DUNE-ND LArTPC Cryostat Muon Window

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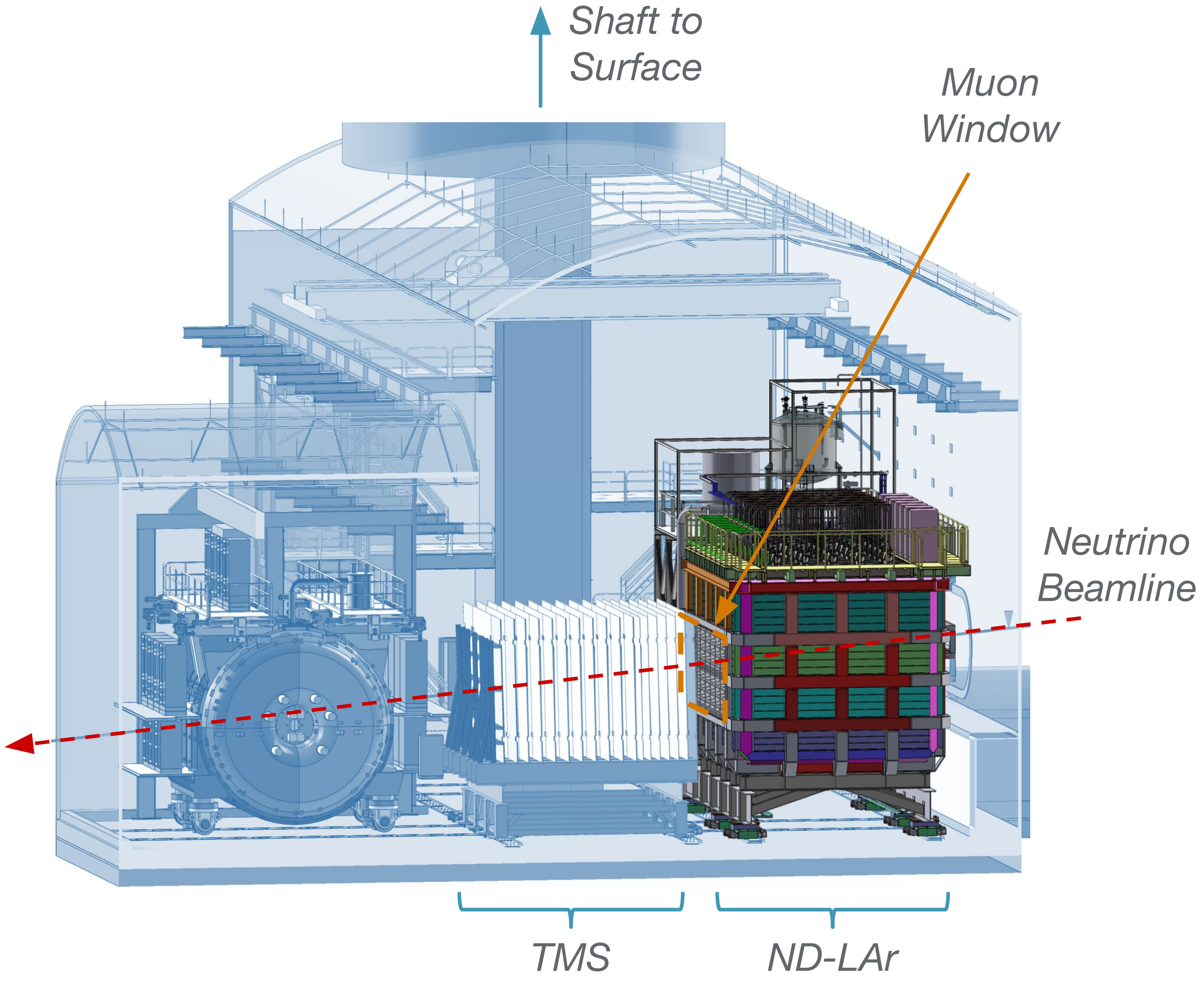
BERKELEY LAB

The Muon Window allows muons generated in ND-LAr to be tracked across both ND-LAr and TMS

- Muons are generated in ND-LAr by neutrino-argon interactions
- For those muons to be reliably measured by TMS, the energy loss from intersecting passive material must be less than 3% at 600 MeV
- From a practical standpoint, this means the Cryostat walls must have…
  - **Low average density** to minimize muon energy loss
  - **High mass uniformity** to reliably correct for muon energy loss

