131.ND.02 ND-LAr Systems Engineering and Management

Andrew Lambert, ND-LAr Lead Engineer

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

Mechanical Engineer at Lawrence Berkeley Lab since October 2011

Joined DUNE in January 2020

Previous projects:

Dark Energy Spectroscopic Instrument (DESI): 2013-2019

- Contributed to Focal Plane, Fiber, and Spectrograph Systems – DESI Builder Award
- Conceptual design through instrument installation at Kitt Peak outside of Tucson, AZ

LUX-Zeplin (LZ) Dark Energy Experiment: 2016-2020

- Contributed to Thermosiphon, Signal Breakout, and LXe Systems

Project X Injector Experiment (PXIE): 2011-2014

- Analysis and fabrication of 162.5 MHz radio-frequency quadrupole (RFQ) for PXIE

Other Projects: Muon Ionization Cooling Experiment (MICE), Zwicky Transient Facility (ZTF) Camera

Outline

- Key Documents
- ND-LAr Engineering Team
- ND-LAr Module Overview
- Design Elements & Status / CAD model
- Requirements
- Interfaces
- Analyses
- Documentation Tour
- EH&S / Codes & Standards
- Open design issues / Final Design
- Summary

Key Documents can be found at PDR Documentation Directory, EDMS 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

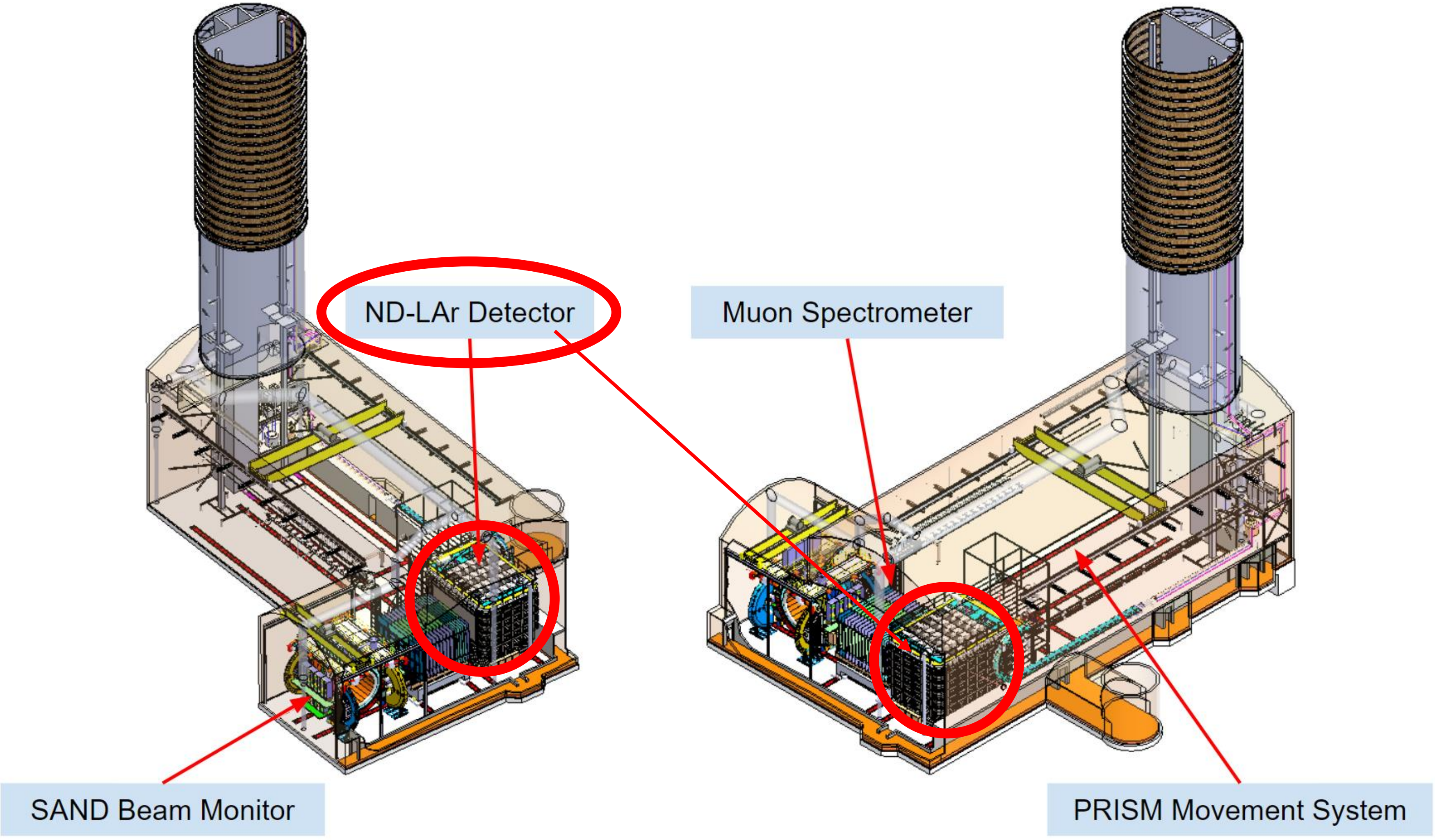
The ND-LAr engineering team has broad and deep experience with members hailing from all over the globe

- Engineering contributions from a dozen different institutions spanning multiple time-zones across both the USA and Europe
  - Mechanical, electrical, cryogenic engineering expertise
  - Reviewers will hear from Lead Engineers from each major ND-LAr subsystem over the coming days
- Weekly engineering meetings
  - https://indico.fnal.gov/category/924/

Name	Area	Institution	Yrs. Exp.
Silas Bosco	Mech	Bern	16
Roger Hanni	Mech	Bern	25
Jan Christen	Mech	Bern	15
Lorenzo Meier	Mech	Bern	10
Camilla Tognina	Elec	Bern	11
Knut Skarpaas	Mech	SLAC	32
Haufai Auyeung	Mech	SLAC	30
Marco Oriunno	Mech	SLAC	26
Brian Qui	Cryo	SLAC	18
Armin Karcher	Elec	LBNL	25
Carl Grace	Elec	LBNL	18
Dario Gnani	Elec	LBNL	18
Tarun Prakash	Elec	LBNL	4
Panos Zarkos	Elec	LBNL	1
Andrew Lawrence*	Mech	LBNL	5
Rama Kuravi*	Mech	LBNL	10
Thomas Rathmann*	Mech	LBNL	20
Hans-Gerd Berns	Elec	UC Davis	31
Priya Sundararajan	Elec	UC Irvine	20
Chithra Kurup	Elec	Rutgers	10
Alexander Selyunin	Elec	JINR	12
Sergei Sokolov	Mech	JINR	9
Dmitriy Fedoseev	Elec	JINR	15
Chetverikov Alexey	Elec	JINR	4
Vladislav Sharov	Soft	JINR	4
Vladimir Kozhukalov	Soft	JINR	17
Denis Korablev	Soft	JINR	17
Kuznetsova Kseniya	Mech	JINR	5
Vyatcheslav Chalyshev	Mech	JINR	48
Morgan Bonnet	Mech	U-Hawaii	17
Dean Schooltz	Mech	MSU	15
Michael Geynisman	Cryo	FNAL	43
Michael Zuckerbrot	Cryo	FNAL	13
Jay Jablonski	Mech	CSU	22
Zach Rautio	Mech	CSU	5
Culmulative Years Experience			**591**

**Moved on to other opportunity*

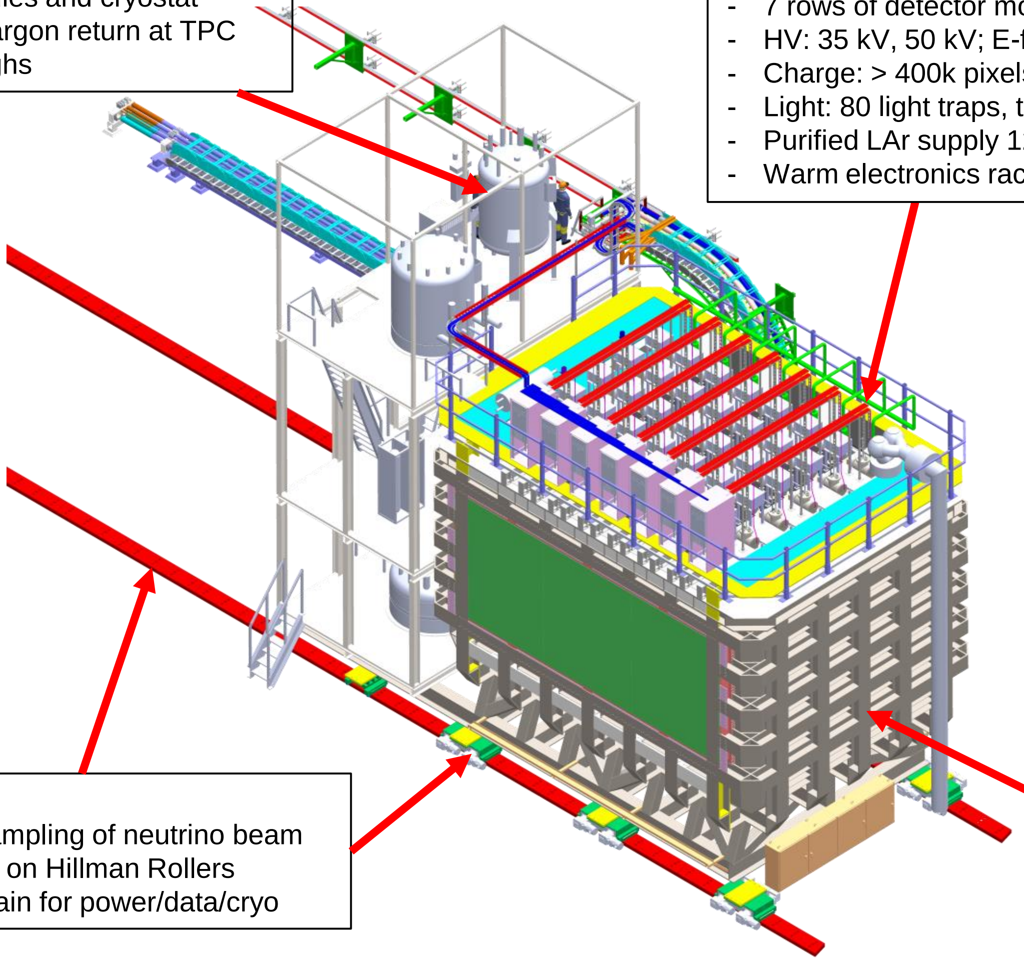
ND Hall Layout; ND-LAr is one of three detectors in at the Near Site → first detector the neutrino beam encounters

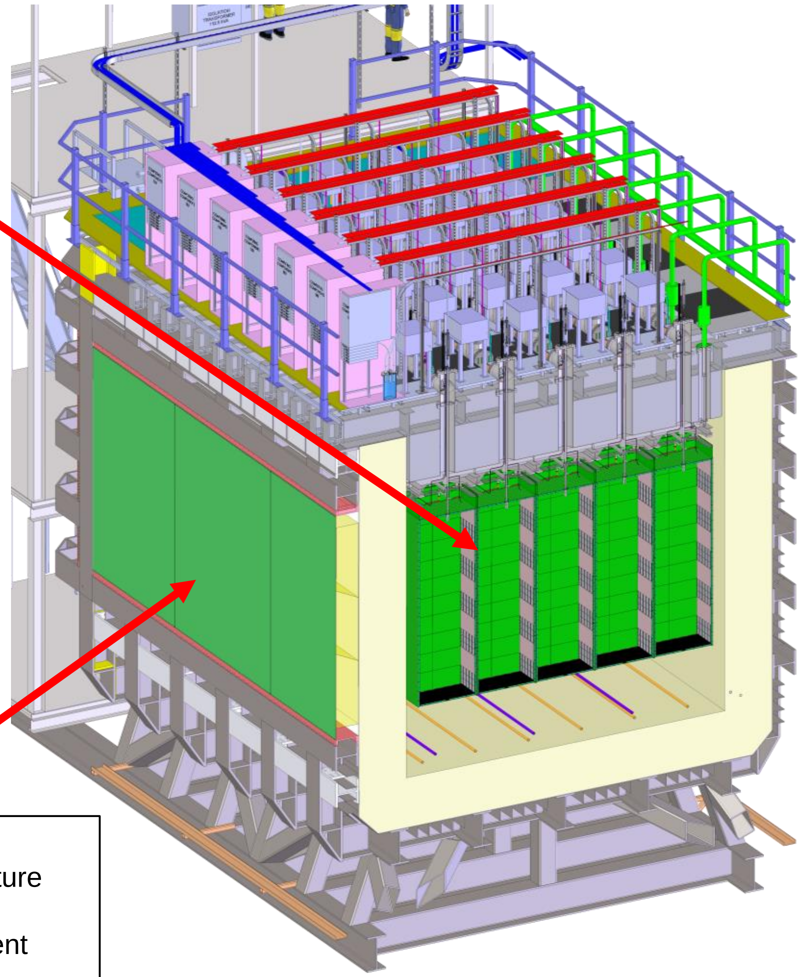


ND-LAr provides the TPC detectors to the Near Site, which are later integrated with other ND systems to realize the full detector capability

Cryogenics
- Provides purified liquid argon to TPC modules and cryostat
- Gaseous argon return at TPC feedthroughs

ND-LAr Consortium (TPCs)
- 3m x 5m x 7m detector volume
- 7 rows of detector modules, 5 per row
- HV: 35 kV, 50 kV; E-filed: 0.5 kV/cm, 1.0 kV/cm
- Charge: > 400k pixels, resolution < 4.7 mm
- Light: 80 light traps, time resolution < 10 ns
- Purified LAr supply 125 g/s per row
- Warm electronics racks, cable trays

