Overview of DUNE Vertical Drift detector

(*CDR: https://www.overleaf.com/project/5ff88c5ef3c28f9daffb2f74*)

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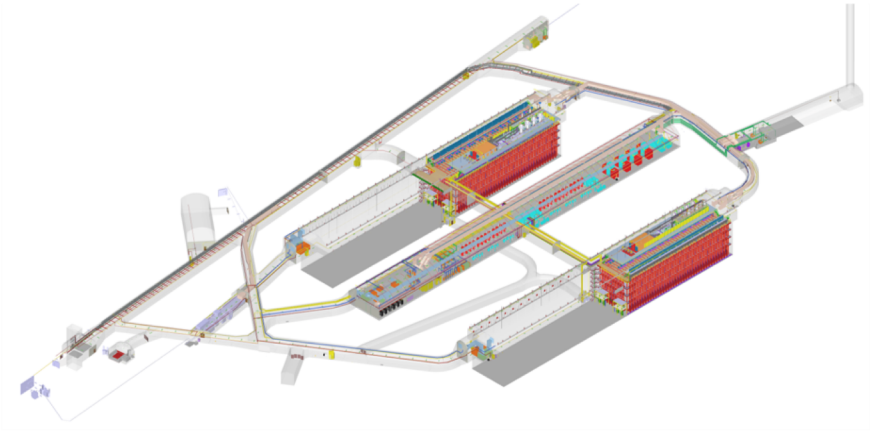
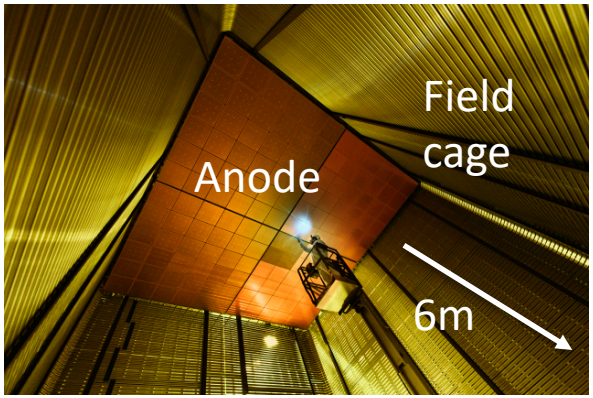
DUNE DAQ consortium meeting

2 August 2021

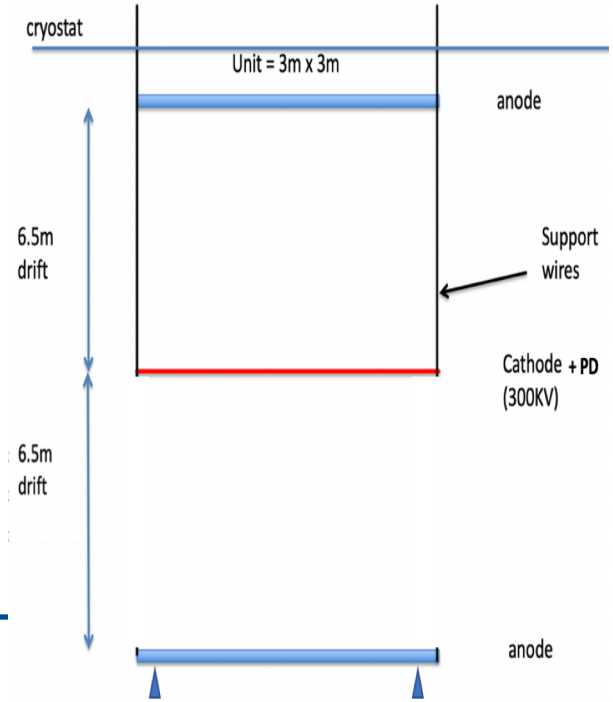


Motivations for VD LAr-TPC technology for the second DUNE module: lessons learned from ProtoDUNE-SP/DP

- LAr purity in ProtoDUNE is outstanding, allowing us to plan for longer drift length (aim for 6-7m)
- Readout electronics in NP04/NP02 demonstrated excellent S/N (30-40)
- APA anodes are complex to construct and expensive
- Installation of PCB anodes is simple and fast (based on ProtoDUNE-DP)
- ARAPUCA technology (PD) is demonstrated. Reconfigure layout of PD units to maximize performance
- Xe-doping to improve photon performance
- NP02 field cage is easy to construct and install. Drift volume (delimited by the single field cage and cathode) is monolithic and free of dead material

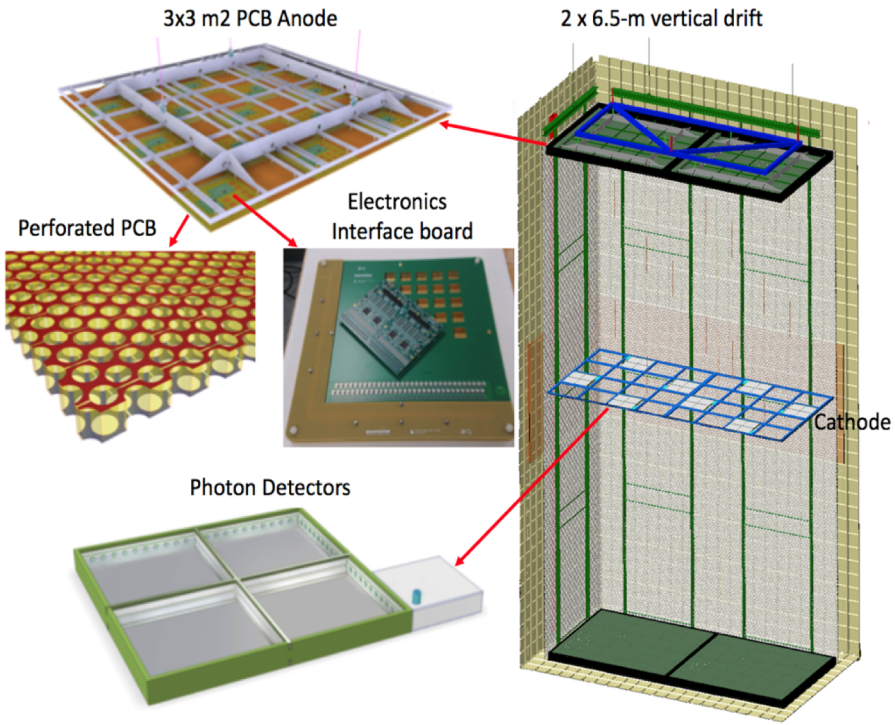


cathode



Vertical Drift concept and main components

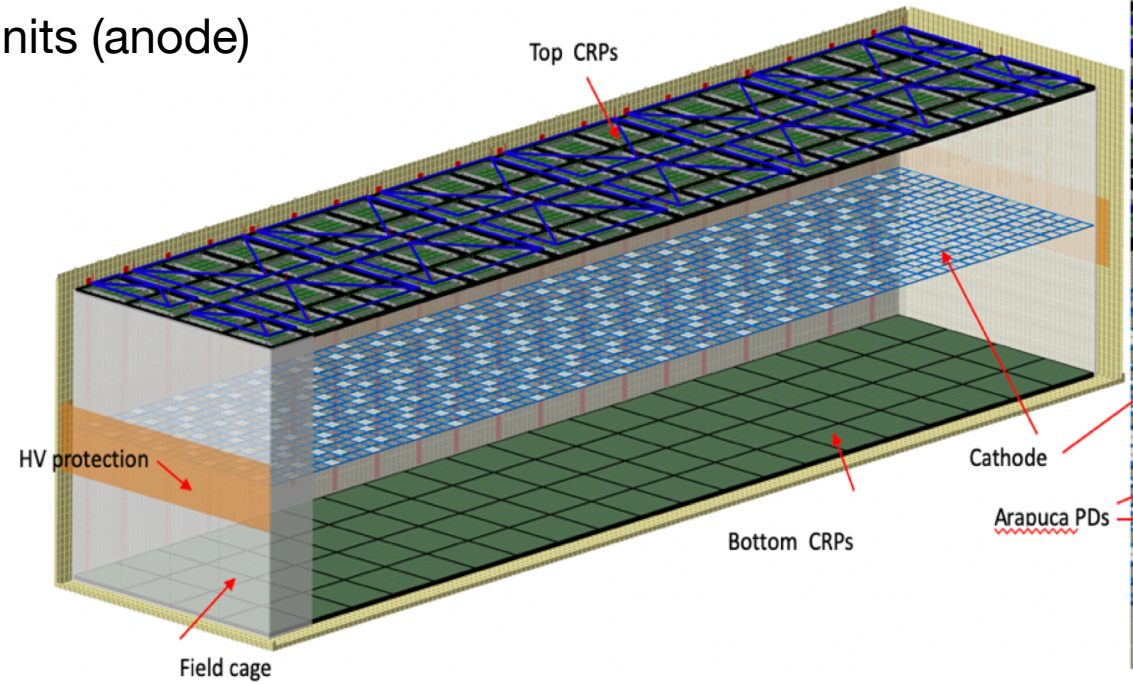
- Designed to maximize active volume
  - Readout units close to LAr surface and cryostat floor.
  - Cathode at middle height: better HV stability due to LAr hydrostatic pressure → closer distance to cryostat walls
- Perforated PCB's with segmented electrodes (strips) as readout units with integrated electronic interfaces
  - 2 or 3 view both feasible
  - Optimizable strip orientation, pitch, length and PCB modularity
- Modular supporting structures for readout planes
  - Derived from CRP design of DP Incorporates cathode hanging system
- Single field cage surrounding entire active volume
  - derived from DUNE-DP design

