DUNE-ND LArTPC Cryostat Introduction

2024-09

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U.S. DEPARTMENT OF ENERGY | Office of Science
BERKELEY LAB

Meet the Cryostat Team

Fabrice Matichard, Cryostat L2 / CAM (LBNL)

- 14 years with LIGO (Laser Interferometer Gravitational-Wave Observatory)
- Lead Engineer for Advanced LIGO sub-systems and subsequent detector upgrades (Quantum Optics Squeezer)
- Joined LBNL in 2021 as lead engineer for DUNE-ND

Peter Tennessen, Cryostat Lead Engineer (LBNL)

- 15 years at private sector energy projects (Tesla, Primus Power, Amber Kinetics)
- Joined LBNL in 2020 as lead engineer for ND Cryostat

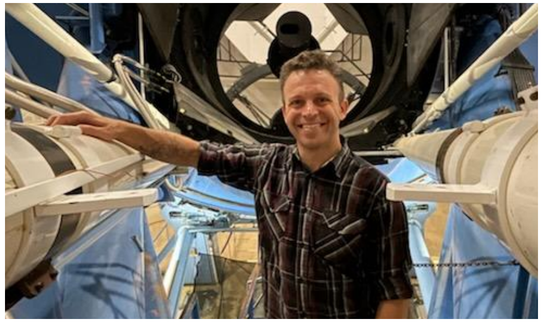
Meet the Cryostat Team

Shishir Shetty, Mechanical Engineer (FNAL)

- SBND Support Frame
- SBND Roof Hangers

Joe Angelo, Mechanical Engineer (LBNL)

- LBNF Target Hall Shield Pile
- ALS-U, ALS



Joe Silber, Mechanical Engineer (LBNL)

- 14 years in LBNL composites group
- L2/CAM on DESI and CMB-S4 projects
- STAR-HFT, ATLAS, LuSEE-Night, Alpha AI, Spec-S5

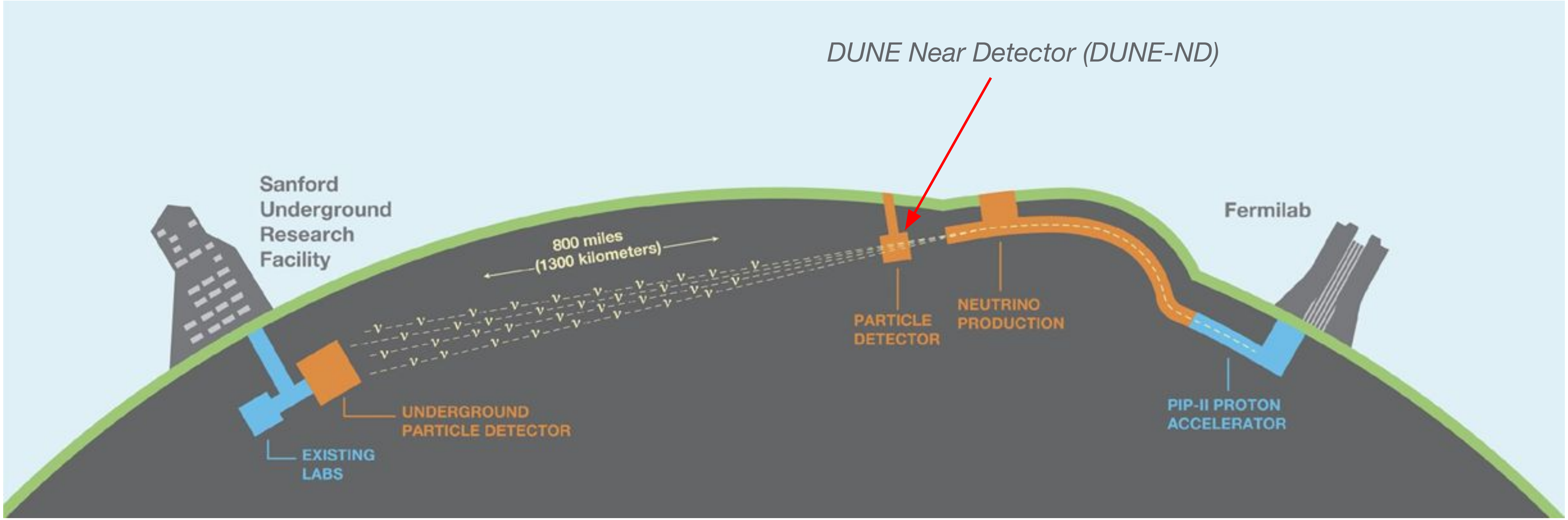
Steve Hentschel, Mechanical Designer (FNAL)

- SBND CAD Assy Integration
- SBND Support Frame, Cryogenics Mezzanine and Piping Layout

Design Overview

The Deep Underground Neutrino Experiment (DUNE) project will use two detectors separated by 1300 km to study neutrino oscillation

The Near Detector (DUNE-ND) will record particle interactions near the source of the beam, at the Fermi National Accelerator Laboratory (FNAL) in Batavia, Illinois. A set of larger Far Detectors (DUNE-FD) will be installed at the Sanford Underground Research Facility (SURF) in Lead, South Dakota — 1,300 kilometers downstream of the source. These detectors will enable scientists to search for new subatomic phenomena and potentially transform our understanding of neutrinos and their role in the universe.

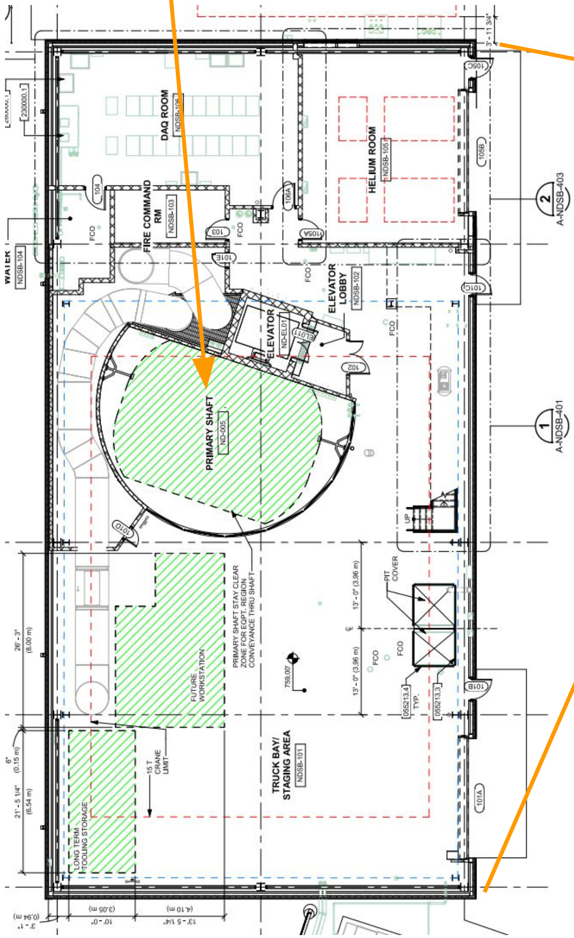


The DUNE Near Detector is on Fermilab's site in Batavia, Illinois USA

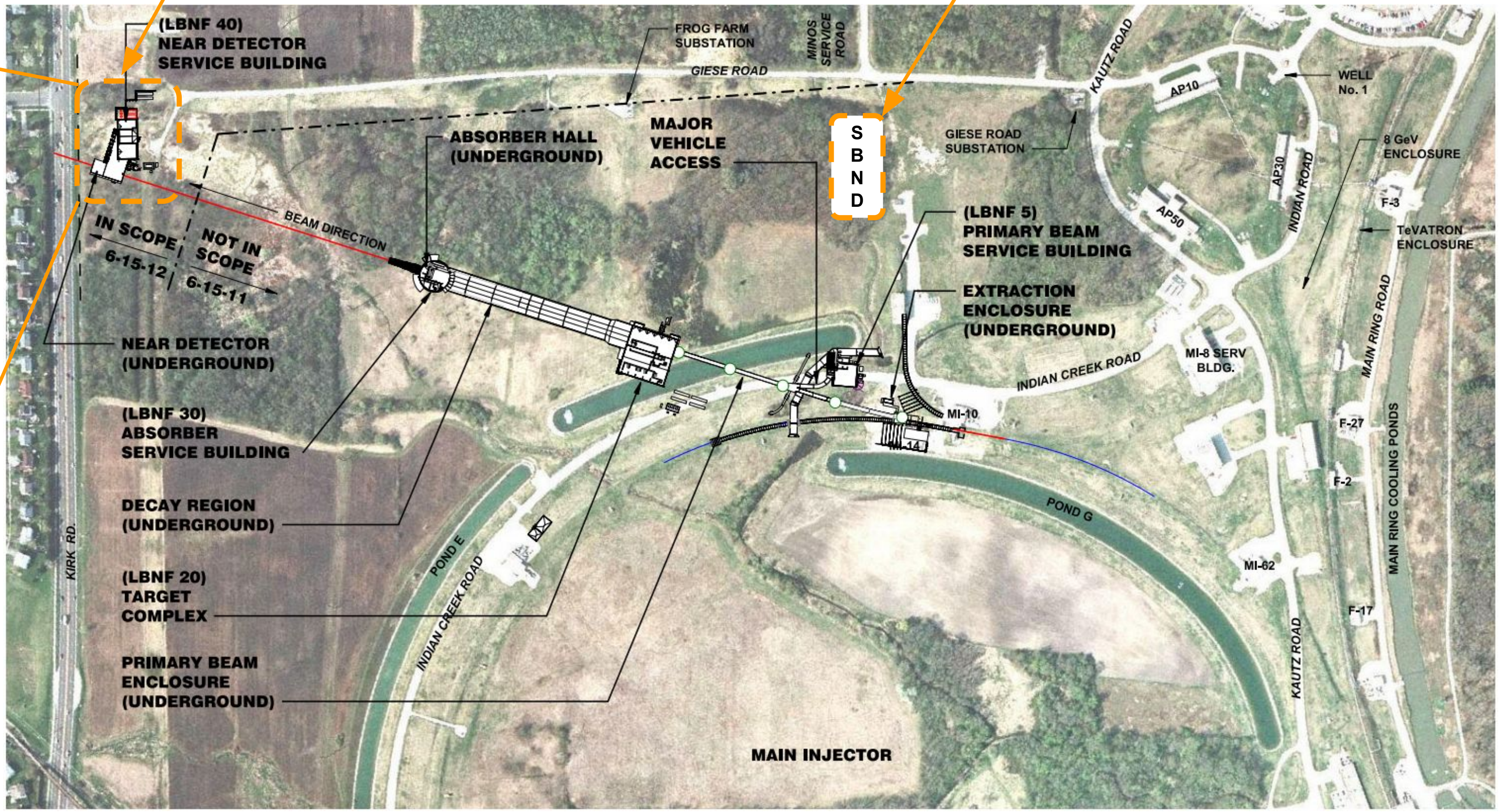
Shaft and Elevator provide Cavern Access

DUNE-ND Complex

SBND Building (GPS image predates SBND construction)

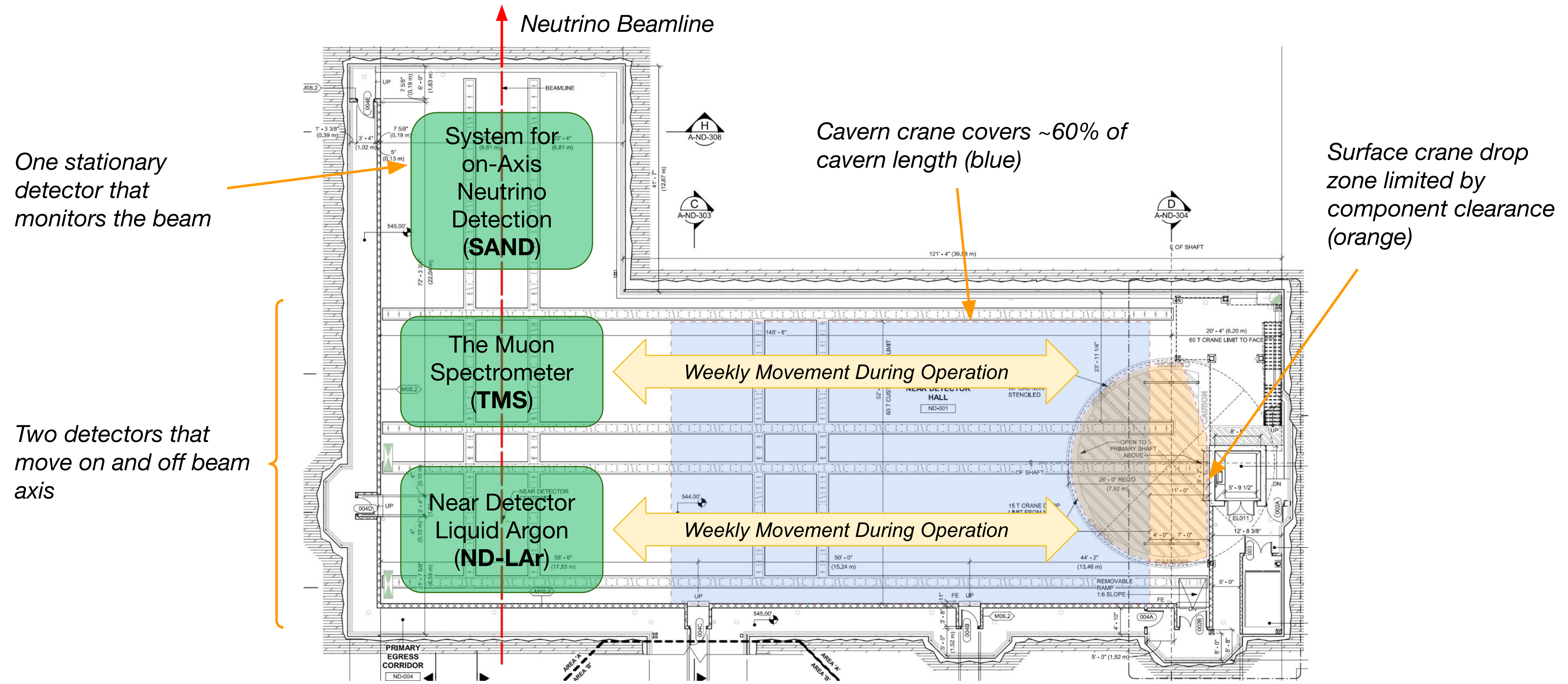


DUNE-ND Service Building



DUNE-ND Site Plan

The DUNE-ND Cavern is 60m below the DUNE-ND Service Building, accessible by crane and elevator



