Vertical drift single phase LArTPC for DUNE

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Lessons learned from ProtoDUNEs and positive starting points

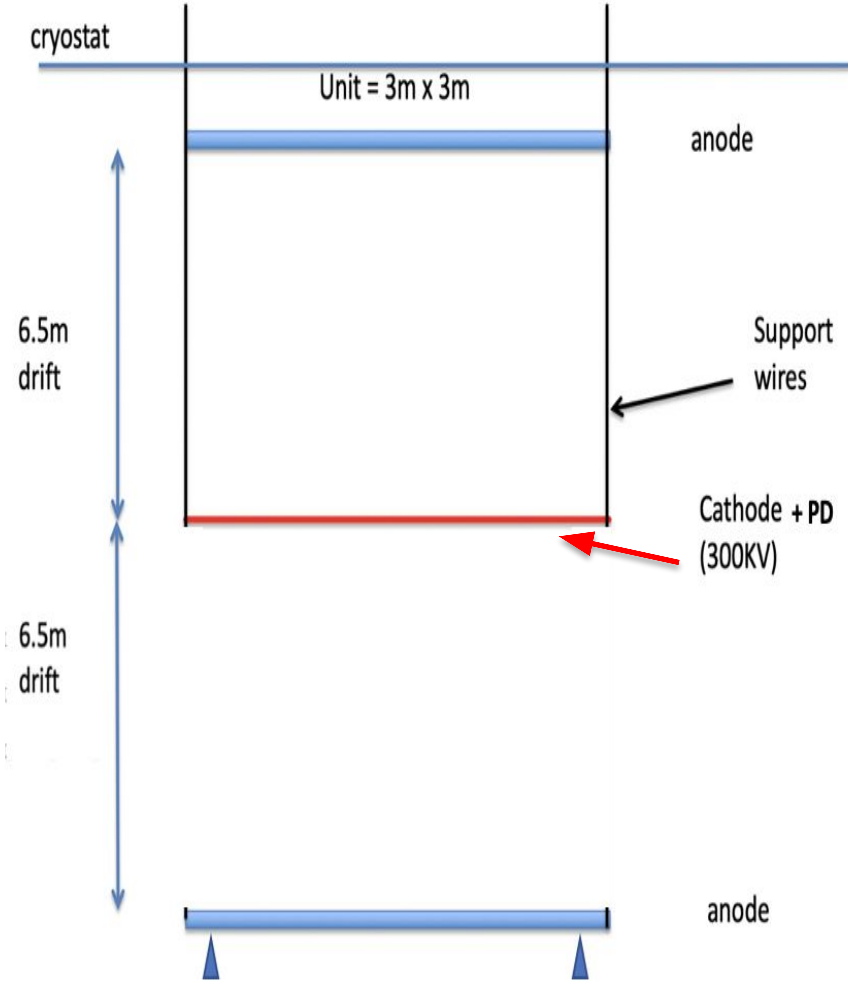
- LAr purity in ProtoDUNE is outstanding, allowing us to plan for longer drift length (aim for 6-7m) and better use of the drift space

- *The charge readout electronics in NP04/NP02 demonstrated excellent S/N (30-40)*

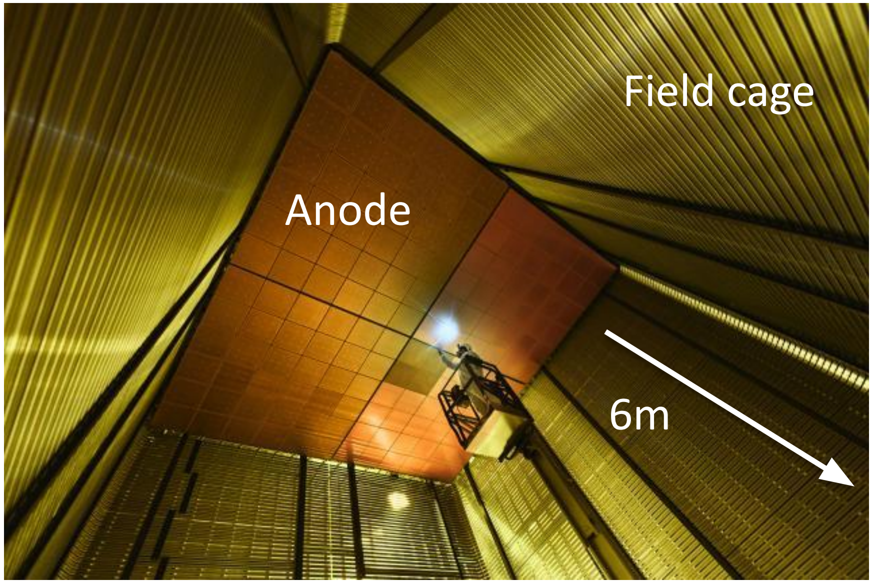
- Dual-phase detector layout is simpler to construct, uses the drift space in a more efficient way, reduce schedule and financial risks by increasing the level of modularity

- *Xe-doping improves the photon budget and opens the possibility to optimize the photon detector in its physics performance.*

Basic new concept (VD) !

