131.ND.02.04 Field Structures: Overview

James Sinclair, Field Structures

ND-LAr Preliminary Design Review

28 June 2022

Outline

- Scope
- Requirements
- Interfaces
- Procurement, Manufacturing, QA/QC
- Risks and Prototyping
- Recommendations from Previous Reviews
- Cost and Schedule
- Summary

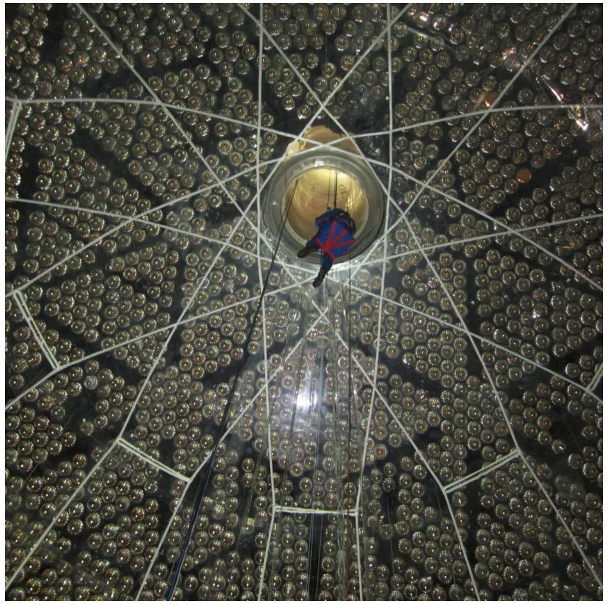
Speaker's Biography

SLAC
Project Scientist DUNE 2021 → present

Bern
DUNE/ArgonCube 2015 → 2021
LArTPC development for the ND
(pixelated anode, continual E-field shaping, dielectric light r/o, cryogenic design, 2x2).
MicroBooNE/SBND 2015 → 2021
Cosmic ray tagger, Laser E-field calibration.

SNOLAB/Sussex
SNO+ 2010 → 2015
Optical and timing calibration.
NeutronEDM 2009 → 2010
Ultra-cold Neutron storage, E-field breakdowns in LHe3.

Technician 2007 → 2009



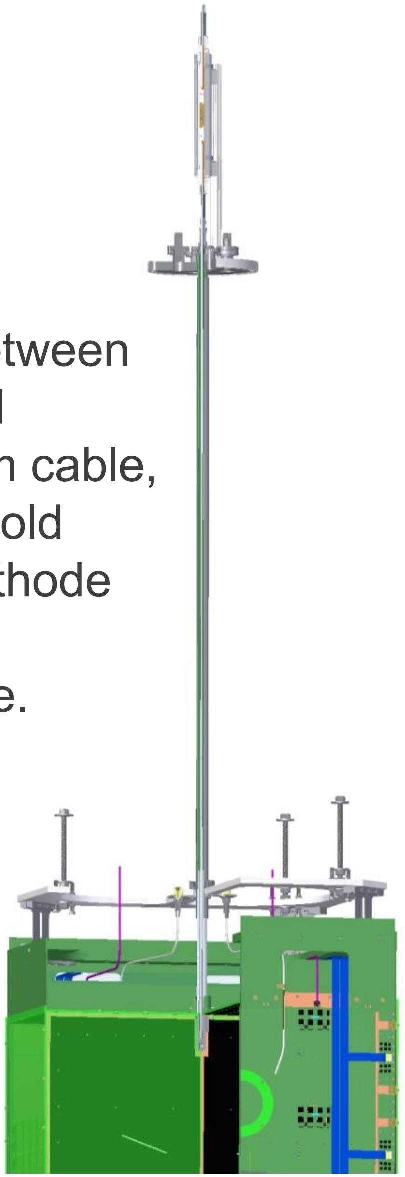
The Arse of SNO+

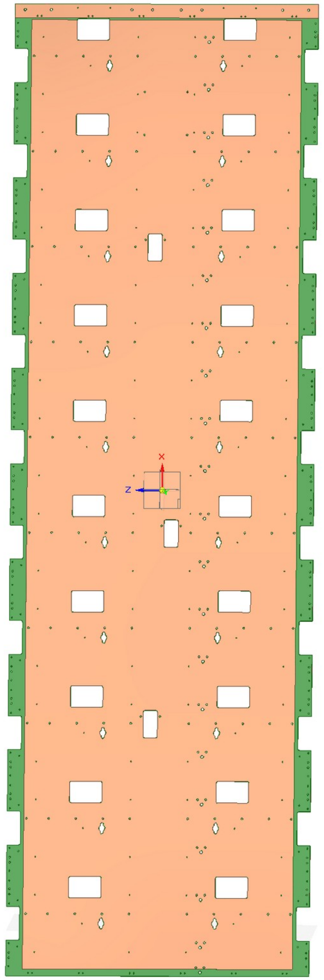
Documentation Summary

Field Structures Documentations	Description	EDMS Link
Field Structures Folder	Top level folder for documentation	https://edms.cern.ch/project/CERN-0000217527
Requirements	Spreadsheet with all ND-LAr requirements, see sheet "Field structures"	https://edms.cern.ch/document/2589287/1
Interface Matrix	Matrix describing ND-LAr Interfaces	https://edms.cern.ch/document/2640807/3
Analyses	Collection of analyses write-up: Mechanical analysis, Electric field simulations, electric field measurements, active volume simulations	https://edms.cern.ch/project/CERN-0000230582
QAQC Plan	Subsystem QAQC plan with focus on high-level QAQC test plans	https://edms.cern.ch/document/2683351/1
Manufacturing Plan	Subsystem Manufacturing plan with focus on manufacturing methods of key items	https://edms.cern.ch/document/2683353/1
Procurement Plan	Subsystem Procurement plan with focus on procurement management of key items	https://edms.cern.ch/document/2683352/1
Previous Review Tracking	Spreadsheet with previous review recommendations, see "Field structures"	https://edms.cern.ch/document/2741842
Cost	Basis of estimate and detailed M&S costs for field structures subsystems	https://docs.google.com/spreadsheets/d/1NtgO_rBCqmX_EAvlkQ6UzSGQZNhOEp7D/edit?usp=sharing&ouid=100144310335902562844&rtpof=true&sd=true
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
Mechanical Component Drawings	Subsystem mechanical component drawings	https://edms.cern.ch/project/CERN-0000220713
Mechanical Assembly Drawings	Subsystem assembly drawing	https://edms.cern.ch/project/CERN-0000220714
Parts list	Parts list for field structures	https://edms.cern.ch/project/CERN-0000220715

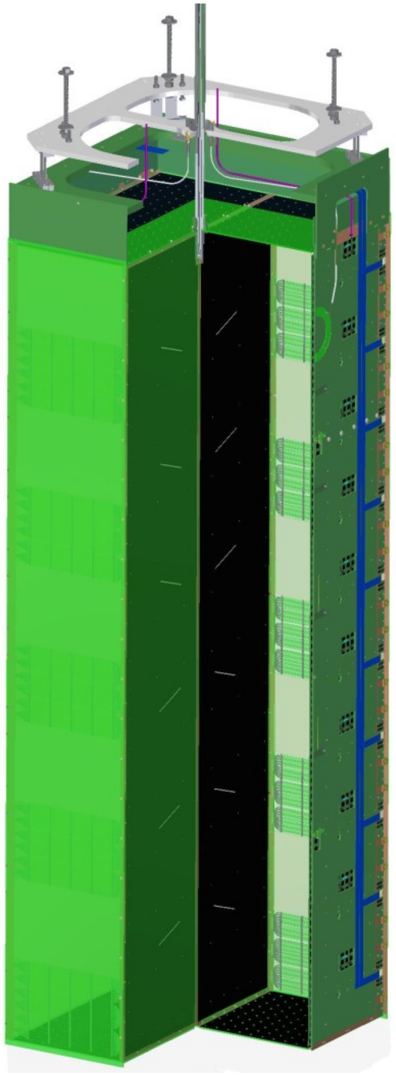
Scope

HV Cable & Feedthrough
Connection between HV supply and cathode: Warm cable, feedthrough, cold cable, and cathode connection.
Resistive cable.





Cathode & Field Shell
Weir to contain cold & pure LAr.
TPC panels with resistive material for continuous electric-field shaping and HV-breakdown protection.
Maximal active volume.
Dielectric shielding.
Opaque to scintillation light.



Anode support plane
Integrate all instrumentation & calibration. Provide rigidity to TPC.
Provide HV ground return.

