The vertical Drift LAr-TPC for the DUNE Experiment

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On behalf of the DUNE Collaboration and the CERN Neutrino-Platform Team

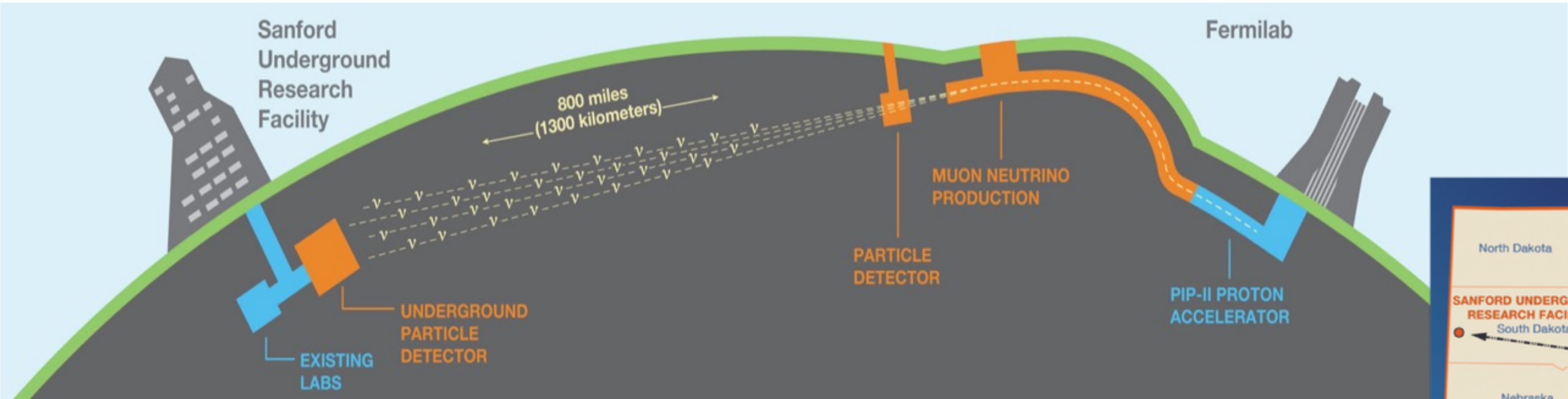
CERN Detector Seminar, December 10th, 2021

Outline

- The DUNE Experiment
- The LAr-TPC for multi-kt detectors
- Lessons learned from of NP04 and NP02 at the CERN ν-platform
- Motivation and main design features of the Vertical Drift single phase LAr-TPC
  - Charge readout anode planes based on large perforated PCB's
  - High Voltage system for the drift volume
  - Scintillating light readout system for trigger, T=0 and calorimetry
- R&D effort for the VD-LAr-TPC validation and first results

The Deep Underground Neutrino Experiment

- Next generation long baseline neutrino experiment: 1300 km from Fermilab to SURF (SD), 4300 m water equivalent depth
- Very intense wide band ν_μ & $\bar{\nu}_\mu$ beam (0.5 – 7 GeV): 1.2 MW, upgradable to 2.4 MW
- Two detectors location, Near/Far, giant liquid argon TPC detector as far detectors (70 kt)
- A worldwide Collaboration: 1300+ people, 200+ institutions w/ CERN, 34 countries



The DUNE Experimental program

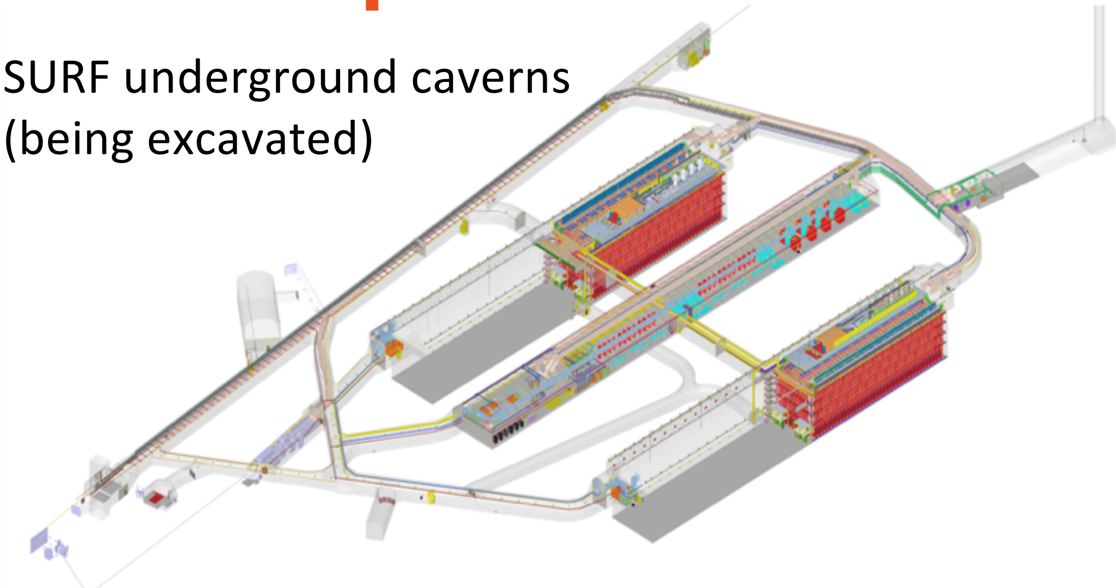
- **Three-flavor long-baseline neutrino oscillation**
  - Precise neutrino oscillation parameters for $\nu_e/\overline{\nu}_e$ appearance, $\nu_\mu/\overline{\nu}_\mu$ disappearance searches, CP violation, mass hierarchy in the ν sector