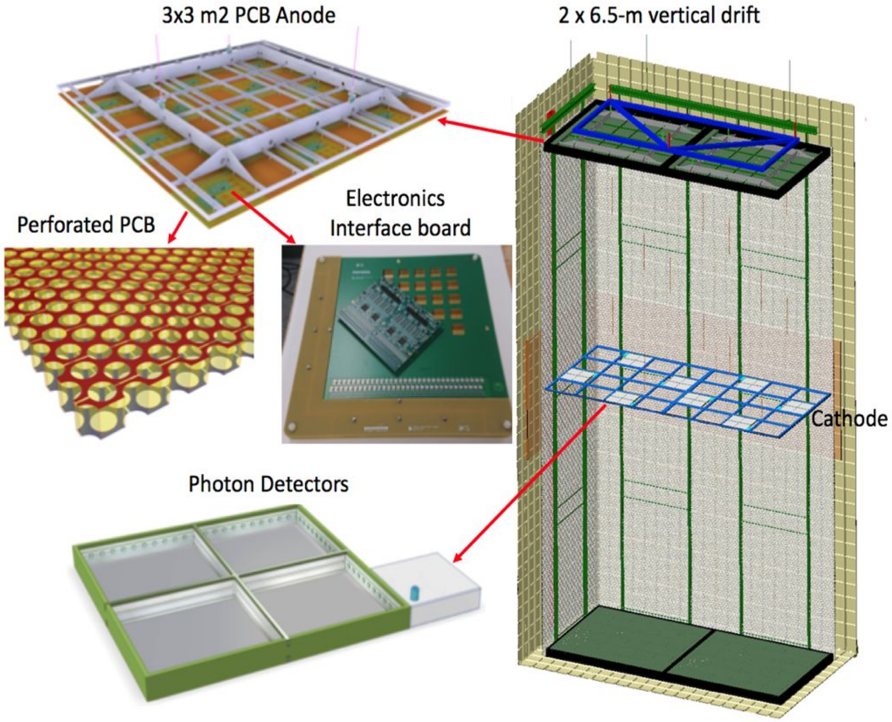


NP02 layout



cathode

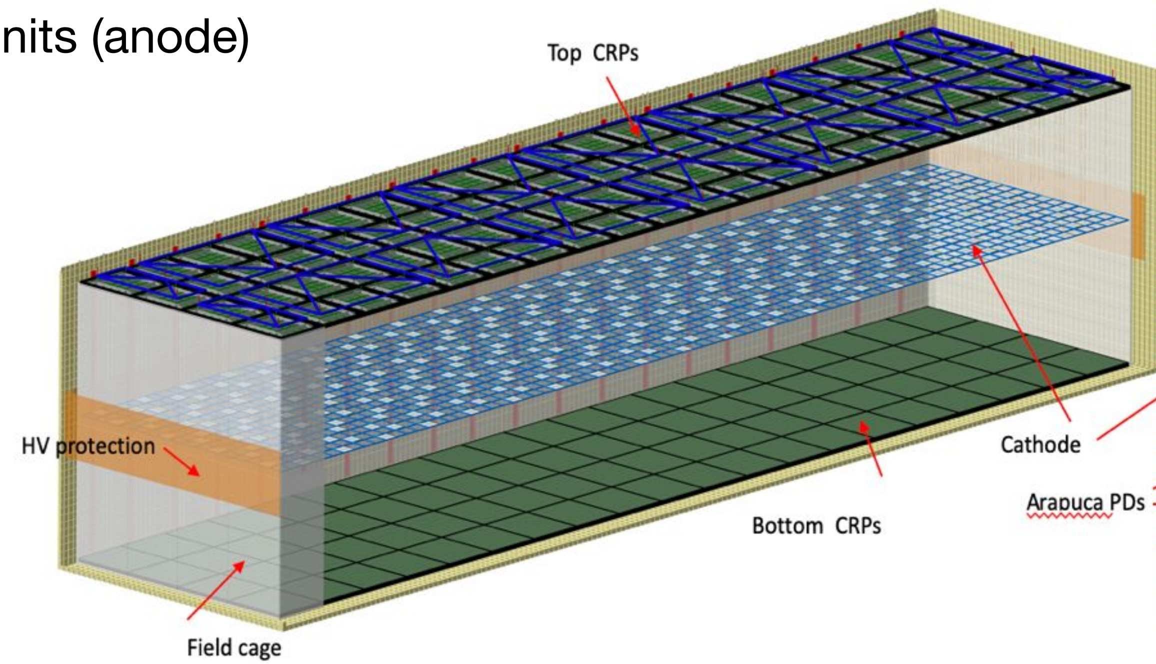
Vertical Drift Detector components

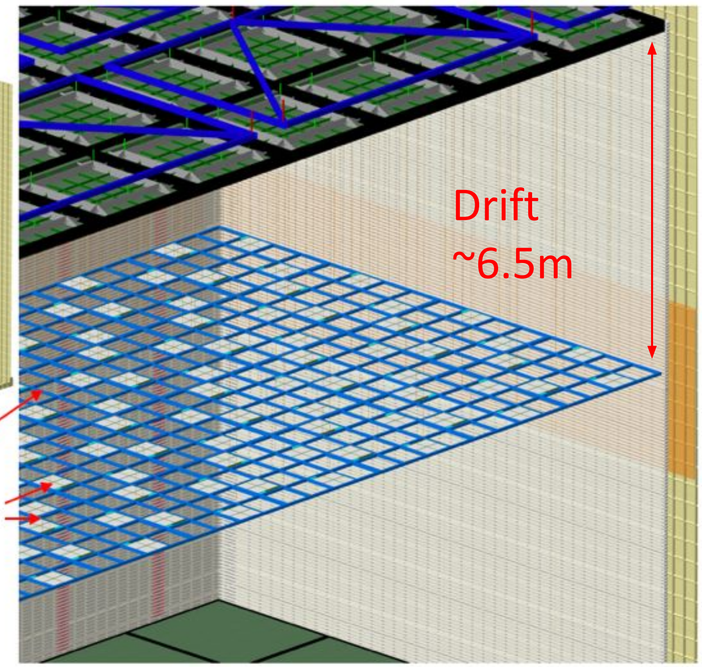


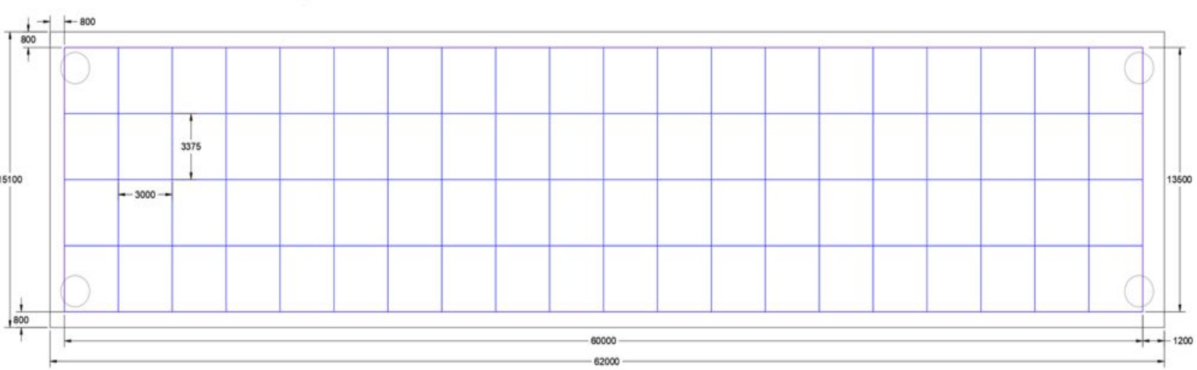
- Designed to maximize active volume
  - Readout units close to LAr surface and cryostat floor.
  - Cathode at middle height: better HV stability due to LAr hydrostatic pressure → closer distance to cryostat walls
- Perforated PCB's with segmented electrodes (strips) as readout units with integrated 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

Proposed reference layout for DUNE far detector

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







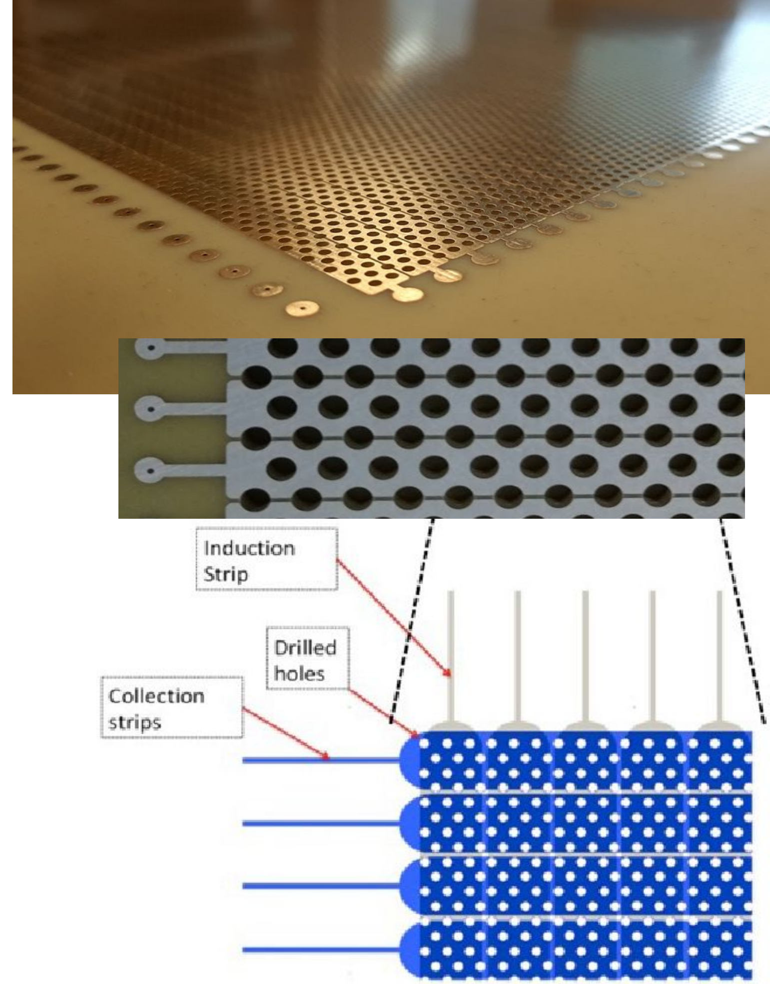
- ✔ 160 CRP units (80 on top, 80 on the bottom)
- ✔ Drift active volumes 2*5’265 m^3 = LAr 14.74 Ktons

Main R&D to validate the VD concept

- Project build on solid ground (NP04/NP02) but vigorous R&D required on:
  - Perforated PCB anode
    - Both 2-view and 3-view options technically feasible
    - Reference 2-view layout, already tested successfully on small scale
    - 3-view readout under demonstration
    - Effort on physics simulations/reconstruction ongoing to define
  - HVS operation at 300 kV (or more)
    - Critical elements of the HV distribution: HV feedthrough, HV "extender"
    - Long term stability runs and NP02 demonstrator
  - Photon detector
    - Operation at HV: demonstration of Power over Fiber and Optical Readout (alternative plans also under consideration)
    - Optimization of detection efficiency for Xenon light

Perforated PCB Anode

- In the past years a dedicated R&D program was carried out at CERN to develop a LAr-TPC with perforated multilayer printed circuit board (PCB)
  - Electrons are 2D focused in the PCB holes
  - Strips in the front sense induction signal
  - Strips at the back collect the ionization electrons
- The idea was 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.