Scope

Task/Item	Institutions	Funding Source	Funding Status	Detailed description
HV Cables	SLAC	DUNE-US Project	Allocated	Design, production, and assembly
HV Feedthroughs	SLAC	DUNE-US Project	Allocated	Design, production, and assembly
HV Cathode Attachments	SLAC	DUNE-US Project	Allocated	Design, production, and assembly
Cathode panels	MSU/SLAC	DUNE-US Project	Allocated	MSU/SLAC: Design; MSU production and assembly including the assembly of calibration targets (currently in Calibration WBS)
Field Cage panels, top	SLAC	DUNE-US Project	Allocated	Design, production, and assembly
Field Cage panels, bottom	SLAC	DUNE-US Project	Allocated	Design, production, and assembly
Field Cage panels, side	SLAC	DUNE-US Project	Allocated	Design, production, and assembly
Anode Support panels	SLAC	DUNE-US Project	Allocated	Design, production, and assembly (Need to talk with Mike)
Field Structure Assembly	SLAC/CSU/MSU	DUNE-US Project	Allocated	Design, SLAC/MSU/CSU: Assembly of First Module@MATF
Attachment hardware	SLAC	DUNE-US Project	Allocated	Design and production, SLAC/MSU/CSU: Assembly of First Module@MATF
Field Structure QA/QC tooling	SLAC/MSU/CSU	DUNE-US Project	Allocated	SLAC/MSU: Sub-components Design, production, and assembly, SLAC/MSU/CSU: QA/QC of First Module@MATF
Field Structure QA/QC labor	SLAC/MSU	DUNE-US Project	Allocated	SLAC/MSU: Sub-components Execution of QA/QC program, SLAC/MSU/CSU: QA/QC of First Module@MATF
Packaging and shipping	SLAC/MSU	DUNE-US Project	Allocated	Packaging and shipping to MATF
Assembly Procedures	SLAC/MSU	DUNE-US Project	Allocated	Subsystem procedures for use during A&T and I&I
Support during ND A&T	SLAC/MSU	DUNE-US Project/ SLAC (in-kind)	Allocated	Technical/scientific support during TPC Module assembly and test program at the MATF, including travel.
Support during ND I&I	SLAC/MSU	DUNE-US Project	Allocated	Technical/scientific support during TPC Module installation and integration at the DUNE Near Detector Site, including travel.

HV Cable & Feedthrough
35 x cathode connections, feedthroughs, warm cables, cold cables, cable splices.
Overage 10%.

Cathode & Field Shell
35 x cathode, 70 x side panels, 70 x perforated top/bottom panels.
Overage 19%, driven by vendors minimum order.

Anode support plane
70 x anode support panels.
Overage 19%, driven by vendors minimum order.

Contributing institutes:
CU-Boulder – alternative technology design & e-field sim
CSU – Assembly/transport fixtures
MSU/Hawaii – Integrated calibration design, production
SLAC – Design, production and assembly

Requirements

FCG-002 Electric Field Uniformity Provide an electric field with < 5% distortion throughout fiducial volume. Validated with Mod0 analysis, controlled with QAQC.

FCG-003 Electric Field Strength Able to support an electric field strength 0.5 kV/cm to match FD response. Design for 100% safety factor.

FCG-004 Unobstructed drift volume Full pixel plane should be exposed without physical obstructions. Design requirement.

FCG-005 Dead volume Detract <14% from the active volume. Validated through simulation (EDMS 2746966).

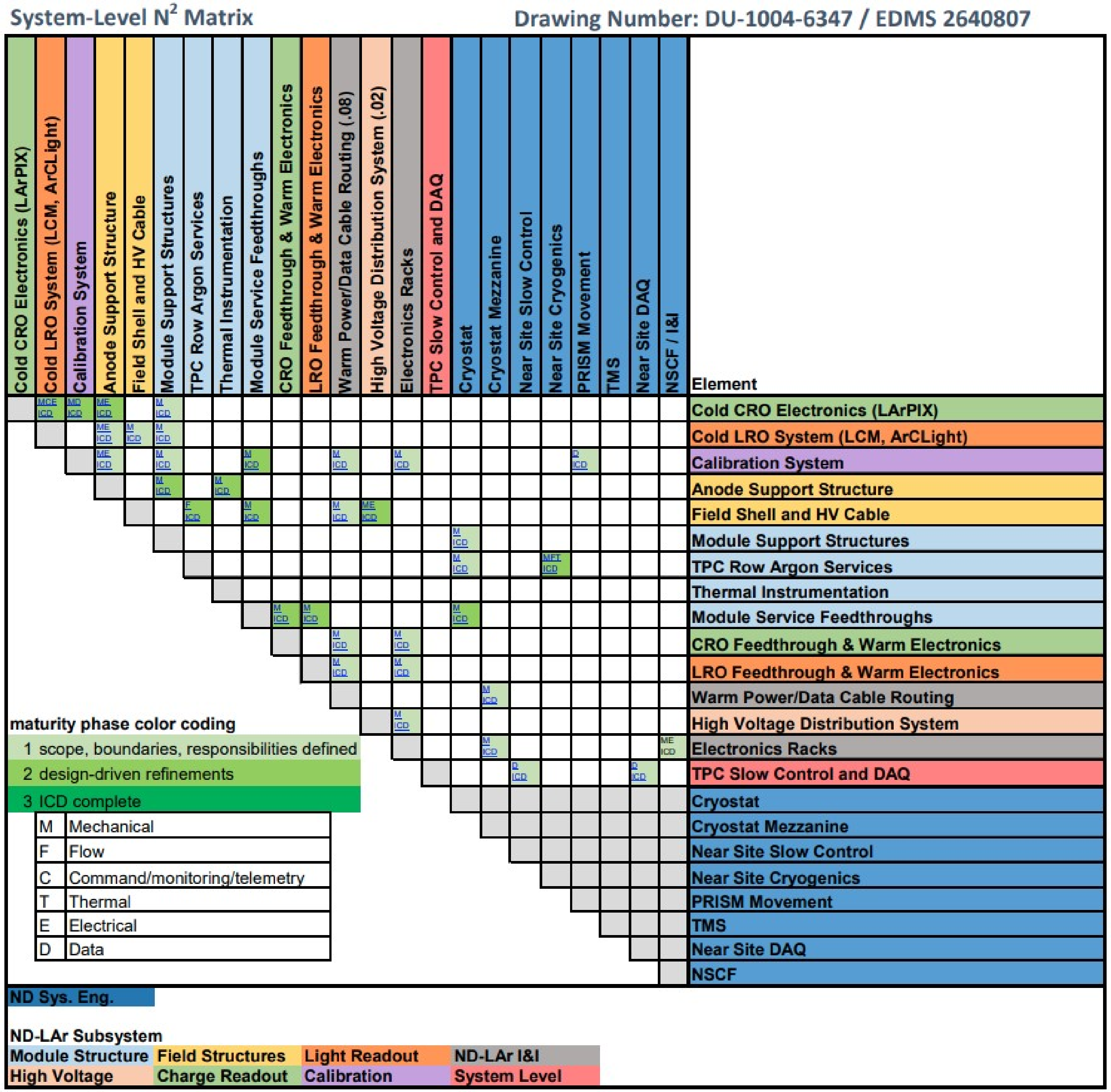
FCG-010 Contamination LAr impurity contributions from components shall be < 300 ppt (1 ms electron lifetime). Set material choice, validated with Mod0, EXO, & nEXO data.

FCG-012 Structural Support for instrumentation The FC shall mechanically support the light & charge readout components. Design requirement.

FCG-037 Optical containment Facilitate the measurement of prompt light signals, opaque structure and the optical path below the Rayleigh scattering length in Argon. Validated through simulations.

Interfaces

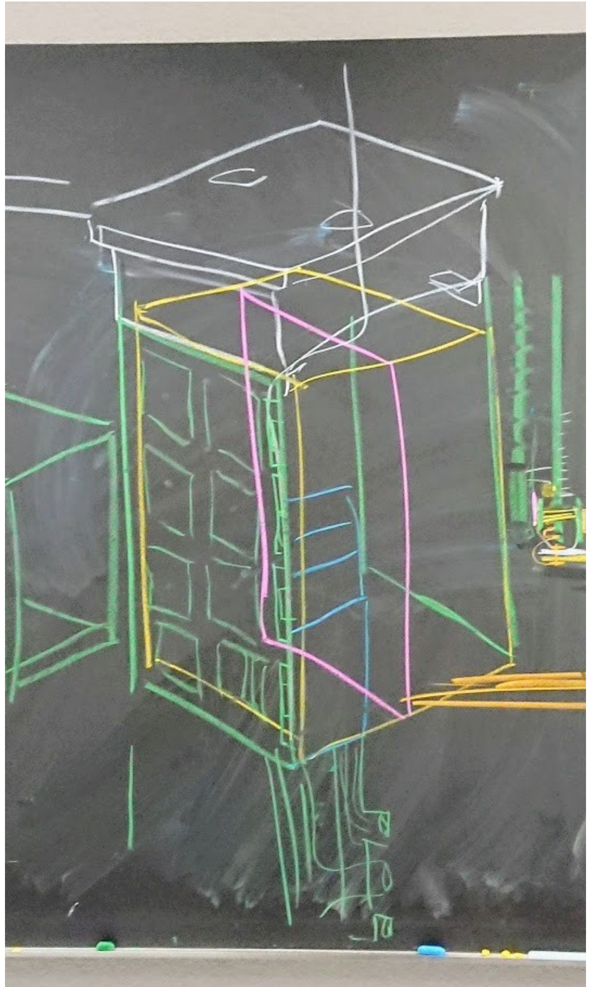
Subsystem	Interface	Maturity
Charge R/O	Electrical	Partially Defined
Charge R/O	Mechanical/Cabling	Defined
Calibration system	Mechanical/Cabling	Defined
Module Structures	Mechanical/Cabling	Partially Defined
Light readout	Mechanical/Cabling	Partially Defined
HV	Mechanical/Cabling	Partially Defined
I&I	Mechanical/Cabling	Partially Defined
Cryostat structure	Mechanical	Defined



