

131.ND.02 Technology Status and Prototyping

Igor Kreslo, Detector Subsystems 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

Prof. Dr. Igor Kreslo

coordinator of detector development group at LHEP, Uni-Bern

Physicist (experiment) with technical and engineering background

R&D for LAr detectors in Neutrino physics - since 2007

ArgonTube

ArgonCube

Other detector R&D since 1992:

E289 SciFi vertex detector

Chorus SciFi capillary vertex detector

OPERA Scintillating target tracker

OPERA automated emulsion DAQ

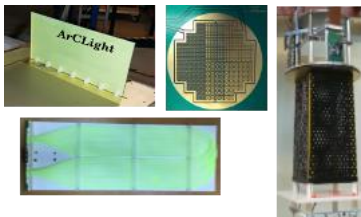
uBooNE/SBND cosmic ray tagger

Prototyping and Risk mitigation - relevant documents

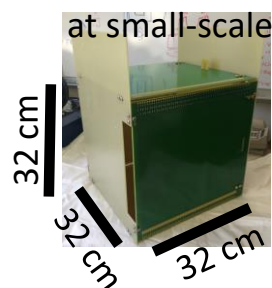
<u>Folder/Document</u>	<u>Description</u>	<u>EDMS Link</u>
Requirements	Spreadsheet with all ND-LAr requirements, see sheet "System"	https://edms.cern.ch/document/2589287
Risk Registry	ND-LAr TPC Risk Registry	https://edms.cern.ch/document/2589288
Prototyping Plan	Prototyping plan for the ND-LAr Consortium	https://edms.cern.ch/document/2459149
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
Module-0 performance paper	Summarizes experimental results from the 2x2 Module-0 tests on cosmics	https://edms.cern.ch/document/2746204
Previous Review Tracking	Spreadsheet with previous review recommendations	https://edms.cern.ch/document/2741842
PDR writeup	Preliminary design report writeup	

ND-LAr Consortium Prototyping Plan in Pictures

2016-2019
ArgonCube R&D
Demonstrations of
component technologies

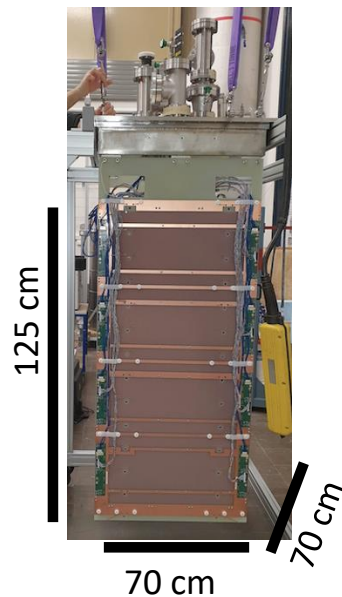


2020
SingleCube
Integrated TPC
test



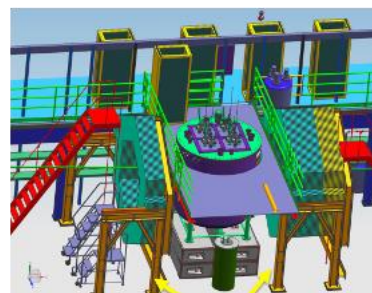
TRL-5

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



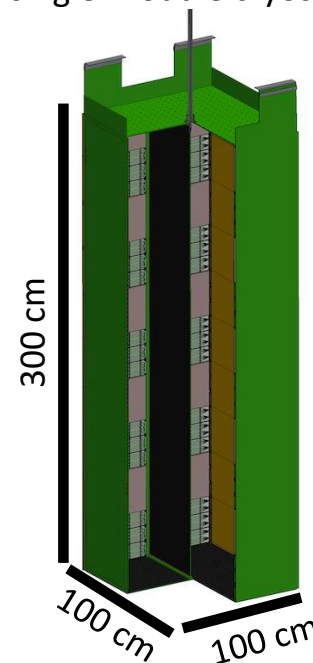
TRL-6
- Ready for CD-2

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 - Ready for CD-3
(engineering)

ND-LAr: Prototyping of Critical Elements

ArgonCube R&D Collaboration:

2016-2019: Successful program of LArTPC technology demonstrations

Advanced Light Readout:

- LCM and ArCLight dielectric light traps
- Enables high-coverage scintillation light detection

Pixel Charge Readout:

- LArPix ASIC and Integrated Pixel Tile
- Enables true 3D ionization charge readout

Resistive Field Cage:

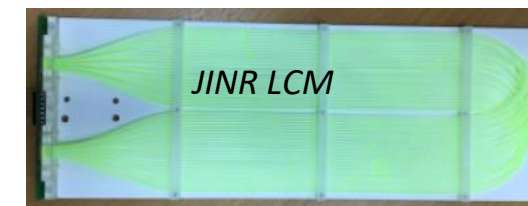
- High-resistivity film as continuous resistive field cage
- Enables low-profile field cage

Modular TPC Design:

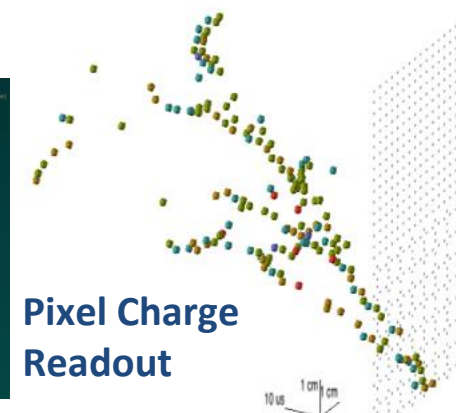
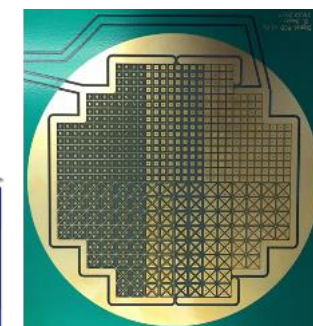
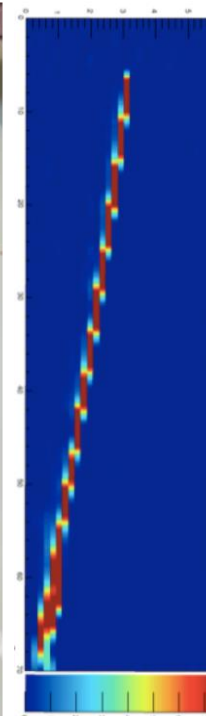
- All fiberglass (G10) LArTPC structure
- Enables optical segmentation

Prototyping program achieved TRL-4 in 2019.

Advanced Light Readout



Resistive Field Cage



Pixel Charge Readout

Modular TPC Design



Retired / Mitigated Risks

Risks related to LArPix basic performance - **retired**

Risks related to ArCLight/LCM cryo-compatibility - **mitigated** (small scale)

Risks related to ArCLight/LCM performance - **mitigated**

Risks related to use of DR8 as a field shell material (basic) - **retired**

ND-LAr: SingleCube TPC

SingleCube LArTPC Prototype:

Integrated test of ArgonCube readout:

- Production-scale pixel tile (32 cm x 32 cm, 4.9k pixels)
- Production-scale ArCLight scintillation light trap
- Same system interfaces as 2x2 Demonstrator
- Same 30-cm drift as 2x2 Demonstrator (3/5 of ND)

Progress:

- Assembled and installed in medium cryostat @ Bern
- Uses 2x2 Demonstrator High-purity LAr system
- Initial cooldown and fill: *26 Oct 2020*

Initial Result:

- Imaged cosmic rays within a few hours of filling!

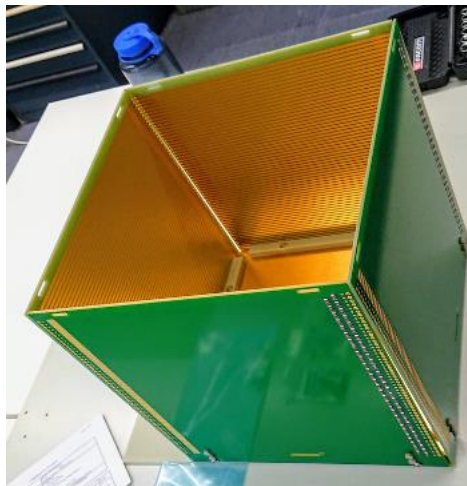
Successfully achieved many technical targets:

- **Charge & Light readout integration**,
with low-noise and low-power
- **LAr Purity**, > 500 us e- lifetime
- **HV stability**, up to 1 kV/cm

*Prototyping program
achieved TRL-5 in 2020.*

SingleCube LArTPC

Full 30-cm drift



Charge & Light Readout



Installation of Integrated Charge & Light Readout

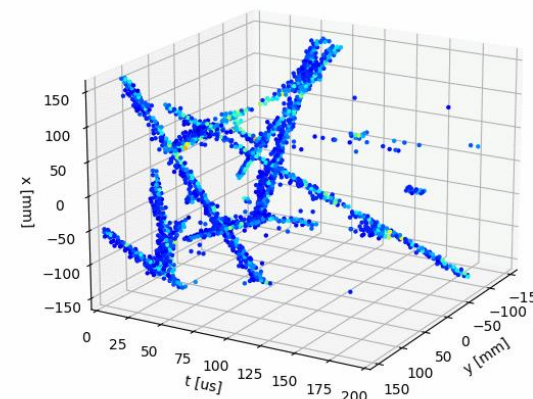


Integration with LAr Cryo-system



3D images of cosmic rays

in SingleCube LArTPC, 8 events overlayed



Retired / Mitigated Risks

Risks related to LArPix array full performance - **retired**

Risks related to thermal performance of CRS & LRS - **mitigated** (small scale)

Risks related to ArCLight/LCM cryo-compatibility - **retired** (full scale)

Risks related to ArCLight/LCM performance - **retired**

Risks related to merging charge-light data flow - **retired**

With increasing scale of the prototypes engineering aspects together with QA/QC quickly gain importance!