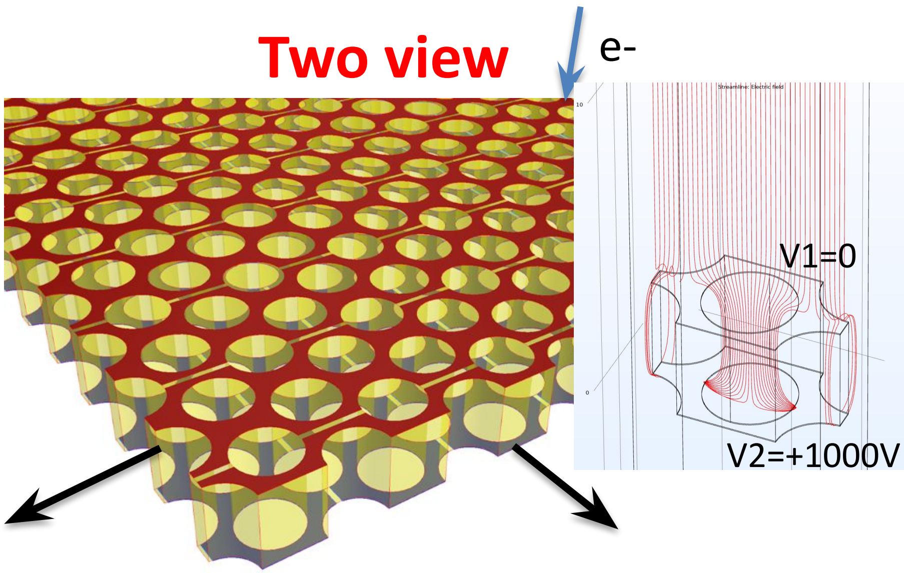


- Holes to surface ratio: 30 - 60 %
- Hole positioning not critical (many holes per strip)
- Standard PCB thickness: ~3 mm
- Hole rim not critical due to operation in LAr and absence of amplification

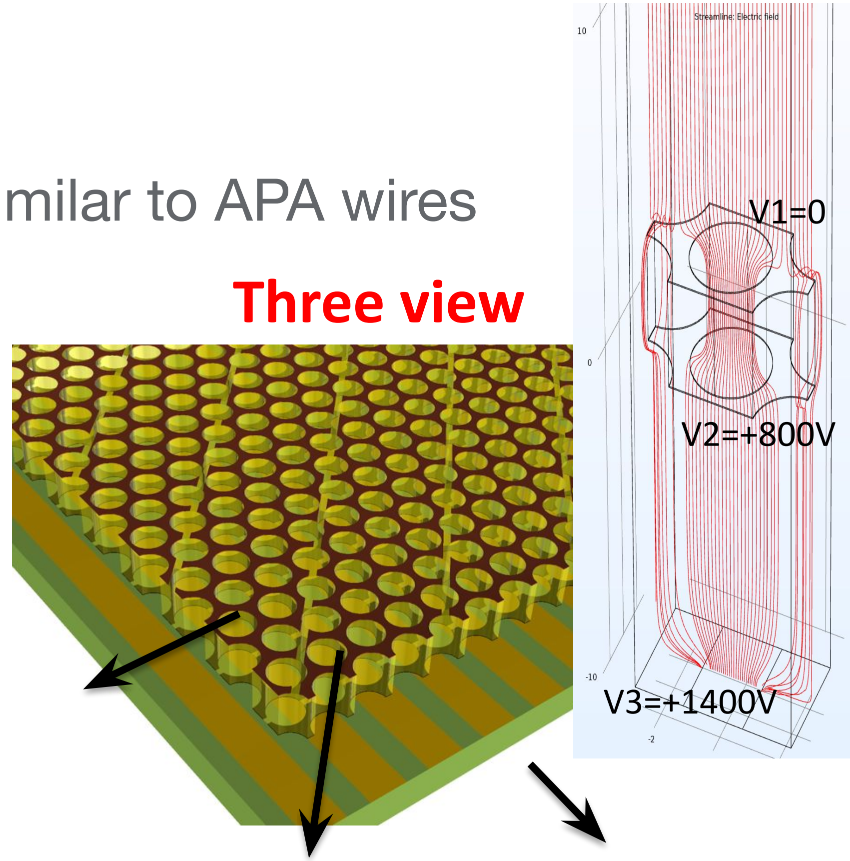
Perforated PCB Anode layout

- PCB perforated strips, with pitch similar to APA wires

Two view



Three view



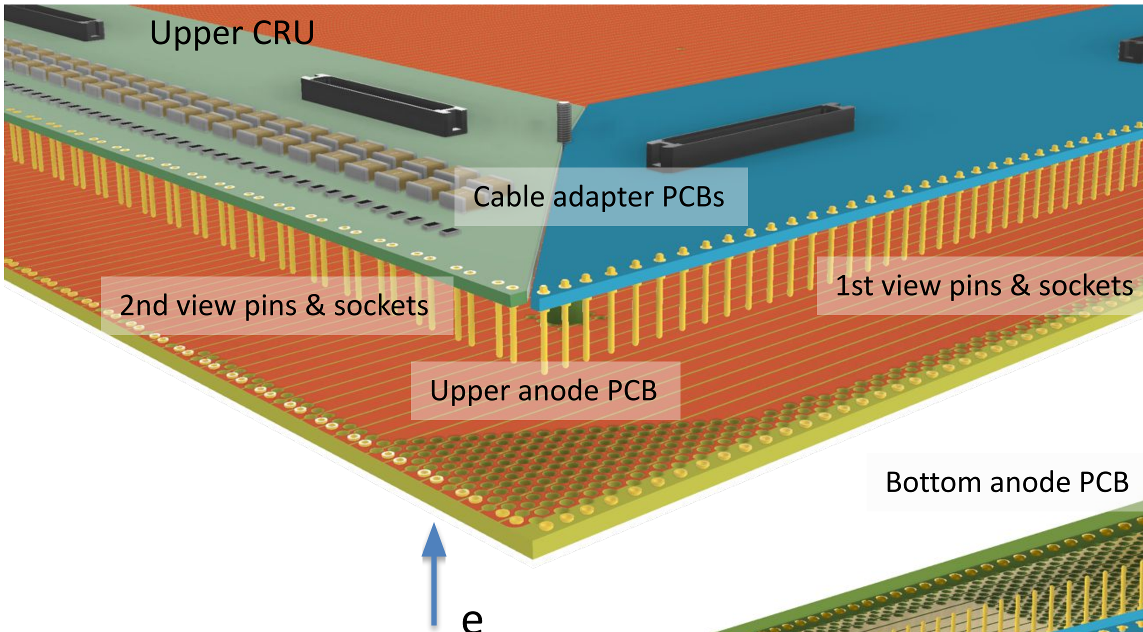
- ✔ 2.5 mm holes
- ✔ Collection strips in the transverse direction, 5.2mm width
- ✔ Induction strips along beam, 5.2mm width

- ✔ Adding 3rd view at ~45°
- ✔ Strip pitch 8.7mm
- ✔ 32% more channels
- ✔ 10 mm PCB spacing

Active and evolving design...

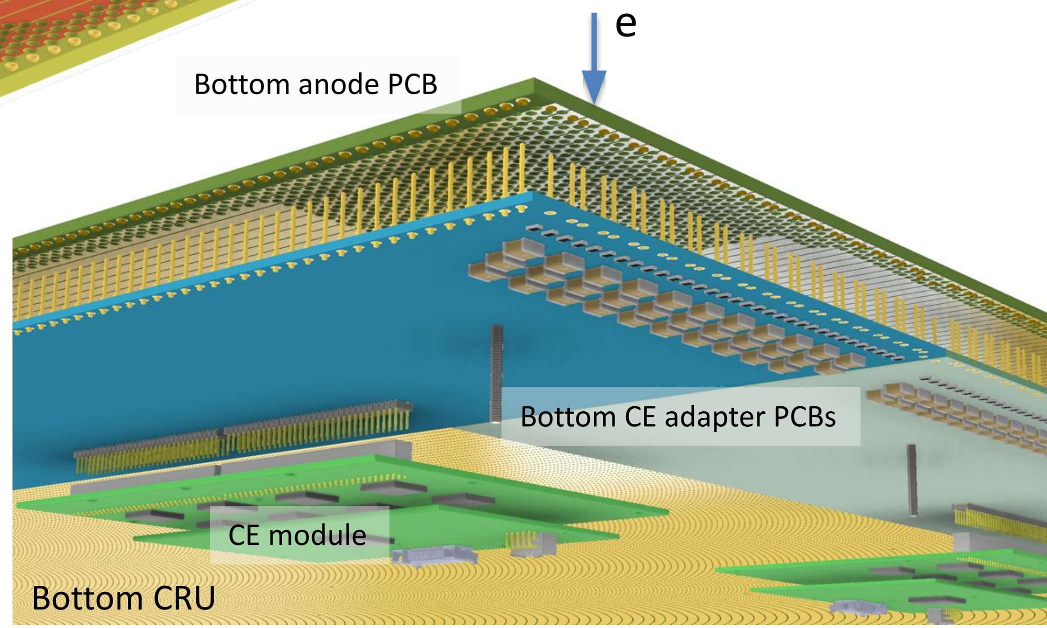
Both feasible, 2 views tested, 3-view will be tested with 50L TPC

2-View Design: CRU Assembly Details



4 CRUs are attached to a CRP support structure. Upper CRPs are suspended to SuperCRP structures under the ceiling, while the bottom CRPs are resting on the floor.

The 1st view strips are at ground potential, the 2nd view strips are at +1kV. This avoids the PCB mounting screws from influencing the drift field.