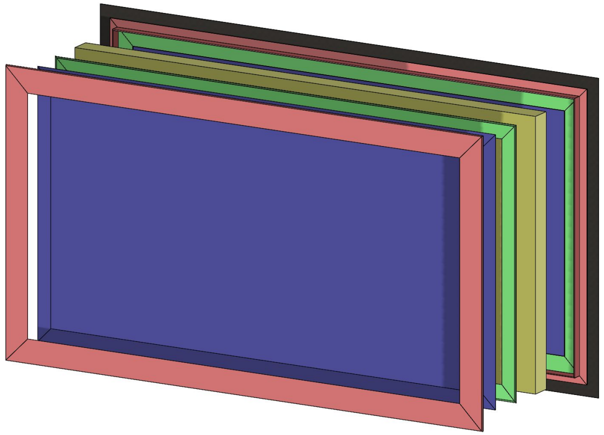


Charge # 2, 4

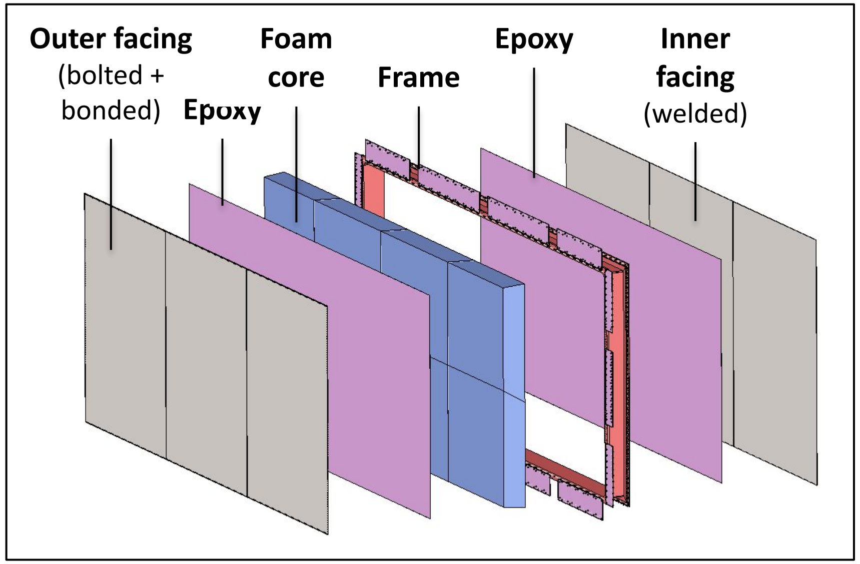
Three versions of low density, high uniformity walls were evaluated. The all-steel version was selected.

- All meet structural and density requirements
- All-steel design selected because it uses standard steel construction methods and can be designed, analyzed and fabricated alongside warm structure, minimizing cost and risk

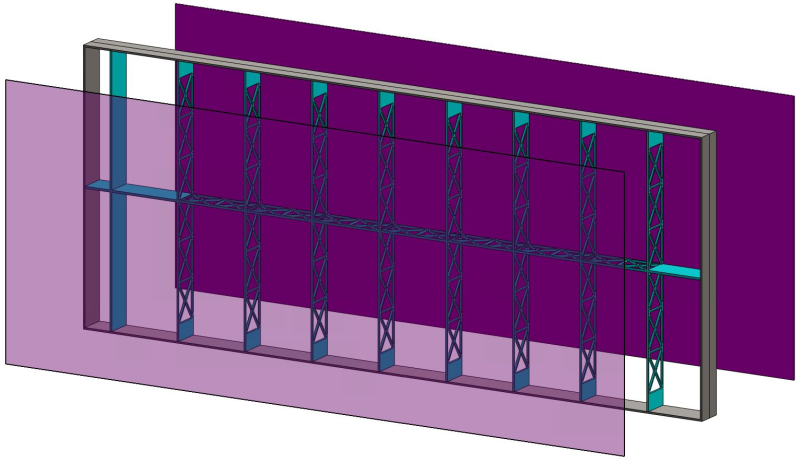
FIBERGLASS / FOAM (2020)



STEEL / FOAM (2021)



ALL-STEEL (2022)



