LBNF/DUNE

ND-LAr Overview

Dan Dwyer, ND-LAr Technical Lead

ND-LAr Preliminary Design Review

27 June 2022

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

U.S. DEPARTMENT OF ENERGY | Office of Science

Who am I

- Senior Staff Scientist, LBNL
  - Head of LBNL Physics Division Neutrino Group
  - DOE Early Career Research Fellow, 2018 - now
  - LBNL Particle Data Group, 2014 - 2018
  - APS Henry Primakoff Award, 2014

- Scientific Activities
  - KamLAND: Ph.D. on measurement of neutrino oscillation, Δm^2_{21}
  - Daya Bay: Detector Commissioning co-coordinator and Analysis co-coordinator
  - DUNE:
    - Creator of LArPix pixelated LArTPC readout electronics
    - Technical Lead of ND-LAr Consortium

Outline

- Key documents
- Management & Scope
- Requirement & Interface Management
- Preliminary Design and Validation
- Risk Management
- Hazard Analysis
- Cost, Schedule
- Summary

ND-LAr Key Documents

https://edms.cern.ch/document/2611200

Folder/Document	Description	EDMS Link
ND-LAr Top-Level Folder	Top level folder for all ND-LAr Consortium documentation	https://edms.cern.ch/project/CERN-0000217521
ND-LAr Scope Overview Drawing	Scope overview drawing of Near Site detector	https://edms.cern.ch/document/2459141
ND-LAr TPC Scope Overview Drawing	Scope overview drawing of the ND-LAr TPC	https://edms.cern.ch/document/2459142
ND-LAr Scope and MOU Tables	Tables detailing Consortium subsystem scope and deliverables	https://edms.cern.ch/project/CERN-0000220117
ND-LAr WBS Dictionary	Work Breakdown Structure (WBS) Dictionary for ND-LAr Consortium	https://edms.cern.ch/document/2619609
ND-LAr Resource Matrix	Resource matrix for ND-LAr Consortium	https://edms.cern.ch/document/2619602
ND-LAr Key Document List	List of key documents for ND-LAr Consortium	https://edms.cern.ch/document/2741772
CAD Release Process	CAD release process for ND-LAr official CAD	https://edms.cern.ch/document/2612310
Windchill CAD Model Structure	Windchill CAD model structure definition	https://edms.cern.ch/document/2683349
Environmental, Health, and Safety (ESH)	ESH document detailing key FESHM sections for ND-LAr acitivities at FNAL	https://edms.cern.ch/document/2602421
Hazard Registry	Hazard registry for all ND-LAr activities	https://edms.cern.ch/document/2663898
Prototyping Plan	Prototyping plan for the ND-LAr Consortium	https://edms.cern.ch/document/2459149
Requirements	Spreadsheet with all ND-LAr requirements, see sheet "System"	https://edms.cern.ch/document/2589287
System-Level Interface Flow Diagram	Flow diagram for ND-LAr system design and interfaces from event to data collection	https://edms.cern.ch/document/2636568
N2 Matrix for ICDs	N2 matrix that defines ND-LAr interfaces with EDMS links to unique ICDs	https://edms.cern.ch/document/2640807
Internal ICDs	Interface control documents (ICDs) internal to the ND-LAr Consortium	https://edms.cern.ch/project/CERN-0000223195
External ICDs	Interface control documents (ICDs) external to the ND-LAr Consortium	https://edms.cern.ch/project/CERN-0000229879
Installation ICD	Interface control document between ND-LAr Consortium and Near Site Installation	https://edms.cern.ch/document/2730726
Analyses	Collection of analyses/studies/eng notes	https://edms.cern.ch/project/CERN-0000217538
2x2 Lessons Learned	Spreadsheet with a collection of 2x2 lessons learned	https://edms.cern.ch/document/2737729
Cost	High-level cost estimate for ND-LAr and subsystems	https://edms.cern.ch/document/2742778
Schedule	High-level "one-pager" schedule for ND-LAr Consortium activities	https://edms.cern.ch/document/2603073
CAD Model (Row Assembly, TPC Assembly)	Solidworks "Pack & Go" and Parasolid exports of CAD models	https://edms.cern.ch/project/CERN-0000230732
ND-LAr Grounding Plan	Document that details detector-wide grounding plan	https://edms.cern.ch/document/2459151
ND-LAr TPC Grounding Plan	Document that details TPC-specific grounding plan	https://edms.cern.ch/document/2459152

What is the ND-LAr Consortium?

The DUNE detectors are delivered by **International Detector Consortia**, instituted and **managed by the DUNE International Scientific Collaboration.**

The ND-LAr Consortium is **responsible for design, production, and installation of the Near Detector Liquid Argon Time-Projection Chamber** (ND-LAr) Detector, which is the most crucial of the three detectors at the DUNE Near Site.

The **LBNF/DUNE US DOE Project is a significant contributor** to the ND-LAr Consortium, along with international and domestic partner institutions.

High-level Snapshot:

Team: 111 members from 39 institutions

Scope: Design, production, and installation of 35 LArTPC detector modules, with supporting electronics.

Schedule:

Design: 2018 - 2024

Production: 2025 - 2028

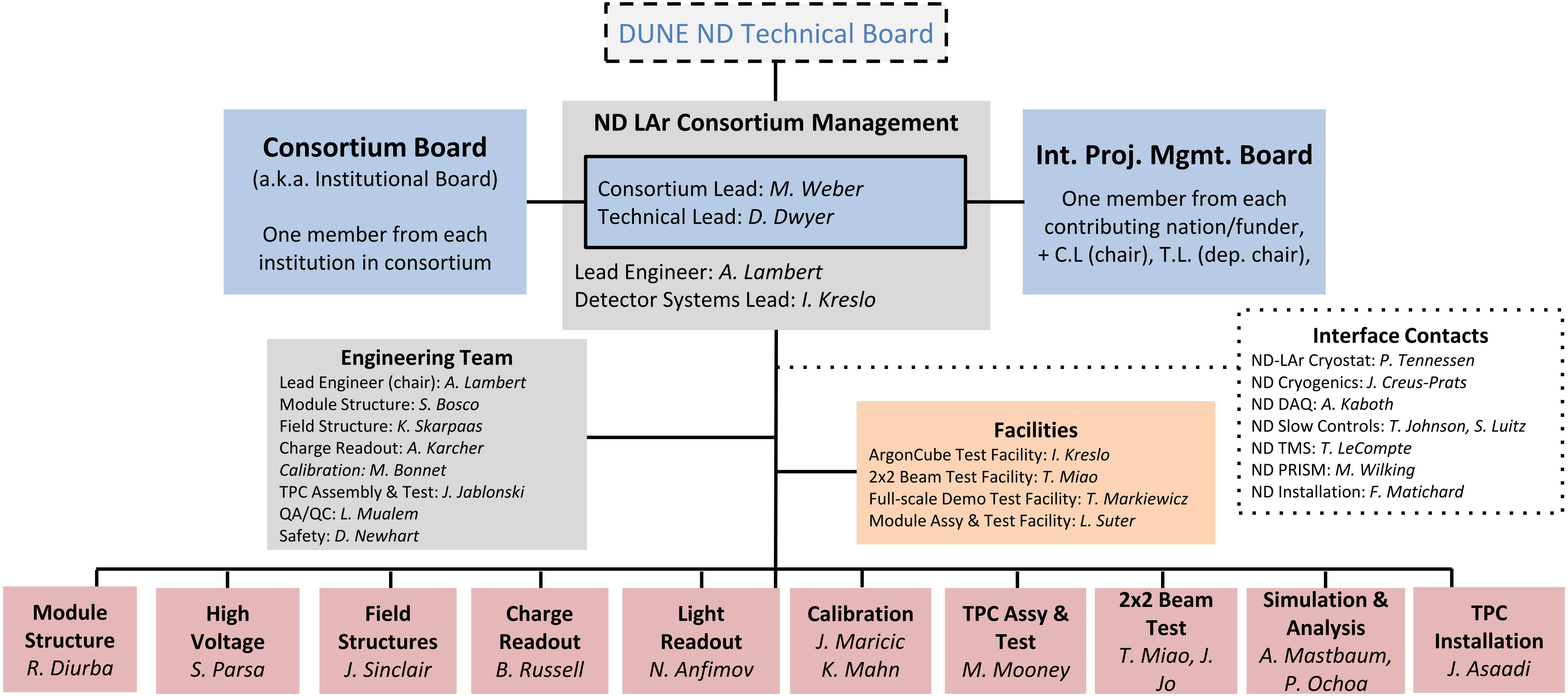
Installation: 2028 - 2031

ND-LAr Members:

ANL
BNL
Caltech
Cambridge
CSU
KSU
FNAL
JINR
LBNL
MSU
Rutgers
SLAC
Stanford Univ.
Syracuse Univ.
Tel Aviv Univ.
Tufts Univ.
UC Berkeley
UC Davis
UC Irvine
UCSB
Univ. at Albany
Univ. of Bern
Univ. of Colorado
Univ. of Hawaii
Univ. of Houston
Univ. of Iowa
Univ. of Mainz
Univ. of Manchester
Univ. of Minnesota
Univ. of Lancaster
Univ. of Rochester
Univ. of Sheffield
U-Penn
UTA
Warwick
Wichita State Univ.
William and Mary
Yale Univ.
York Univ.

ND-LAr Consortium Management

https://edms.cern.ch/document/2645457



See "ND-LAr Physics" (Mastbaum, Ochoa)

DUNE Physics and the Near Detector

'Phase-1' System Requirement:

Enable a 3σ observation of maximal CP violation

3σ Max-CPV is difficult:

Only modest variation in ν_e signal

In 3.5 yrs (staged), ν-only operation, NO:

~1100 ν_e appearance events

~300 background

Max CPV:

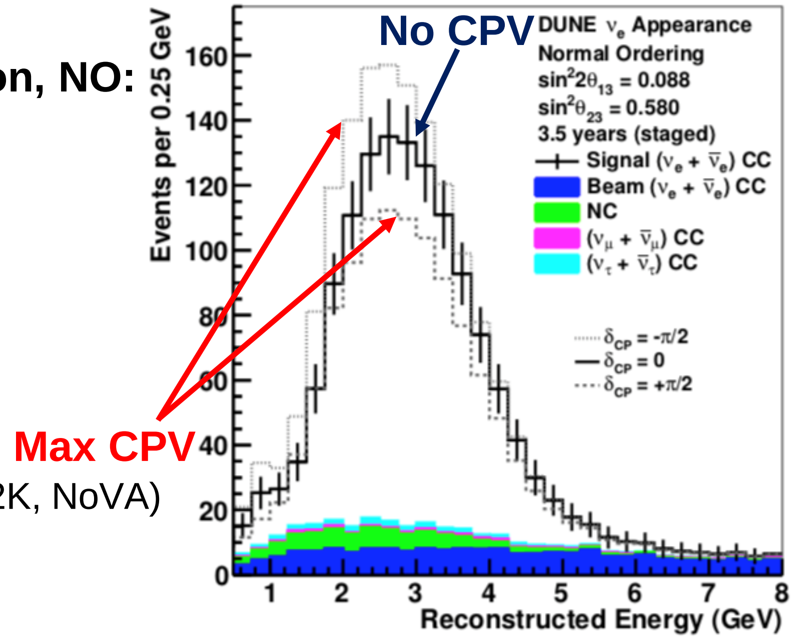
Variation in signal: ~15%

Statistical uncertainty: ~3%

Requires total systematic uncertainty less than ~3%

Compare with state-of-the-art of ~7-8% (T2K, NoVA)

From DUNE TDR



Physics Milestone	Exposure (staged years)
5σ mass ordering ($\delta_{CP} = -\pi/2$)	1
5σ mass ordering (100% of δ_{CP} values)	2
3σ CPV ($\delta_{CP} = -\pi/2$)	3
3σ CPV (50% of δ_{CP} values)	5
5σ CPV ($\delta_{CP} = -\pi/2$)	7
5σ CPV (50% of δ_{CP} values)	10
3σ CPV (75% of δ_{CP} values)	13
δ_{CP} resolution of 10 degrees ($\delta_{CP} = 0$)	8
δ_{CP} resolution of 20 degrees ($\delta_{CP} = -\pi/2$)	12
$\sin^2 2\theta_{13}$ resolution of 0.004	15

See "ND-LAr Physics" (Mastbaum, Ochoa)

ND-LAr Consortium: Requirements Flowdown

Note: My abridged summary.

Enable precise prediction of DUNE Far Detector neutrino signal. *Precise ~2% rate, ~4% shape*

- Measure ν beam flux × cross section (on argon) at Near Site → Active **argon-based detector(s)** at near site
- Precisely characterize FD neutrino interaction, detector response model *same,better fidelity as FD* → **LArTPC component** of Near Detector System
  - With sufficient signal rate for relevant neutrino interactions *e.g. ν-e⁻ scat.* → **O(100 ton) active volume** in LArTPC
  - Sufficient LAr acceptance/containment of relevant neutrino interactions *except forward-going muons.* → Active LArTPC **3m height, 7m width, 5m depth**, with **downstream muon spectrometer**
  - Cope with signal pileup at Near Site → LArTPC with **pixelated readout**, **optical modularity**
  - Disentangle energy-dependence of cross section and detector response → **Off-axis measurements** with LArTPC
  - Verify beam stability when LArTPC off-axis → Supp. **stationary beam monitor** detector: SAND
  - Precisely constrain LArTPC deficiencies *ν-int channel accuracy, charge, E vs. p* → Supp. **magnetized low-density Ar detector**: TMS

Key Requirements: https://edms.cern.ch/document/2723207
Full List: https://edms.cern.ch/document/2589287

ND-LAr Consortium: Requirements

Requirements:

- Flow down from DUNE Science Requirements
- Documented in ND-LAr Consortium Technical Specifications table
- Subsystem Requirements/Specifications flow down from ND-LAr system-level specifications

Major Design Drivers:

SYS-002: ND LArTPC Active Size

- Significant fraction of relevant neutrino-nuclear reactions have up to ~7m transverse extent. Must be measured at Near Detector in order to accurately predict Far Detector signal.