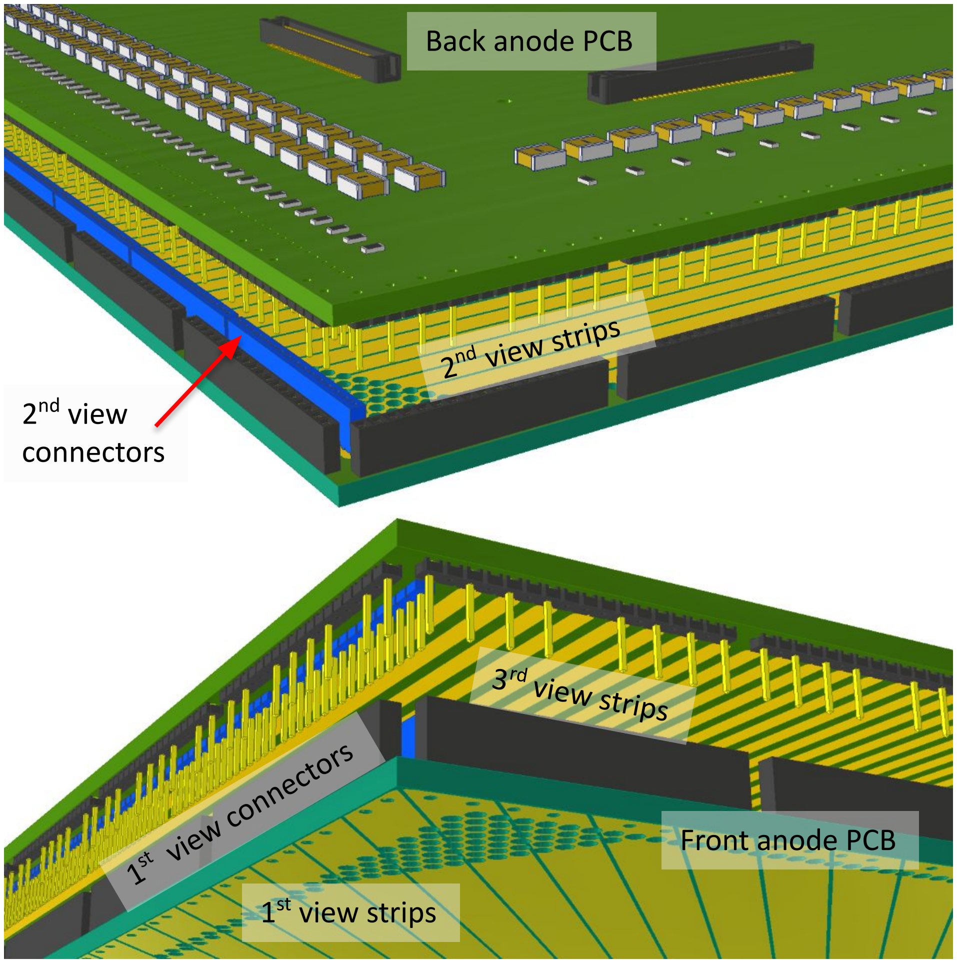


3-View Design: CRU Assembly Details

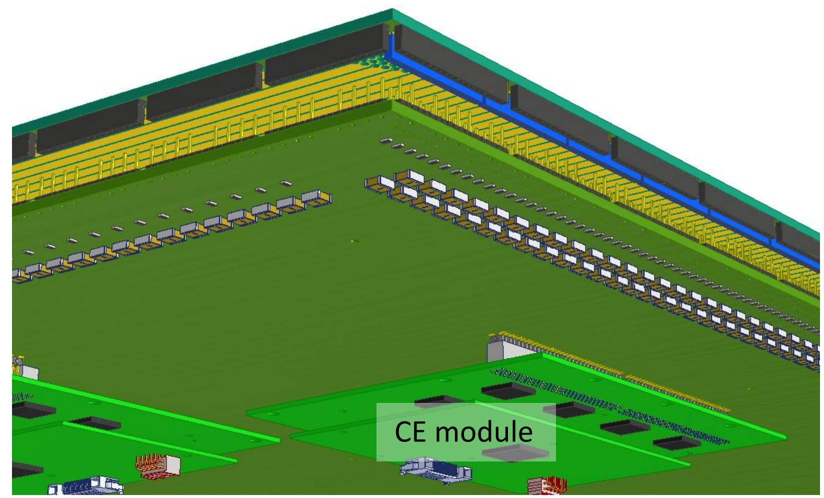
The 1st view is at ground potential, the bias voltage on the 2nd view is +800V, and on the 3rd view is +1400V.

The back PCB will be perforated to allow LAr flow. Porosity will be determined by CFD analysis.

A small version of this construction (integrated with CE) will be tested at CERN early next year to demonstrate its performance.