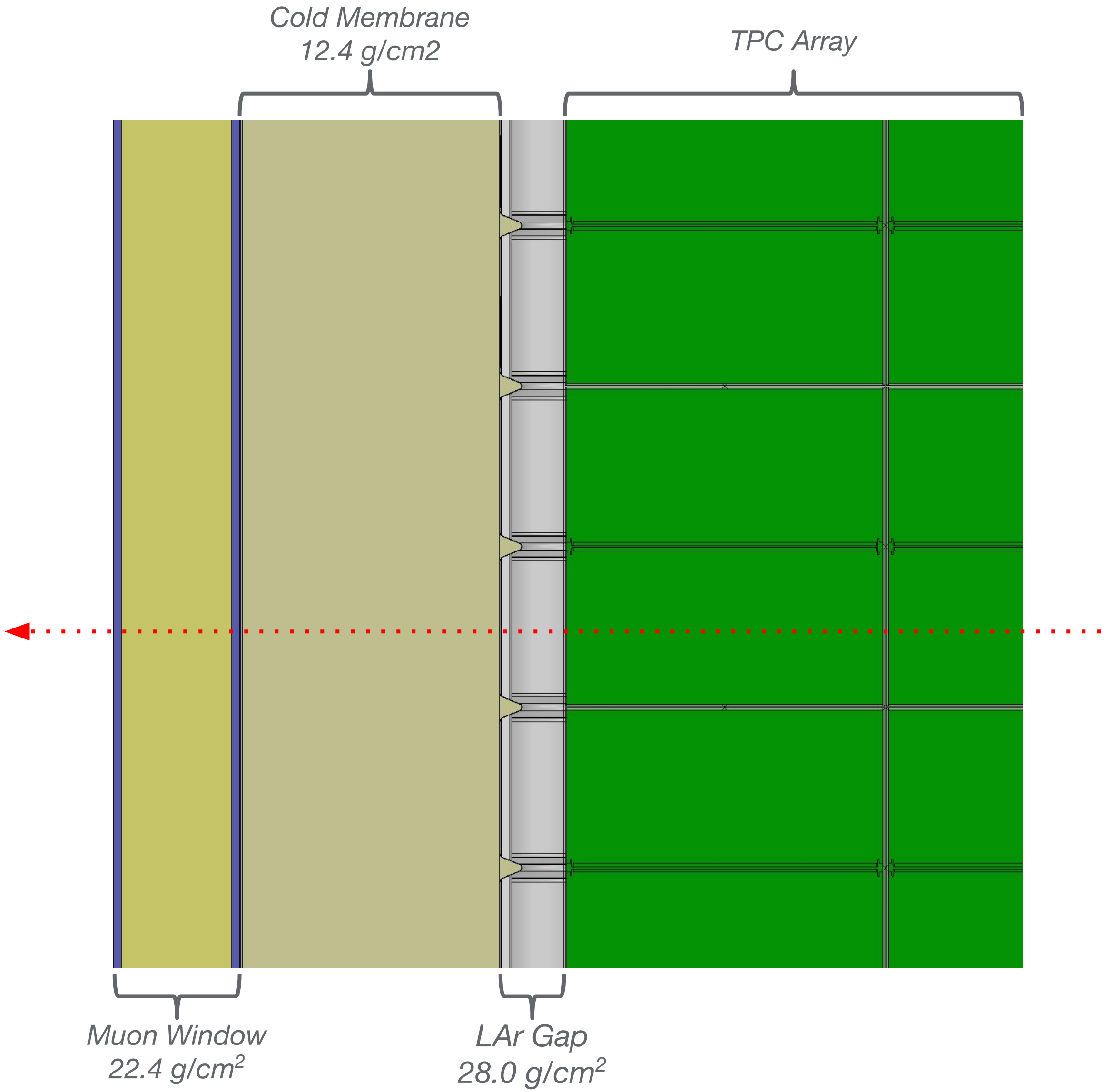
← HIGHER UNIFORMITY

LESS COST AND RISK →

The inactive liquid argon and cold membrane also affect muon energy loss

Charge # 1

- Physics requirement of 3% muon energy loss at 600 MeV equivalent to ~60 g/cm^2 areal density (thickness * volumetric density)
  - Inactive LAr is a large areal density contribution but is inherently uniform
  - Cold membrane contribution is relatively small and thermal insulation requirements also promote uniformity
- Physics team performing detailed simulation to validate entire material stackup
  - Minor cold membrane changes (such as swapping one gap filler material for another) may be necessary



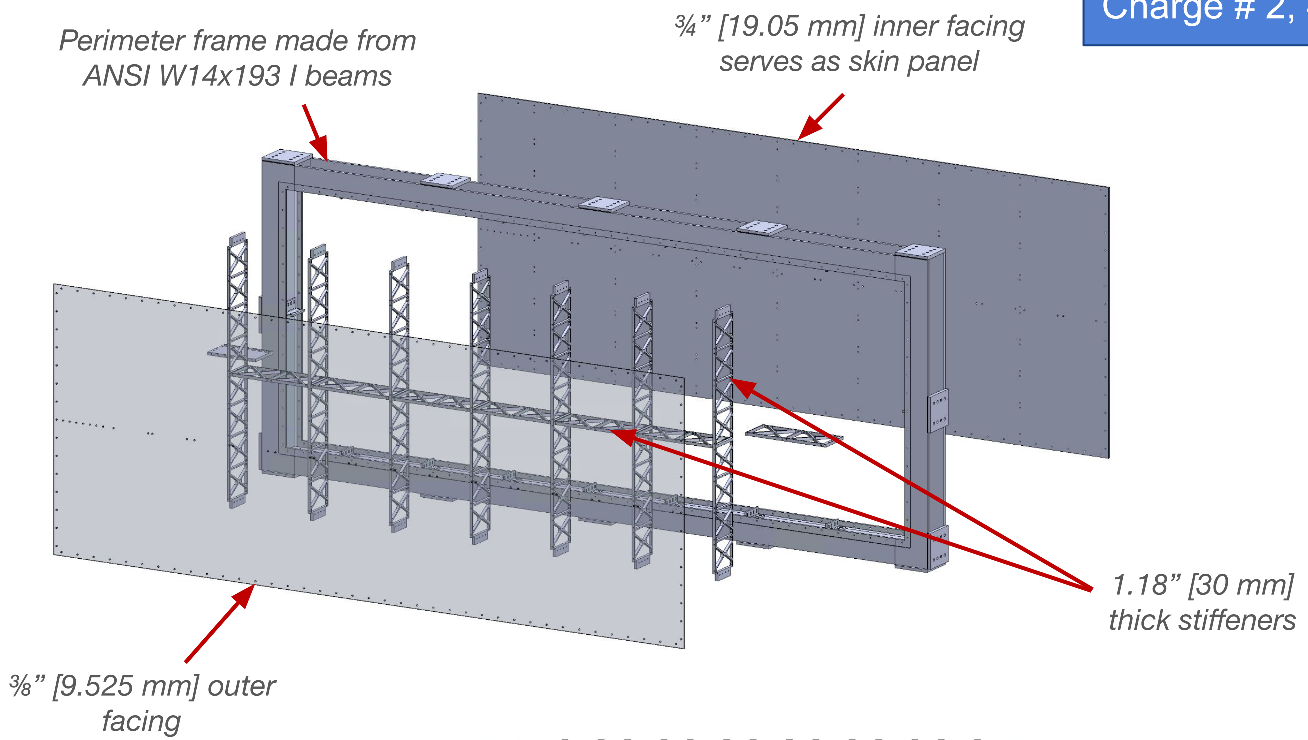
As part of the Warm Structure, the Muon Window shares the same requirements and interfaces

Charge # 6.e, 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

Design Overview

- 8.3 x 3.5 x 0.4 m (L x W x H) outside dimensions
- 11.5 metric tons [12.7 US tons]
- 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
  - Plates cut and machined
  - Plates water jet (or laser) cut
  - Welded subassemblies
  - Bolted final assembly
  - Painting
- Part count
  - 2 Facings
    - 3 m [118”] plates cut from 120” raw material, confirmed available from mills as single piece
  - 15 Internal stiffeners
    - 7 identical vertical stiffeners
    - 6 identical horizontal stiffeners
    - Unique left and right horizontal stiffeners with frame interface
  - Misc brackets and shims