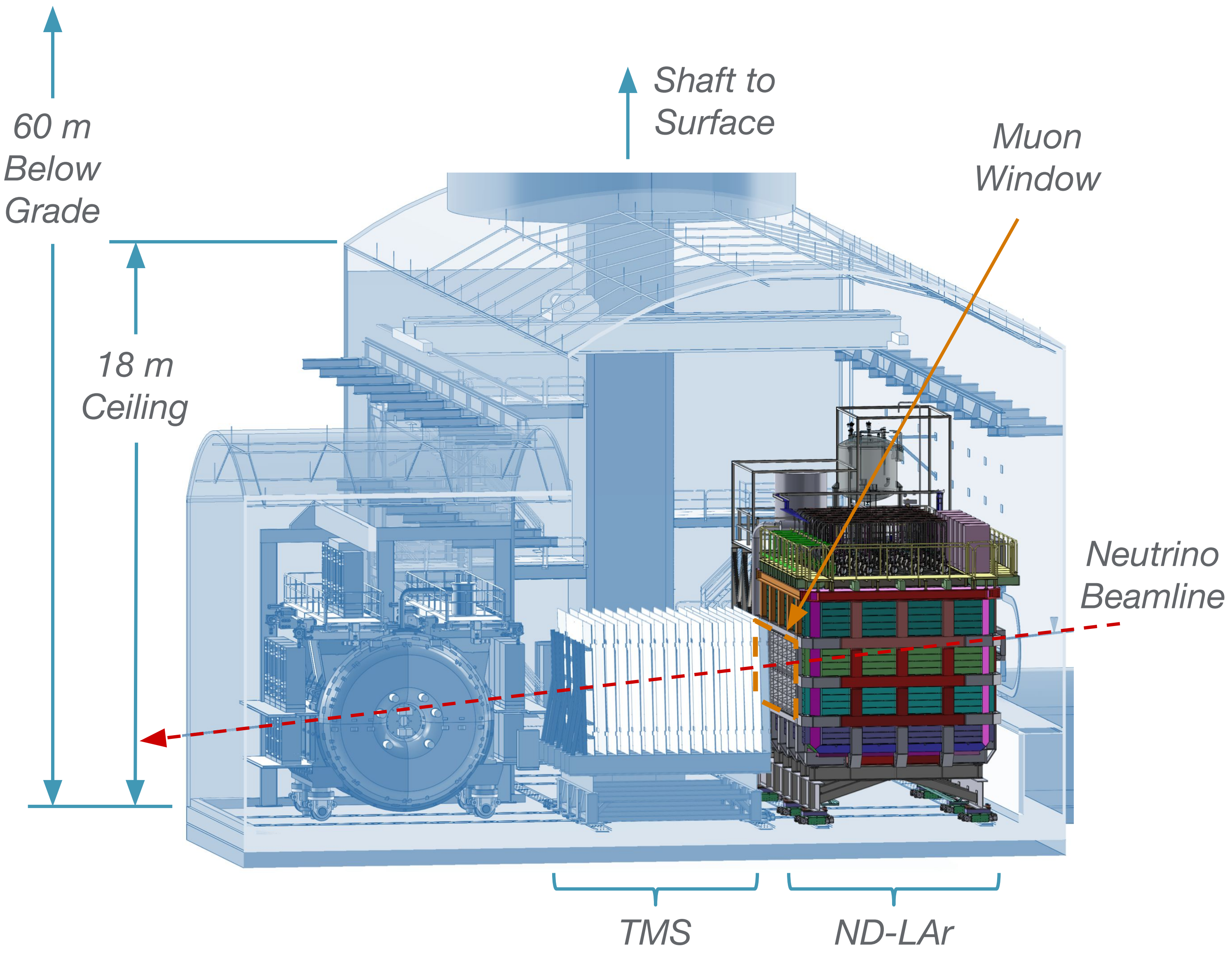
The ND Cryostat holds the ND-LAr Detector Time Project Chambers (TPCs)

ND-LAr Detector and Cryostat designs driven by physics requirements

- Dimensions optimized to match DUNE FD
- PRISM rollers and energy chain allow detector to move off beam axis
- Muon window on downstream side minimizes muon energy loss between ND-LAr and TMS

ND Cryostat leverages SBND & ProtoDUNE experience

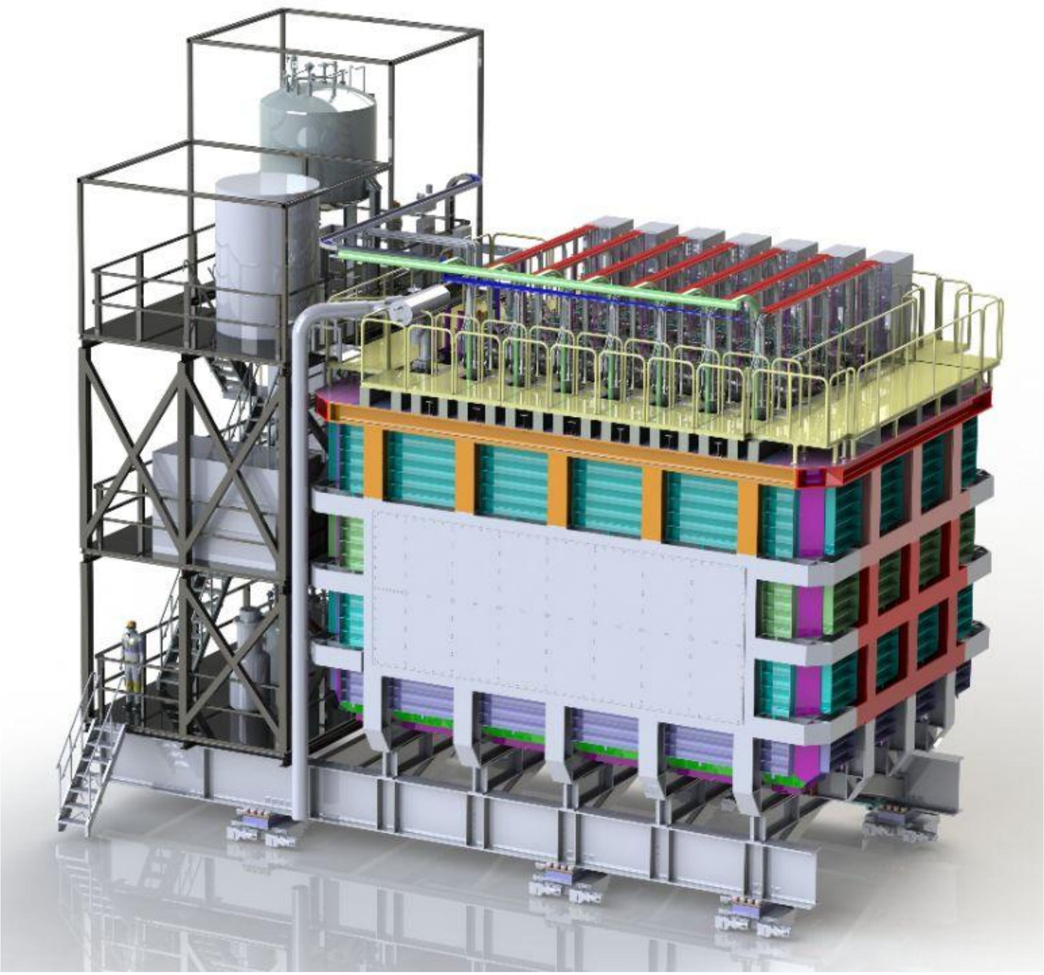
- Membrane cryostat construction
  - Steel outer warm structure
  - Corrugated stainless steel and polyurethane foam cold membrane liner
- Lid mounted detector (SBND)
- 196 m^3 liquid argon
  - vs 189 m^3 SBND, 485 m^3 ProtoDUNE



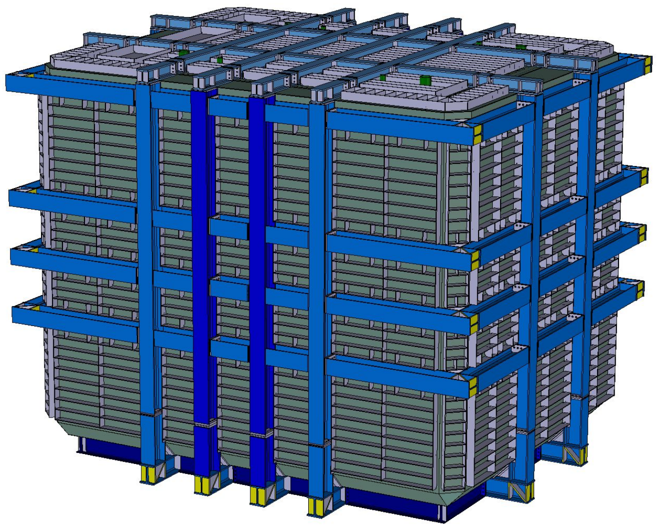
Charge # 3, 4, 5

DUNE-ND and Short Baseline Near Detector (SBND) Cryostats share many design features

	DUNE-ND	SBND
Steel warm structure with GTT cold membrane	✔	✔
Lid mounted detector	✔	✔
FNAL installation with partner institution support	✔	✔
Maximum gas pressure (mbar)	350	350
Liquid argon volume (m^3)	196	189
Warm structure exterior dimensions, L x W x H (m)	11.0 x 7.8 x 6.9	9.4 x 7.6 x 7.4
Number of lid segments	9	4
PRISM detector movement system	✔	✘
Muon window: high uniformity downstream wall	✔	✘
Underground installation	✔	✘



DUNE-ND Cryostat and ND-LAr Detector

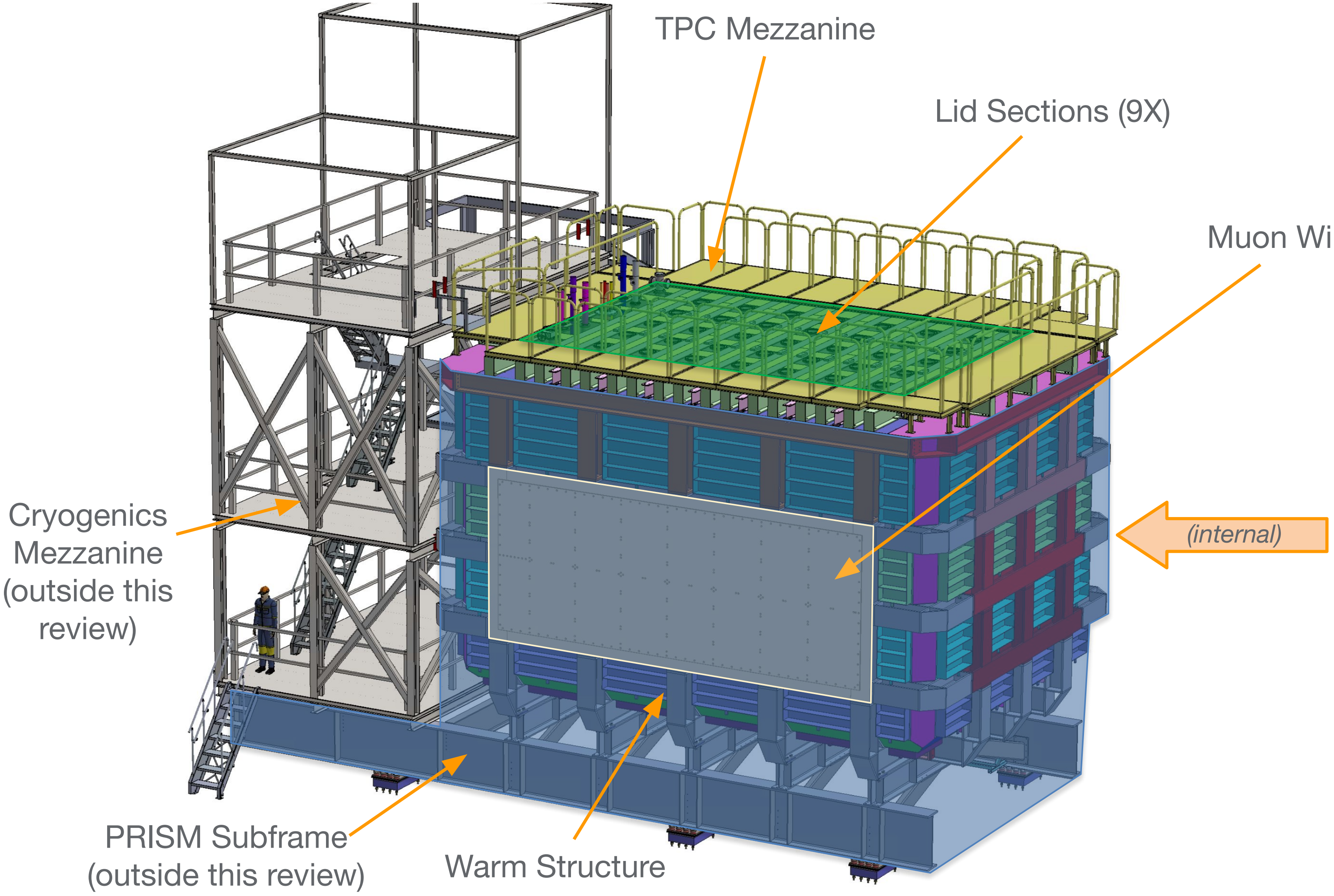


SBND Cryostat

Cryostat scope includes the liquid argon tank for the ND-LArTPC detector, a subframe which connects to the PRISM movement system, and two mezzanines. *This review excludes the PRISM subframe and cryogenics mezzanine.*

