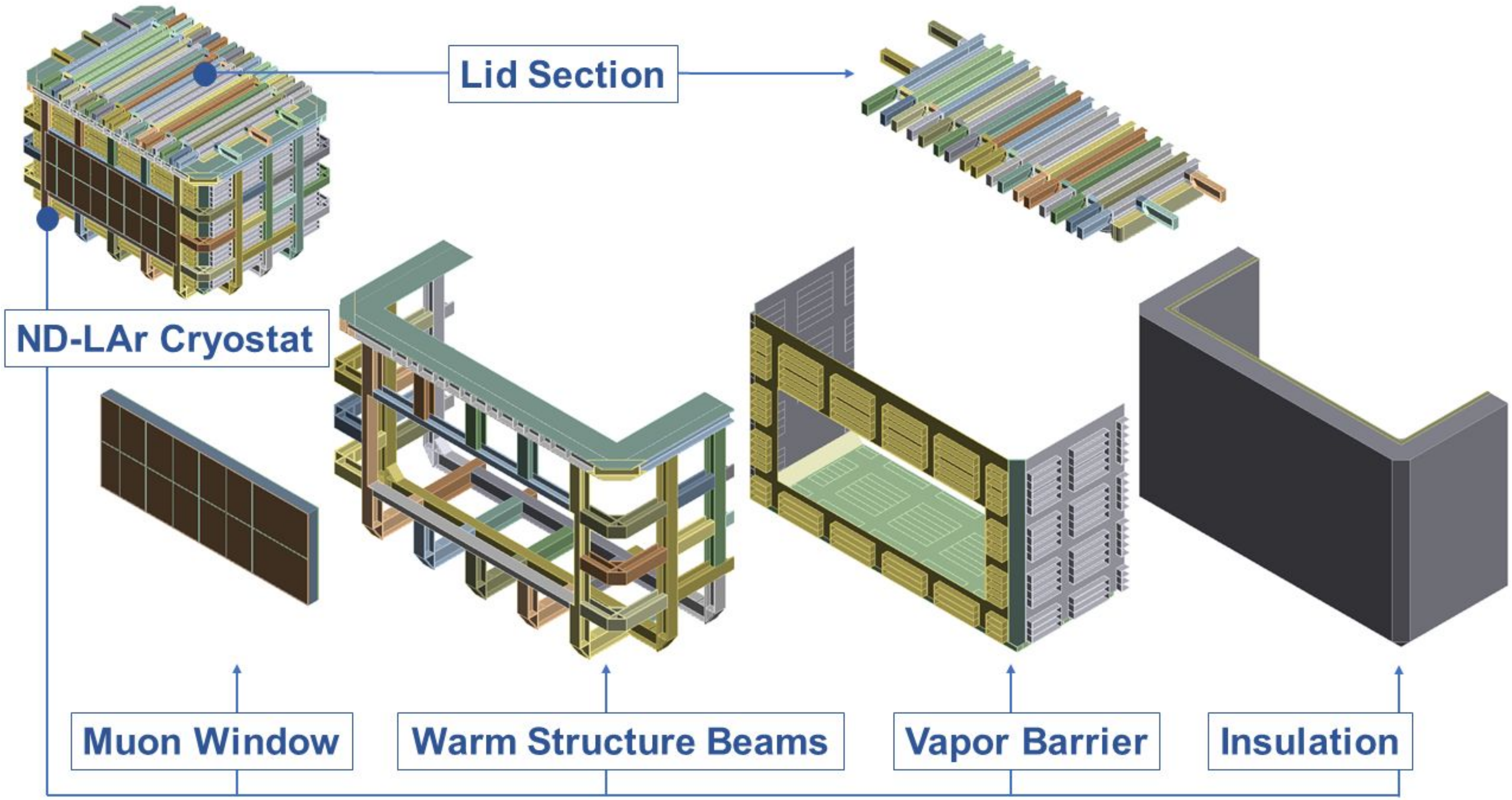
Requirements

- Safety factor >2 on yield strength (best practice to ensure we meet AISC 360)
- Deflection
  - 4mm / m and 15 mm total out of plane deflection at stiffeners (cold membrane requirement)