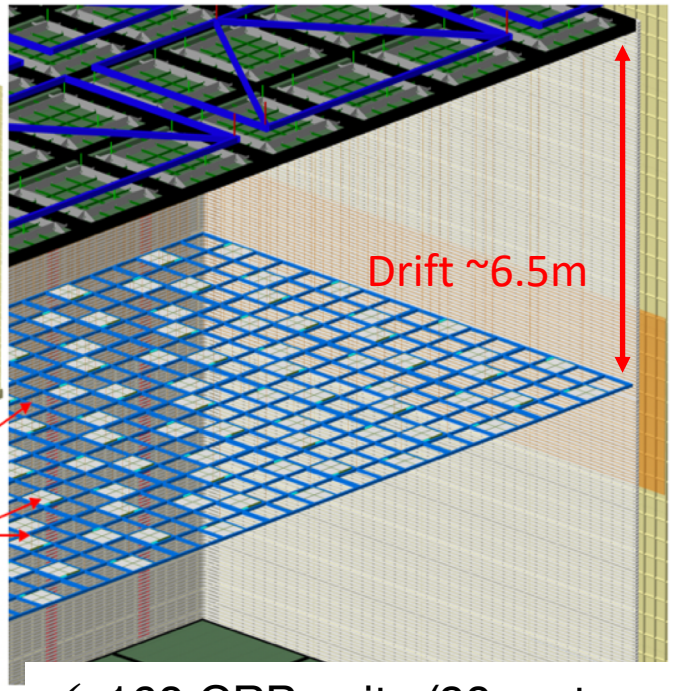


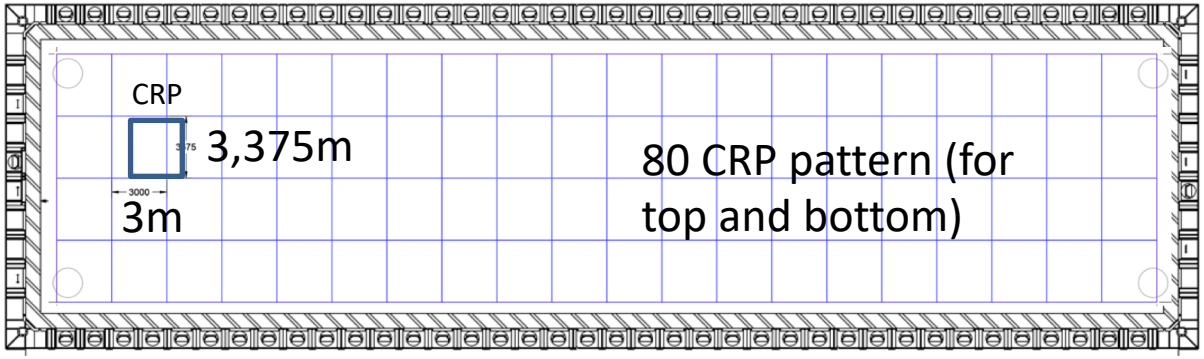
- Photon detectors based on X-ARAPUCA technology (DUNE-SP)
  - integrated on cathode plane and on the field cage walls.
  - decoupling from HV, achieved with optical fibers for signal and power transmission.
  - Alternative plan with "copper" bias/readout also considered

Vertical Drift reference layout

CRP= 3x3.375 m^2 readout units (anode)



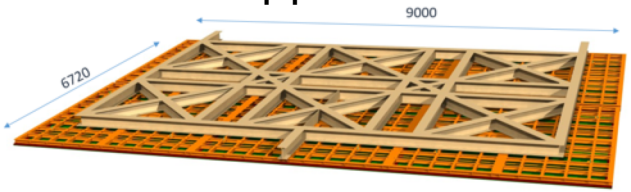


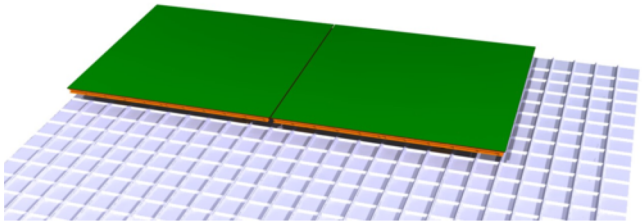


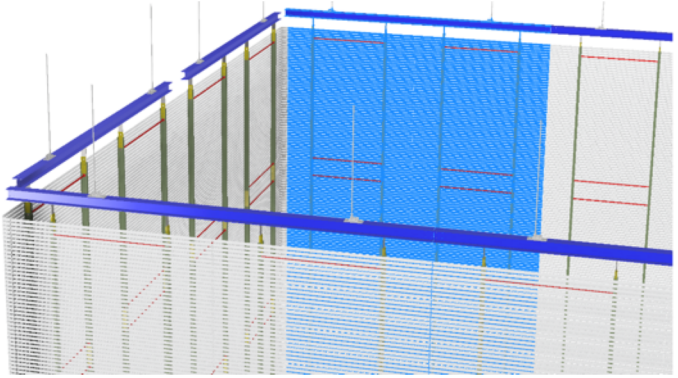
- ✓ 160 CRP units (80 on top, 80 at the bottom)
- ✓ PD on Cathode and/or cryostat membrane (~14% coverage)
- ✓ Active drift volumes 2 * 5'265 m^3 ~ LAr 14.74 Kt

Proven ProtoDUNE technologies

Anode support structure

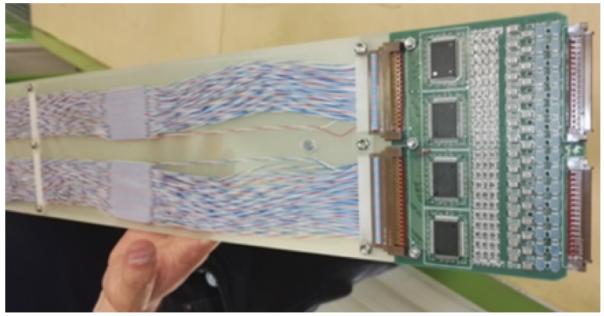




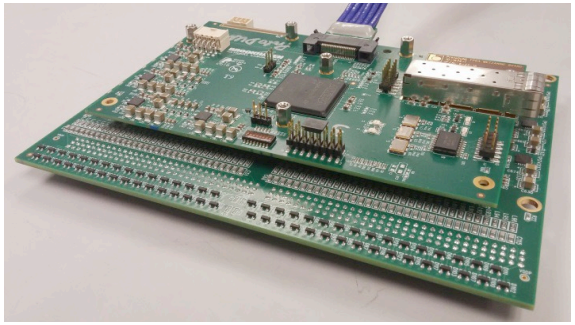


HV system

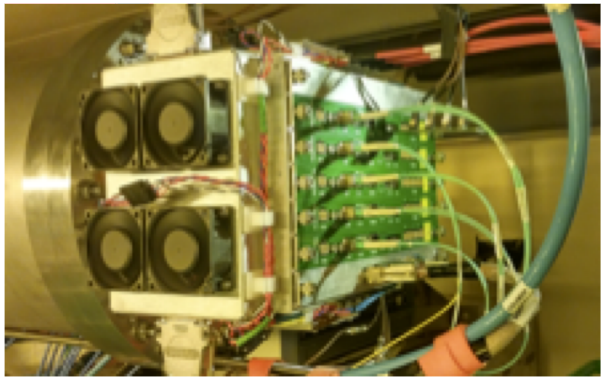
Readout electronics



Top (NP02)



Bottom (NP04)



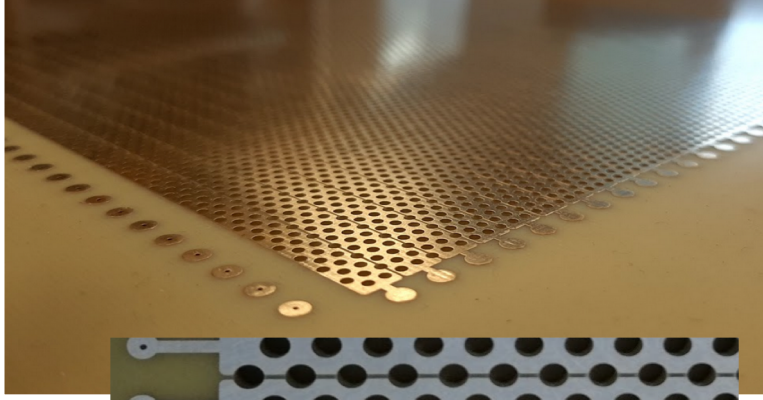
Signal feedthrough assembly

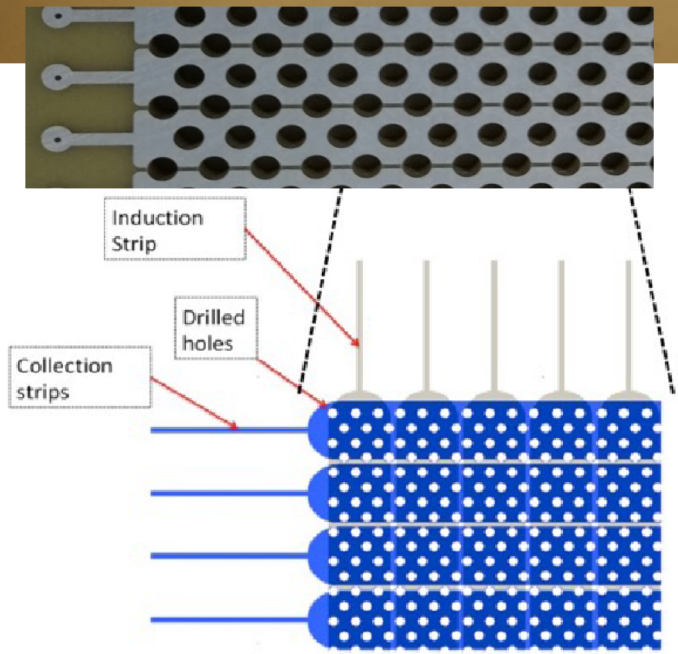
DAQ System (NP04/NP02)