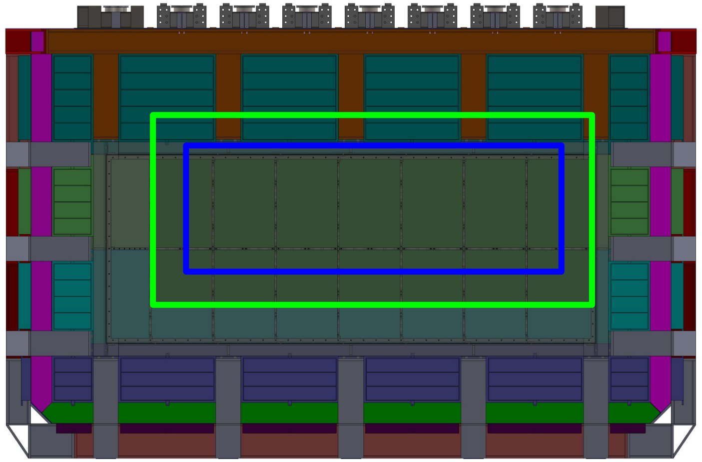
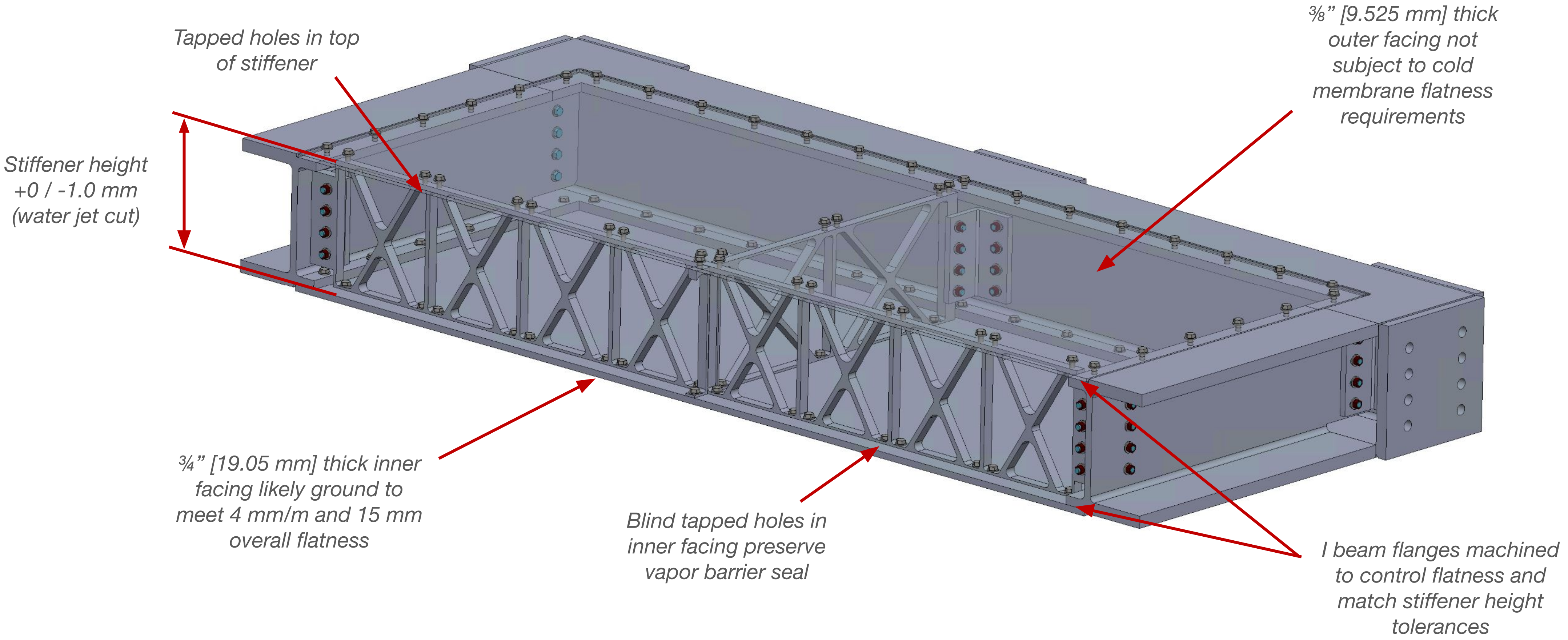


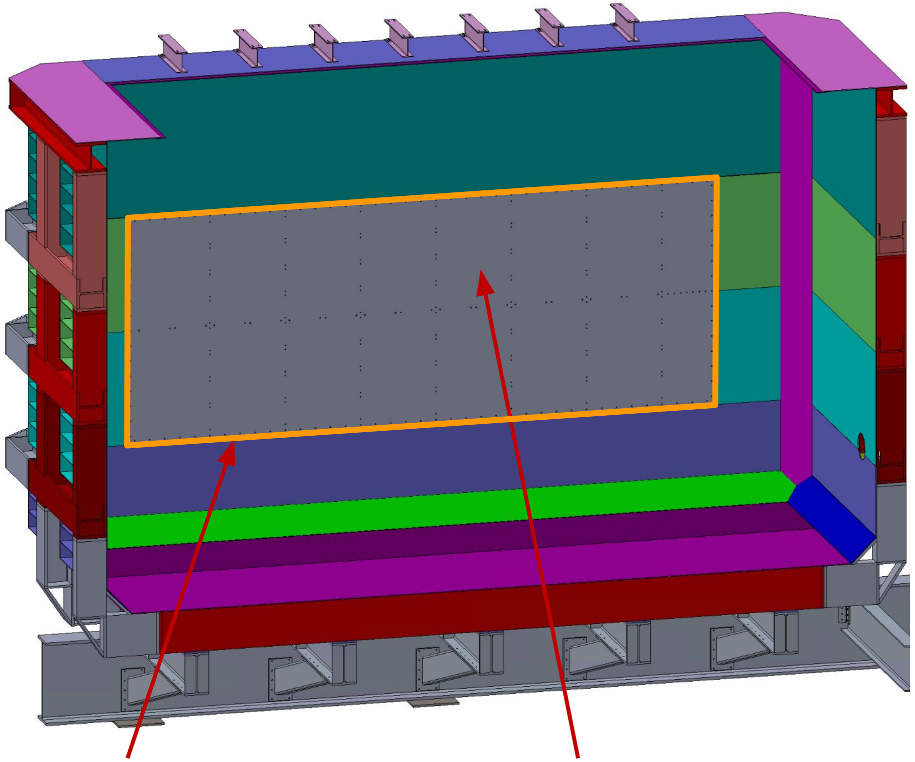
Illustration of stiffener placement.
TPC array envelope in green, TPC fiducial volume in blue.