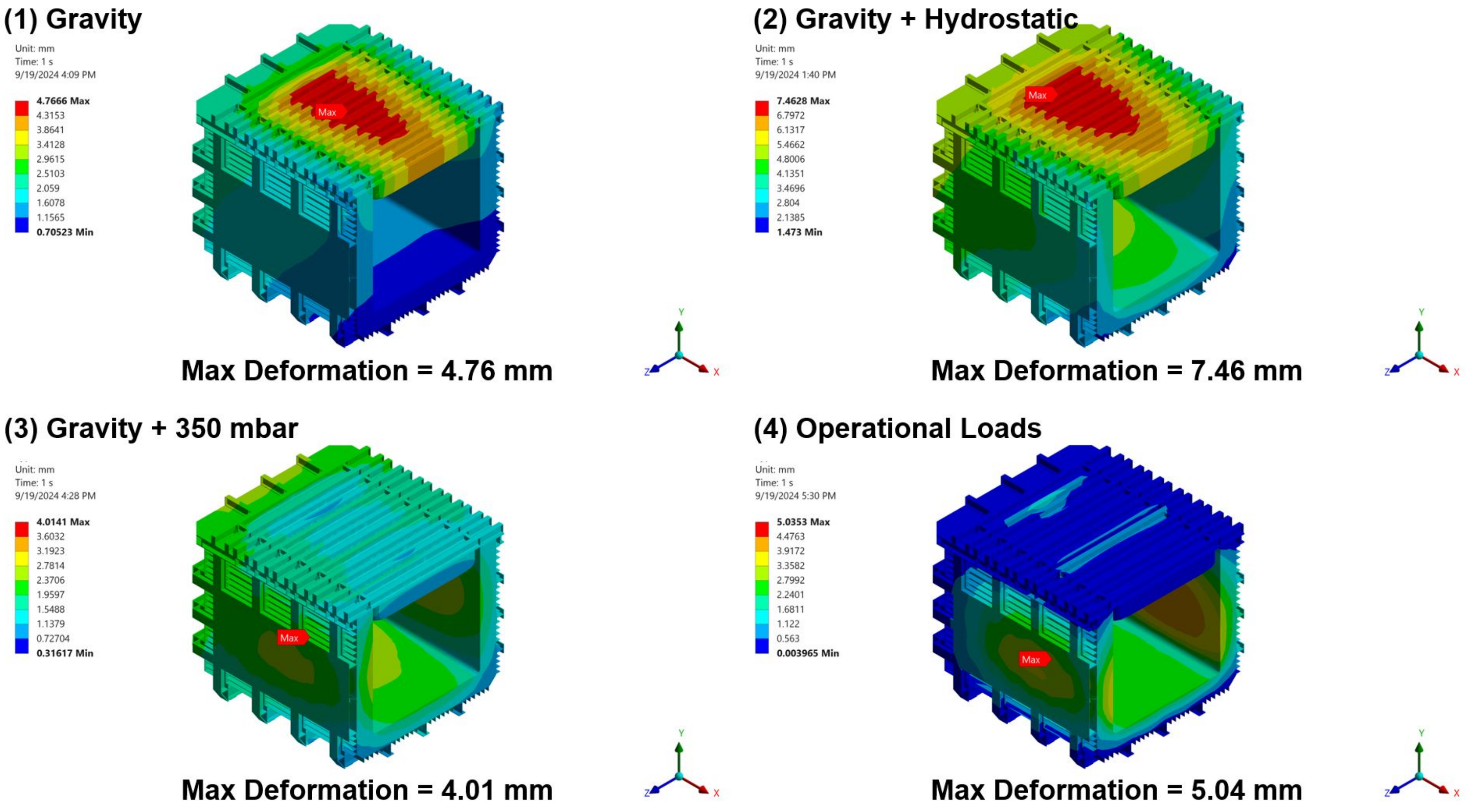
Global structural model gives system-level results and provides loads and boundary conditions for detailed solid models of subassemblies and critical parts

Analysis Results: Model



- A global FEA model with 743,610 solid elements and 1,789,449 nodes.