Charge 5, 6a

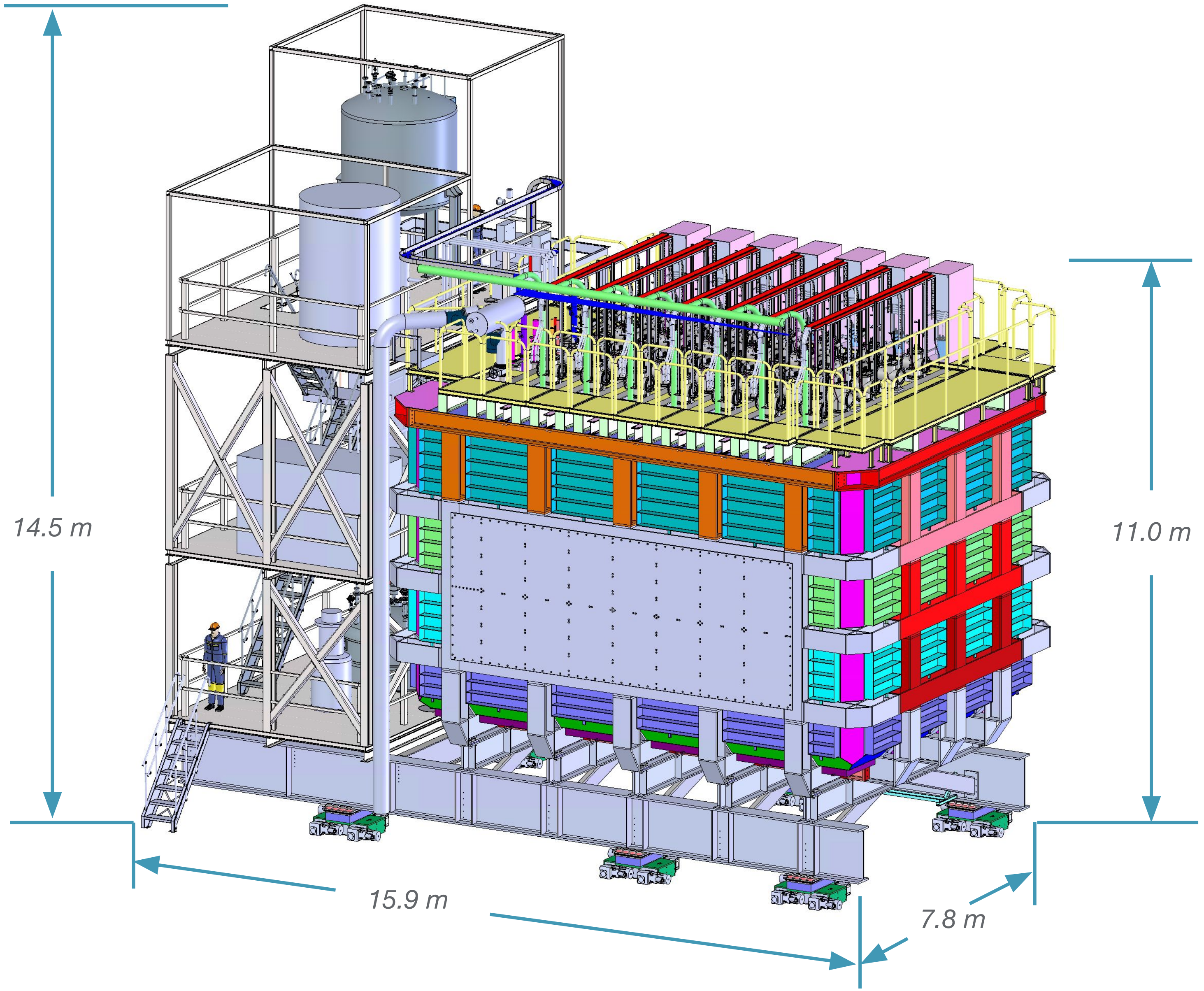
Management
Design Integration
Installation Planning



Cold Membrane

DUNE-ND LAr Detector Overall Dimensions

Description	***Weight (US tons)***
Liquid Argon	321
Cryostat Warm Structure	157
Cryogenics Mezzanine (including Cryogenic Components)	80
Cryostat Lid	52
TPC Mezzanine (including TPC Electronics and Hardware)	43
Cryostat Cold Membrane	22
TPC Modules	23
Total	*698*



Material selection follows SBND and ProtoDUNE precedent

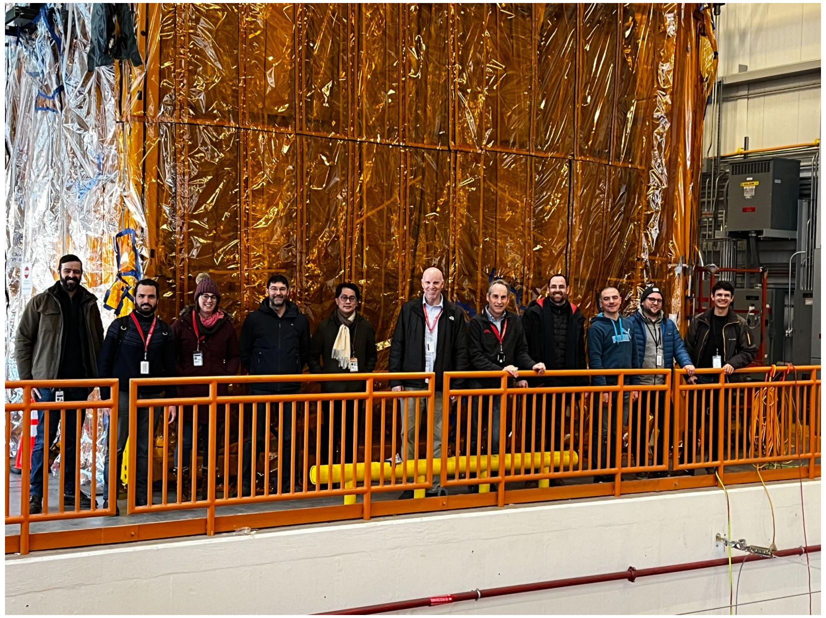
- Our baseline plan is to use S460ML, a low temperature (-50°C) qualified steel with minimum σ_y = 460 MPa used in SBND and ProtoDUNE
- If this material presents procurement challenges in the U.S. we will qualify an ASTM A572-65 steel for low temperature
- To be conservative, the safety factors are evaluated against the slightly lower yield strength of A572-65, σ_y = 65 ksi [448 MPa].

Caractéristiques mécaniques / Mechanical properties / Mechanische Eigenschaften

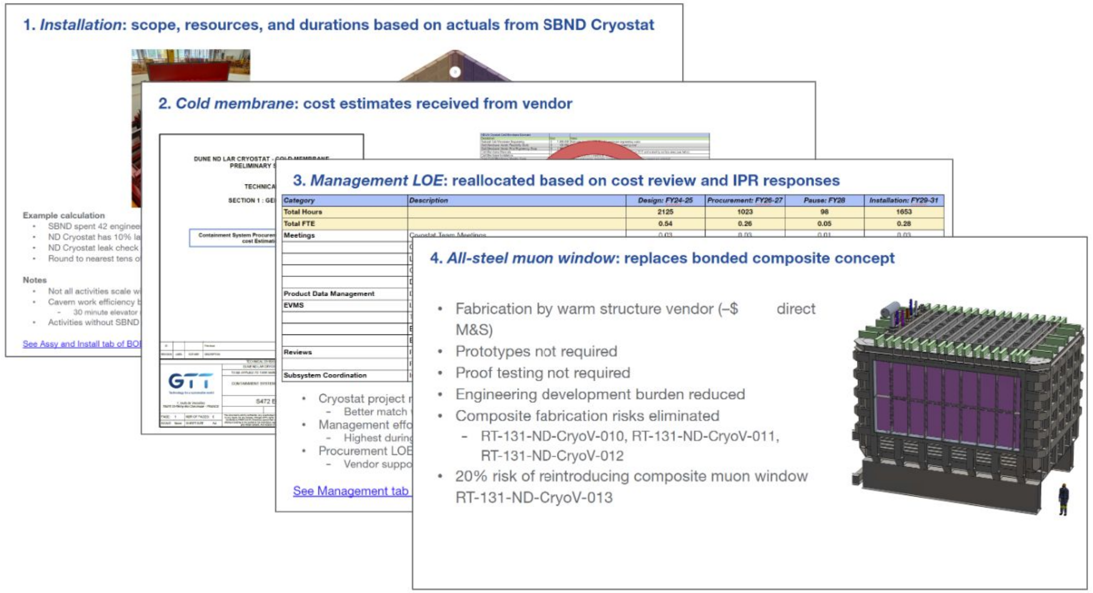
Norme Standard Norm	Nuances Grades Güten	Limite d'élasticité minimale R_{eH} Minimum yield strength R_{eH} Mindestwert der oberen Streckgrenze R_{eH} MPa							Résistance à la traction R_m Tensile strength R_m Zugfestigkeit R_m MPa						Allongement minimal A Minimum elongation A Mindestwert der Bruchdehnung A $L_0 = 5{,}65 \cdot \sqrt{S_0}$ %	Essai de flexion par choc, en long Notch impact test, longitudinal Kerbschlagbiegever-such, längs	
		Epaisseur nominale (mm) Nominal thickness (mm) Nenndicke (mm)							Epaisseur nominale (mm) Nominal thickness (mm) Nenndicke (mm)							Temp. Temp. Temp.	Energie absorbée min. Min. absorbed energy Mind. Kerb-schlagarbeit
		≤16	>16 ≤40	>40 ≤63	>63 ≤80	>80 ≤100	>100 ≤125	>125 ≤140	≤40	>40 ≤63	>63 ≤80	>80 ≤100	>100 ≤125	>125 ≤140		°C	J
EN 10025-4: 2004	S275M*	275	265	255	245	245	240	240	370-530	360-520	350-510	350-510	350-510	350-510	24	-20	40
	S355M	355	345	335	325	325	320	320	470-630	450-610	440-600	440-600	430-590	430-590	22	-20	40
	S355ML	355	345	335	325	325	320	-	470-630	450-610	440-600	440-600	430-590	-	22	-50	27
	S420M	420	400	390	380	370	365	365	520-680	500-660	480-640	470-630	460-620	460-620	19	-20	40
	S420ML	420	400	390	380	370	365	-	520-680	500-660	480-640	470-630	460-620	-	19	-50	27
	S460M	460	440	430	410	400	385	385	540-720	530-710	510-690	500-680	490-660	490-660	17	-20	40
	S460ML	460	440	430	410	400	385	-	540-720	530-710	510-690	500-680	490-660	-	17	-50	27

Since 2022 we have met regularly with the SBND installation team to review lessons learned

- Used SBND cryostat installation experience to improve the ND cryostat schedule, leading to a major BCR in October 2023
- Refined cold membrane procurement and installation plans, informing subcontract and statement of work discussions with GTT
- Leveraged SBND experience to improve assembly process, lift plans, lid and mezzanine design



2023-Feb Visit: SBND Lid and Detector (background) Installation Preparation



BCR preparation using SBND actuals

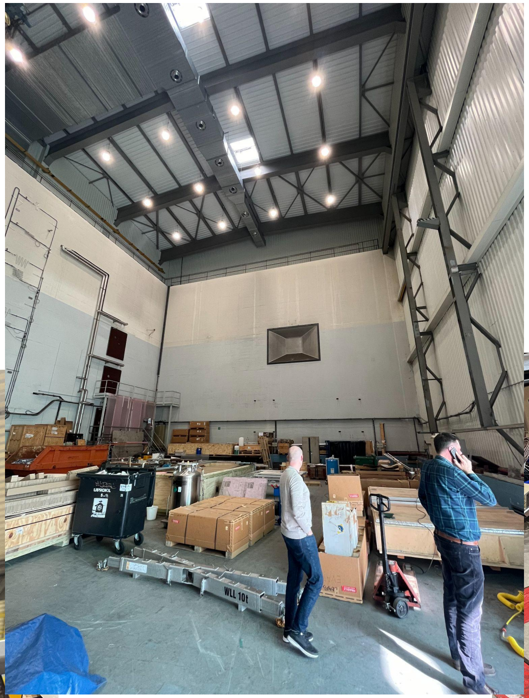
In March 2024 we met with the CERN cryostat team to present the ND cryostat design and review lessons learned from DUNE FD, SBND and ProtoDUNE

Charge # 3

30 pages of notes from two days of discussion! Key takeaways include:

- Identify stakeholders and agree on validation plans early
- Define detector position tolerances in detail
- Our warm structure has lots of margin
- A lid with a thick lap weld (like SBND) can be serviced without major rework

Lid design details



SBND warm structure fabrication workshop

ProtoDUNE mezzanine panels

Documentation

Charge # 1,5,6

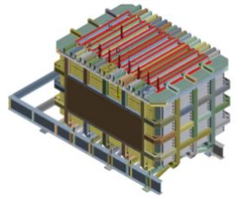
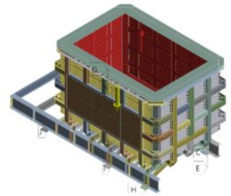
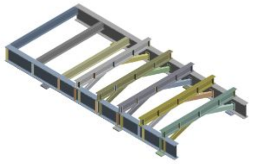
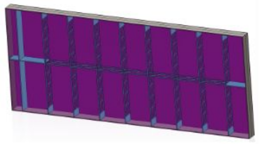
Key documents list is at EDMS 3161464

- Provides EDMS links to design documentation
- Based directly on DUNE PDR Deliverables, EDMS 2374096v1
- Also linked from PDR Indico page
- Drawing binder at EDMS 3165710

Category	Document	EDMS (Rev Ctrl Doc)
1. Design Documents		
Design Documents	TDR Chapter	EDMS 3161169
Design Documents	Design Updates	N/A
Design Documents	Grounding & Shielding Plan	EDMS 2459151
Design Documents	Mechanical CAD Model for Sub-system	EDMS CERN-0000234909
Design Documents	Mechanical Engineering Drawings	EDMS CERN-0000234910
Design Documents	Mechanical Assembly Drawings and Parts Lists	EDMS CERN-0000234910
Design Documents	Electrical Schematics & Board Layouts	N/A
Design Documents	Specification of Electrical Cabling and Wiring Connections	TBD
Design Documents	Bills of Materials for Electronic Board Components	N/A
Design Documents	Documentation Links for Commercial, Off-the-Shelf Powered Components	N/A
2. Requirements Documents		
Requirements Documents	Executive Board-Held Requirements	TBD
Requirements Documents	Technical Board-Held Requirements	EDMS 3153294
Requirements Documents	Consortium-held Requirements	EDMS 3158082
3. Installation Documents		
Installation Documents	Detector Installation Plan	TBD
Installation Documents	ProtoDUNE-II Installation Plan	N/A
4. Interface Documents		

Analysis Plan is at EDMS 3161164

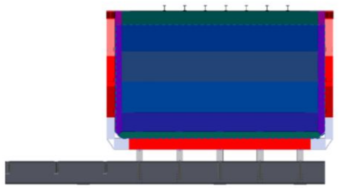
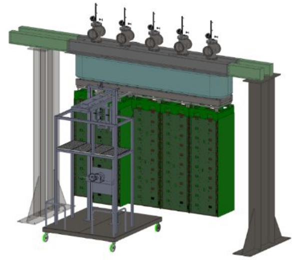
- Global structural FEA model provides overall deflection, boundary conditions for detailed models, and interface loads for bolted joint calculations
- Detailed FEA models use finer mesh and more detailed geometry to evaluate peak stress
- Coupled thermal-structural lid FEA evaluates combined effects of cool down, pressure and gravity
- Thermal spreadsheet calculations provide heat leak estimates for overall Cryostat

System	FESHM Chapter	Additional Standards and Codes	Analysis Type	Model Type	Model Image
Integration (Top Level)	5031.7 Membrane Cryostats	American Institute of Steel Construction (AISC) 360	Thermal, Structural	Global structural model based on simplified export of DU-1003-6059: solid models of warm structure, muon window, PRISM frame, lid, cold membrane foam. Simplified thermal model of entire cryostat tub: warm structure, muon window, lid.	
Warm Structure	5031.7 Membrane Cryostats	American Institute of Steel Construction (AISC) 360	Structural	Warm structure results extracted from global structural model (see above). Analyzing in the context of the global model ensures realistic results: for instance, the bottom of the warm structure is supported by the PRISM frame and not by boundary conditions from FEA software. Contact loads extracted from the model are used to perform detail design of bolted joints and welds between parts.	
PRISM Frame	5031.7 Membrane Cryostats	American Institute of Steel Construction (AISC) 360	Structural	PRISM frame results extracted from global structural model (see above). Analyzing in the context of the global model ensures realistic results: for instance, the PRISM frame members are reinforced by the presence of the warm structure and do not have a dead load simply imposed on them. Contact loads extracted from the model are used to perform detail design of bolted joints and welds between parts.	
Muon Window	5031.7 Membrane Cryostats	American Institute of Steel Construction (AISC) 360	Structural	Solid model of muon window assembly DU-1005-0413. Results compared to those seen in the global structural model. If interaction between muon window and surrounding structure is different enough from simply supported assumption, boundary conditions for the muon window specific model are extracted from the global structural model.	