FELIX

Perforated PCB Anode

- The idea driven by several possible improvements wrt wire chambers:
  - Most components can be mass produced commercially
  - The anode plane is robust, without risk of broken wires, has simpler support structure
  - Possibility of integrating the FE electronics on the PCB
- The design took advantage of the technological development of wide area Thick-GEMs at CERN.
  - Electrons are 2D focused in the PCB holes
  - Strips in the front sense induction signal
  - Strips at the back collect the ionization electrons
- Recently proven at CERN in two and three view configuration on small scale LAr-TPC
  - coupled with NP04/SBND Cold electronics

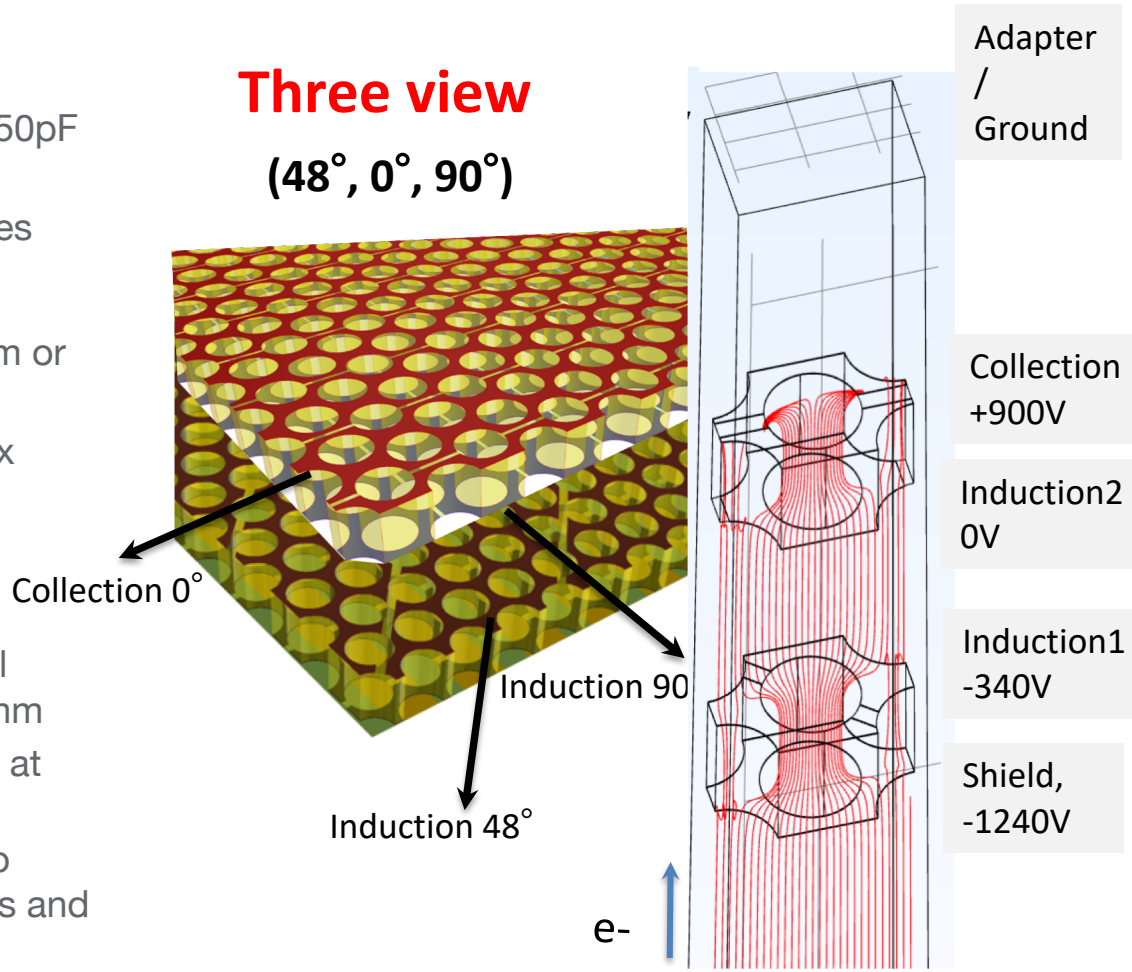




- Holes to surface ratio: 30 - 60 %
- Hole positioning not critical (many holes per strip)
- Standard PCB thickness: ~3 mm
- Hole rim not critical due to operation in LAr and absence of amplification

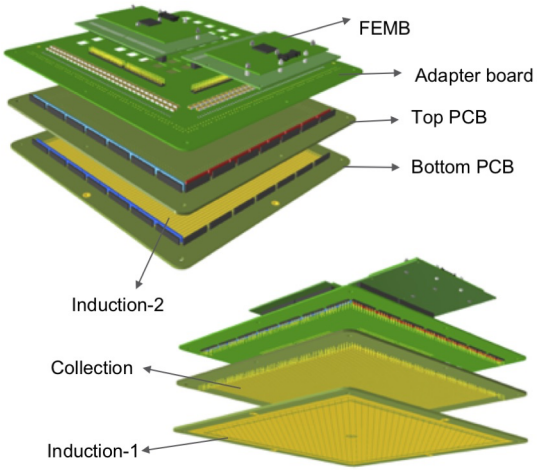
Perforated Anode PCB's reference design for VD

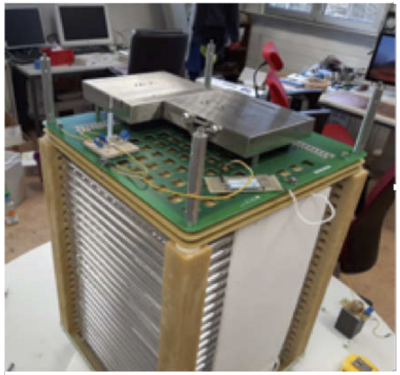
- Assumptions:
  - Use DUNE readout electronics
  - input capacitance similar to APAs ~150pF (~1.5m strip)
  - Minimize dead areas between modules
- Practical boundary conditions
  - Common PCB core thickness: 3.2mm or less
  - PCB fabrication limitation, but 1.5m x 1.7m in plating is feasible.
- Reference design
  - Two PCB's with ~ aligned holes
  - Collection and Induction2 orthogonal views on one PCB: strip pitch ~5.2 mm
  - 3rd view (Induction1) on second PCB at ~48°; pitch: 8.7mm
  - Shield layer facing the drift volume to protect FEE from cathode instabilities and HV ripple
  - PCB's spacing: ~ 9 mm -> asymmetric bipolar induction signals: beneficial for visibility due to reduced cancellation effect of opposite polarity lobes

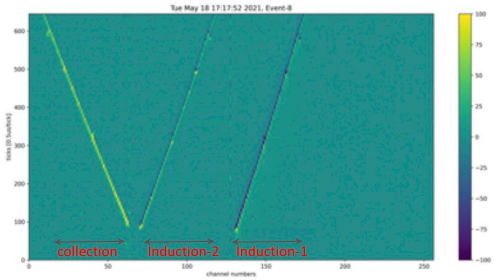


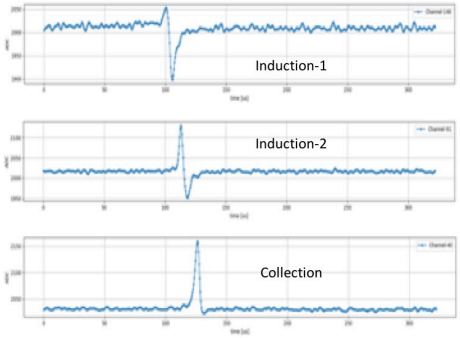
Small scale tests

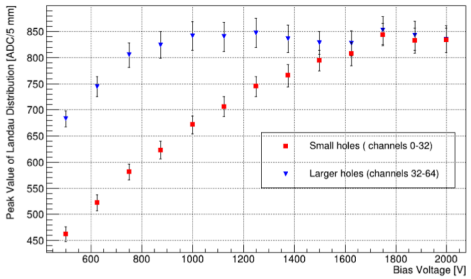
- 50 liter LArTPC:
  - 2 and 3-view PCB anode with CEs, resistive cathode, 52cm drift, Al field shaping rings, 500V/cm field
- Study of bias voltage, transparency and hole sizes
  - good agreement with COMSOL simulations)
- Study of signal shapes:
  - response functions, cross talk
- Noise level: ~300 electrons at LAr
  - Extrapolating SNR to ~1.7m PCB strip:
    - *~33 for collection*
    - *~23 for induction*
    - very similar to values reported in ProtoDUNE-SP performance paper. Energy/space resolution (muon dE/dx, Bi207 source)