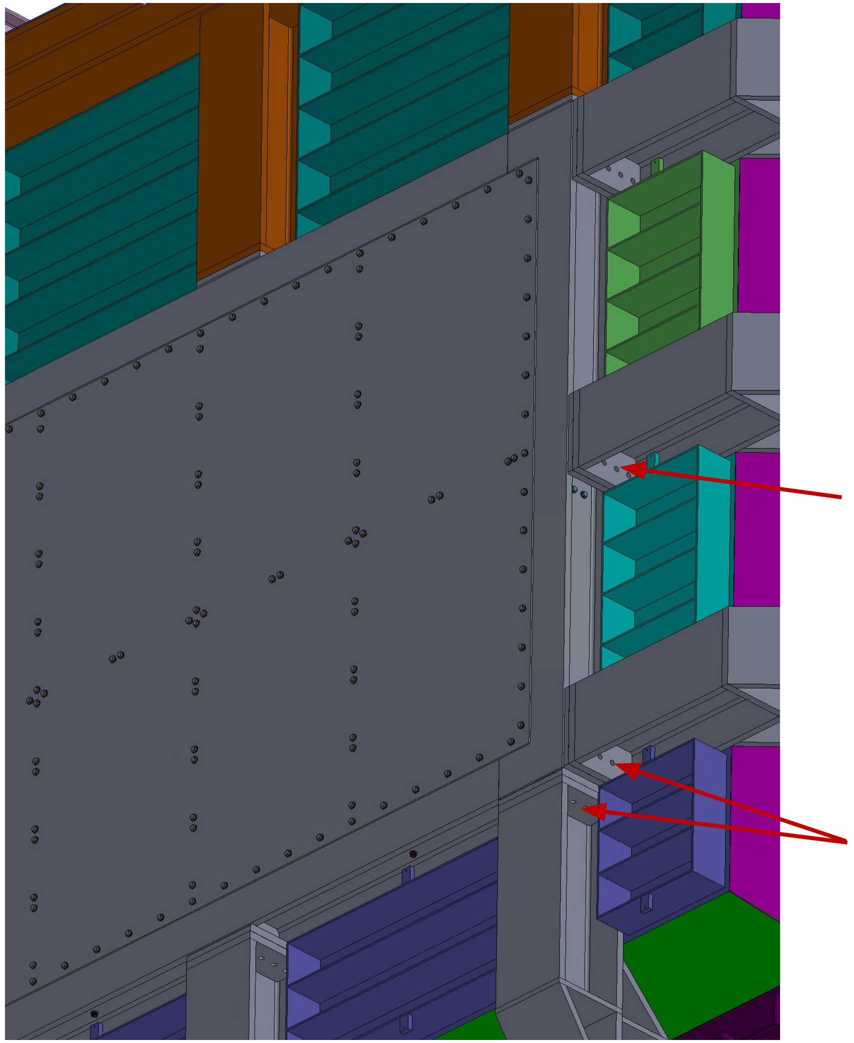
The window is assembled from the inside out



- Bolted rather than welded to minimize distortion
- Tight stiffener height tolerances enable tight finished assembly flatness tolerances

Integration into Warm Structure





- Inner facing serves as skin panel and is welded to neighboring panels to form vapor barrier
- Same bolted joints as rest of warm structure
  - Outer rows of bolts on corners of window use tapped holes rather than nuts because corner renders back side of joint inaccessible

Analysis Plan

Approach

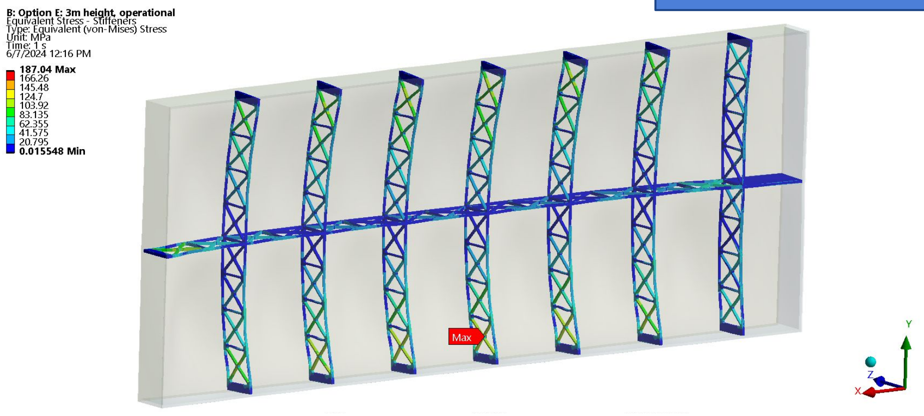
- Preliminary design: cryostat team analyzes with ANSYS and hand calcs, targeting safety factor >2 on yield strength
- Final design: Illinois-licensed structural engineer evaluates against AISC 360 requirements