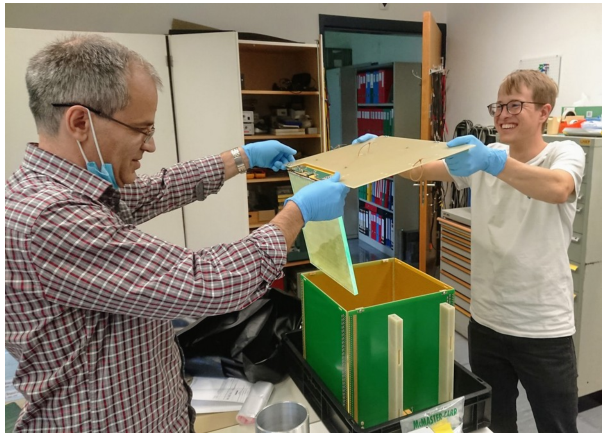
LBNF/DUNE

Interfaces

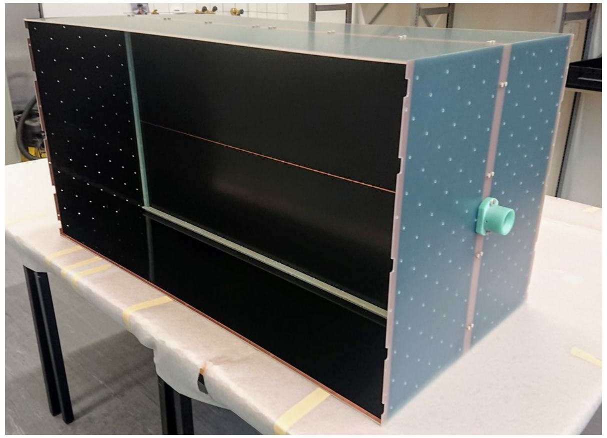
The interfaces have been validated using real-world experience with the 2x2.



April 2019

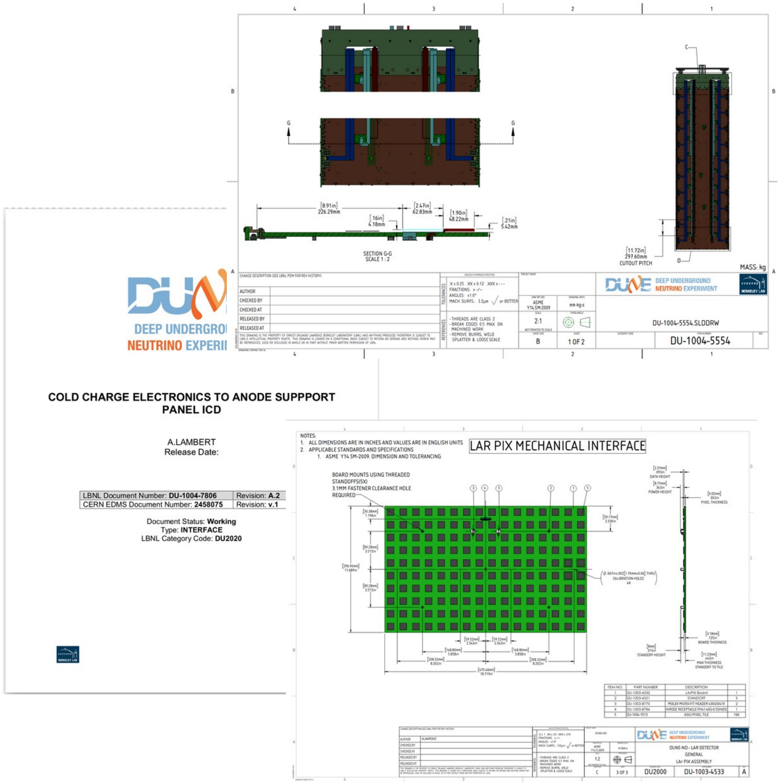


October 2020



November 2020

March 2021



QAQC, Procurement, Manufacturing

HV

Informed by EXO, & nEXO experience and prototyping. Production largely in house, only G10 guide tube externally produced. Full-Scale prototyping and first-article testing requires dedicated cold-HV test stand. Cable has been purchased, all other components need manufacturing.

Anode, Cathode, & Field shell Panels

QAQC Informed by 2x2, although technology not scale-able for ND (production/procurement). Only QAQC and assembly in house, production entirely with industrial partners.

The FSD will serve as a first-article purchase for all G10/FR4 panels. After panels clear QC for thickness, flatness, and fiber density, they are sent for water jetting. Following dimensionality check, the panels are plasma coated with Zn. Following metalization dimensional check, resistive layer applied at set thickness (75 um to 125 um) and carbon-loading ration (~0.6%).

The resistivity of every panel is verified, by bulk measurement and surface probe for local defects.

https://edms.cern.ch/ui/file/2683351/1/DU-1004-8566_FIELD_STRUCTURES_QAQC_PLAN.pdf

https://edms.cern.ch/ui/file/2683352/1/DU-1004-9081_FIELD_STRUCTURES_PROCUREMENT_PLAN.pdf

https://edms.cern.ch/ui/file/2683353/1/DU-1004-9080_FIELD_STRUCTURES_MANUFACTURING_PLAN.pdf

Risk and prototyping

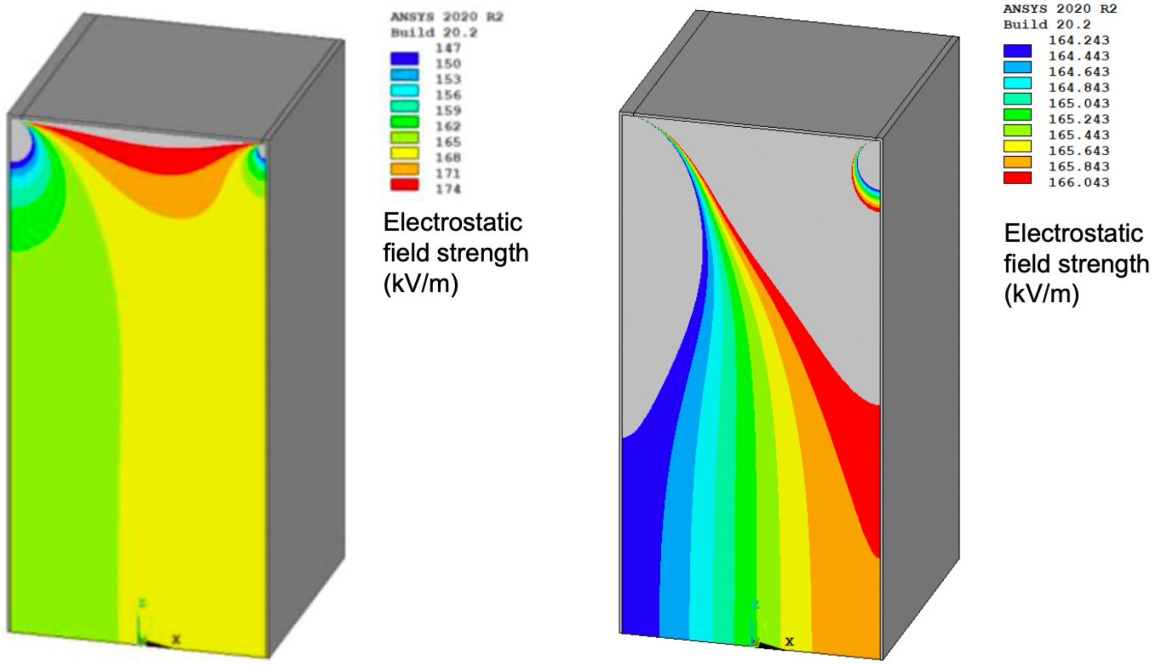
RI-ID	Title	Summary	Risk Mitigations	Post Mitigation Risk Exposure
RT-131-ND-200	ND-LAr: HV Cable No Longer Manufactured to Spec by Vendor	If the supplier of the HVE cable no longer provides the same product/design as that tested in all previous prototypes, then previous method of connecting to the core may need to be redesigned.	1 Work with manufacturer to develop a replacment with original product spec. 2 Redesign connection method	Medium, 35% 57 -- 105 -- 153 k$ 3 -- 6 -- 9 months somewhat substandard
RT-131-ND-080	ND-LAr: Fluid Flow across the module	If the LAr fluid flow within a module is insufficient to cool the power density of the electronics then there could be impact on electric field, noise or redesign of electronics	1. CFD Fluid flow analysis completed by E. Voirin @ FNAL - shows good thermalization and flow - running final study 2. Test with the 2 x 2 - compare liquid levels, see heat build-out near readout. temperature sensors. 3. Test full-scale demonstrator Proposed action: CSU could set up a dummy test with field cage mock-up and resistors ($50k)	Medium, 25% $400 k$ 3 -- 4 -- 6 months significantly substandard
RT-131-ND-119	ND-LAr: Uncosted Labor - Field Structure	If the uncosted labor for field structure is not realized or qualified, THEN schedule will be delayed	Identify and train students early	Medium, 35% -- -- k$ 3 -- 6 -- 12 months negligible impact
RT-131-ND-078	ND-LAr: Electric field uniformity	If the design does not meet field uniformity requirements, THEN event reconstruction performance will be degraded	1. Design and fabricate alternative prototype Field Structures. 2. Test in SLAC Single Cube - Off Project by SLAC 3. Select FS design and perform FEA Analysis to optimize field performance 4. Build 2 x 2 module and test at Bern Test Facility 5. Build Full Scale Demonstrator and test at SLAC Test Facility	Medium, 15% 48 -- 239 -- 429 k$ 1 -- 5 -- 9 months somewhat substandard
RT-131-ND-121	ND-LAr: Alternative Field Structure Concept does not meet performance	If a new alternative field structure concept that meets performance and reduces cost is not developed and verified by CD-3, then additional schedule and labor may be required to iterate on new concepts or the original MOD0 concept will have to be baselined	In kind prototyping and testing of four alternative field structure concepts	Low, % 200 -- 250 -- 500 k$ 2 -- 3 -- 6 months somewhat substandard