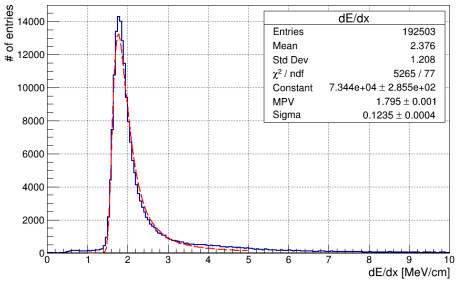




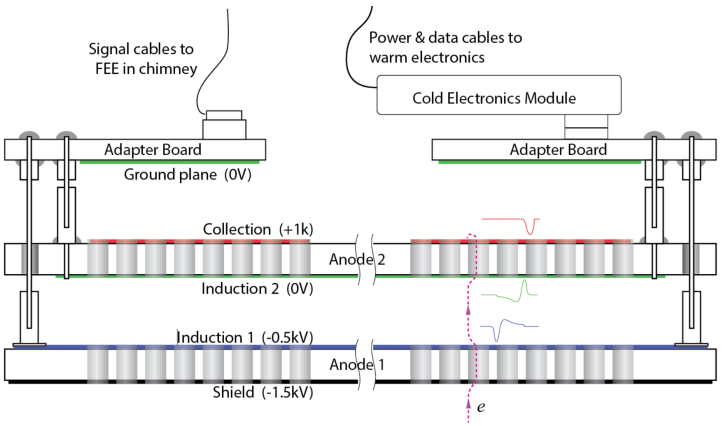






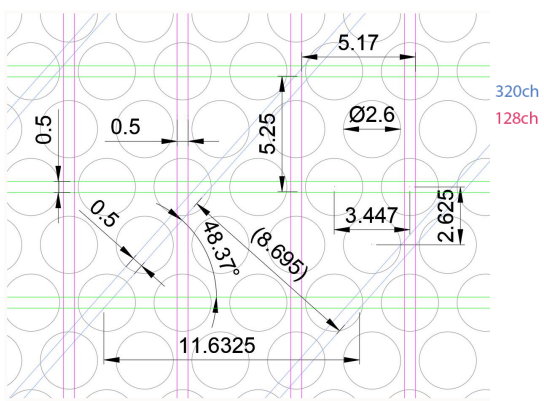


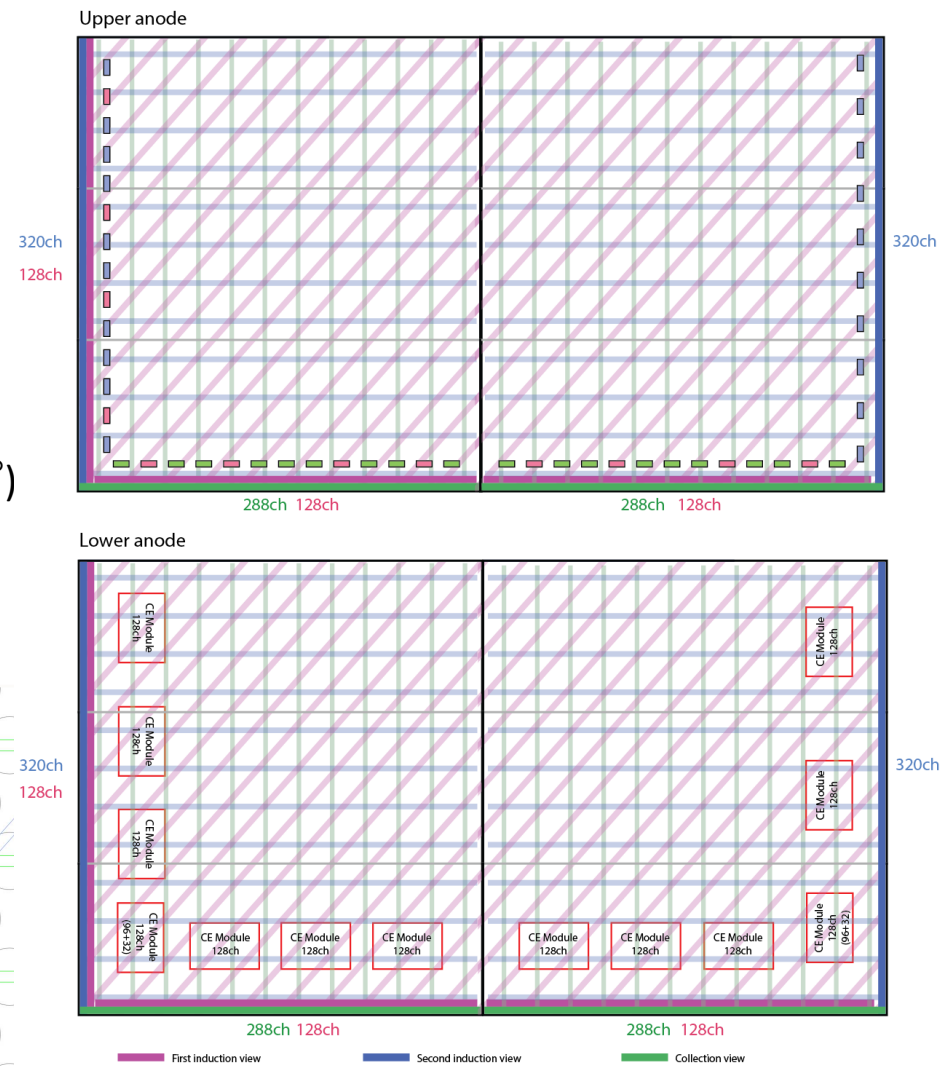
CRP 3-View Design: CRU (1/2 CRP) layout PCB's



Collection view strips orthogonal to the beam.
The 1st induction along the diagonal of the CRU (48°)
Strips across long gap between pair of CRUs on the same CRP interconnected to save r/o channels.
Layout with strips at 60 ° also under consideration

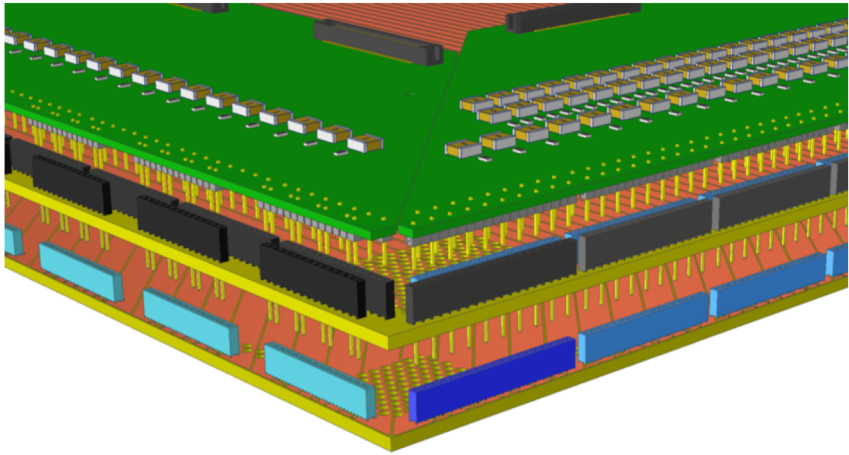
Channel count per CRU pair (CRP):
1st view: 384
2nd view: 640
3rd view: 576

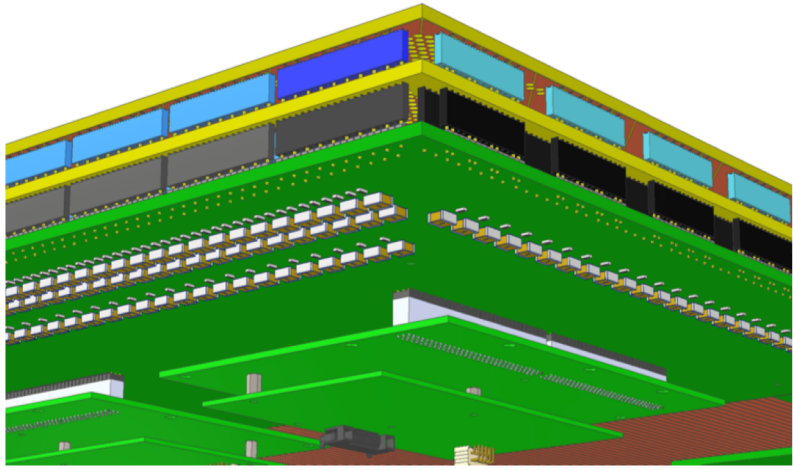




CRP assembly and read out integration

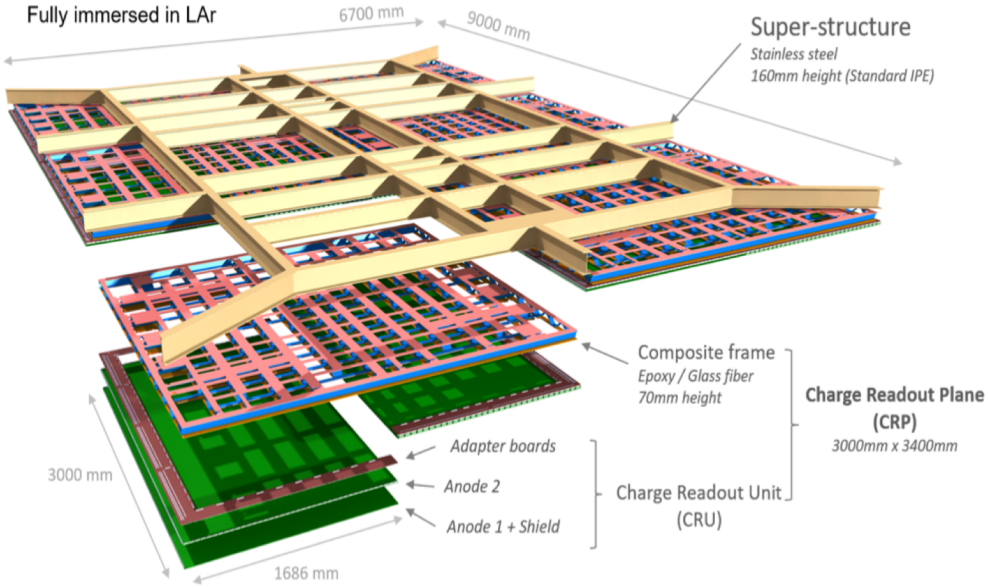
- PCB's assembly (including FEE adepted boards) through thin connector/pins on boundary
  - Mimimal dead space (< 1 strip width)
- Top CRP read out with extractable NP02-like front end electronics localted in dedicated chimneys
  - Adapter board equipped with cable connectors
- Bottom CRP equipped with NP04 like cold frond end electronics
  - localted directly on adapter board.
- Adapter boards include biasing resistors and decoupling capacitors

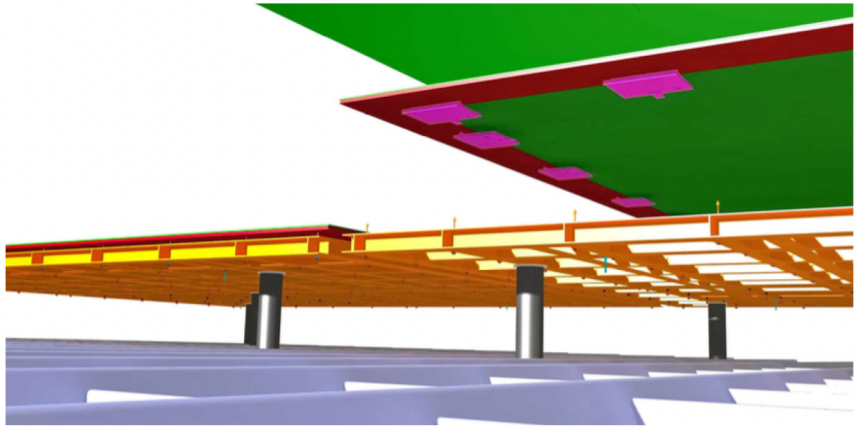




CRP support structures

- Top CRP frame holding CRUs (anodes+adapter boards)
- Top suspension superstructure holding 6 CRP's
- Bottom CRP's on composite frames: alignment and planarity controlled by the supporting feet
- Both designed to guarantee planarity and deformation within few mm range and deal with shrinkage at cold





