Toward the FDR:
Design Development and Prototyping

Michele Weber, Consortium Lead

ND-LAr Preliminary Design Review

29 June 2022

Schweizerische Eidgenossenschaft
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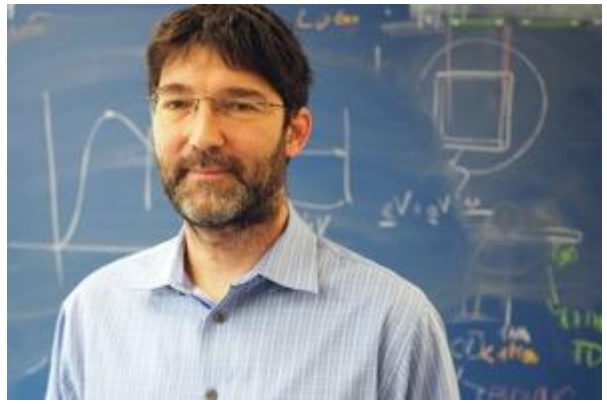
U.S. DEPARTMENT OF ENERGY | Office of Science

Who am I

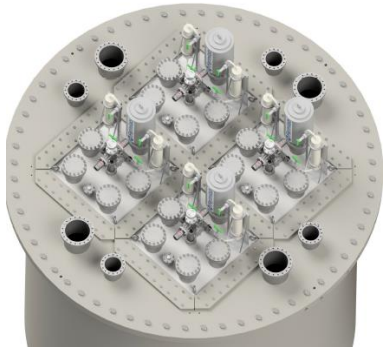


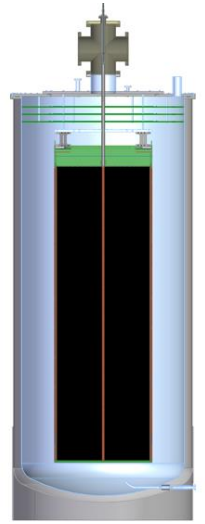
- **Michele Weber**
- Professor at the University of Bern
- Director of the Laboratory for High Energy Physics
- Involved in HEP detector development since 1995, calorimetry, ToF, silicon detectors, LArTPCs since 2007
- Heavy ions (NA52), Collider physics (D0, ATLAS), neutrino physics (ArgoNeuT, MicroBooNE, DUNE), medical applications

- ND-LAr consortium lead
- Previously MicroBooNE physics coordinator and several technical, management and physics roles in D0, ATLAS

Introduction

- We have presented details on each subsystem and how the ND-Lar TPC will be assembled
- This talk in the path beyond the PDR, toward the FDR
- Main steps before proceeding to production:
  - Physics/reconstruction demonstration
    - ➢ “2x2” as smallest module assemble, test in the NuMI neutrino beam at FNAL
  - Complete technical engineering and retire design risks
    - ➢ Build a 1:1-size module with the final design
  - Industrialization of 1:1-size component production and production workflows





Technology development from the PDR toward the Final Design Review

Single Cube

Published July 2021

CDR

Conceptual design review

Single Module

June 2022

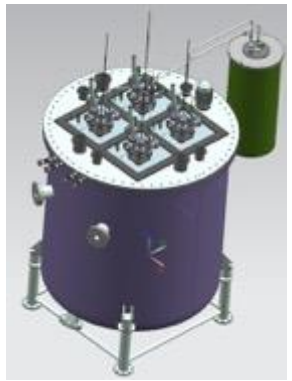
PDR

Preliminary design review

We are here

TRL-6

2x2 neutrino beam test



Full size demonstrator(s)

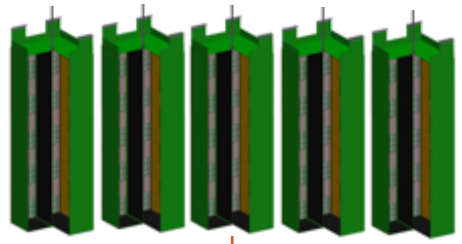
TRL-7

+ 1.5 Years

FDR

Final design review

Pre-production x5



+ 1 Year

PRR

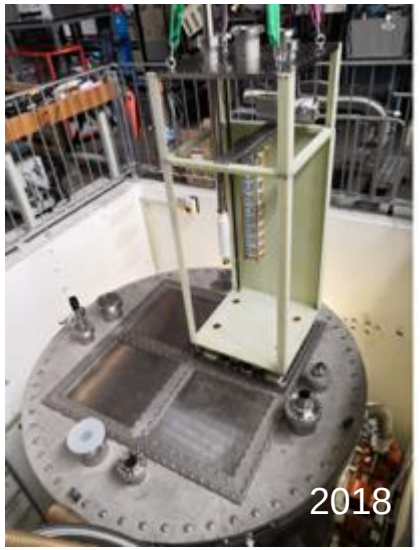
Production readiness review

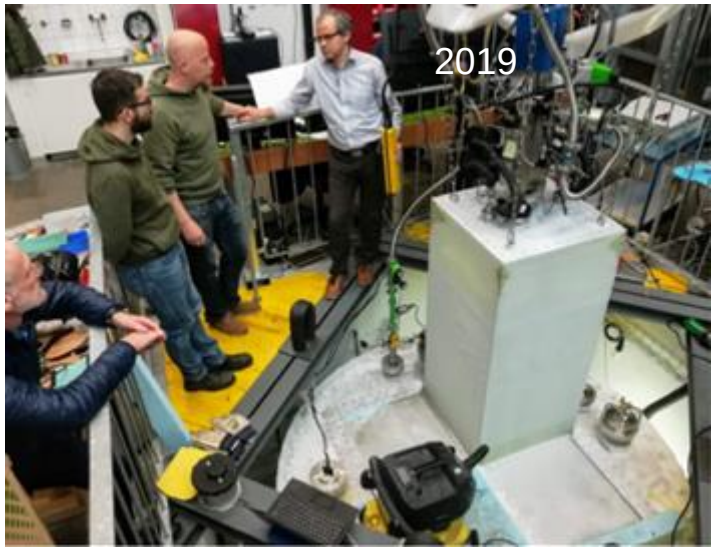
LBNF/DUNE

2x2, history

See also talk on prototyping by Igor Kreslo on the first day

- Idea born together with the “modular” LArTPC (ca. 2014)
  → a modular setup needs to be tested in cosmic rays or in a neutrino beam
- Preparations underway for the cryostat and modules in 2016—2018 in Bern
- 2019 first cryogenic operations in Bern





- As the ArgonCube technology was chosen as core component of the DUNE ND
  a **dedicated effort was planned to operate the 2x2 in the NuMI beam in 2018**

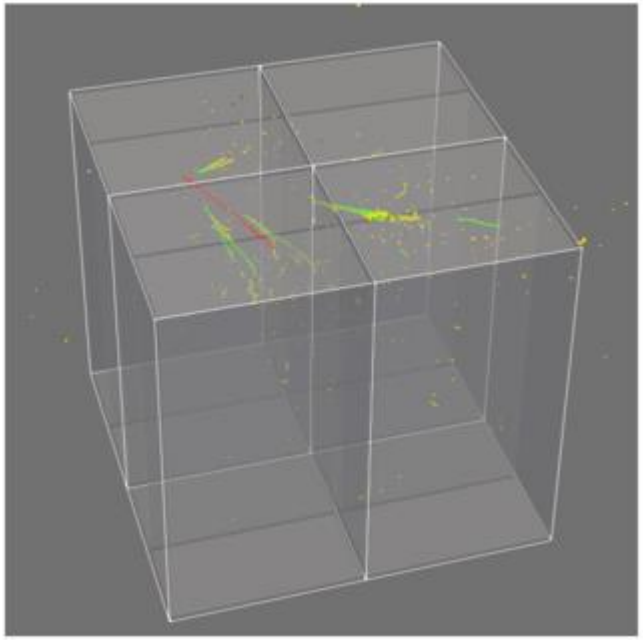
  → Agreements with FNAL/DoE, LoI, proposals, funding (starting 2019; Bern and FNAL)

2x2 scope

- Complete a first “Module-0” for tests to informs the Preliminary Design Review PDR, **done**
- Build, transport and test 4 modules total, assemble, integrate at Fermilab, ongoing
- Combine with re-used MINERvA planes as tracker, ready
- Operate at Fermilab in the NuMI neutrino beam, aim at Nov/Dec 2022

→ “ProtoDUNE-ND”, at Fermilab (final site), with neutrinos

- The 2x2 will develop and demonstrate the reconstruction of neutrino interactions with the chosen technology.
  Using a detector with 70% size in drift and lateral dimensions
- The 2x2 will demonstrate the capability to extract physics results



(b) $E_\nu = 3.36$ GeV

2x2 link to requirements

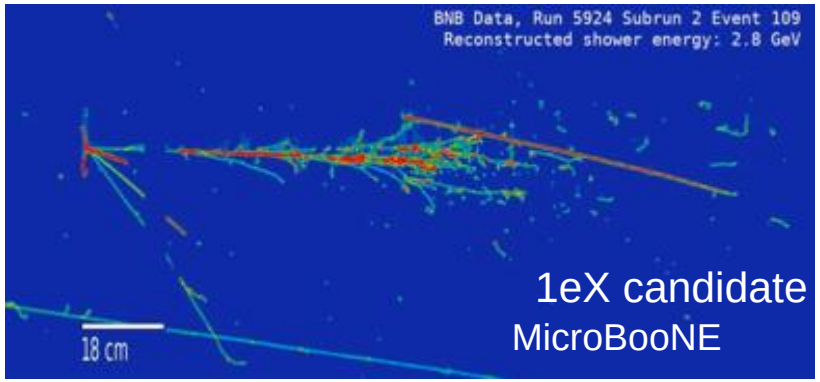
- Related to key requirements:
  - SYS-003: pileup/association of energy deposition to neutrino vertex
  - SYS-004: 3D charge imaging accuracy
  - SYS-005: charge-light matching

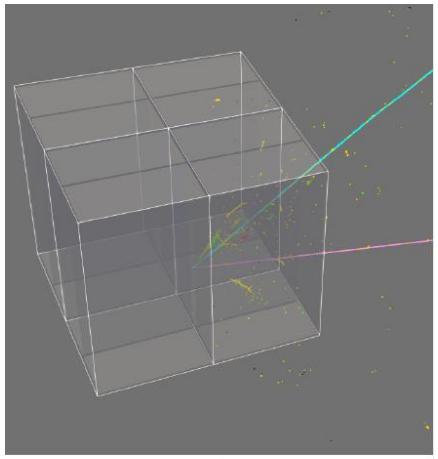
While the requirement will be fulfilled through simulation in actual ND-LAr, since it has to be done with the actual detector design and size,
the 2x2 is needed to informs this simulation

- The 2x2 will inform us on construction, assembly, transport, Q&A, installation and operation (all subsystems involved); and internal interfaces
- The 2x2 will inform a number of technical requirements (see other talks), but the FSD will be main mean for that (needs to be full-size)