RT-131-ND-078: Electric field uniformity

Electric field simulation for the 2x2 geometry and comparison Mod0 results

DUNE Drift simulation 1

John Hodgson
8/18/2020

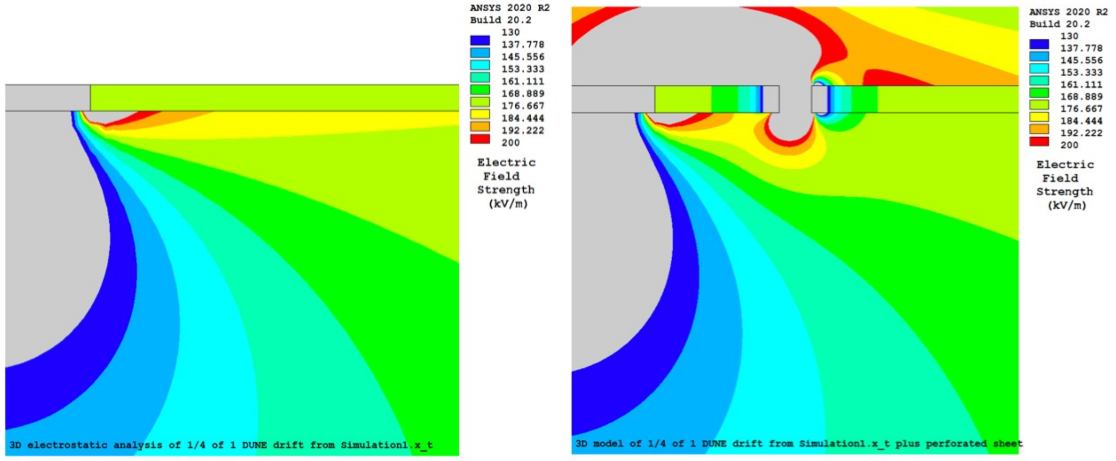


Rescaling legend shows how disturbance due to discontinuities extends some distance into LAr volume.

Rescaling legend again shows that even at the center plane of the drift the field is not uniform to much better than 1%.

DUNE Drift Electric Field Near Recirculation Holes

John Hodgson
11/18/2020



When viewed side-by-side with prior 3D analysis with no holes (left), new 3D analysis with holes (right) shows that the disturbance in the electric field due to these holes is small compared with the disturbance due to the cathode lip.

10

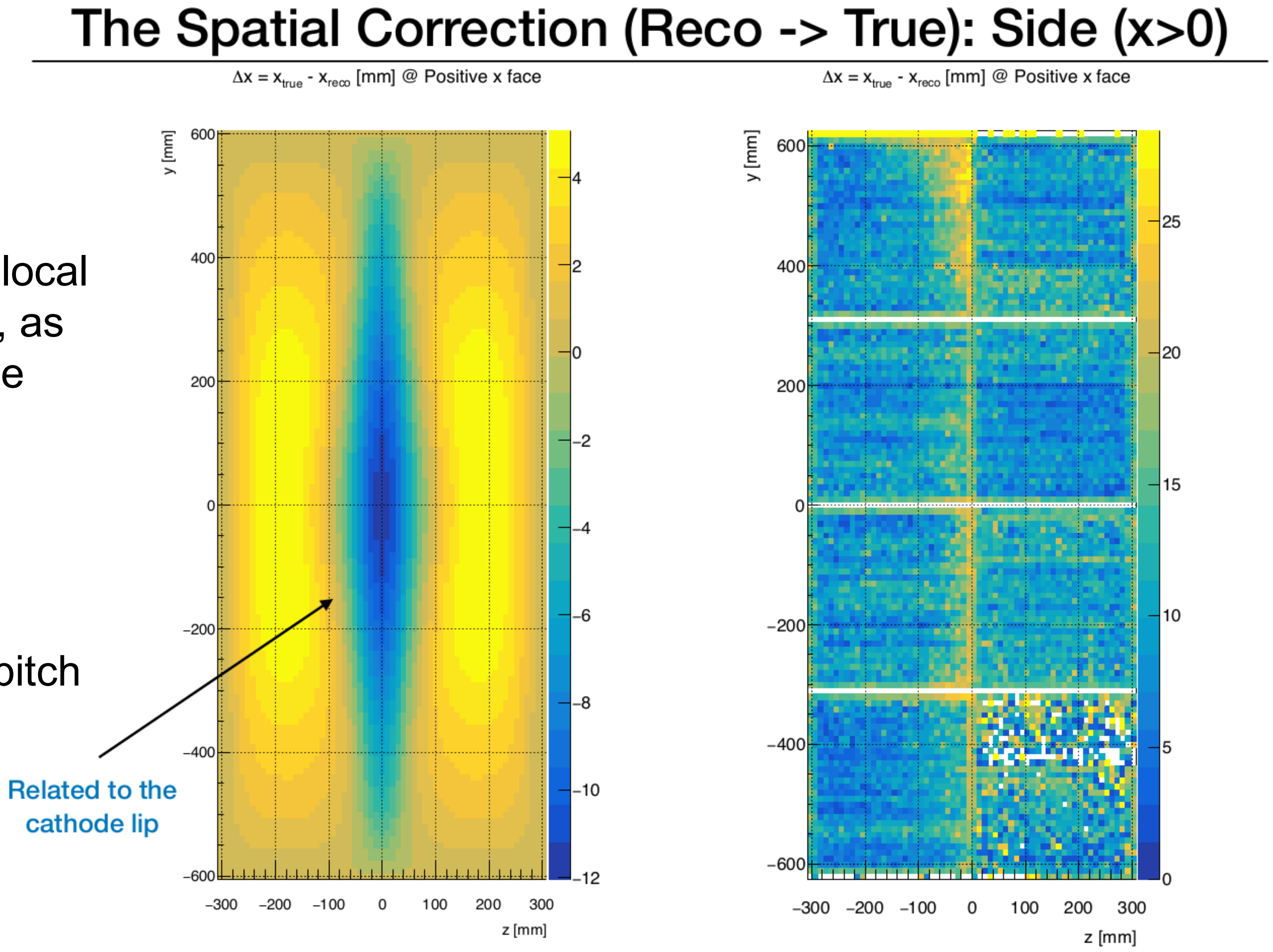
RT-131-ND-078: Electric field uniformity

Reconstructed spatial distortions need to be considered for this **NOT** variations in e-field.

It is possible for an e-field to have a very high local variation without measurable spatial distortion, as the spatial distortion is the integration along the drift length.

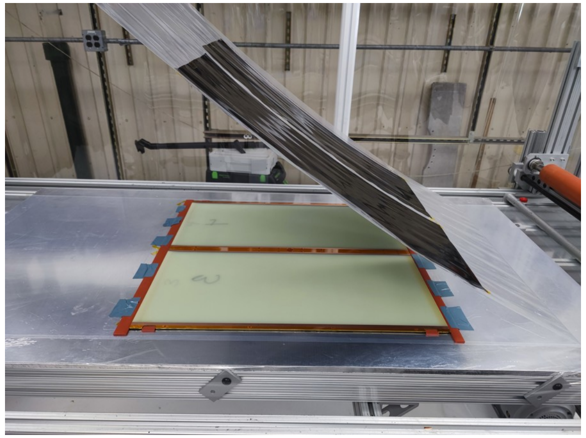
Simulation suggest ~2mm distortion.