Charge # 2, 6.e

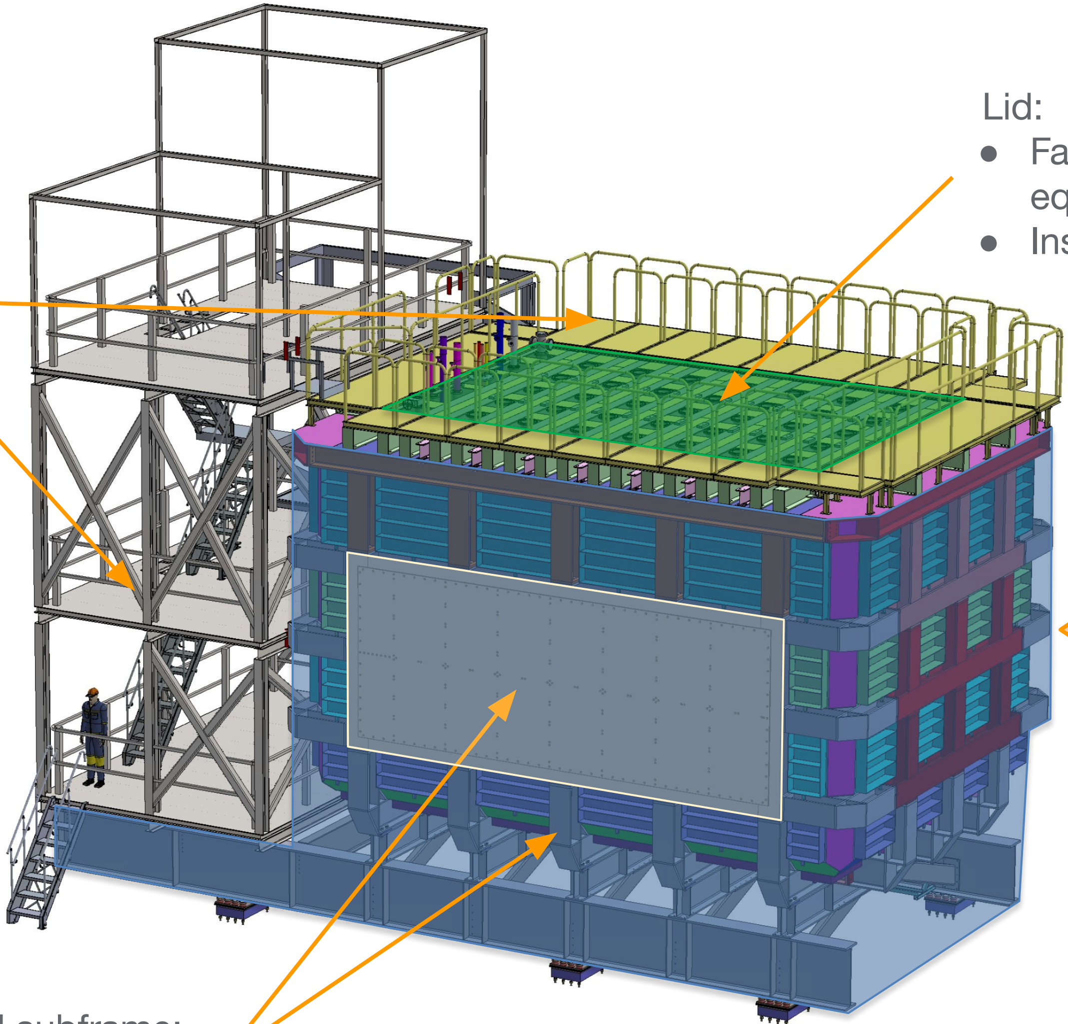
Prototype and Test Plan is at EDMS 3161168

- 5 Module Row Pre-Production tests integration of TPC modules to lid during final design phase
- Integrated PRISM Test (currently under evaluation for inclusion in schedule) provides payload for PRISM validation and correlates FEA results to real world before cavern installation
- 250 mbar N_2 pressure test after final cavern assembly as required by FESHM 5031.7

System	Prototype Summary	Documentation	Requirements and Processes to be Validated	Timing	Image
Warm Structure, Muon Window, PRISM Frame	Integrated PRISM test: Assemble PRISM frame, warm structure and muon window on PRISM movement system. Line cryostat tub with plastic pool liner and fill with water to simulate fully assembled detector weight. Use strain gauges and laser tracker survey to measure structural response to water load.	Decision Matrix - CRST a… -- see Integrated Test Stage 2 Integrated PRISM Test Pl…	Compare measured strain and deflection to FEA results. Update FEA boundary conditions and/or load application to more accurately represent real results. Use updated FEA to predict performance under operational loads. The primary test motivation is to address PRISM system risks, but it presents an opportunity to test the cryostat as well.	As soon as parts are available, approx 2027. Target >1 year before installation in ND cavern.	
Lid	Module Row Prototype with ND-LAr: Assemble five TPC modules (or mockups) to full scale TPC Row lid using production intent fixtures and processes. Weld and grind access mockup: Use simplified mockup of lid weld (1x1m slice of end of TPC Row lid in steel or cardboard) to evalute personnel and tool access for welding and service of lid.	EDMS 2591433	Requirements: TPC alignment accuracy, lid deflection under gravity load. Processes: lid alignment, installation, welding, lifting.	During final design phase, 2025.	

Procurement Plan is at EDMS 3161167

Mezzanines:
- Design-build contracts with engineering, procurement and construction (EPC) firm
  - Cryostat team provides assembly drawings only
  - Detailed design by vendor
- Install by construction firm or ND team (TBD)



Lid:
- Fab by refrigeration or scientific equipment supplier
- Install by ND team

(internal)

Cold Membrane:
- Design by GTT
- Fab and install by GTT-licensed subcontractor

Warm structure, muon window, PRISM subframe:
- Fab by shipbuilding or heavy duty steel supplier
- Install by supplier or ND team (TBD)

Charge # 6.d, 7

Procurement Plan is at EDMS 3161167

System	Capabilities	Facilities	Precision	Materials	Scale	Experience Base	Contracts and Supply Agreements	Notes
Warm Structure	Sourcing, cutting and machining I beams and plates. Structural welding. Bolted joints 1/2" to 2". Painting.	3000+ sq ft shop space for staging and assembly of 1000 sq ft finished assembly. 20 US ton crane with 40 ft hook height for building 30 ft tall assembly.	0.080" [2 mm] precision fabricating large assemblies. Experience using strategic build and fixturing processes to enable loosely toleranced piece parts to create tightly toleranced assemblies.	Carbon Steel (A572-50)	30 ft [10 m] parts. 150 US ton finished assembly, 15 US ton parts.	Shipbuilding, heavy duty construction equipment, building construction.	Seeking single supplier for warm structure, muon window and PRISM frame. Stretch goal to also include lid.	Location close to Fermilab preferred to reduce travel and shipping costs.
PRISM Frame	Sourcing, cutting and machining I beams and plates. Structural welding. Bolted joints 1/2" to 2". Painting.	3000+ sq ft shop space for staging and assembly of 1000 sq ft finished assembly. 20 US ton crane with 40 ft hook height for building 30 ft tall assembly.	0.080" [2 mm] precision fabricating large assemblies. Experience using strategic build and fixturing processes to enable loosely toleranced piece parts to create tightly toleranced assemblies.	Carbon Steel (A572-50)	30 ft [10 m] parts. 150 US ton finished assembly, 15 US ton parts.	Shipbuilding, heavy duty construction equipment, building construction.	Seeking single supplier for warm structure, muon window and PRISM frame. Stretch goal to also include lid.	Location close to Fermilab preferred to reduce travel and shipping costs.
Muon Window	Sourcing, cutting and machining plates. Structural welding. Grinding large (30 x 10 ft) plates flat. Large (15 ft) water jet or laser cutter. Bolted joints 1/2" to 2". Painting.	3000+ sq ft shop space for staging and assembly of 1000 sq ft finished assembly. 20 US ton crane with 40 ft hook height for building 30 ft tall assembly.	0.020" [0.5 mm] precision water jet or laser cutter. 0.080" [2 mm] precision fabricating large assemblies.	Carbon Steel (A572-65)	30 ft [10 m] parts. 15 US ton finished assembly, 7 US ton parts.	Shipbuilding, heavy duty construction equipment, building construction.	Seeking single supplier for warm structure, muon window and PRISM frame. Stretch goal to also include lid.	Location close to Fermilab preferred to reduce travel and shipping costs.
Cold Membrane	Specialized cryogenic membrane technology, GTT is sole source.	Materials fabricated worldwide, installation in DUNE ND cavern.	Requirements determined by GTT.	Various	N/A	Liquefied natural gas tankers and onshore storage tanks.	Three separate contracts: engineering, materials and installation. LBNL to place engineering contract and possibly material contract. FNAL to place installation contract to allow for direct authority over work happening on FNAL site.	GTT NA to provide estimate of alternative turn key sourcing under single contract.
Lid	Sourcing, cutting and machining I beams and plates. Sourcing vacuum flanges and feedthroughs (ConFlat hardware). Machining large (3 ft) foam blocks. Structural and hermetic welding. Welding carbon steel to stainless steel. Adhesive bonding. Painting.	2000+ sq ft shop space for staging and assembly of 9 assemblies with total footprint ~1000 sq ft. 10 US ton crane.	0.080" [2 mm] precision fabricating large assemblies. 0.040" [1 mm] precision after machining or grinding flat.	Carbon Steel (A572-50), Stainless Steel (304), Polyurethane Foam	25 ft [8 m] parts. 8 US ton finished assembly, 2 US ton parts.	Refrigeration systems, shipbuilding, scientific equipment.	Same supplier as warm structure, muon window and PRISM frame if possible.	Same supplier to provide 1-2 prototypes in 2025 and 9 production lids in 2026.
Cryogenics Mezzanine	Creating detailed fabrication drawings using provided assembly drawings. Bolted joint design and hardware sourcing. Sourcing, cutting and machining I beams. Specification and sourcing of OSHA compliant flooring, railings, and stairs.	2000+ sq ft shop space for staging and assembly of 3 mezzanine floors at 400 sq ft each. 20 US ton crane.	0.125" [3.18 mm] precision fabricating large assemblies.	Carbon Steel (A572-50), Fiberglass Floor Panels	30 x 15 ft foot print, 50 ft height split into three floors. 20 US ton finished assembly.	Building construction, civil engineering.	Same supplier for both mezzanines if possible.	Location close to Fermilab preferred to reduce travel and shipping costs.
TPC Mezzanine	Creating detailed fabrication drawings using provided assembly drawings. Bolted joint design and hardware sourcing. Sourcing, cutting and machining I beams. Specification and sourcing of OSHA compliant flooring, railings, and stairs.	2000+ sq ft shop space for staging and assembly of panels with total footprint ~1000 sq ft. 10 US ton crane.	0.125" [3.18 mm] precision fabricating large assemblies.	Carbon Steel (A572-50), Fiberglass and Plywood Floor Panels	30 x 40 ft foot print. 20 US ton finished assembly.	Building construction, civil engineering.	Same supplier for both mezzanines if possible.	Location close to Fermilab preferred to reduce travel and shipping costs.

- Targeting same supplier for warm structure, muon window, PRISM frame and (as a stretch goal) lid
- Targeting same supplier for cryogenics and TPC mezzanines
- After LBNL finishes contract for cold membrane engineering study, all contracts are planned to run through FNAL procurement

Charge # 6.e

Quality Assurance / Quality Control Plan is at EDMS 3161161

- Warm structure, muon window and PRISM subframe assembled (but not welded) at vendor for fit check and pre-shipment inspection
- Warm structure skin panels 100% bubble tested after welding in cavern
- Cold membrane primary containment 100% helium leak tested after welding in cavern
- Lids and lid interfaces surveyed to ensure compliance with detector position requirements. Datum scheme and survey points coordinated with ND-LAr TPC team so lid survey data can be used to infer TPC positions after assembly.

System	Fabrication Controls	Adjustability	Inspection Methods	Inspection at Factory	Inspection at Final Assembly
Integration (Top Level)	N/A	N/A	Survey by laser tracker.	N/A	Survey lid interfaces on top of Cryostat befo installation. Survey final TPC row positions.
Warm Structure	Factory fit check: assemble warm structure, PRISM frame & muon window at factory to verify and inspect as-built dimensions.	Shims at interface between PRISM frame and LAr tub allow for +/- 15 mm adjustment to level LAr tub (and ultimately lid mounting surface). Matched shims fastened to parts for shipment and reused in final assembly.	Survey by laser tracker. Inspection by coordinate measuring machine (CMM). Shim gap inspection by feeler gauge.	Inspect parts and subassemblies against all specified tolerances, provide inspection reports before factory fit check. Inspect finished assembly against all specified tolerances, provide inspection report before shipment.	Survey I beam frame subassemblies before assembly, changing shim thicknesses if nee Feeler gauge check of gaps at bolted joints. Vacuum bubble test 100% of skin panel wel Cold membrane installer repeats inspection internal wall flatness before stud welding. Survey finished assembly against all specifi tolerances.
PRISM Frame	Factory fit check; see warm structure section.	Shims at interfaces to warm structure bottom panel allow for +/- 15 mm adjustment at factory fit check.	Survey by laser tracker. Inspection by coordinate measuring machine (CMM). Gap inspection by feeler gauge.	Inspect parts against all specified tolerances, provide inspection reports before frame assembly. Inspect finished assembly against all specified tolerances, provide inspection report before shipment.	
Muon Window	Factory fit check; see warm structure section.	Stiffeners can be machined or shimmed to ensure flatness of assembled facings, but adjustment is not expected to be needed thanks to tight tolerances of fabrication processes (water jet and CNC machining).	Survey by laser tracker. Inspection by coordinate measuring machine (CMM).	Inspect parts against all specified tolerances, provide inspection reports before window assembly. Inspect finished assembly against all specified tolerances, provide inspection report before shipment.	Vacuum bubble test 100% of skin panel wel Cold membrane installer repeats inspection internal wall flatness before stud welding. Survey finished assembly against all specifi tolerances.
Cold Membrane	Defined by cold membrane supplier GTT.	Defined by cold membrane supplier GTT.	Go/no-go gauges (wall flatness, edge perpendicularity). Survey by laser tracker. Helium leak test.	Defined by cold membrane supplier GTT. GTT recommends a DUNE project technician witnesses final inspection before shipment.	Vacuum decay baseline at 200 mbar for sec containment (too large a volume for pass/fa criteria, goal is to characterize decay rate a compare to later tests). Helium leak test 100% of primary containme membrane welds.