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

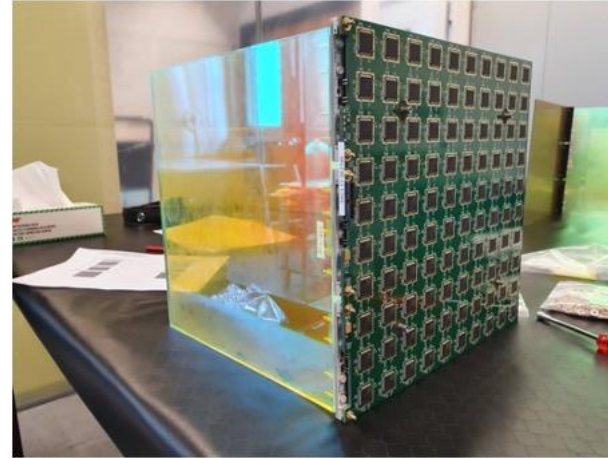
Achievements:

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

More pictures:

<https://argoncube.org/gallery.html>

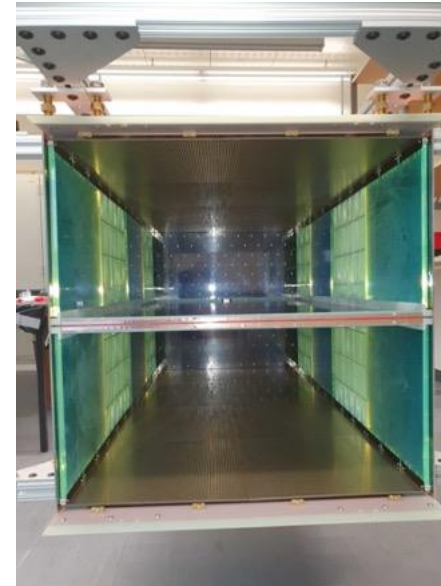
Single pixel tile & light module assembly



LArTPC module attached to cryostat lid



Two anodes, installed inside field cage



One anode, fully-assembled



Single Module Cryostat



LArTPC inside cryostat



Prototyping: ArgonCube 2x2 LArTPCs - cryogenics and purity

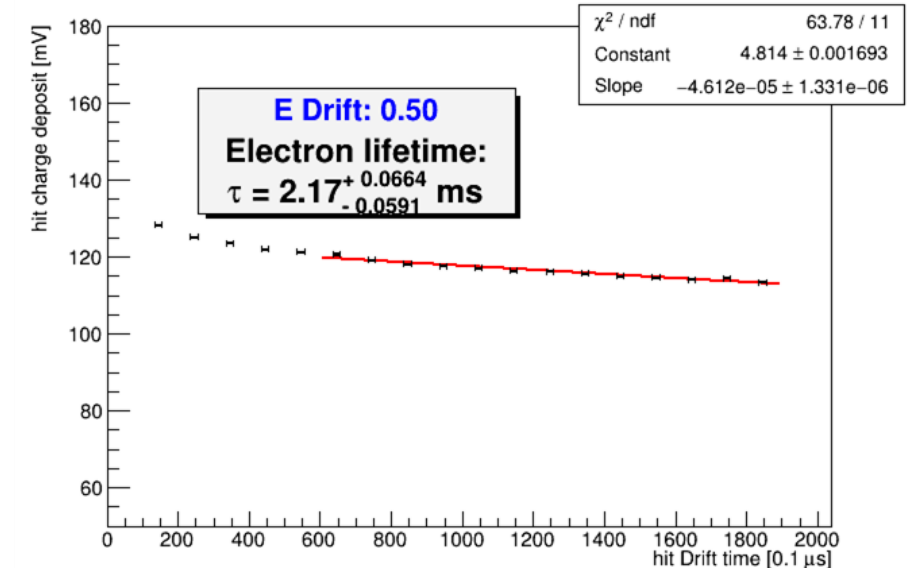
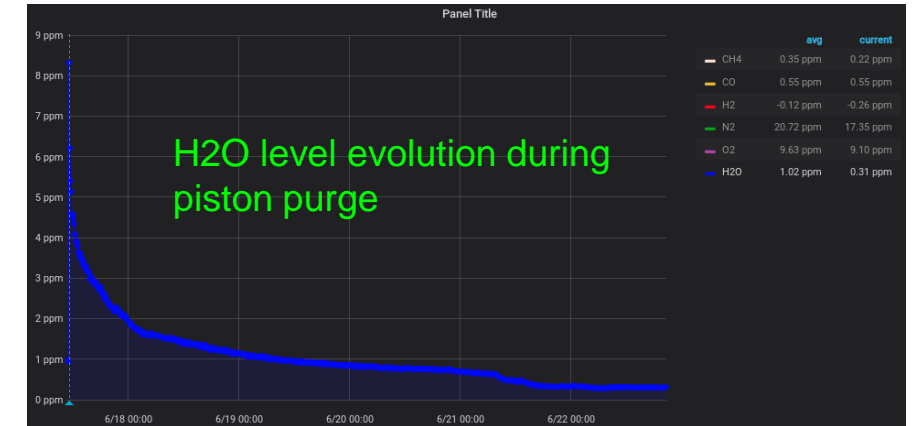
Crucial for ND-LAr

LAr purity:

- GAr Piston purge (no prior evacuation)
- 200 gas volume exchanges
- H₂O level dropped below 1 ppm -> filling with LAr (additional cold purge)
- recirculation for 1 day -> we are at >2 ms electron life time (>4x required)

No-flow test (thermal management):

- LAr recirculation was stopped for >1 hour (cooling by natural convection and evaporation)
- DAQ is stable, no signs of boiling inside drift volume, no extra noise
- HV is stable at 0.5 kV/cm



Retired / Mitigated Risks

Risks related to:

- LArPix array full performance in medium scale (80k pixels) - **retired**
- thermal performance of CRS & LRS - **mitigated**
- assembly cryo-compatibility - **mitigated** (scale is still smaller than ND-LAr)
- combined LRS/CRS performance in medium scale - **retired**
- merging charge-light data flow in medium scale - **retired**
- timing performance of the combined CRS/LRS - **retired**
- HV-stability - **mitigated** (scale is still smaller than ND-LAr)
- support mechanical integrity - **mitigated**
- full-size ND thermal management - **mitigated**
- LAr purity - **mitigated** (material outgassing and amount)

Prototyping: ArgonCube 2x2 LArTPCs

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

Verified design meets technical requirements:

- Collected $>10^7$ cosmic ray events
- Stable **HV** at $\sim 30\text{kV}$ ($\sim 1\text{ kV/cm}$ drift, 2x target)
- Stable **Purity** at $>2\text{ms}$ ($>4\text{x}$ required)
- 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 ($\sim 50\%$ larger in ND-LAr)

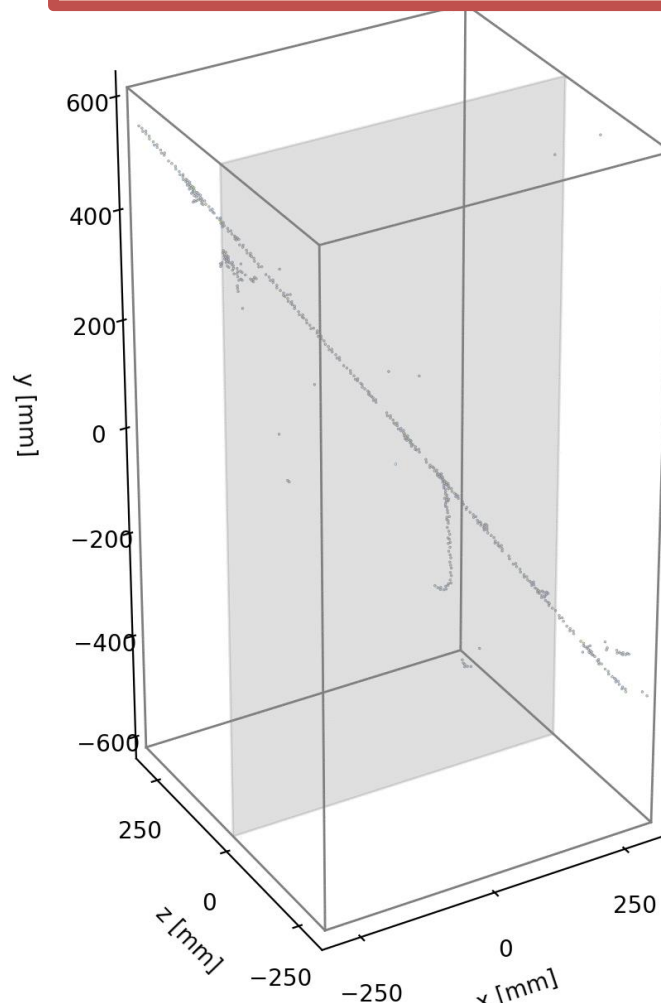
Informed development of future program:

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

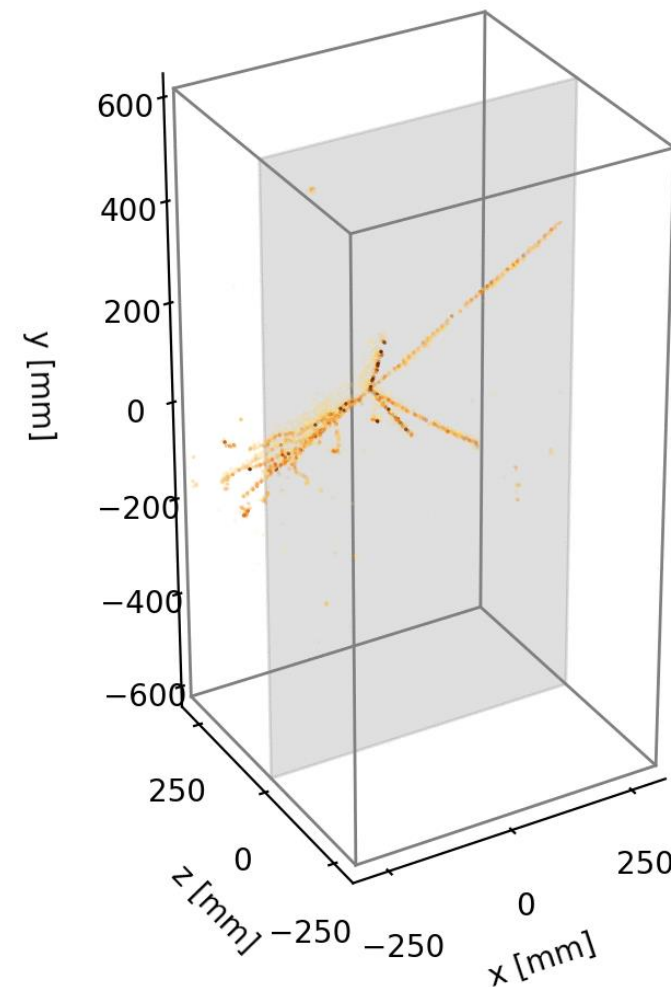
Retired the most significant technical risks in ND-LAr design.

Arguably the most performant ton-scale LArTPC to date.

Achieved TRL-6 in 2021.