Neutrino interaction reconstruction

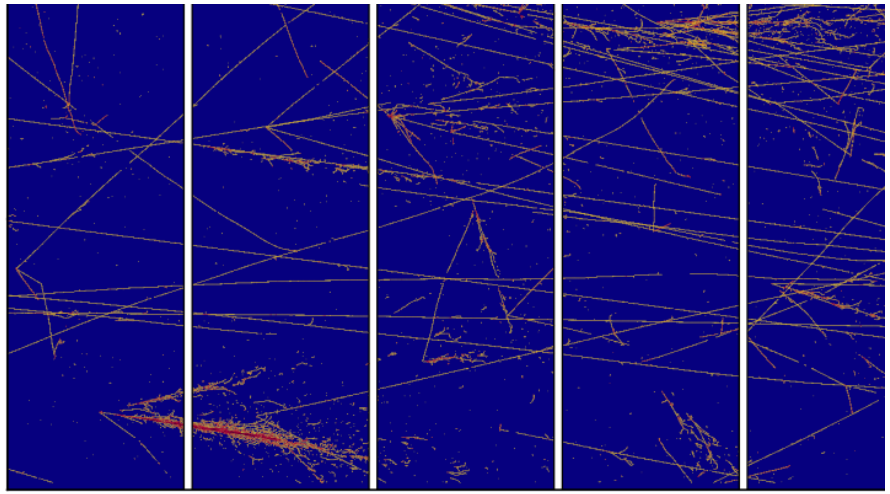
- It will be crucial to use neutrino interactions to demonstrate the physics performance
  - Topology
  - Matching between modules
  - Neutrino energy determination
  - Separation in final states
  - Final state particle ID
  - Busy environment @ ND




(d) $E_\nu = 9.37$ GeV

2x2

- Related to overall ND requirements
  - Translate flux to FD
- Systematics dominated regime

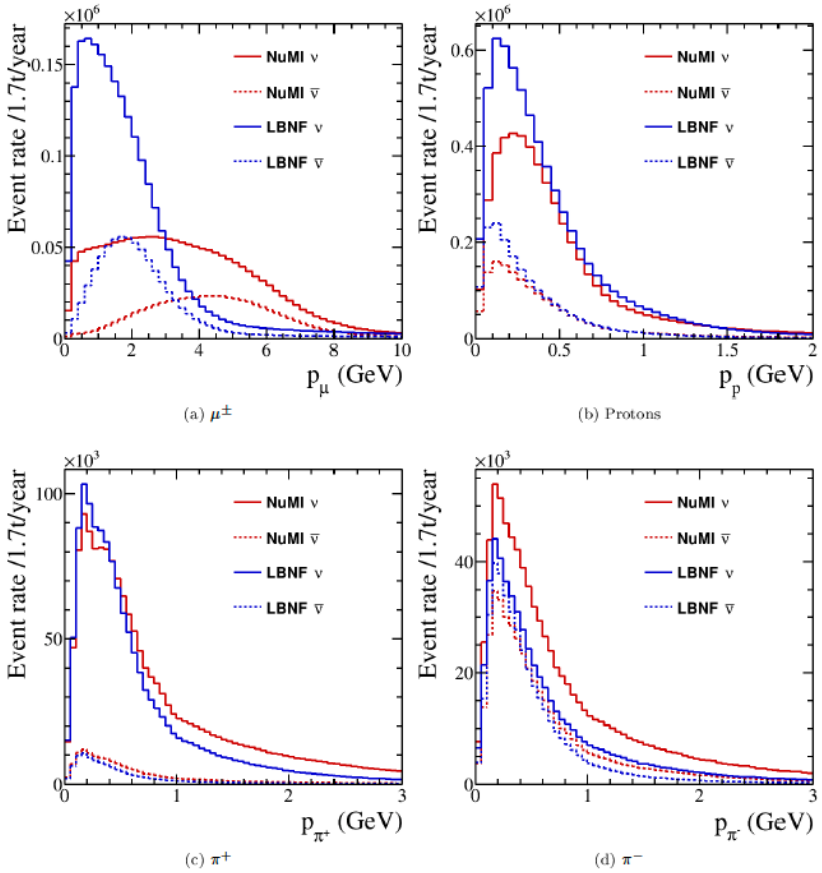


ND-LAr

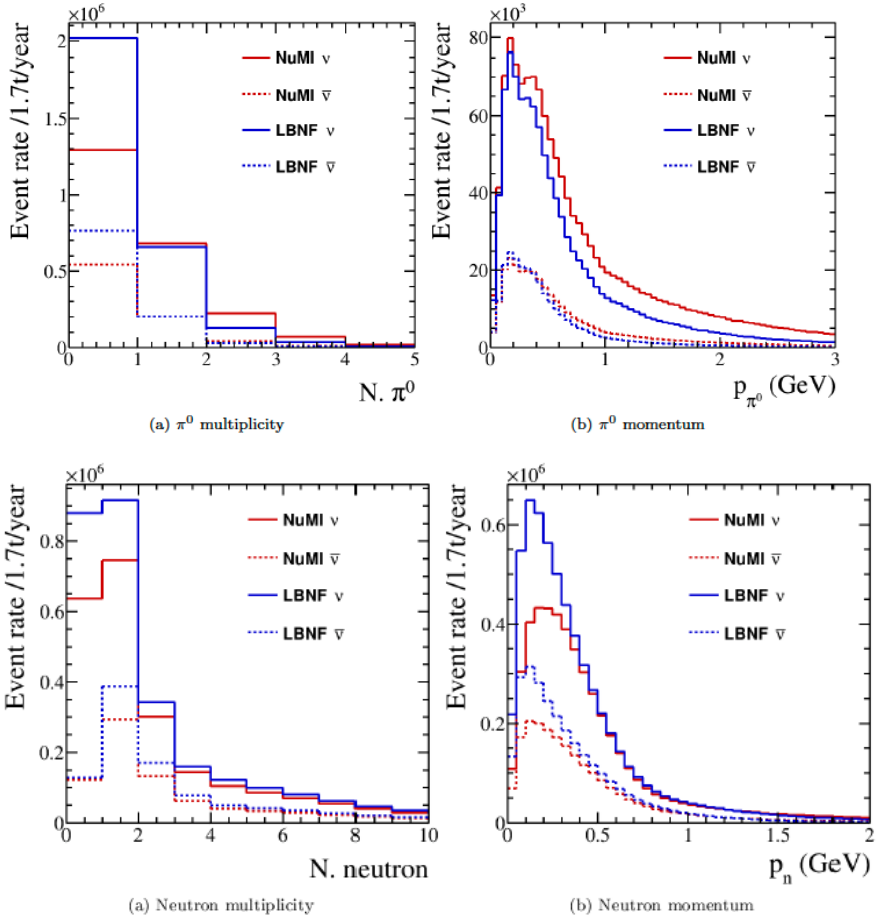
LBNF/DUNE

Expected neutrino event rates and reconstruction demonstration

- Overall ~130k CC interactions/year expected within the fiducial mass (0.5 t) and 5.6E20 POT (Plots below with full mass and higher POT)
- Plan is to iterate over data/MC comparisons with improving reco/sim as soon as data taking starts