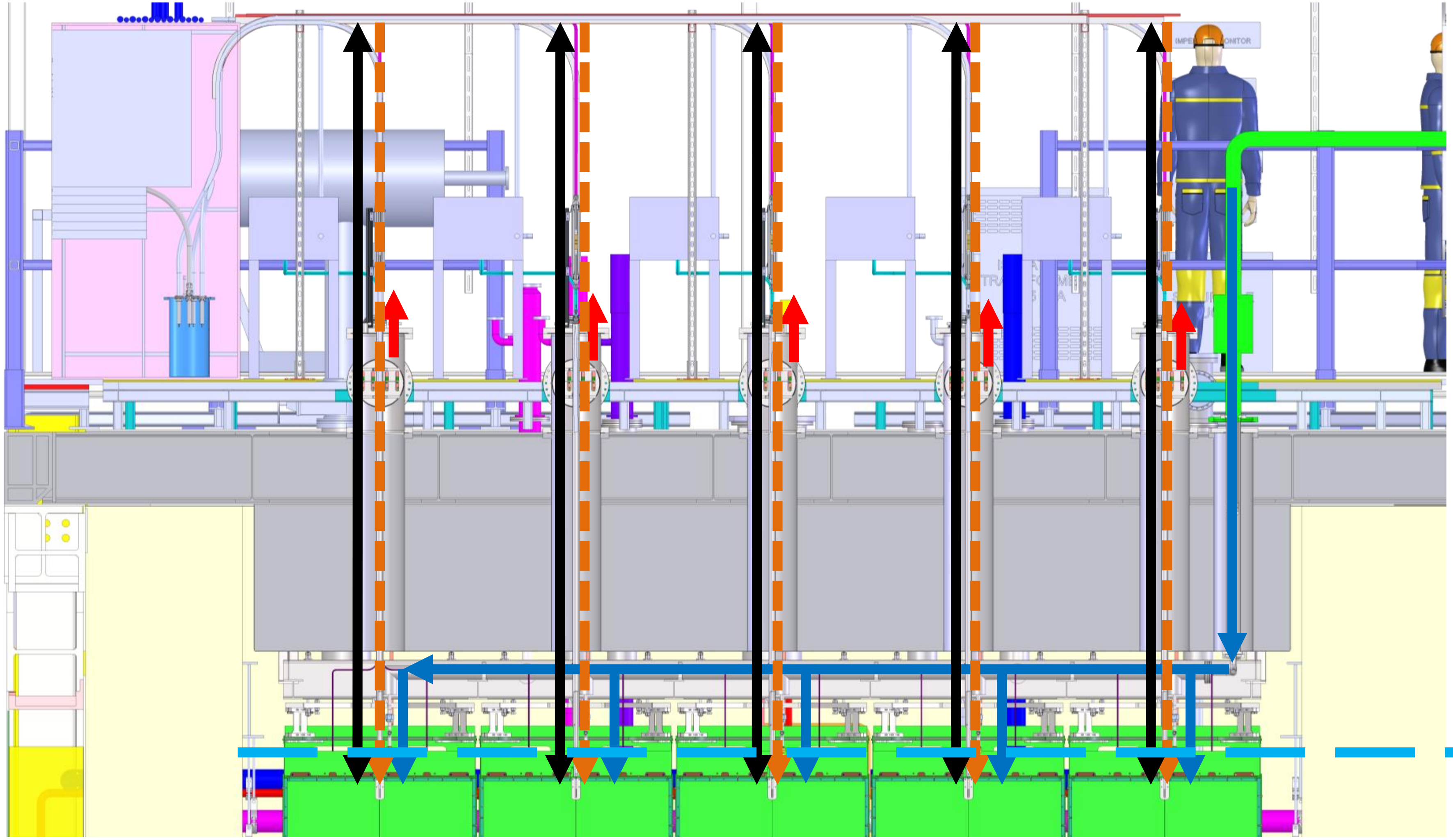




PRISM
- Off-axis sampling of neutrino beam
- 28m travel on Hillman Rollers
- Energy chain for power/data/cryo

LAr Cryostat
- Exterior warm steel structure and warm muon window
- Stainless steel containment membrane
- Top lid and mezzanines

Each TPC module has individual services for cryogenics, high voltage, power/ground, signal I/O – all services go through the cryostat lid (Interface)



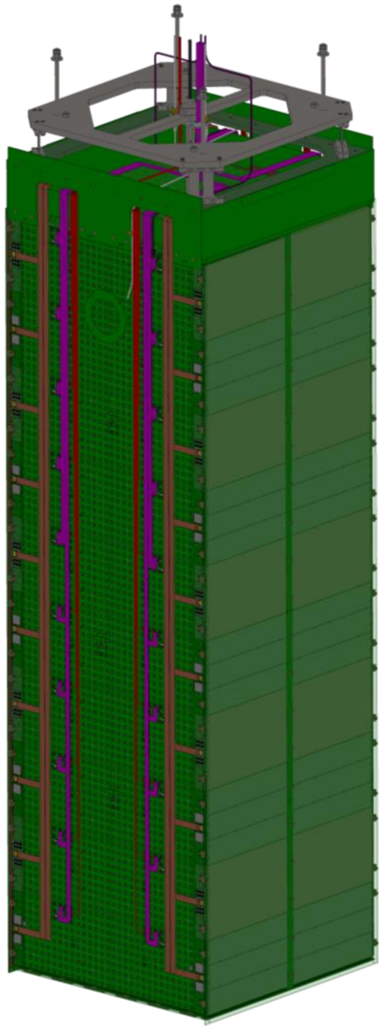
- LAr Supply
- GAr Return
- High Voltage
- Signal and Power

Gaseous Argon

LAr Level

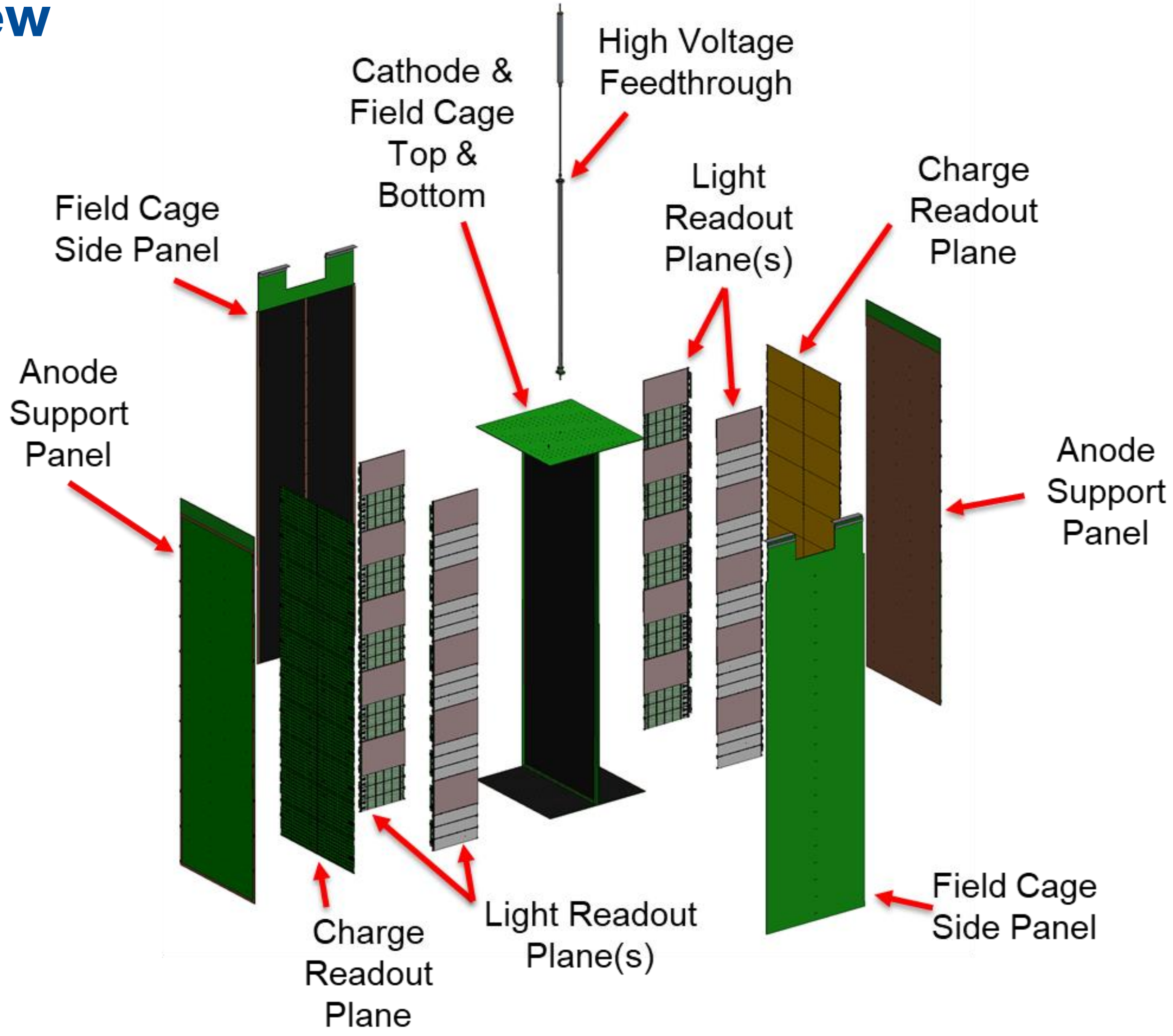
Liquid Argon

131.ND.02 ND-LAr TPC Detector Overview



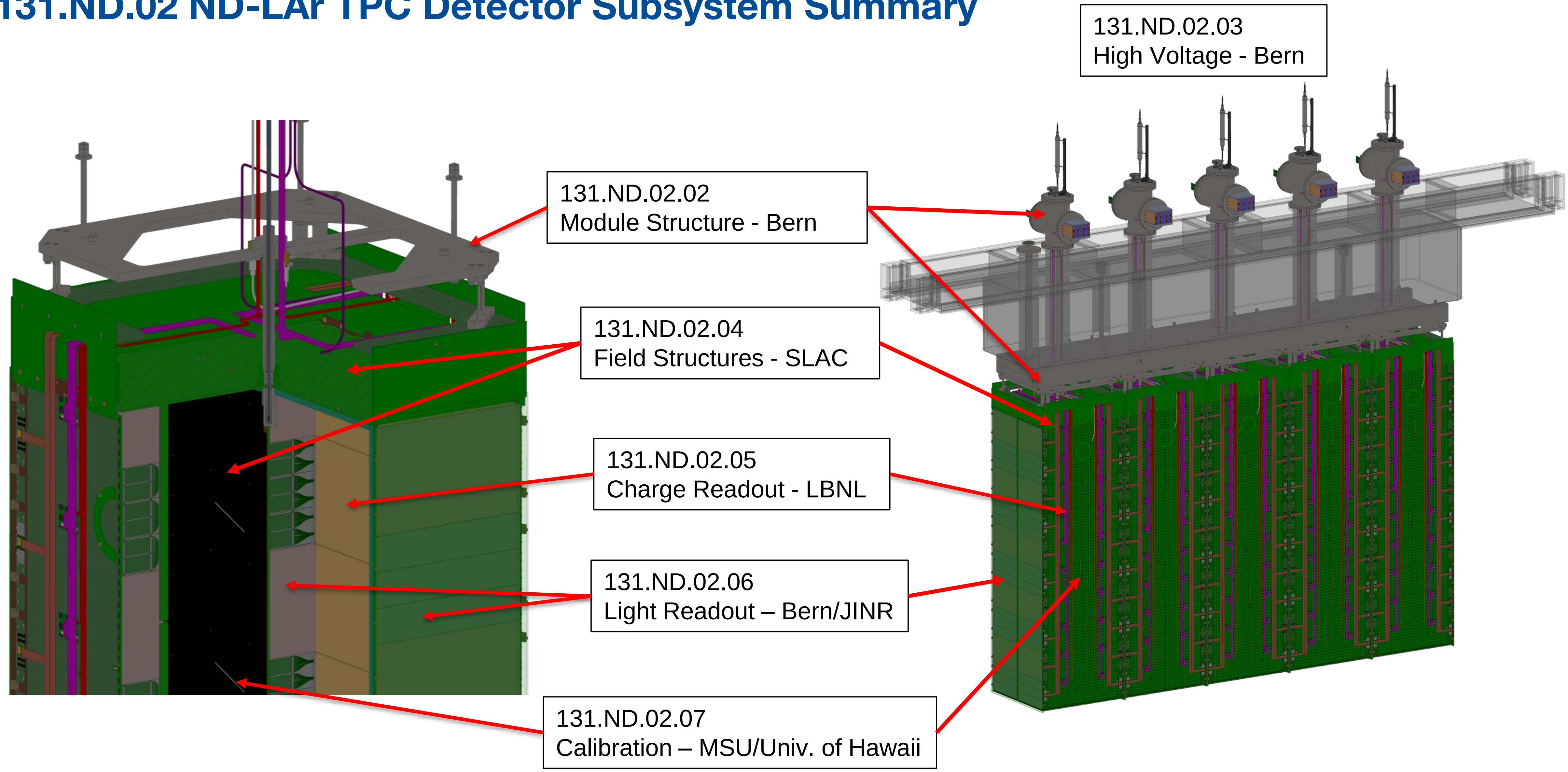
Top Level TPC Assembly, DU-1004-5554, EDMS 2737744
ND-LAr produces 35X TPCs

- **Modular LArTPC** utilizing true **3D charge imaging** and scintillation light containment via **optical segmentation** to match charge-light signals -> accurate reconstruction of neutrino-Argon nucleus reactions in a high pile-up environment
- **Low profile field cage** and cathode structure to maximize instrumented region and provide optical segmentation
- **1m x 1m x 3m nominal module size** -> mean of 6 events per half module per beam spill -> less ambiguity in neutrino event reconstruction



Main Elements of ND-LAr TPC Module

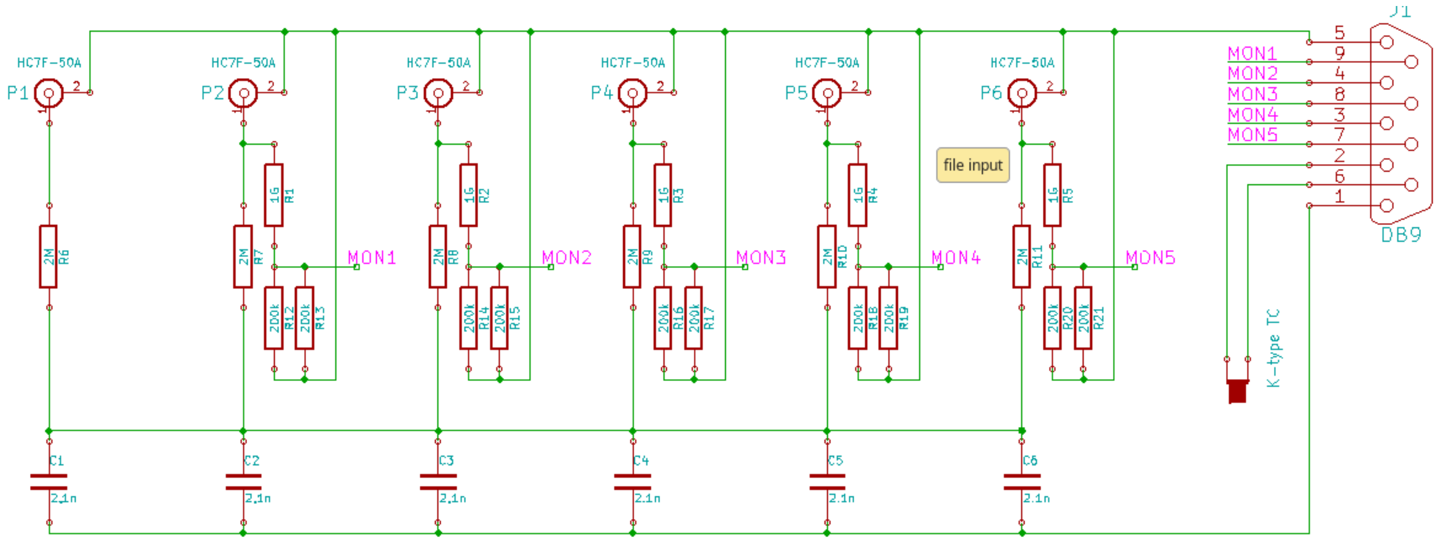
131.ND.02 ND-LAr TPC Detector Subsystem Summary