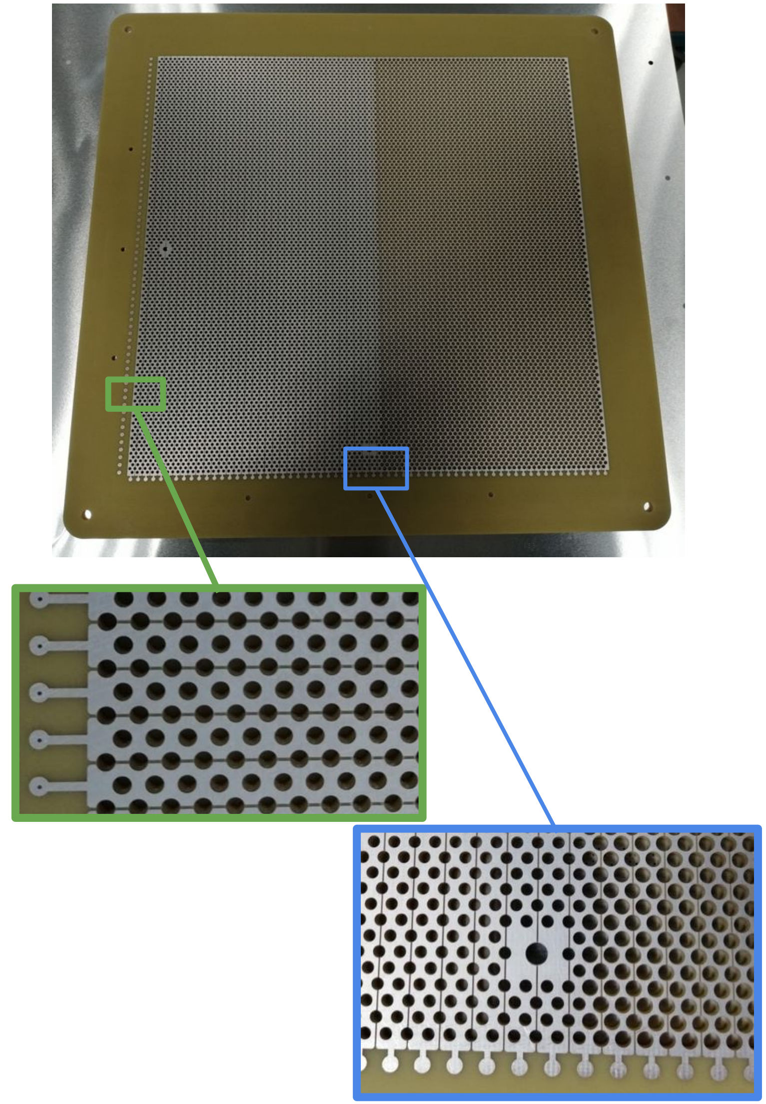
Upper CRU assembly details



Bottom CRU assembly details

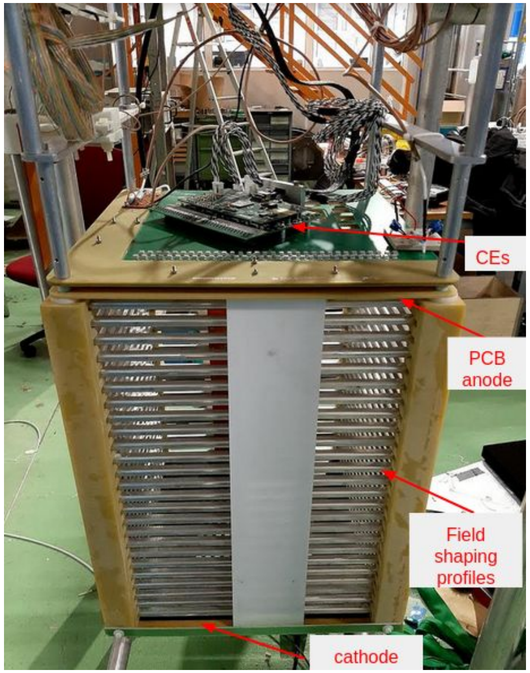
2-view PCB anode tests at CERN

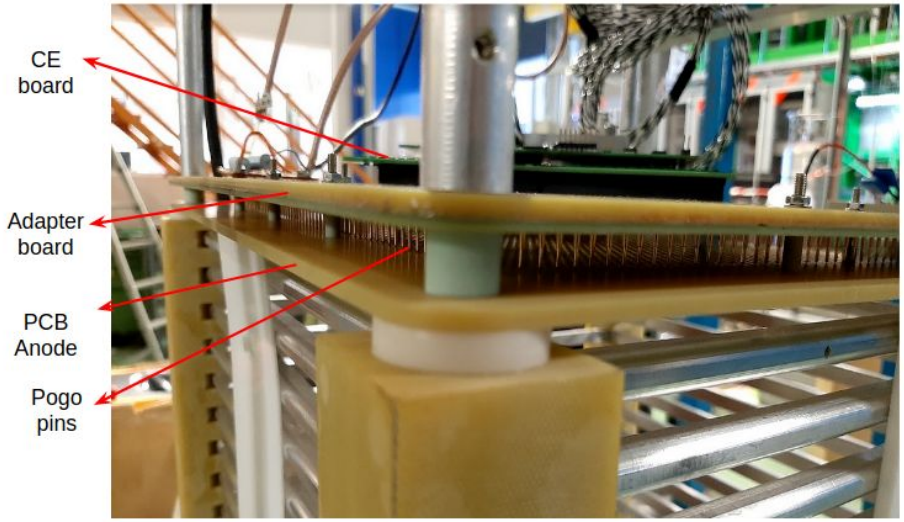
- Proof of principle: Small scale tests at CERN 50L setup
  - LArTPC with perforated PCB anode and integrated CEs
- Collect cosmic data and perform long term stability runs
  - Study the fundamental properties of PCB anode
    - Electron transparency, bias voltage, hole size and pitch configuration
  - Evaluate signal and noise characteristics
- 2-view perforated PCB
  - 64 induction and 64 collection channels orthogonal to each other on two sides of the PCB
  - 5 mm channel pitch
  - 32 cm x 32 cm active area
  - Two hole configuration: 2mm, 2.5mm diameters with 3.33mm hole pitch
  - Strip capacitance: ~40 pF (~5 x wires in LAr)

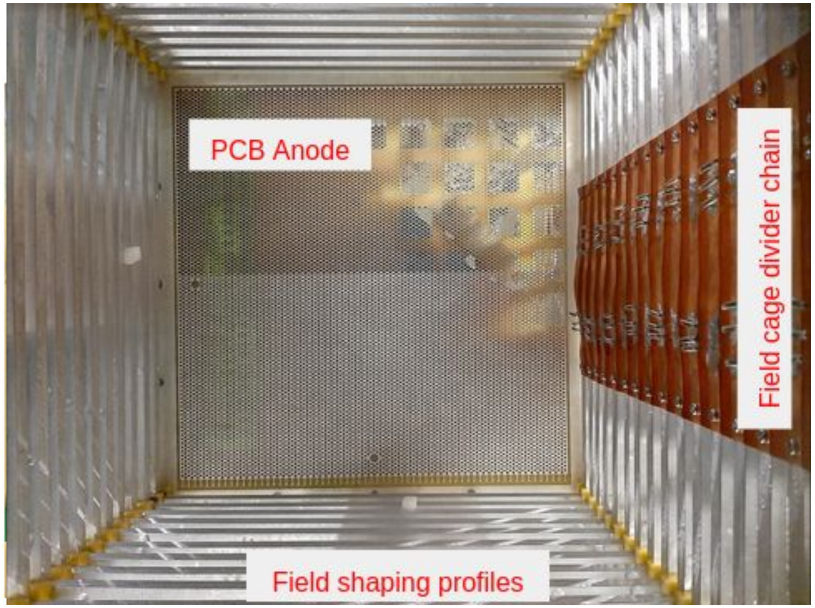


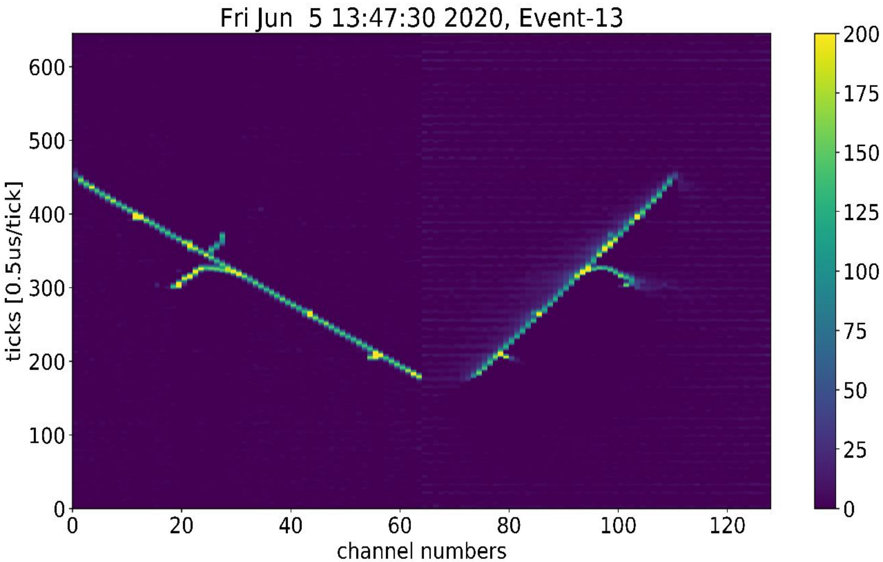
Test setup at CERN 50L

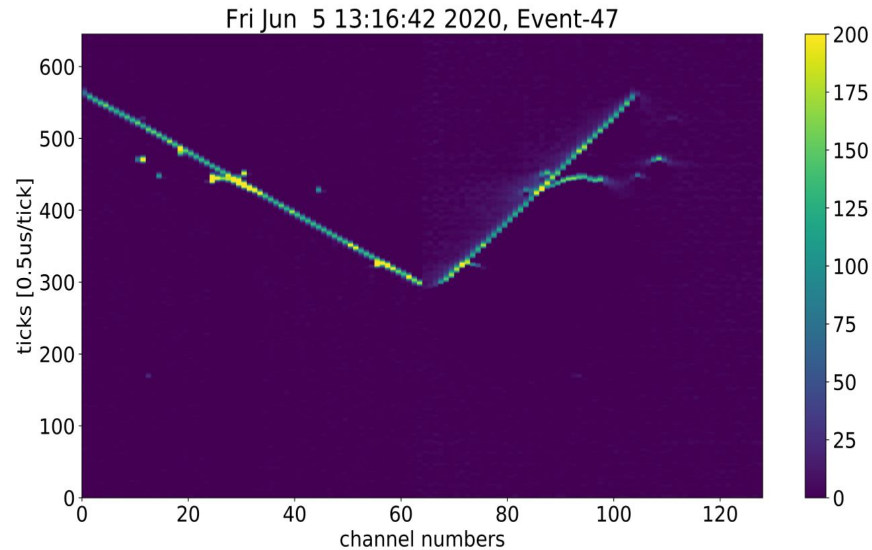
- LArTPC:
  - 2-view PCB anode with CEs, resistive cathode, 52cm drift, Al field shaping rings, 500V/cm field
- Trigger to select cosmic tracks with similar angles:
  - Coincidence from 2 scintillator paddles external to the cryostat
- Readout/data handling/analysis:
  - CE firmware, data with internal and external trigger, custom data handling, event display and analysis tools