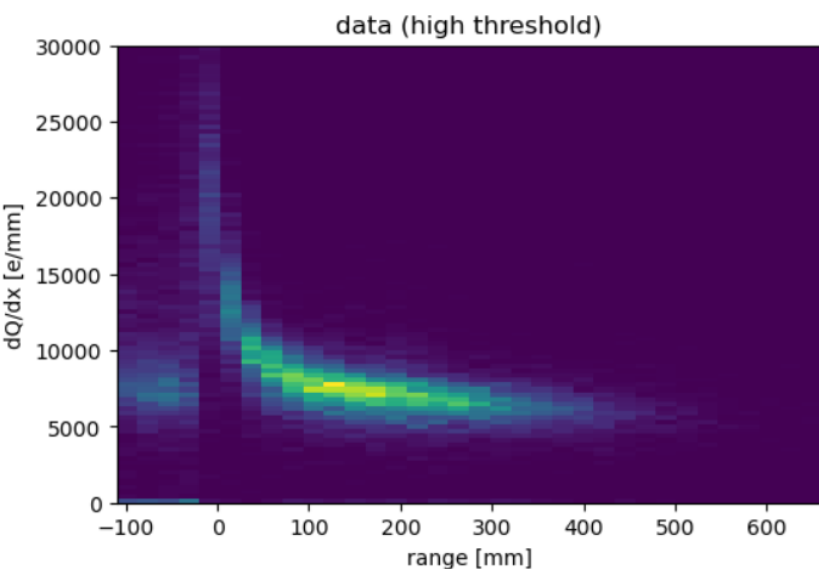


Module 0 LArTPC



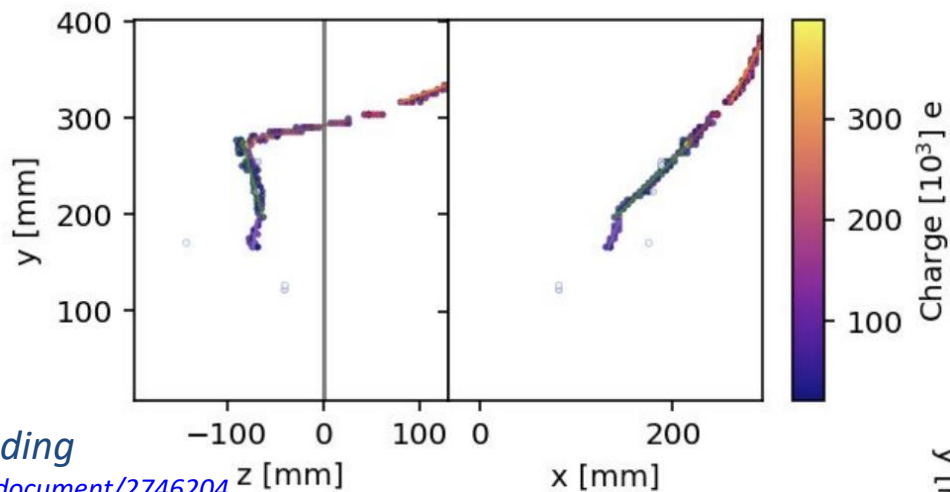
Module 1 LArTPC

2x2 Module 0/1 Physics Performance

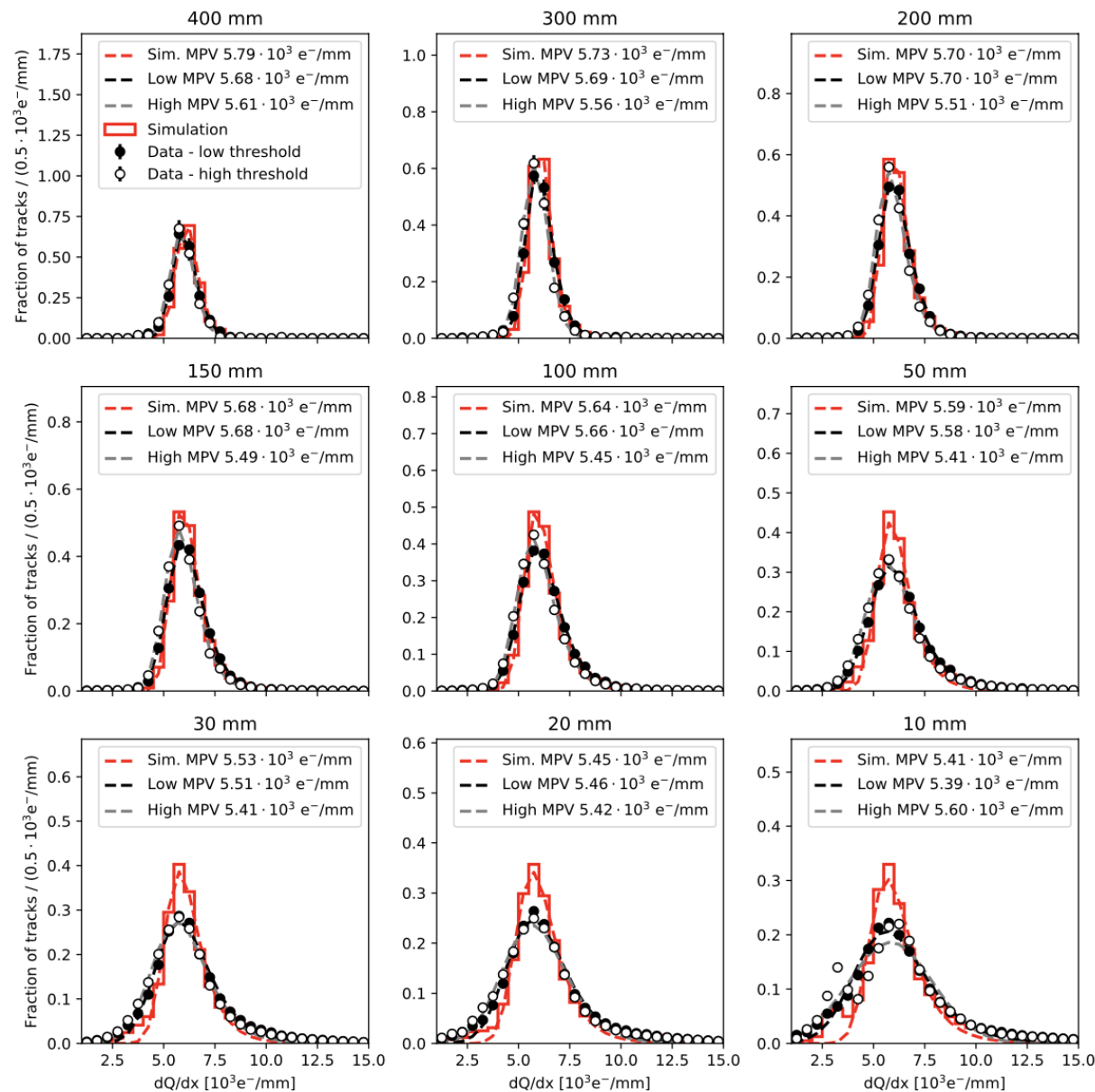


Energy loss for stopping muons

Observation of decay positron



Energy loss for minimum ionizing muons (dQ/dx)

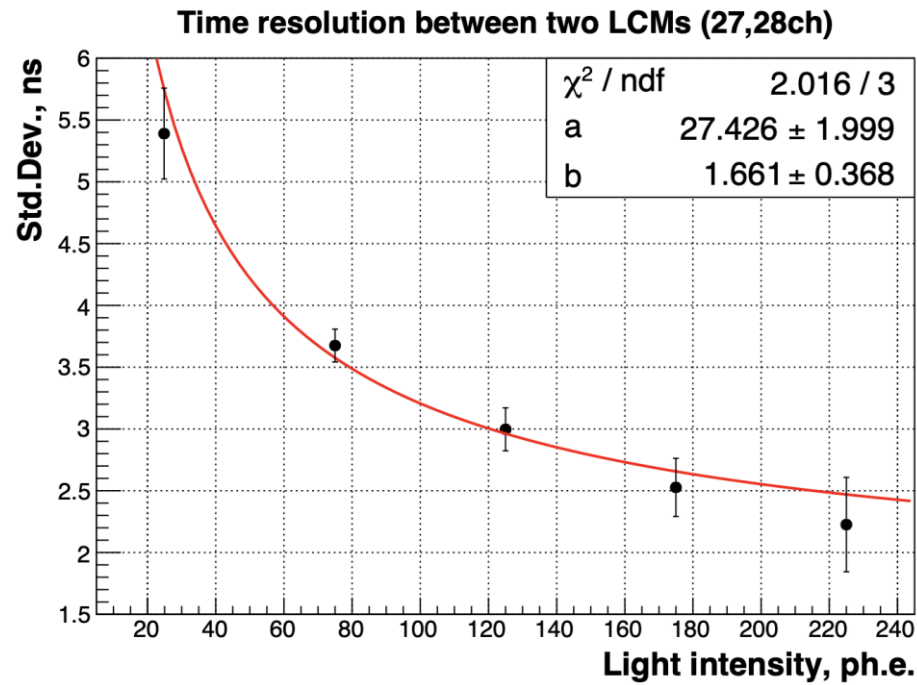


Publication Pending

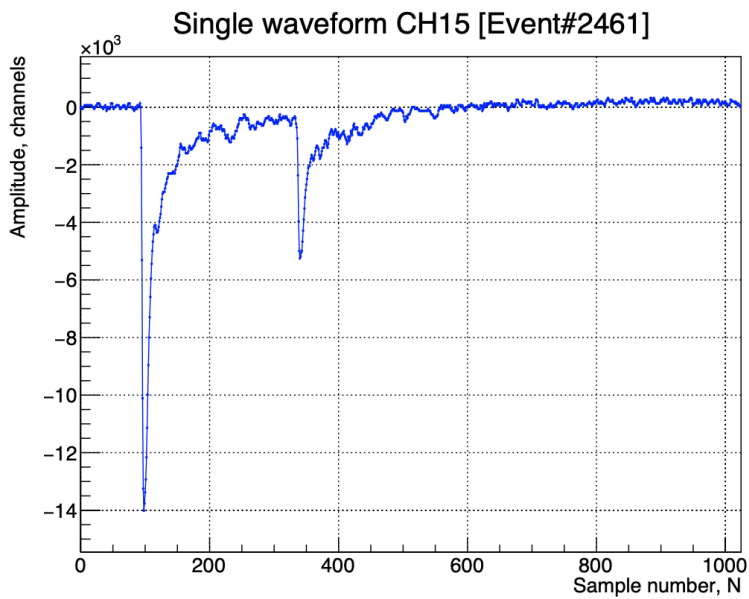
<https://edms.cern.ch/document/2746204>

2x2 Module 0/1 Physics Performance

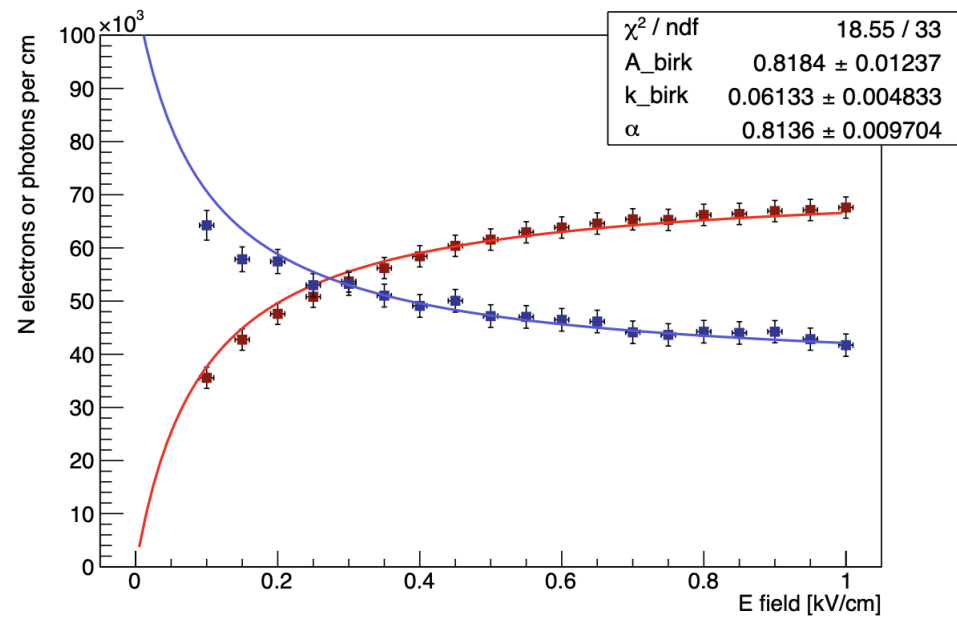
Time resolution of Light readout system < 2ns (x5 target)



High efficiency light readout gives clear signals for Michel Decays



Anticorrelation of charge and light signal amplitude vs. drift field strength



Retired / Mitigated Risks

2x2 lessons learned table: <https://edms.cern.ch/document/2737729>

Risks on improper grounding/shielding approach - mitigated

Risks related to reconstruction challenges in large scale - retired

Risks related to achieving energy resolution - retired

Risks of not achieving triggering threshold - retired

Risks of not achieving coordinate resolution - retired

Most challenging remaining risks:

Physics performance , event reco, grounding, thermal management, interfaces @ ND-LAr scale, QA/QC, assembly procedures, personnel

Required for next step: **2x2 at neutrino beam** and **FSD**

Prototyping Facilities

- ArgonCube Test Facility (Bern) - in operation since 2016 (in the context of ArgonCube - ND-LAr)
- 2x2 NUMI Test Beam Facility (FNAL) - in progress of construction
- Full-Scale Demonstrator Test Facility (SLAC/Bern) - design, procurement and sites preparation

ND-LAr prototyping facilities enable the Consortium to conduct key prototype testing in a realistic operational environment in order to achieve technical readiness for eventual ND-LAr module production.