SYS-003: Pileup Rejection Efficiency

- ND-LAr measurements must not be biased by high-intensity near-site environment.

Label	Name	Description	Rationale	Design Validation	Verification Method
			131.02.03.02: System Level		
SYS-001	ND LArTPC Fiducial Mass	The ND LArTPC shall provide >20 tons fiducial liquid argon target mass	To deliver the required statistical precision (<2%) for the measurement of neutrino-electron elastic scattering	Design	Test/Inspection
SYS-002	ND LArTPC Active Size	The ND LArTPC active volume shall be ≥ 5 m in the beam direction, and ≥ 7 m x 3m in transverse directions	To sufficiently contain the ionization signal from beam neutrino interactions on argon, except for forward-going muons and energetic neutrons. The size is driven by maintaining sensitivity to the kinematic phase space of the cross-section, not by detector efficiency. Detector efficiencies as low as ~5% can be tolerated, as long as the detector is not blind to substantial (few-%) regions of the cross-section phase space.	Design	Test/Inspection
SYS-003	Pileup Rejection Efficiency	The ND LArTPC shall be able to associate ionization signals to fiducial neutrino interactions with a purity, averaged over interactions, of > 97% by energy .	After the rejection of pileup, the residual pileup systematic uncertainties should be sub-dominant to other uncertainties in the prediction of the far detector signal based on near detector data.	ScSimulations	ScSimulations
SYS-004	3D Charge Imaging Accuracy	The ND LArTPC shall be able to associate ionization signals to fiducial neutrino interactions with completeness, averaged over interactions, of > 97% by energy .	Accurate 3D charge signal imaging is required in order to correctly associate charge depositions to their parent neutrino interactions in the high-pileup ND environment.	ScSimulations	ScSimulations
SYS-005	Charge-Light Signal Matching Efficiency	The ND LArTPC shall be able to associate scintillation light signal times to ionization signal clusters from fiducial neutrino interactions with an efficiency, averaged over interactions, of > 97% by energy .	Efficient matching of the charge signals with the fast (~ns-scale) light signals enable accurate discrimination of the charge signals from the approximately 50 neutrinos contributing to the charge signals per ~10us-wide beam spill.	ScSimulations	ScSimulations
SYS-006	Detector Optical Modularity	The ND LArTPC shall have optically isolated regions, nominally 1.5 m^3 , to facilitate matching between the charge and optical signals	Isolation of scintillation light within LArTPC modules facilitates charge-light signal matching.	Design	Test/Inspection
SYS-008	ND LArTPC performance after PRISM detector move	The ND LArTPC shall meet operational performance requirements (Electric field uniformity & stability, module alignment, noise, live pixels), within 1 hour after PRISM movement of the detector	Start taking high quality data within an hour. This is a allocation of time to complete all activites associated with PRISM move within an 8 hour shift, driven by operational resource, and to achieve the required number of moves in a year with a 5% integrated downtime attributed to moving the detector (1 move/week)	Eng Analysis	Eng Analysis
SYS-009	Electric Field Strength	The ND LArTPC shall be able to achieve an electric field strength >250 V/cm (goal 500 V/cm)	Equivalent electric field as FD to enable operation of the near detector with equivalent levels of electron recombination and other field-dependent effects.	Full Scale Demonstrator	MIF Integrated Testing
SYS-010	Electric Field Uniformity of 96% of active volume shall be 95%	Nominal Electric Field of 96% of active volume shall be uniform to <5%	Equivalent electric field uniformity as FD.	Full Scale Demonstrator	MIF Integrated Testing

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ND-LAr in the DUNE Near Detector

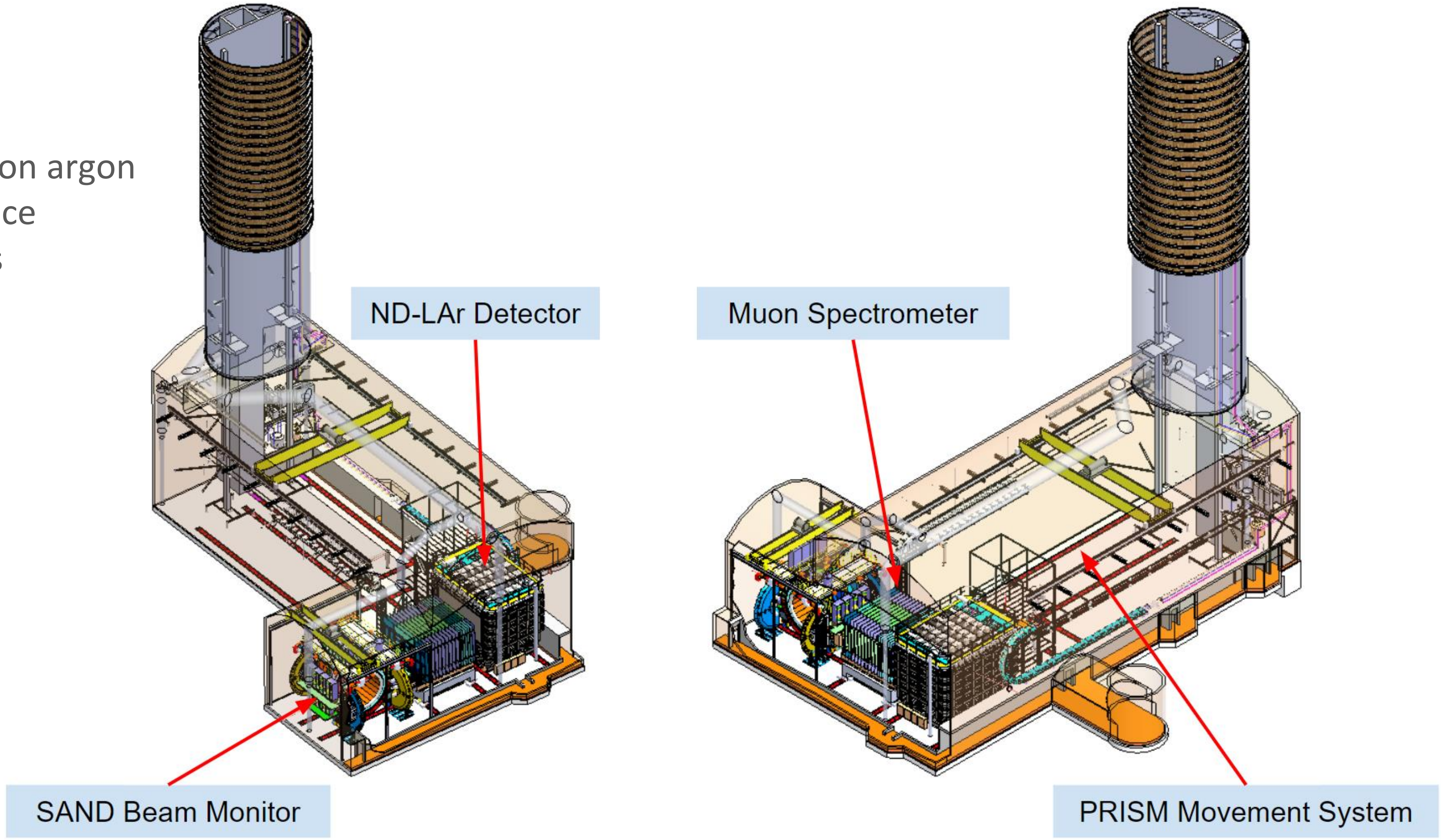
The ND-LAr Detector:

Measures:

LBNF beam neutrino interactions on argon
in a detector of similar performance
as the DUNE Far LArTPC detectors

Constrains:

1. LBNF neutrino beam model
2. Neutrino-argon cross-section
3. LArTPC detector model



ND-LAr Detector: From Requirements to Design

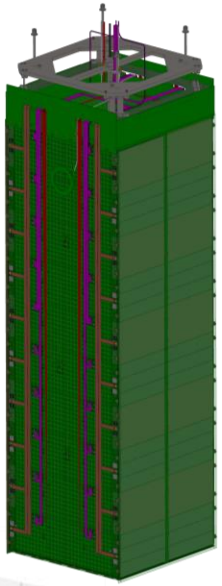
The most significant technical aspects for ND-LAr:

Common to all LArTPCs:

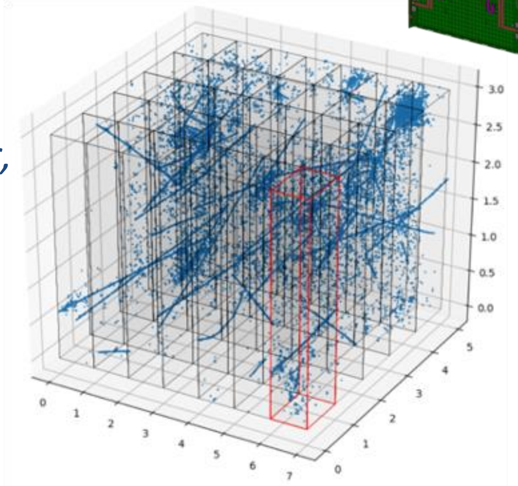
- Unstable or insufficient high voltage
- Insufficient argon purity
- Non-uniform drift field
- Electronics/anode failure in cryogenic environment
- Excess noise in charge readout

Novel for ND-LAr:

- Maintain signal fidelity in high-occupancy environment



One simulated beam spill in ND-LAr, with typical pileup of ~50 neutrinos



The modular ND-LAr design addresses these requirements:

Short drift distance (1/6th of Far Detector):

- Substantially reduces requirements/risks associated with HV, purity, and field uniformity

Modular/independent TPC regions:

- Potential failures contained to finite sub-region; robust system
- Contained scintillation light to mitigate near site signal pileup

Pixelated charge readout:

- True 3D readout mitigates near site signal pileup
- Lower channel capacitance; less sensitive to system noise
- PCB-based construction mechanically robust, scalable

High-performance light readout:

- 30% coverage provides O(10cm) spatial resolution, mitigates pileup

ND-LAr Detector: Basic Concept

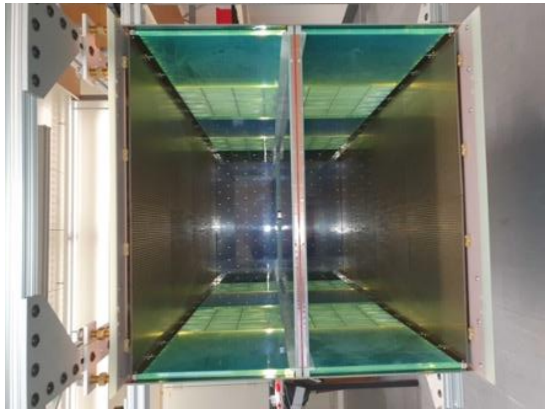
ND-LAr TPC Module:

- A fiberglass box, 1m x 1m, 3m tall
- Divided vertically by a cathode (resistive film on fiberglass)
- Two pixelated anodes (printed circuit boards) opposite cathode
- Remaining walls provide field cage (resistive film on fiberglass)
- Side field cage walls covered by scintillation light traps (two types)
- Top/bottom walls perforated (allows LAr flows from top to bottom)

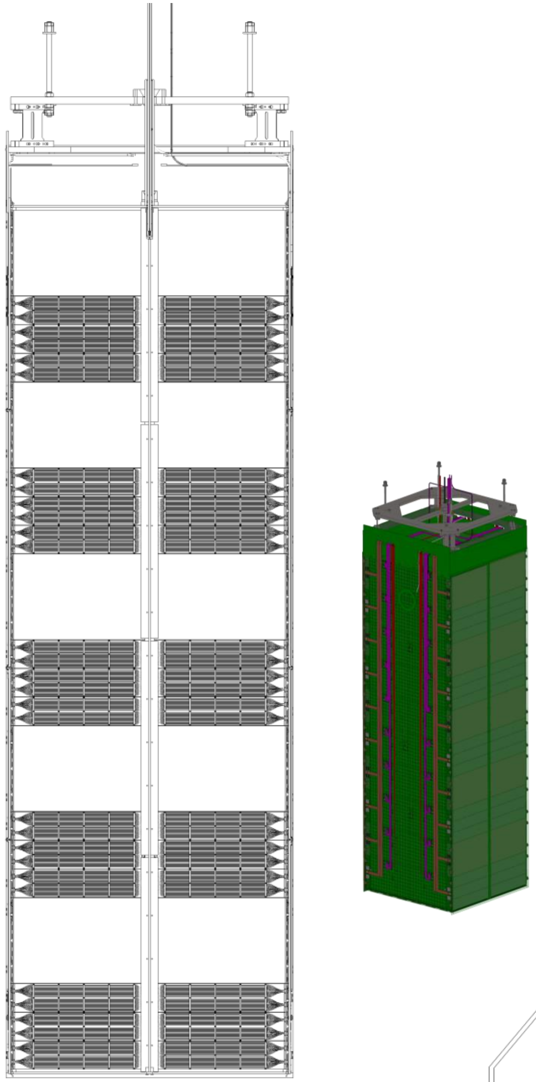
ND-LAr Detector:

- 35 TPC modules, arranged in 7 banks each of 5 modules
- Each module has independent feedthrough for power, signal, etc.
- Modules suspended from cryostat lid, immersed in LAr bath