High Voltage (131.ND.02.03)

Engineering Lead – Saba Parsa (Bern)

Module Row High Voltage Schematic



HV Filter

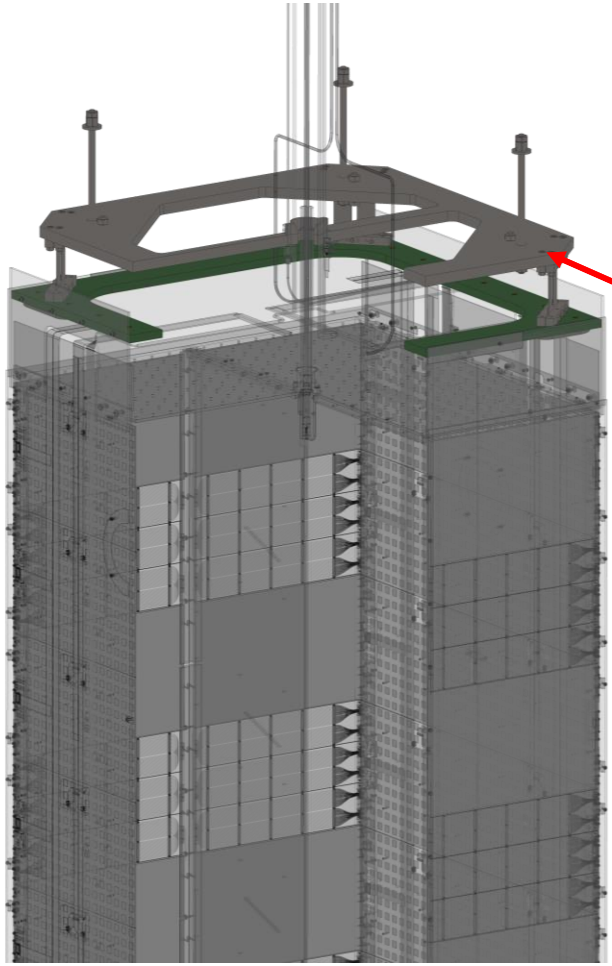
- Low-pass filter with large capacitor & small resistor to prevent voltage drop
- Additional resistors at outlet set to match cathode voltages

HV Supply

- Provide 60kV and 5 mA
- Within range of standard power supplies

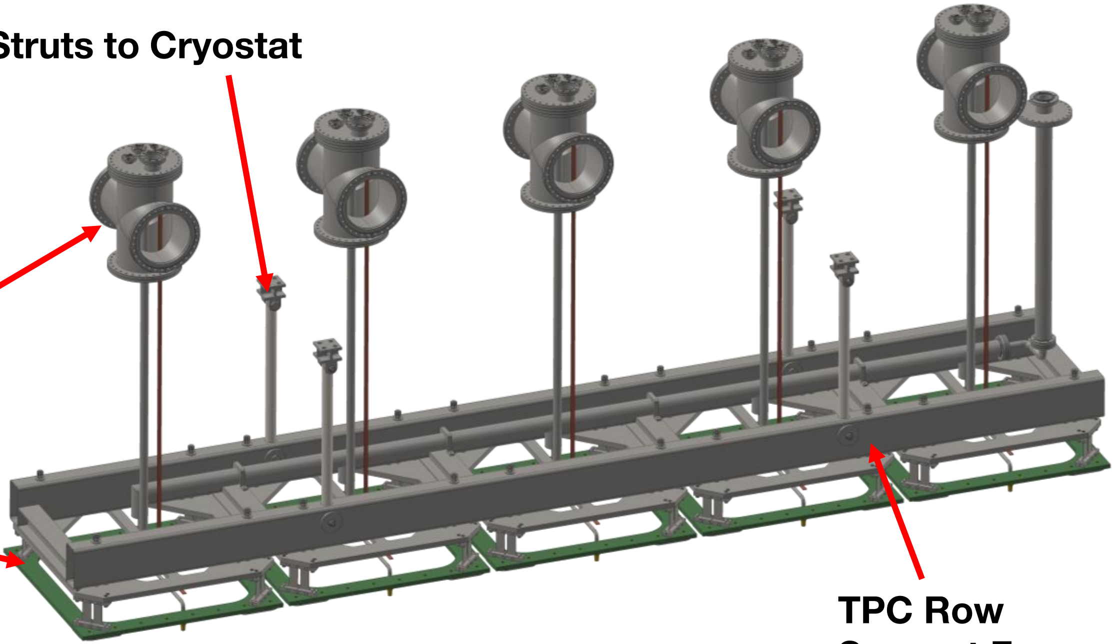
Module Structure (131.ND.02.02)

Engineering Lead – Silas Bosco (ME, Bern)



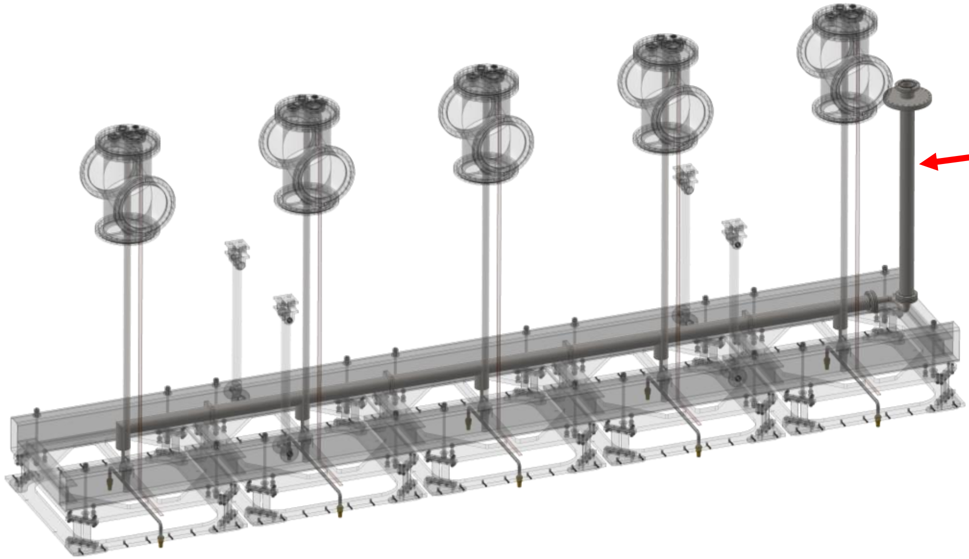
Struts to Cryostat

4-way Cross Feedthroughs and Top Flange

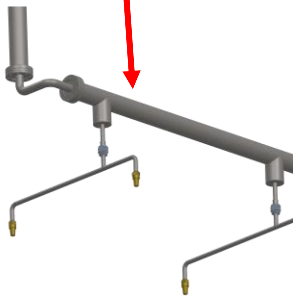


TPC Support Structure

TPC Row Support Frame



LAr Distribution Line, supply to each module



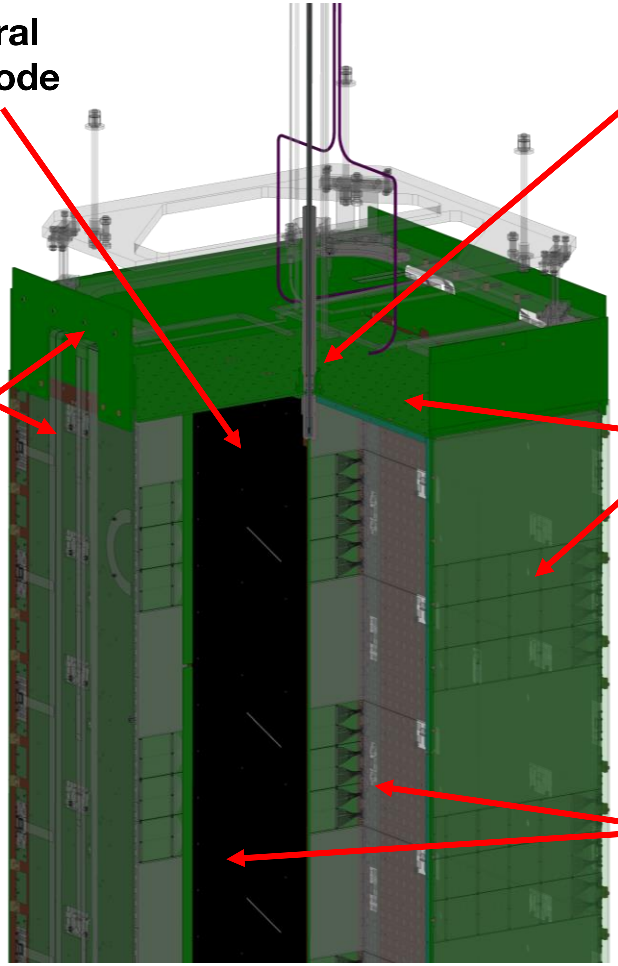
Field Structures (131.ND.02.04)

Engineering Lead – Knut Skarpaas (ME, SLAC)

Central Cathode

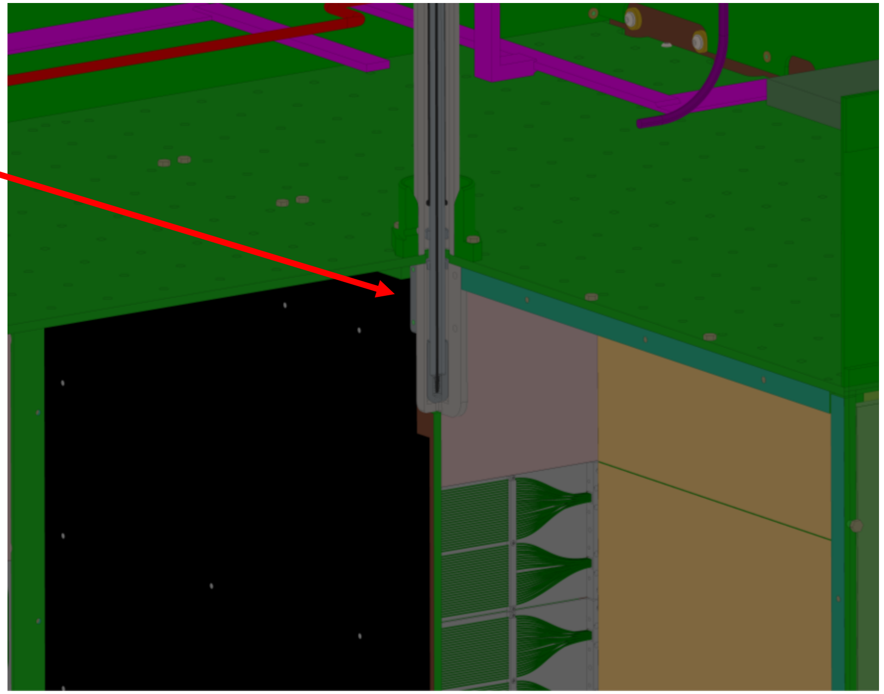
HV Delivery

Anode Panels
- **Supports charge and light readout**



Field Cage
- **G10 construction**
- **Optical segmenataion**

Dual drift field regions at 500 V/cm



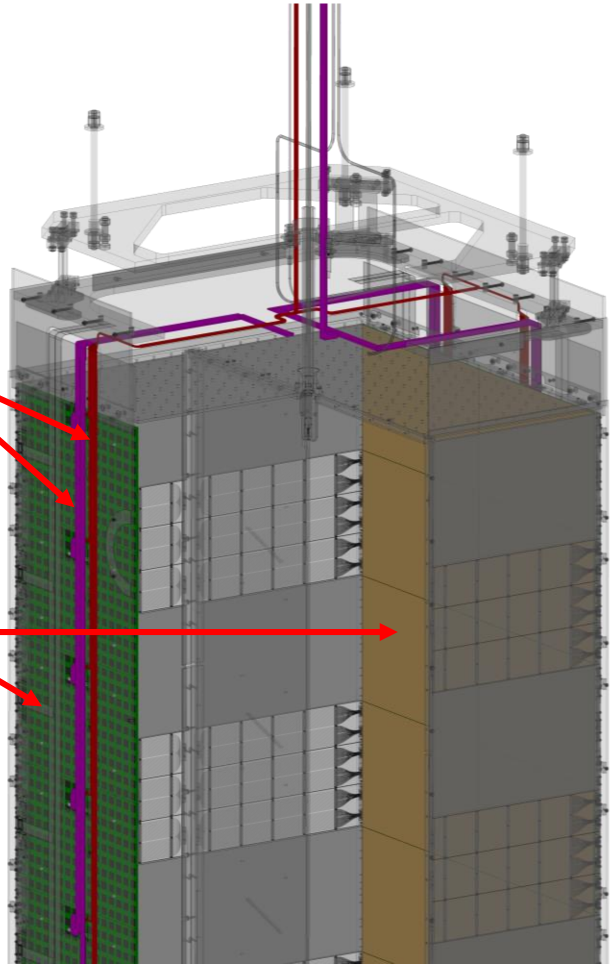
High voltage feedthrough input at top of cathode (25 kV)
- Resistive polymer central conductor
- PTFE tube guide to provide support
- Conductive “pill” termination
- Designed for (n)EXO and ArgonCube 2x2
- Successfully fabricated and tested at SLAC – also successfully used in Univ. of Bern Module 0 and Module 1 tests

Institutions:
SLAC, Bern, CSU, MSU, U-Mich, UCSB

Charge Readout (131.ND.02.05)

Engineering Lead – Armin Karcher (EE, LBNL)