Load cases

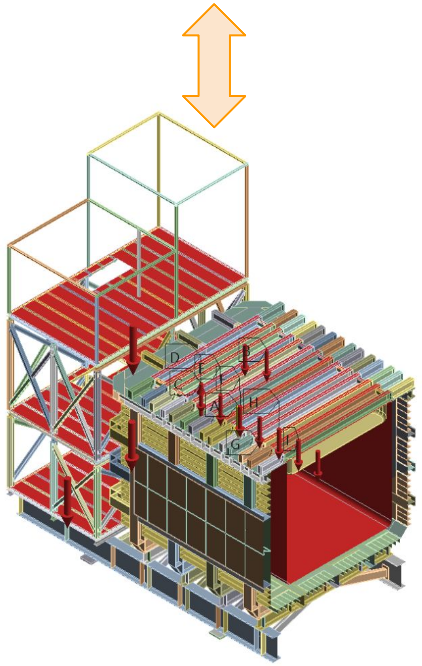
- Operational: LAr hydrostatic pressure, 350 mbar gas pressure, gravity
- Pressure test: 250 mbar gas pressure, gravity

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)

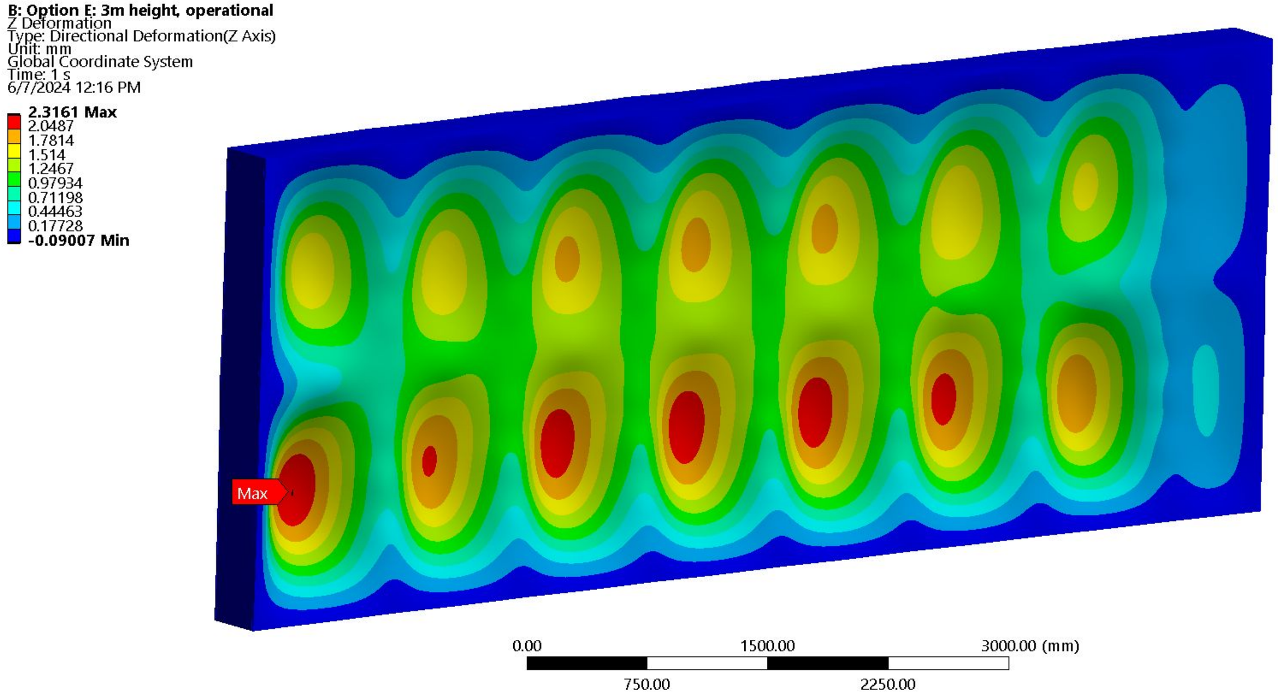


Muon window solid model used to evaluate performance of detailed features and iterate on window design.

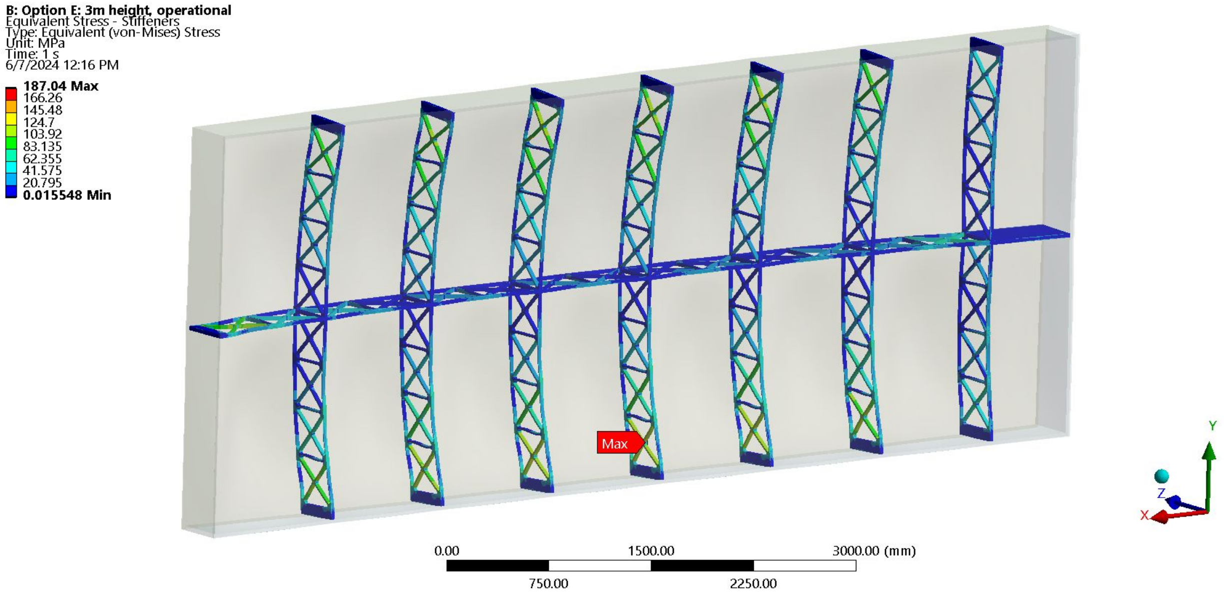


Global solid model uses representative muon window geometry, just with larger mesh.