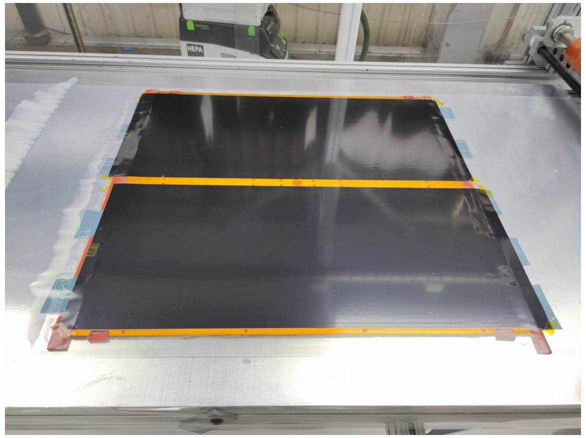
Data shows spatial distortions less than pixel pitch – not measurable.

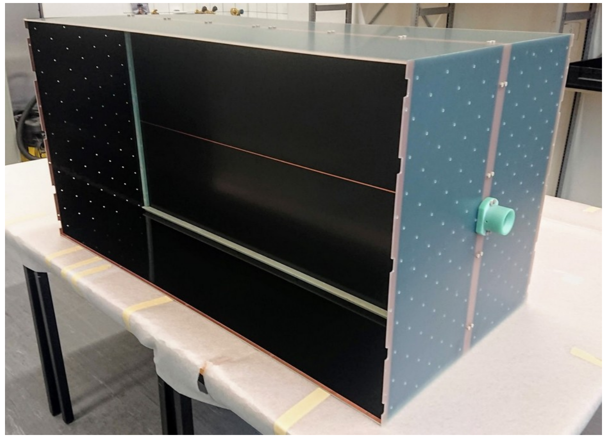


RT-131-ND-121: Alternative resistive materials

A field shaping technology was developed and refined for the 2x2, based on carbon-loaded Kapton (DuPont DR8). It formed the baseline design of the ND. Unfortunately, funding was not secured for this solution.



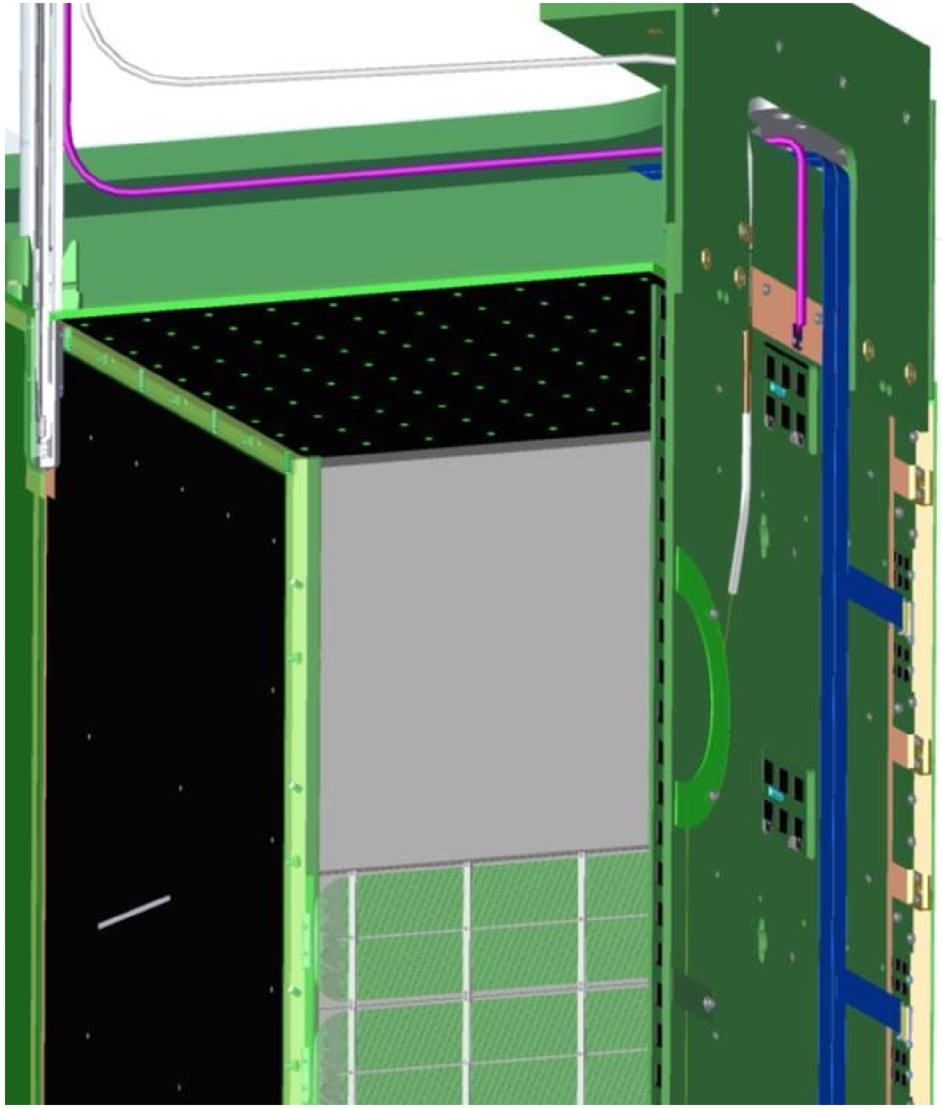




Two alternatives are being pursued.

- The preferential option is based on resistive carbon-loaded epoxy.
- The ultimate backup is based on a conventional resistor chain.

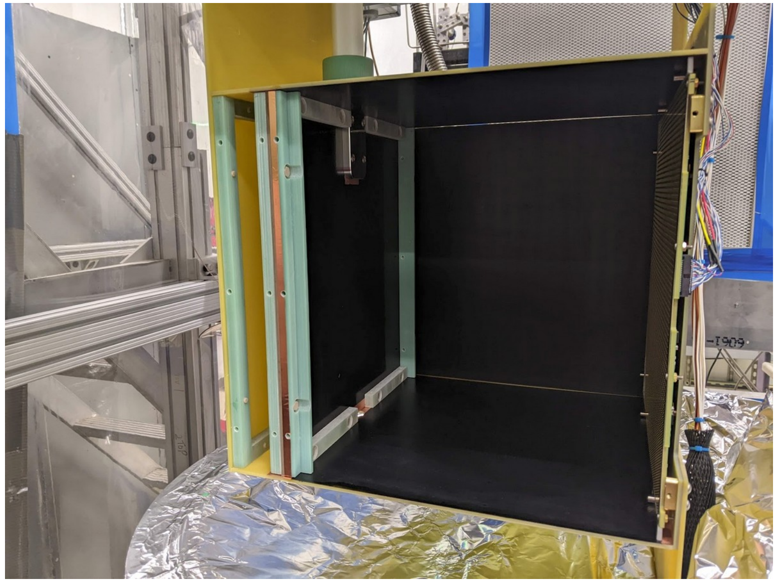
RT-131-ND-121: Alternative Carbon-Loaded Epoxy



This option requires no change to the mechanical design, it also uses the same epoxy as the DR8 lamination (cryo compatible and clean).

It has the same advantages as DR8 (breakdown protection), but is simpler to produce.

The technology has required significant R&D. The two current paths forward are working with industrial partners to optimize the coating and to demonstrate the scale-ability of the technology.