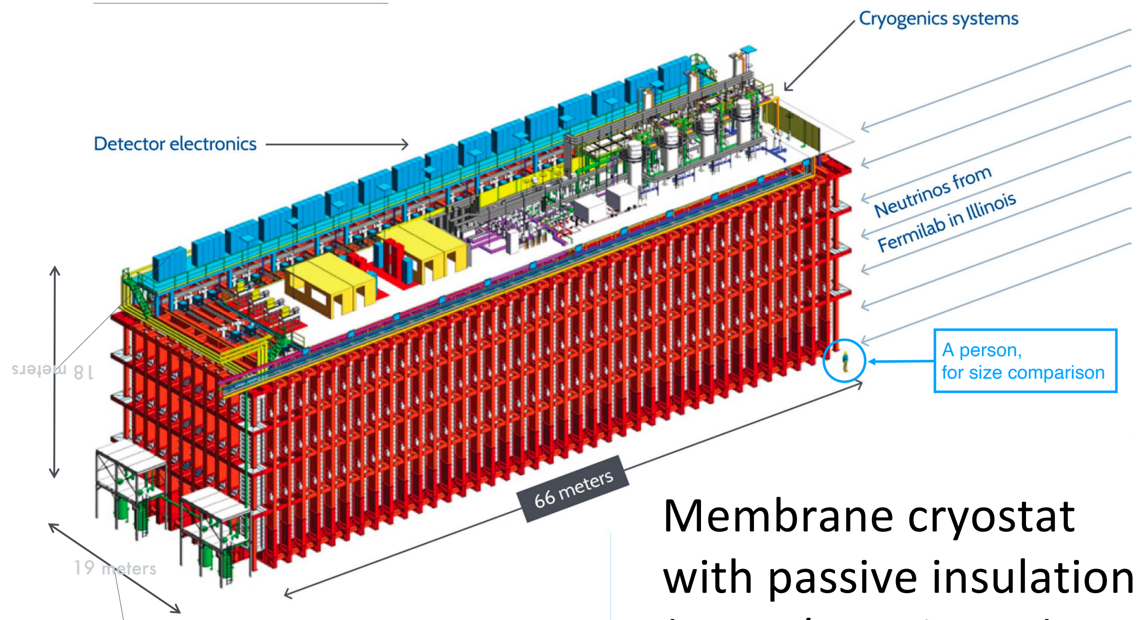
- **Supernovae burst neutrinos**
  - Large sample of neutrinos for SNB in our galaxy flavor content, spectra, time evolution of SNB neutrinos

- **Beyond Standard Model**.
  - Proton decay, baryon number violation, sterile neutrinos, non-standard interactions and more.

The DUNE far detector complex

- Four independent detector modules
- Main detector technology: Single phase LAr-TPC modules, ~17 kt total Ar mass each module (62x14x15 m^3):
  - **FD #1**: SP LAr-TPC, Horizontal Drift (HD): operational by 2028
  - **FD #2**: SP LAr-TPC, Vertical Drift (VD): operational by 2029
  - **FD #3**: SP LAr-TPC technology TBD
  - **FD #4**: Ongoing R&D for Module of Opportunity

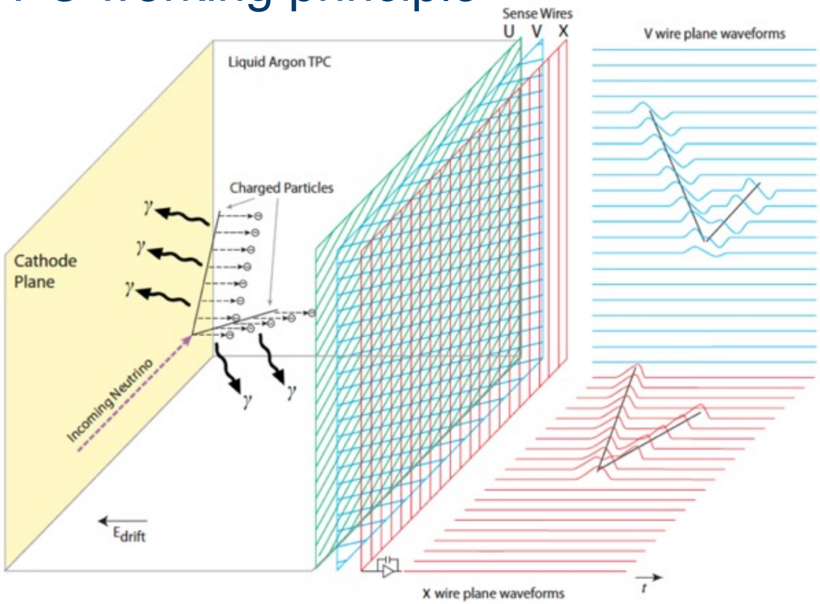




Membrane cryostat with passive insulation (CERN/GTT design)