Summary of CRP features

- Main CRP components

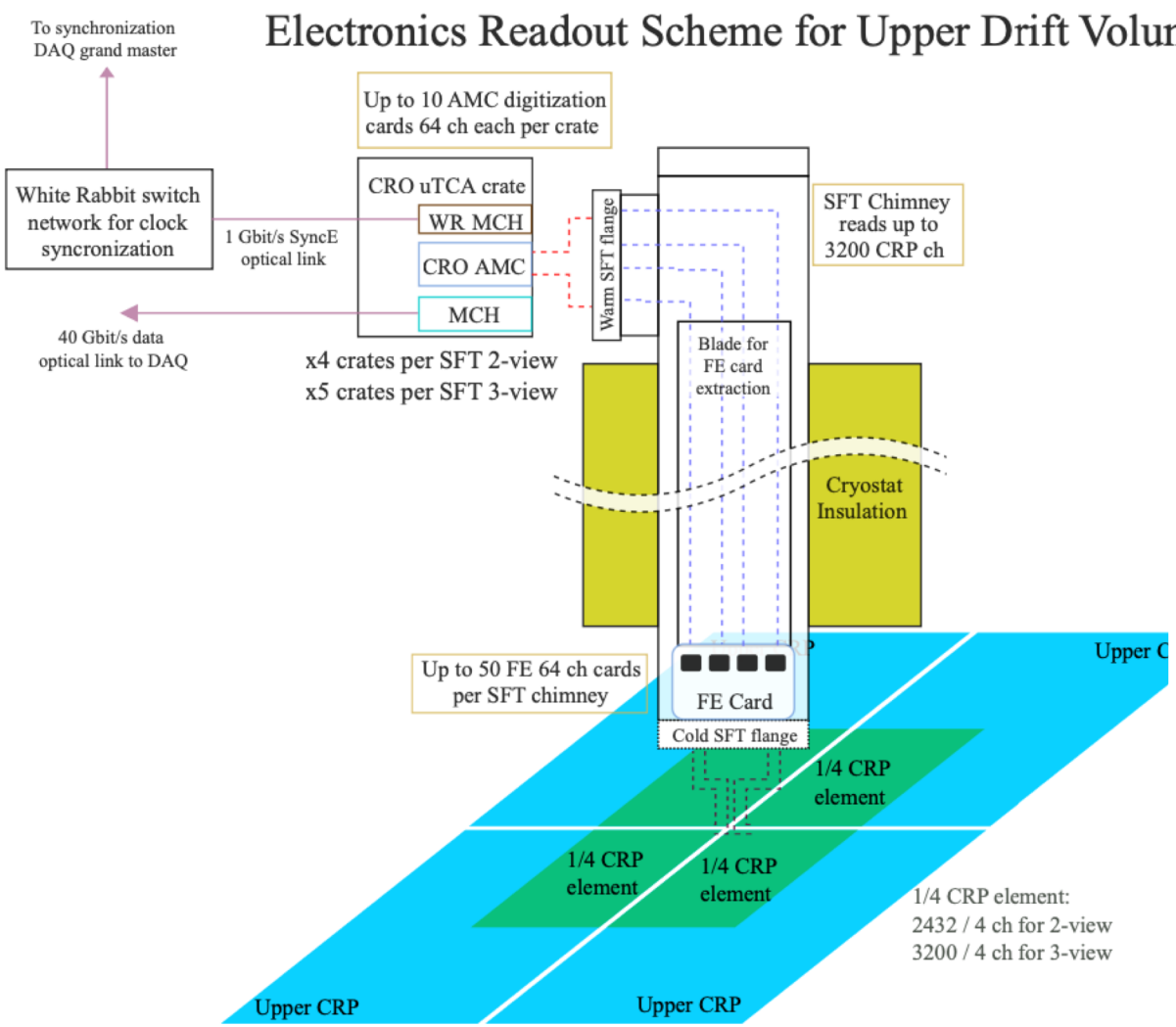
Component	Sub-components	Quantity	Size
PCB panel	-	2 per CRU (stacked), 640 total	$1.6875\,\mathrm{m} \times 1.5\,\mathrm{m}$
View (also called "layer")	electrode strips on PCB	1 set of parallel strips per PCB panel side	See Table 3.2
Adapter board	4-layer PCB + bias capacitors and resistors	8 per CRU, 2560 total	in 8 different flavors and sizes for top and bottom
CRU	2 PCB panels + 8 adapter boards	2 per CRP, 320 total	$1.6875\,\mathrm{m} \times 3.0\,\mathrm{m}$
CRP	2 CRUs + composite frame	80 per anode plane, 160 total	$3.0\,\mathrm{m} \times 3.375\,\mathrm{m}$
Anode plane	80 CRPs	2	$60.0\,\mathrm{m} \times 13.5\,\mathrm{m}$

- CRP Key parameters

Parameter	Induction 1	Induction 2	Collection
Strip length [m]	up to 2.24	1.49	1.68
Strip pitch [mm]	8.7	5.25	5.17
Strip gap [mm]	0.5	0.5	0.5
Unit capacitance [pF/m]	109	83	91
Total capacitance [pF]	up to 250	125	153
Number of strips per CRU	384	640	576
Number of readout channels per CRP	3200		
Strip angle w.r.t. beam	48°	0°	90°
Bias voltage [V]	-340	0	+900
Hole diameter [mm]	2.6	-	2.6
Inter-PCB gap within CRP (at room temp.) [mm]	1		

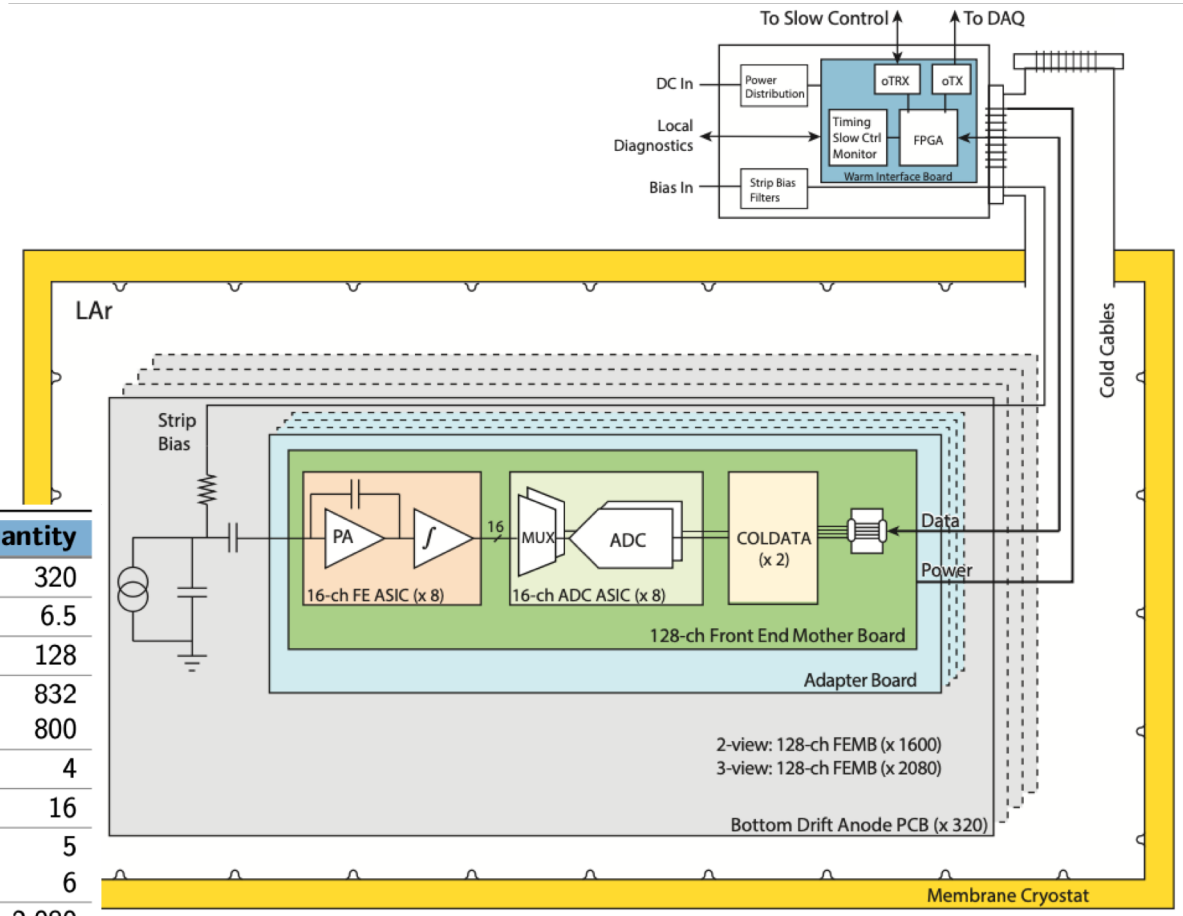
- Main electronics requirements
  - E-noise < 1000 el.
  - FE shaping time ~ 1 us
  - Sig. saturation: 500000 el.
  - Sampling freq> 2 MHz
  - 12 bit ADC
  - CE consuption <50 mW/channel
  - Non FE noise contribution <<1000 el.
  - Dead channels < 1%