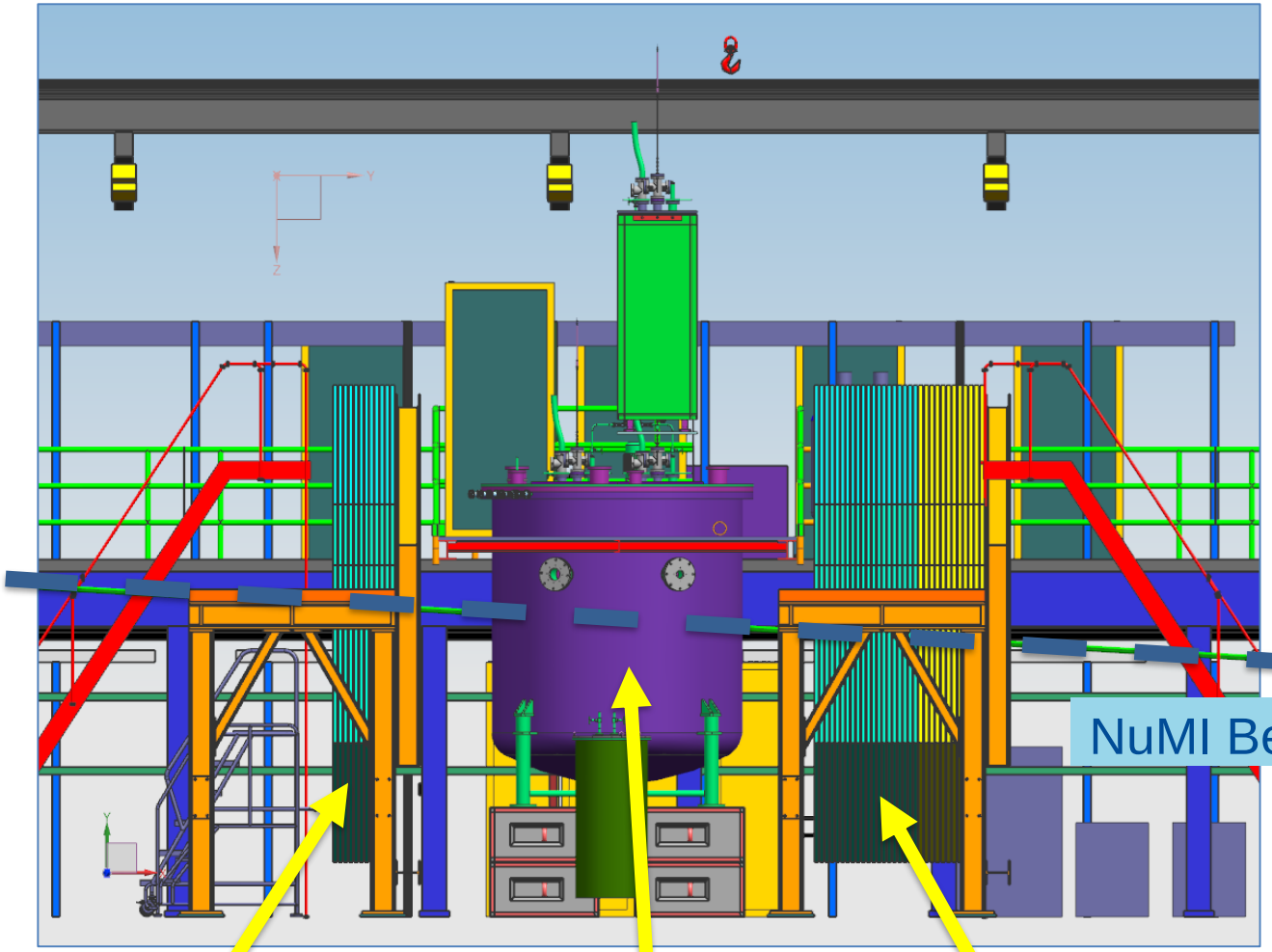


(a) $\mu^{\pm}$ (b) Protons (c) π^{+} (d) π^{-}

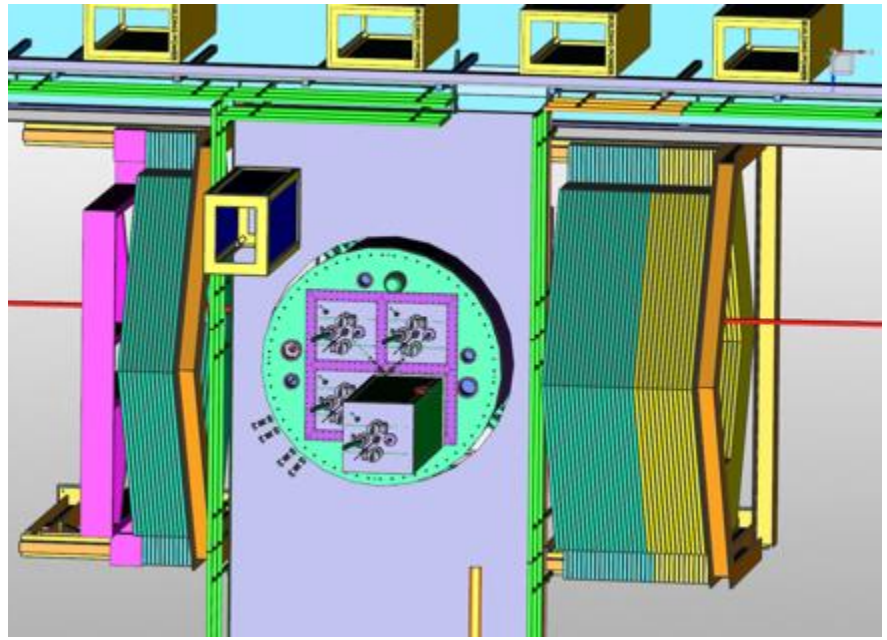


(a) π^0 multiplicity (b) π^0 momentum (a) Neutron multiplicity (b) Neutron momentum

Setup at NuMI



NuMI Beamline



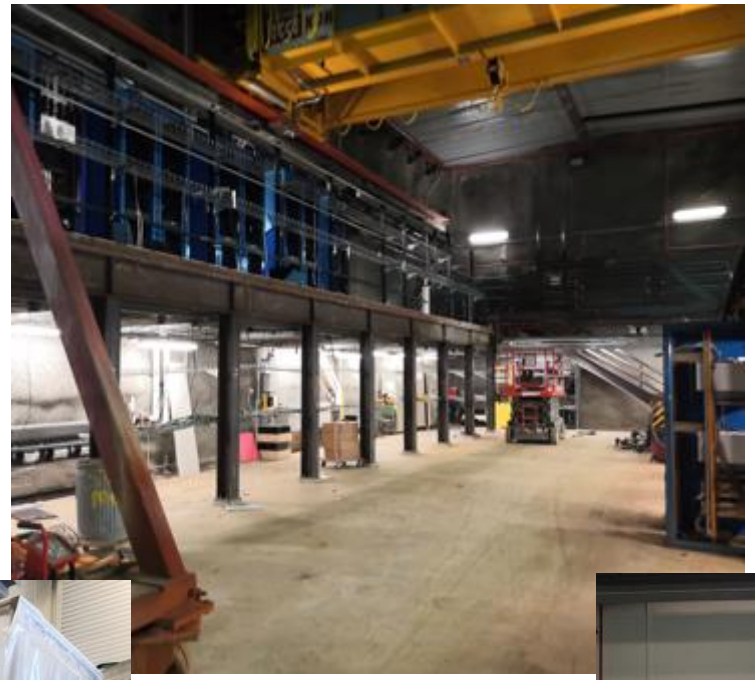
12 MINERvA Modules

2x2 Cryostat and 4 TPCs

32 MINERvA Modules

Cryostat at FNAL
in July 2021

Module-0 at FNAL
Sept 2021



Underground
cleared Fall 2021

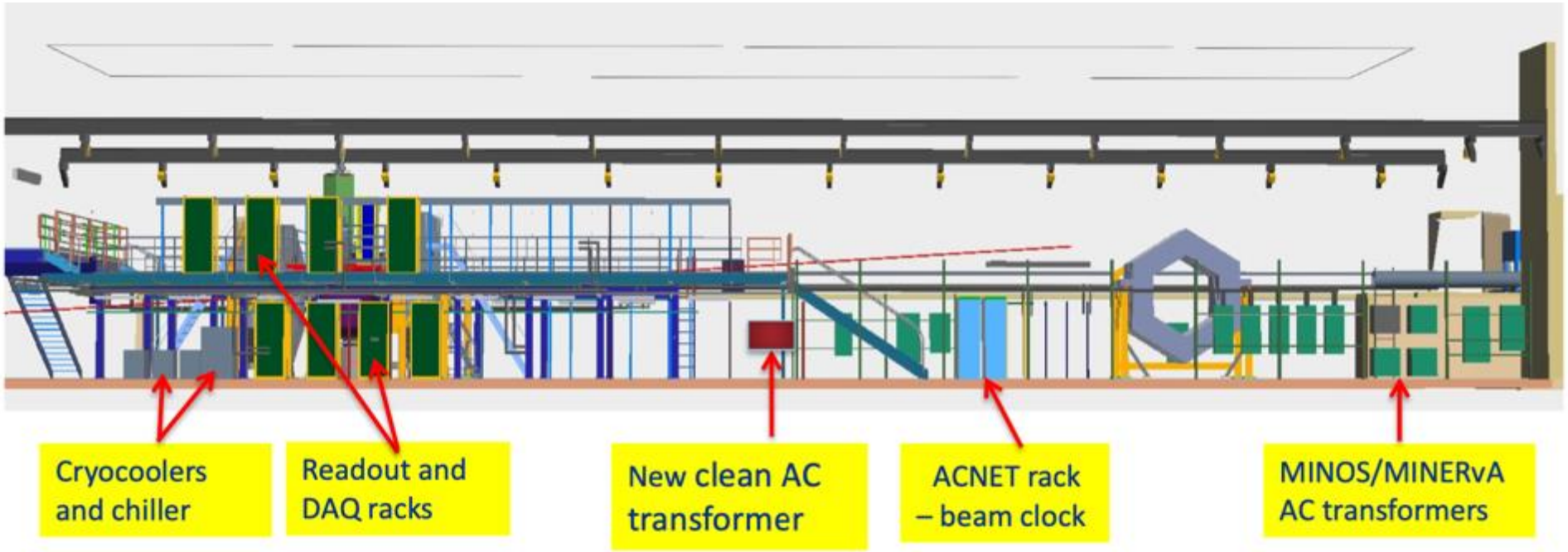
PLC for cryo
at FNAL
Sept 2021

Module-1 at FNAL
June 2022

LBNF/DUNE

2x2 infrastructure and underground area status

- MINOS ND area cleared, MINERVA re-installation ongoing
- Recirculation and filtering of LAr provided through external contractor. Cryocoolers used and delivered by FNAL. Delivery in October/November.
- Power (clean AC), network, venting, ODH (plan for ODH-0)
- Platform for holding cryostat
- Racks, readout electronics, slow control tested at surface,
  in parallel final setup designed and then reviewed



Excerpt from risk registry (which ND-LAr risks the 2x2 is relevant for)

Summary on the next slide

40		Entered	ChRO-023	RT-131-ND-123	Open	Noise pickup	IF noise pickup from other subsystems or detector external environment degrades performance, THEN we will need to engineer additional filtering and shielding options	Test of fully integrated system at full scale demonstrator.	
208		Entered	MATF-030	RT-131-ND-152	Hold	Insufficient FNAL Technical Support	IF FNAL technical support is not available to meet our resouce plan, THEN cost and schedule will be impacted	Identify technical resources early. Obtain in-kind labor commitments.	11/10/20: Lowered percentage based on conversation regarding with Steve Brice for tech avail
42		Entered	ChRO-025	RT-131-ND-122		Full-tile Triggering Instability	IF tiles do not have a stable trigger THEN data quality will be adversly impacted	Existing prototyping and testing plan to diagnose and resolve issue	Issue found in Module 0 testing, beginning studies to identify issue and correct 6/2022: Benchtop demonstrations indicates this effect has been resolved; retire risk when resolution demonstrated in integrated system
43		Entered	ChRO-026	RT-131-ND-124		ESD related failure/damage at vendor	IF ASICS are sensitive to ESD damage during assembly/integration THEN ASIC redesign is required	Test ESD performance of the ASIC to ascertain ESD sensitivity, work with vendors, collaborators to implement a robust ESD safety awareness program	06/10/21: Not currently an issue, but more statistics will help shed light
							If module testing timescale at MATF		

Risks in the risk registry informed by the 2x2

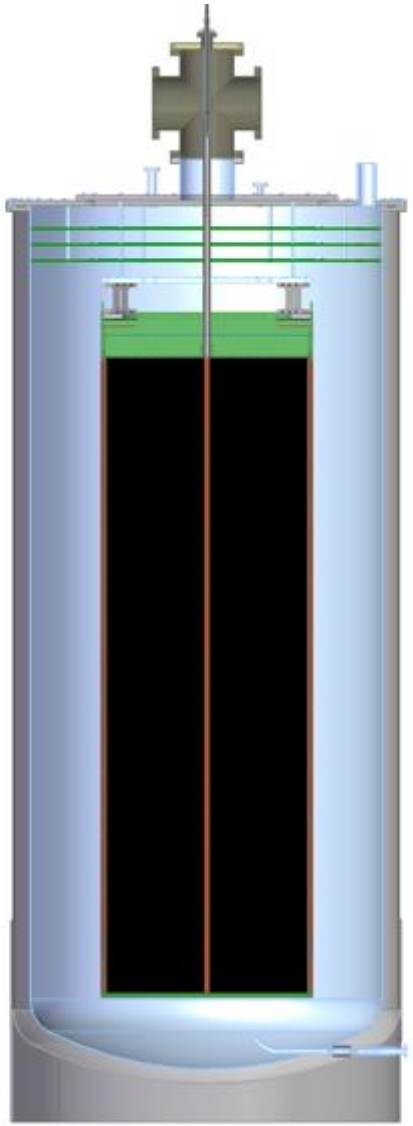
- **Risks related to performance with neutrino interaction on all subsystems, especially charge and light (resolution, efficiency) will be addressed**

In general, 2x2 is a reco/physics demonstrator and only indirectly informs technical risks

- Charge and light signal matching
- Purity concerns for material, purity uniformity
- QC (it's only 4 modules, but the 2x2 will inform about procedures, e.g. cold-testing or not)
- Personnel to assemble, integrate and operate, FNAL technical support
- System noise, grounding scheme
- Argon boiling with neighbouring modules (although cryo/cooling not identical), interaction between subsystems
- Slow control, DAQ, data rates
- Multi-months operation, design limitations for operation at FNAL (MATF risks)
- "Incident tolerance" (leaks, discharges, handling, module failure…)