The Single-Phase LAr-TPC

TPC working principle



- Ionization electrons [~5 fC/cm] drift to the anode in pure LAr & uniform E-field (~500 V/cm)
  - Few mm pitch and ~MHz sampling frequency
  - 3D via multiple 2D view (wire# vs drift time)
  - high imaging capabilities → kinematic reconstruction with mm-scale spatial resolution
  - Intrinsically excellent Calorimetry and Particle Identification (dE/dx) capability
- Prompt scintillation light (@128 nm)
  - T = 0, trigger, calorimetry

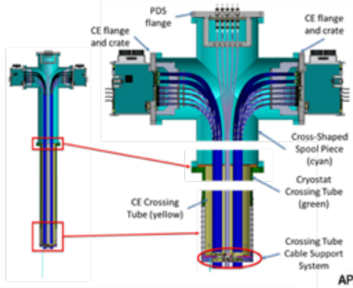
LAr as radiation detection medium

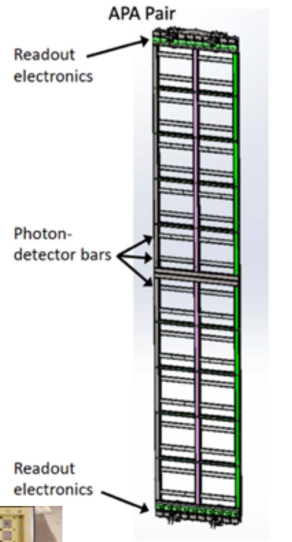
- Dense: 40% more than water
- Abundant primary ionization: 42 000 e^-/MeV
- High electron lifetime if purified → long drifts
- High light yield: 40k γ/MeV
- Easily available: ~1% of the atmosphere
- Cheap: $2/L ($3000/L for Xe, $500/L for Ne)

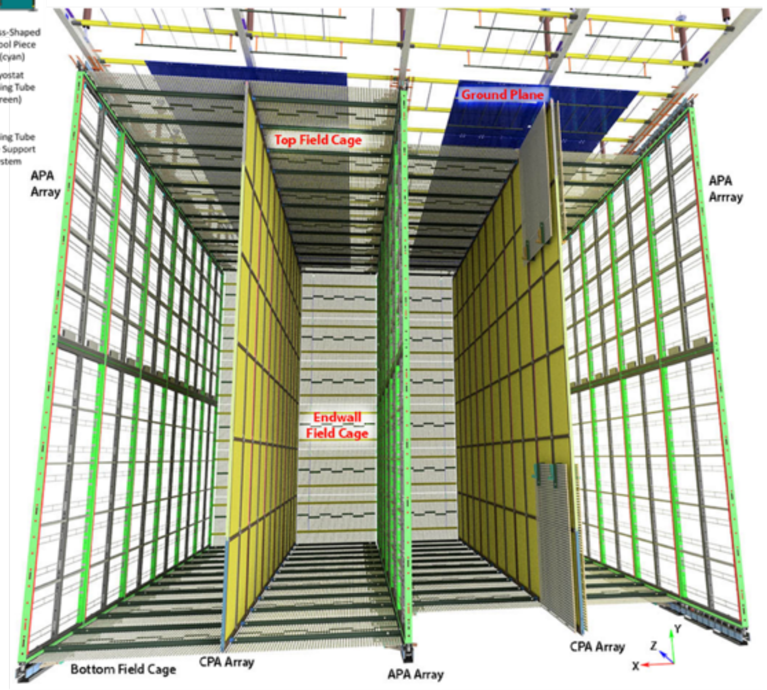
- Technological challenges
  - LAr continuous purification << 0.1 ppt O_2 eq. (>> 3 ms electron lifetime) for long drift
  - Imaging & anode planes
  - Very low noise front end amplifiers to detect ~ fC primary charge deposition
  - Large area photon detectors sensitive to 128 nm wave length
  - HV system to provide uniform/stable E-field in large drift volume
- Pioneered by ICARUS and adopted in present and next generation neutrino ezperiment (μBoone, SBND, DUNE)
  - DUNE: scaling to multi-kt size

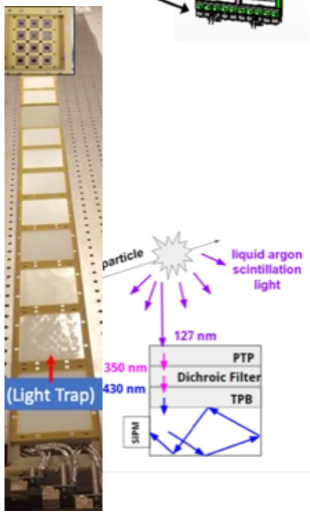
FD1 - LAr-TPC Horizontal Drift Technology