Requirements

Key physics-driven requirements are approved by the ND Technical Board. Process for formal requirements flow down and approval of engineering-driven requirements is being developed.

- The Cryostat team collaborated closely with the ND Technical Board to define physics-driven requirements for detector positioning and muon window geometry

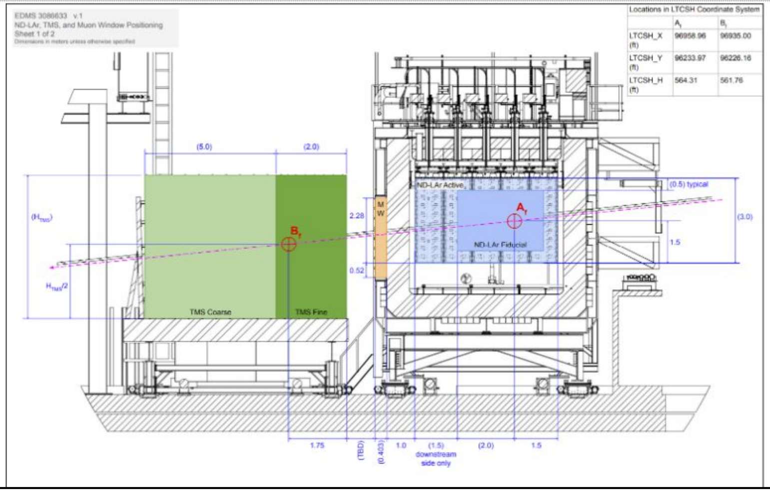
Level (1 =	ID	Requirement Name	Requirement Text	Rationale (Parent Req in Parenthesis)	Parent Requirement	Confidence Level (%)	Verification Method (Analysis, Demonstration, Inspection, Test)
1	Cryostat-11	Electrical Ground Isolation	Cryostat and TPCs shall share an electrical ground which is separated from facilities ground and comply with the ND-LAr grounding plan at EDMS 2459151.	Isolate TPC signals from facilities electrical noise			I
1	Cryostat-12	Lift Requirements	Rigging hardware and lift plans shall comply with FESHM 10200 Lift Plans and FESHM 10130 Slings and Rigging Hardware.	Comply with safety requirements of installation site.			A
2	Cryostat-13	Warm Structure Wall Deflection	Internal walls of warm structure (including muon window) shall deflect <= 4mm / m of length under operational load, as measured at I beams or other primary structural stiffeners.	Limit cold membrane strain per GTT interface requirements document S472 IRQ RPT 001.			A, T
2	Cryostat-14	Structural Factor of Safety	Warm structure (including muon window), PRISM frame, lid, and cryogenics mezzanine shall have a safety factor >= 2.0 above yield stress under nominal service load.	FESHM 5031.7 Membrane Cryostats requires compliance with American Institute of Steel Construction (AISC) Specification for Structural Steel Buildings (ANSI/AISC 360-16) which defines a FOS >= 2.0 typical above ultimate strength.	Cryostat-7		A
2	Cryostat-15	Operational Loads	The cryostat shall be designed to safely operate under the following loads: - Hydrostatic pressure load of liquid argon to >= 4.5 m depth. - Gas design pressure in ullage of >= 350 mbarg. - Gas vacuum pressure in ullage <= -30 mbarg.	Liquid argon fill level set by TPC height Pressure relief valve setpoint 350 mbarg Vacuum relief valve setpoint -30 mbarg	Cryostat-8, Cryostat-9		A
2	Cryostat-16	Dry Gas Volume Sealing	The cold membrane insulation volume shall be sufficiently sealed such that a 30 L/min supply of continuous dry gas into the enclosure maintains the dewpoint <= -20 °C under the full range of cavern ambient conditions.	Support purge gas flow requirement	Cryostat-9		A, T
2	Cryostat-17	Dry Gas Volume Permeation	The cold membrane insulation volume shall be sufficiently sealed to keep permeation of water vapor below 0.5 g/m^2 per day.	Satisfy requirement in FESHM 5031.7 section 7.1	Cryostat-9		T
2	Cryostat-18	Dry Gas Volume Leak Test	The cold membrane insulation volume shall be leak checked and verified bubble leak tight.	Satisfy requirement in FESHM 5031.7 section 6	Cryostat-9		T
2	Cryostat-19	LAr Temperature	Cryostat shall be capable of maintaining liquid argon at the required temperature continuously when the ND-LAr detector is in operation.	Comply with interface requirements defined by Cryogenics, ND-LAr and NSCF	Cryostat-8		A
2	Cryostat-20	TPC Positional Accuracy	Alignment features shall be provided to position the TPC rows with the accuracy specified in the 'TPC requirement document' EDMS 2589287.	Enable accurate event reconstruction [L1 req't ID]	Cryostat-8		I, A
2	Cryostat-21	Conductive Electrical Insulation, Cryostat Ground to Facilities Ground	Cryostat/TPC shared ground shall be isolated from facilities ground used by cryo mezzanine components, PRISM system, and general cavern power with >= 100 MΩ (TBC) resistance.	Value provided by System EE, prevents noise from facilities ground from affecting TPC.	Cryostat-11		T
2	Cryostat-22	Electrical Creepage, Cryostat Ground to Facilities Ground	Cryostat/TPC shared ground shall be separated from facilities ground used by cryo mezzanine components, PRISM system, and general cavern power with >= 100 mm (TBC) creepage distance.	Value provided by System EE, prevents loss of isolation due to surface contamination across insulators.	Cryostat-11		A
2	Cryostat-23	Capacitive Electrical Isolation, Cryostat Ground to Facilities Ground	Cryostat/TPC shared ground shall be separated from facilities ground used by cryo mezzanine components, PRISM system, and general cavern power with >= 305 mm (TBC) clearance.	Value provided by System EE, prevents capacitive coupling between conductively isolated components.	Cryostat-11		A
2	Cryostat-24	Pressure Test	The cryostat shall be tested to 250 mbar gas pressure after final assembly.	Pressure test required by FESHM 5031.7 Membrane Cryostats.			T
2	Cryostat-25	Cryogenic Piping	Piping must be ASME B31.3 compliant and have welding WPS, welder WPQ and material certificate. Qualification tests include pressure test and helium leak test. Degreasing for oxygen service required.	ASME B31.3 compliance required by FESHM 5031.7 Membrane Cryostats.			A

Extended cryostat requirements list including engineering-driven items (EDMS 3158082)

7. REQUIREMENTS

The interface tables define necessary interfaces, their development status, and provide the defining document number where the detailed interface definition can be found.

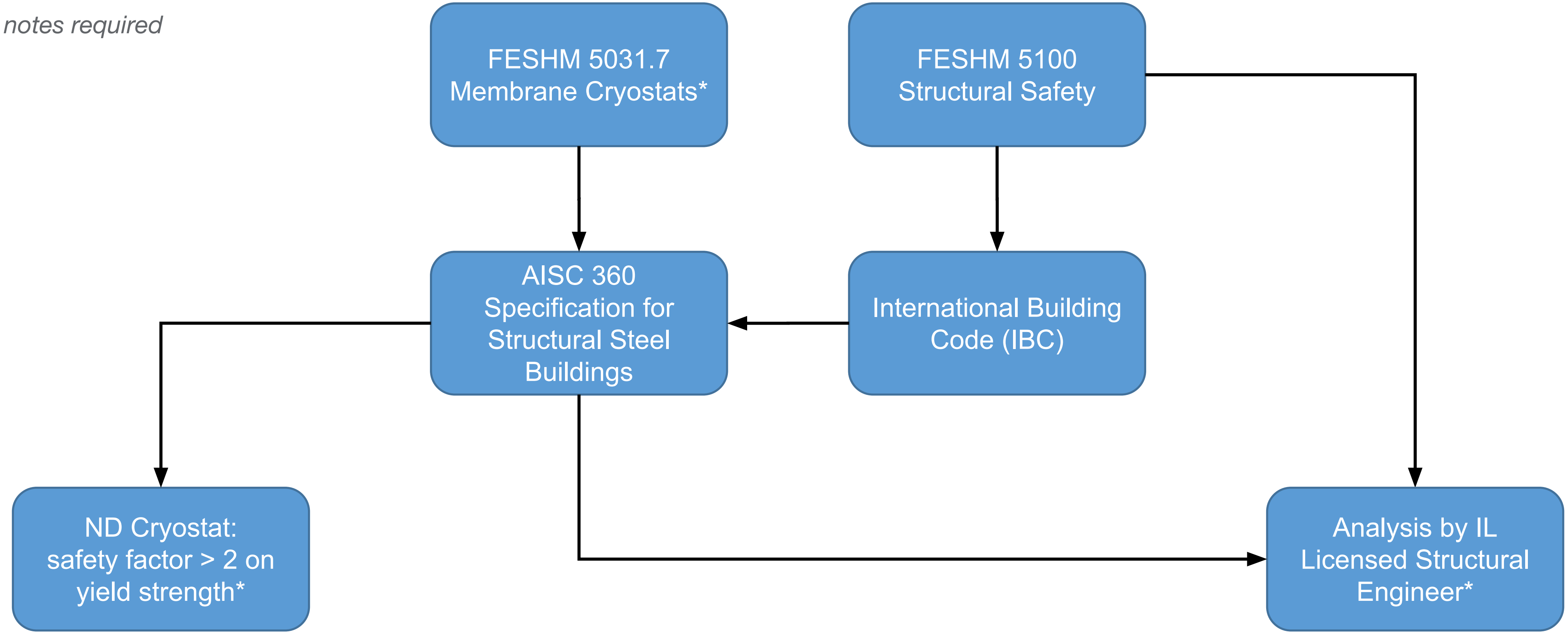
ID	Name	Description	Rationale
Cryostat-1	Downstream Wall Position	The low density region of the downstream wall (or "muon window") shall be positioned according to drawing EDMS 3086633.	Energy loss from muons intersecting passive material must be <3% at 600 MeV in order to enable reliable reconstruction of muon tracks between ND-LAr and TMS detectors.
Cryostat-2	Downstream Wall Density	The total areal density of cryostat components downstream of the ND-LAr active volume shall be ≤ 60 g/cm² ± 10 g/cm² over ≥ 82% of the low density region, measured perpendicular to the wall. Parts of the low density region falling outside of the 60 g/cm² ± 10 g/cm² density range shall be spaced at >= 30 cm (both vertically and horizontally) or 30x their width, whichever is greater. See drawing EDMS 3153292 for current reference design.	Energy loss from muons intersecting passive material must be <3% at 600 MeV in order to enable reliable reconstruction of muon tracks between ND-LAr and TMS detectors.
Cryostat-3	TPC Volume Position	When the PRISM system is parked on the beam axis, the ND-LAr active volume shall be positioned according to EDMS 3086633. The tolerance on this position is 10 cm in any direction (a ⌀20 cm diameter spherical zone) under the full range of operating conditions (i.e. pressure and temperature variation). The ND-LAr active volume position is impacted by multiple systems including Cryostat, PRISM, ND-LAr and NSCF and the allocation of the tolerance budget is still to be determined. In principle, Cryostat does not expect to have issues meeting dimensional tolerances on the cm scale.	



Excerpt from standalone record of decision document for physics-driven requirements (EDMS 3153294)

Applicable codes flow down from FESHM

**Engineering notes required*



- Yield safety factor > 2 used for preliminary design FEAs, a conservative simplification of 600+ page AISC 360 code
- Illinois-licensed structural engineer performs analysis against AISC 360 code
  - Verifies that safety factor approach was successful
  - Structural engineer sign off required by FESHM 5100

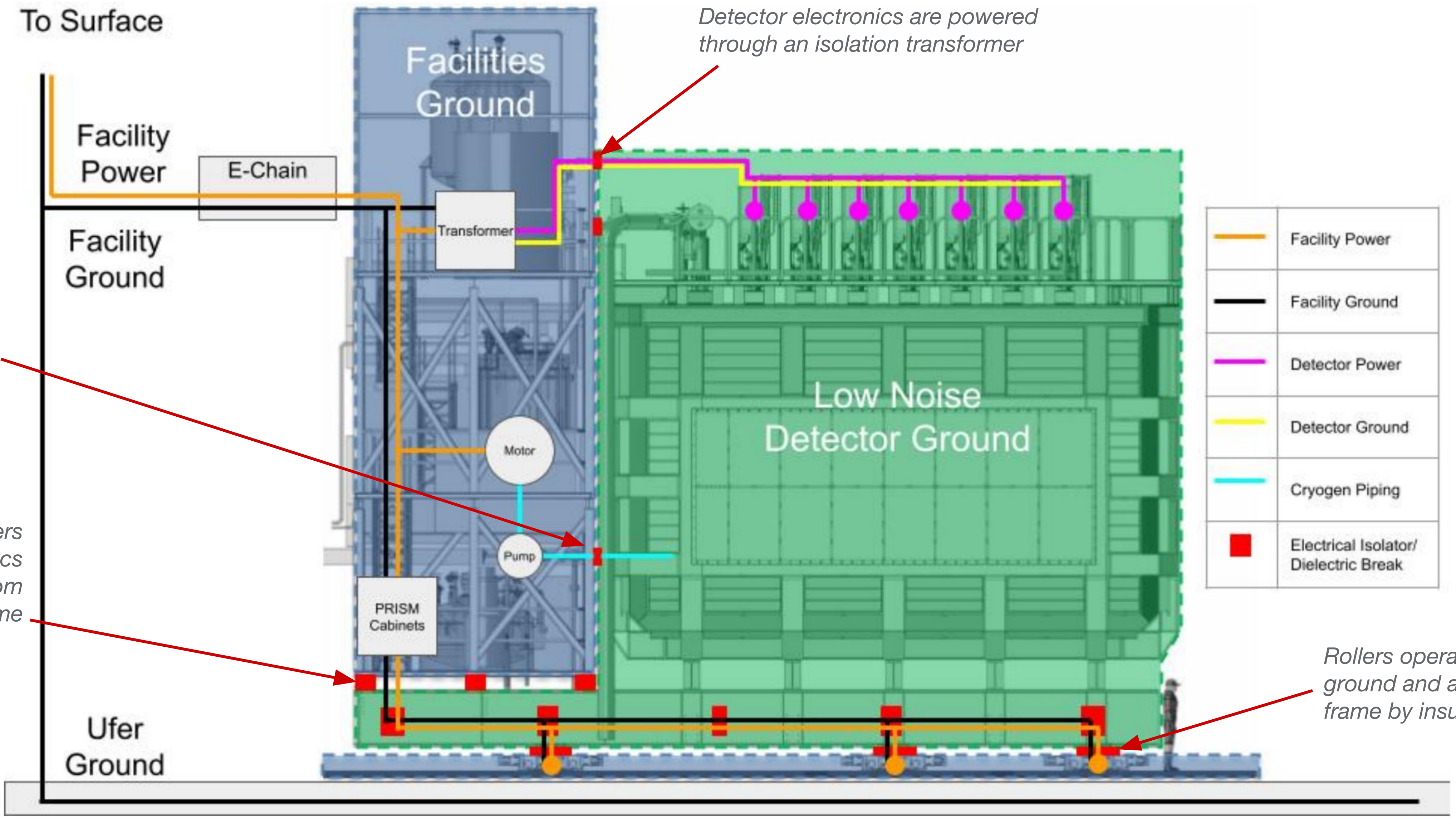
Scope division between Cryostat team, Structural Engineer, vendor and FNAL ISD defined through close collaboration with FNAL ISD