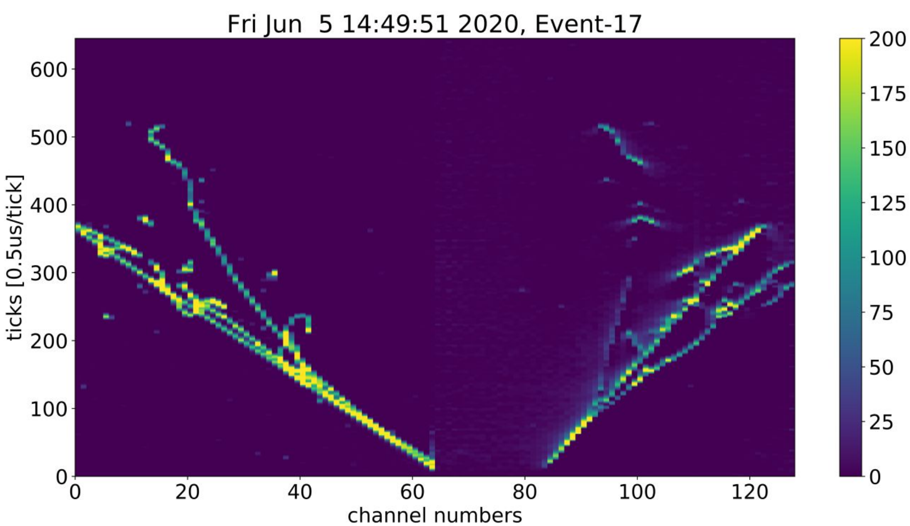


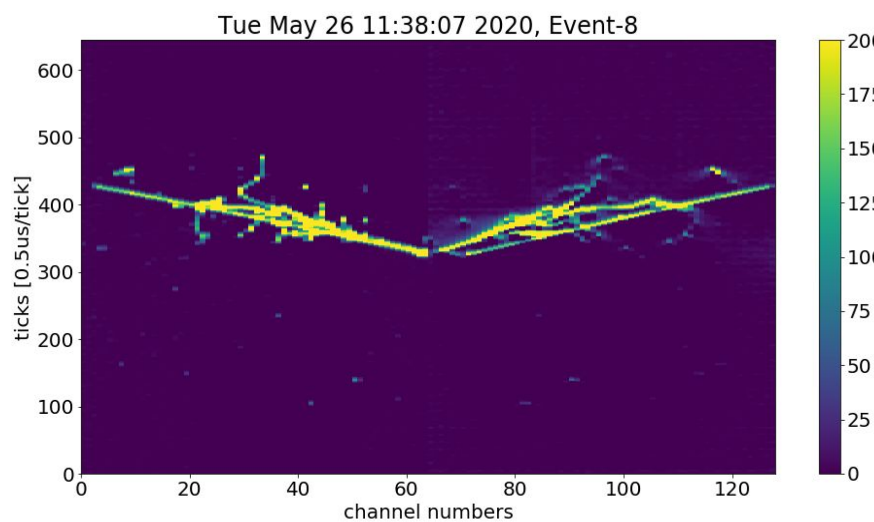






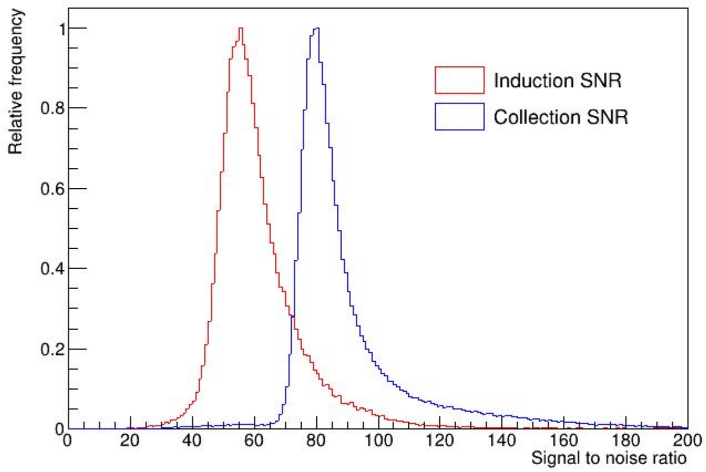
High S/N, clear mip and shower events, excellent imaging capability !!

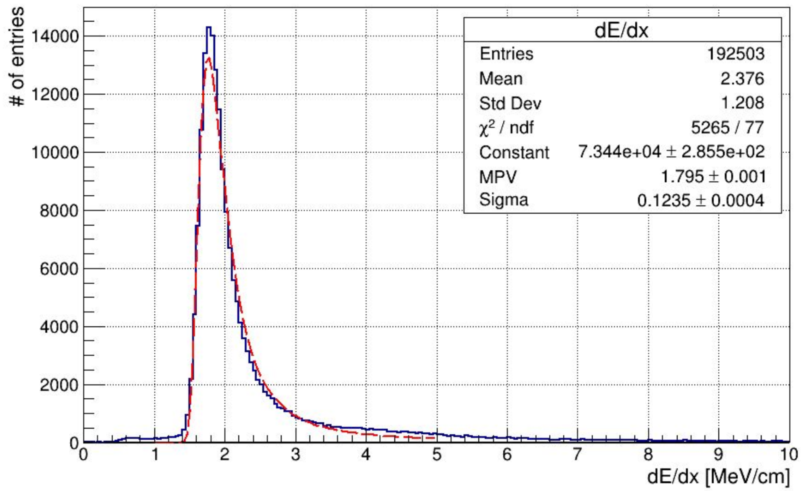


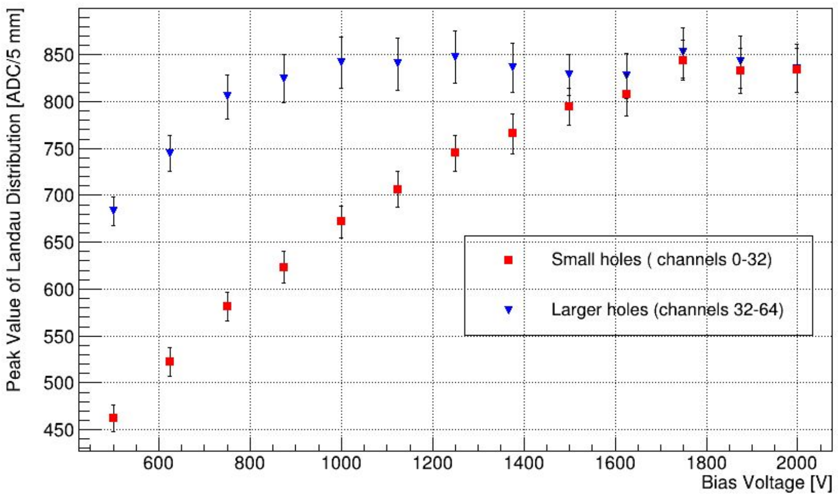


Studies with 2-view PCB

- Noise performance
  - ENC: ~300e⁻ for both layers in LAr
  - SNR: Most probable value of 81 for collection and 57 for the induction (using only the negative peak)
  - Extrapolating SNR to ~1.7m PCB strip:
    - SNR is 33 for the collection and 23 for the induction (similar to ProtoDUNE-SP)
- Bias voltage setting for full transparency for different hole sizes
  - 2.5 mm holes at > 850 V
  - 2 mm holes at > 1800 V
- dE/dx with collection signal
  - very good agreement with expectations
- Field response estimation using single hits



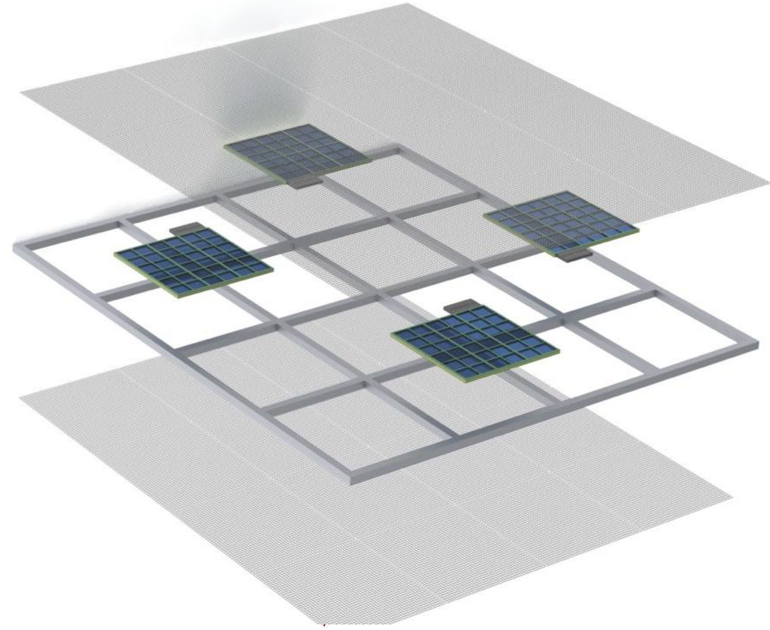




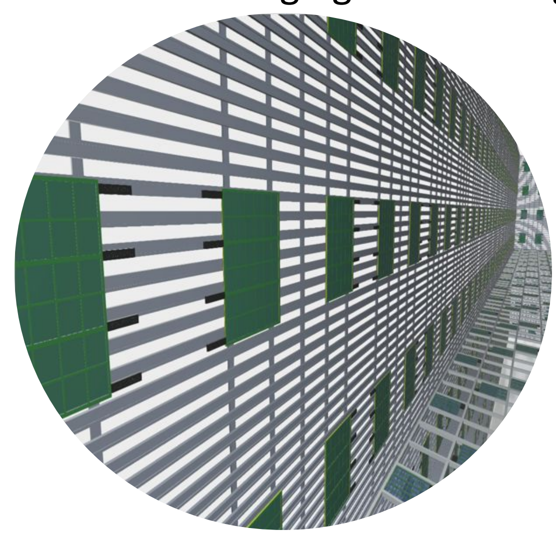
VD photon detector layout

- ARAPUCA units inside the cathode at 325kV (reference layout)
  - Active coverage similar to HD-SP (~14%)
  - Additional units on the field cage → 4 pi coverage
- Optimized for Xe doping
- Developing power over fiber (PoF) technology for the PDS
  - SiPMs powered and read out by optical fiber
  - R&D and tests are ongoing at FNAL and CERN
- Alternative plans relying on more classical biasing and readout approaches are also being considered:
  - ARAPUCAS placed on the cryostat walls facing active volume through FC
  - thinner field cage electrodes for improved transparency