- Alternated Anode and Cathode Plane Assemblies (APA/CPA)
  - Segmented: 4 drift volumes, Drift distance: 3.5 m
  - Electric field = 500 V/cm (HV = -175 kV)
  - High-resistivity CPAs to prevent fast discharges
  - Anode: 150 APAs (6x2.3 m2) 4 wire planes each Grid, 2x Induction, Collection
  - Wire pith ~ 4.7 mm
  - Full cryogenic readout chain (analogue FE + Digitizer)
- Photon Detectors:
  - X-ARAPUCA SiPM based light traps integrated into APA frame









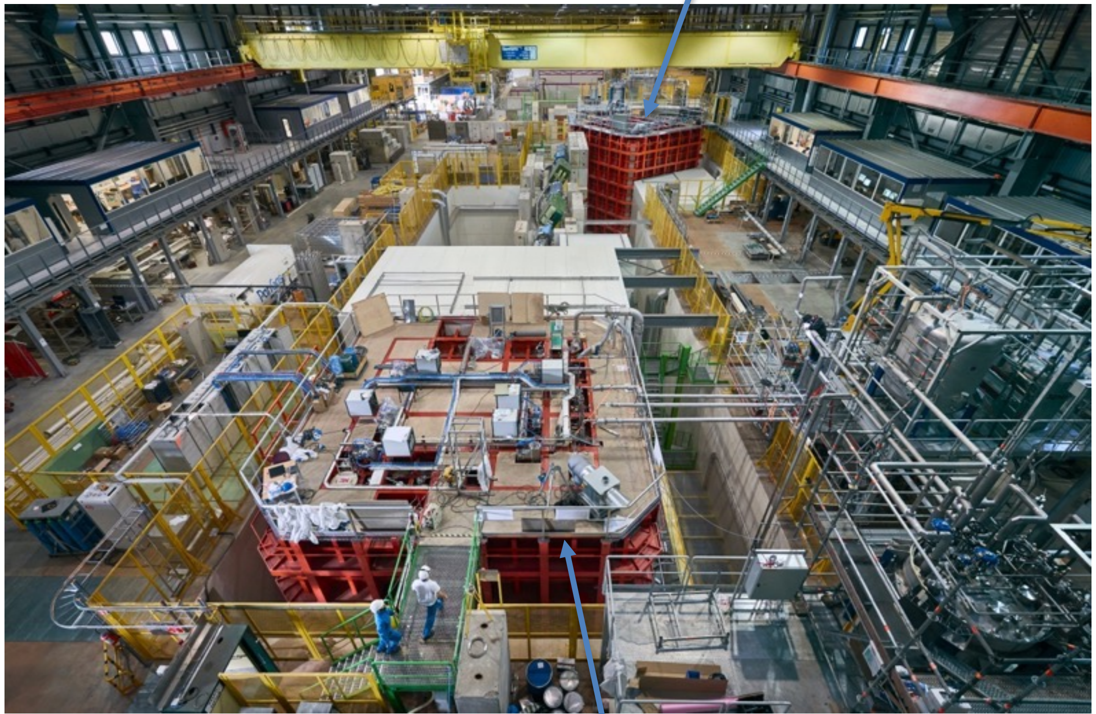
- Module-0 in ProtoDUNE NP04 in 2022. Final validation of
  - Components production
  - Assembly procedures
  - Detector performance and stability

ProtoDUNE's @ the CERN Neutrino Platform

- **Two 750 t prototypes ~8 x 8 x 8 m3**
  - Design validation of all FD components at full scale
  - **N04 Single-phase HD: 2018-20**
    - Charged particle beam + cosmic rays
    - Event reconstruction, full analysis
    - Neutron calibration, Xe doping, HV tests
    - Phase-II starting in 2022
  - **NP02 Dual-phase: 2019-20**
    - Signals produced in Liquid, amplified in Gas phases
    - Evolving into SP Vertical Drift from late 2020