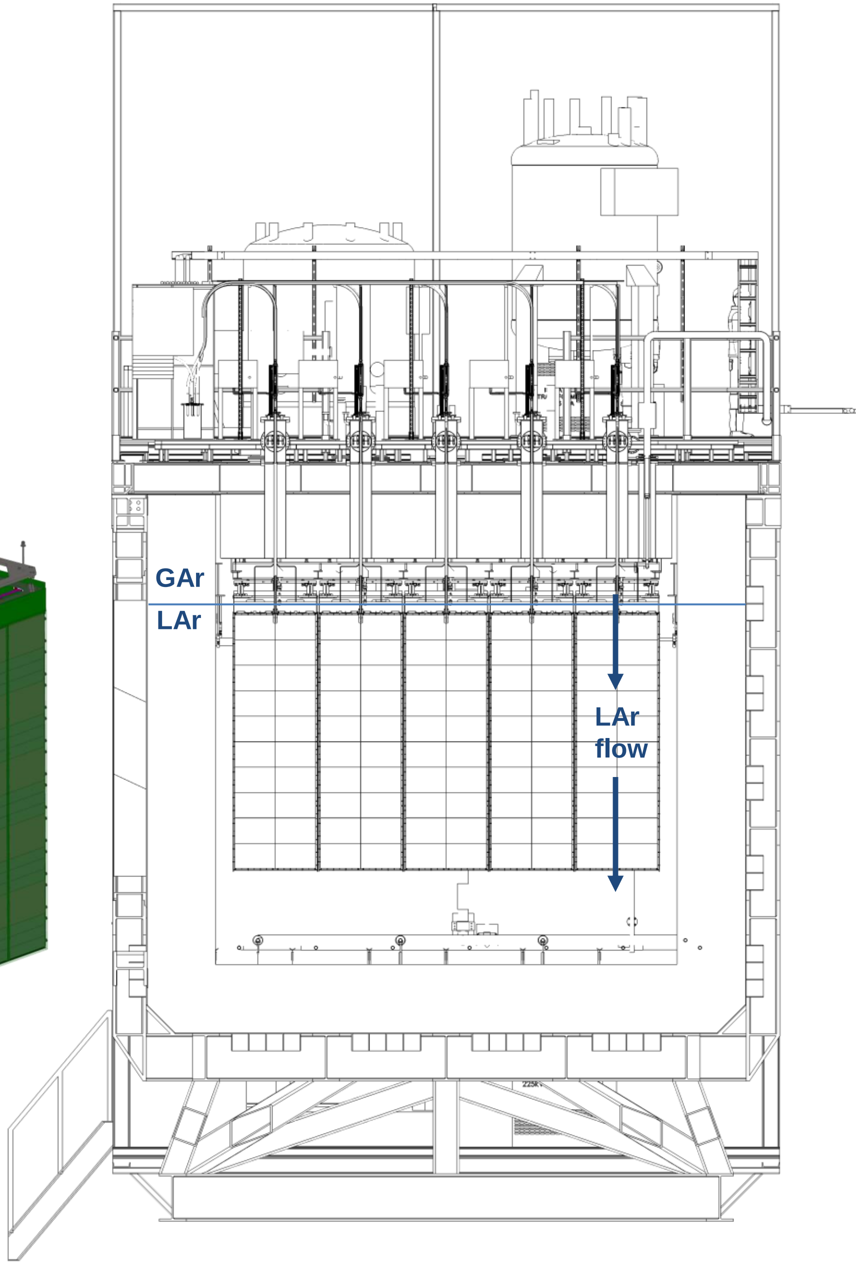
Top-down view of prototype module, with top field cage panel removed.



Anode Cathode Anode



Anode Cathode Anode



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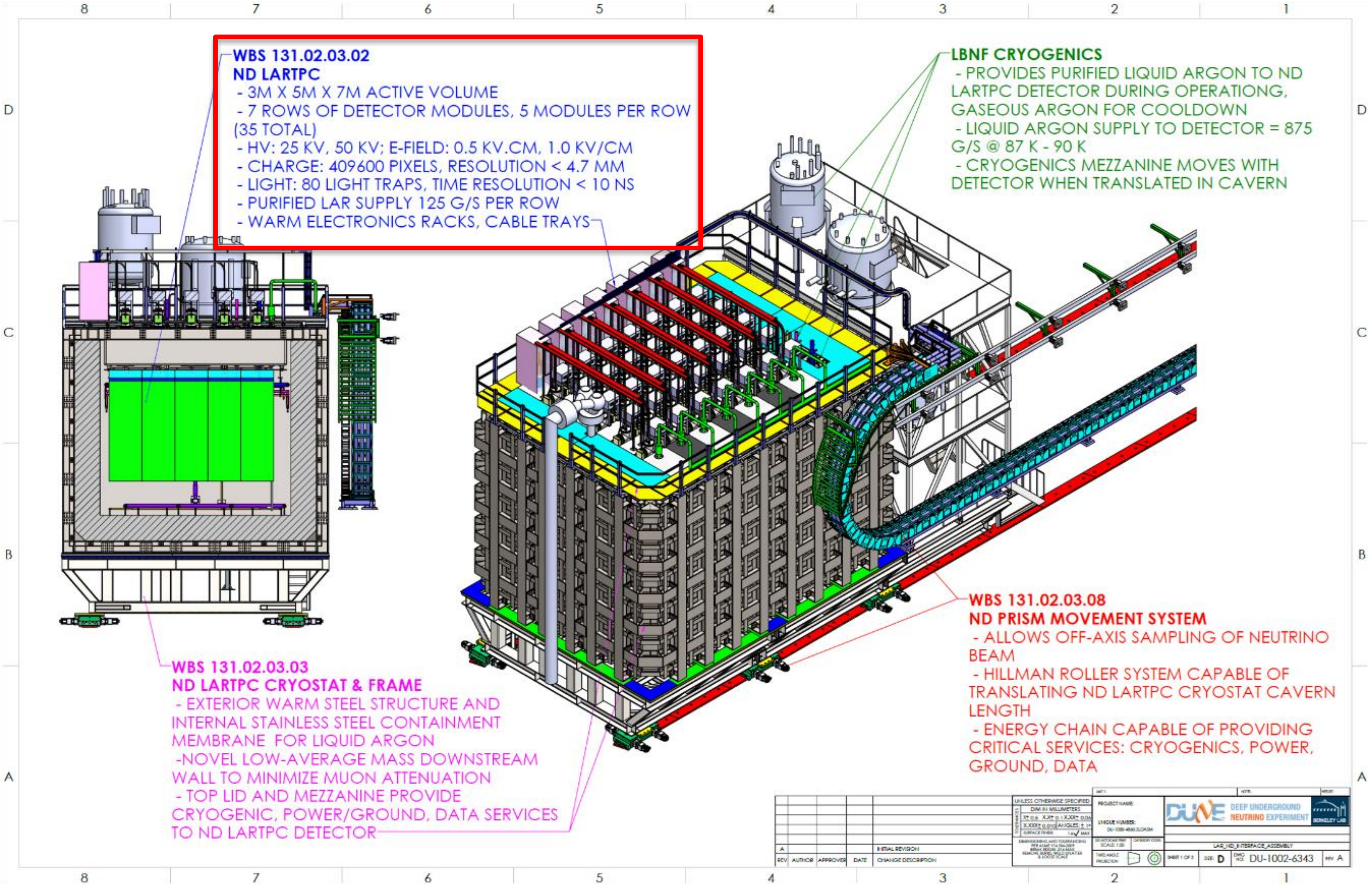
https://edms.cern.ch/project/CERN-0000220117

ND-LAr Consortium Scope

Key Deliverables:

- Deliver 35 TPC modules to the Near Site
- Deliver all TPC front end electronics to the Near Site
- Integrate TPC Array to LAr Cryostat
- Integrate all front end electronics on LAr Cryostat Mezzanine
- Perform pre-cooldown functional verifications
- Pre-operations and commissioning for LAr TPCs



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ND-LAr Consortium Scope

ND-LAr Management:

131.ND.02.01: Management (LBNL)

ND-LAr Core Detector Elements:

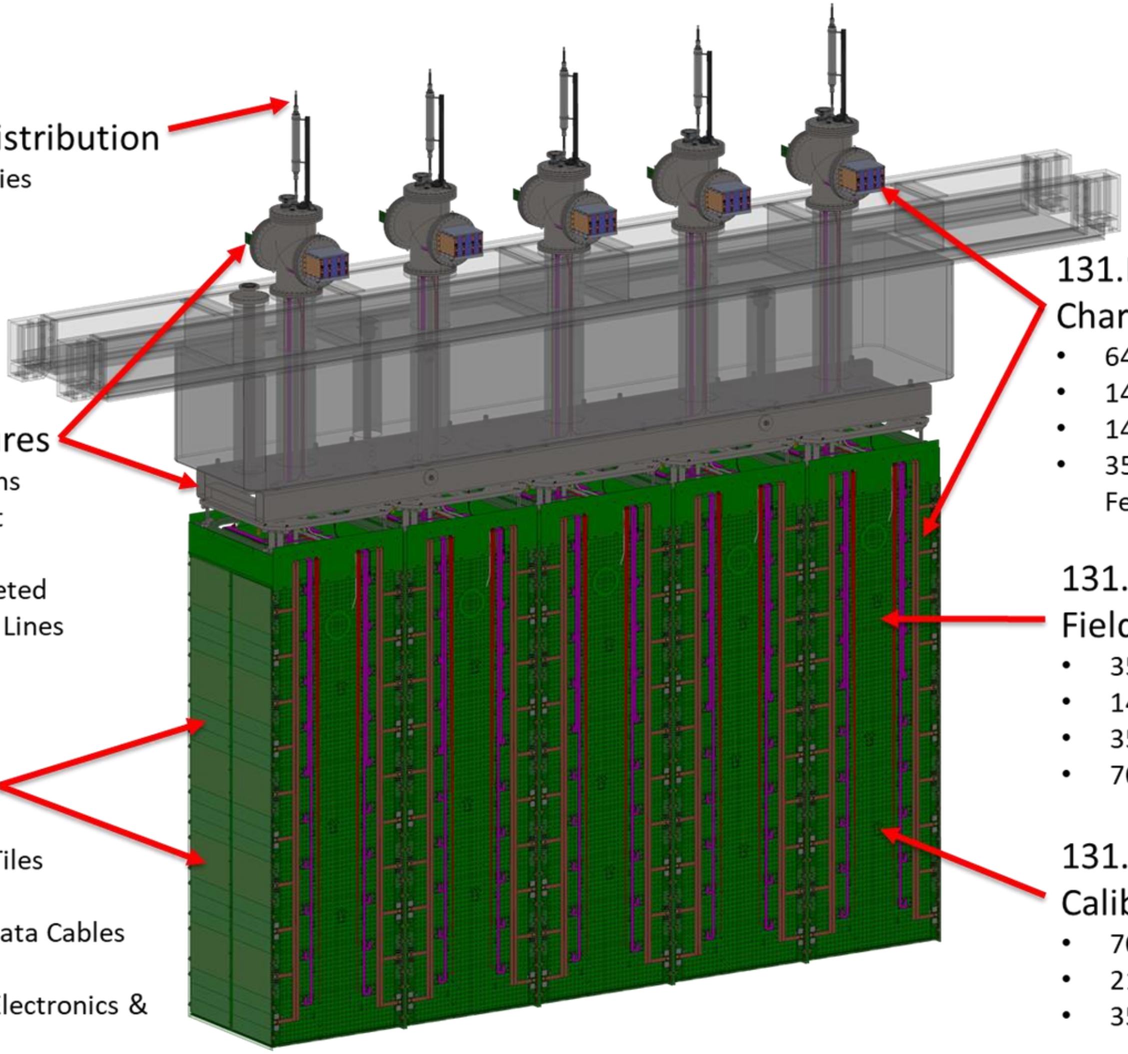
131.ND.02.02: Module Structure (Bern)
131.ND.02.03: High Voltage (Bern)
131.ND.02.04: Field Structure (SLAC)
131.ND.02.05: Charge Readout (LBNL)
131.ND.02.06: Light Readout (JINR)
131.ND.02.07: Calibration (MSU/U-Hawaii)

ND-LAr Assembly, Test, Integration, Installation:

131.ND.02.08: TPC Assembly & Test (CSU)
131.ND.02.09: TPC Integration & Installation (UTA/LBNL)

ND-LAr Prototyping and Production Facilities:

131.ND.02.10: Module Assembly and Test Facility (FNAL)
131.ND.02.11: Full-Scale Demonstrator Test Facility (SLAC)
131.ND.02.12: 2x2 NUMI Test Beam Facility (FNAL)
131.ND.02.13: ArgonCube Test Facility (Bern)

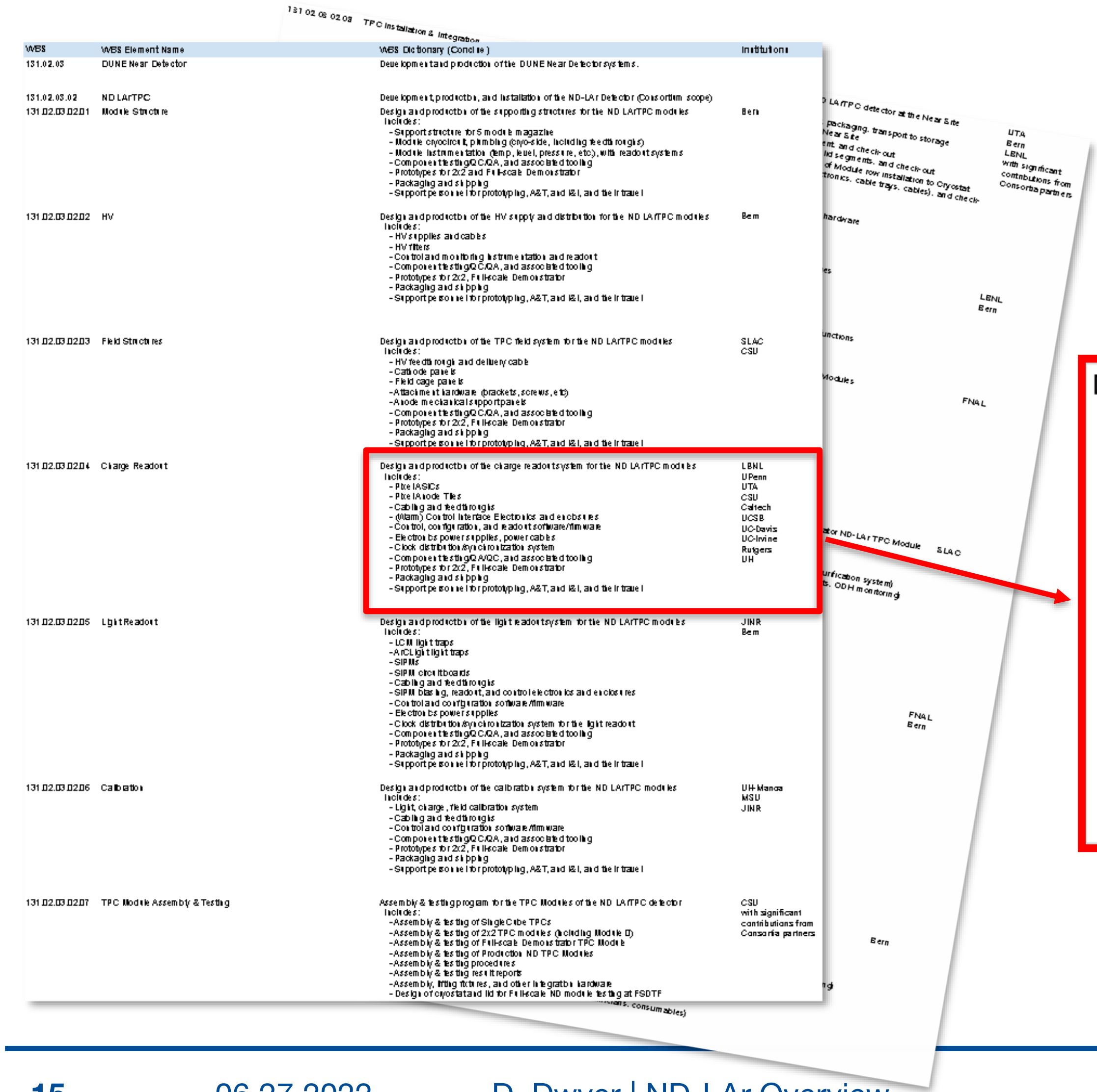


ND-LAr Row Assembly, 5 TPC modules per row, 7 total rows produced for ND
***Quantities are for array of 35 TPCs*

https://edms.cern.ch/project/CERN-0000220117

ND-LAr Consortium: WBS Dictionary

WBS Dictionary captures entire ND-LAr Consortium scope (on- and off-project)