Prototyping Facility - 131.ND.02.12 2x2 NuMI Beam Test Facility (FNAL)

Facility for “Physics” demonstration of the ND-LAr TPC Technology (TRL-7)

- ~15 ton cryostat and high-purity liquid argon recirculation system
- Detector support mezzanine, equipment racks, power supplies
- Site utility upgrades (low-noise electrical power, ventilation)
- Supporting technical labor and consumables for installation and operation

Simulated NuMI Neutrino Events in 2x2

DUNE docDB #12571: ProtoDUNE-ND proposal

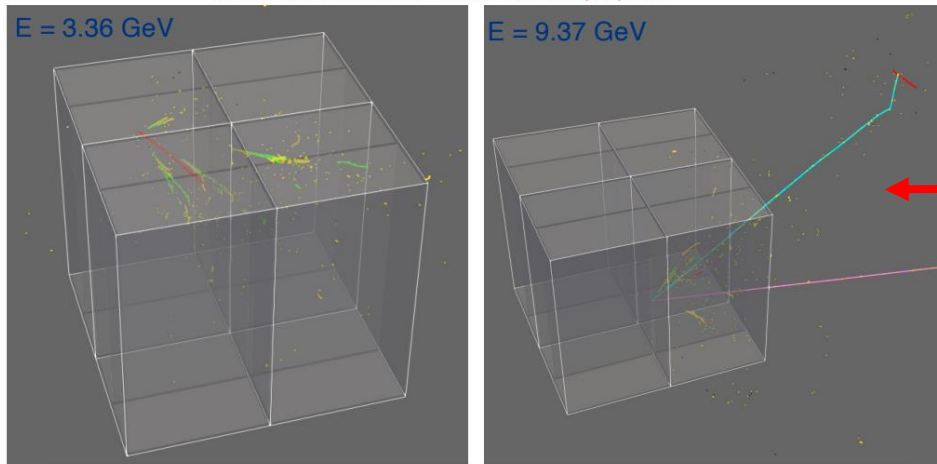
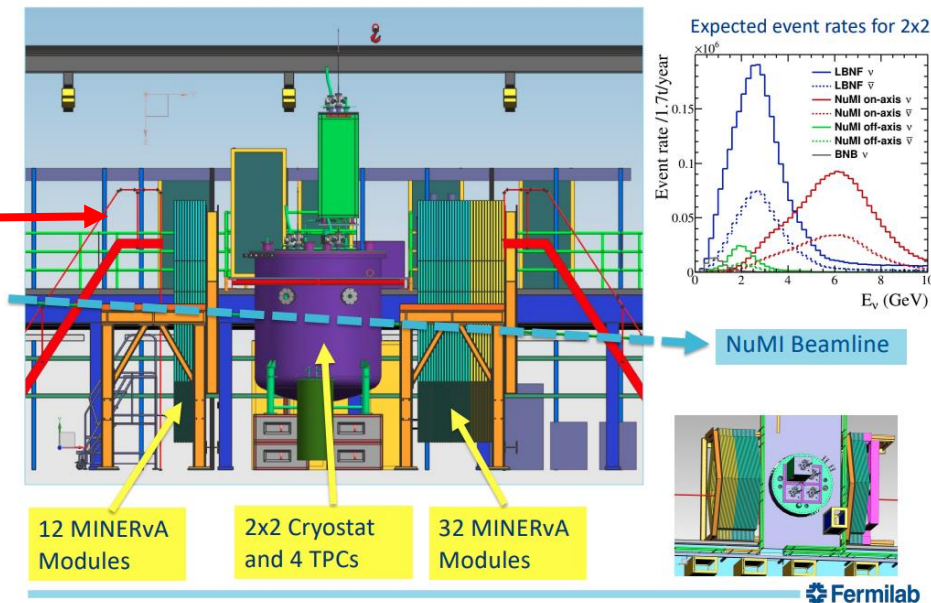


Figure 7: ArgonBox simulated events for a number for different incident neutrino energies, where the energy deposits in a bulk volume of 1.7ton LAr are color-coded according to the particle type: π^+ —blue; K^+ —purple; e^+ —green; e^- —yellow; proton—red

Fermilab

Detector Configuration in MINOS Hall



ND-LAr: 2x2 NuMI Beam Test

2x2 Operation in NuMI Neutrino Beam: 2022-2025

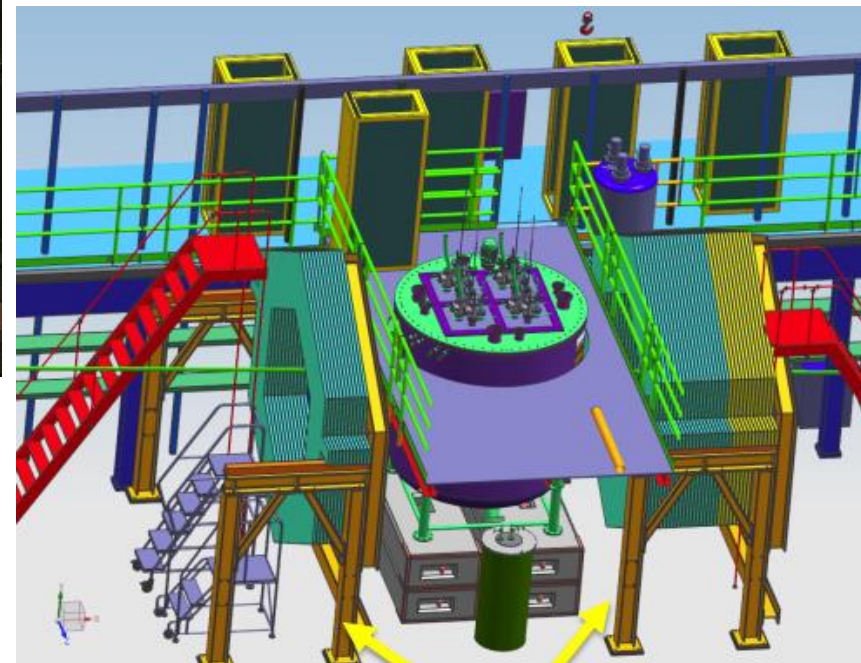
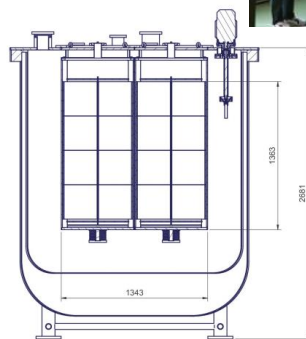
- Install four TPC modules in former location of MINOS-ND
- Includes upstream/downstream trackers, repurposed from Minerva

Goals:

- Develop neutrino signal analysis and reconstruction techniques
 - 3D reconstruction of neutrino signals
 - Charge-light signal correlations, tolerance to beam pileup
 - Track matching with external trackers

Context on the 2x2 Effort:

- Plan pre-dates the ND-LAr detector in the DUNE-US ND project
- Cemented via an iCRADA between Univ. of Bern and FNAL
- Effort is off-project, supported by substantial contributions from many institutions
- TPCs assembled and tested at Bern, shipped to FNAL for installation and commissioning



Major Commitments:

Bern:

- Cryostat and most of cryogenics components (pumps, LAr purifier, valves, feedthroughs, etc)
- Pre-assembled TPCs, tested and ready for installation
- HV supply and filters, half of scintillation light traps

FNAL: Cryocoolers, cryogenics integration, PLC system, support platform, onsite facilities support and management

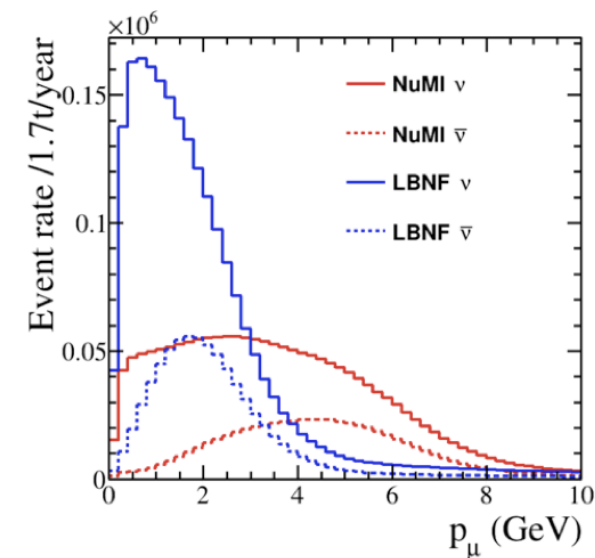
JINR: Light readout system, including all electronics & prototype DAQ

LBNL: Charge readout system, including all electronics & prototype DAQ

SLAC: Field structures (cathodes, field cages, HV feedthroughs)