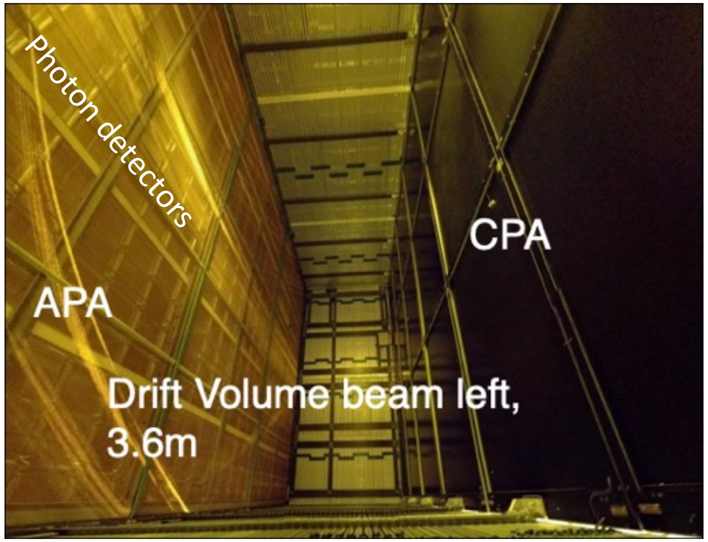
CERN Neutrino Platform EHN1

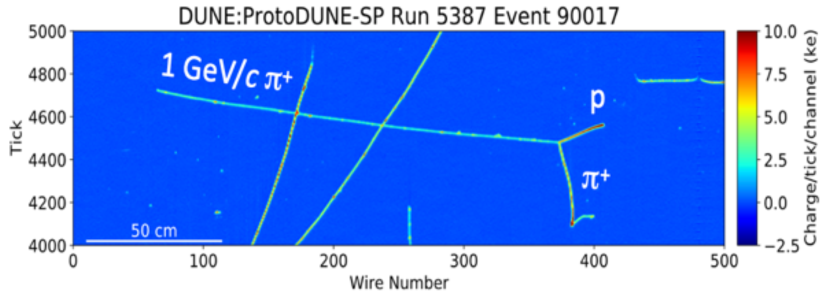
ProtoDUNE-DP/SP-VD

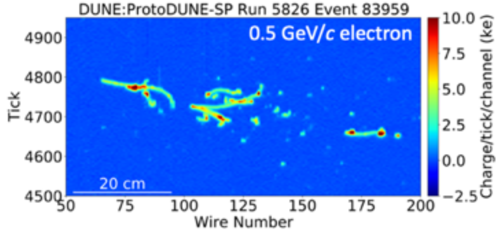


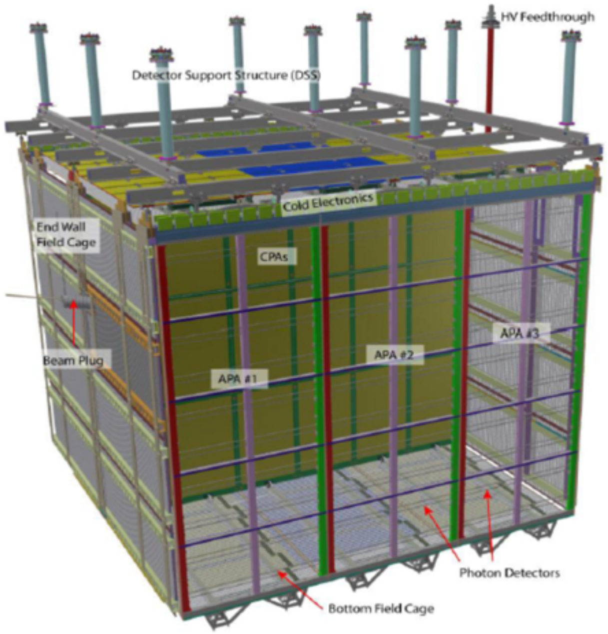
ProtoDUNE-SP-HD

ProtoDUNE (NP04) performance summary





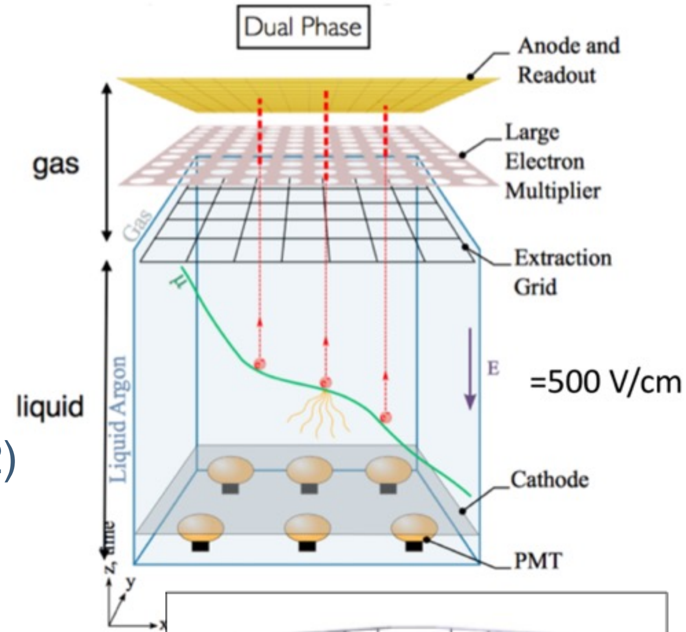




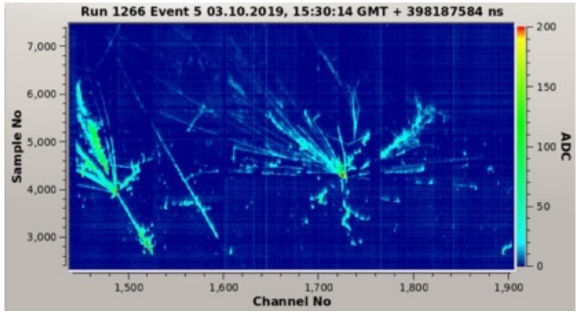
Detector Parameter	Specification	Goal	ProtoDUNE Performance
Electric Drift Field	> 250 V/cm	500 V/cm	500 V/cm *
Electron Lifetime *Impurity Concentration*	> 3 ms *(<100 ppt [O_2-equiv])*	10 ms *(<30 ppt [O_2-equiv])*	> ~30 ms in TPC ** *< 10 ppt*
TPC Electronics Noise	< 1000 e ENC	ALARA	550-650 e ENC (raw) 450-560 e ENC (cnr)***
TPC dead channels	< 1%	ALARA	0.2 % (of ~15,360 channels over 1.5 yr operation)
PhotoDetector Light Yield	> 0.5 Ph/MeV (at cathode plane - 3.6 m distance)		1.9 Ph/MeV ++ (at 3.3 m distance)
PhotoDetector Time Resolution	< 1μs	< 100 ns	14 ns ^^