Full Size Demonstrator

Involves also
new investments
in facilities



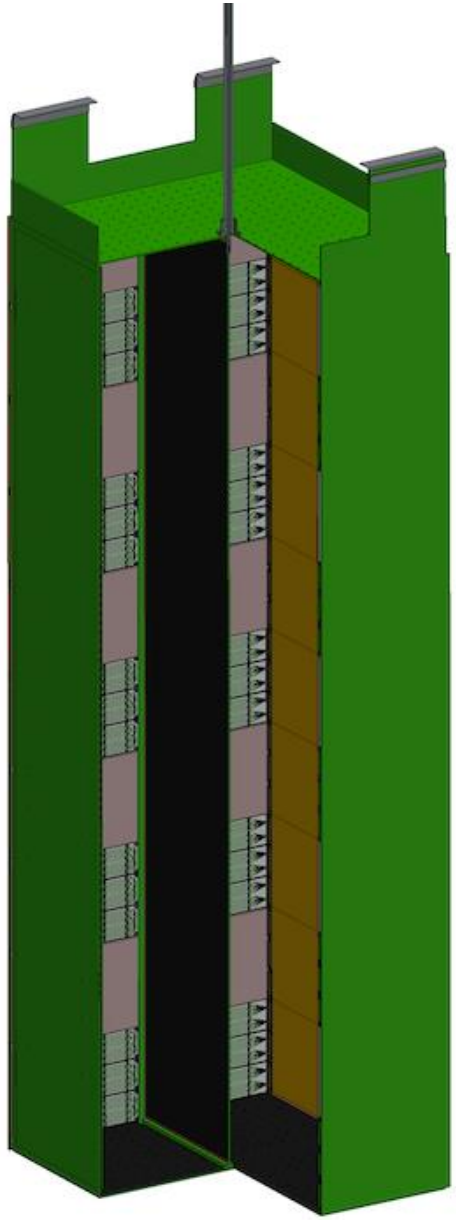
Mission Need

- Operate complete, full-sized ND-LAr module (1x1x3m^3)
  - **Validate 1:1 size design and procedures**
- Validate QA/QC for all subcomponents
- Exercise all procedures for MATF
- Build up expertise for ND installation, testing and operation

- The successful construction, deployment, and operation of a full-size module is an essential element of achieving TRL7 DOE: Technical Readiness Assessment Guide:
  - ***TRL7: Full-scale similar system validation in relevant environment***

Scaling to “full-size” (from 2x2)

	2x2	Full Size
Charge tile or light module size	30 cm x 30 cm	30 cm x 50 cm
Channels (asics) per charge tile	6400 (100)	10240 (160)
Number of charge tiles or light mod. per module	2 drift regions x 2 lateral x 4 in height	2 drift regions x 2 lateral x 10 in height
SiPMs per LCM/ArcLight	6	6
Module dimension	70 cm x 70 cm x 120 cm	100 cm x 100 cm x 300 cm
Active mass per module	~600 kg	~4200 kg
HV	up to 50 kV (1.3 kV/cm)	up to 50 kV (1 kV/cm)



Full Size module
100cm x 100cm x 300cm

2x2 module
70cm x 70cm x 120cm

FSD and ND-LAr key requirements

- 23 of the DUNE ND LArTPC Key Requirements will be tested by the FSD
- E.g.

Label	Name	Description	Rationale	Design Validation	Verification Method
CRO-003	Pixel Time Resolution	The pixel timing resolution for spatial resolution in the drift direction and in the transverse directions shall be < 3 μs	The pixel timing resolution should provide equivalent spatial resolution in the drift direction as in the transverse directions.	Full Scale Demonstrator	Full Scale Demonstrator

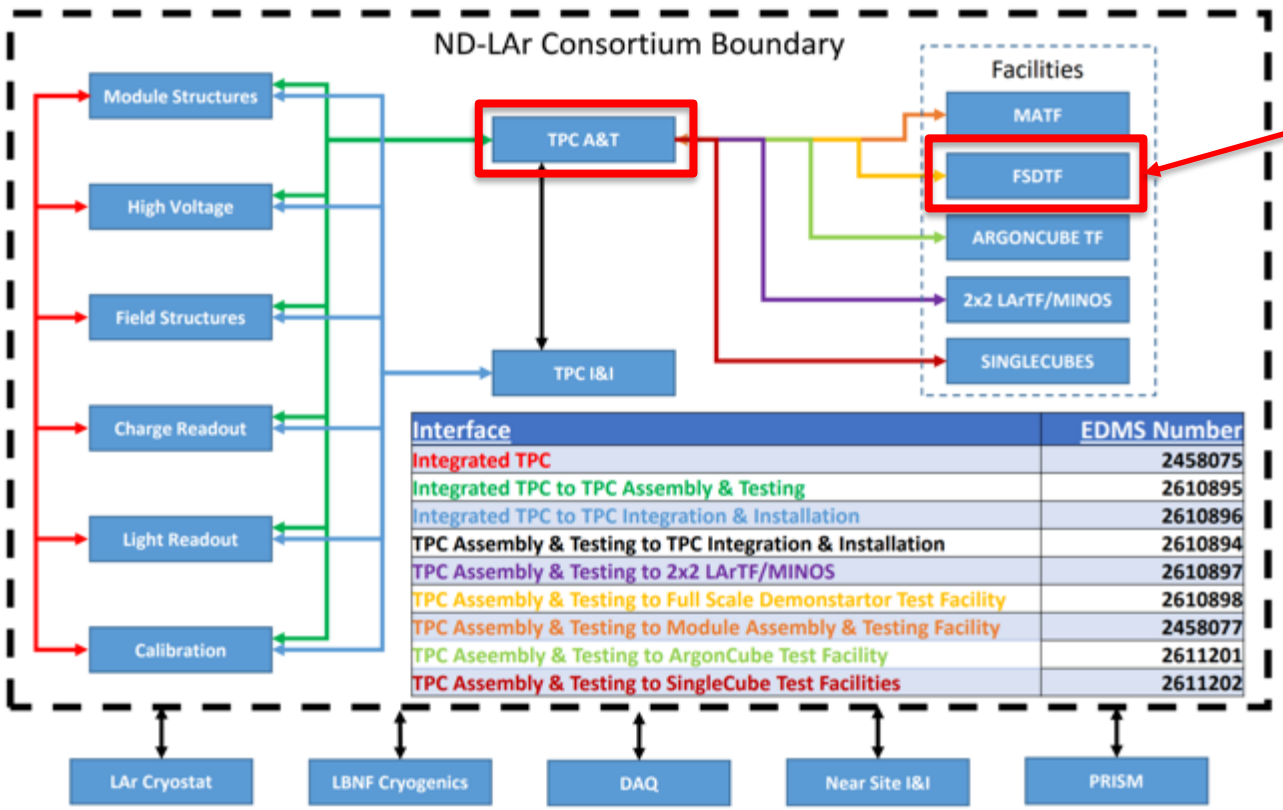
- SYS-009,10, 23 (E-Field strength, uniformity, calibration)
- MOD-008 (LAr flow rate)
- HV-001 to 5 (HV)
- FCG-001,3,10,12 (field shell uniformity, strength, impurities)
- CRO-003,4,8,11 (pixel sampling, noise, active/performant channels)
- LRO-007 to 12 (timing, pileup, resolution, active/performant channels)

Requirements for an FSD facility

- A liquid argon purification system that can get 500 us e- lifetime in a system that can handle 220W electronic heat (+system heat loss) and big enough to handle the TPC
  - 1.9m x 4.3m dewar
  - 1.0-1.5kW cooling
  - 5-20 LPM pump
  - Cu + Mol. Sieve + particulate filter stacks
- 6-month testing period with 3 refills of liquid argon with fill, purification and emptying times ~ several days
- Clean power, ground and infrastructure for readout
- Adequate assembly & handling infrastructure: clean room, office & floor space, crane w/ hook height

- DUNE ND LArTPC Technical Specifications: FSD Requirements
- FSD Cryogenics Requirements EDMS 2603461

Interfaces



Interface	EDMS Number
Integrated TPC	2458075
Integrated TPC to TPC Assembly & Testing	2610895
Integrated TPC to TPC Integration & Installation	2610896
TPC Assembly & Testing to TPC Integration & Installation	2610894
TPC Assembly & Testing to 2x2 LArTF/MINOS	2610897
TPC Assembly & Testing to Full Scale Demonstartor Test Facility	2610898
TPC Assembly & Testing to Module Assembly & Testing Facility	2458077
TPC Aseembly & Testing to ArgonCube Test Facility	2611201
TPC Assembly & Testing to SingleCube Test Facilities	2611202

Interface Control Document List: ND-LAr External	EDMS #
— ND-LAr Detector to LBNF Cryogenics	2458074
— ND-LAr Dectector to DAQ	2458098
— ND-LAr TPC to LAr Cryostat	2458099
— ND-LAr TPC to Near Site I&I	2450639
— ND-LAr Detector to PRISM	2458097

Formally, interface is between FSD & A&T

TPC ASSEMBLY AND TESTING TO FULL-SCALE DEMONSTRATOR TEST FACILITY INTERFACE CONTROL DOCUMENT (in draft)	DU-1004-4487

Physical Interface to removable “physics” lid holding TPC and readout provided by A&T

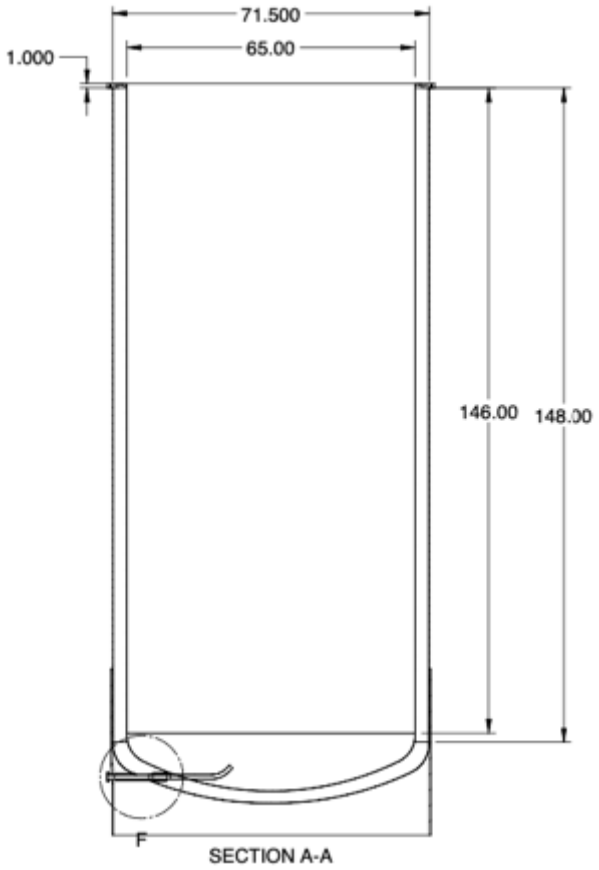
A&T provides fixtures/people for A&T assembly & test as shown yesterday