Deflection results meet 4 mm/m requirement

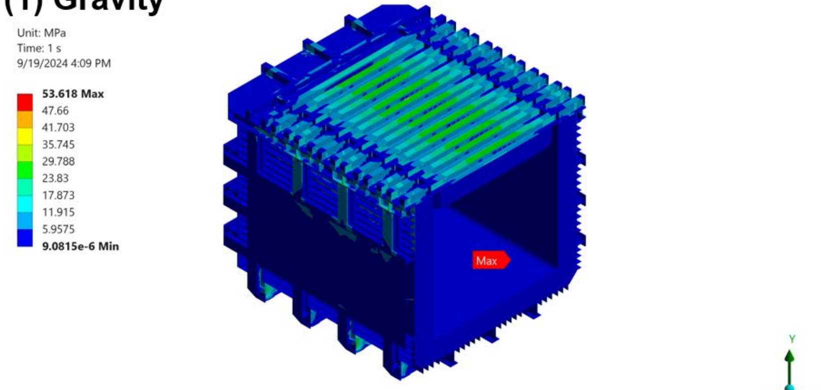


- With 7 m walls, approximate allowable peak deflection is 14 mm
- For details see warm structure analysis report (EDMS 3161162)

Stress results meet safety factor >2 requirement

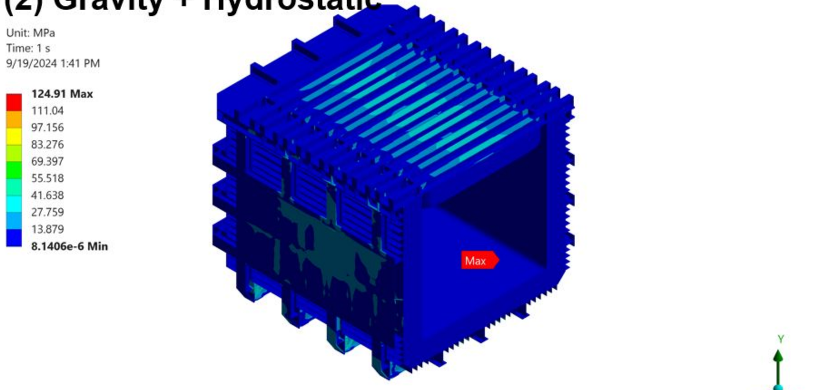
Charge # 2

(1) Gravity



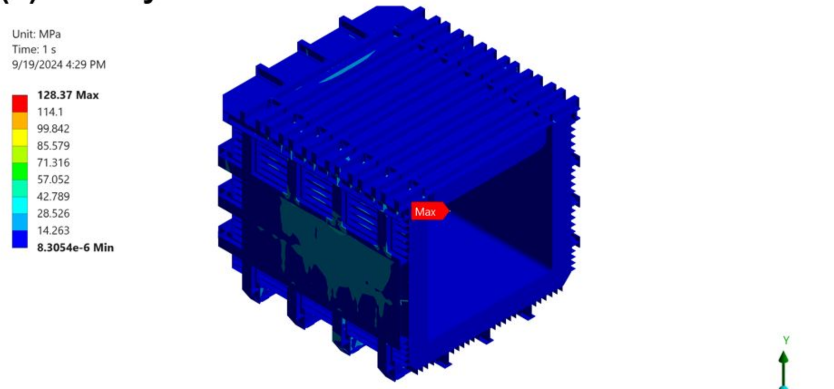
Max Stress = 54 MPa

(2) Gravity + Hydrostatic



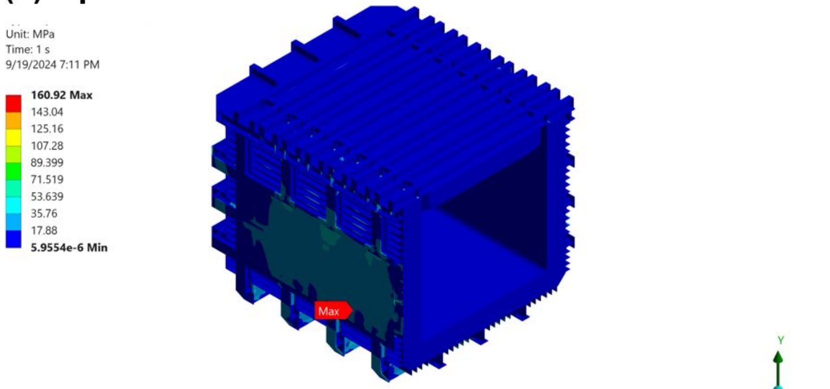
Max Stress = 125 MPa

(3) Gravity + 350 mbar



Max Stress = 128 MPa

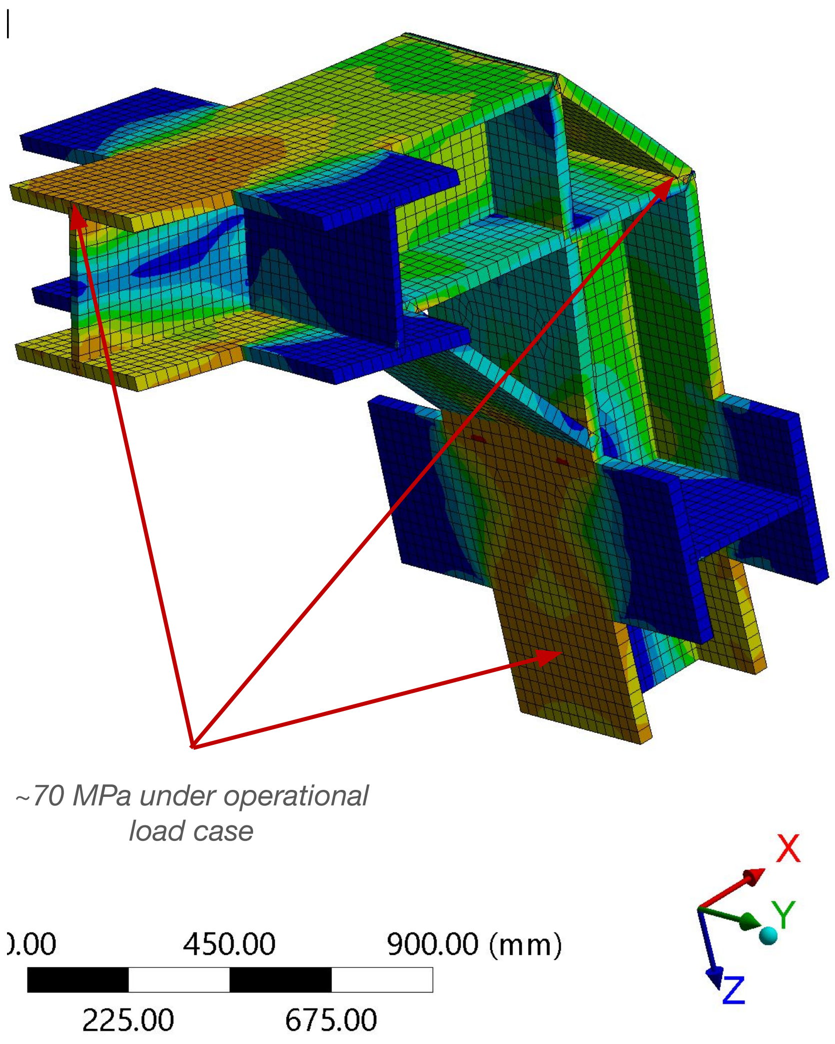
(4) Operational Loads



Max Stress = 161 MPa

- With σ_y = 448 MPa, safety factor ranges from 2.7 to 8.3 across modeled load cases