Charge # 1, 6.e, 6.f

- Preliminary Design
  - Cryostat team designs to safety factor >2 on yield strength
  - Cryostat team creates 3D models of all parts, 2D drawings of key assemblies
- Final Design
  - Illinois licensed structural engineer (SE) performs analysis against AISC 360 code
  - Cryostat team creates 2D drawings of all assemblies and subassemblies plus any key parts (SE reviews)
- Fabrication
  - Vendor creates shop drawings for individual I beams, plates, etc
  - Vendor helps us develop assembly procedures during dry build and integrated test
- Installation
  - ND team installs in cavern (no SE or vendor involvement)
  - ND team performs pressure test of final assembly (FESHM 5031.7 requirement)

Date	Phase	Activity	DUNE-ND Cryostat Team	Illinois-licensed Structural Engineer (SE)	Vendor	Fermilab Structural (ISD)
2024	Preliminary Design	Identify load cases and boundary conditions				
		Design beam layout, custom welded joints, bolted joints				
		Analyze in ANSYS, target yield strength safety factor > 2				
		Create preliminary drawing package: top level assemblies and representative wall/frame subassemblies				
		Conduct preliminary design review				
	Final Design	Prepare statements of work, load cases, preliminary drawings for SE subcontract				
		Request quotes from structural engineers				
		Request quotes from vendors to inform cost estimates				
		Review quotes and select SE and vendor				
		Process baseline change request as needed to reflect latest quotes and development plans				
2025		Conduct CD2 review				
		Prepare contract with structural engineer for analysis against codes				
		Analyze against International Building Code (IBC), American Institute of Steel Construction (AISC) 360 codes				
		Create final drawing package: top level assemblies, subassemblies, drawings of key components (lid membrane and insulation)				
		Review final drawings and analysis results (multiple steps at 60%, 90%, 100%)				
		Conduct final design review				
2026		Request updated quotes from vendors using final drawing package				
		Process baseline change request as needed to reflect latest quotes				
		Conduct CD3 review				
2027	Procurement	Prepare contract with vendor for fabrication				
		Create fabrication drawing package: shop drawings for individual parts based on final drawing package				
		Review fabrication drawings				
		Fabricate parts				
		Deliver parts to integrated test site				
		Assemble Liquid Argon Tub, Muon Window, PRISM Frame for integrated test				
		Disassemble and ship to Fermilab				
2028	Installation	Install in DUNE-ND cavern				

Detector ground is isolated from facilities ground



Detector electronics are powered through an isolation transformer

Cryogenic piping uses dielectric breaks

Fiberglass spacers isolate cryogenics mezzanine from subframe

Rollers operate on facilities ground and are isolated from frame by insulating plates

Interfaces

Charge # 1, 5, 6.a

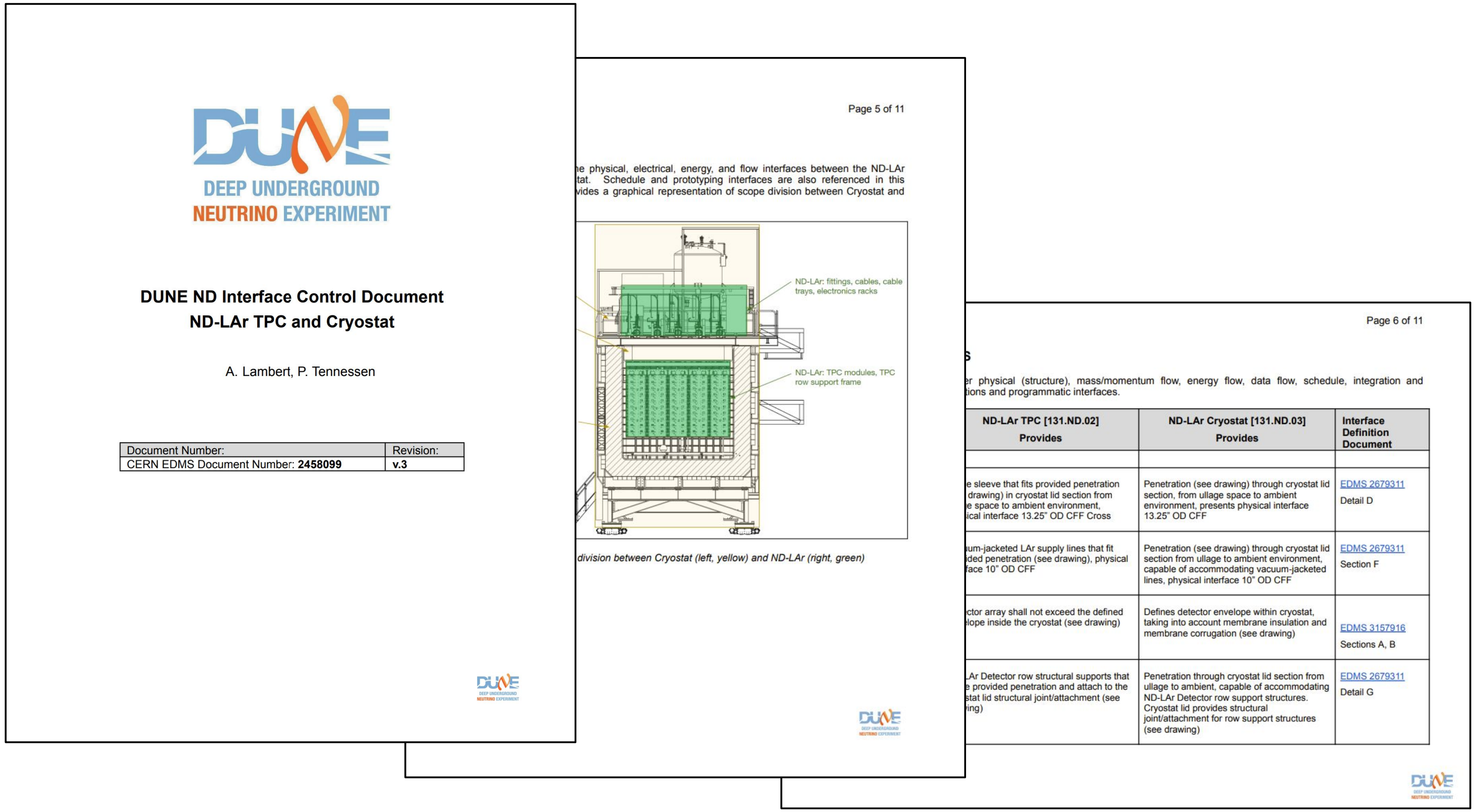
Cryostat has interfaces to ND-LAr, Cryogenics, Installation and Integration (I&I), Slow Controls, and PRISM (not in review scope)

LAr TPC	LAr Cryostat	Muon Spectrometer	Beam Monitoring	PRISM	Cryogenics - LAr	Cryogenics - LHe	ND Electrical Engineering	DAQ and Slow Controls	Installation and Integration	Near Site Conventional Facilities	
	3	2		2	2		2	2	2	3	LAr TPC
				2	3		3	2	3	3	LAr Cryostat
			2	2			2	0	2	3	Muon Spectrometer
				0	2	2	2		2	3	Beam Monitoring
					2	2	2	0	2	3	PRISM
						2	2		2	3	Cryogenics - LAr
							2		2	3	Cryogenics - LHe
								0		3	ND Electrical Engineering
									2	3	DAQ and Slow Controls
										3	Installation and Integration
											Near Site Conventional Facilities

Maturity phase color coding

0	Identified interface without a document
1	Draft in Work
2	Phase 1: Scope boundaries, critical interface definition (CD-1)
3	Phase 2: Interface details affecting component preliminary design and possibly costs (CD-2)
4	Phase 3: Final details to fully define all aspects of the interface (CD-3)

DUNE-ND Systems Engineering team manages N^2 diagram and identifies interfaces between ND subsystems

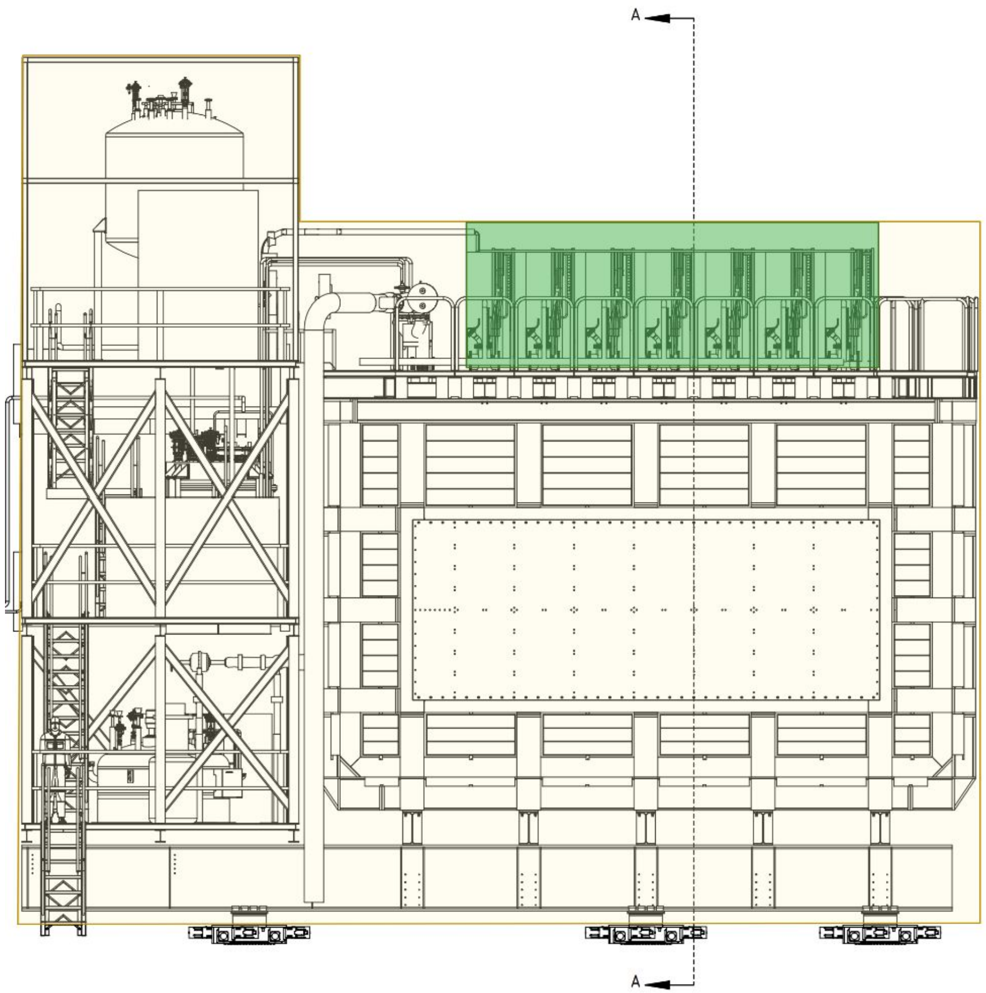


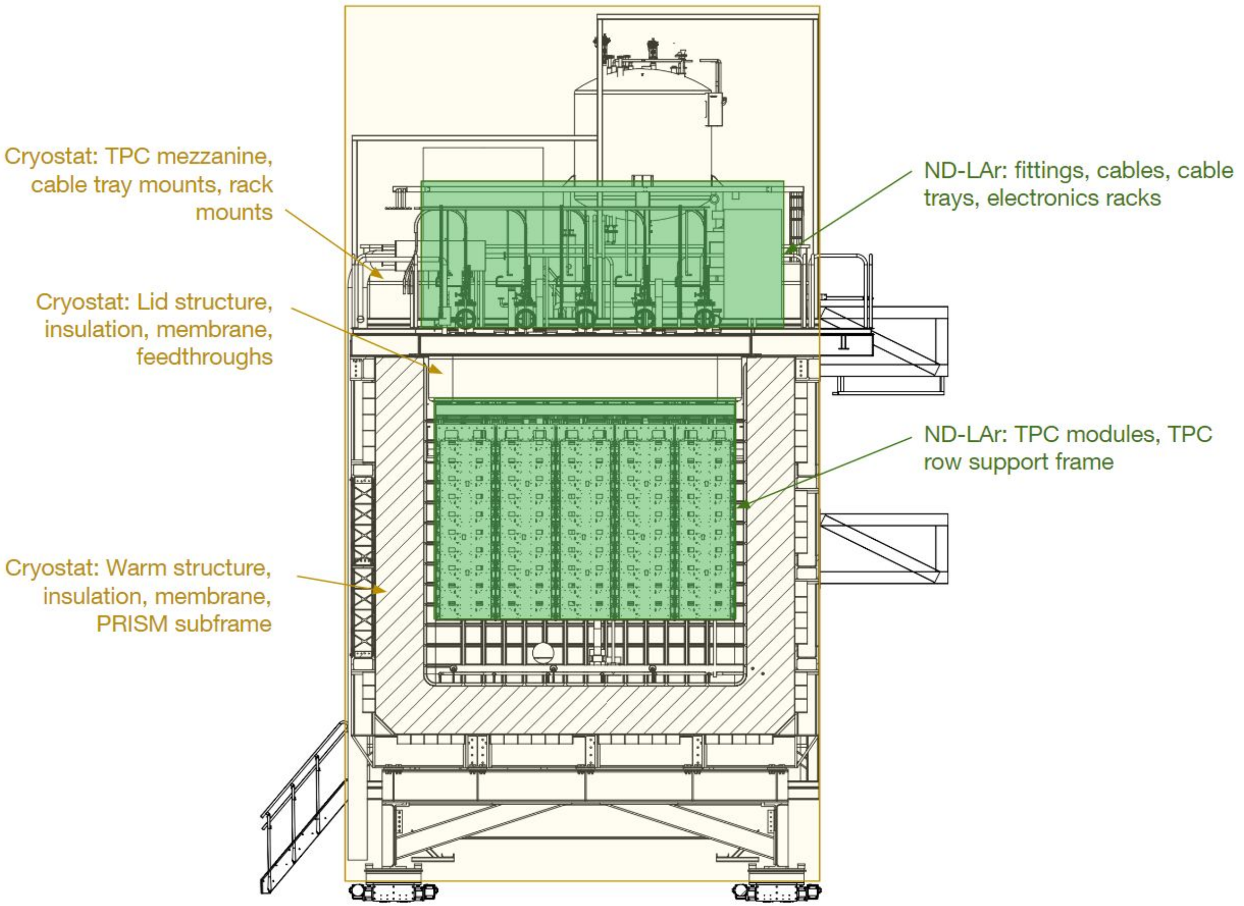
ND-LAr to Cryostat ICD Example

Controlled versions of interface control documents (ICDs) are stored on EDMS at CERN-0000218521