RT-131-ND-121: Alternative Carbon-Loaded Epoxy Optimization

Optimization parameters

- metallization – cryogenic stability, thickness, surface roughness (50 um Zn)
- substrate surface roughness – epoxy wetting – (2 um RMS)
- thickness currently 400 um (site limit), investigating 75 um to 125 um with industrial partner.
- carbon loading as function of thickness (0.75% by weight at 400 um)
- cold warping – thickness dependent, currently requires double layer epoxy
- coating and curing temperatures & time (baking reduces cryo stability) currently 24hrs at 36^{o}C, <20% humidity
- electric field curing

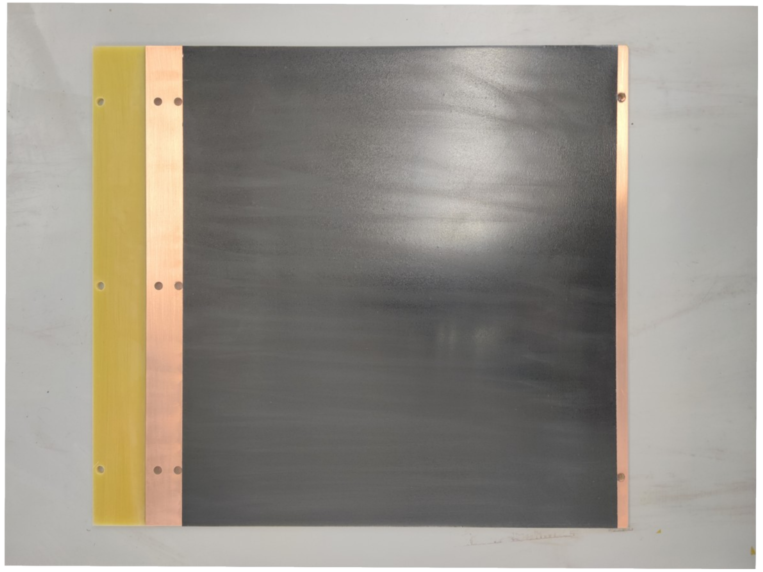
QC items

-bulk resistance measurements

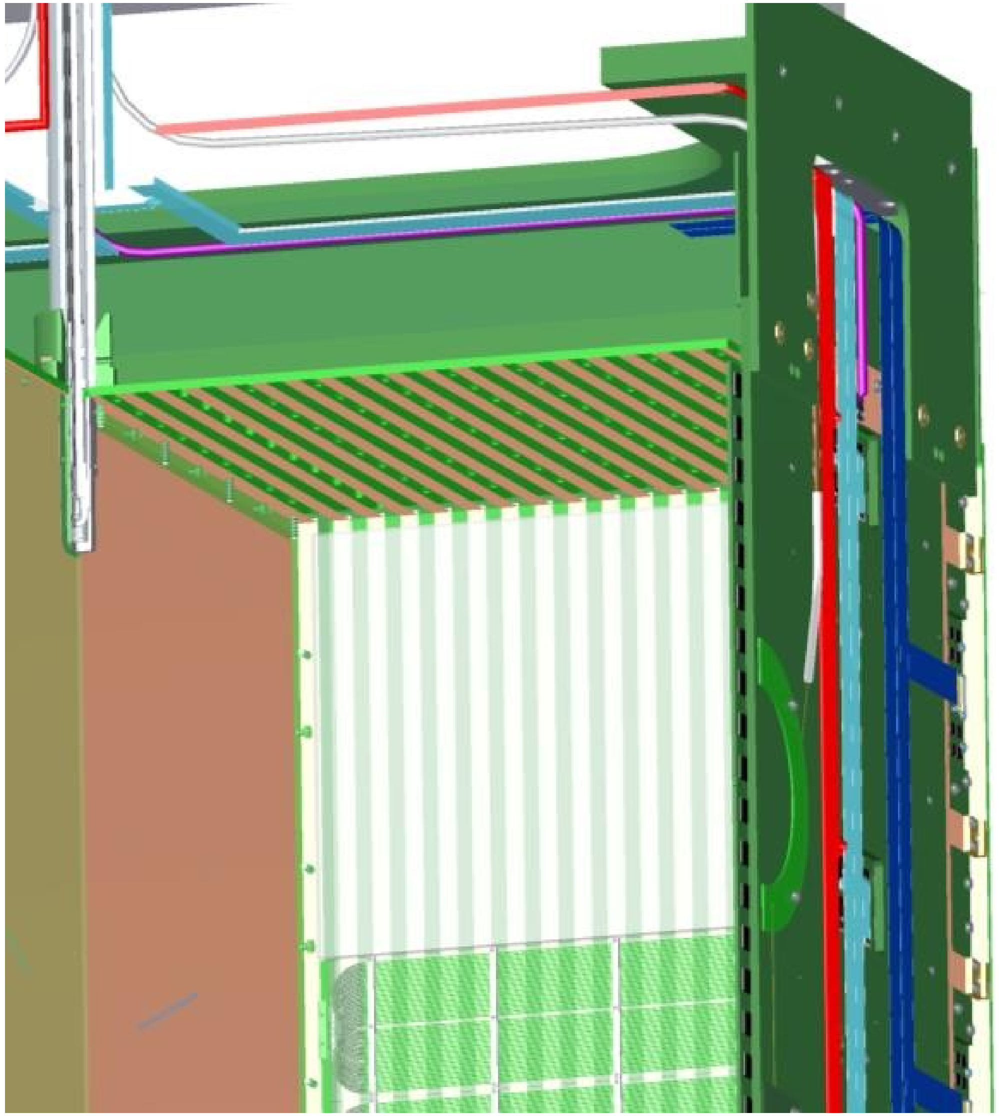
-segmented conductor (bulk/path test)

-surface resistance probe for local variation

-LN2 test stand cryo compatibility (mechanical & HV)



RT-131-ND-121: Alternative Resistor Chain



This option negates the robustness to HV breakdown.

It requires changes to the mechanical design of the top/bottom panel (same item) and weir panel. It also requires an additional resistor carrier board (x8 per module), and photo-etched metal clips.

Metalization remains the same, with only a change to the mask used for plasma coating.

For each TPC, 4 resistor carrier boards are clipped to the outer surfaces of the top and bottom panel, flush to the panels to not extend the electric field. The outer surface means no localized heating within the TPC. 4 resistor chains/TPC for redundancy.

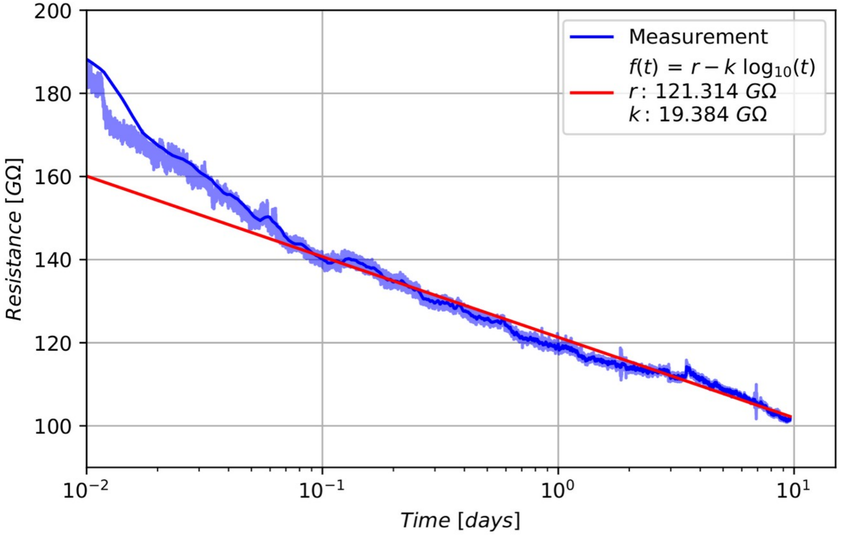
Resistor carrier is 50 x 2 cm^2 PCB with Gull-wing or J-lead mount resistor to mitigate heat-cycle fatigue failures in the solder joints.

Prototype plan: HV Test stand

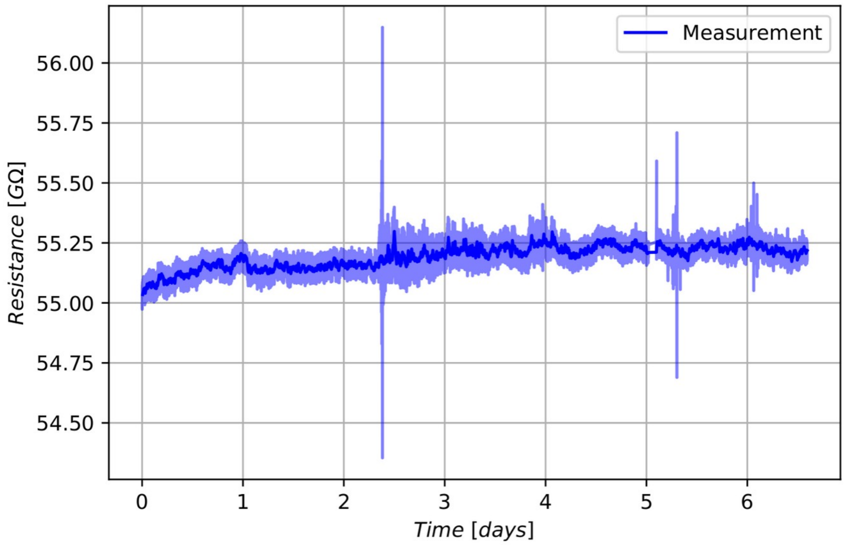
Uses 15 x 15 cm^2 samples to determine:

– Material/component stability in LAr at e-field

– Long-term e-field dependent aging



Carbon-loaded epoxy sample prior to field aging (log scale).