Corner joint analysis results in a large joint strength safety factor



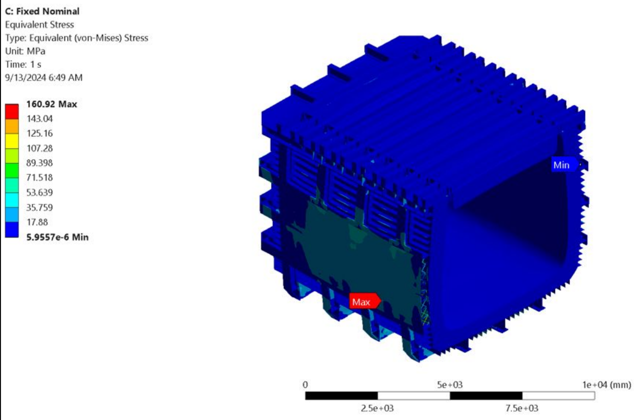
- Different from stress safety factor, this method compares joint strength to beam strength
  - Worst case moment load extracted from global model
  - Applied moment on joint increased until material yields
  - Joint safety factor = load at yield / expected load

Frame performance is comparable to prior experience with concrete bases.

PRISM vs Concrete	Stress (MPa)		Displacement (mm)	
	PRISM	Concrete	PRISM	Concrete
Beams	108	110	5.72*	3.12
Vapor Barrier	98.5	96.9	5.69*	3.12
Insulation	0.20	0.19	6.80*	5.04
Muon Window	161	158	5.50*	3.96
Lid	35.4	35.7	5.54*	1.36
Maximum	161	158	6.80*	5.04