Top electronics layout



Item	Quantity
1.5 m x 1.7 m CRUs in the top drift	320
Anode channels per CRP	3200
Channels per FE card or AMC card	64
FE cards or AMC cards per CRP	50
Number of SFT	105
FE card slots per SFT	50
Installed FE cards per SFT	50
μTCA crates	400
AMC cards per crate	10
WR-MCH	400
40 Gb/s data links	400
Anode channels in the top drift	256,000

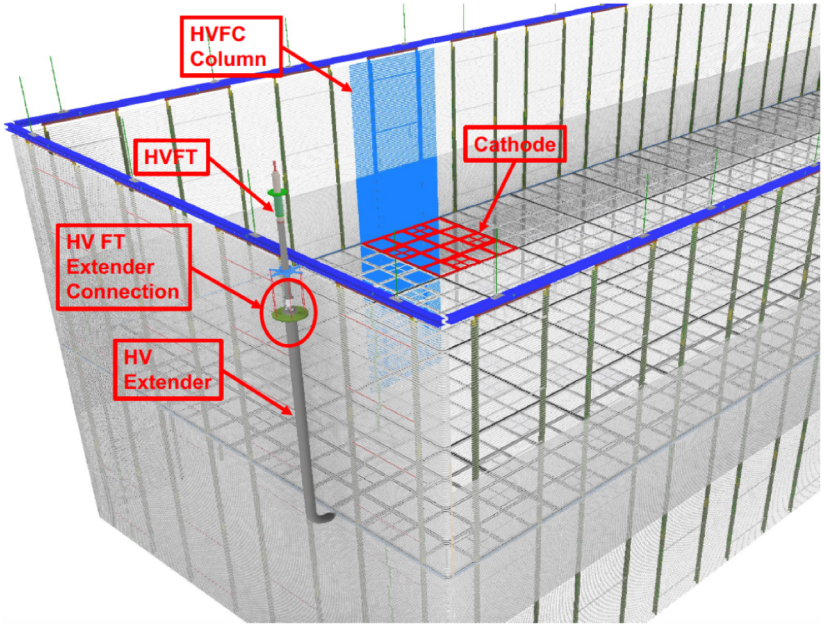
Bottom electronics layout

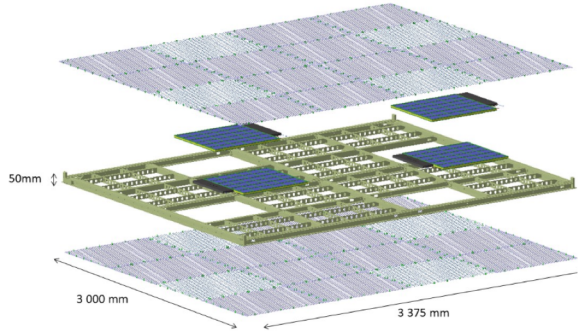


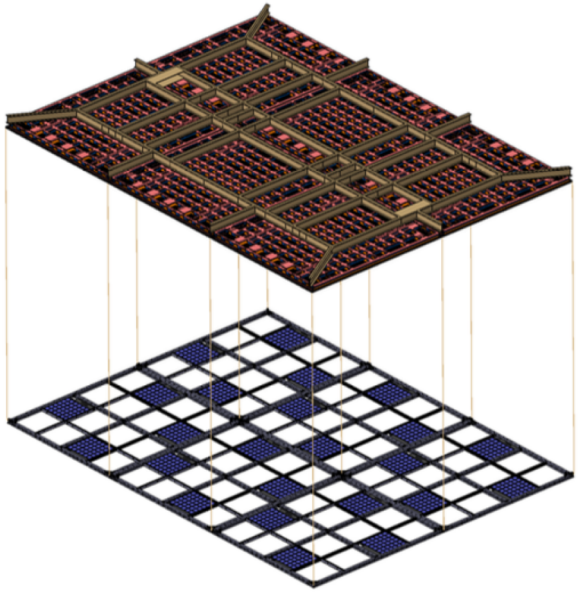
Item	Quantity
$1.5\,\mathrm{m} \times 1.7\,\mathrm{m}$ CRUs in the bottom drift	320
FEMBs per CRU	6.5
Channels per FEMB	128
Available readout channels per CRU	832
Used readout channels per CRU	800
1.25 Gb/s links per FEMB	4
1.25 Gb/s links per WIB	16
WIBs per WIEC (standard configuration)	5
(alternate for three-view)	6
FEMBs in the bottom drift	2,080
Used readout channels in the bottom drift	256,000
Available readout channels in the bottom drift	266,240
WIBs in the bottom drift	520
WIECs (FT flanges) in the bottom drift: 5 WIBs	80
6 WIBs	20

High Voltage system

- Field cage suspended independently from cryostat roof
- Top and bottom 4 m FC with 70% transparency (for the PD's on the membrane)
- Modular (3x3.75 m2) light cathode suspended from top CRP structure. (planarity < few cm)
- Double resistive layers (80% transparency) to incorporates X-ARAPUCA modules.
- *Max Voltage: 294 kV limited by HV-PS avalaiblity*
  - *450 V/cm*
  - *4300 us max drift time*

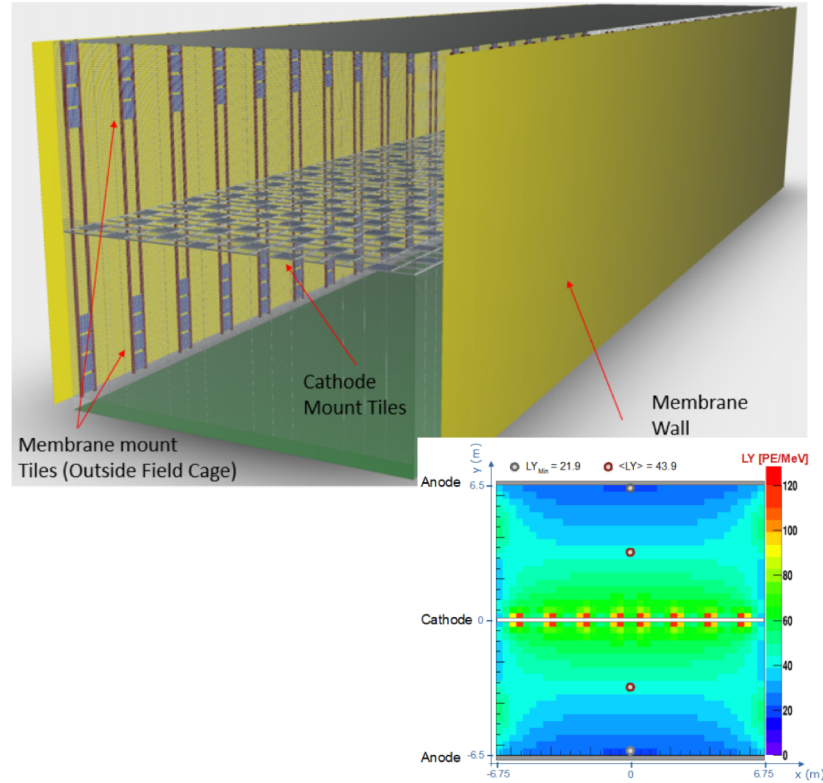


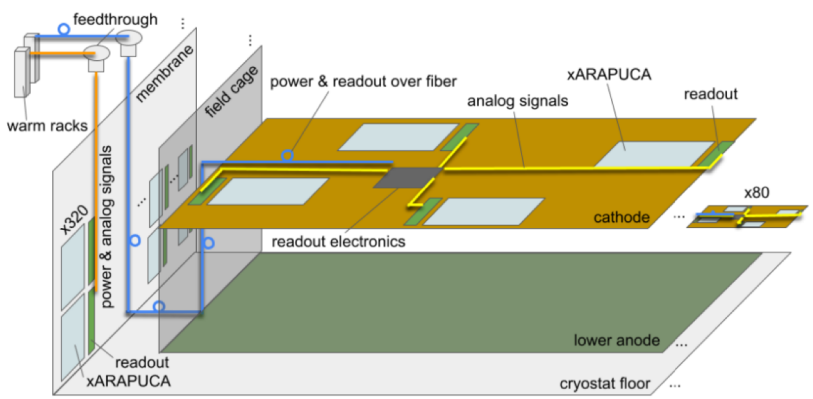




Photon Detectors

- Purposes: Trigger, T=0 and calorimetric measurements down to tens of MeV
- X-ARAPUCA units inside the cathode (14% coverage) and on cryostat walls (7%) to improve response uniformity
- Optimized for Xe doping
- Power and Signal over Fiber development required.
- Intense on going R&D
- Standard readout for X-ARAPUCA on walls.
- Alternative plan (increased PD coverage on cryostat walls only) also investigated.