WBS	WBS Element Name	WBS Dictionary (Concise)	Institutions
131.02.03	DUNE Near Detector	Development and production of the DUNE Near Detector systems.	
131.02.03.02	ND LArTPC	Development, production, and installation of the ND-LAr Detector (Consortium scope)	
131.02.03.02.01	Module Structure	Design and production of the supporting structures for the ND LArTPC modules Includes: - Support structure for 5 module magazine - Module cryocircuit, plumbing (cryo-side, including feedthroughs) - Module instrumentation (temp, level, pressure, etc), with readout systems - Component testing/QC/QA, and associated tooling - Prototypes for 2x2 and Full-scale Demonstrator - Packaging and shipping - Support personnel for prototyping, A&T, and I&I, and their travel	Bern
131.02.03.02.02	HV	Design and production of the HV supply and distribution for the ND LArTPC modules Includes: - HV supplies and cables - HV filters - Control and monitoring instrumentation and readout - Component testing/QC/QA, and associated tooling - Prototypes for 2x2, Full-scale Demonstrator - Packaging and shipping - Support personnel for prototyping, A&T, and I&I, and their travel	Bern
131.02.03.02.03	Field Structures	Design and production of the TPC field system for the ND LArTPC modules Includes: - HV feedthrough and delivery cable - Cathode panels - Field cage panels - Attachment hardware (brackets, screws, etc) - Anode mechanical support panels - Component testing/QC/QA, and associated tooling - Prototypes for 2x2, Full-scale Demonstrator - Packaging and shipping - Support personnel for prototyping, A&T, and I&I, and their travel	SLAC CSU
131.02.03.02.04	Charge Readout	Design and production of the charge readout system for the ND LArTPC modules Includes: - Pixel ASICs - Pixel Anode Tiles - Cabling and feedthroughs - (Warm) Control Interface Electronics and enclosures - Control, configuration, and readout software/firmware - Electronics power supplies, power cables - Clock distribution/synchronization system - Component testing/QA/QC, and associated tooling - Prototypes for 2x2, Full-scale Demonstrator - Packaging and shipping - Support personnel for prototyping, A&T, and I&I, and their travel	LBNL UPenn UTA CSU Caltech UCSB UC-Davis UC-Irvine Rutgers UH
131.02.03.02.05	Light Readout	Design and production of the light readout system for the ND LArTPC modules Includes: - LCM light traps - ArCLight light traps - SiPMs - SiPM circuit boards - Cabling and feedthroughs - SiPM biasing, readout, and control electronics and enclosures - Control and configuration software/firmware - Electronics power supplies - Clock distribution/synchronization system for the light readout - Component testing/QC/QA, and associated tooling - Prototypes for 2x2, Full-scale Demonstrator - Packaging and shipping - Support personnel for prototyping, A&T, and I&I, and their travel	JINR Bern
131.02.03.02.06	Calibration	Design and production of the calibration system for the ND LArTPC modules Includes: - Light, charge, field calibration system - Cabling and feedthroughs - Control and configuration software/firmware - Component testing/QC/QA, and associated tooling - Prototypes for 2x2, Full-scale Demonstrator - Packaging and shipping - Support personnel for prototyping, A&T, and I&I, and their travel	UH-Manoa MSU JINR
131.02.03.02.07	TPC Module Assembly & Testing	Assembly & testing program for the TPC Modules of the ND LArTPC detector Includes: -Assembly & testing of SingleCube TPCs -Assembly & testing of 2x2 TPC modules (including Module 0) -Assembly & testing of Full-scale Demonstrator TPC Module -Assembly & testing of Production ND TPC Modules -Assembly & testing procedures -Assembly & testing result reports -Assembly, lifting fixtures, and other integration hardware - Design of cryostat and lid for Full-scale ND module testing at FSDTF	CSU with significant contributions from Consortia partners

131.ND.02.05: Charge Readout

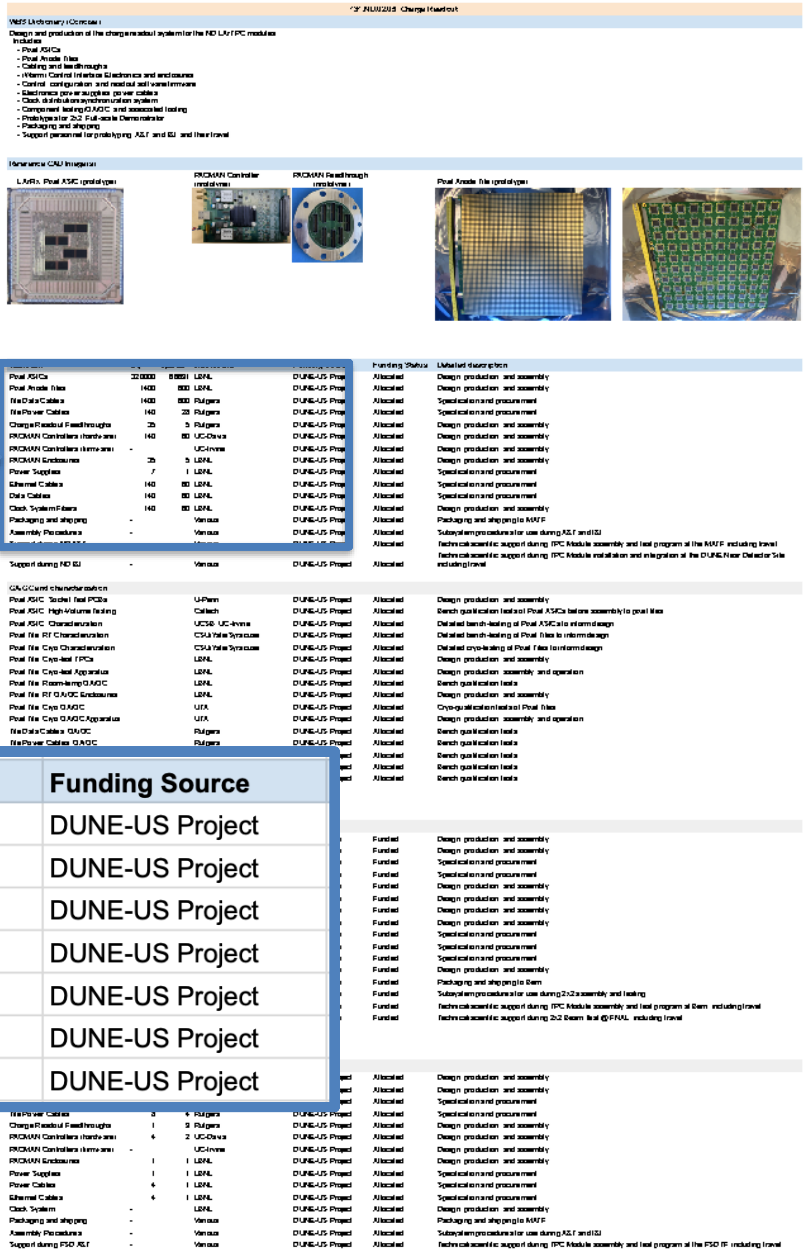
Design and production of the charge readout system for the ND LArTPC modules Includes: - Pixel ASICs - Pixel Anode Tiles - Cabling and feedthroughs - (Warm) Control Interface Electronics and enclosures - Control, configuration, and readout software/firmware - Electronics power supplies, power cables - Clock distribution/synchronization system - Component testing/QA/QC, and associated tooling - Prototypes for 2x2, Full-scale Demonstrator - Packaging and shipping - Support personnel for prototyping, A&T, and I&I, and their travel	LBNL UPenn UTA CSU Caltech UCSB UC-Davis UC-Irvine Rutgers UH

https://edms.cern.ch/project/CERN-0000220117

ND-LAr Consortium: Scope Tables

Tables provide scope details for each subsystem

- Flow from WBS dictionary
- Informed by ND-LAr CAD and 2x2 Module 0 prototype
- Identify deliverables, quantities, institutions, funding source
- Aligned with BOEs and Resource-loaded Schedule
- Used as foundation for development of ND-LAr Annex to the DUNE Multi-institutional MOU



Task/Item	Qty	Spares	Institutions	Funding Source
Pixel ASICs	320000	66691	LBNL	DUNE-US Project
Pixel Anode Tiles	1400	600	LBNL	DUNE-US Project
Tile Data Cables	1400	600	Rutgers	DUNE-US Project
Tile Power Cables	140	28	Rutgers	DUNE-US Project
Charge Readout Feedthroughs	35	5	Rutgers	DUNE-US Project
PACMAN Controllers (hardware)	140	60	UC-Davis	DUNE-US Project
PACMAN Controllers (firmware)	-		UC-Irvine	DUNE-US Project

ND-LAr Consortium: Interfaces

https://edms.cern.ch/project/CERN-0000217522

ND-LAr Interface Development:

- Flows from ND-LAr Scope Tables
- Detailed in ND-LAr CAD Model
- Informed/validated by ArgonCube 2x2 Prototyping program
- Formalized with Interface Control Documents (ICDs)
- Includes both internal (within ND-LAr Consortium) and external (outside ND-LAr Consortium) interfaces
- Tracked and managed by Lead Engineer

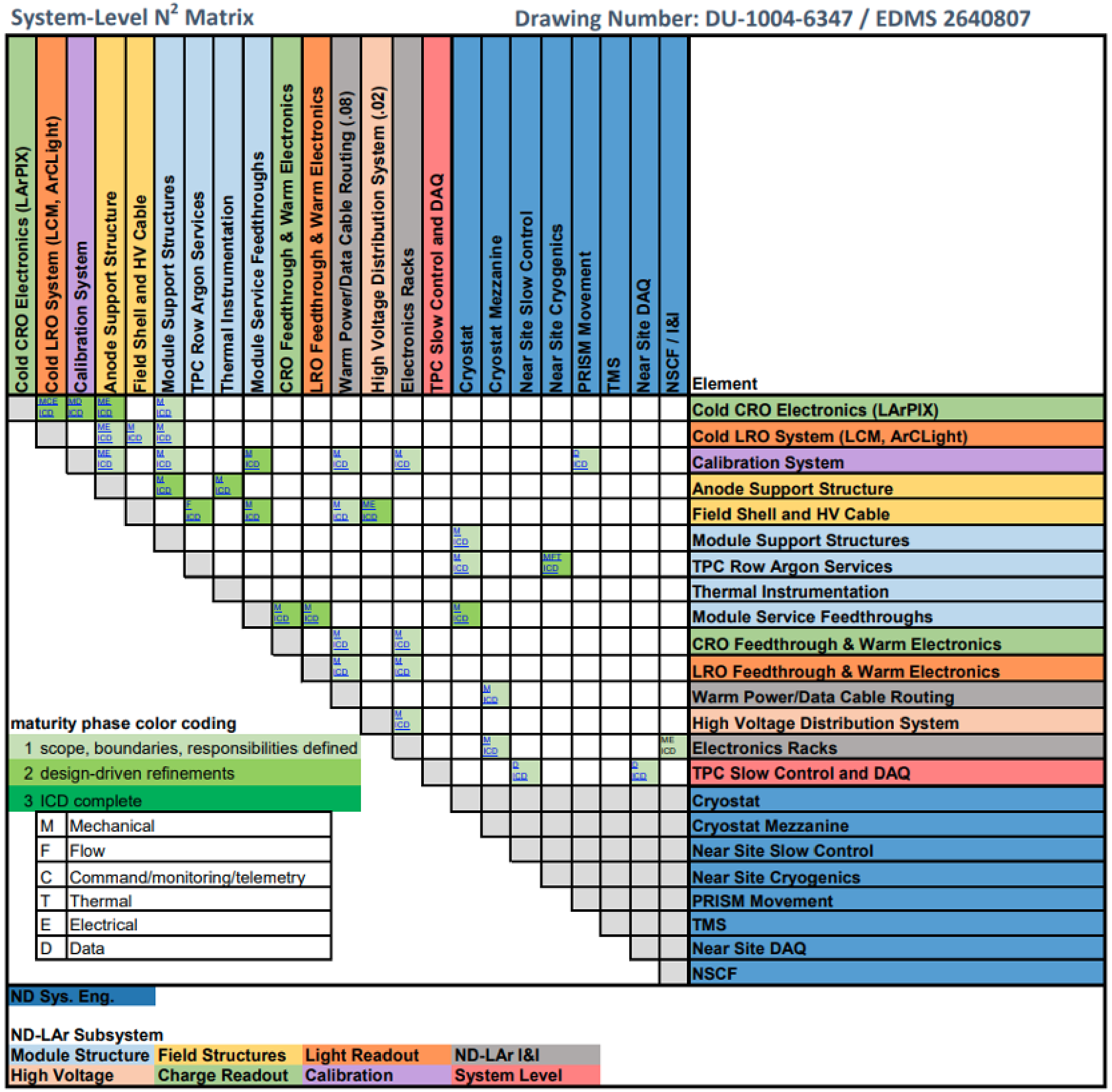
Major External Interfaces:

- 131.ND.03: ND-LAr Cryostat
- 131.ND.04: Muon Spectrometer - TMS
- 131.ND.06: ND DAQ and Slow Controls
- 131.ND.07: PRISM Movement System
- 131.ND.08: Near Site Cryogenics
- 131.ND.10: Near Site Installation

See "Systems Engineering" (Lambert)

Status:

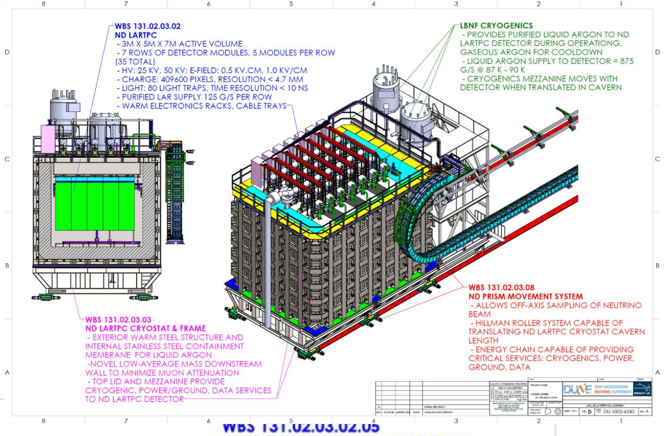
- Maturity of most interfaces exceeds CD-1 needs
- Slow Controls is least mature
- Near Site Installation is most complex external interface



LBNF/DUNE

ND-LAr Consortium: Integrated CAD Model

https://edms.cern.ch/document/2737743
https://edms.cern.ch/document/2737744



Comprehensive CAD Model:

- Contains detailed model of all ND-LAr components

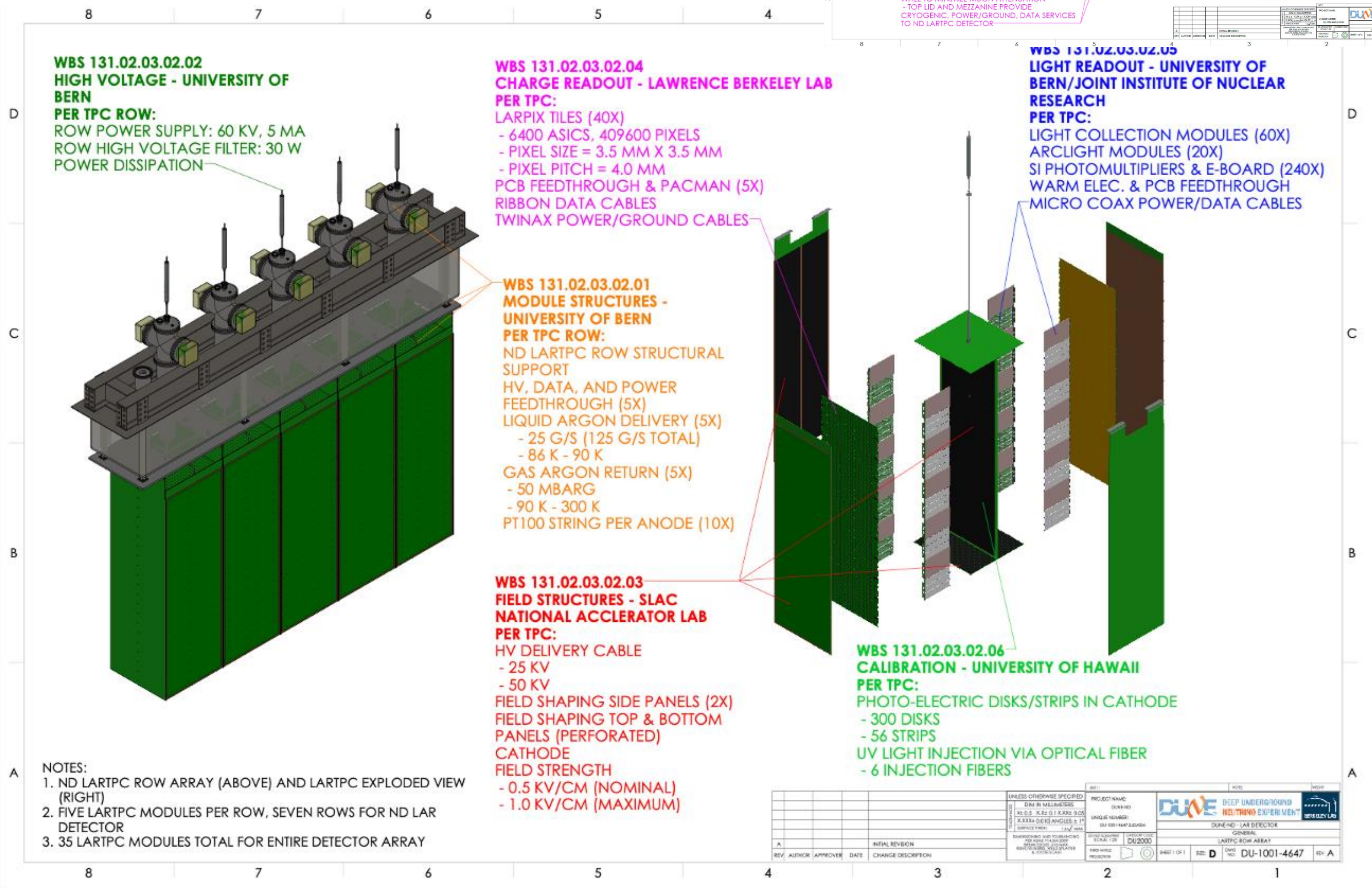
- Single source of truth in detector design

- Accessible by all Consortium engineers, with access mgmt and version control
  Solidworks on LBNL Windchill system

- Same system hosts entire Near Site CAD model, facilitates interface development and avoids conflicts

- Regular exports provided to LBNF/DUNE Systems Engineering Team

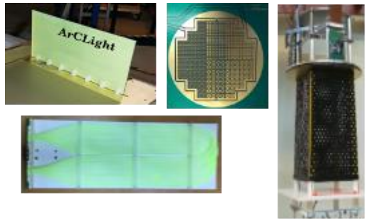
See "Systems Engineering" (Lambert)



ND-LAr Consortium Plan in Pictures

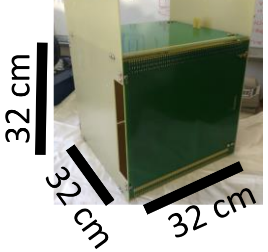
See "Prototyping" (Kreslo) and "Path to FDR" (Weber)

2016-2019
ArgonCube R&D
Demonstrations of component technologies



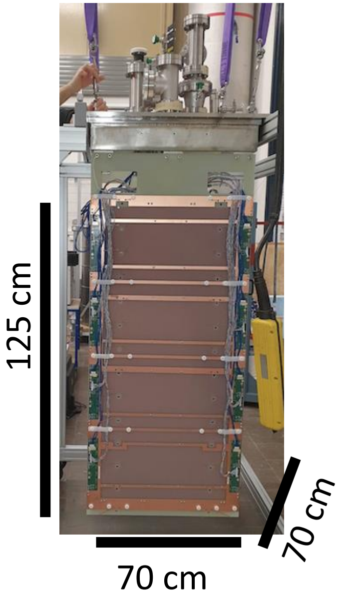
TRL-4

2020
SingleCube
Integrated TPC test at small-scale



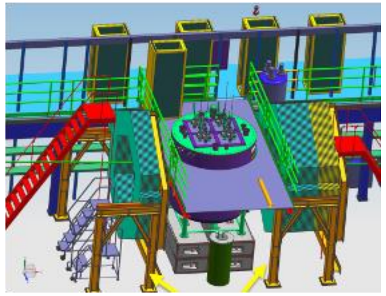
TRL-5

2021
ArgonCube Module 0
One mid-scale TPC module in single-module cryostat



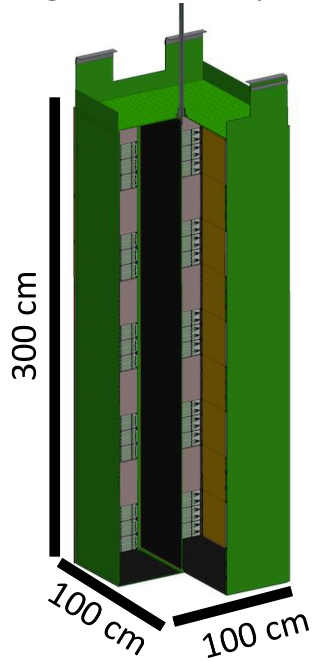
TRL-6

2022-2025
ArgonCube 2x2 Demonstrator
Four mid-scale TPC modules in neutrino beam



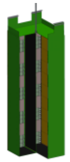
TRL-7 (physics)

2023-2024
Full-scale ND Demonstrator
1 Full-scale ND-LAr TPC module in single-module cryostat



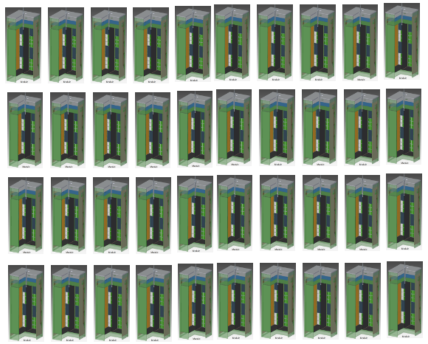
TRL-7 (engineering)

2025-2028
Production



1 production 'first article'

35 (+5) production modules each fully tested in a single-module cryostat

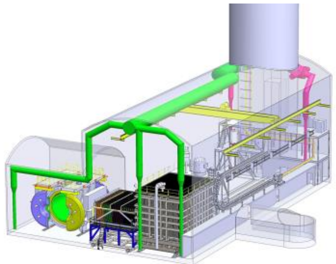


Deliverable: modules packed and ready for installation underground

2028-2031
Installation

Support of TPC module installation in Near Site

Activity driven by Near Site Integration (NSI)



Prototyping: ArgonCube 2x2 LArTPCs

Four ton-scale Prototype TPC Modules to validate Near Detector Design

Each TPC Module:

- Active Size: 0.7m x 0.7m x 1.25m
- 16 pixel tiles, with ~80k pixel channels total
- 16 light collection modules, with 96 light sensors (SiPMs)
- Resistive-film-on-fiberglass field cage

Progress @ Univ. of Bern:

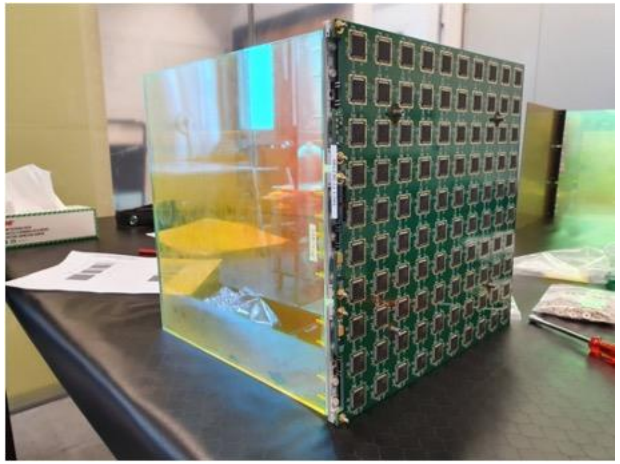
- TPC Module 0:
  Run 1 (Demonstration): *Apr. 1-10, 2021*
  Run 2 (Extra Cryo-test): *Jun. 21-26, 2021*
- TPC Module 1 Operation:
  Feb. 5-13, 2022

Achievements:

Demonstrated fully-integrated prototype detector module at a scale relevant to the DUNE Near Detector

See "Prototyping" (Kreslo)

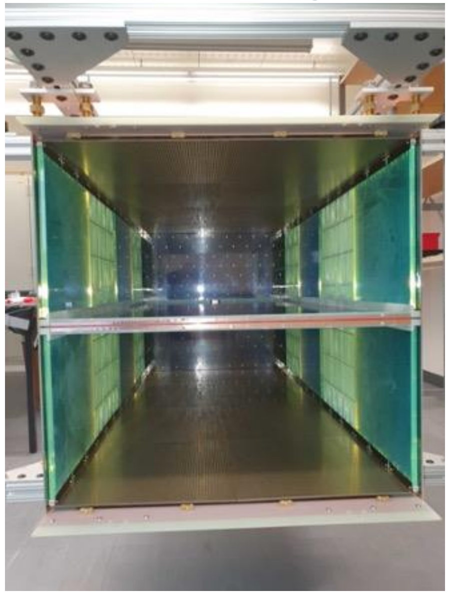
Single pixel tile & light module assembly



LArTPC module attached to cryostat lid

One anode, fully-assembled

Two anodes, installed inside field cage



Single Module Cryostat

LArTPC inside cryostat

See "Prototyping" (Kreslo)
and "ND-LAr Physics" (Mastbaum, Ochoa)

Prototyping: ArgonCube 2x2 LArTPCs

Verified design meets technical requirements:

- Collected >10^7 cosmic ray events
- Stable **HV** at ~30kV (~1 kV/cm drift, 2x target)
- Stable **Purity** at >2ms (>4x target)
- MIP Charge Signal-to-**Noise** >20:1 (at target)

Exercised scope and interfaces:

- ND-LAr scope and interfaces follow 2x2 model
- Technical elements (charge, light) already close to ND-LAr scale (~50% larger in ND-LAr)

Informed development of future program:

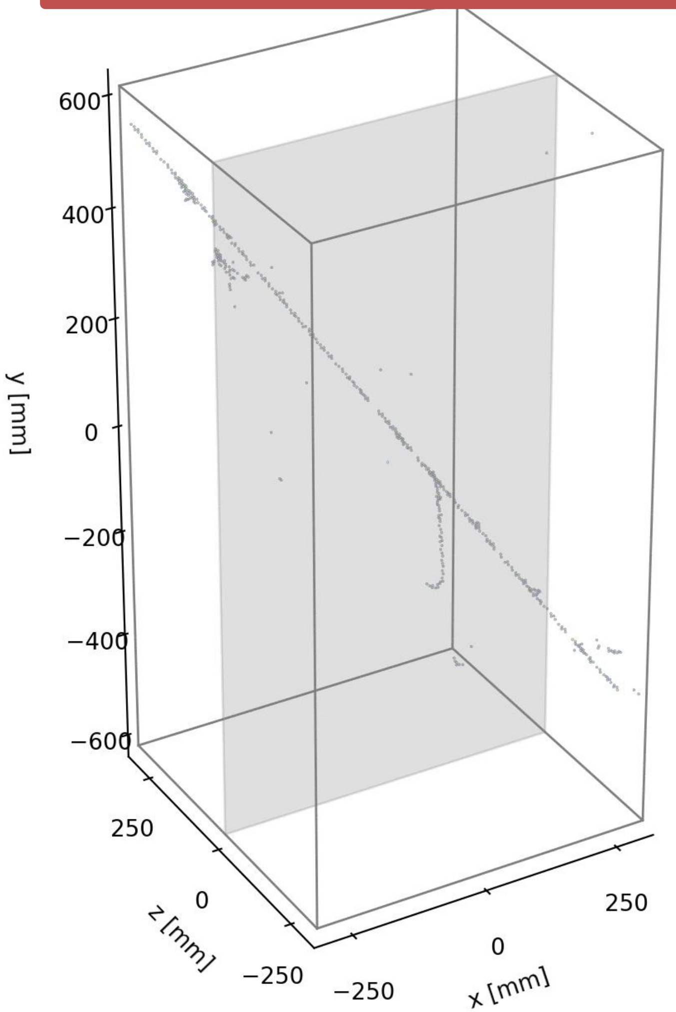
- Full-scale module prototyping
- Production TPC Assembly & Testing Plan
- Installation plan at the Near Site

Retired the most significant technical risks in ND-LAr design.

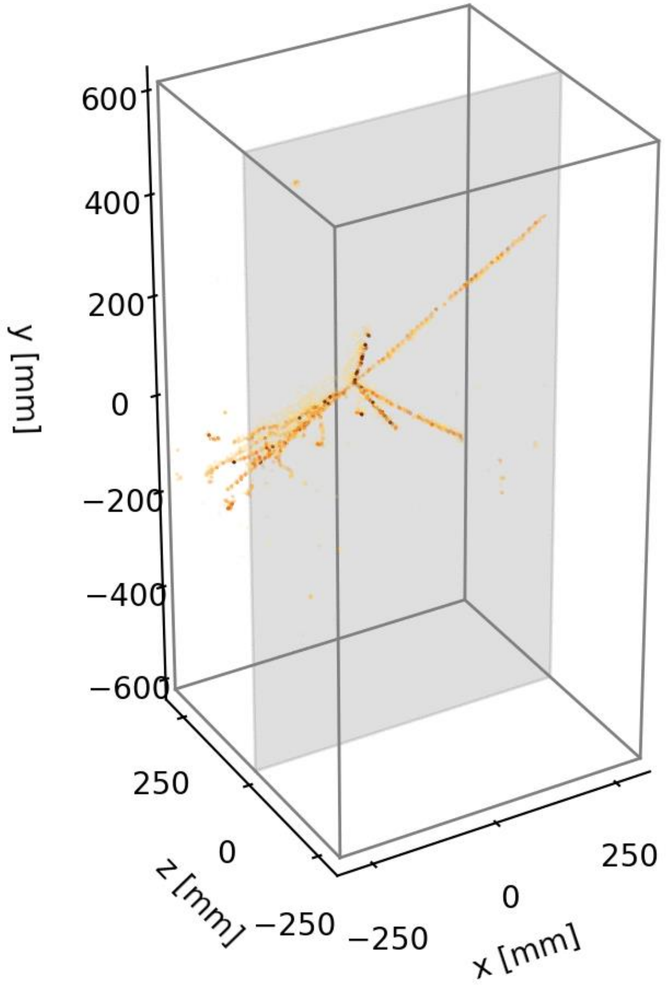
Arguably the most performant ton-scale LArTPC to date.

Achieved TRL-6 in 2021.

*Typical **raw data** from cosmic ray interactions imaged in 3D prototype detectors*



Module 0 LArTPC



Module 1 LArTPC

https://edms.cern.ch/document/2746204

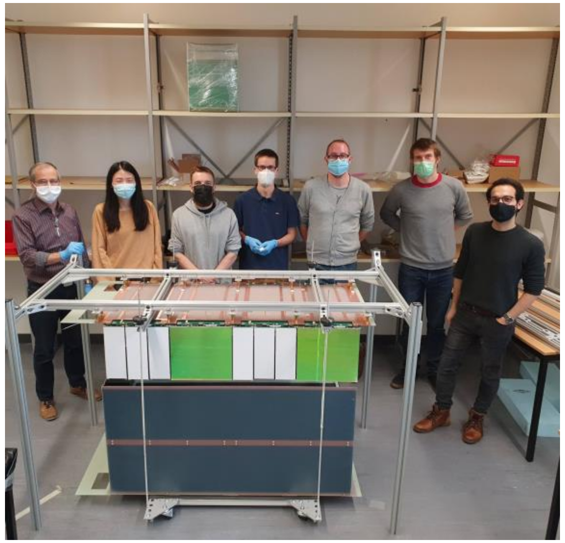
ND-LAr Consortium: Assembly and Testing

See “TPC Assembly and Testing” (Mooney, Jablonski, Suter)

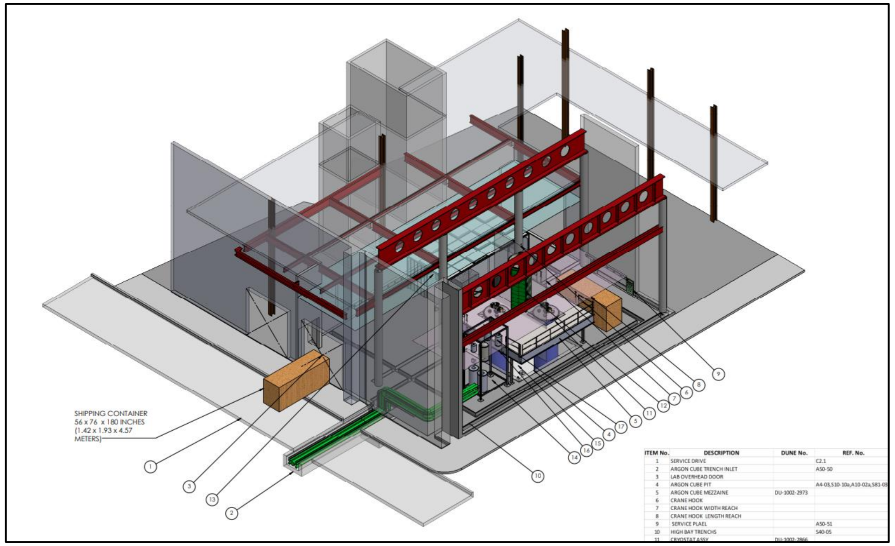
TPC Module Assembly and Testing Plan:

- Covers the assembly and testing of TPC modules
- Includes procedures, processes, fixtures
- Testing ensures modules ready for installation
- Prototyped through 2x2 and FSD program

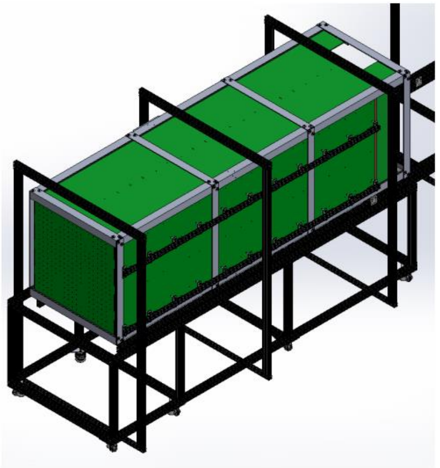
2x2 Prototype Assembly Fixture



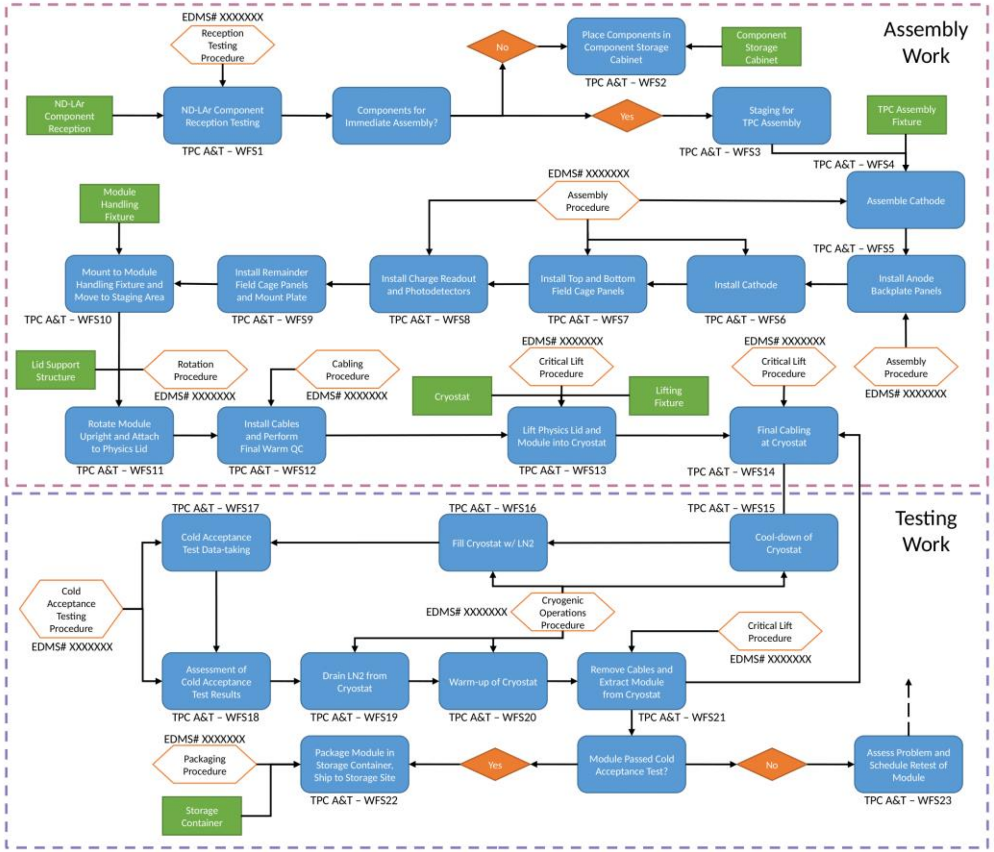
Floorplanning of Module Assembly Facility



Full-scale Module Assembly Fixture



TPC Module A&T Process Flow Diagram



https://edms.cern.ch/document/2742799

https://edms.cern.ch/document/2589288

ND-LAr Consortium: Risk Management

Title	Mitigation	Probability	Schedule Impact [months]			Cost Impact [$k]		
ND-LAr: Electronics Supply Chain Issues	Place procurements as early as possible and build conservative schedules for electronics production and delivery; expand list of vendors, explore domestic market (if available)	30%	3	9	24	250	1000	4000
ND-LAr: TPC module performance loss post-installation at Near Site	Robust 2x2 prototyping program and subsequent engineering Full-Scale Demonstrator program to verify operation of integrated TPC systems and assess system performance. QAQC program to verify component specifications and quality, acceptance testing of assembled TPC modules.	35%	6	9	12	-	1250	-
ND-LAr: ASIC foundry access	Continue to monitor vendor and start on acquisition strategy with vendor early, paying special attention to "Buy America Act" changes. Migration to 130nm design rule is an additional mitigation to this risk.	10%	6	12	24	500	1000	4000
ND-LAr: Stop Work Order	Adherence to institutional ESH requirements will help to mitigate a stop work order related to a safety incident. Robust quality assurance testing and quality control procedures will help mitigate a stop work order related to inferior production quality Integrated Safety Management (ISM) practices for all activities	20%	3	6	12	110.5	221	441
ND-LAr: Significant failure during ND Component Quality Control	Identify and task a specific fraction of ND engineering oversight to quality assurance and quality control. Establish training for scientific staff. Work with the overall LBNF/DUNE QA/QC team to ensure engineering resources for QA/QC are sufficient. Site visits to ensure production facility is performing as planned. 2x2 components used as "prototype" QAQC for ND-modules. Leverage experience towards development of ND quality assurance and control plans, required resources, schedule, etc.	30%	1	-	12	0	200	1000

Other Risks: Partner System Delays, Field structure Alternative, Loss of Key Personnel, Component Cryo-Failures, Insufficient Quality Control