Charge and Data Cables

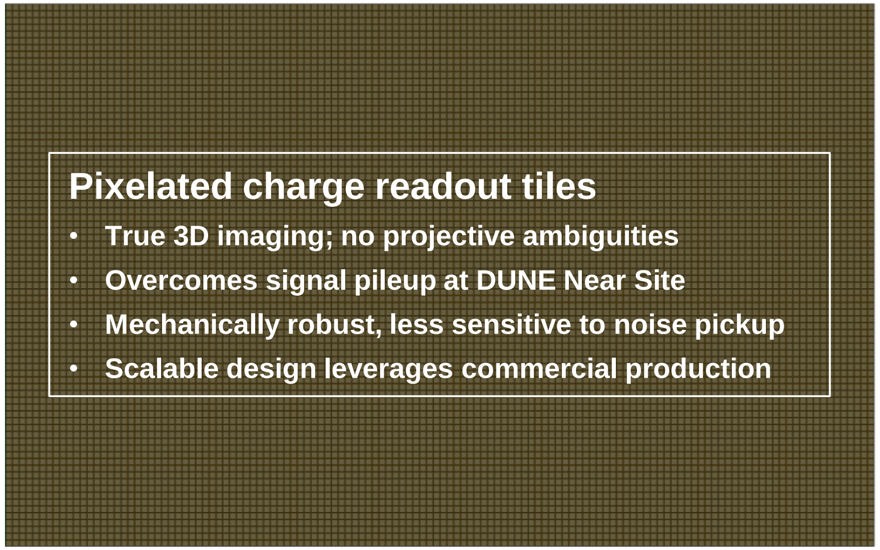


Pixel Tile w/ASICs

Institutions:
LBNL, Caltech, CSU, Rutgers, UC-Davis, UCSB, UPenn, UTA

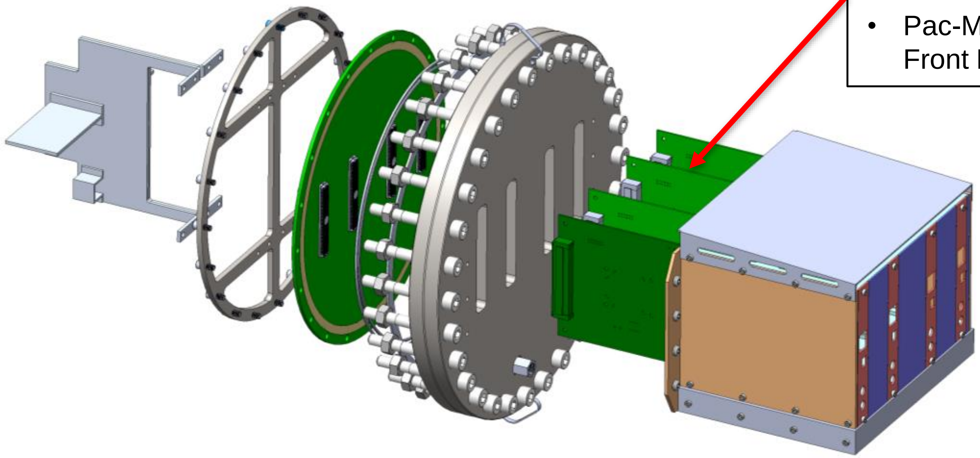
LArPix: Custom pixel readout ASIC

- Provides low-noise, low-power, cryogenic readout
- SOC: amplification, digitization, triggering, readout
- Implements highly-scalable control, I/O architecture



Pixelated charge readout tiles

- **True 3D imaging; no projective ambiguities**
- **Overcomes signal pileup at DUNE Near Site**
- **Mechanically robust, less sensitive to noise pickup**
- **Scalable design leverages commercial production**

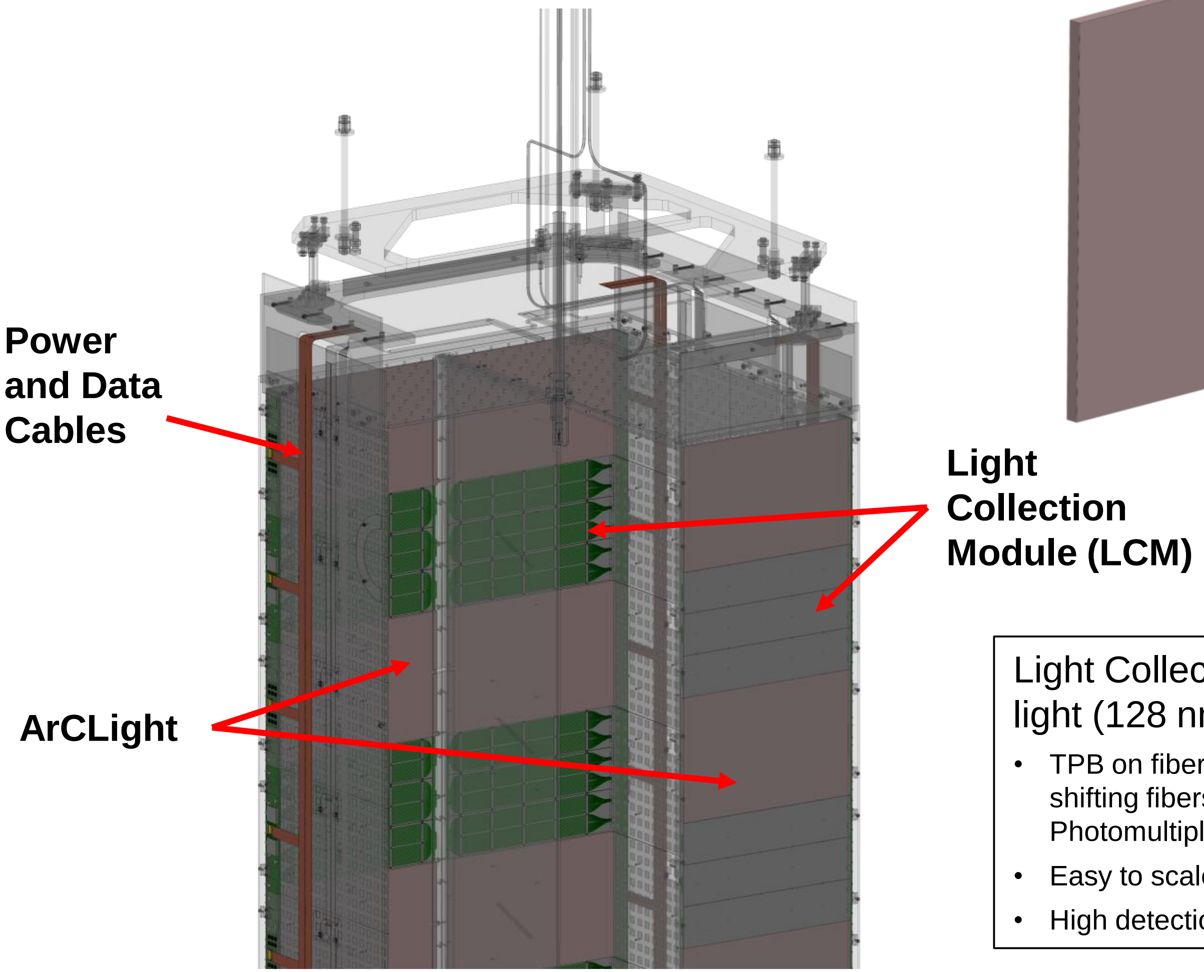


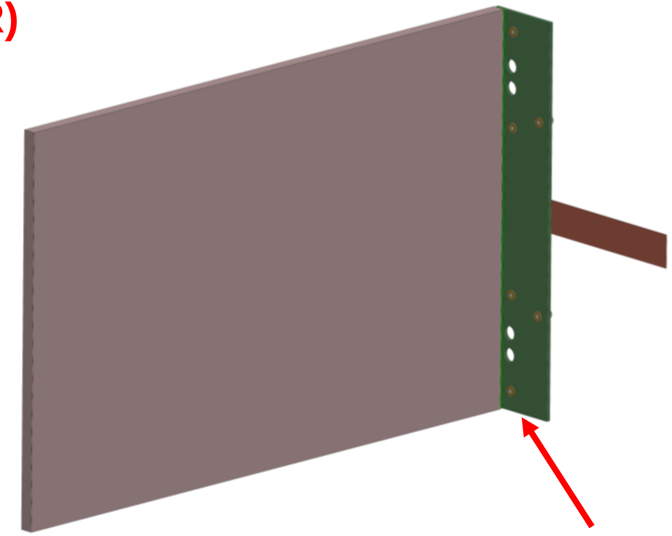
Front End Electronics Assembly:

- Pac-Man, Feedthrough Flange, PCB, Front End Enclosure

Light Readout (131.ND.02.06)

Engineering Lead – Alexander Selyunin (EE, JINR)



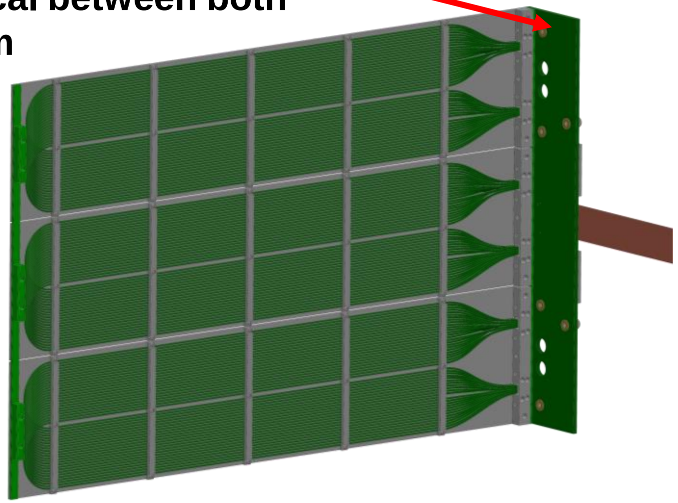


ArCLight: Shifts UV light (128 nm) into visible light (425nm)

- Wavelength shifting plastic (WLS) traps photons that pass through filters -> random photon movement until capture in Silicon Photomultipliers (SiPMs)
- Rigid construction
- Good spatial resolution

Cold Electronics Board

- **Identical between both system**

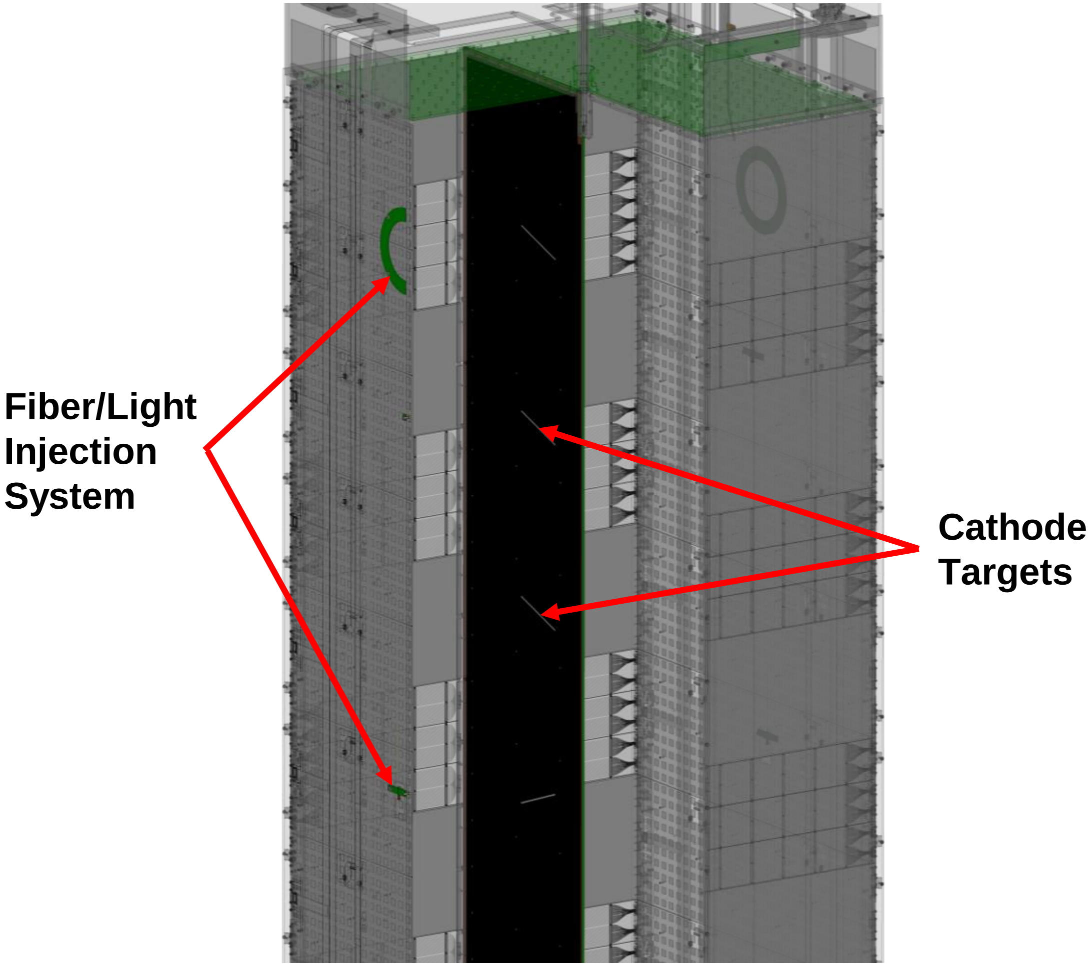


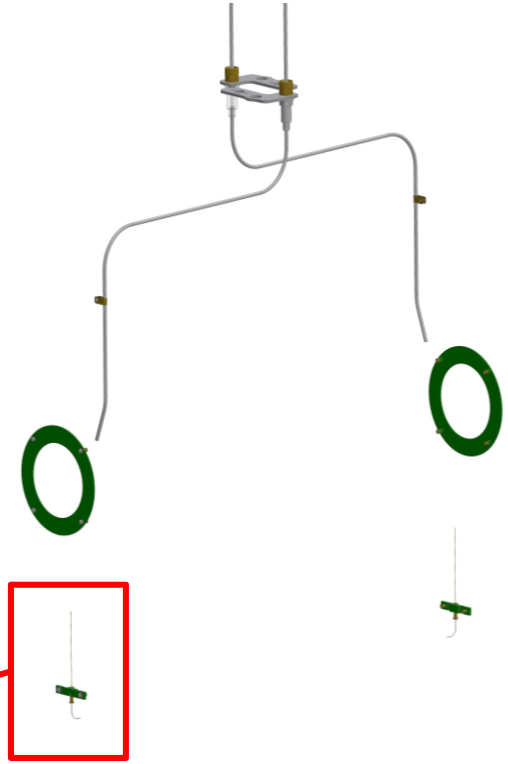
Light Collection Module (LCM): Shifts UV light (128 nm) into visible light (510nm)

- TPB on fibers shift 128 nm to 425 nm -> wavelength shifting fibers shift 425 nm to 510 nm -> Silicon Photomultipliers (SiPMs) detect 510 nm light
- Easy to scale -> fibers have long attenuation
- High detection efficiency, PDE ~ 1-2 %

Calibration (131.ND.02.07)

Engineering Lead – Morgan Bonnet (U-Hawaii)





Light Injection for Photo-Emission

- Fibers inject light into TPC
- Cathode Targets are photo-emissive and electrons are generated for charge calibration

ND-LAr CAD model is at PDR maturity with the detector elements fully modeled and integrated into the TPC structure

Note: Cryostat Lid Section not in ND-LAr Scope

ND-LAr Management:

131.ND.02.01: Management (LBNL)

ND-LAr Core Detector Elements:

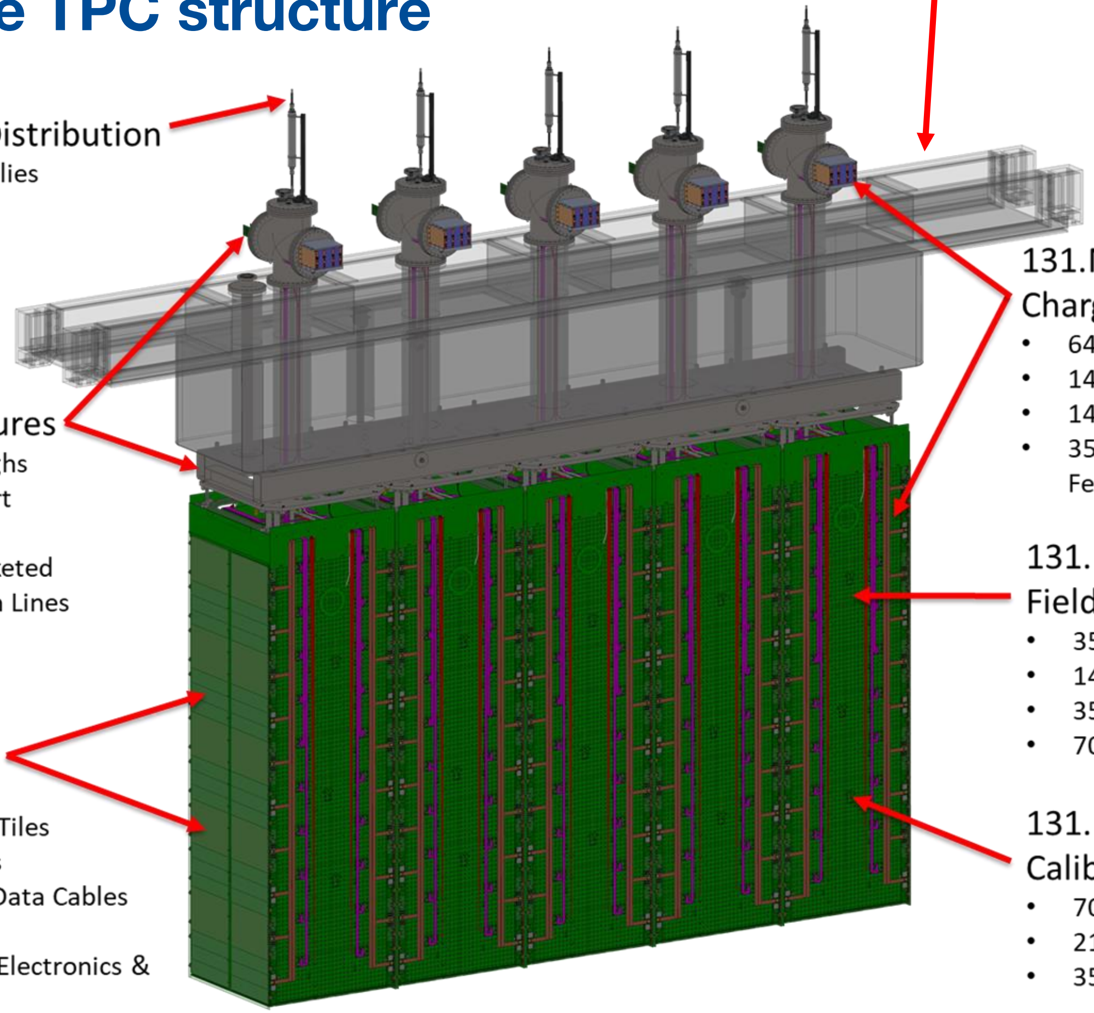
131.ND.02.02: Module Structure (Bern)
131.ND.02.03: High Voltage (Bern)
131.ND.02.04: Field Structure (SLAC)
131.ND.02.05: Charge Readout (LBNL)
131.ND.02.06: Light Readout (JINR)
131.ND.02.07: Calibration (MSU/U-Hawaii)

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)



Top Level TPC Row Assembly, DU-1003-7330, EDMS 2737743
ND-LAr produces 7X TPC Row Assemblies for Near Site

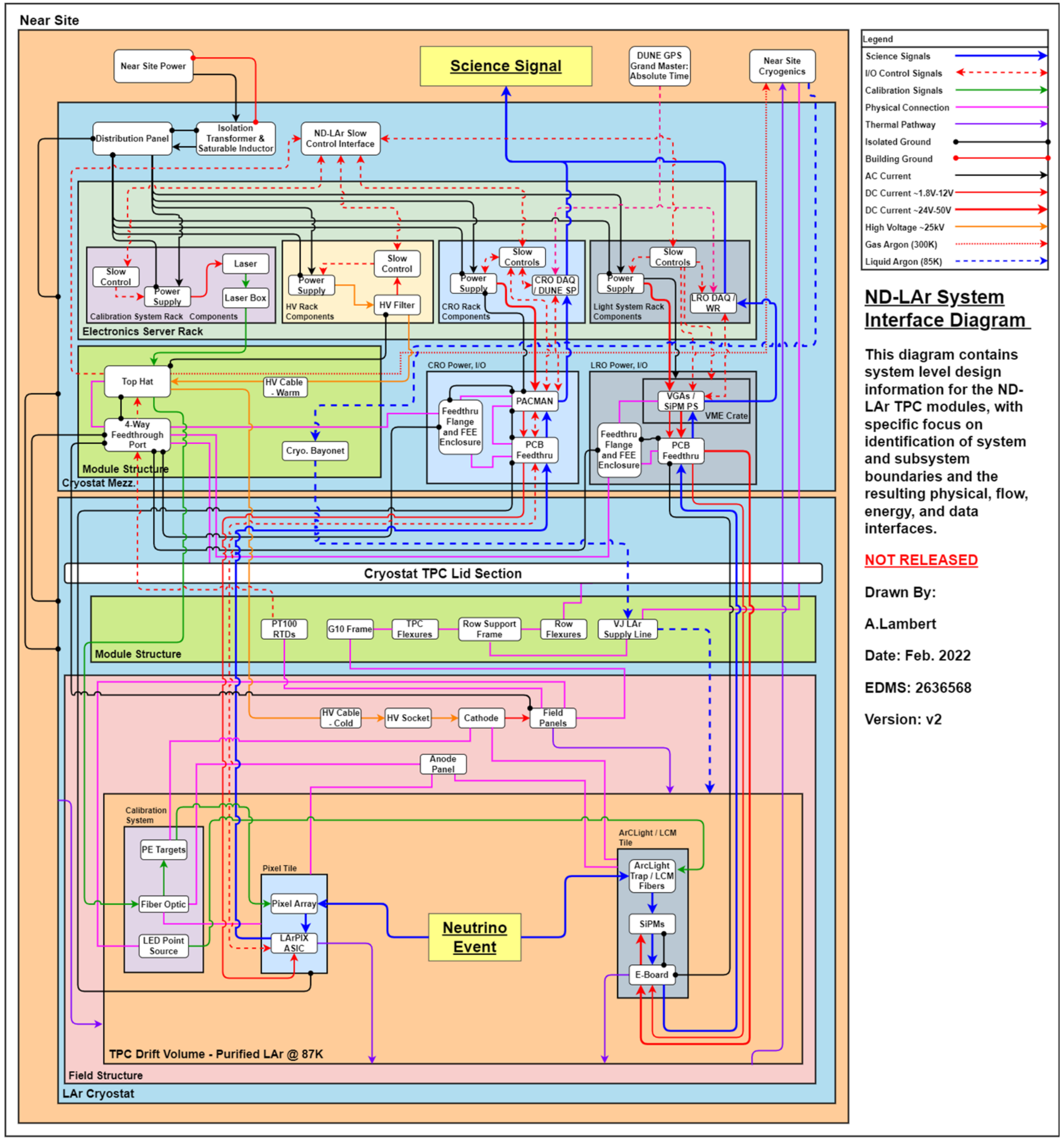
The ND-LAr CAD is managed using a Product Lifecycle Management (PLM) system; it is integrated into the large Near Site CAD model for full NS CAD fidelity

- Solidworks CAD model is managed in using Windchill Product Lifecycle Management (PLM) System, support from LBNL Engineering Division
  - Versioning on “working” files uploaded and stored on server
  - Version control on “released” files uploaded and stored on server
    - CAD release process per EDMS 2612310; all CAD files go through Windchill prior to EDMS

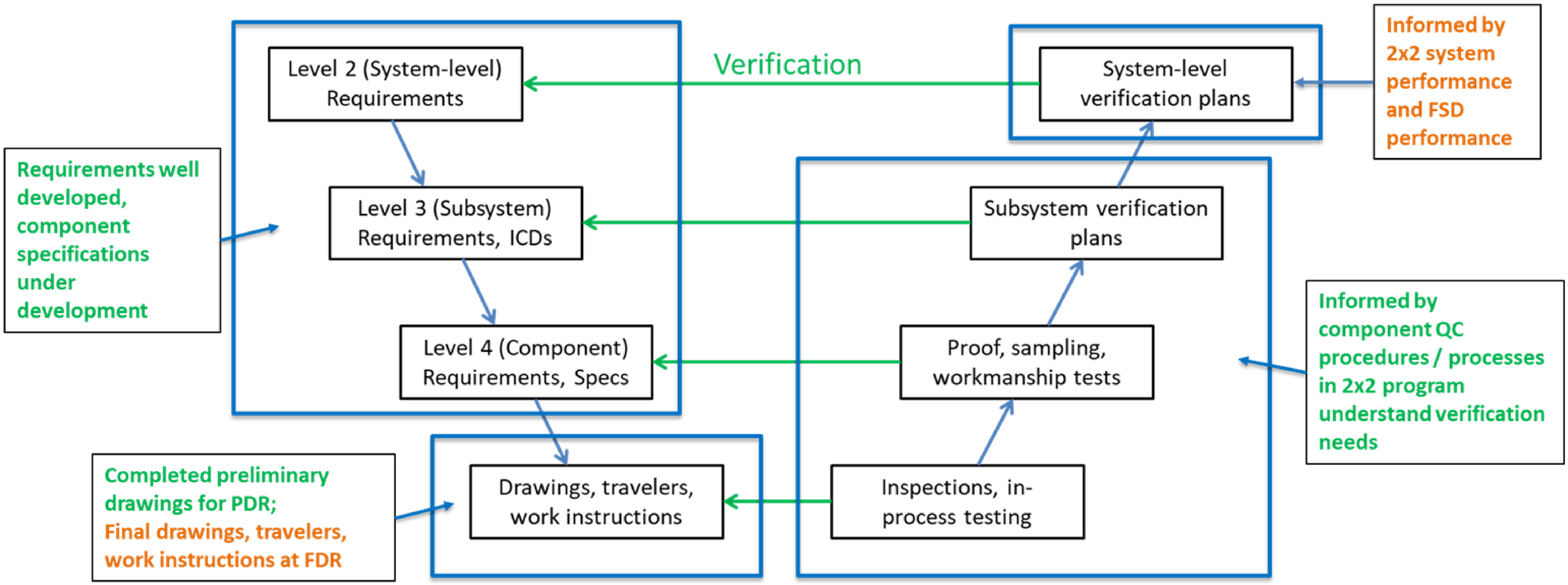
- Windchill CAD assembly structure is organized by detector WBS group
  - Enforcement of subsystem boundaries and interfaces
  - Working “sandbox” for each engineering team to develop their system
    - Windchill CAD model structure per EDMS 2683349

ND-LAr uses Systems Engineering principles to define requirements, interfaces, and overall design

- Requirements for ND-LAr system and subsystem found at [EDMS 2589287]
  - **Overarching → Measurement → Capabilities → ND-LAr System (L2) → ND-LAr Subsystems (L3)**
    - **ND Sub-Project Requirements**
    - **Consortium Requirements**
- System design flow diagram (right) provides an overview of system design and interfaces, [EDMS 2636568]
  - Provide **"Big Picture"** of ND-LAr
- Flow diagram identifies how Science Signals flows out of detector, provides high-level view



Requirements validation and verification methods largely identified, next step is verification planning, integration of prototyping program procedures



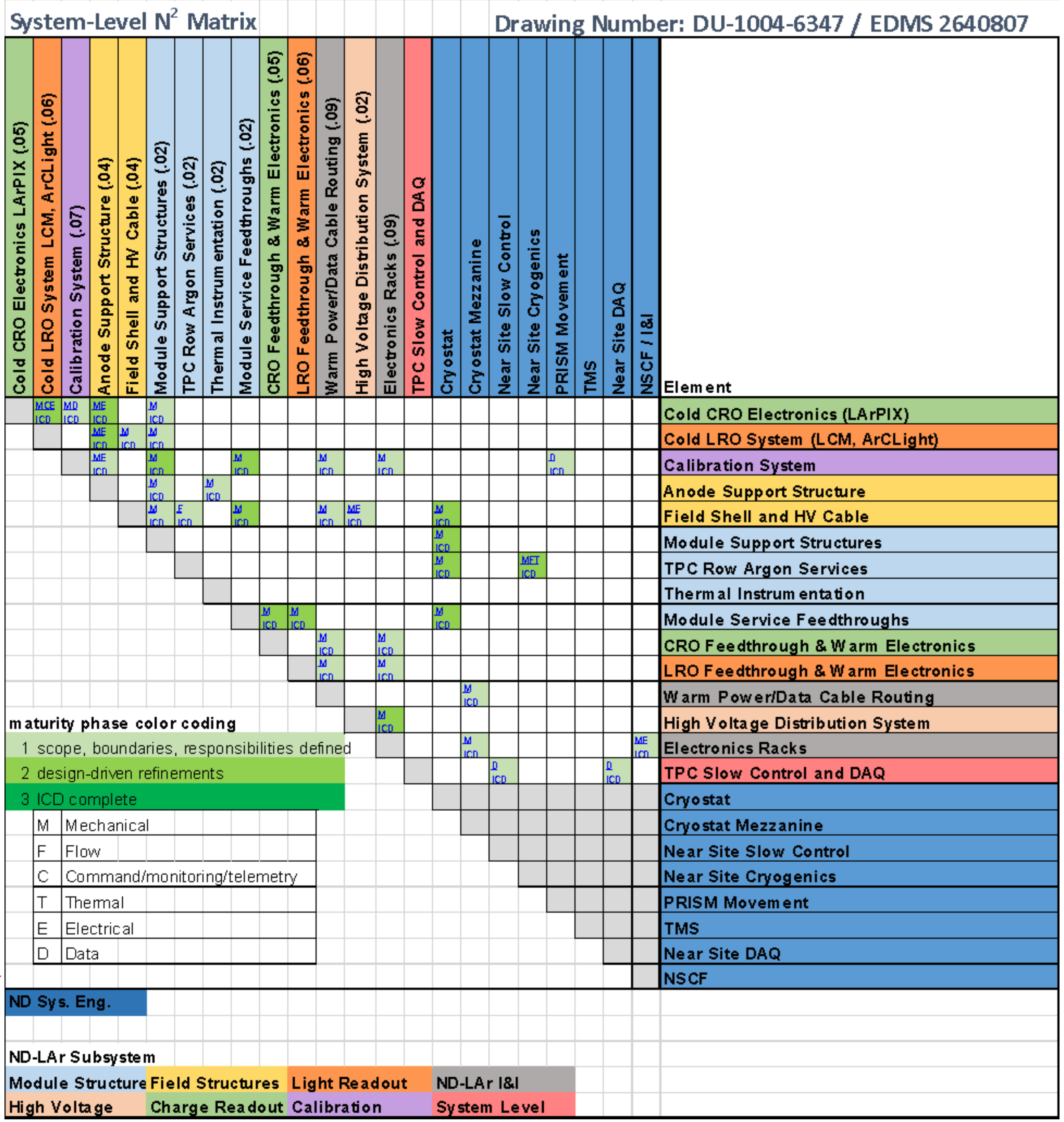
LBNF/DUNE

ND-LAr interfaces are defined in [EDMS 2640807] and tracked in [EDMS 2667883]

- Level of maturity of ICDs rated by Phase:
  - **Phase 1: At Preliminary Design maturity--scope, boundaries and responsibilities defined.**
  - Phase 2: Design-driven refinements to boundaries and responsibilities. Loads, flows, and functional requirements defined.
  - Phase 3: At Final Design maturity--all details fully-documented. Subsystems can finalize their respective designs independently.