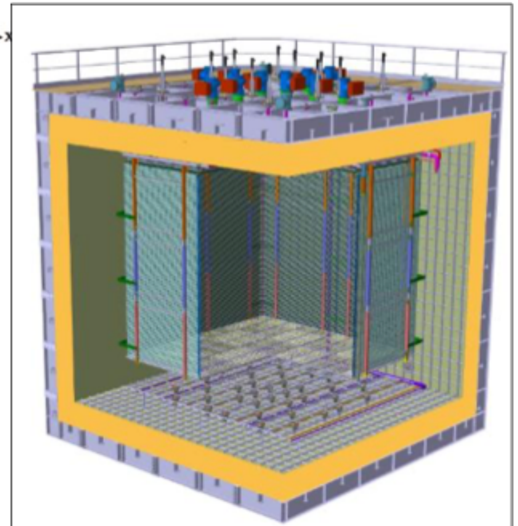
Xenon doping (~20 ppm) successfully demonstrated: efficient WLS to 175 nm beneficial to improve light collection: longer Rayleigh scattering and recovering quenching contamination

ProtoDUNE NP02 Dual phase



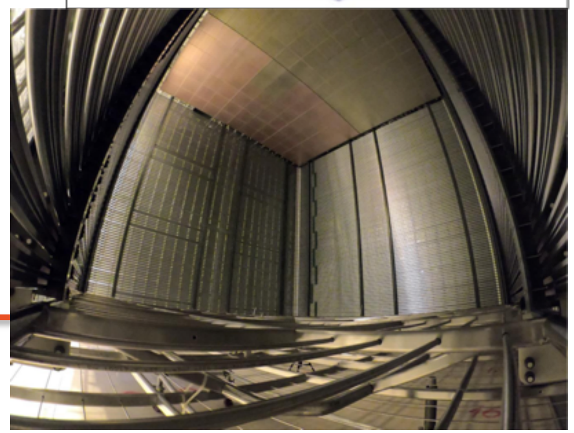
- Lessons Learned:
  - Overall detector design easy to assemble.
  - Field cage/Cathode hanging from the cryostat roof (independently from other components)
  - Charge Readout Planes (CRP) support structure (3x3 m2) allows precise alignment and mm planarity of anode
  - Scintillation light detection over 6 m demonstrated and understood with PMT's (also with Xenon doping)
  - Cold FE Electronic performance demonstrated: good S/N with moderate amplification (Noise ~ 600 el.)