Interfaces with the ND-LAr TPC system include the TPC modules hanging from the lid and the electronics on the TPC mezzanine

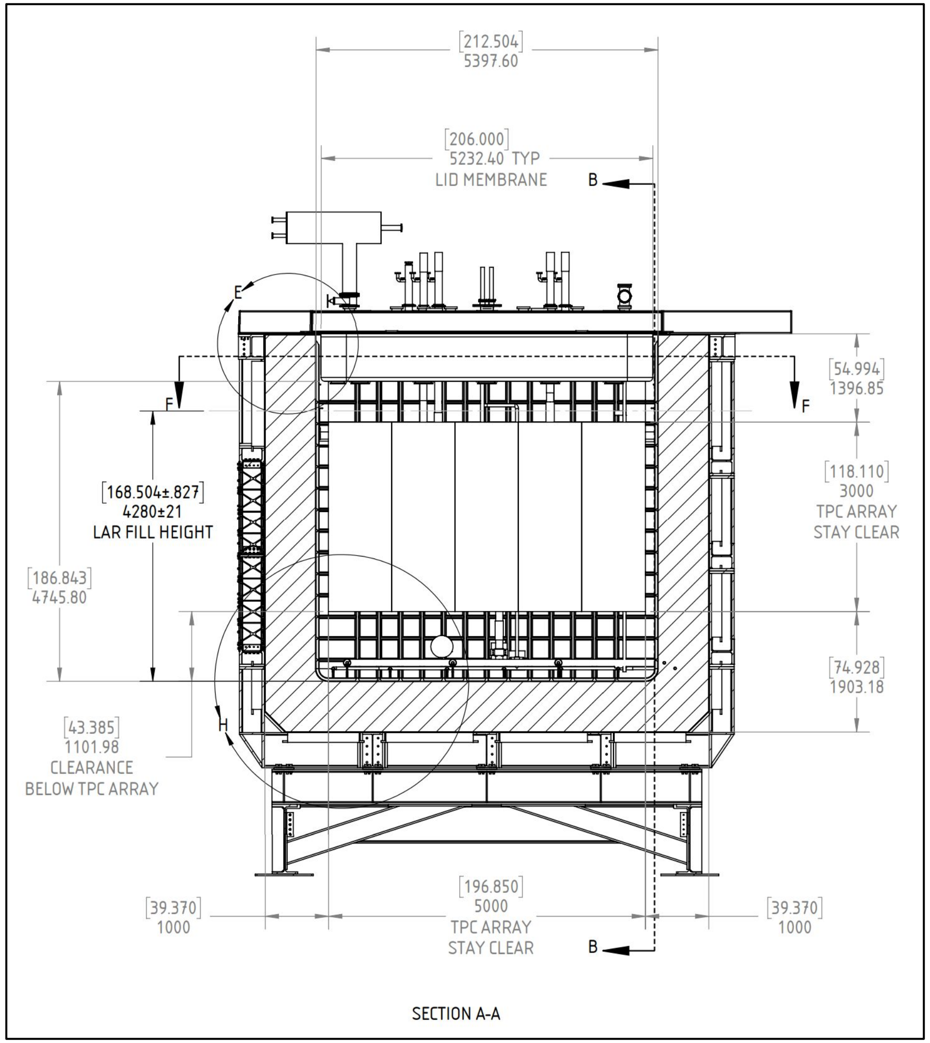
Charge # 1, 5, 6.a



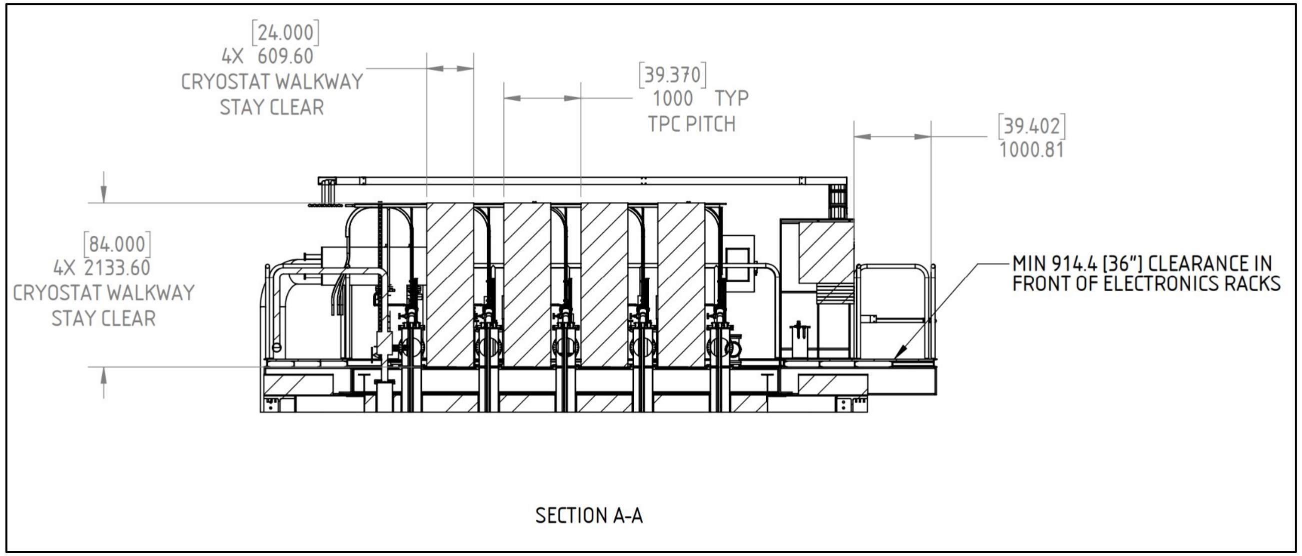


- Like SBND, detector modules hang from the lid
- Unlike SBND, the 9 lid sections are installed individually rather than pre-assembled outside of the cryostat

Interfaces with the ND-LAr TPC system include the TPC modules hanging from the lid and the electronics on the TPC mezzanine

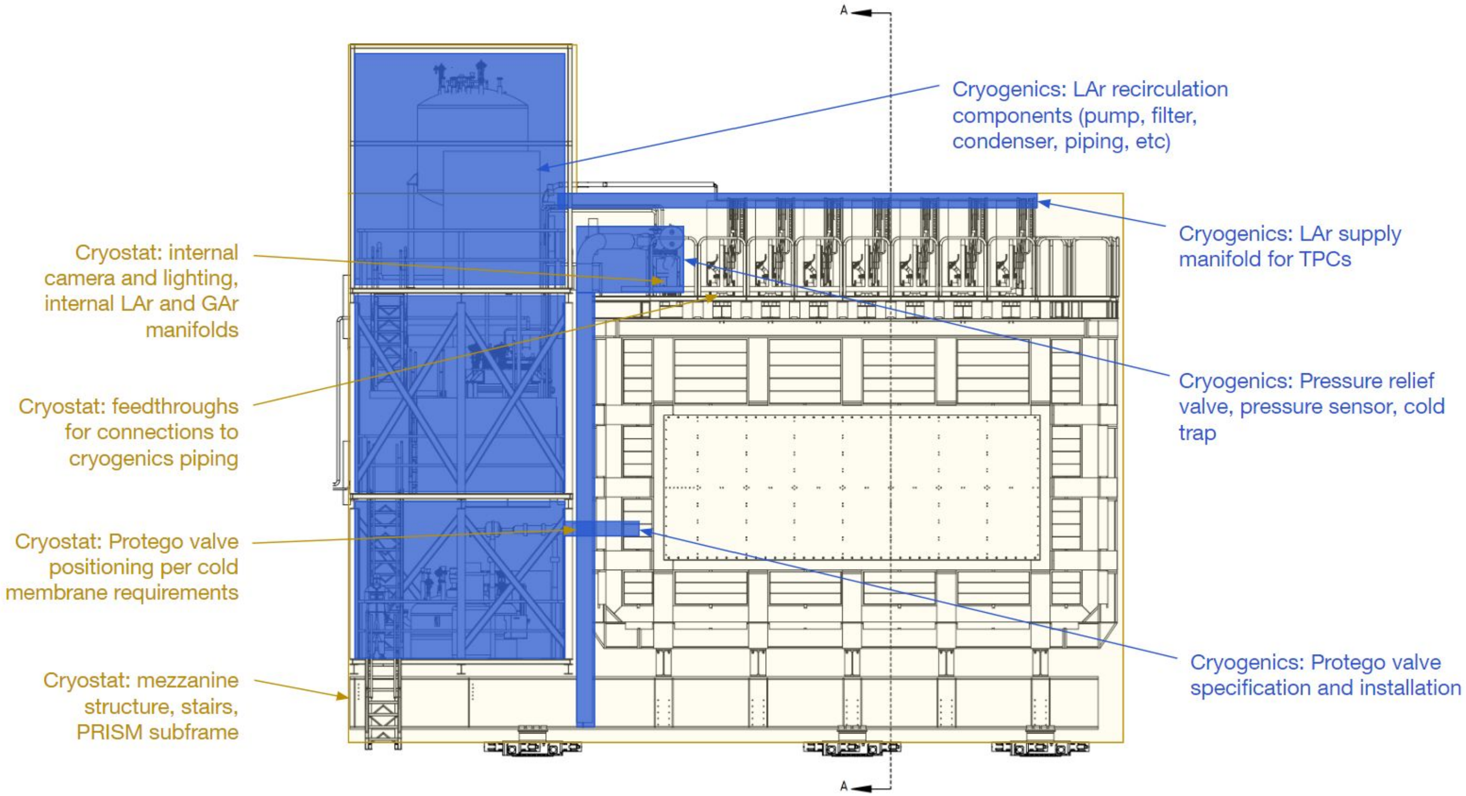


Excerpt from TPC Array Envelope Drawing (EDMS 3157916)



Excerpt from TPC Mezzanine Interface Drawing (EDMS 2679314)

Interfaces with the Cryogenics system include the LAr recirculation components on the cryogenics mezzanine and feedthrough connections on the lid



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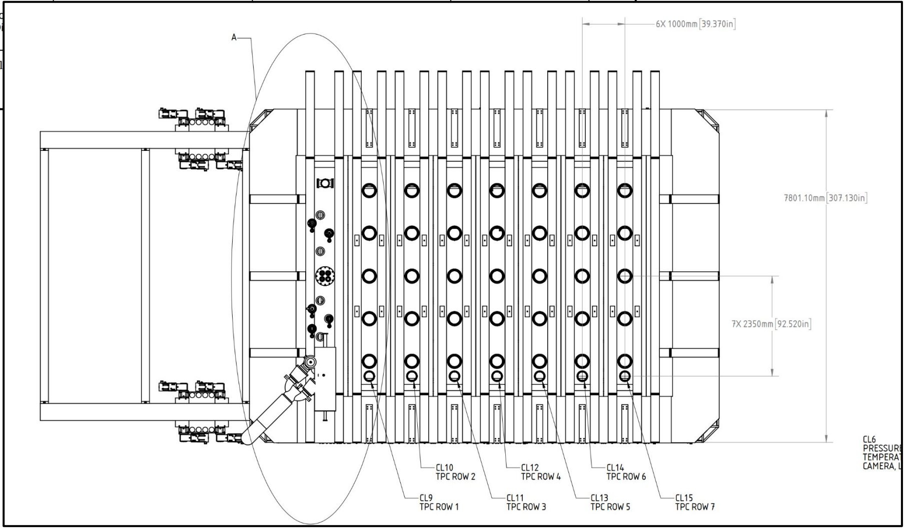
ID	Item	ND-LAr Cryostat Provides	Near Site Cryogenics Provides	Interface Definition Document
INT-109	Pressure sensors	Provides the feedthrough and flange with two 1/8th capillary tubing fittings and radiation baffles with enough cross section to ensure correct pressure measurement.	Provides a differential pressure transducer (DPT) to measure relative pressure of cryostat with atmosphere for structural purpose. Provides a pressure transducer (PT) to measure absolute pressure inside the cryostat to regulate bath saturation temperature.	
INT-111	Membrane insulation space purge flow	Provides feedthroughs on cryostat and lids : Inlet and outlet for each lid section (18 total). Inlet and outlet for both cold membrane volumes (4x total). Pressure safety valve and pressure sensor for both cold membrane volumes (4x total).	Provides gaseous nitrogen supply, pressure safety valves, pressure sensors, piping and means to regulate pressure in the insulation space. Includes electrical breakers to decouple ground.	EDMS 3157927
INT-112	Detecto… Heat Di…			