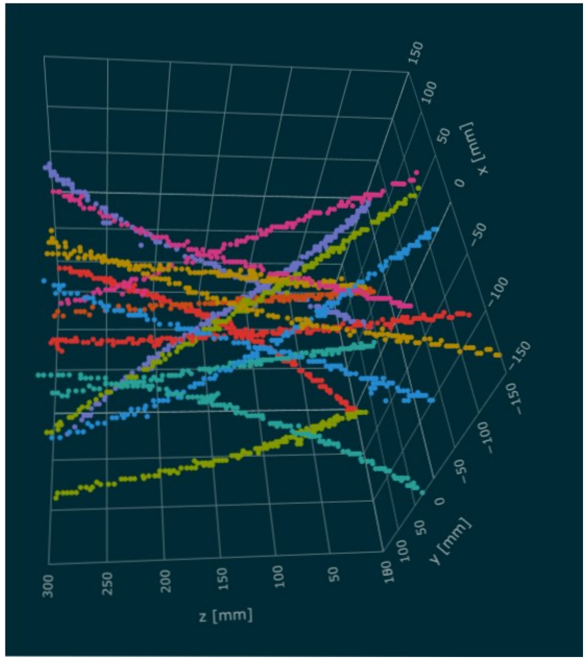


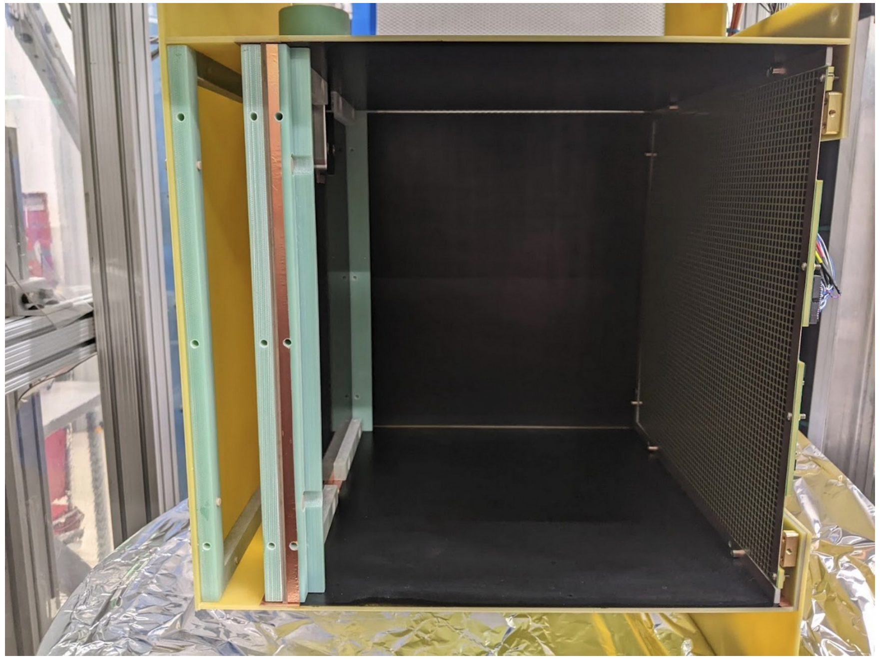
Carbon-loaded epoxy sample post field aging.

Prototype plan: SLAC SingleCube

SingleCube TPC with additional ground planes to ensures parallel e-field lines, plus full G10 frame at cathode to reduce e-field non-uniformity. (1.6 ms initial lifetime from single-pass filter)

– TPC Functionality
– HV stability, power consumption, and e-field uniformity
– LArPix cold testing for 2x2