- All ICDs advanced as possible at this moment
  - **All ICDs at Preliminary Design maturity**
  - **14 ICDs advanced past PD maturity**

ND-LAr Interface N^2 Matrix -> Identify functional interfaces, define scope boundaries and responsibilities, design and boundary refinement, final specifications and requirements → ICD Complete



LBNF/DUNE

External (L2) interfaces are as mature as possible, will continue to mature as overall ND design progresses

- Cryostat, [EDMS 2458099]
  - **Shown at right**
- PRISM, [EDMS 2458097]
- DAQ, [EDMS 2458098]
- Slow Controls, [EDMS 2667881]
- Cryogenics, [EDMS 2458074]
- I&I, [EDMS 2730726]
- TMS, [EDMS 2735492]
- **L2 interfaces at Preliminary Design maturity – scope, boundaries, and responsibilities defined**

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

ND-LAr TPC MODULES TO ND-LAr CRYOSTAT INTERFACE CONTROL DOCUMENT

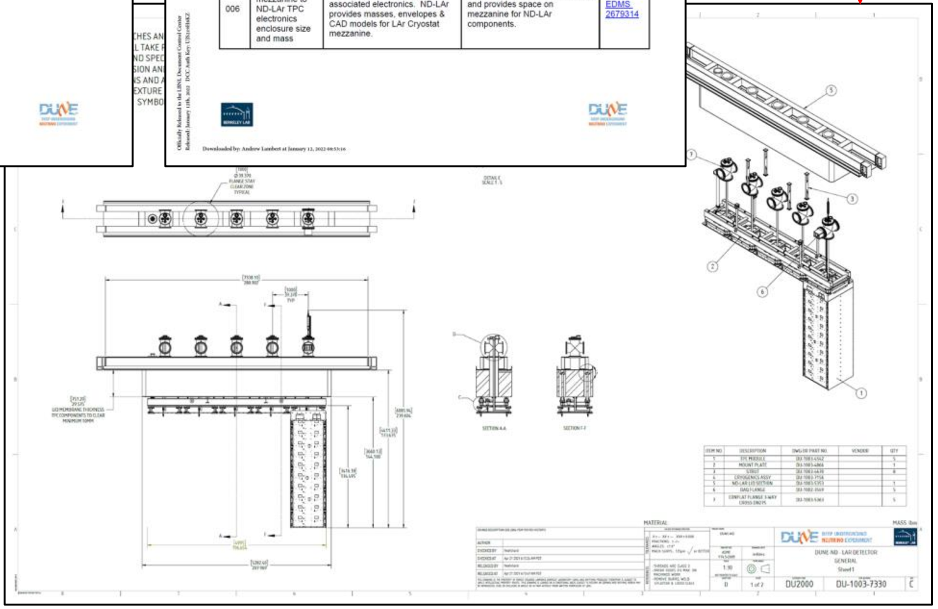
A.LAMBERT, P.TENNESSEN
Release Date:Jan 12 2022 8:49:35 AM PST

LBNL Document Number: **DU-1001-8056**	Revision: **A.11**
CERN EDMS Document Number: **2458099**	Revision: **v.1**

Document Status: **Released**
Type: **INTERFACE**
LBNL Category Code: **DU2020**

DU-1001-8056 Rev. **A.11** Document Status: **Released** Page 6 of 8

ID#	Item	WBS 131.ND.02 ND-LAr TPC Provides	WBS 131.ND.03 ND-LAr Cryostat Provides	Interface Drawing
	Physical			
001	ND-LAr Module Services Penetration	Cable sleeve that fits provided penetration (see drawing) in cryostat lid section from ullage space to ambient environment, physical interface 13.25" OD CFF Cross	Penetration (see drawing) through cryostat lid section, from ullage space to ambient environment, presents physical interface 13.25" OD CFF	EDMS 2679311
002	Detector Row LAr Supply Penetration	Vacuum-jacketed LAr supply lines that fit provided penetration (see drawing), physical interface 10" OD CFF	Penetration (see drawing) through cryostat lid section from ullage to ambient environment, capable of accommodating vacuum-jacketed lines, physical interface 10" OD CFF	EDMS 2679311
003	Detector Array to Cryostat Stay Clear Zones	Module array shall not intrude into the defined stay clear zones (see drawing)	Defines stay clear zone with respect to cryostat membrane insulation and membrane corrugation (see drawing)	EDMS 2679312
004	ND-LAr Detector Row Structural Connection	ND-LAr Detector row structural supports that fit the provided penetration and attach to the cryostat lid structural joint/attachment (see drawing)	Penetration through cryostat lid section from ullage to ambient, capable of accommodating ND-LAr Detector row support structures. Cryostat lid provides structural joint/attachment for row support structures (see drawing)	EDMS 2679311
005	ND-LAr Detector to ND-LAr Cryostat Datum / Metrology Scheme	See EDMS 2679313	See EDMS 2679313	EDMS 2679313
006	ND-LAr cryostat TPC mezzanine to ND-LAr TPC electronics enclosure size and mass	ND-LAr provides electronics enclosures, cable trays, and all associated electronics. ND-LAr provides masses, envelopes & CAD models for LAr Cryostat mezzanine.	LAr Cryostat observes envelopes and provides space on mezzanine for ND-LAr components.	EDMS 2679314

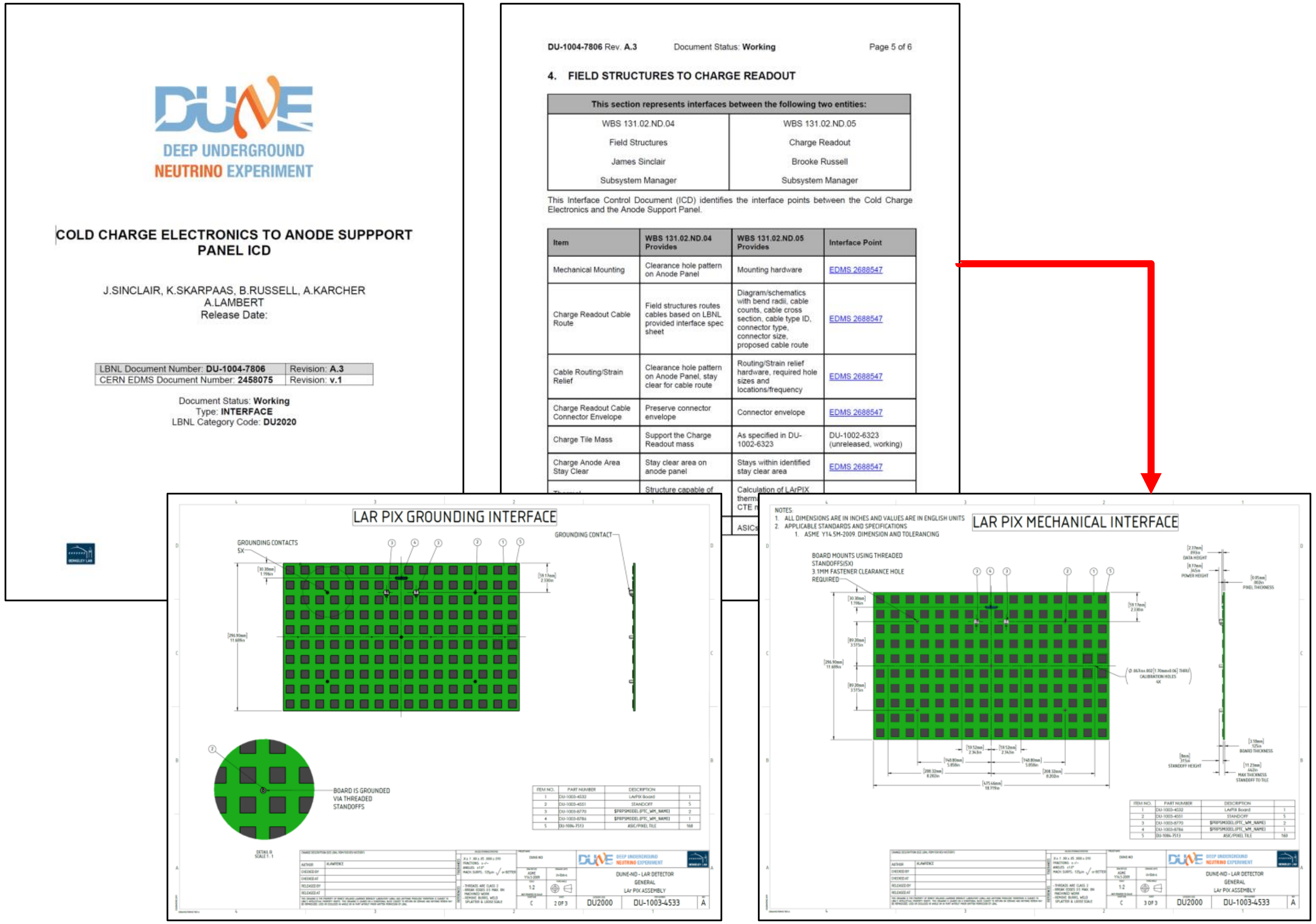


Internal (L3) interfaces are more mature than the L2 interfaces and have been informed by 2x2 module experience and operations, will be realized at FSD module

- ND-LAr internal L3 ICDs at EDMS Folder: https://edms.cern.ch/project/CERN-0000223195

- **L3 ICDs at Preliminary Design maturity**, some beyond
  - Detailed interface drawings / diagrams still needed at many ICDs → final design phase to detail all interface drawings

- System is in place to populate ICD with relevant drawings, some teams already turning attention to this

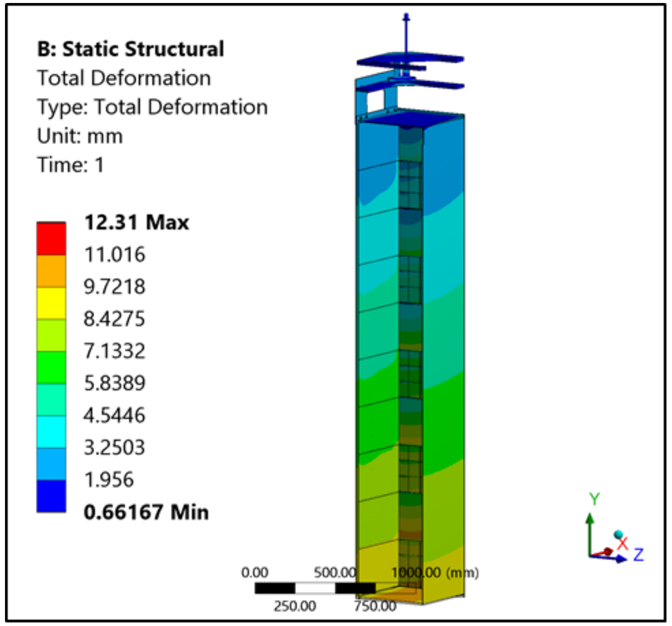


Many of the engineering challenges on the ND-LAr TPC have been addressed through the 2x2 program; the FSD will address remaining challenges

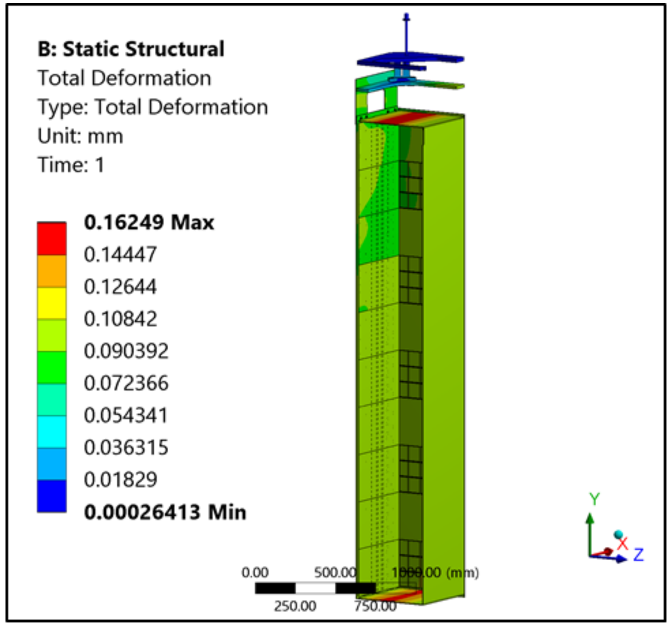
- Grounding considerations (see Electrical Overview talk by A.Karcher)
- High voltage stability and discharge (see High Voltage talk by S.Parsa, Field Structures talk by J.Sinclair and K.Skarpaas, and Prototyping talk by I.Kreslo)
- Liquid argon purity (see Prototyping talk by I.Kreslo)
- Low-noise electronics (see Charge Readout talks by B.Russell and A.Karcher)
- Performance of structures at cryogenic temperatures and thermal management (see next few slides w/EMDS references)

FEA study indicates TPC deflections primarily thermally-driven due to cryogenic operational temperatures; deflection due to gravity is comparatively minor

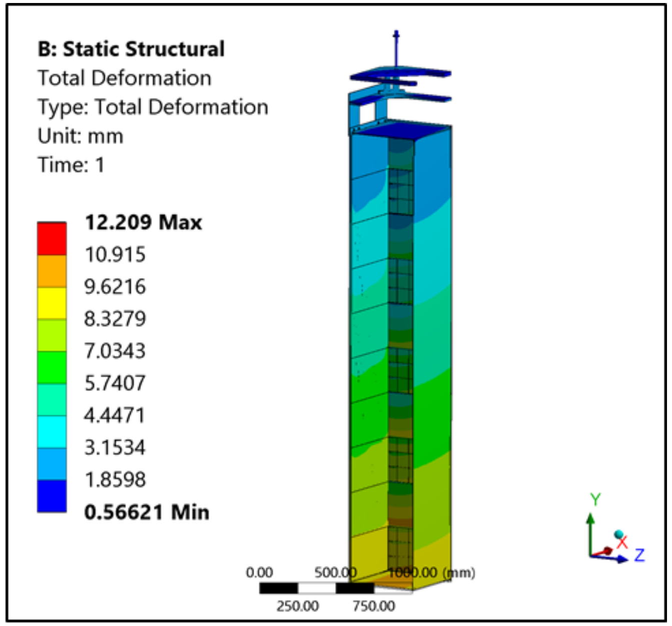
- Thermal-Structural FEA of single ND Module
  - Studied TPC deflection under gravity and shrinkage at cryo-temps, plus combined solution **Deflections of module during operations in thermally-driven → module is robust against gravity loading**
  - **Next steps are deflection optimization and TPC row FEA in tandem with cryostat lid design**