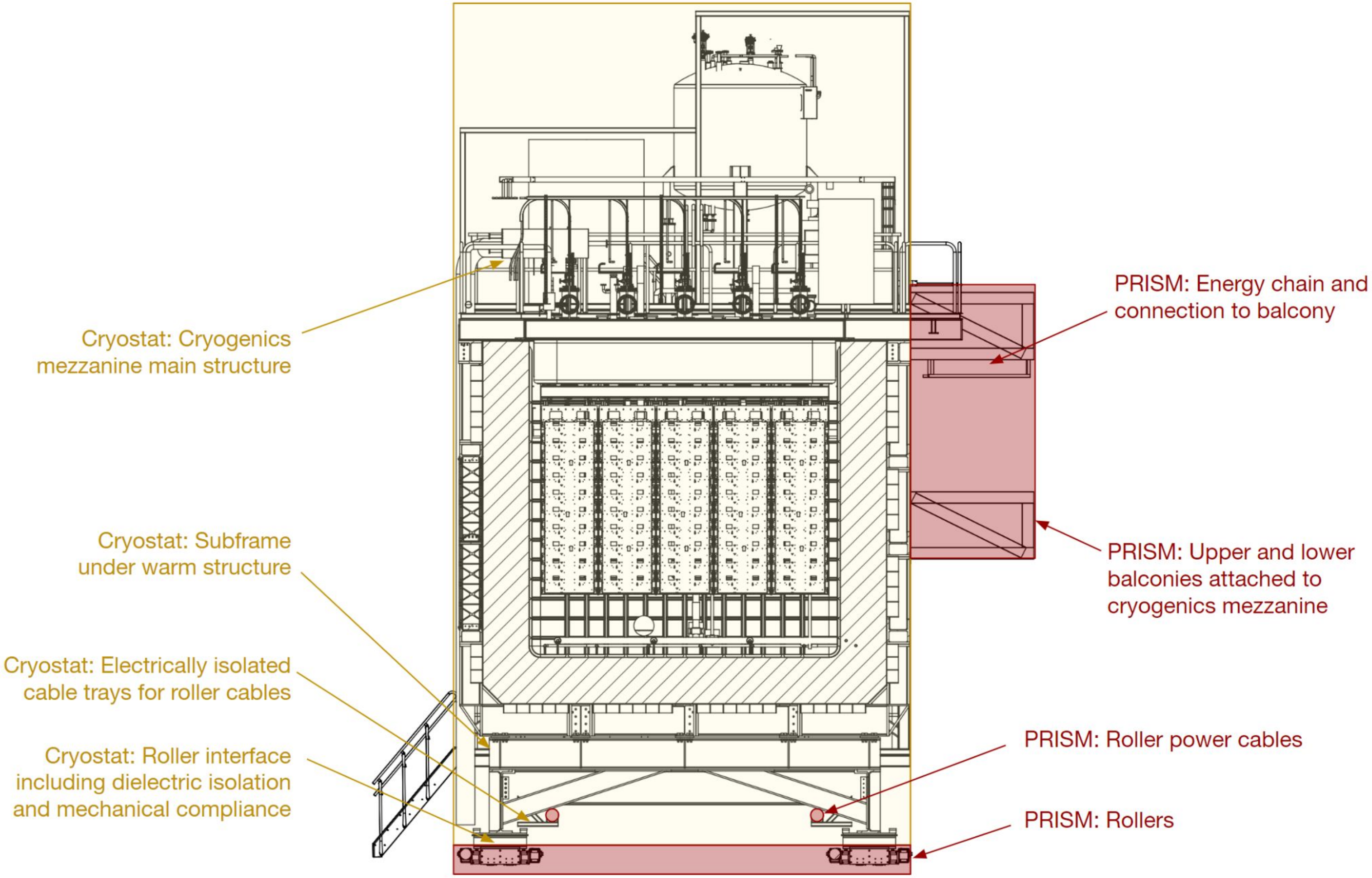
For the official…



- Cryogenics system is broadly similar to SBND except that it moves with the detector on the PRISM rails

Interfaces with the PRISM system include the rollers under the Cryostat and the Energy Chain which provides power, data, gas and cryogen connections

Charge # 1, 5, 6.a



ID	Item	Cryostat [131.ND.03] Provides	PRISM [131.ND.07] Provides	Interface Definition Document
	systems	monitors, and rail cameras 2. Connection points for power and data cables	power and data cables	
017	Cryostat frame / PRISM safety systems	1. Mounting locations for emergency stop buttons & pull cables and safety PSC 2. Connection points for power and data cables	Emergency stop buttons, safety PSC, and power & data cables	[drawing number TBD]
018	Rail and Roller Installation	Waits to start Cryostat assembly until after rail and roller installation	Rail and roller installation before start of Cryostat assembly	ND P6 Schedule
019	PRISM Roller Maintenance access	Design the PRISM frame such that it can allow access to remove the PRISM roller for maintenance.	Provides maintenance access requirements.	TBD
020	Maximum PRISM roller acceleration	Design Cryostat to withstand maximum acceleration in operation	Roller acceleration not to exceed 2.54 cm/s^2	TBD
021	Maximum PRISM	Design Cryostat to withstand	Roller speed not to exceed	TBD FM note: 28m/4 hours = 2mm/s

- The PRISM system allows the ND-LAr and TMS detectors to move 28.5 m off of the neutrino beam center

Charge # 1, 5, 6.a

PRISM accelerations and forces are low. Static loads from gas pressure, hydrostatic pressure and gravity drive Cryostat structural performance.

- Upper bounds on PRISM speed and deceleration rate are established
    - Max velocity with 28.5 m in 4 hours is 2 mm/s
    - Shortest possible deceleration (hard stop) is estimated to be 0.1 s
    - Corresponding deceleration is 20 mm/s^2 [$2e^{-3}$ g]
    - Effects of lateral accelerations on the structure studied by FEA
- Maximum tilt angle induced by 12mm elevation change over 10m is 1.2 mRad
    - Ran a structural FEA with lateral acceleration applied for the purpose of documenting results
- Liquid argon sloshing is negligible per Voirin CFD sloshing study EDMS 2737398
- PRISM tests will be performed to validate assumptions and conclusions

Charge # 1, 5, 6.a

Interfaces with Slow Controls include camera and temperature sensor readouts

Cryostat

- Camera output
- Cold membrane insulation temperature sensor output

Slow Controls

- Wiring from camera to DAQ, distribution of video
- Wiring from temperature sensors to DAQ, distribution of signals

Charge # 6.b

Interfaces with Installation and Integration (I&I) define scope divisions for material handling and installation planning

Cryostat

- Labor to perform lift and assembly work in ND cavern
- Lift, assembly and test procedures
- Custom assembly fixtures

I&I

- Material handling from storage to ND cavern
- Cranes, forklifts, pallet jacks and rigging equipment used in ND cavern
- Coordination of install activity across ND subsystems
- Coordination of FNAL safety reviews

Interfaces with Facilities are managed by ND Installation and Integration (I&I)

Charge # 6.b

2348	Underground crane	Requirement	NSCF shall provide an underground crane of 60 US ton capacity in the detector hall. The hook height will be a minimum of 49 ft -4 in above the cavern floor invert. The bottom surface of the crane beam structure shall be a minimum of 49 ft above the floor surface. See interface drawing 2440425v2 for details. The underground crane is required to cover from the CL of the shaft to as close as reasonably possible to the beginning of the SAND alcove. The hook should be able to lift items approx 5 ft (1.5 m) from each of the cavern walls (side approach).
2350	Floor embedment locations and surface requirements	Requirement	NSCF shall design, procure, and install rails for the PRISM system. Rail system specifications are provided in EDMS 2804572v1. Rail system general layout shown in NSCF Drawing 6-15-12 Vol 1 - S-ND-108, at 100% Issued for Bid.
2351	Surface crane	Requirement	NSCF shall provide a crane in the surface building of 15 US ton capacity capable of reaching the underground hall invert. Crane shall cover equipment staging areas and shaft according to interface drawing 2443706v2.
2355	Main cavern dimensions	Requirement	NSCF shall provide a cavern with minimum dimensions of 166 ft (50.6 m) x 63 ft (19.2 m). The cavern height and spring line shall accommodate an overhead crane with a 43 ft (13.1 m) hook height. NSCF shall add an alcove at the south west corner of the cavern with minimum dimensions of 44' 8" (13.6 m) x 46' (14 m) x 34' 11" H (10.7 m)
2356	Access shaft dimensions	Requirement	NSCF shall provide a vertical shaft to the surface with a minimum diameter of 38 ft (11.6 m). A minimum shaft cross-sectional area as indicated in interface drawing 2443706v2 (Sections AL-AL and AN-AN) (26 feet from shaft septum to opposite shaft wall) shall be free of obstructions for lifting equipment. Shaft areas shall be reserved for scientific utility routing (data, electrical, cryogenics) as indicated in interface drawing 2443706v2 (Section AN-AN).
2588	ND Cavern Ventilation duct routing	Requirement	NSCF shall provide ventilation ducts that are routed according to interface drawing 2440425v2 and shall not encroach into detector space claims.
2606	ND Surface Building Main Rollup Door	Requirement	NSCF shall provide a rollup door to surface building high-bay with minimum opening shown in interface drawing 2443706v2. Minimum width shall permit standard truckbed width plus space to walk around. Height should be maximized to next horizontal beam (approx. 17 to 18 ft).

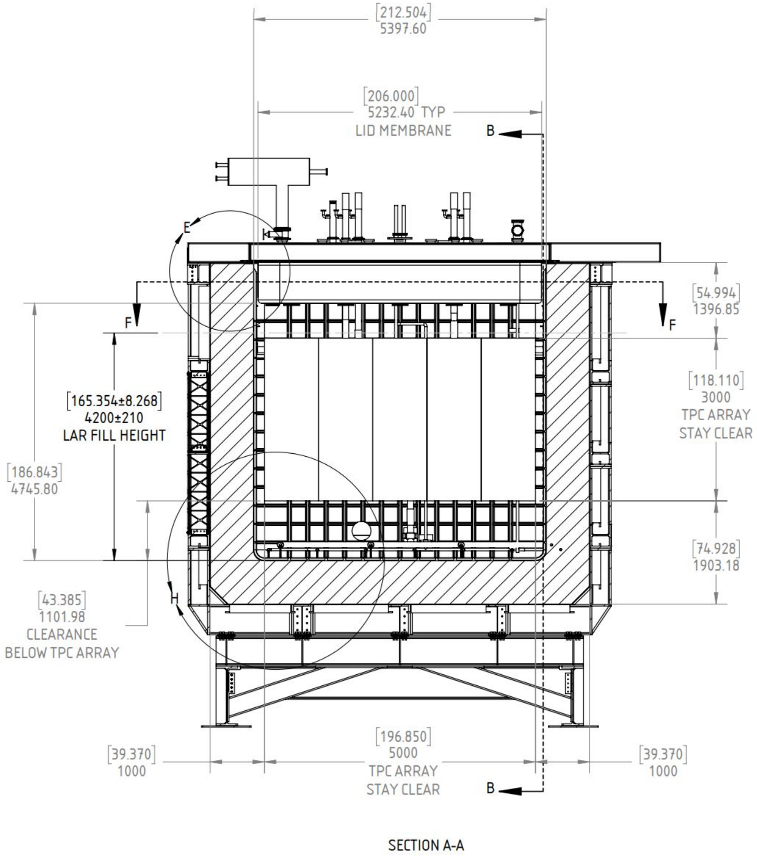
Interfaces with the Cold Membrane are internal to Cryostat but are treated like external interfaces because the cold membrane is vendor engineered

Charge # 7

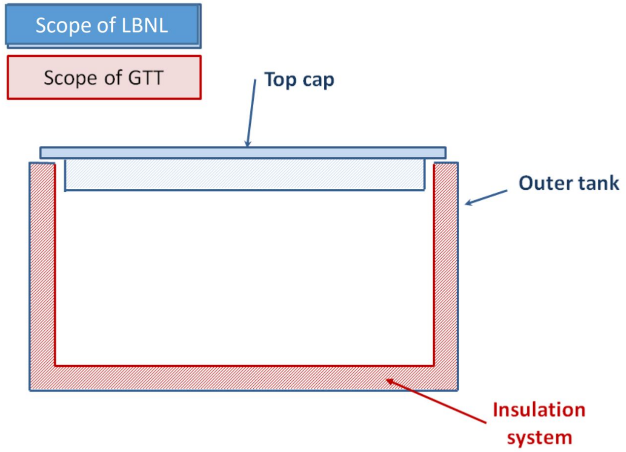
- Interfaces are defined in the statement of work for GTT's detailed engineering study
- Statement of work is at the final approval stage

Parameter	Quantity	Notes
Cavern Temperature	15 - 27°C	Active temperature control
Cavern Humidity	15 - 85% RH	Active humidity control
Cavern Maximum Dew Point	9°C	Active humidity control
Atmospheric Pressure	1020 mbar	Elevation 226 m above sea level
Cavern Size	Approx 45 x 19 x 15 m [L x W x H]	See EDMS 2440425 drawing for details
Cavern Depth	60 m	See EDMS 2443706 drawing for details
Shaft Opening	Approx 6 x 6 m	See EDMS 2443706 drawing for details
Surface Crane Capacity	15 US tons	60+ US Ton rental crane planned for special cases
Cavern Crane Capacity	60 US tons	
Seismic Hazard	Design Category A Soil Class C	See ASCE 7 report for details

DUNE ND Cavern Characteristics



Warm structure, lid and feedthrough dimensions



Scope division

Project Management

Charge # 6.g

Cryostat is at the end of the Preliminary Design Phase

Year	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Phase	Preliminary Design		Final Design	Procure-ment Planning	Fabric-ation	Testing & Shipment	ND Installation			

Path to Final Design Completion

- Identify vendors, get feedback and quotes
- Process BCR to capture updated vendor quotes
- Complete detailed analyses, both in house and with structural engineer
- Perform TPC Row Prototype tests
- Complete detailed 3D models
- Create part drawings

Summary

- The materials presented here cover the preliminary design of the **warm structure, cold membrane, lid sections and TPC mezzanine**. They are designed to meet specifications and interface requirements for components outside of the scope of this review such as the PRISM structure.
- **Requirements flow down** from physics have been thoroughly reviewed and approved by the ND Technical Board. Other engineering and safety requirements are detailed in the lower tier of Cryostat requirements.
- There is detailed **interface documentation** in place with ND-LAr, Cryogenics, PRISM and I&I, which can be navigated through the N^2 matrix.
- **Assembly and detail drawings** are accessible through the drawing tree.
- Fruitful collaboration with the SBND and FD teams at FNAL and CERN made it possible to capture **lessons learned** from previous cryostat construction projects. Actions from **previous recommendations** are thoroughly documented.
- **Grounding schemes** are developed in close collaboration with the EE team at FNAL, under the purview of Integration and Installation.
- **Installation plans** are developed in close collaboration with the Integration and Installation team. An internal review was recently held with subject matter experts at FNAL, and covered the details of the Cryostat installation.
- The cryostat is designed to meet **engineering standards, structural codes, FESHM, and other ES&H requirements** as indicated in the following presentations for each of the components.
- The **procurement strategy, cost and schedule** are developed under the purview of the ND project (no consortium). The plans and estimates incorporate the experience from the SBND cryostat recently deployed at FNAL.
- The next presentations detail out **how the design meets the requirements and interface specifications**.