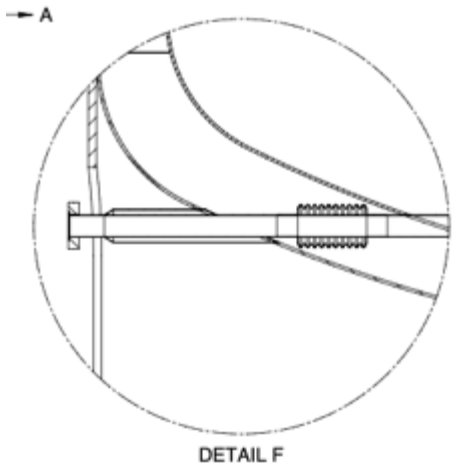
TPC System Managers have not yet begun to specify in detail what they they will bring to FSD, what they require from FSD

- Rack needs, networking, DAQ, …

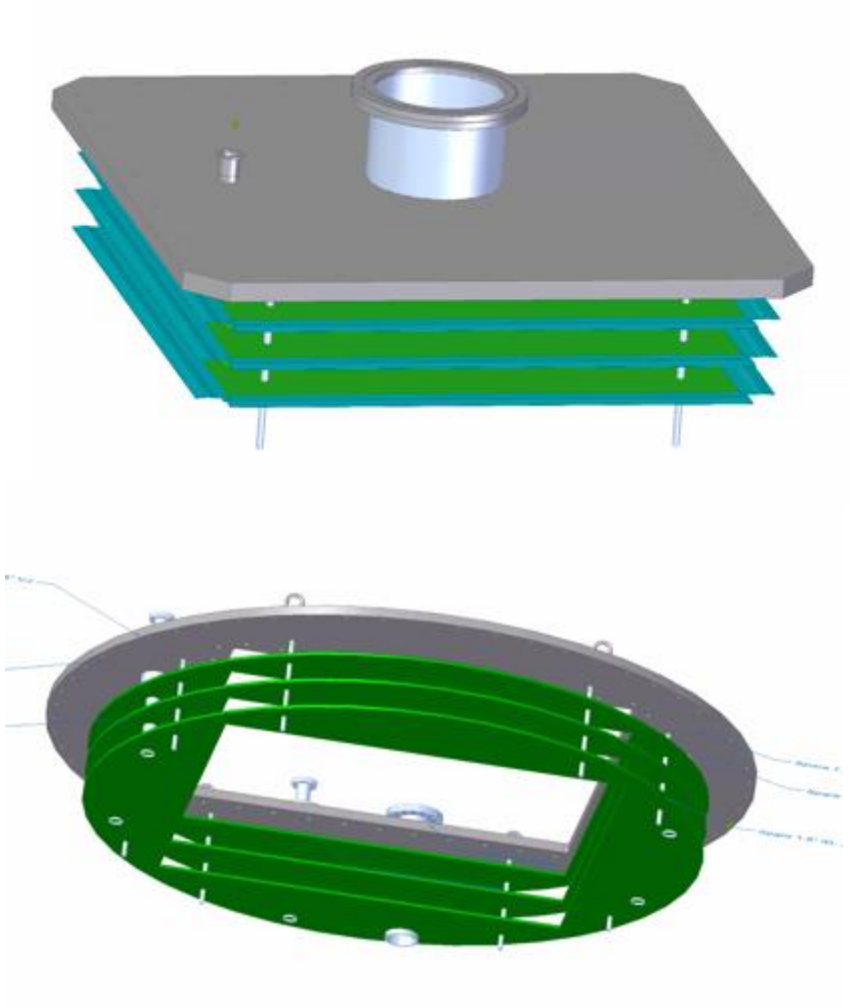
Current FSD TPC-Readout Interface design based on Bern and 2x2 experiences

Devices: Dewar with Drain and Lids





FSD needs dedicated dewars
(dimensions)



FSD needs dedicated top dewar
and top module flanges
(single and not in a row)

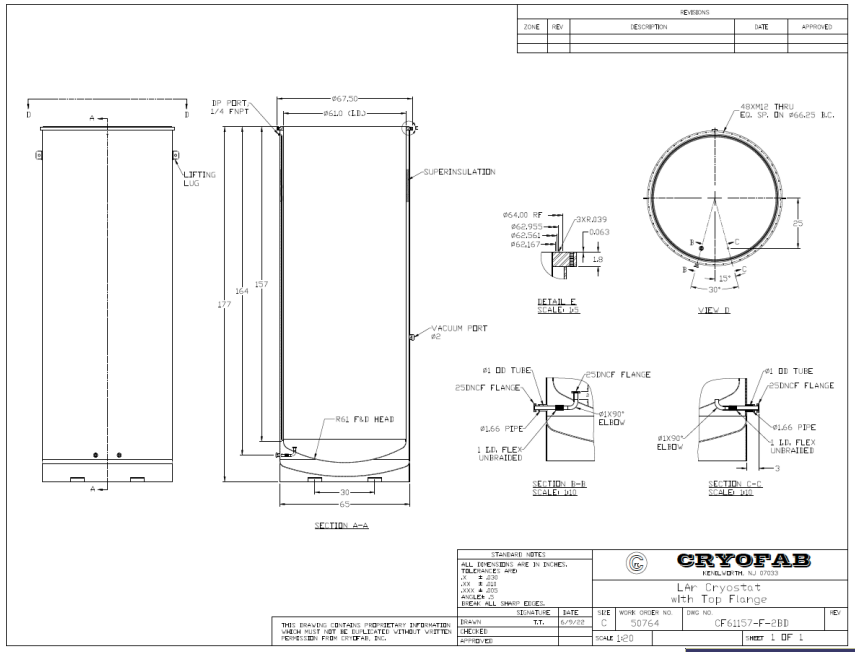
Full size tests in Bern

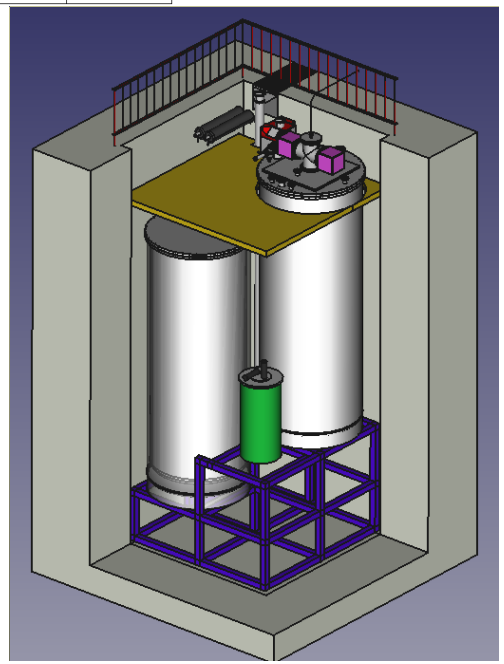
- Order for two cryostats placed in April 2022
- Delivery expected Feb 2023

- Both fit in the pit in the main cryo lab in Bern
- Re-use cryogenic setup from R&D and 2x2
- Re-use slow control, readout
- One cryostat used for a module, one as LAr dewar