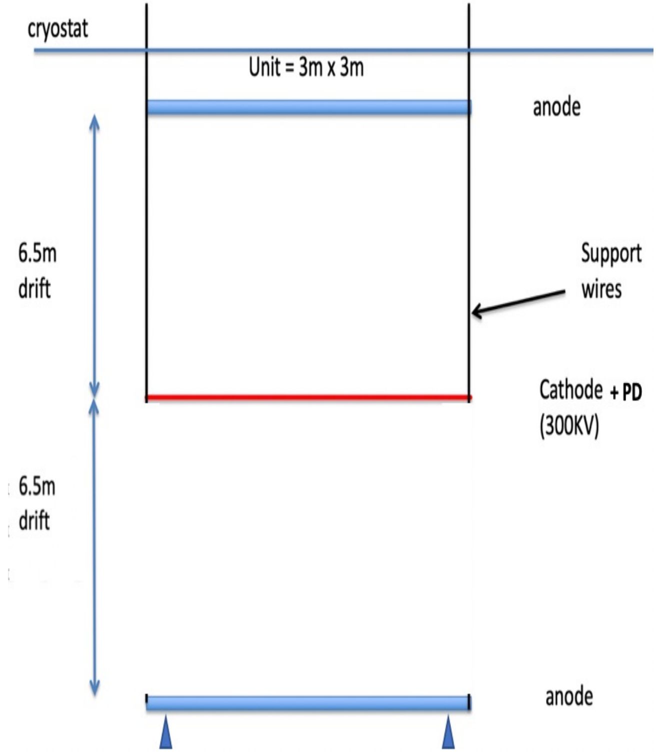
6x6x6 m3
active volume

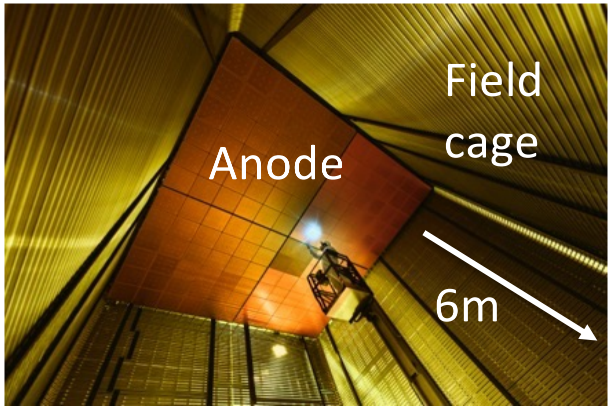
- Not demonstrated:
  - 6 m drift with 300 kV on Cathode (damage of HV delivery)
  - *Long term stability of extraction/multiplication stages very sensitive to LAr-Gar interface conditions: specific R&D activities would still be required to address this issue.*



FD2 Vertical drift concept and motivation

- Capitalizing on the important R&D done in the last 4 years with the Proto-DUNE, new solutions emerged for the FD2 project:
  - LAr purity in ProtoDUNE's is outstanding
    - allows longer drift path (6-7m)
  - Charge readout electronics in NP04/NP02 demonstrated excellent S/N (>30).
    - No need of multiplication in gas phase.
  - The Vertical drift layout is simpler to construct.
    - More efficient use of LAr volume
    - reduce schedule and financial risks
  - Lightweight CRP support developed for DP well suited for immersed PCB anodes (SP)
  - Xe-doping improves the photon budget
    - Allow more uniform light detection over long distance.
- Investments & know-how from institutions on DP moving to SP-VD