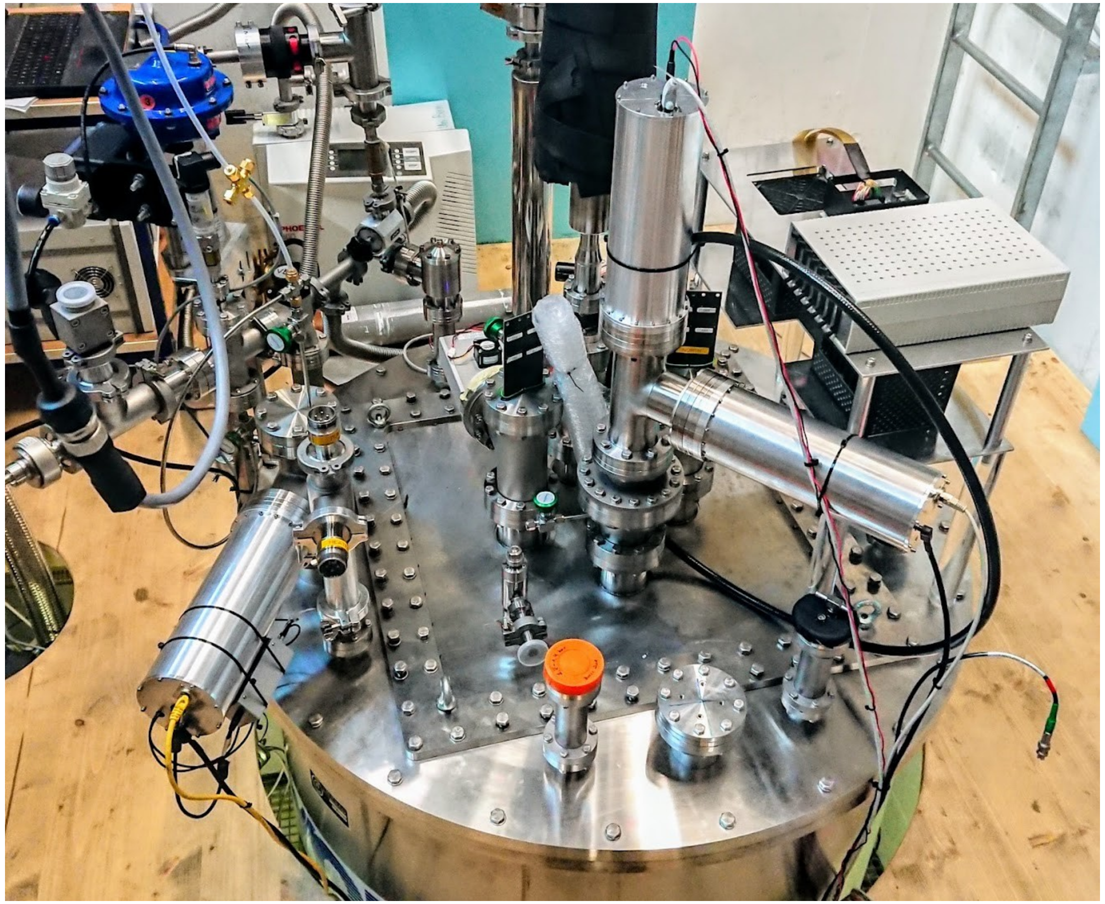


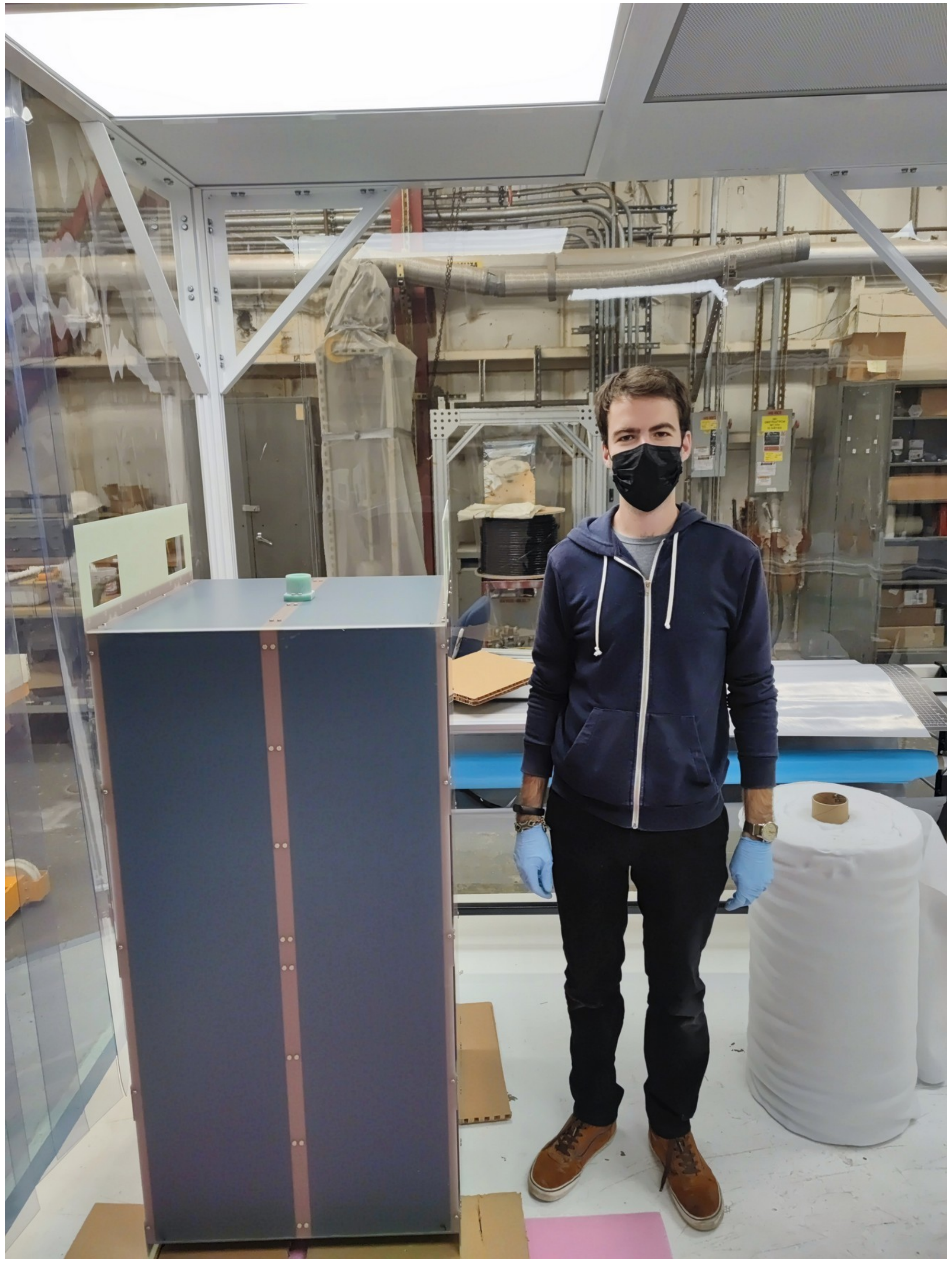


Prototype plan: Bern SingleModule

Demonstrate the scale-ability of the field-shaping technology (0.3 m → 1.3 m tall).

Cannot interfere with 2x2 production. Therefore, currently on hold.





LBNF/DUNE

ESH Codes and Standards

Adheres to all ESH codes/standards established by LBNF/DUNE & home institutional ESH requirements.

All Near Site deliverables must satisfy FNAL FESHM requirements.

2x2 Program providing experience through ORC process (HV) https://eshq.fnal.gov/manuals/feshm/

Specifically ND-LAr has completed an initial review of applicable areas of FESHM, found at EDMS 2602421
ND-LAr has also completed a Hazard Registry in coordination with the ND sub-project, found at
EDMS 2663898

- Occupational Safety
  - -Respiratory Protection (FESHM 4150), epoxy coating produces organic vapors
- Electrical Safety
  - -Electrical safety program (FESHM 9100)
  - -Grounding requirements (FESHM 9190)
  - -High Voltage Connections (FESHM 9150)

Recommendation from previous reviews

Recommendation	Status	Response
Study/calculate the effectiveness of the resistive cathode design in reducing the impact of unexpected HV discharges. Given the material and labor costs in the fabrication, decide if a simpler design is sufficient.	In progress	Input from needed from Charge RO group on max pixel current. Electrostatic simulation of discharge pending. Resistive components where possible, and low-resistance (<1 Ohm) HV ground return.
Conduct a Grounding Review with the DUNE Grounding and Shielding Committee.	In progress	Simulation and prototyping efforts on-going
Rephrase requirement FCG-010 in terms of outgassing rate.	Closed	Changed to <300ppt, corresponds to <1ms. Validated with Mod0, EXO, & nEXO.
Demonstrate that the uniformity of the DR8 film, or alternative resistive surfaces, is sufficient to meet the drift field uniformity requirement.	Closed	Mod0 data confirms expected electric-field induced distortions from simulation. See https://edms.cern.ch/document/2746965/1
Consider testing the performance of a Field Shell module in case of failure of adjacent modules.	In progress	Will require operational module array - 2x2

M&S Cost

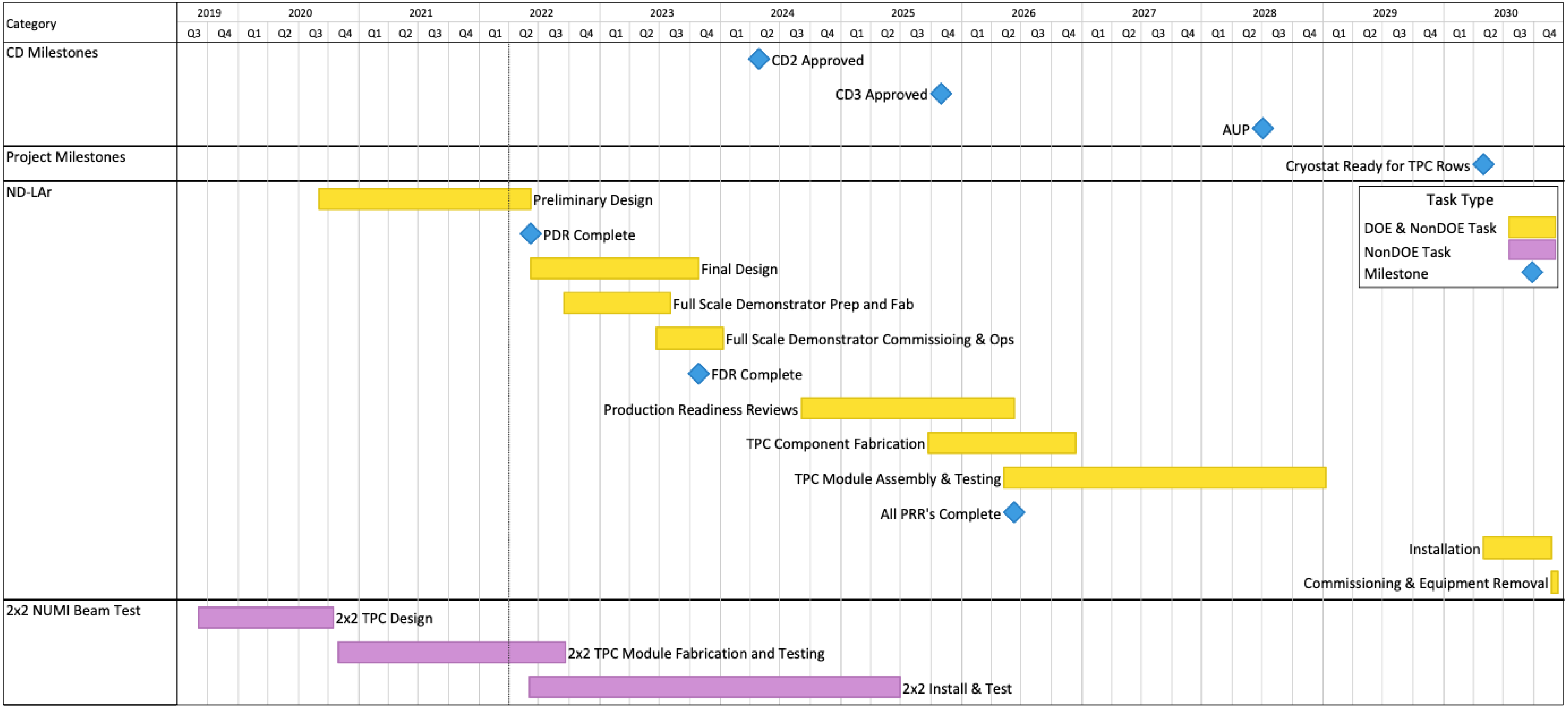
From Mar. 2022 cost review

WBS items	2x2 Module Actual Costs	FSD latest quotes	ND Module latest quotes
High Voltage	$5,231.72	$16,696.31	$1,549.40
Anode support panel	$2,050.70	$17,384.72	$11,985.75
Cathode	$7,271.34	$13,620.20	$8,534.47
Fiel Shell	$3,412.50	$23,885.59	$11,080.83
Epoxy	$3,000.00	$5,150.00	$1,293.43
Resistive Kapton	$18,191.77	N/A	N/A

G10/FR4 Panel increase significantly as no longer standard PCB dimensions.

Resistive Kapton was the 2x2 driving cost. It would correspond to $2.6M in the ND.
Risk RT-131-ND-121 was added in case alternative could not be found. Alternatives have been found.

Schedule



Category
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 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
2x2 NUMI Beam Test
2x2 TPC Design
2x2 TPC Module Fabrication and Testing
2x2 Install & Test
Task Type
DOE & NonDOE Task
NonDOE Task
Milestone

Summary

Based on 2x2 experienced the field structure design and its interfaces have advanced significantly.

Risk are well understood. We have had to realize the change in HV cable and adjust the design accordingly. Electric field simulations have informed design changes between the 2x2 and ND, 2x2 data has validated these simulations.

The risk burdened by not funding the DR8 is being mitigated by two options, the R&D for the resistive option is well advanced, and we are now working with industrial partners.

Costs are based on experience with 2x2 production and recent quotes using advanced drawings.

The only prior recommendation remaining to be studied is the impact of HV breakdowns. To minimize this, we have worked to make all components in the HV path resistive, and keep a dedicated ground return <1 Ohm.