Thermal Load Only



Gravity Load Only

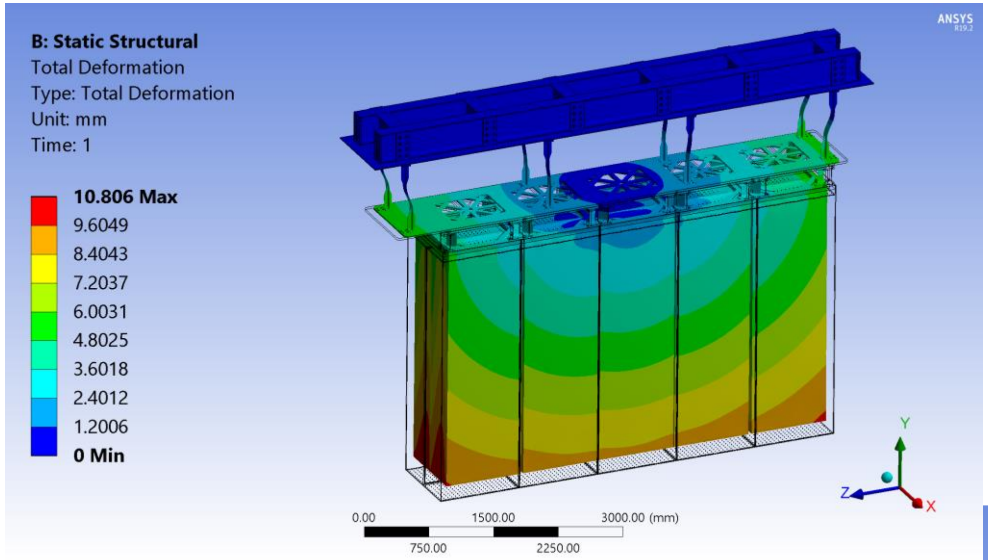


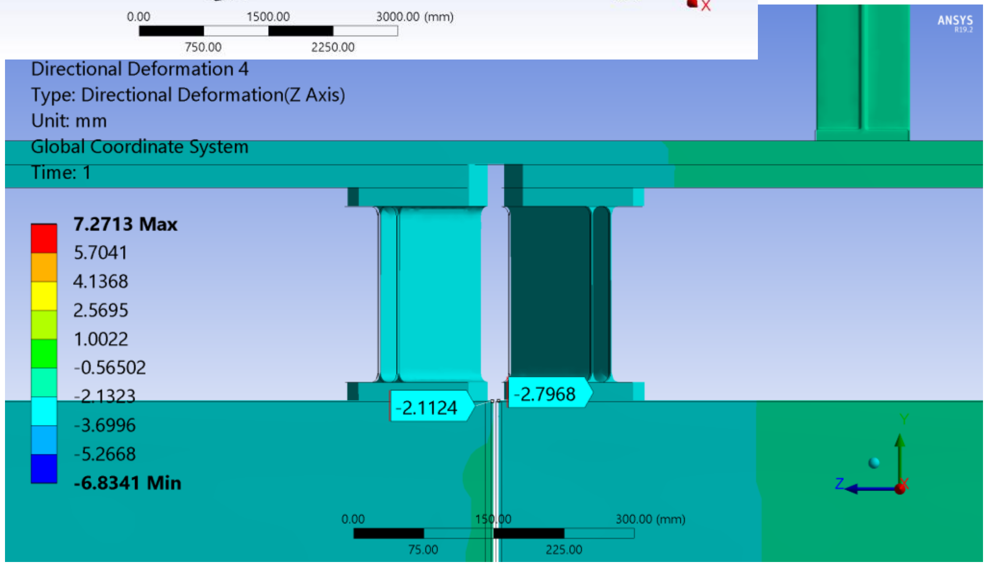
Thermal + Gravity Load

Single module thermal-structural FEA, EDMS 2747315

Previous studies indicated that TPC clearances sufficient to avoid collision of modules upon cool-down

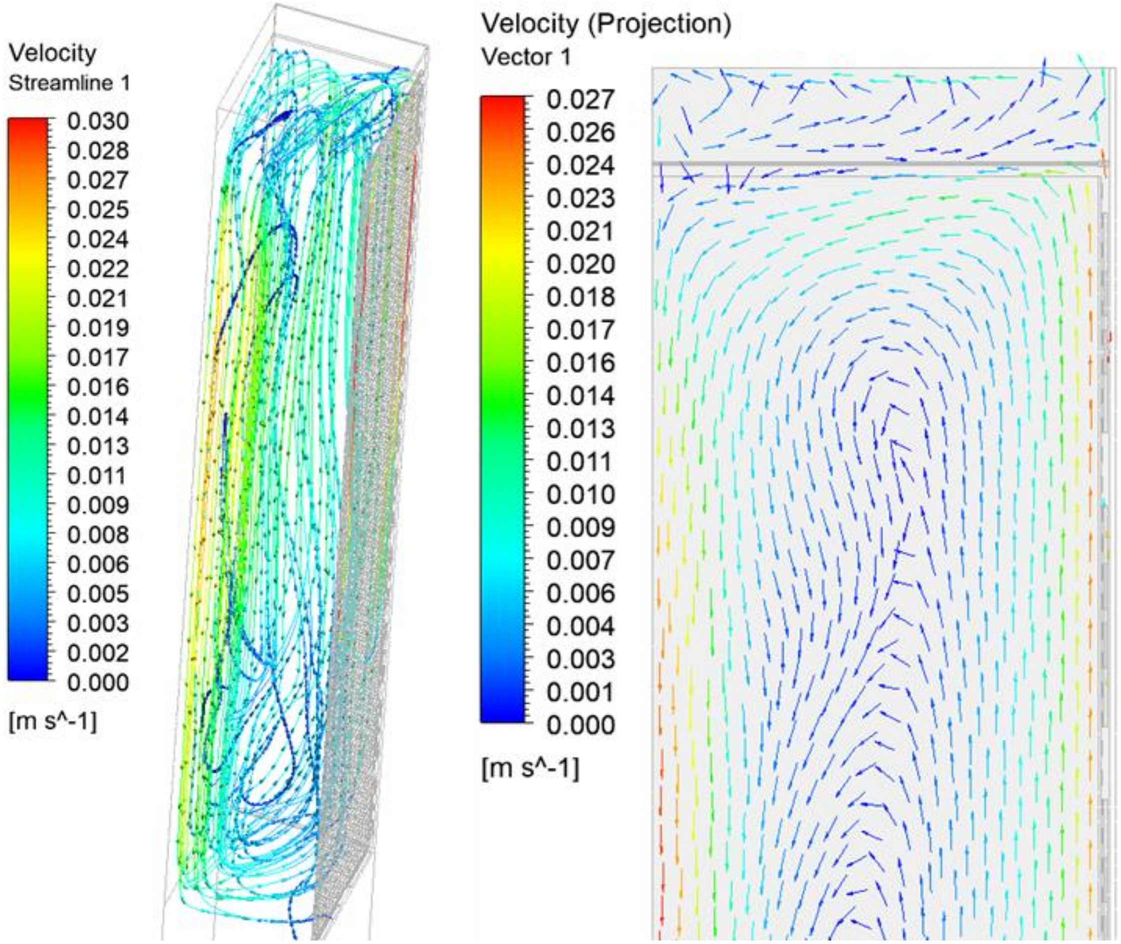
- ND row FEA study considers thermally-driven deflection only
- Utilizes a simplified TPC row geometry
  - No readout systems in TPC -> assuming that the field structures represents the module bounds upon cool-down and interior components do not impede field structure contraction
- **Minimal change in module to module gap indicates that thermal driven deflections are OK**
  - **Decrease in module spacing ~ 0.7 mm**
- Plan to re-run study with updated row support design, however material properties (CTE) will be unchanged
- Similar TPC contraction as shown on previous slide





ND Row Thermal Contraction FEA, EDMS 2748097

CFD analyses indicate good LAr mixing within the TPC volume with no dead zones where impurities can gather; heat transfer to LAr modeled using realistic TPC heat load → modest temperature gain



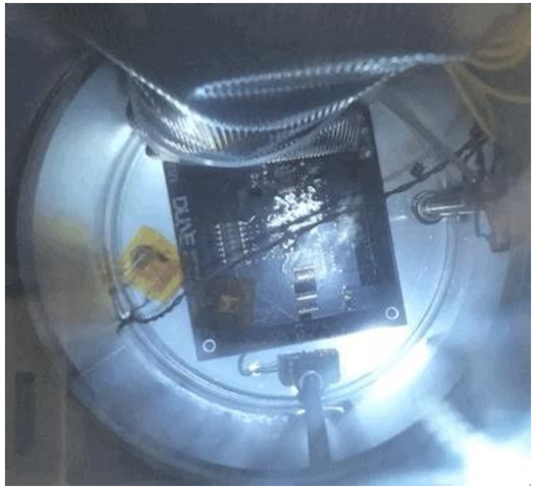
CFD Study of LAr Transfer in ND Module, [EDMS 2747314]

- CFD shows convection cell in main TPC volume (left) → **good mixing, no dead zones where impurities can gather**
- Inlet flow temperature = 89K → **average temperature rise of 0.8 – 1.6 K depending on TPC heat load (see below)**

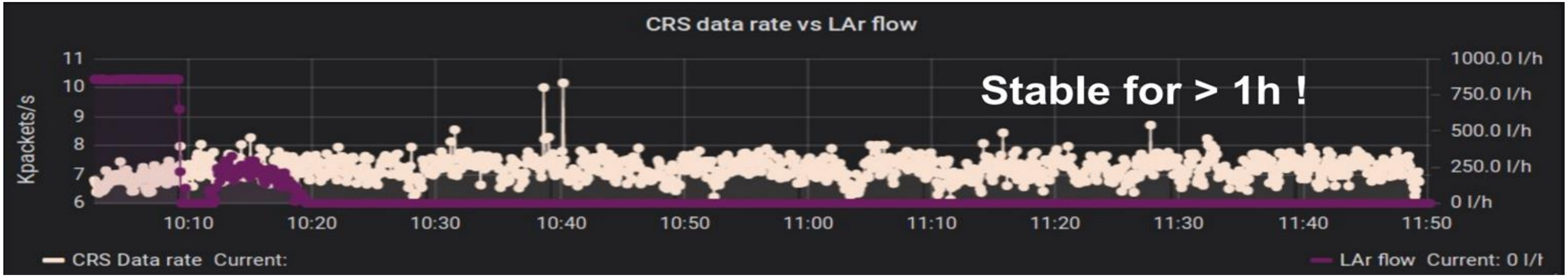
		Inlet Loc#1; Low Flow; Low Heat;	Inlet Loc#1; Low Flow; High Heat;	Inlet Loc#1; High Flow; Low Heat;	Inlet Loc#1; High Flow; High Heat;
	Case #	1	2	3	4
	Inlet Location #	#1: 450 mm from CPA, On Sym Plane			
	LAr Inlet Mass Flow per module	Low (10 gm/s)		High (23 gm/s)	
UNITS	Heat Load Configuration	Min	Max	Min	Max
[mm/s]	Ave Velocity	5.133	8.26	5.5	8.628
[K]	Ave Temperature in FC Volume	89.72	90.4	89.66	90.29
[K]	Ave Temperature In Gap Volume	89.75	90.45	89.69	90.34
[K]	Ave Temperature @ Floor Outlet	89.71	90.39	89.65	90.28
[K]	Max Superheat	2.341	3.049	2.279	2.938
[K]	Ave Liquid Surface Adjacent Superheating	0.6322	1.207	0.5753	1.109
[Watts]	Liquid Surface Cooling	19.87	48.93	17.53	44.39
[K]	Ave Amplifier Temperature	91.12	91.8	91.06	91.69
[K]	Ave ASICs Temperature	89.79	90.51	89.73	90.41
[K]	Ave Side FC Temperature	89.74	90.57	89.68	90.46
[K]	Ave Interface Temperature	89.77	90.49	89.71	90.39

LAr boiling has been investigated in an LBNL test stand and with a "No Flow" test on Module 1 in Bern, no observed boiling signals on charge system

- LBNL LArPIX Boiling Test Stand: Operated chips at maximum power consumption (nominal control voltages, trigger threshold = 0 on all channels, ~10mW according to previous measurements)
  - **No observed boiling on PCB until liquid level was below 3 cm above chip (right), liquid level above chips in ND-LAr is ~14 cm**
- No Flow test run with Module 1: LAr pump turned off to mimic similar flow as CFD and validate ND LAr flow rate specification
  - **No observed boiling signal seen in the charge readout data rate (below)**

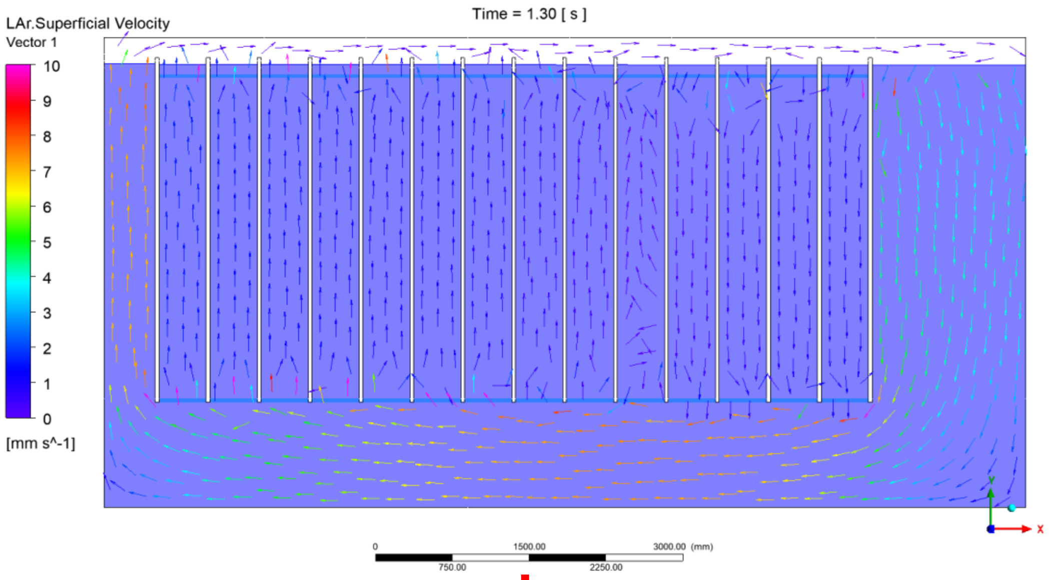


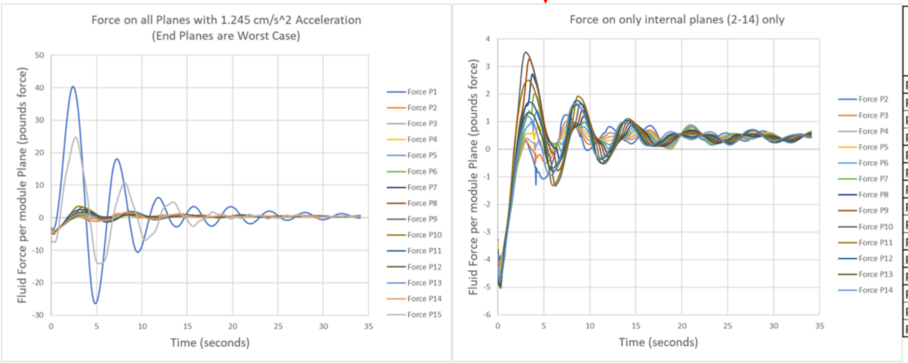
LBNL LArPIX Boiling Test Stand, EDMS 2748098