ND-LAr Consortium Risk Registry

- ~200 Risks across entire Consortium activities
- 84 Tracked by US Project: 34 Open, 37 Proposed, 3 Realized, 10 Retired/Managed

https://edms.cern.ch/project/CERN-0000219039

Technical Pre-Baseline: Hazard Registry

- Completed by ND Team and reviewed by ND Safety Officer

2. DUNE ND Hazard List — DUNE Near Detector Hazard List — DRAFT
Effective Date: 17-Dec-21
Print Date: 18-May-22

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
2.01	NDLArTPC	Press/ Vac	Piping Systems	Piping systems need to be designed, fabricated and tested according to specific requirements in order to safely operate them..	2	B	5	High	Control hazard	Design, fabrication, testing, implementation and operation according to standards and regulations.Including but not limited to overpressure protection safety devices.	3	E	17	Medium	Audit	Part of FESHM 5032 cryogenic system review. For specific requirements see FESHM 5031.1 Piping Systems
2.04	NDLArTPC	Elec	High Voltage Safety	High voltage systems that are not properly designed and rated could result in harm to personnel or damage to the instrument	2	C	6	Serious	Control hazard	Design, fabrication, and testing of high voltage systems shall adhere to FESHM requirements	3	D	14	Medium	Inspection	TBD
2.08	NDLArTPC	Installa tion	Fall Hazards	Working on elevated surfaces at the FSDTF, MATF, and Near Site poses a fall hazard to personnel	1	D	8	Serious	Procedure, training	Fall protection training and fall protection harnesses shall be required for all work that has an associated fall hazard, along with any additional requirements per home institution ES&H manuals. All work done that has an associated fall hazard must be done in a team or two or greater.	3	D	14	Medium	Process control	Governed by FESHM 7060
2.09	NDLArTPC	Env	Ladders and Scaffolds	Working on ladders and scaffolds at the FSDTF, MATF, and Near Site can pose a hazard to personnel	1	D	8	Serious	Procedure, training	Ladder and scaffold training shall be required per host institution ES&H	3	D	14	Medium	Process control	Governed by FESHM 7070
2.10	NDLArTPC	Fire	Egress	If egress is not preserved then personnel are unable to exit the facility in the event of a fire	1	C	4	High	Control hazard	Egress requirements per host institution shall be maintained. All personnel shall be trained by host institution for proper evacuation routes and congregation points.	3	D	14	Medium	Inspection	Governed by FESHM 6020.4
2.14	NDLArTPC	Elec	Power Grounding	If electrical cables and connections are not properly grounded it could result in personnel injury or instrument damage	1	C	4	High	Control hazard	Power delivery systems shall be grounded per the requirements as specified in FESHM	3	D	14	Medium	Review	Grounding requirements per FESHM 10130
4.01	TMS	Mech	Steel Stack Weight	TMS weighs 1000 tons and is ~2m off the ground. There are ~25 MJ of stored energy.	1	E	12	Medium	Control hazard	Design Support structure to ensure adequate margin, both in place and in motion	1	E	12	Medium	Review	Review when design complete
				Magnet power supplies are low						Minimize current. Insulate bus bars. Ensure crowbar circuit or similar in						

ND-LAr Detailed Schedule

Detailed Consortium Schedule:

- Includes full Consortium Scope and Resources
  Both on- and off-project

- Managed in LBNF/DUNE Primavera P6

- Integrated with broader DUNE schedule
  Key DUNE milestones, installation, etc.

- In active use for almost 3 years

- Total of 1,378 activities
  Past: 269
  In progress: 30
  Future: 1,079

#wbs elements

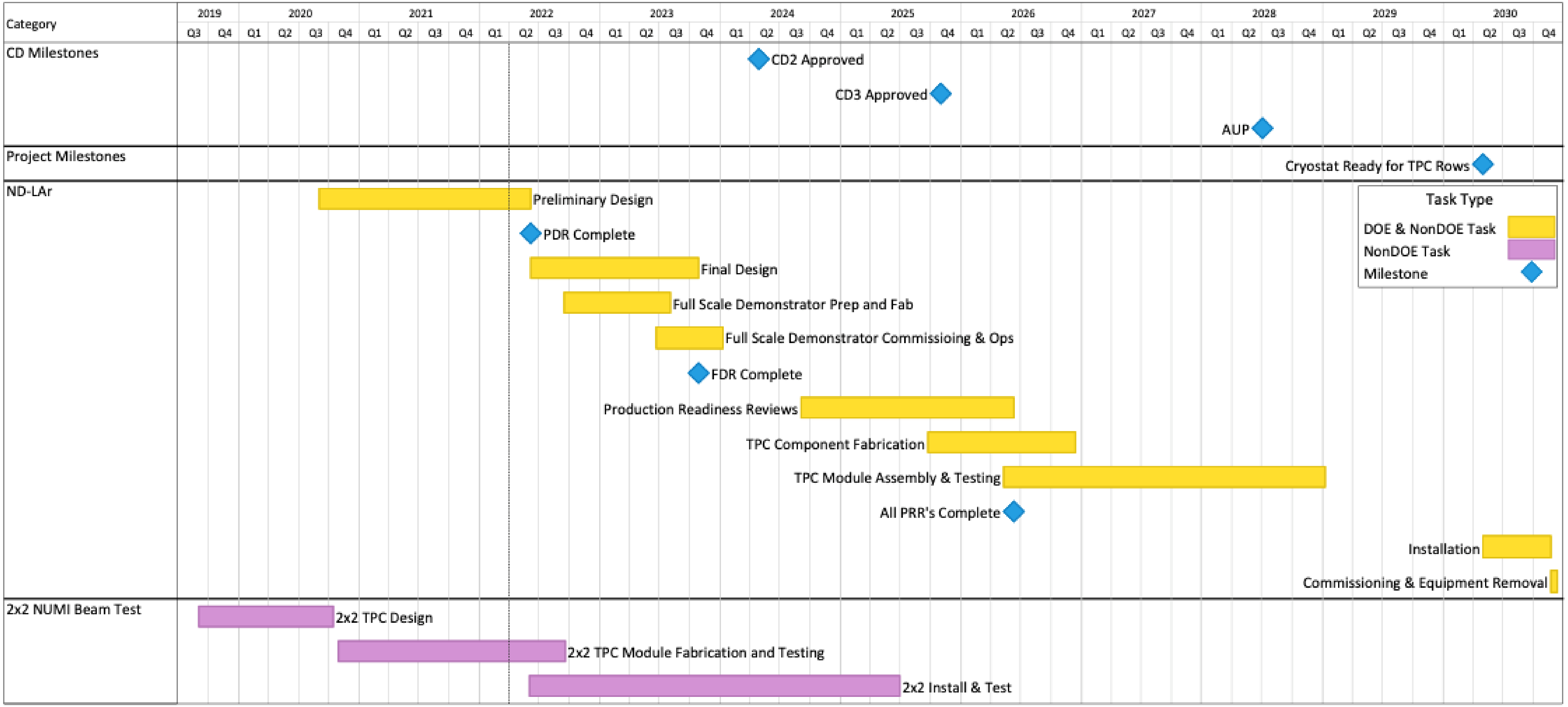
Data Date 5/1/22

Activity ID	Activity Name	Planned Duration	Start	Finish
131.ND-LAR.SB	Near Detector - ND LAr Sandbox - F9 check I&I managment dates	3076	03-Sep-2019 A	17-Jun-2031
131.ND-LAR.SB.02	ND LArTPC	3076	03-Sep-2019 A	17-Jun-2031
131.ND-LAR.SB.02.00	Milestones	2283	18-Aug-2022	19-May-2031
131.ND.200.010.MS	TS MS - ND LAr: PDR Complete	0		18-Aug-2022
131.ND.200.020.MS	TS MS - ND LAr: 2x2 TPC Assembly and Test Complete	0		19-Sep-2022
131.ND.200.040.MS	TS MS - ND LAr: Ready for CD-2	0		13-Oct-2022
131.ND.200.050.MS	TS MS - ND LAr: Full-Scale Demonstrator Test Complete	0		21-Jul-2023
131.ND.200.030.MS	TS MS - ND LAr: 2x2 NUMI Ready for Operations	0		31-Jul-2023
131.ND.200.060.MS	TS MS - ND LAr: FDR Complete	0		23-Oct-2023
131.ND.200.070.MS	TS MS - ND LAr: Ready for CD-3	0		18-Dec-2023
131.ND.200.080.MS	TS MS - ND LAr: PRRs Complete	0		04-Dec-2026
131.ND.200.090.MS	TS MS - ND LAr: TPC Component Production Complete	0		10-Sep-2027
131.ND.200.100.MS	TS MS - ND LAr: TPC Assembly and Test Complete	0		22-Jan-2030
131.ND.200.110.MS	TS MS - ND LAr: Start of TPC Installation at Near Site	0		22-May-2030
131.ND.200.120.MS	TS MS - ND LAr: TPC Installation at Near Site Complete	0		02-May-2031
131.ND.200.130.MS	TS MS - ND LAr: Ready for CD-4	0		19-May-2031
131.ND-LAR.SB.02.01	ND LArTPC Management	2895	01-Apr-2020 A	04-Apr-2031
131.ND-LAR.SB.02.01.1	Mgmt	2895	01-Apr-2020 A	04-Apr-2031
131.ND-LAR.SB.02.01.1.1	Systems	2873	01-Apr-2020 A	04-Apr-2031
13123.A10680	Near Detector LArTPC Systems Electrical Engineering - LBNL - FY20Q3	64	01-Apr-2020 A	30-Jun-2020 A
13123.A10690	Near Detector LArTPC Systems Electrical Engineering Mgmt - LBNL - FY20Q4	64	01-Jul-2020 A	30-Sep-2020 A
13123.A10700	Near Detector LArTPC Systems Electrical Engineering Mgmt - LBNL - FY21Q1	61	01-Oct-2020 A	30-Dec-2020 A
13123.A11290	Near Detector LArTPC Systems Electrical Engineering Mgmt - LBNL - FY21Q2	62	04-Jan-2021 A	31-Mar-2021 A
13123.A11300	Near Detector LArTPC Systems Engineering Mgmt - LBNL - FY21Q3	64	01-Apr-2021 A	30-Jun-2021 A
13123.A11310	Near Detector LArTPC Systems Engineering Mgmt - LBNL - FY21Q4	64	01-Jul-2021 A	30-Sep-2021 A
13123.A107101	Near Detector LArTPC Systems Engineering Mgmt - LBNL - FY22 - Q1	61	01-Oct-2021 A	30-Dec-2021 A
13123.A107102	Near Detector LArTPC Systems Engineering Mgmt - LBNL - FY22 - Q2	63	04-Jan-2022	01-Apr-2022
13123.A107103	**Near Detector LArTPC Systems Engineering Mgmt - LBNL - FY22 - Q3**	62	4-Apr-2022	30-Jun-2022
13123.A107104	Near Detector LArTPC Systems Engineering Mgmt - LBNL - FY22 - Q4	64	1-Jul-2022	30-Sep-2022
13123.A10720	Near Detector LArTPC Systems Engineering Mgmt - LBNL - FY23	249	3-Oct-2022	29-Sep-2023
13123.A10730	Near Detector LArTPC Systems Engineering Mgmt - LBNL - FY24	250	2-October-2023	30-Sep-2024
13123.A10740	Near Detector LArTPC Systems Engineering Mgmt - LBNL - FY25	250	1-Oct-2024	30-Sep-2025
13123.A10750	Near Detector LArTPC Systems Engineering Mgmt - LBNL - FY26	250	01-Oct-2025	30-Sep-2026
13123.A16630	Near Detector LArTPC Systems Engineering Mgmt - LBNL - FY27	250	1-Oct-2026	30-Sep-2027
13123.A16640	Near Detector LArTPC Systems Engineering Mgmt - LBNL - FY28	250	1-Oct-2027	29-Sep-2028
13123.A16642	Near Detector LArTPC Systems Engineering Mgmt - LBNL - FY29	250	2-October-2028	01-Oct-2029
13123.A16644	Near Detector LArTPC Systems Engineering Mgmt - LBNL - FY30	250	2-Oct-2029	01-Oct-2030
13123.A16646	Near Detector LArTPC Systems Engineering Mgmt - LBNL - FY31	126	2-October-2030	04-Apr-2031
131.ND-LAR.SB.02.01.1.2	Support	2720	01-Oct-2020 A	04-Apr-2031
13123.A1196	LAr TPC Management/Engineering Support - FY21Q1 - LBNL	61	01-Oct-2020 A	30-Dec-2020 A
13123.A11230	LAr TPC Management/Engineering Support - FY21Q2 - LBNL	62	04-Jan-2021 A	31-Mar-2021 A
13123.A11240	LAr TPC Management/Engineering Support - FY21Q3 - LBNL	64	01-Apr-2021 A	30-Jun-2021 A
13123.A11250	LAr TPC Management/Engineering Support - FY21Q4 - LBNL	64	01-Jul-2021 A	30-Sep-2021 A
13123.A100001	LAr TPC Management/Engineering Support - FY22 - LBNL - Q1	61	01-Oct-2021 A	30-Dec-2021 A
13123.A100002	LAr TPC Management/Engineering Support - FY22 - LBNL - Q2	63	4-Jan-2022	01-Apr-2022
13123.A100003	LAr TPC Management/Engineering Support - FY22 - LBNL - Q3	62	4-Apr-2022	30-Jun-2022
13123.A100004	LAr TPC Management/Engineering Support - FY22 - LBNL - Q4	64	1-Jul-2022	30-Sep-2022
13123.A10100	LAr TPC Management/Engineering Support - FY23 - LBNL	249	3-Oct-2022	29-Sep-2023
13123.A10200	LAr TPC Management/Engineering Support - FY24 - LBNL	250	2-Oct-2023	30-Sep-2024
13123.A10300	LAr TPC Management/Engineering Support - FY25 - LBNL	250	1-October-2024	30-Sep-2025
13123.A10400	LAr TPC Management/Engineering Support - FY26 - LBNL	250	1-Oct-2025	30-Sep-2026
13123.A10500	LAr TPC Management/Engineering Support - FY27 - LBNL	250	1-October-2026	30-Sep-2027
13123.A10600	LAr TPC Management/Engineering Support - FY28 LBNL	250	1-Oct-2027	29-Sep-2028
13123.A10605	LAr TPC Management/Engineering Support - FY29 - LBNL	250	2-Oct-2028	01-Oct-2029
13123.A10607	LAr TPC Management/Engineering Support - FY30 - LBNL	250	2-Oct-2029	01-Oct-2030
13123.A10608	LAr TPC Management/Engineering Support - FY31 - LBNL	126	02-Oct-2030	04-Apr-2031
131.ND-LAR.SB.02.01.1.3	Mgmt	315	01-Apr-2020 A	30-Jun-2021 A
131.ND-LAR.SB.02.01.1.3.3	SLAC	315	01-Apr-2020 A	30-Jun-2021 A

Extracted table of activities from ND-LAr P6 sandbox, currently ~28 pages

https://edms.cern.ch/document/2603073

ND-LAr Schedule



ND-LAr Total Resource By WBS: Proposed (from Mar. 2022 cost review, not US project baseline)