Analysis Results: Muon Window meets stress and deflection criteria



2.3 mm peak deflection meets the 4 mm/m slope limit set by the cold membrane. Deflection is highest on the left side where the span between stiffeners is larger. Note that deflection measured at the stiffeners (as specified) is lower still at roughly 1 mm peak and sub-mm stiffener to stiffener.

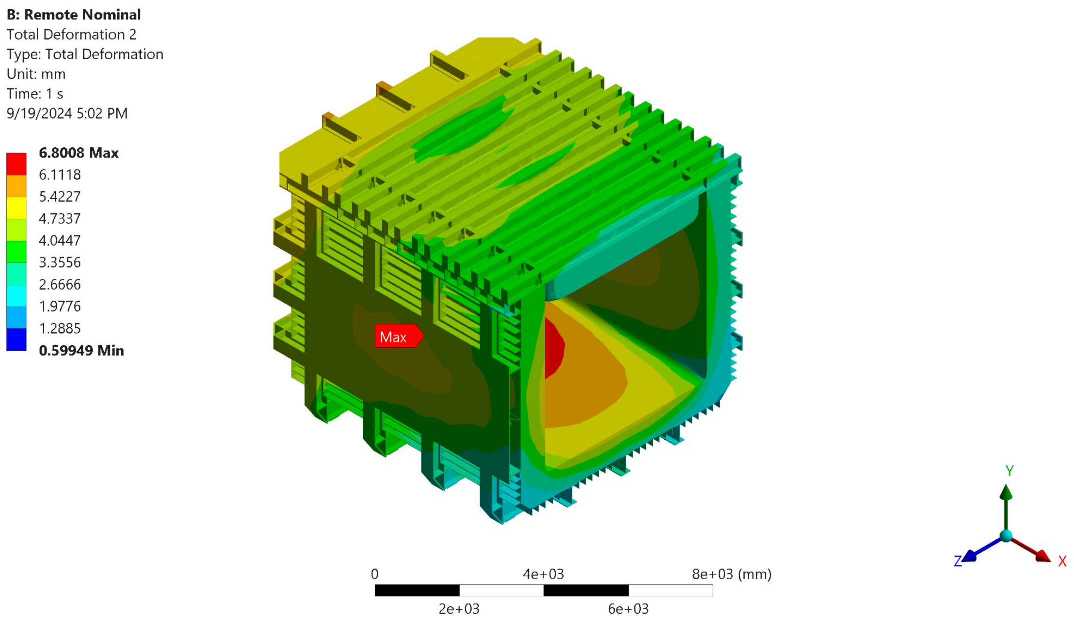


187 MPa stiffener peak stress gives a 2.4 safety factor (vs 2.0 requirement) thanks to the 448 MPa yield strength. 85 MPa facing peak stress (not pictured) gives a 5.3 safety factor.

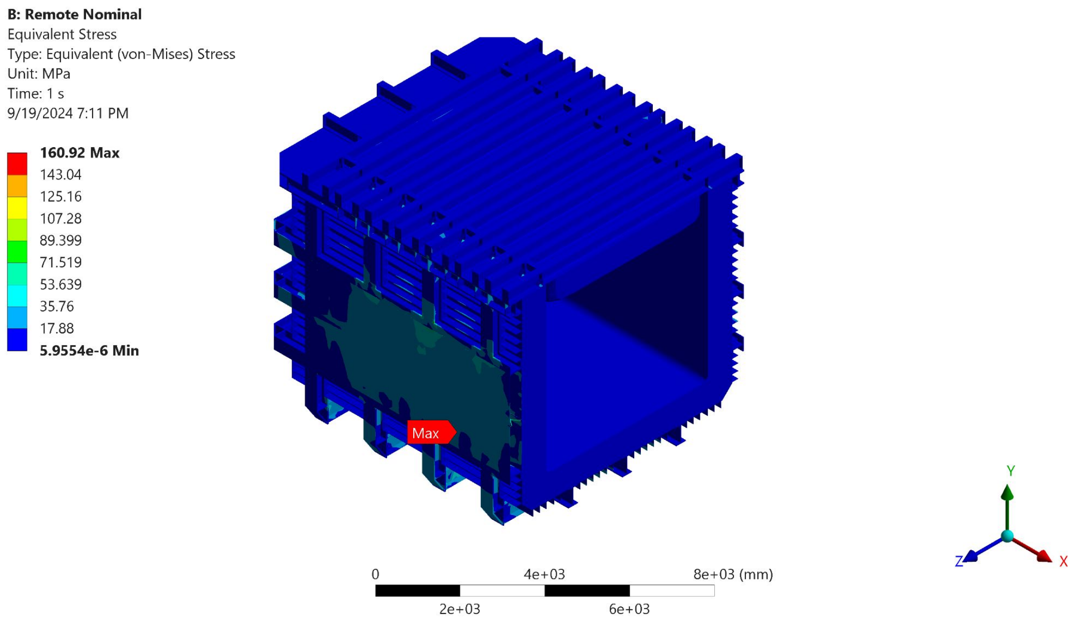
- Operational load case: 350 mbar gas pressure (PRV setpoint) + 0 to 485 mbar hydrostatic LAr pressure
- Conservative simply supported perimeter boundary condition neglects bending stiffness of surrounding warm structure