CSU: Assembly fixtures

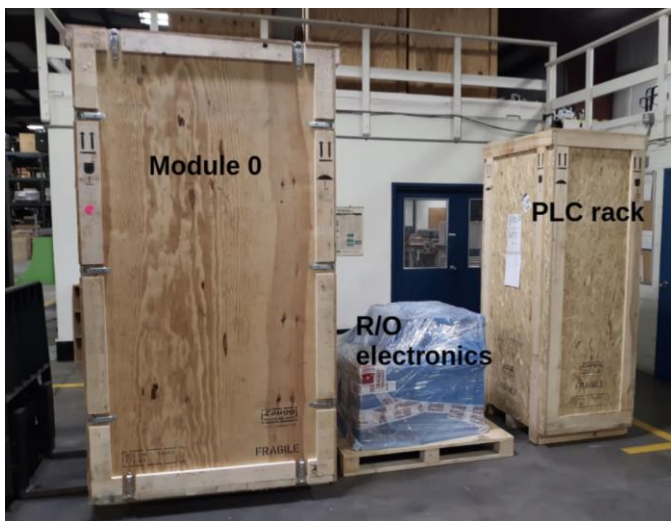
*and ~40 institutions
providing scientific labor*



ND-LAr: 2x2 NuMI Beam Test

2x2 Status:

- Cryostat & controls commissioned at Bern
Delivered to FNAL: July 2021
- TPC Module 0,1 commissioned at Bern
Delivered to FNAL: June 2022
Acceptance testing in progress.
- TPC Modules 2-3 currently in production
To be delivered to FNAL: Autumn 2022
- Remaining cryogenics system procurements/production
To be delivered to FNAL: Autumn 2022
- Installation and commissioning in NuMI hall
Targeting ~Autumn/Winter 2022

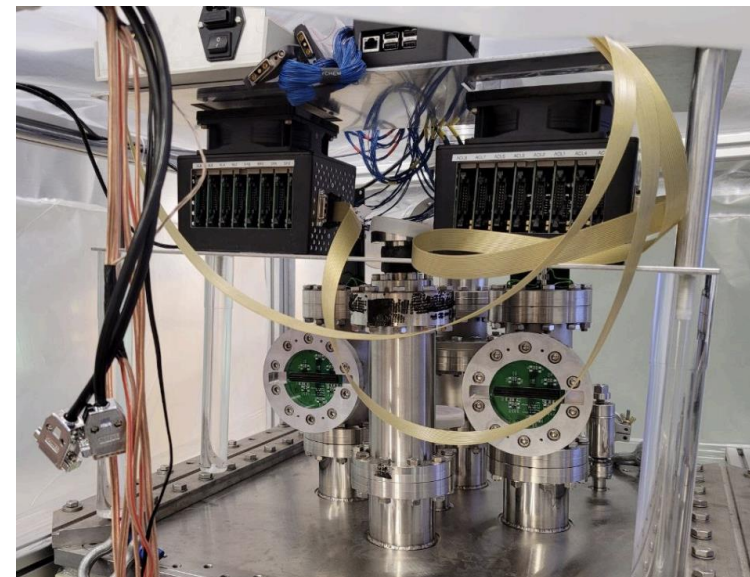


Modules 0 & 1, electronics, and PLC at FNAL

Module 0 in shock-isolated shipping frame



Module 0 post-shipment testing @ FNAL



NuMI hall in preparation for 2x2 installation



Retired / Mitigated Risks

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

LArPix array performance in medium multi-module scale (4x80k pixels)- to be **retired**

3D reconstruction of neutrino signals - to be **retired**

charge-light signal correlations, tolerance to beam pileup - to be **retired**

track matching with external trackers - to be **retired**

mitigated (informed) risks :

LAr flow distribution

multi-module mechanical structure integrity

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

Slow control, DAQ, data rates

Multi-months operation, design limitations for operation at FNAL (MATF risks)

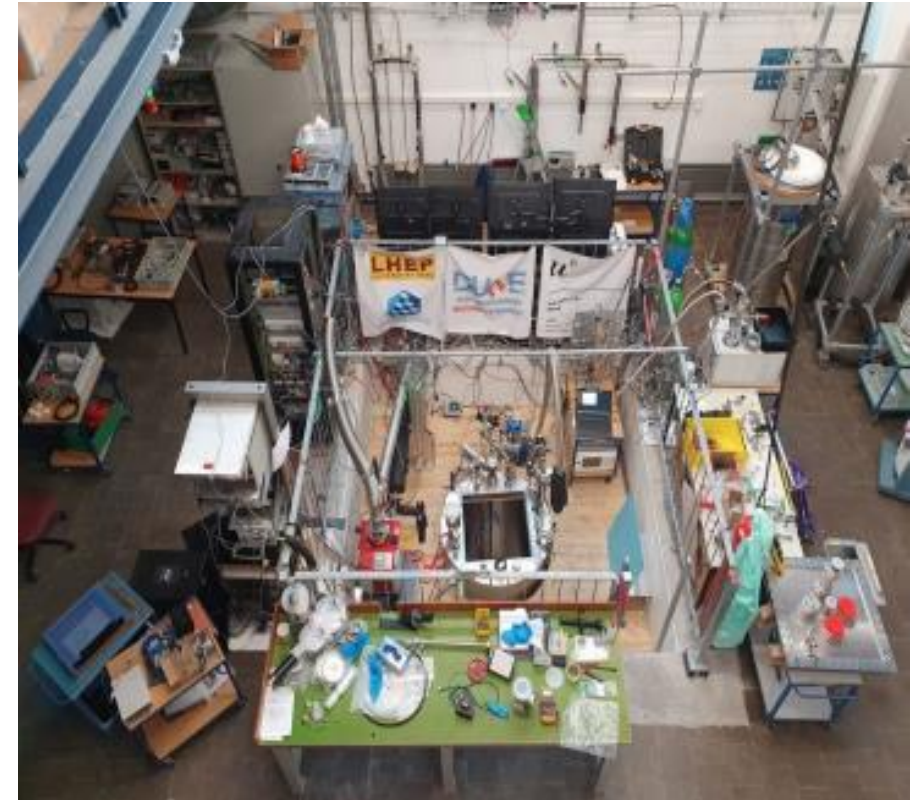
“Incident tolerance” (leaks, discharges, handling, module failure...)

FSD for further assessment !

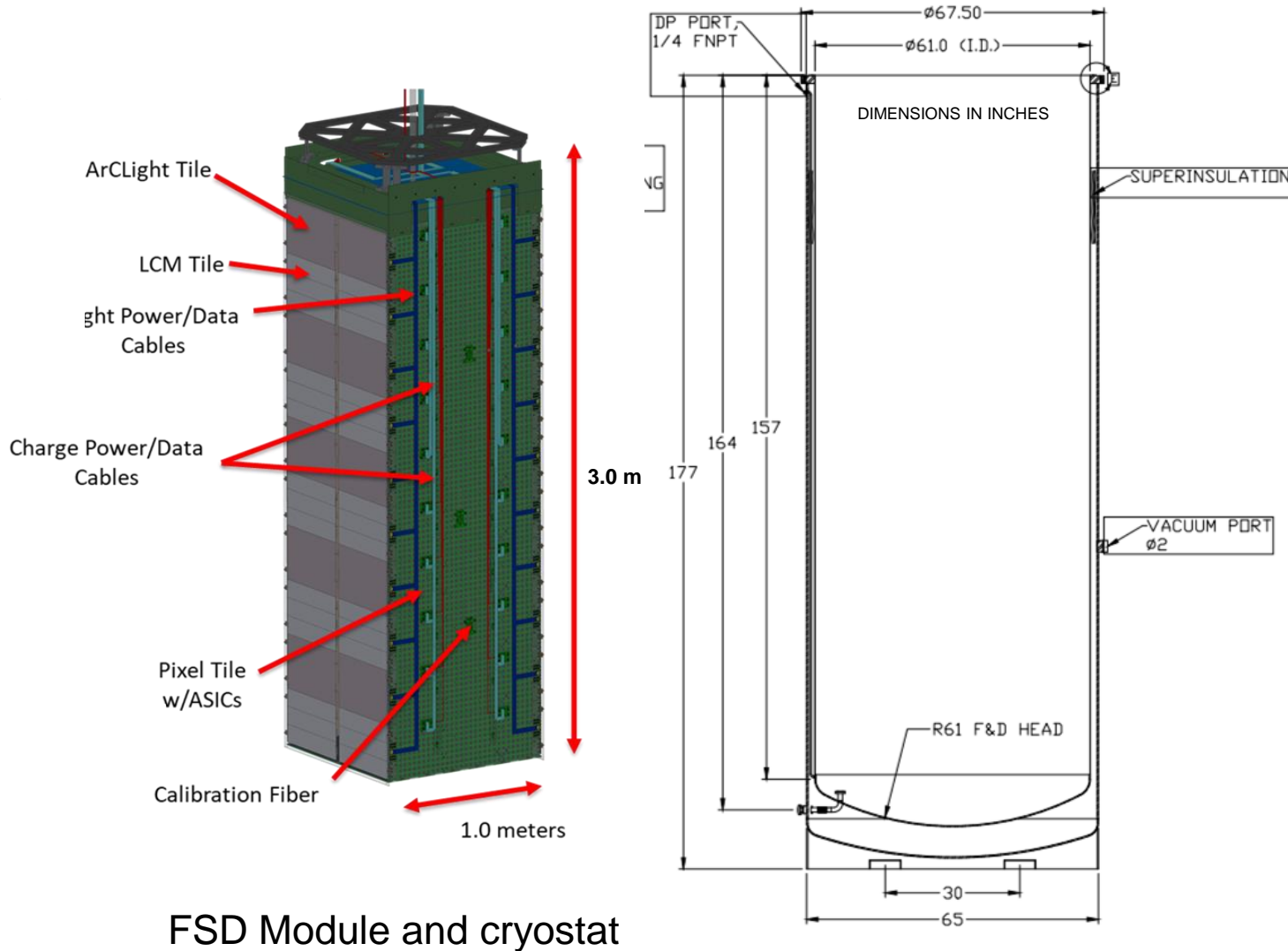
Prototyping Facility - 131.ND.02.13 ArgonCube Test Facility (Univ. of Bern)

Facility for individual 2x2 module testing and cryogenic commissioning prior to module delivery to FNAL for 2x2 NuMI Test Beam.