Module 1 "No Flow" test, cryostat pressure held stable, no observed increase in data rate, EDMS 2747811

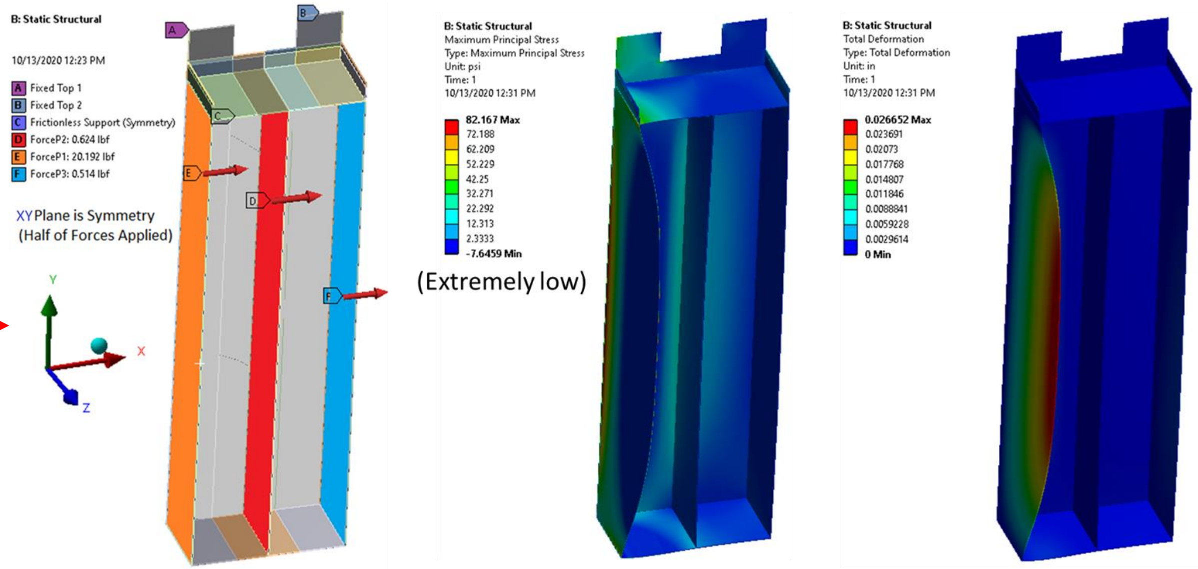
CFD sloshing analysis examined PRSIM acceleration and resulting LAr forces on ND-LAr modules → TPCs capable of withstanding maximum possible acceleration





	Maximum X force (lbf / module)	Minimum X force (lbf / module)
Plane 1	40.384	-26.426
Plane 2	1.247	-4.036
Plane 3	1.029	-4.258
Plane 4	0.948	-4.477
Plane 5	0.884	-4.634
Plane 6	1.395	-4.807
Plane 7	2.020	-4.878
Plane 8	2.721	-4.976
Plane 9	3.275	-5.015
Plane 10	3.519	-5.034
Plane 11	2.497	-4.988
Plane 12	1.768	-4.939
Plane 13	1.605	-4.858
Plane 14	1.668	-4.805
Plane 15	24.820	-14.129

- Sloshing analysis of full detector at 1.245 cm/s^2
  - Max force on end wall = 178 N, deflection = 0.68 mm
- **PRISM acceleration requirement on ND-LAr = 0.25 cm/s^2 (maximum possible)**
  - **5X smaller than analysis, scaling by F=ma**
  - **Max force on end wall = 35.6 N, deflection = 0.136 mm**



ND Sloshing Analysis, EDMS 2737398

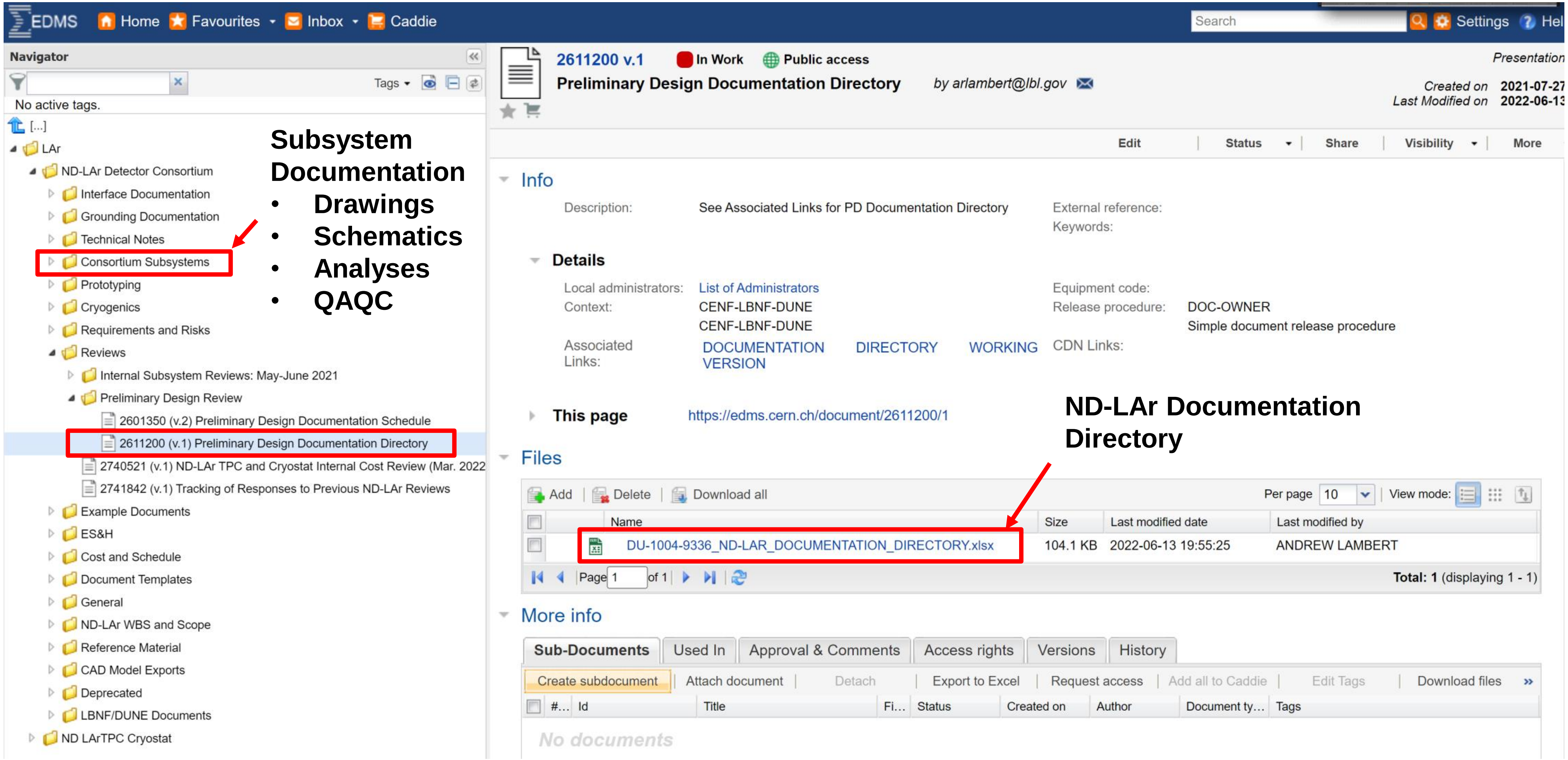
ESH Codes and Standards

- Adheres to all ESH codes/standards established by LBNF/DUNE Project plus home institutional ESH requirements
- All Near Site deliverables must satisfy **FNAL FESHM requirements**
  - **2x2 Program providing experience through ORC process**
  - 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

Documentation Directory is found at EDMS 2611200, documents and drawings are available for exploration in folder structure



LBNF/DUNE

Remaining Design Items and Path to FSD/FDR

- Execute the FSD program and uses the results to inform the final ND-LAr module design
  - Production of FSD components
  - Development of all handling, assembly, testing procedures
  - Required safety review of applicable procedures (lifting by crane/forklift)
  - Site travel and support by Consortium members
  - Data analysis and requirements validation
- Production of Final Design and Documentation Package
  - Final CAD model and production drawings
  - Released ICDs with corresponding interface drawings
  - Production QAQC procedures, manufacturing, and procurement plans; travelers
  - Final assembly, testing, integration, and installation plans
  - Final engineering analyses, tech notes, prototyping result write-ups
- What is our biggest challenge ahead? → Shifting from team that can successfully produce four 2x2 modules in a “prototyping” environment to a team that can produce 35X ND-LAr modules in an “production” environment
  - **<u>Scale up, quality control, staffing, communications (building 1000s vs 10s)</u>**

Summary

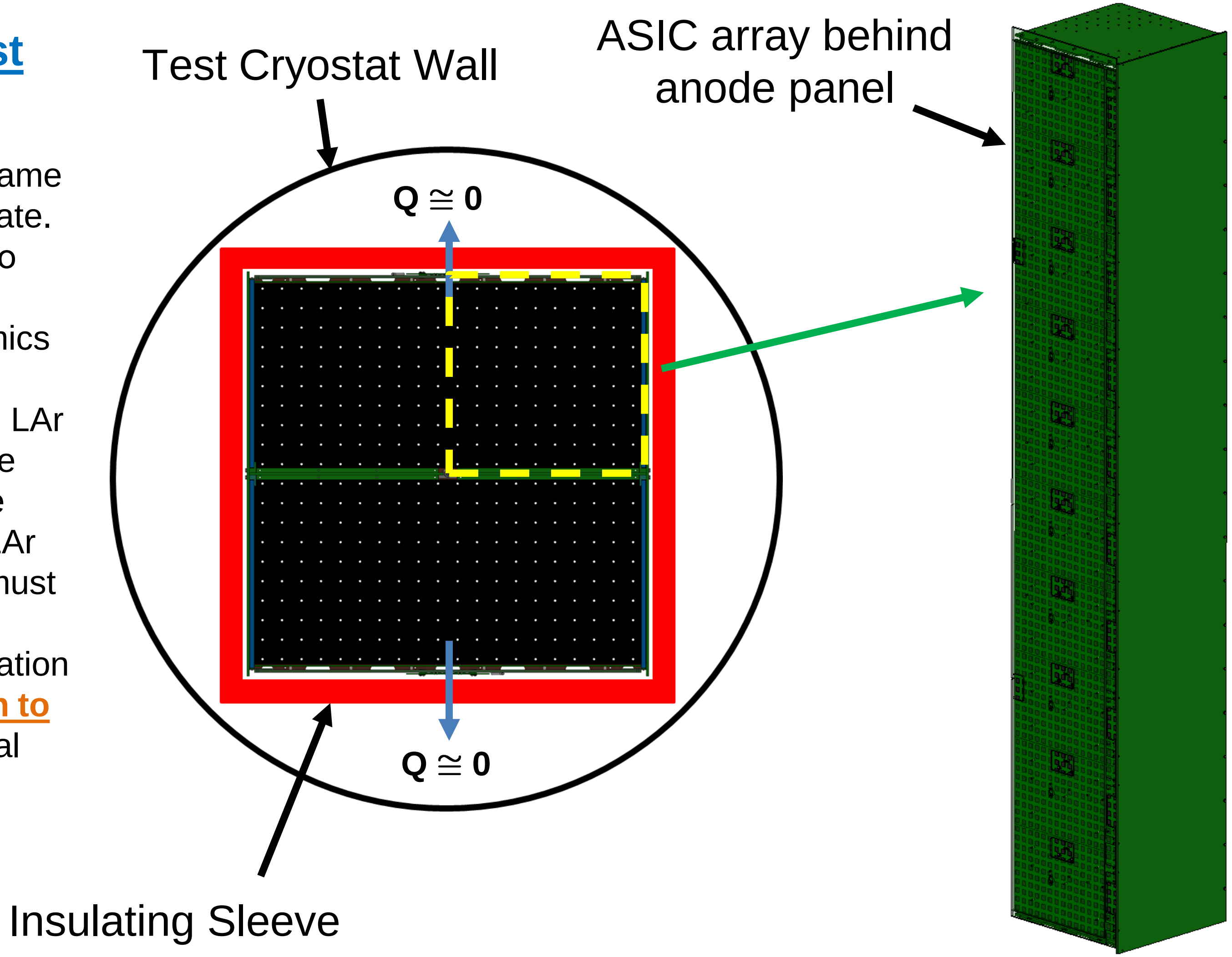
- ND-LAr has an experienced engineering team focused on tackling the technical challenges of this detector and has delivered results for the 2x2
- The CAD model and associated design documentation is developed and in-place to continue to final detailing and construction of the FSD module
- Remaining technical challenges will be addressed through continuation of prototyping program (2x2, FSD)
- Requirements and interfaces are at the appropriate level of maturity for preliminary design; systems and methods are in place to continue their maturation
- **Ready for the final design phase and construction of the FSD module**

Backup

Future flow studies to validate ND flow rate and thermal management

FSD LAr Flow Test

- Flow rate = 25 g/s, same as ND module flow rate. Can also repeat "zero flow" test
- Insulated sleeve mimics thermal symmetry boundary -> external LAr bath does not provide additional convective cooling -> supplied LAr within TPC volume must cool electronics and maintain stable operation
- Use CFD simulation to validate experimental approach



CFD Validation Study

- ¼ model to utilize symmetry at the cathode and half of single drift region; apply TPC heat loads
- At flow domain behind anode apply two different boundary conditions and compare thermal profiles
  - **- Symmetry BC**
  - **- Insulated Wall BC**
- If thermal profiles near ASICs are similar enough can conclude that insulated wall mimics symmetry condition well-enough for FSD LAr Flow Test to represent ND thermal environment

Module Array Spacing (Dimensions in millimeters)