Global model results agree with individual model results

Charge # 2, 4



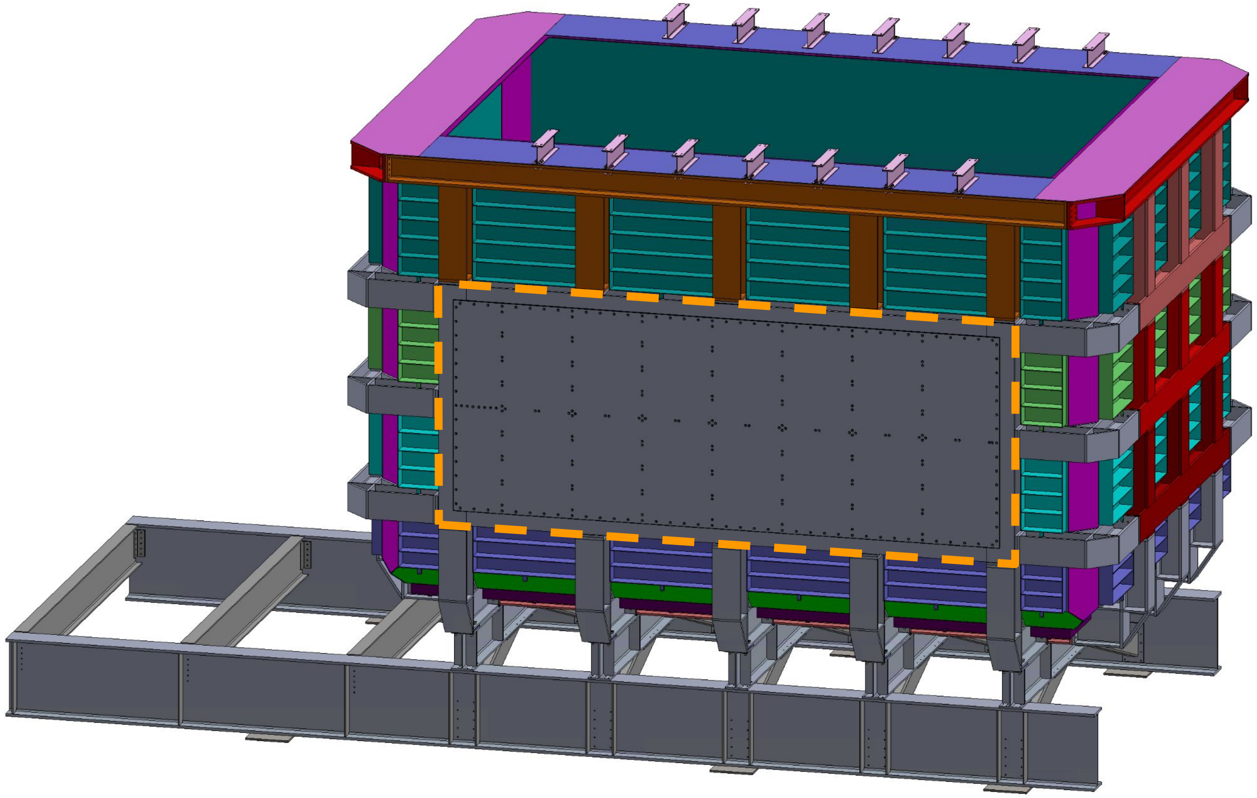
~5 mm total displacement of muon window comes from the combination of muon window deflection and surrounding warm structure deflection.



161 MPa peak stress is similar to 187 MPa reported by individual muon window FEA model.

Manufacturing Plan

- Methods
  - Plates cut and machined
  - Plates water jet (or laser) cut
  - 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

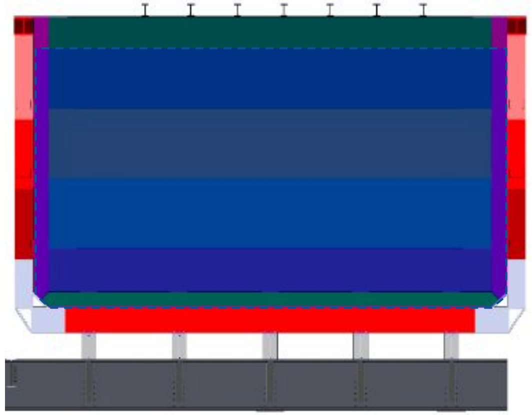


Seeking single supplier for warm structure, muon window and PRISM frame as all use similar heavy duty steel fabrication methods

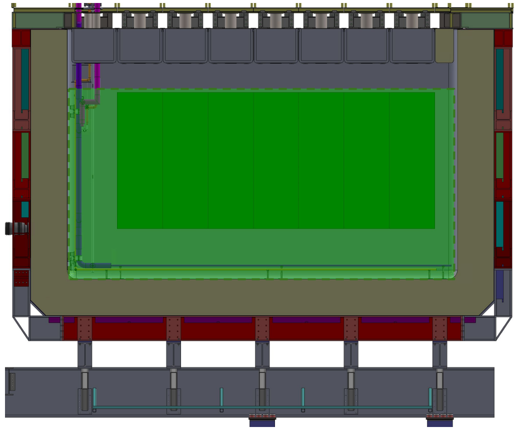
Quality Assurance Plan

- 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

Charge # 3, 4

Selecting the all-steel design allowed us to retire muon window engineering and fabrication risks

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

- The remaining muon window risk addresses a potential failure to meet physics requirements
  - If modifications to the all-steel design are insufficient, we would revert back to a composite design
- A detailed physics study of the ND-LAr / muon window / TMS joint acceptance is underway and is expected to reduce the probability later this year
- FNAL risk registry

Charge # 2

Path to Final Design

- Bolted joint calculations and sizing
- Incorporate detailed contact conditions into FEA model
  - Currently facings are simply bonded to stiffeners
- Buckling analysis
- AISC 360 analysis by structural engineer
- Vendor selection
- Vendor quotes and feedback