- Currently in operation (2 of 4 ArgonCube 2x2 TPC modules completed) (TRL-6)
- Will be upgraded to support full-scale module testing in 2023 (TRL-7)



Prototyping Facility - 131.ND.02.13 ArgonCube Test Facility (Univ. of Bern)

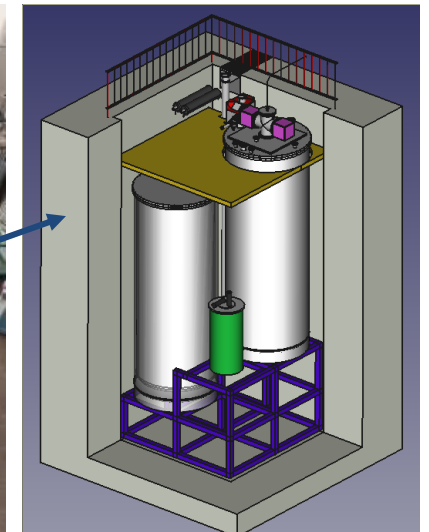


LAr distribution system: informed by 2x2 test program

Module support structure to be partly prototyped in FSD test program

2 cryostats of required size are ordered, delivery expected by February 2023

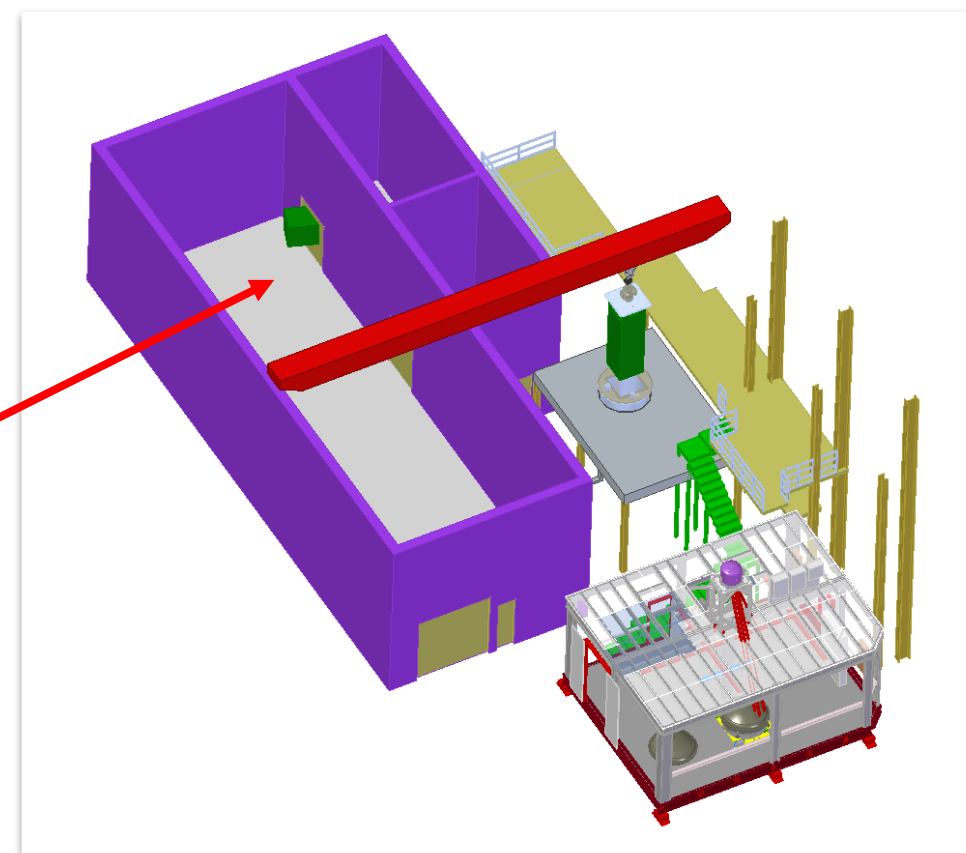
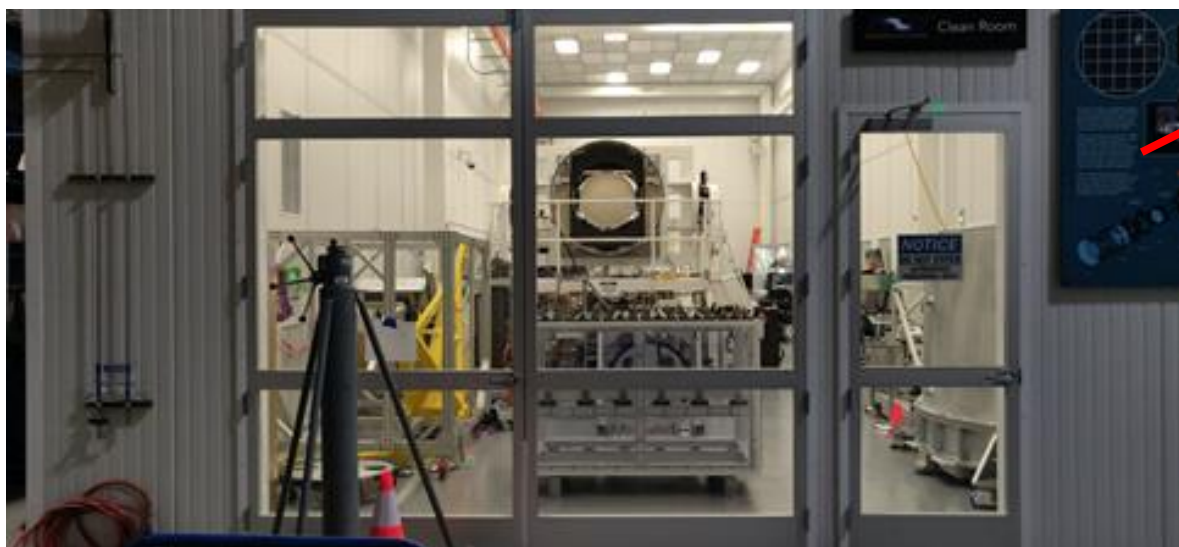
Facility upgrade starts right after completion of the 2x2 module assembly and test program.



Prototyping Facility - 131.ND.02.11 Full Scale Demonstrator Test Facility (SLAC)

Facility for demonstration of engineering readiness for Near Detector LArTPC module production (TRL-7)

- ~10-15 ton Liquid Argon Purification & Recirculation System
- Cryostat and Mezzanine for Access
- Low-Noise Electrical Isolation
- Clean Assembly Area
- Supporting technical labor and consumables



Prototyping Facility - 131.ND.02.11 Full Scale Demonstrator Test Facility (SLAC)