Main goal: 1 successful FSD run

Then can serve as production facility or equipment reused for QC



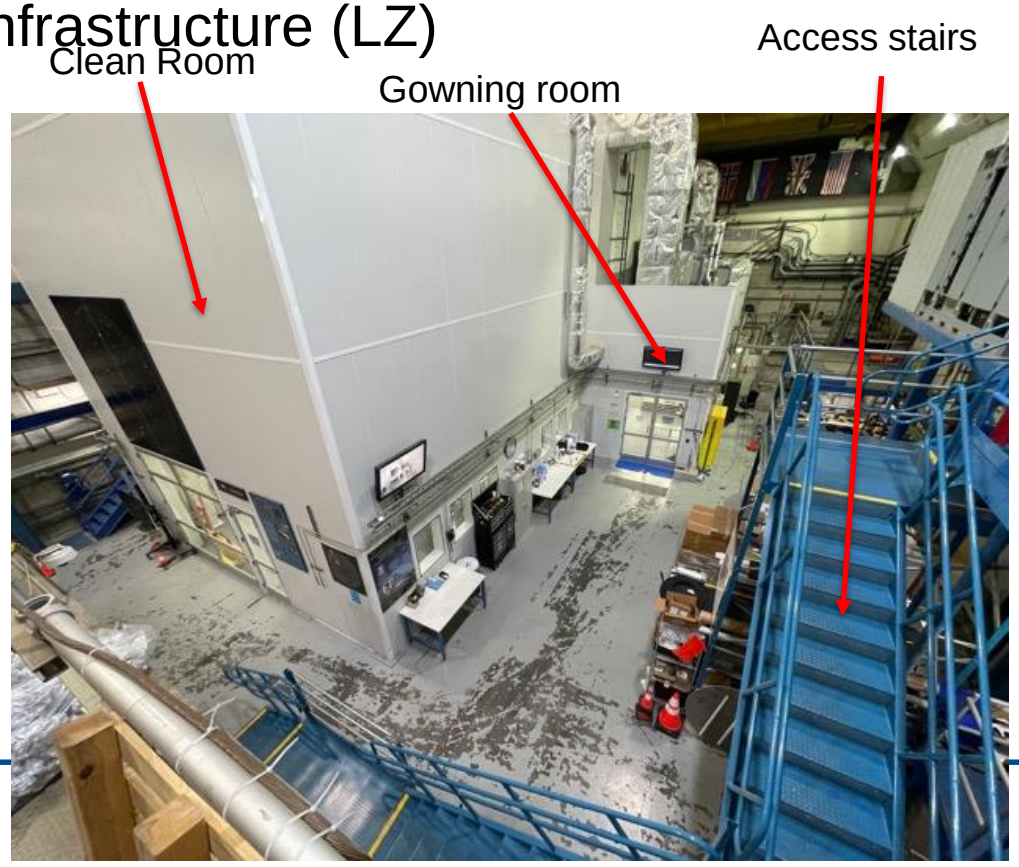


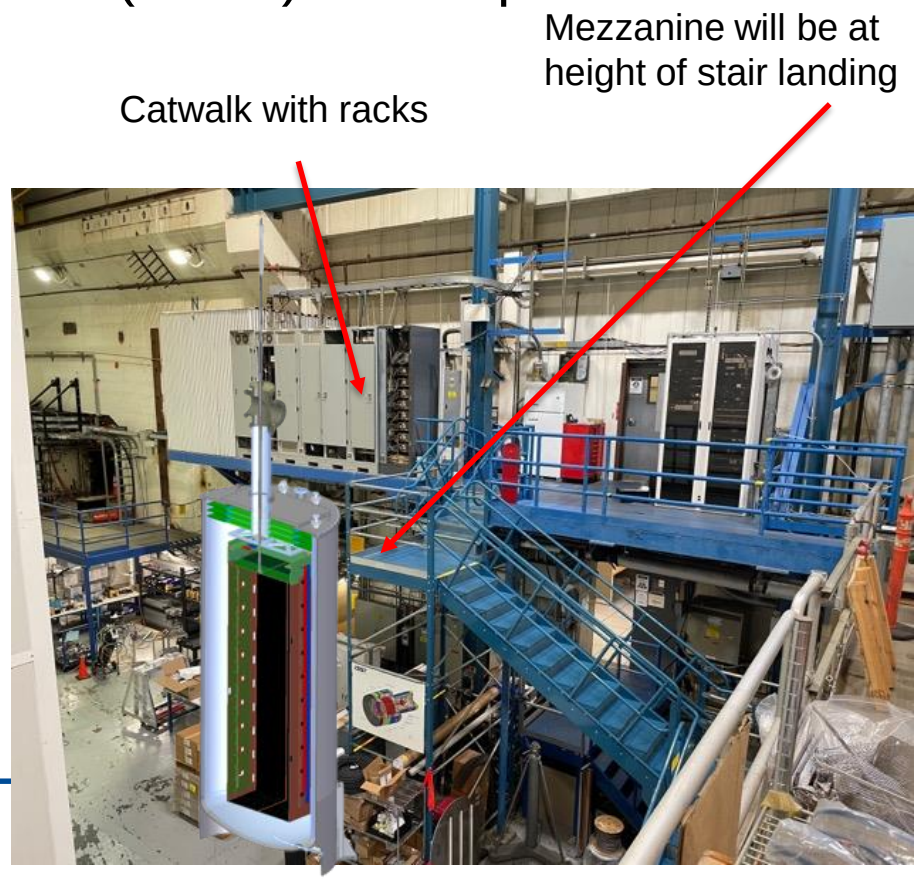
Full size tests at SLAC

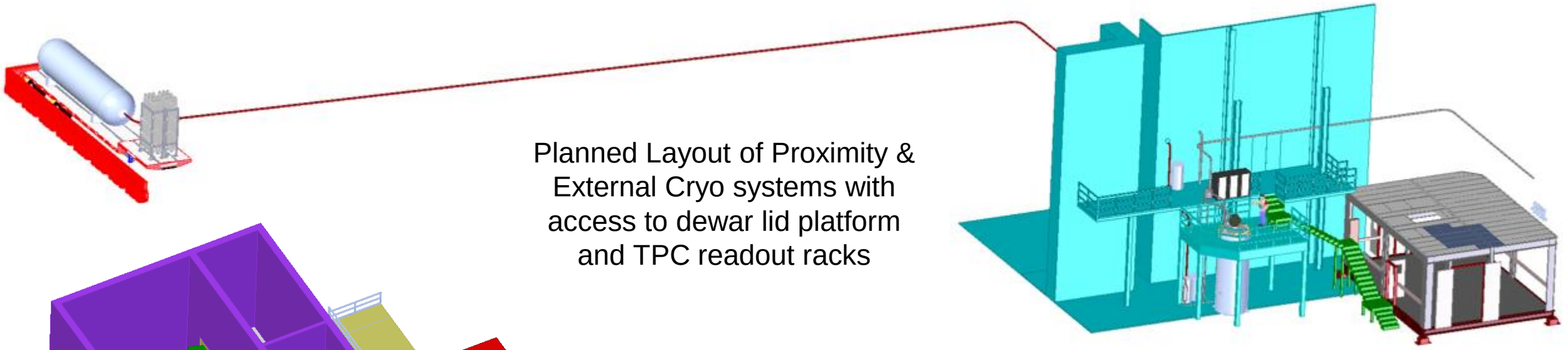
- Extended FSD runs, study long-term operation
- Build up expertise on 1:1 module operation in USA
- Implement DAQ, slow control as DUNE-ND tools are developed

Funding not secured

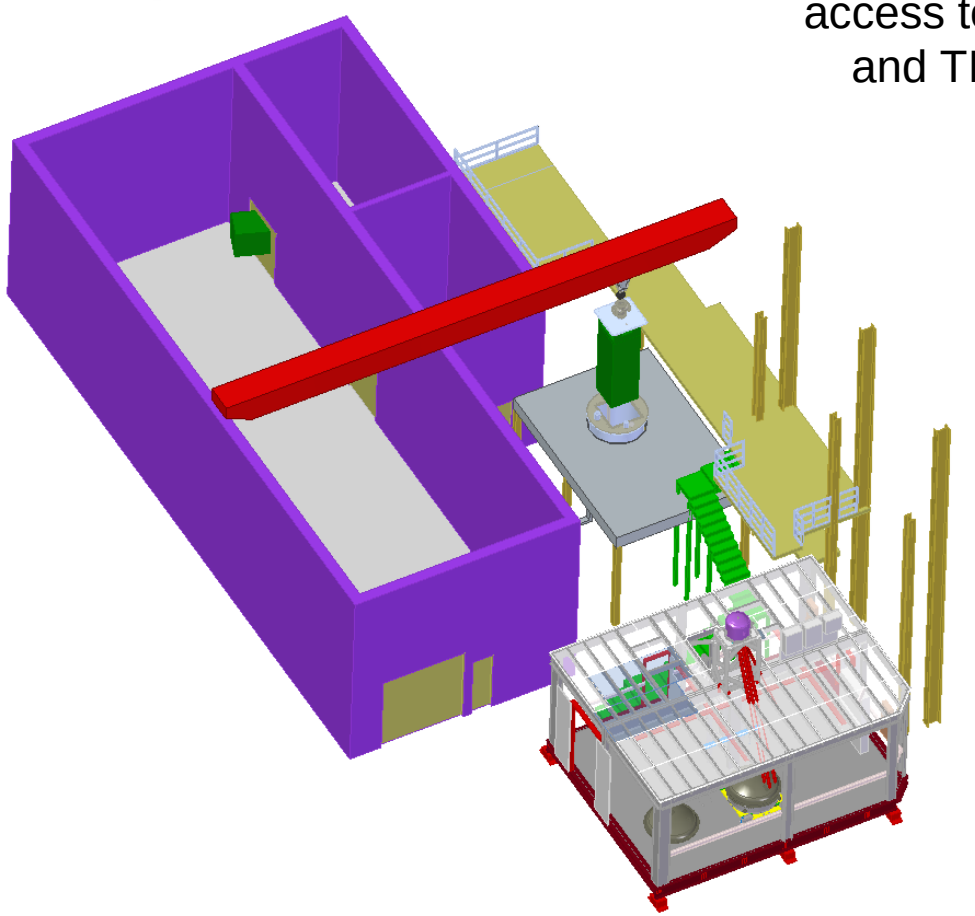
Location: IR2 High Bay with 50/10T Crane, Large Clean Room (LSST) and Liquid Nitrogen Infrastructure (LZ)

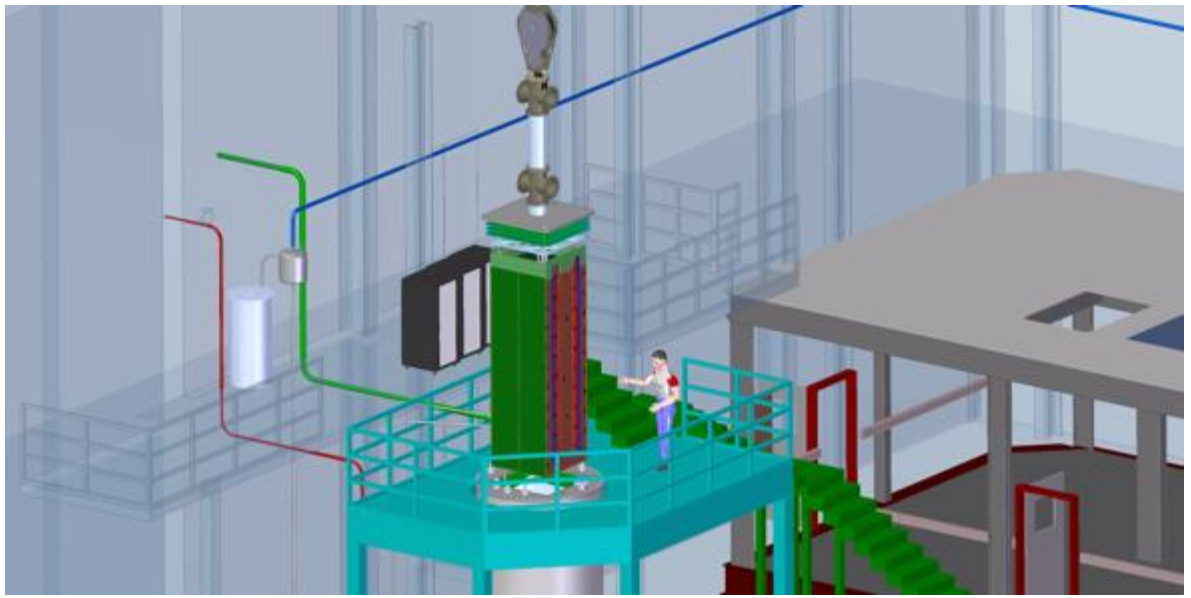






Planned Layout of Proximity & External Cryo systems with access to dewar lid platform and TPC readout racks





FSD Documentation Register

Document	Doc Type	Format	Status	Maturity (1-5)	Doc#	EDMS	Notes	Author
Full Scale Demonstrator Facility Requirements	Management	Text	Draft	3	DU-1004-4743	EDMS 2612989	Requirement Table Copied via Script from DUNE ND LArTPC Technical Specifications	Tom Markiewicz
DUNE ND LArTPC Technical Specifications	Management	Spreadsheet			URL		Tab 11 is FSD	
FSD Cryogenics Requirements	Technical	Text	Draft	3		EDMS 2603461		Marco Oriunno
TPC ASSEMBLY AND TESTING TO FULL-SCALE DEMONSTRATOR TEST FACILITY INTERFACE CONTROL DOCUMENT	Management	Text	Draft	3	DU-1004-4487	EDMS 2610898	Subsystem Interfaces not yet specified; Version 5/25/22 uploaded to EDMS	twmark, arlambert, mrmooney
SLAC FSD Manufacturing, Procurement and QA/QC Plan	Management	Text	Draft	1	?	EDMS 2745431	Placeholder file sent to arlambert 9/3/2021; uses FSD Basis of Estimate worksheet	Tom Markiewicz
02.11: Full-scale Demonstrator Test Facility @ SLAC: Scope/MOU Details	Management	Spreadsheet	Draft		URL		On Dwyer Google Drive	Dwyer, Kurita, Tanaka
DUNE ND LArTPC Risks	Management	Spreadsheet	Draft	2	URL		See FSD Tab	twmark, kurita, dwyer
FSD Basis of Estimate Worksheet	Management	Spreadsheet	Draft	1	URL	EDMS 2745432	Google Drive: DUNE-SLAC>2.0 Near Detector Full Scale Demonstrator	Kurita, twmark
Pressure Relief Device Analysis for the DUNE FSD Argon Plant	Technical	Text	Draft	4	URL	EDMS 2745429	Google Drive: DUNE-SLAC>3.0 Full Scale Demonstrator>Documents	Marco Oriunno
FSD ODH Assessment	Technical	Text	Draft	3	URL	EDMS 2745430	Google Drive: DUNE-SLAC>3.0 Full Scale Demonstrator>Safety Reviews>ODH>ODH Reports	Tom Markiewicz, Marco Oriunno
FSD P & ID	Technical	pdf	Draft	4	URL	EDMS 2744577	Google Drive: DUNE-SLAC>3.0 Full Scale Demonstrator>P&ID (current version 4/27/22)	Marco Oriunno
FSD Dewar for Cost Quotation	Drawing	pdf	Final	5		EDMS 2745425	12/7/2021 version send to 5 manufactures 1/7/2022 for cost quotes	Marco Oriunno
FSD Annular Lid	Drawing	pdf	Draft	4		EDMS 2745426	5/22/22	Marco Oriunno
FSD Square Physics Lid	Drawing	pdf	Draft	4		EDMS 2745427	5/22/22	Marco Oriunno
FSD Dewar with Covers and TPC	3DCAD	STP	Draft	4		EDMS 2746961	4/7/22	Marco Oriunno
IR2 Layout	3DCAD	STP	Draft	2		EDMS 2746962	8/2/21	Marco Oriunno