	Design & Prototyping				Production					
	On-Project		Off-Project		On-Project		Off-Project		On-Project	
131.ND.02: ND-LAr	M&S [CY-k$]	Labor [k-hrs]	M&S [CY-k$]	Labor [k-hrs]	M&S [CY-k$]	Labor [k-hrs]	M&S [CY-k$]	Labor [k-hrs]	Total Cost [FBAY-k$]	*Avg. Uncert.*
01 ND LArTPC Management	$401.5	18.3	-	43.9	$412.5	13.8	-	72.5	**$10,114.9**	*10%*
02 Module Structure	-	-	-	14.3	-	-	$2,448.0	22.0	-	-
03 HV	-	-	-	10.5	-	-	$816.0	14.0	-	-
04 Field Structure	$159.1	9.4	-	0.6	$3,560.1	4.9	-	6.5	**$7,642.6**	*60%*
05 Charge Readout	$1,331.3	17.7	-	16.6	$3,366.0	5.5	-	20.8	**$10,741.6**	*35%*
06 Light Readout	-	-	-	71.1	-	-	$5,508.0	15.1	-	-
07 Calibration	$193.7	1.3	-	33.1	-	-	-	20.3	**$414.0**	*50%*
08 TPC Module Assembly and Testing	$368.1	7.1	-	8.6	$103.0	5.7	-	32.0	**$1,865.1**	*41%*
09 TPC Integration and Installation	$584.2	11.4	-	12.4	$426.0	9.6	-	15.0	**$5,384.2**	*50%*
10 Module Assembly & Test Facility	-	5.7	-	-	$1,483.0	10.8	-	27.3	**$4,114.0**	*60%*
11 Full-scale Demonstrator Test Facility	$1,497.5	9.1	-	6.3					**$3,726.2**	*60%*
12 ArgonCube Test Facility	-	-	$1,250.0	20.9					-	-
13 2x2 NUMI Test Beam Facility	-	-	$2,300.0	15.0				-	-	-
Total:	**$4,535.3**	**79.9**	**$3,550.0**	**253.2**	**$9,350.6**	**50.5**	**$8,772.0**	**245.5**	**$44,002.5**	**43%**

Notes:

1. Extracted EAC from working resource-loaded schedule for internal cost review (P6/Cobra ND-LAr Sandbox, 22 Mar. 2022)
2. Includes all on-project and majority of off-project resource estimates for ND-LAr Consortium.
3. Off-project resources include both international and domestic investments
4. CY-k$: Costs in current-year direct kilo-dollars.   FBAY-k$: Costs in fully-burdened at-year (escalated) kilo-dollars.

ND-LAr Review Recommendations

https://edms.cern.ch/document/2741842

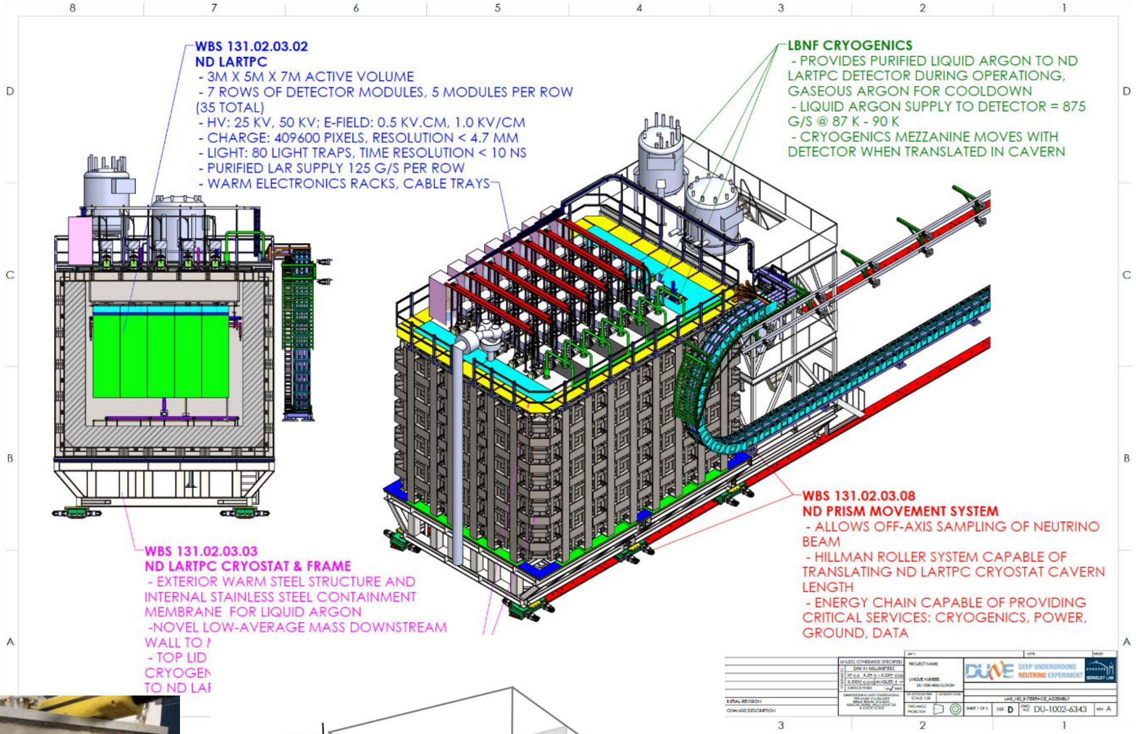
Recommendations are tracked and managed by ND-LAr Consortium Leadership

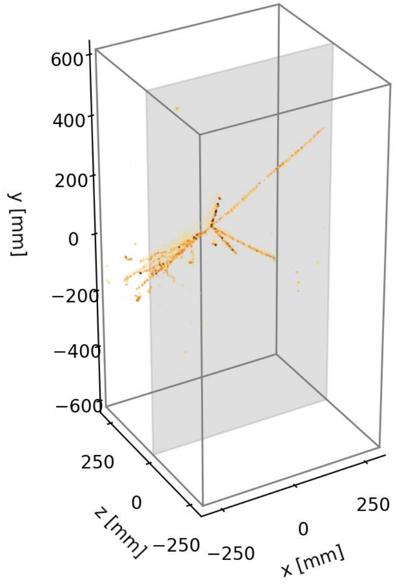
	Name	Short Description	Source	Date added	Who	Status	Complete Text of Recommendation	Comments
1	**2x2 Cryotest**	Test 2x2 module using ND cryo plan	ND CDR	14-Jul-2020	Michele	Closed	The test plan should be revised, considering an additional apparatus (not necessarily the one to be sent near MINOS) that can test all cryogenic issues since cryogenics is not mature yet and there are many unconventional choices to be validated that may jeopardize the project	We have modified the plan to operate Module 0 without bucket. Initial results from Module 0 HV/Purity test have shown sufficient purity and cooling. CFD simulations suggest approach is sufficient for purity, although cooling should be assessed more closely.
2	**ND Risks**	Refine ND risk registry	ND CDR	14-Jul-2020	Dan	Closed	Establish a risk registry, update it periodically, and track the retirement of risks, generally, and include those retired via the prototyping program.	Agreed: Significant effort on training team on the risk management process. Over >100 risks in ND-LAr registry. Risks registry is a continuous process and the NDLAr team is regulary updating their registry
3	**Module Size**	Execute study on module size	ND CDR	14-Jul-2020	Dan	In progress	The light + charge particle ID in a spill should be substantiated by a full simulation.	B. Russell has performed an initial study of charge-to-light signal correlation for both 1.2 MW and 2.4 MW. Further work is required.
4	**Light tagging**	Demonstrate cosmic charge-light tagging in Module 0	ND CDR	14-Jul-2020	Michele	In progress	Some tests on light tagging should be done with cosmics as soon as possible.	Initial results of charge-light spatial and amplitude correlation. Need to be documented in a technical note.
5	**US Scope in ND**	Clarify US scope in ND-LAr Consortium	DOE IPR, Jan 2021	13-Jan-2021	Dan	In progress	Identify the complete DOE scope, including any possible contribution to the SAND tracker, by the June IPR.	Significant progress in formal interface documents. Remaining areas: slow controls, test facilities.
6	**Refine KPPs**	Refine ND-LAr KPPs	DOE IPR, Jan 2021	13-Jan-2021	Dan	Closed	Work with OHEP to adjust the threshold KPPs by the June IPR so they capture levels of achievement that guarantee that the objective KPPs can be achieved in the pre-operations or operations phase.	Nadine will coordinate. Dan and Michele will review and sign-off.
7	**ND Simulation**	Improve ND-LAr simulation effort	DOE IPR, Jan 2021	13-Jan-2021	Michele	Closed	Strengthen the interaction with the International DUNE collaboration to carry out the simulations to optimize the detector and demonstrate that the Day1 detector meets the requirements for the full physics program	The recommendation is mostly addressed to ND-wide simulaiton activities, outside the ND-LAr Consortium. The ND-LAr Consortium should support this broader effort. Recent steps taken: organization of ND-LAr simulation workshop: https://indico.fnal.gov/event/47255/
8	**Mgmt Travel Cost**	Consistently capture travel costs	US ND Cost Review	7-Apr-2022	Dan	Open	Review all plans to ensure that travel costs are appropriately captured and consistent with travel expectations for Reviews (including CD Reviews and yearly DOE Status Reviews).	
9	**CAM Training**	CAM training for Subsystem Leads	US ND Cost Review	7-Apr-2022	Dan	Open	Ensure appropriate training is planned for staff that is expected to assume CAM responsibilities.	
		[illegible]	US ND [illegible]				Consider using a more navigable tool or [illegible]	

LBNF/DUNE

ND-LAr Preliminary Design Progress

- ND-LAr has:
  - Strong institutional commitments and scientific interest (111 members from 39 institutions)
  - Well-developed requirements, scope, and interfaces
  - Detailed design at PDR-maturity
  - Track-record of successful large-scale prototyping
  - Actively managed risks, hazards, cost, schedule





Backup

ND-LAr Consortium: Value Engineering / Alternative Analyses

ND-LAr Active Dimensions:
- Forsake containment of forward-going muons in ND-LAr active volume (in contrast to Far Detectors)
- Maintain physics performance by using more compact downstream muon spectrometer (+ intermediate muon window)
- Yields substantial cost savings from smaller ND-LAr TPC, ND-LAr Cryostat, and less Near Hall excavation: O($100M)

ND-LAr Charge Readout:
- Aggressively revised design to enable commercial production of pixelated charge readout, as opposed to custom in-house production
- Successfully demonstrated in 2x2 program: all parts produced by commercial partners, ready for testing/installation
- Reduced system costs by more than an order of magnitude: now O($10k) per m^2 of anode, O($0.10) per channel, full system production cost

Alternative: Conventional Monolithic LArTPC:
- Reduce risks associated with novel segmented ND-LAr design
- Unable to overcome Near Site neutrino optical signal pileup based on physics studies
- Disfavored

Alternative: Conventional Wire-plane Charge Readout:
- Reduce costs and technical risks associated with pixelated readout design
- Unable to overcome Near Site neutrino charge signal pileup based on physics studies
- Disfavored

ND-LAr Consortium: Value Engineering / Alternative Analyses

Key Design Feature	ArgonCube 2x2	SBND in SBND Cryostat (CS)	Mono. Pixel LArTPC in SBND Cryostat	ND-LAr modules in SBND Cryostat	ND-LAr in ND-LAr CS (20 modules)	ND-LAr in ND-LAr CS (35 modules)
Total LAr Active LAr (w x l x h) m³	2 (ø) x 2.5 (h) 1.3x 1.3 x 1.2 ~full loss of acceptance	6.8 x 8.6 x 7.6 4 x 5 x 4 ~25% loss of acceptance	6.8 x 8.6 x 7.6 4 x 5 x 4 ~25% loss of acceptance	6.8 x 8.6 x 7.6 4 x 5 x 3 ~25% loss of acceptance	10.6 x 7.0 x 6.3 4 x 5 x 3 ~15% loss of acceptance	10.6 x 7.0 x 6.3 7 x 5 x 3 ~2% loss of acceptance
Downstream inactive material (g/cm^2)	~70	>118 ~10-15% muon energy resolution in TMS	>118 ~10-15% muon energy resolution in TMS	>118 ~10-15% muon energy resolution in TMS	< 60 ~5-6% muon energy resolution in TMS	< 60 ~5-6% muon energy resolution in TMS
Charge Readout	5 x 5 mm² pixel Native 3D readout	5 mm U/V/Y wire Significant degradation in high rate environment	5 x 5 mm² pixel Native 3D readout	5 x 5 mm² pixel Native 3D readout	5 x 5 mm² pixel Native 3D readout	5 x 5 mm² pixel Native 3D readout
Modularity	2x2 (0.7x0.7x1.2) m³ dual drift/op. modules	4x5x4 m³ dual drift/op. volume <5% spills with unambiguous matching	4x5x4 m³ dual drift/op. volume <5% of spills with unambiguous matching	4x5 array of (1x1x3) m³ dual drift/op. volumes ~70% of events with fully unambiguous matching	4x5 array of (1x1x3) m³ dual drift/op. volumes ~70% of events with fully unambiguous matching	7x5 array of (1x1x3) m³ dual drift/op. volumes ~70% of events with fully unambiguous matching
Cost difference	- Remove ND-LAr CS/TPC +Move/install 2x2	- Remove ND-LAr CS/TPC + Replica SBND CS + Assembly + Installation	- Remove ND-LAr CS + Replica SBND CS - Reduce pixels - Reduce field structure	- Remove ND-LAr CS - 15 fewer modules + Replica SBND CS + SBND CS lid redesign	-15 fewer modules	
Physics Summary	Inadequate for phase 1 physics (acceptance)	Inadequate for phase 1 physics (pileup)	Inadequate for phase 1 physics (pileup)	~25% loss of FD accept. irrecoverable	~15% loss of FD accept. recoverable	

Adequacy for Phase 1 Physics

(green)	Adequate
(olive)	Compromised but likely sufficient
(orange)	Significantly compromised, likely insufficient
(red)	Insufficient