Item	Quantity	Detector Surface
X-ARAPUCA modules	320 double-side	Cathode plane
	320 single-side	Membrane long walls
Dichroic Filters	34,560	
WLS plates	640	
PhotoSensors (SiPMs)	51,200	Cathode plane
	51,200	Membrane long walls
Signal Channels	640	Cathode plane
	640	Membrane long walls
SiPMs per channel	80	
Optical Area	115 $m^2 \times 2$	Cathode plane
	115 m^2	Membrane long walls
Active coverage	14.8%	Cathode plane
	7.4%	Membrane long walls
	0%	Membrane end walls

Photon Detectors key parameters

- Specifications

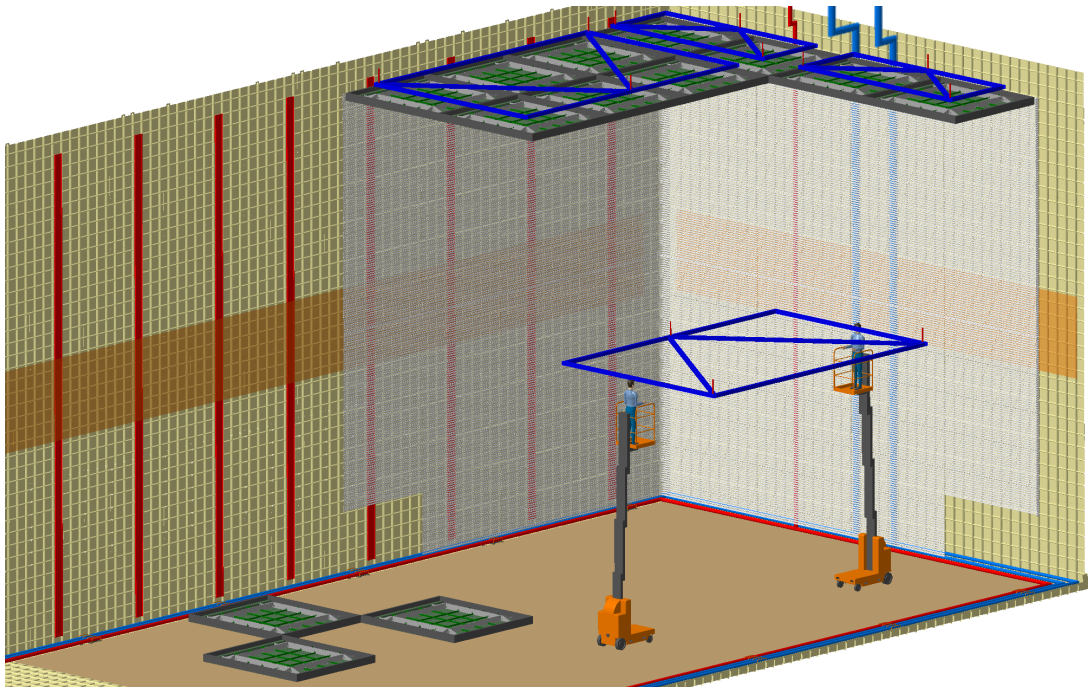
Physics Performance Indicator	Value	Physics Purpose
Average light yield	$\simeq 40$ PE/MeV	Detailed timing information and PDS-based energy reconstruction for low-energy events.
Minimum light yield	$\simeq 10$ PE/MeV	Tagging of $> 99\%$ of nucleon decay backgrounds with light at all points in detector.
Trigger efficiency for interactions with energy deposit $E_{dep} \geq 20$ MeV in 100% of detector fiducial volume	$\geq 95\%$	SN burst trigger up to the Large Magellanic Cloud (50 kpc) yielding 10 interactions in 10 kt LAr. Low-energy background rejection.
Spatial resolution for interactions with energy deposit $E_{dep} \geq 5$ MeV	≤ 1 m	Background rejection for SN, solar, nucleon decay.
Energy resolution for interactions with energy deposit $E_{dep} \geq 5$ MeV	$\leq 9\%$	Identification of SN spectrum features from different SN dynamical models.

- Expected performance

Description	Specification	Rationale
Light yield	>20 PE/MeV (avg), >0.5 PE/MeV (min)	Gives PDS energy resolution comparable to that of the TPC for 5-7 MeV SN νs, and allows tagging of $> 99\%$ of nucleon decay backgrounds with light at all points in detector.
Time resolution	< 1 μs Goal: < 100 ns	Enables 1 mm position resolution along drift drift direction.
Spatial localization in plane perpendicular to drift	< 2.5 m	Enables accurate matching of photon detector (PD) and TPC signals.
Single PE pulse height per baseline noise RMS	> 4	Signal-to-noise sufficiently high to keep data rate within electronics bandwidth limits and to ensure efficient trigger.
Dark rate per electronics channel	< 1 kHz	Dark noise sufficiently low to keep data rate within electronics bandwidth limits and to ensure efficient trigger.
Fraction of beam events with saturating channels	$< 20\%$	Sufficient dynamic range is needed to reconstruct the energy calorimetrically, but a small amount of saturation can be mitigated.

Integration and Installation

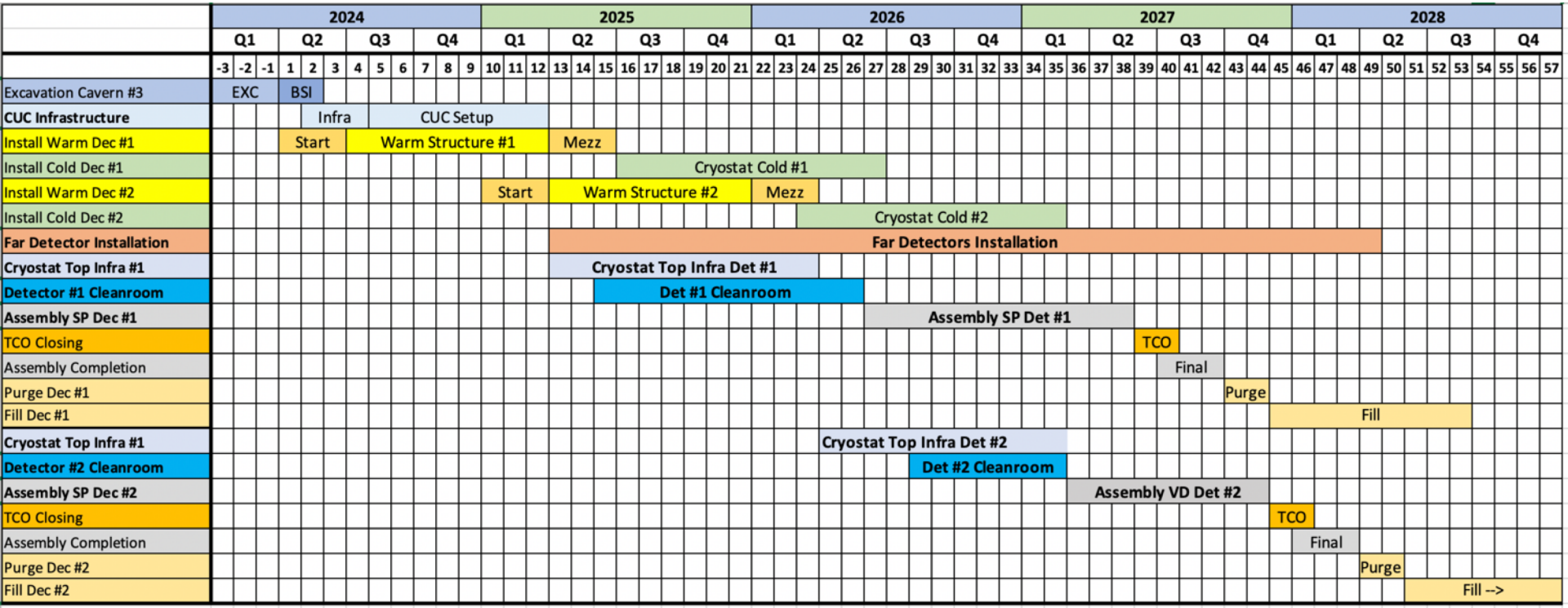
- ✓ Cryogenics and Installation : based on established LBNF I&I activities
- ✓ Installation possible in 9 months
- ✓ Very simple infrastructure components, no need for a large and complex clean room
- ✓ Installation in 6 steps, starting from the top
- ✓ Installation procedure very similar to the NP02 experience



Detailed installation engineering still under development by the I&I group

LBNF/DUNE tentative schedule

- December 2020: presented VD proposal to then DUNE Collaboration
- 2021 technology demonstrators (CRP in cold box, 300kV tests in NP02)
- December 2021/March 2022: Technology decision and baseline (US CD-2)
- **If approved as 2nd far detector: 2022–23 *Module-0* in NP02**
- 2024–26 components mass production
- 2027 installation in the cavern at SURF
- 2028 cool down and filling

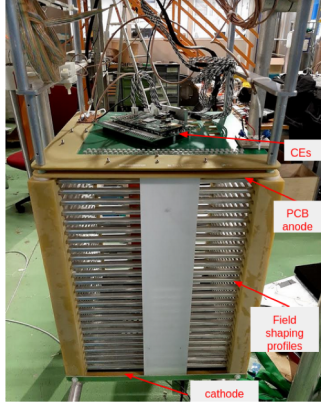


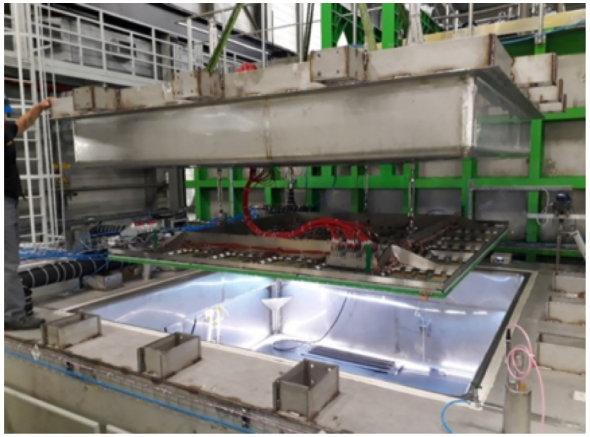
Main R&D to validate the VD concept

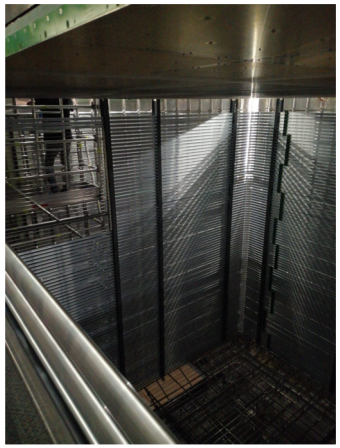
- Project build on solid ground (NP04/NP02) but vigorous R&D required on:
- Perforated PCB anode
  - 2-view and 3-view options proven to be feasible feasible and tested on small scale
  - Reference 3-view readout to be demonstrated in NP02 cold box
  - Effort on physics simulations/reconstruction ongoing to define best anode layout
- HVS operation at 300 kV
  - Critical elements of the HV distribution: HV feed through, HV “extender”
  - Long term stability runs and NP02 demonstrator
- Photon detector
  - Operation at HV: demonstration of Power over Fiber and Optical Readout (stand alone test and NP02 coldbox)
  - Optimization of detection efficiency for Xenon light