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

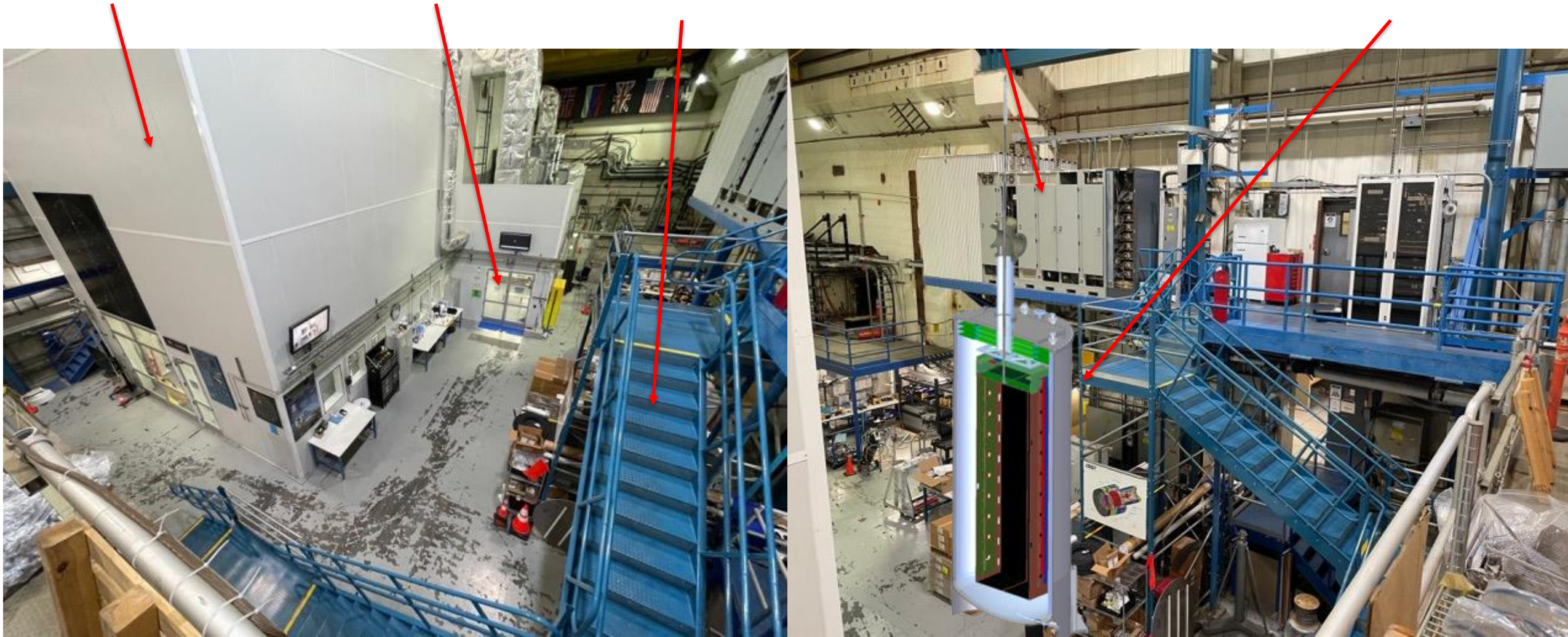
Clean Room

Gowning room

Access stairs

Catwalk with racks

Mezzanine will be at height of stair landing



Retired / Mitigated Risks

Module sssembly procedures, logistics and QA/AC - to be **retired**

LArPix array performance in full scale module (205k pixels)- to be **retired**

Thermal performance of CRS & LRS - to be **retired**

Full-size ND thermal management - to be **mitigated** (scale of 1 module)

LAr purity - to be **mitigated** (material compatibility and amount)

Data flow/management - to be **retired**

HV - performance/stability - to be **retired**

Support mechanical integrity in cryo - further **mitigated** (at the module level - **retired**)

Calibration system - to be **retired**

Summary

Prototyping plan adequately addresses major technical and engineering risks.

Majority of detector performance risks are already **retired based on the plan progress.**

Majority of technical risks are **retired.**

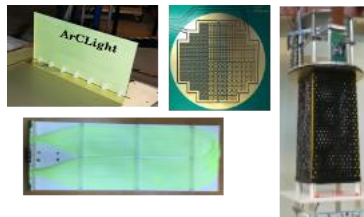
Many risks requiring larger scale are substantially **mitigated by the plan progress.**

Bonus: a unique set of cosmic and neutrino events for eventual physics analysis

Backup slides

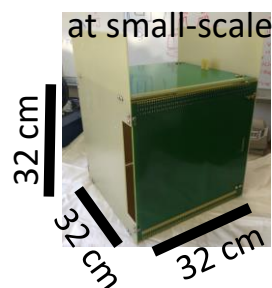
ND-LAr Consortium Prototyping Plan in Pictures

2016-2019
ArgonCube R&D
 Demonstrations of
 component technologies



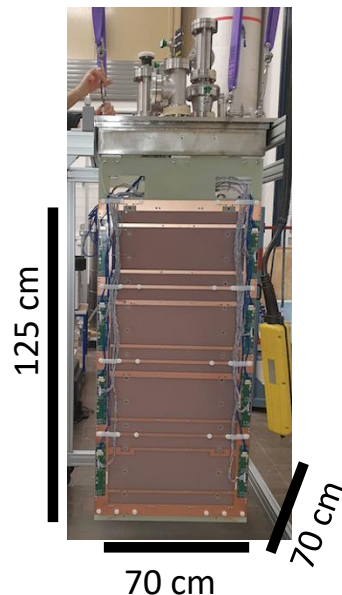
TRL-4
 - Ready
 for CD-1

2020
SingleCube
 Integrated TPC
 test



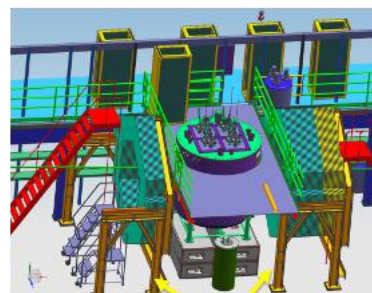
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Module 0
 One mid-scale
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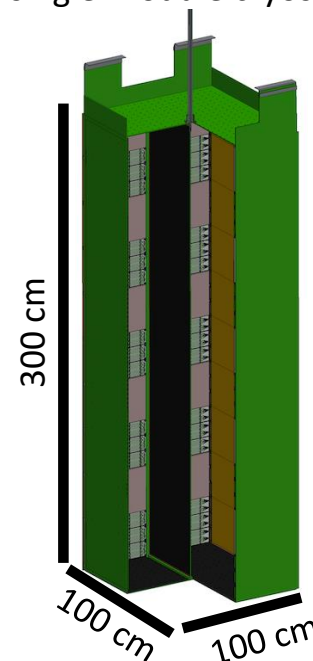
TRL-6
 - Ready for CD-2

2022-2025
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 Four mid-scale
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 neutrino beam



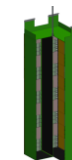
TRL-7
 (physics)

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



TRL-7
 (engineering) - Ready for CD-3

Production



1
 production
 'first article'

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



2x2 Lessons learned

<https://edms.cern.ch/document/2737729>

Known Issue:	Subsystem:	Description:	Entered By:	QA /QC	Proposed Mitigation:
Failed E-board @ ACL -007	Light System	Broken connector at feedtrough or bad contact.	Kreslo	QC	Soldering procedure adjusted to avoid the problem
Failed DAC channel	Light System	ADC ch 14 (DAC ch 63) on LCM015 is dead	Kreslo	QC	QC procedure introduced at the provider (JINR)
Failed SiPM channel	Light System	ADC ch 99 (DAC ch 17) on ACL001 is dead	Kreslo	QC	QC procedure introduced at the assembly site (Bern)
Noise Pick-up between E-board & Charge System	Light System	10 MHz waveform seen on the LRS signals in Module-0	Kreslo	QA	Additional screens introduced to the E-boards
LDS ADCs record not equal number of events	Light System	ADCs miss events from time to time. This breaks event to event match between two ADCs.	Kreslo	QA	Use timestamps to identify missing events and restore consistency.
Failed calibration LED	Light System	Connector of calibration LEDs broke/disconnected during sleeve insertion	Calivers	QA/QC	Change connector type or fixate with cable tie Test LEDs after sleeve insertion
PPS is not aligned with UTC second rollover	Timing	PPS, which is distributed to LDS and CDS is delayed w.r.t. GPS PPS by unknown value. This value, however is stable to 1ns/s. This delay need to be derived comparing NTP and PPS events.	Kreslo	QA	If the PPS is in the middle of the second - assign that second of NTP to that PPS. Retired by implementing WR timing system.

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<u>Known Issue:</u>	<u>Subsystem:</u>	<u>Description:</u>	<u>Entered By:</u>	<u>QA /QC</u>	<u>Proposed Mitigation:</u>
Self-trigger rate jumps	Charge System	After LAr fill, the charge readout self-trigger rate occasionally jumps on single channels, firing at roughly few orders of magnitude higher than nominal self-triggering trigger rate	Russell	QA	Modify control scripts to periodically check/reconfigure ASIC configuration
Edge Pixels on Charge Tiles	Charge System	Onset of rate instabilities originating from pixel pads at edges of anode tiles	Russell	QA	Modified grounding scheme fixed the problem.
Charge feedthrough PCB leak	Charge system	Alignment holes on the feedthrough PCB were not filled with glue	Parsa	QC	Vacuum leakage test as QC measure.
Whole-tile triggering	Charge system	Whole-tile self-triggering due to charge injection on channel frontend from capacitive coupling with VDDD	Russell	QA	Effect removed with additional board capacitance added to VDDD
Sync-induced triggering	Charge system	Many channel self-triggering due to charge injection on channel frontend from capacitive coupling with VDDD	Russell	QA	Effect removed with additional board capacitance added to VDDD
Ghost triggers	Charge system	Self-triggering on summation of induced current from far-field extended charged body resulting in triggers preceding ionization electron arrival at anode by several centimeters	Russell	QA	Anode tile optimization: pixel geometry and/or grid plane; R&D in progress
PFD5 oil leak	HV system	PFD5 developed tiny oil leak at the welding seam	Kreslo	QC	Vacuum leakage control is introduced as QC measure