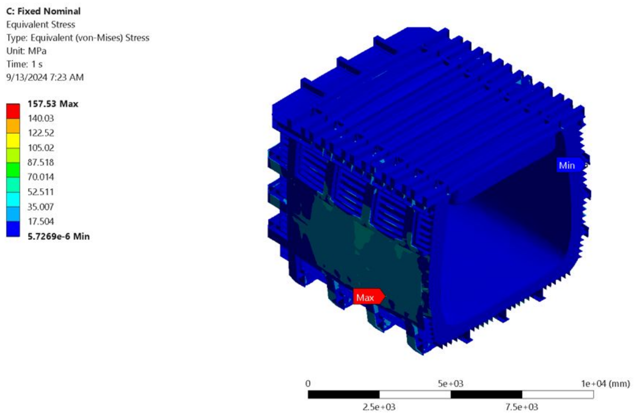
- * Displacement values under the PRISM case account for displacement from the PRISM frame as well as the warm structure components on them.
- The PRISM frame is infinitely stiff in the concrete case, and therefore there is no PRISM displacement.

- PRISM frame displacement creates rigid body motion of rest of Cryostat but has minimal impact on stress



Max Stress = 160.92 MPa

Warm structure on PRISM frame

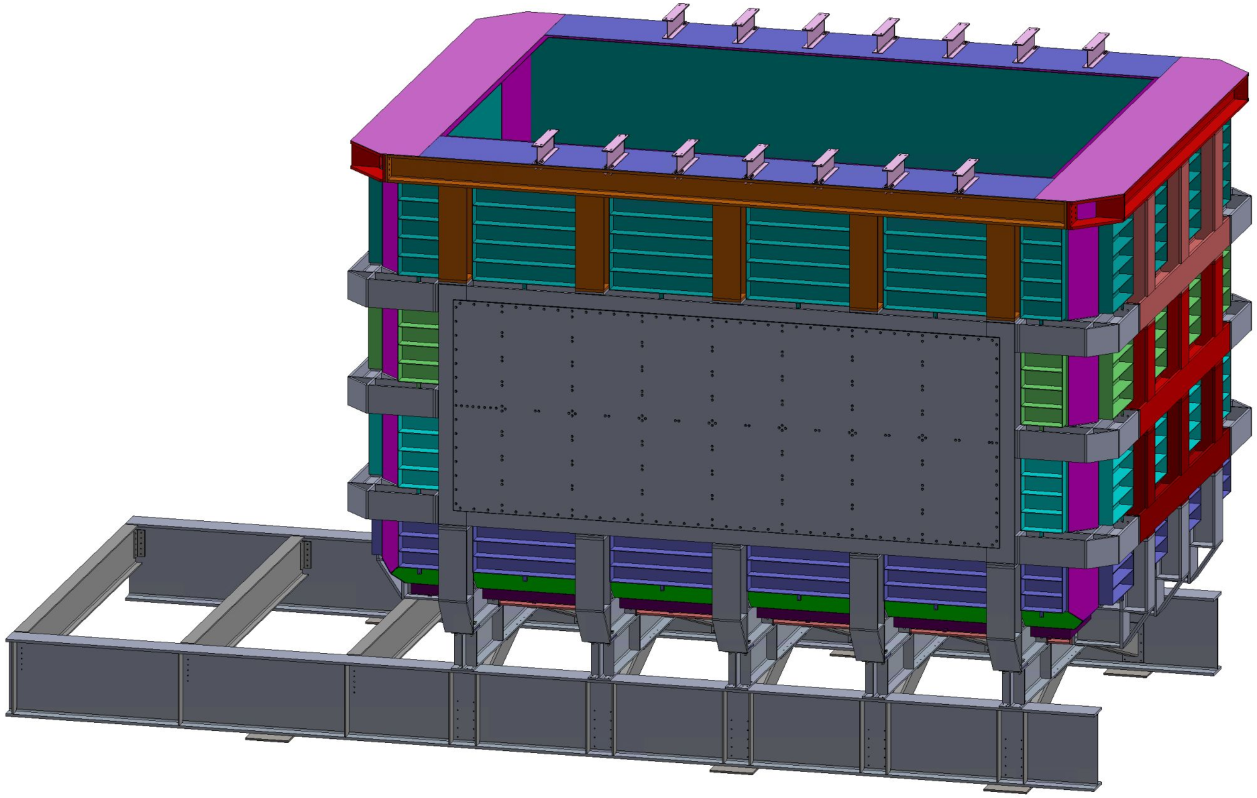


Max Stress = 157.53 MPa

Warm structure on Concrete

Manufacturing Plan

- Methods
  - I beams cut and machined
  - Plates cut and machined
  - Welded subassemblies
  - Bolted final assembly
  - Painting
- Supplier pool
  - Experience in shipbuilding, heavy duty construction equipment, building construction
  - Seeking **single supplier for warm structure, muon window and PRISM frame**
    - Same team builds parts and performs factory fit check