FSD facility at SLAC Risks

- Procurement delay (FSD-012, 50%, 4 mo., $50k)
- Supply Chain Cost Increases over BOE (FSD-016, 50%, 4mo., $200k)
- Clarification of interfaces to TPC electronics (FSD-005,007; 20%, 2 mo.+?; $20k+?)
- Extension of time period required for testing (FSD-013, 20%, 2 mo., $20k)
- Extra ODH ventilation requirements over those foreseen (FSD-003, 35%, 2mo., $50k)
- Argon purity from supplier (FSD-001, 25%, 2 mo., $30k)
- Cost difference of newly quoted price of secondary vessels (condenser, phase separators) based on a smaller system built by that same vendor (FSD-009, 20%, 3 mo., $40k)
- Late departure of LSST from IR2 cleanroom and general area (FSD-010, 5%, 2mo., $10k)

Documentation from DU-1004-9336_ND-LAR DOCUMENTATION DIRECTORY

FSDTF Documentation	Description	EDMS Link
FSDTF Folder	Top level folder for FSDTF documentation	https://edms.cern.ch/project/CERN-0000217535
Requirements	Spreadsheet with all ND-LAr requirements, see sheet "FSDTF (11)"	https://edms.cern.ch/document/2589287
Internal ICDs	Interface control documents (ICDs) internal to the ND-LAr Consortium	https://edms.cern.ch/project/CERN-0000223195
Analyses	Collection of analyses write-up: FEAs, bench testing, 2x2 prototype evaluations	https://edms.cern.ch/project/CERN-0000231276
QAQC Plan	Subsystem QAQC plan with focus on high-level QAQC test plans	https://edms.cern.ch/project/CERN-0000231277
Previous Review Tracking	Spreadsheet with previous review recommendations, see "FSDTF"	https://edms.cern.ch/document/2741842
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 (Facility)	STEP or Parasolid Export	https://edms.cern.ch/project/CERN-0000231278
Mechanical Assembly Drawings	Subsystem assembly drawing	https://edms.cern.ch/project/CERN-0000231274
Parts List	Subsystem parts list	https://edms.cern.ch/project/CERN-0000231279
P&ID Cryo System	Piping and Instrumentation Diagram for Cryogenics System	https://edms.cern.ch/document/2744577

Recommendation from previous reviews for 2x2 and FSD

Recommendations on the 2x2 and FSD:

Investigate if alternate pixel pads / field response:
field shaping studies performed, no evidence. New pixel pad for mod-2

Encourage team for timely discussions on mechanical and electrical compliance with FNAL for 2x2
done

Present general plans (beyond single-cube and more details on 2x2) for prototyping and the calibration of prototypes
done for plans, presented 2x2 here. 2x2 is crucial to demonstrate pile-up mitigation and end-to-end sim/reco
2x2 too advanced for retrofitting major calibrations, will be tested in the FSD

Consider creating hubs around 2x2 and FSD that could lead into construction
Built in Europe (Bern/looking into CERN), US-west-coast (Berkeley, SLAC)
FNAL (with 2x2), US-east-coast (Yale, Syracuse)
→ Hitting funding limitations for infrastructures to completely fulfill the recommendation (SLAC FSD)

Develop strategy for 2x2 analysis
See physics talk

Mention how 2x2 will inform installation planning
See I&I talk, 2x2 is a mini-replica of ND-LAr for assembly, installation, integration

2x2 and FSD should prepare lessons-learned for re-planning
Will do, have done so already from module construction and single-2x2-module testing

Recommendations on tests to be performed in the 2x2 and FSD:

- Consider testing impact of one module HV failure to others (2x2)
- Find a way to address risk of noise with module operated together (2x2)

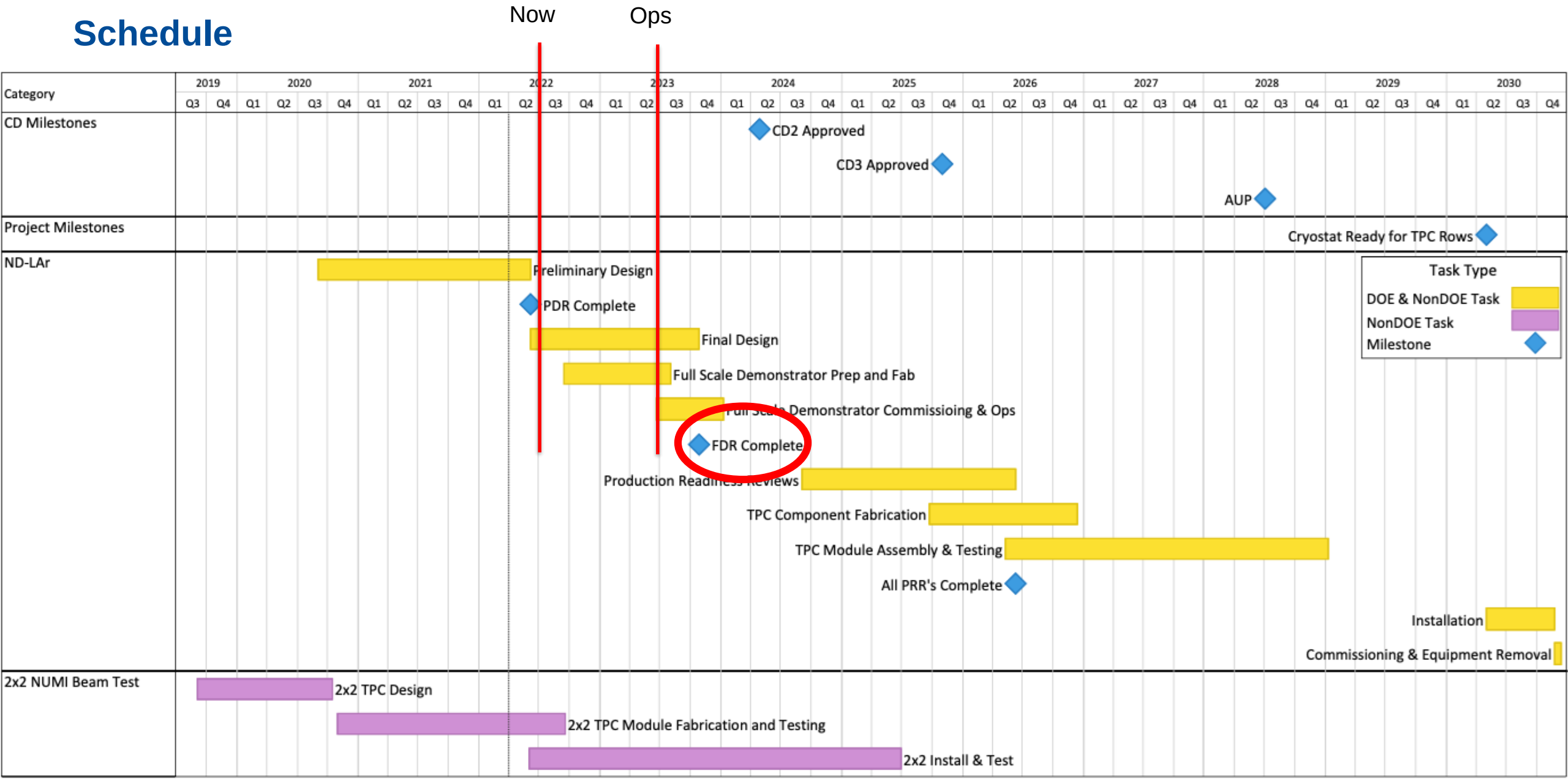
ND-LAr Total Resource by WBS

	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$]
01 ND LArTPC Management	$401.5	19.9	-	43.9	$412.5	17.1	-	72.5	**$10,114.9**
02 Module Structure	-	-	-	14.3	-	-	$2,448.0	22.0	-
03 HV	-	-	-	10.5	-	-	$816.0	14.0	-
04 Field Structure	$142.4	9.4	-	0.6	$3,600.8	4.9	-	6.5	**$7,642.6**
05 Charge Readout	$1,331.3	17.3	-	16.2	$3,366.0	5.9	-	21.3	**$10,741.6**
06 Light Readout	-	-	-	71.1	-	-	$5,508.0	15.1	-
07 Calibration	$193.7	1.3	-	30.6	-	-	-	22.4	**$414.0**
08 TPC Module Assembly and Testing	$247.3	7.1	-	8.6	$235.0	5.7	-	32.0	**$1,865.1**
09 TPC Integration and Installation	$584.2	11.4	-	12.4	$426.0	9.6	-	15.0	**$5,384.2**
10 Module Assembly & Test Facility	-	5.7	-	-	$1,483.0	10.8	-	27.3	**$4,114.0**
11 Full-scale Demonstrator Test Facility	$1,497.5	9.1	-	6.3					**$3,726.2**
12 ArgonCube Test Facility	-	-	$1,250.0	20.9					-
13 2x2 NUMI Test Beam Facility	-	-	$2,300.0	15.0				-	-
Total:	**$4,397.8**	**81.1**	$3,550.0	250.2	**$9,523.3**	**54.1**	$8,772.0	248.0	$44,002.5

Notes:

1. Extracted from current resource-loaded schedule (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.

Schedule

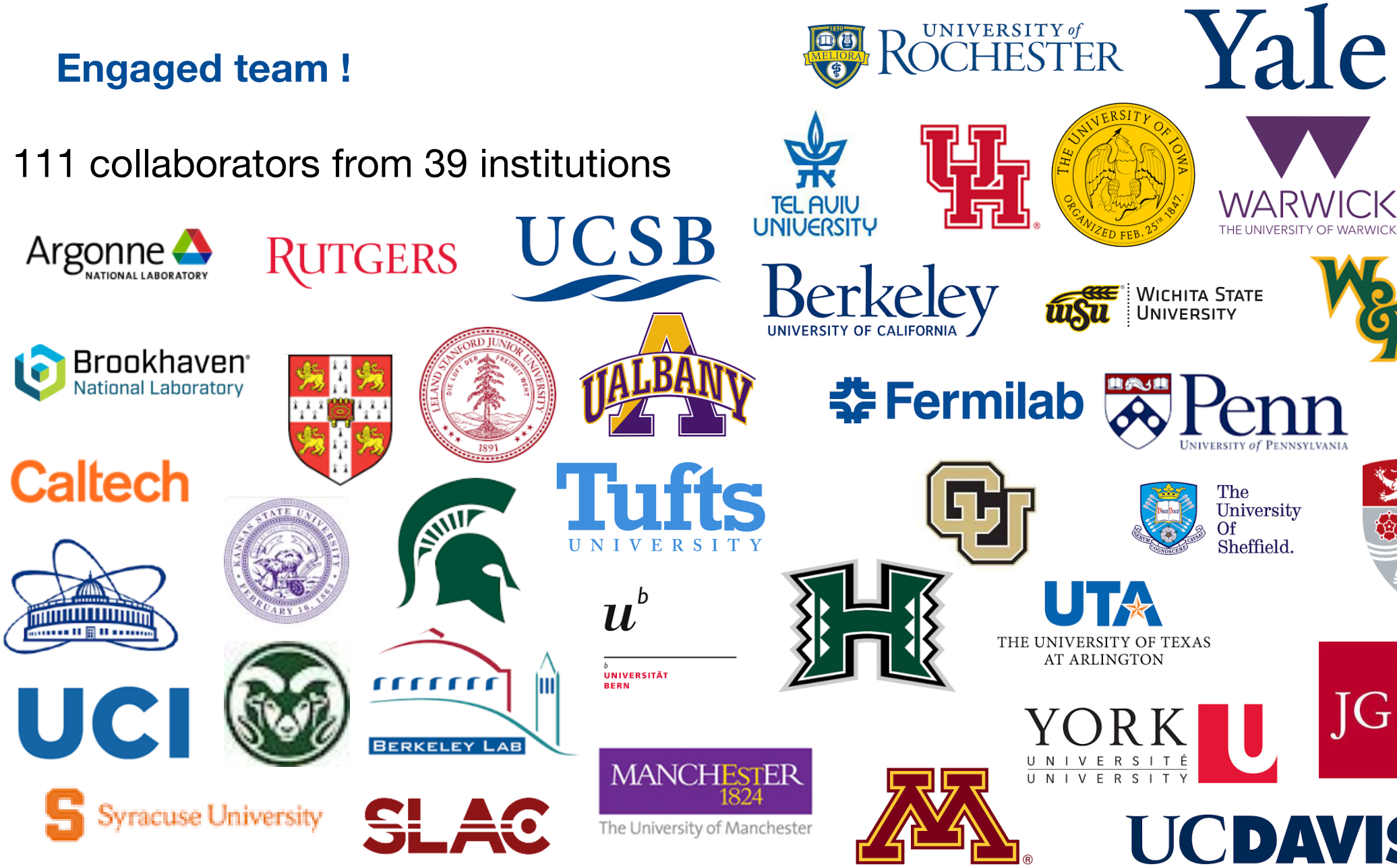

Now
Ops
Category
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
Q1 Q2 Q3 Q4
CD Milestones
CD2 Approved
CD3 Approved
AUP
Project Milestones
Cryostat Ready for TPC Rows
ND-LAr
Preliminary Design
PDR Complete
Final Design
Full Scale Demonstrator Prep and Fab
Full Scale Demonstrator Commissioing & Ops
FDR Complete
Production Readiness Reviews
TPC Component Fabrication
TPC Module Assembly & Testing
All PRR's Complete
Installation
Commissioning & Equipment Removal
Task Type
DOE & NonDOE Task
NonDOE Task
Milestone
2x2 NUMI Beam Test
2x2 TPC Design
2x2 TPC Module Fabrication and Testing
2x2 Install & Test

Summary

- Two major prototyping from PDR to FDR
  - Physics demonstrator (2x2)
  - 1:1 size technical demonstrator (FSD)
- Complete engineering and documentation
- 2x2 well underway
  - 2 out of 4 modules built and at FNAL
  - Expect operation to start in 2022
  - Push neutrino interaction measurements into DUNE realm
- FSD plans mature
  - Cryostats for Bern ordered, SLAC waiting for “go” on procurements (funding decision open)
  - Will also exercise site for MATF fixtures and procedures
  - Component procurement and production for a first module hopefully soon
- 2x2 and FSD address 25 key requirements of ND-LAr

Engaged team !

111 collaborators from 39 institutions



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.

BACKUP

M&S ONLY, USD = CHF	CH	JINR	*US DOE*	Prototyping and other in-kind
Module Structures	2.6			1.0
HV	1.0			0.5
Field Structures			*3.6*	1.2
Charge Readout			*3.4*	4.3
Light Readout	2.1	3.4		1.5
Calibration	0.5			0.2
TPC Assembly & Testing			*0.1*	0.4
TPC Installation & Integration			*0.4*	0.6
Module Assembly & Test Facility			*1.5*	
Full-scale Demonstrator Test Faci	1.0			1.5
2x2 Neutrino Test Facility				2.3
ArgonCube Test Facility @ Bern				2.0
ND-LAr TPC	**7.2**	**3.4**	***9.0***	**15.5**

Scope SLAC FSD

- Cryogenics (ND.11.2.)
  1. 7000 to 8000-liter TPC Test Dewar w/
     - Permanent annular lid with required ports
     - Interface to removable “physics” lid holding TPC and readout (A&T Scope)
  2. Installed Proximity Purification Cryogenics w/
     - Filters
     - Cryo Pump
     - LN2 based Argon Condenser
     - N2 and Argon Phase separators
     - Vacuum jacketed lines, valves, etc.
  3. Instrumentation
     - flow, temperature, pressure, O2, H2O
  4. Cryo Control and monitoring
- Facility (ND.11.3)
  - 3000-gallon rented Liquid Argon trailer and existing 9000-gallon Liquid N2 Supply plumbed to proximity system
  - Safety systems: ODH, Ventilation, PRV, ..
  - Crane w/ adequate load and hook height
  - New Mezzanine with Access to Dewar Lid
  - A/C Power to cryogenic systems
- Support of TPC, Readout and Testing (ND.11.5)
  - Cleanroom for TPC assembly & testing
  - Cryo support for test operations
  - Sufficient rack space / floor area for TPC readout & DAQ
  - Clean A/C for TPC power supplies and readout racks
  - Consumables (Ar, N2, …)
- Engineering
  - Cryo System design (ND.11.1)
  - Cryo Commissioning (ND.11.4)
  - Cryo Operations support during TPC testing (ND.11.5)

Procurement: Vendor Discussions, Budgetary Estimates, Hard Quotes,…

8000-liter dewar: Ability, Cryofab, Meyer

Dewar Lids: As above, plus NorCal, etc.

Cryogenic Pump: Barber-Nichols

Condenser: Eden

Phase Separators: Cryoworks, Eden

Buffer Tank & Argon: Airgas, Praxair

VJ Lines: Technifab, Cryoworks

Pressure Relief Burst Disk: Fike

Mezzanine: TBD

Flowmeter: Promass F 500 Coriolis Flowmeter

Gas Analyzer: TBD: LDETEK LD8000_Multigas

Vacuum Pumps and Leak Checker: Pfeiffer

Filter Vessel, Pump Housing: SLAC

PLC: Beckhoff w/ Ignition Software

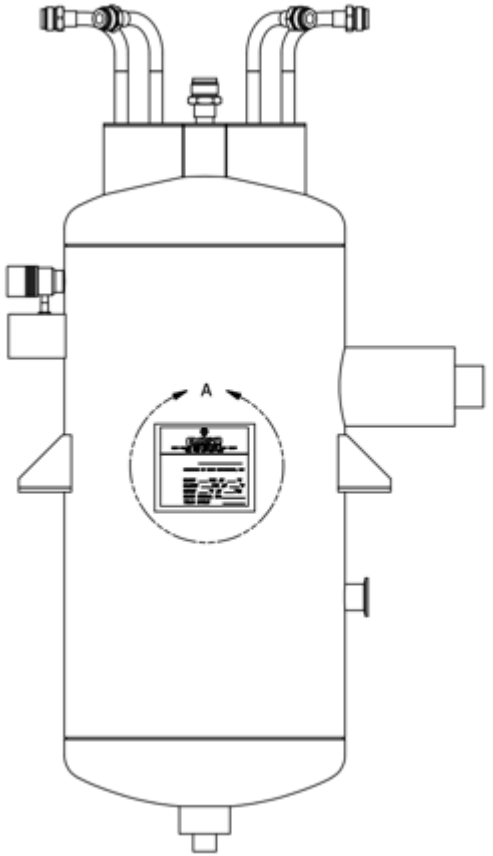
9000 gallon LN2 plumbed to local manifold in IR2 High Bay w/ 50-Ton and 10-Ton Cranes w/ 10.16m hook height

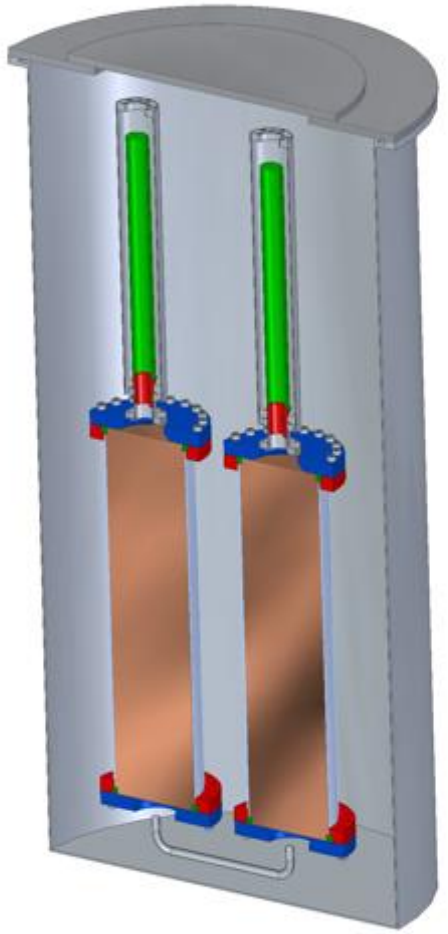
9000 gal LN2

Local LN2 Manifold

50 Ton and 10 Ton crane, 10.16 m hook height

Devices: Phase Separator, Pump, Condenser, Filter





SLAC DUNE Full Scale Demonstrator PI&D (06/10/2022 preliminary)