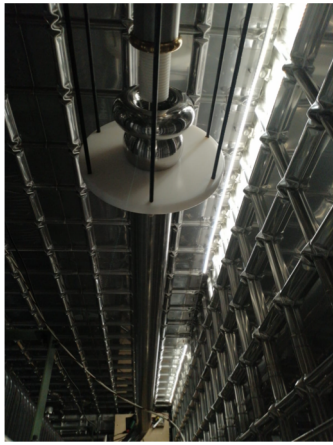
Milestones for 2021

- ✓ TPC 50L anode 2-view, done in 2020
- ✓ TPC 50L anode 3-view, done by April 2021: further additional anode optimization tests also planned
- ✓ New HV FT extender tested (FNAL/CERN), done by July 2021
- ✓ 1 CRP TPC (anode, electronics, cathode, PDs), for NP02 cols box: results by November 2021, several cycles planned also during 2022 (
- ✓ 300kV HV stability test in NP02 by December 2021



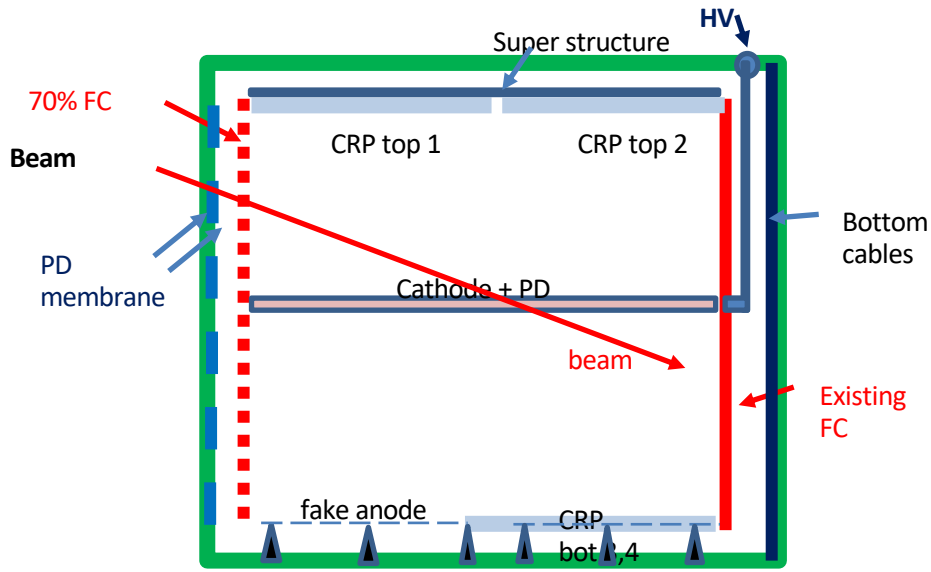


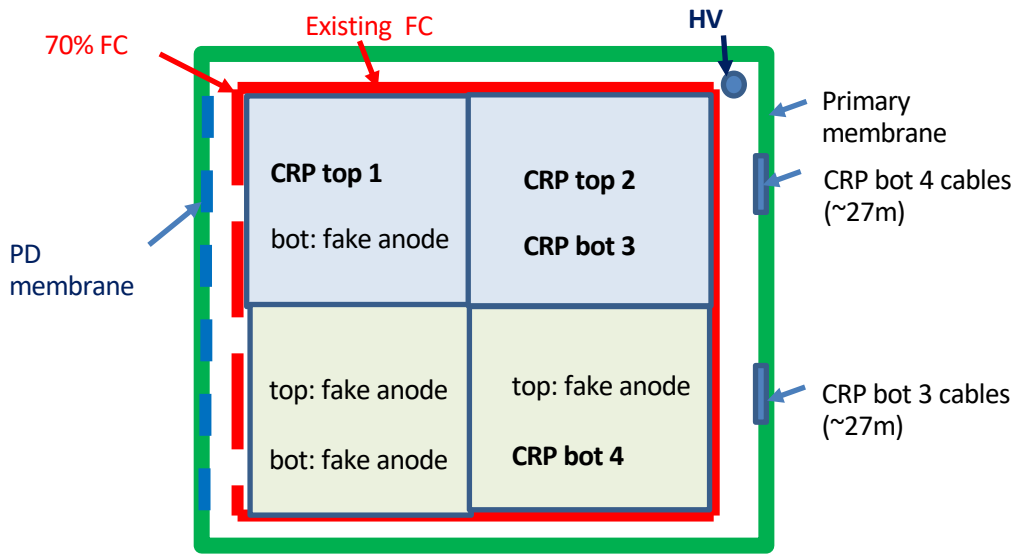




Module-0 (NP02): 2022–23

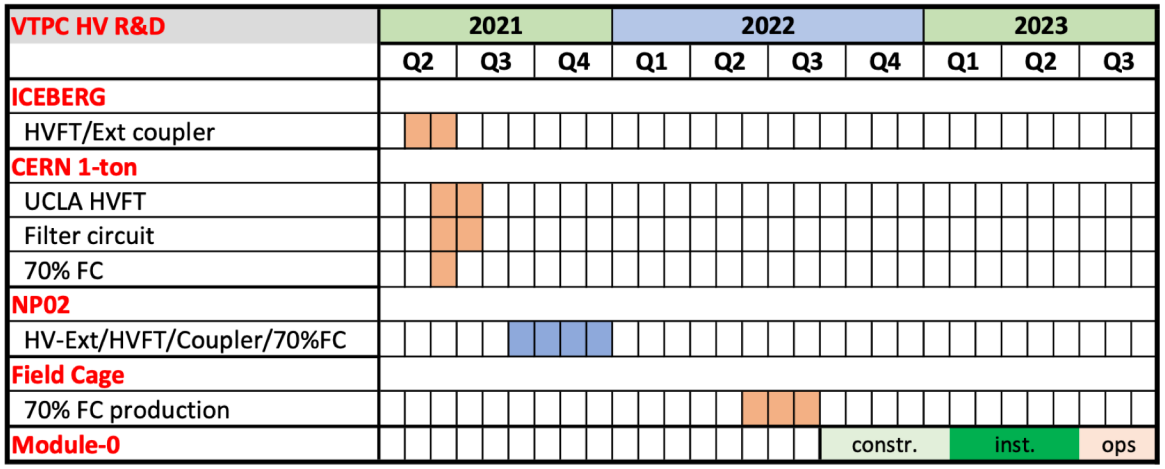
- 2 Top CRP (+ fake)
- SUPER structure to support top CRPs (6x6 m2)
- 2 Bottom CRPs in real conditions (supports, cable length 27m)
- Cathode as in final VD including supports
- Top/bottom electronics and FT/Chimneys)
- 70% FC on one side
- Shorter HV extender
- HV = 300 KV; ~ up to 1KV/cm
- Drift length ~3.5 m
- PDs facing 70% FC wall & on the cathode
- Vertical cable trays as in DUNE
- Beam plug
- Possible exposure to charged particle beams



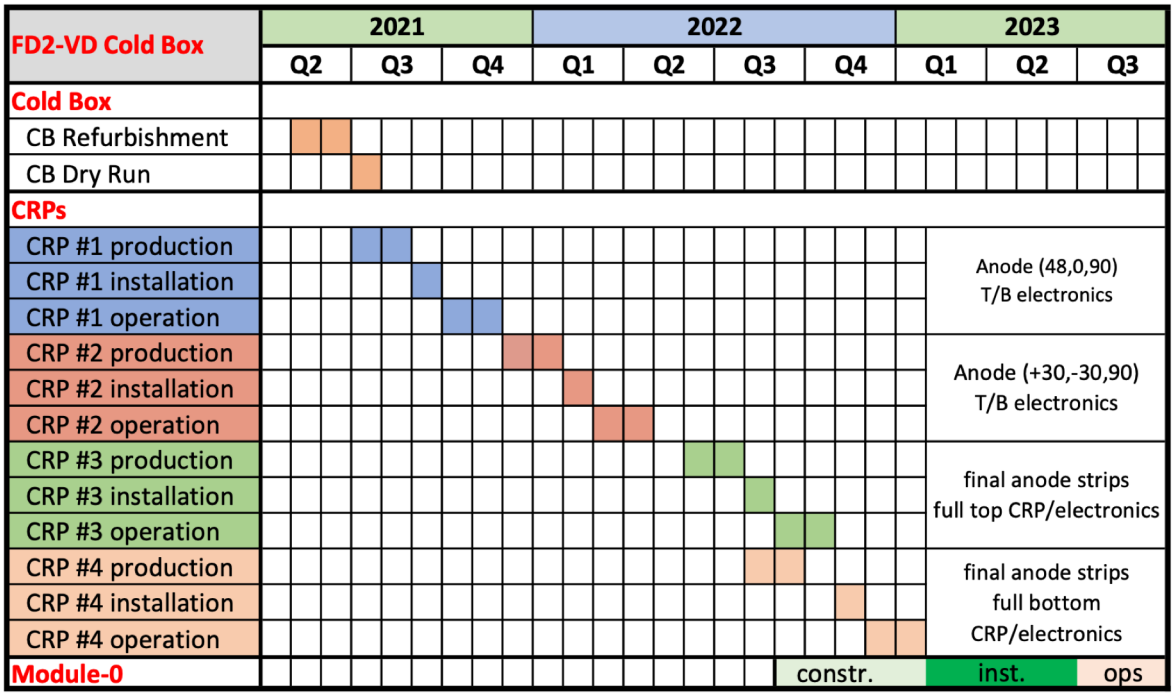


Tentative schedules toward Vertical Drift Module-0

- HV R&D
- Required to demonstrate long term stability at 300 kV



- CRP
- Most likely this item driving the schedule



- *Similar time profiles for PDs and Electronics,*