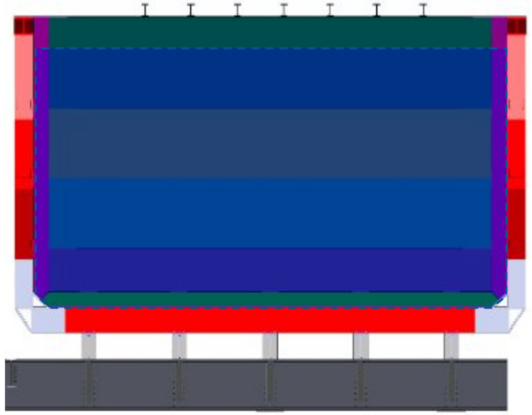


Seeking single supplier for warm structure, muon window and PRISM frame as all use similar heavy duty steel fabrication methods

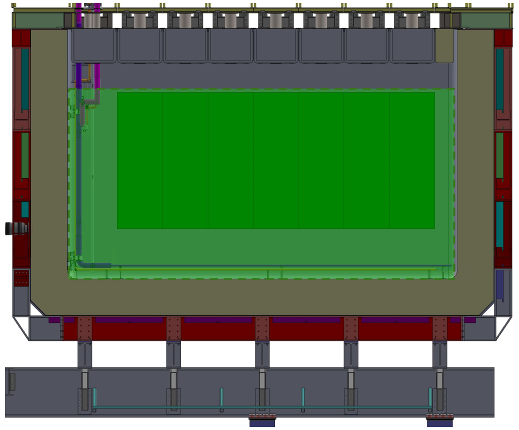
Quality Assurance Plan

- Factory fit check and inspection
  - Warm structure, muon window, and PRISM frame to be assembled and surveyed before shipment
    - Skin panels clamped but not welded
- Gas pressure test required by FESHM 5031.7
  - Pressurize finished Cryostat assembly to 250 mbar N_2
  - Opportunity to refine FEA assumptions
  - Pass/fail criteria
    - If strain or deflection exceed 125% of FEA result, pause for reevaluation
    - If strain or deflection exceed 150% of FEA result, abort test
- Integrated PRISM test is under evaluation for inclusion in schedule
  - Install plastic liner and fill warm structure with water
  - Goal is to provide payload for PRISM validation, not proof test the structure
    - Maximum pressure and total wall loads would be at or below operational levels
    - Would serve as early chance to refine FEA assumptions

Description	Integrated PRISM Test (not in baseline)	Gas Pressure Test	ND-LAr Operation
Temperature (K)	293	293	87
Liquid	Tap Water	none	Liquid Argon
Liquid density (kg/m^3)	998.2	N/A	1400
Fill height (m)	5.6	0	4.28
Max Hydrostatic Pressure (mbar)	550	0	588
Max Gas Pressure (mbar)	0	250	350
Liquid Weight (US tons)	441	0	305
Total System Weight (US tons)	600	375	680
Liner	PVC or similar	Corrugated SST + PU Foam Insulation	Corrugated SST + PU Foam Insulation
Vapor Barrier Panel Attachment	Clamped	Clamped + Welded	Clamped + Welded
Lid	Optional simplified brace	Lid Sections w/ TPC Detectors	Lid Sections w/ TPC Detectors



Integrated PRISM Test



Operational & Gas Pressure

ND Hazard Analysis has informed warm structure design decisions

Charge # 6.f

- Confined space inside of cryostat
  - Preserve two egress paths for as long as possible during warm structure assembly
- Confined space under cryostat
  - Finish PRISM frame installation before warm structure tub is started
  - Preserve egress paths under finished warm structure
- Fall hazard from top of cryostat
  - Interior and exterior perimeter railings on mezzanine

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)

Warm structure risks are addressed by analysis and testing

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 risk
- Pressure test risks mitigated by analysis against established AISC 360 code
  - Risk of structural failure not under consideration; risks captured indicate potential disagreement between analysis and real-world results
- FNAL risk registry

Path to Final Design

- Bolted joint calculations and sizing
- Detailed analysis of highest stress areas
- AISC 360 analysis by structural engineer
- Vendor quotes and feedback
- Vendor selection