Photon Detector into the Cathode frame under conductor mesh (exploded view)



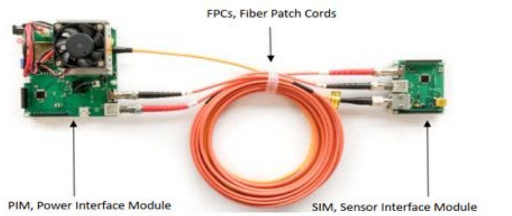
Photon Detectors hanging on Field Cage Walls



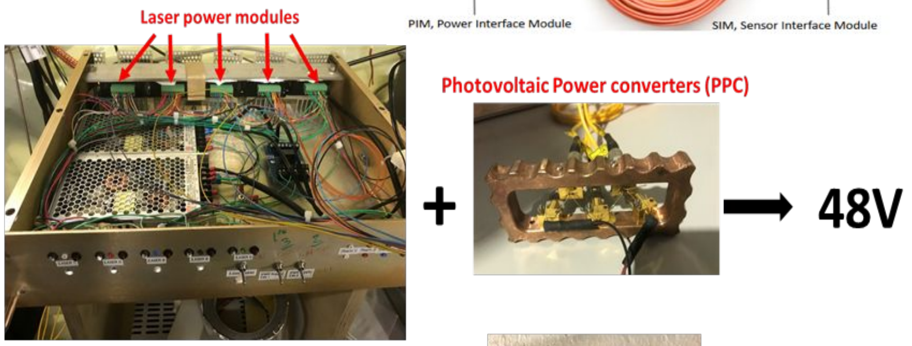
Design options for the VD PD System

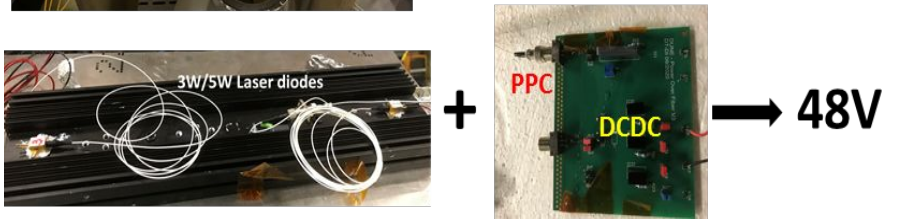
- Reference design: "HD-SP mirror solution"
  - PD active coverage distributed on the Cathode only ("SP mirror solution" w/ PD into APA)
  - PoF technology to bias the SiPM and optical read-out (digital and/or analogue) to operate at HV
  - reflector coverage on Anode side (metallization/lamination on perforated PCB facing LAr)
  - Xe doping to minimize Rayleigh scatter for light at far distance
  - Similar performance compared to HD-SP Module (no expanded physics scope, but lower cost)
- Conceptual design for a "enhanced 4pi PD" solution
  - Act an additional detector based on Ar scintillation, complementary to LArTPC for Charge
  - Complete exploitation of LAr features (collect all energy deposited)
  - Improved uniformity and lower energy threshold for UG events
  - Highest Live Time (PD active also when LArTPC may be OFF for purity drop/maintenance, HV issues/maintenance,..) very relevant for UG Physics
- Fallback design: Operate PD on surfaces at Ground
  - Active coverage distributed onto vertical sides of the Membrane Cryostat (outside FC)
  - Field Cage design modified: thinner profiles, wider gaps btw. profiles to increase FC transparency)
  - Reduced performance compared to the "4pi PD's" ⇒ physics scope not / minimally expanded, fabrication cost not / minimally reduced
  - Possibility for late integration with PD on Cathode if R&D is successfull

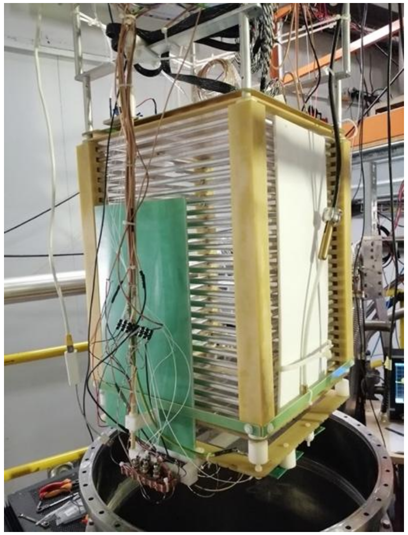
POF Technology for PD application

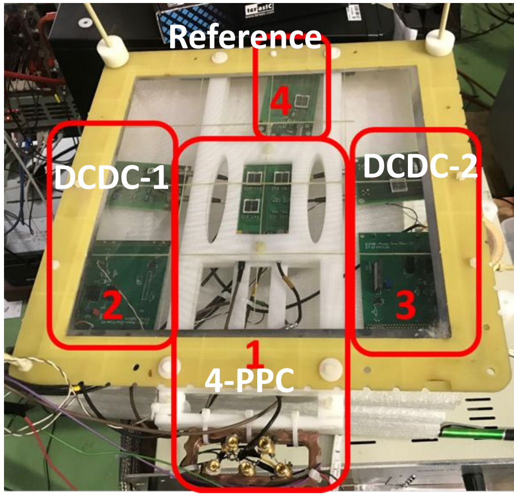


- Power over fiber units:
  - 800 - 967 nm laser source (3-5 W power out)
  - Propagation through multimode fibres (NA 0.22)
  - Photovoltaic Power Converters (PPC) generate up to 12V in LAr with a conversion efficiency of ~23%
- Methods to provide ~48 V for SiPM bias:
  - Four laser power modules (one fibre each) and four PPC connected in series
  - One laser module and a DC-DC converter circuit include one PPC
- 60 W of power is required to bias all SiPM on VD cathode
  - Heat dissipation system integrated on PPC
- Ongoing R&D (@FNAL/CERN)
  - Stand alone tests:
    - Cryogenic compatibility of bias voltage (OK), long term stability, output voltage stability (OK)
  - Integration in 50L LAr-TPC
    - Interference with HV (heat dissipation, bubble formations) (OK)
    - Light leakage along fibres in LAr
    - Signal recording from SiPM









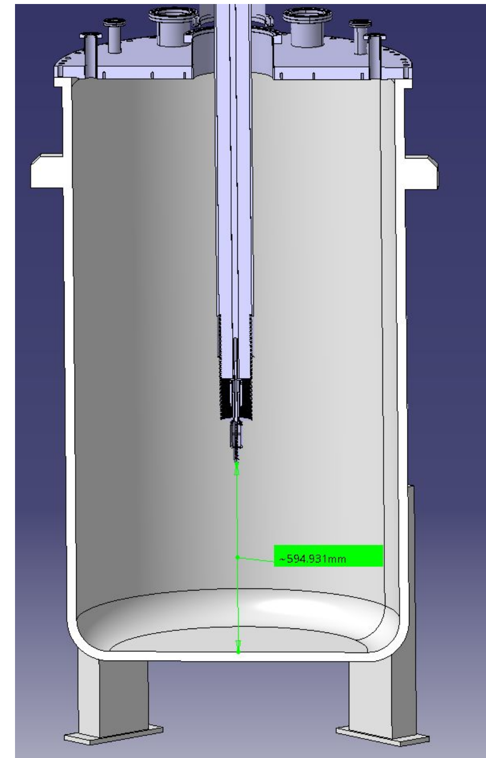
Prototyping activities in 2021

The prototyping is based on a phased approach. The following activities should deliver results in 2021

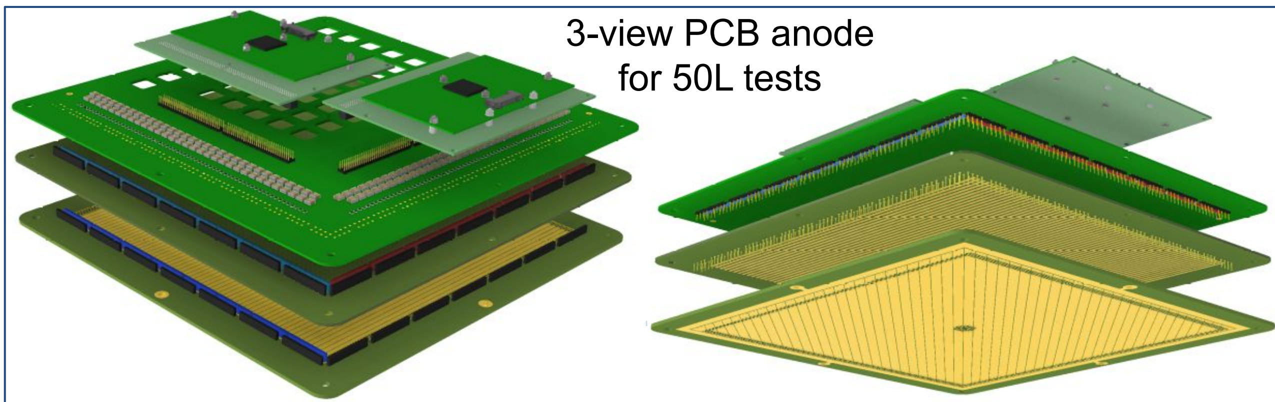
- Small scale prototypes:
  Tests in the 50 L chamber at CERN building 182 to optimize the geometry, the operation point of the perforated anode readout and the integration of the readout electronics.
- R&D on PD operating at HV:
  Validation at small scale of the PoF concept. Investigate solutions for the signal readout. PD optimization for Xe doping.
- Stand-alone HV component tests:
  Series of tests to validate individual components of the HV system at -300 kV in dedicated test stands at CERN and at FNAL.
- Full scale readout operation in a TPC:
  Test to validate full scale Vertical Drift components in a TPC with 30 cm long drift in the NP02 cold box. This test is a full scale demonstrator of the entire charge readout.
- Full scale HV tests:
  HV test in the NP02 cryostat of the entire HV distribution chain to demonstrate stable operation of the full scale HV system in ultrapure liquid argon.

Small scale prototypes and stand-alone HV tests

- 50L tests with 3-view PCB anode
  - pieces are already at BNL. We'll have them at CERN at the end of February
- PoF tests at 50L
  - Operation at HV and readout with fibers
- HV feedthrough tests at a dedicated test stand
  - Validate the performance of HV component at 300 kV under realistic cryogenic and electrical conditions in a 2 ton cryostat at CERN.



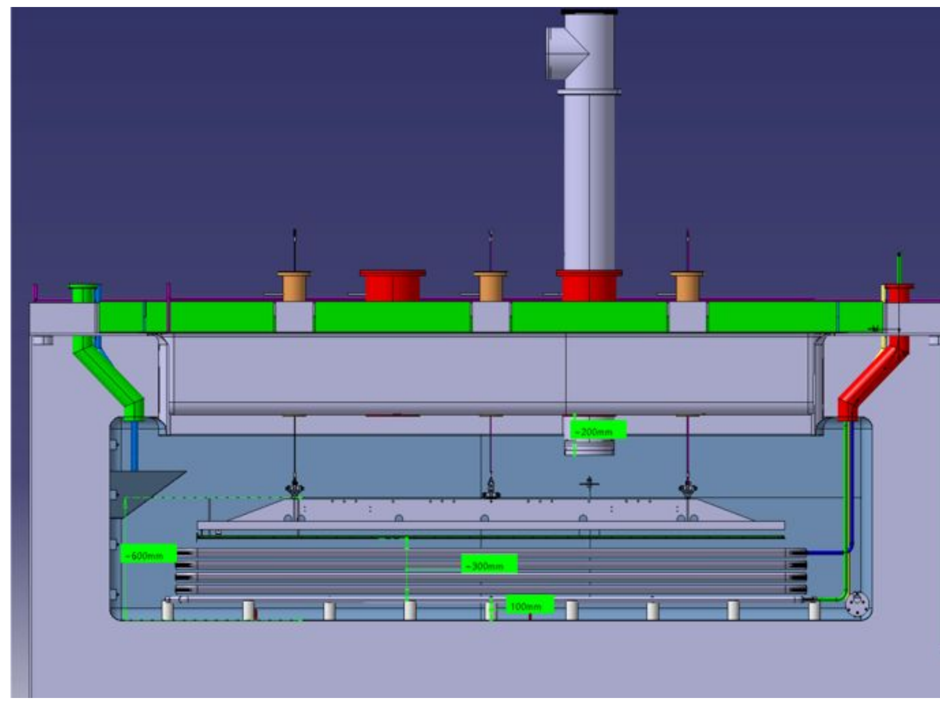
standalone test stand for HV feedthrough



3-view PCB anode for 50L tests

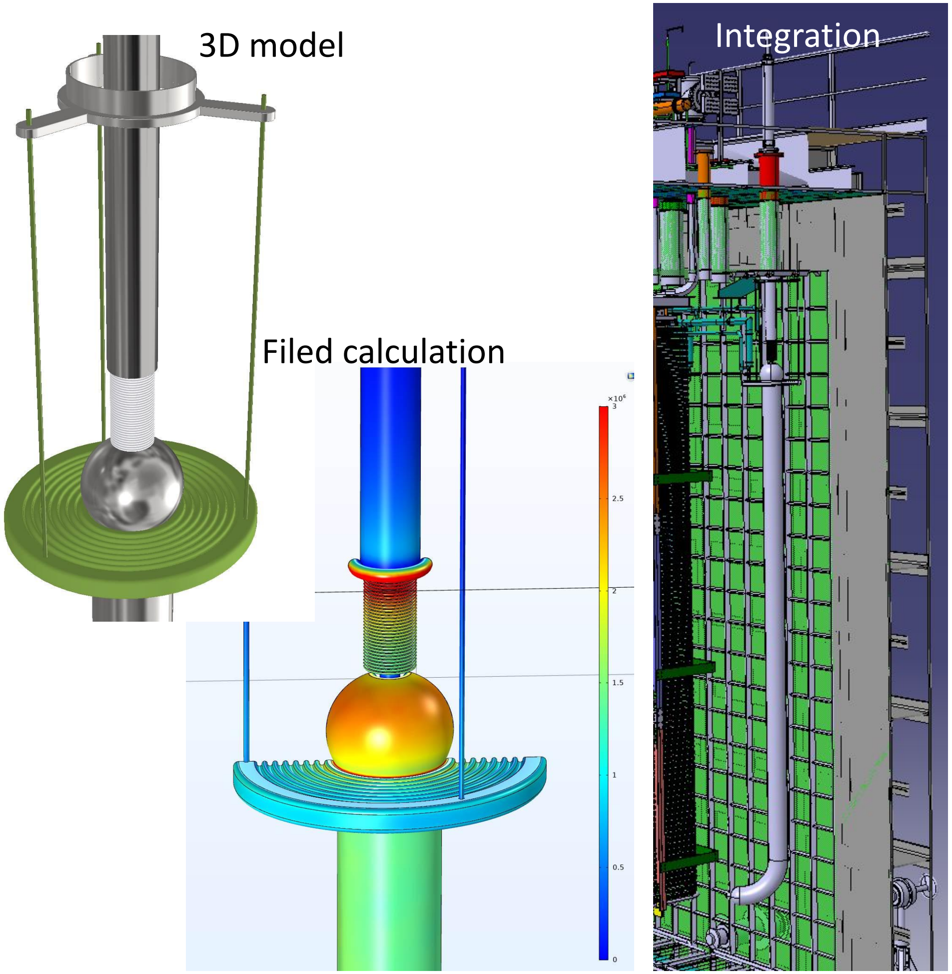
Full Scale Test of a LArTPC in the NP02 Cold-box

- ✔ Full TPC (CRP, perforated anodes, electronics, HV, cathode, ARAPUCA, …)
- ✔ 25-30 cm drift length as the only difference with respect to the final detector
- ✔ Operation in LAr in cold box, several cycles possible in 2021



High Voltage Demonstration in NP02

A full scale test of the HV distribution in the vertical drift layout in NP02 cryostat is an essential milestones to demonstrate this concept.



The complexity of present version of the extender introduces more uncertainty on the HV performance than the expected advantages on the E-field uniformity.

The possible upgrade that is under development is based on a highly simplified version of the extender: highly electropolished metallic pipe of 20 cm in diameter.

Summary: Vertical Drift advantages

- We are developing a new cost-effective far detector for DUNE
- New elements are the anode technology (perforated PCBs) and photon detectors operating at HV
- Vertical drift advantages:
  - Highly modular concept of each detector component
  - Simplified anode structure based on standard industrial techniques
  - Possibility to optimize the integration of the front end electronics on the anode planes
  - Simplified cold test of instrumented anode modules not requiring large cryogenic vessels
  - Field cage structure completely independent from the other detector components
  - Extended drift distance, profiting from excellent LAr purity, allows to maximize the fiducial mass by reducing dead material in the active volume
  - Simplified installation and QA/QC procedures, not requiring large in situ infrastructures
  - Possibility to optimize costs and schedules for the benefits of the entire project
  - Possibility for improved light detection coverage and trigger efficiency
  - Reduction in the need for unconventional and costly local infrastructure
- Intense prototyping campaign through 2021
  - Already started with small scale and standalone tests
  - Preparations for the cold-box and NP02 tests are ongoing

Proposal: https://edms.cern.ch/document/2429382