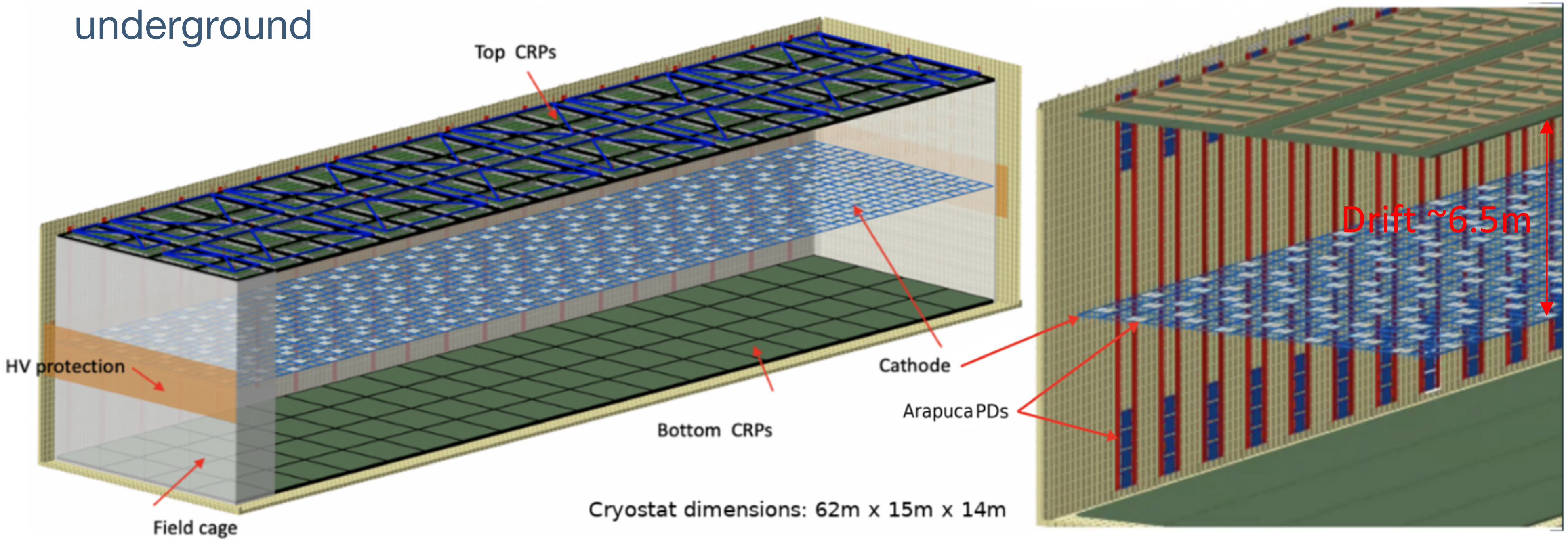


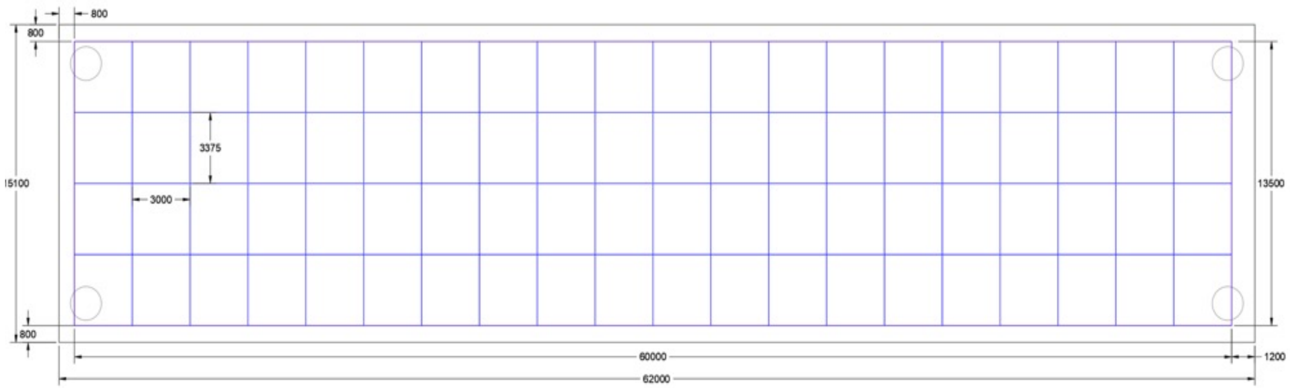


cathode

FD2 Vertical drift proposed layout

- CRP= 3x3.375 m^2 readout units (anode)
- Modularity manly driven by max size transportable underground

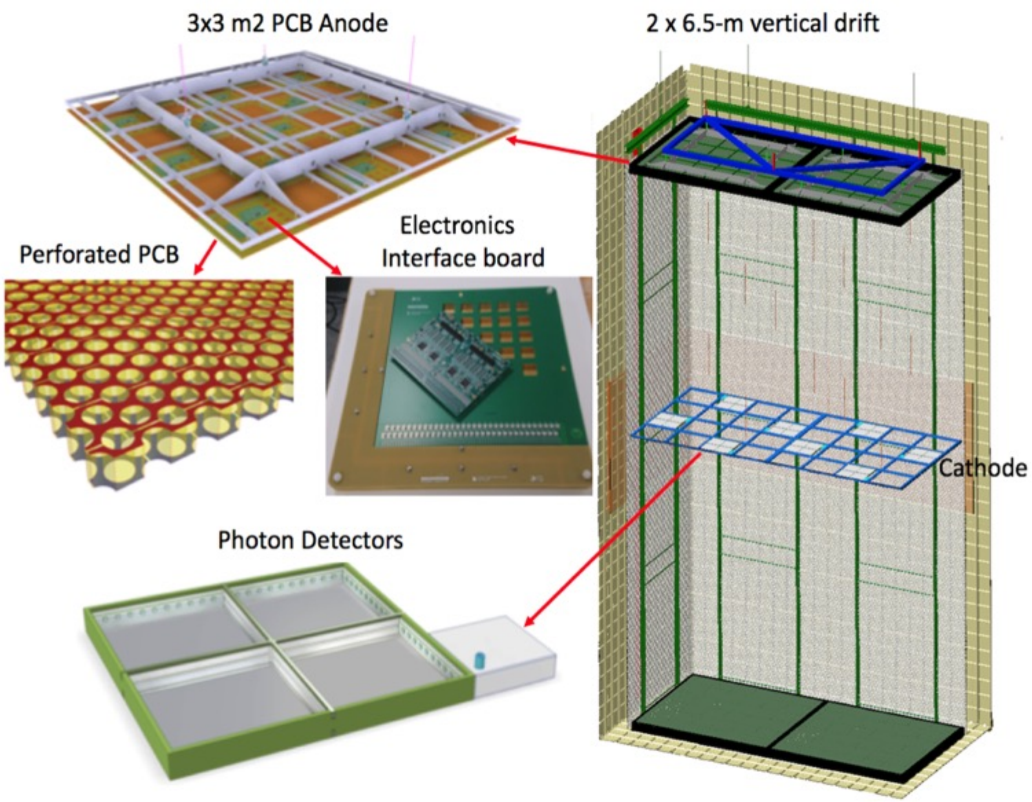




- ✓ 160 CRP units (80 on top, 80 on the bottom)
- ✓ Drift active volumes 2*5’265 m^3 = LAr 14.74 Ktons
- ✓ Photon detectors on cathode and cryostat walls (up to 14% coverage)

Main 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
  - 6.5 m drift , 450 V/cm , 300 kV on Cathode
- Perforated PCB's with segmented electrodes (strips) as readout units with integrated electronic interfaces
  - Good planarity (lightweight) and robust
  - Optimizable strip orientation, pitch, length
  - PCB modularity defined by strip readout length (S/N) and PCB drilling machines
- 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 fibres for signal and power transmission.

R&D for the VD-LAr-TPC validation

- Project build on solid ground (ProtoDUNE) but vigorous R&D required on new detector components
- Perforated PCB anode
  - 2-view and 3-view options for performance comparison
  - Reference 3-view layout on small scale
  - 3-view readout scaling to full size
  - Effort on physics simulations/reconstruction to define the optimal configuration for FD2
- HVS operation at 300 kV (or more)
  - Critical elements of the HV distribution: “extender” + coupling with HV FT
  - Long term stability runs demonstration in NP02 and 6 m drift
- Photon detectors
  - Operation at HV: demonstration of Power over Fiber and Optical Readout (alternative plans also under consideration)
  - Optimization of detection efficiency for Xenon light

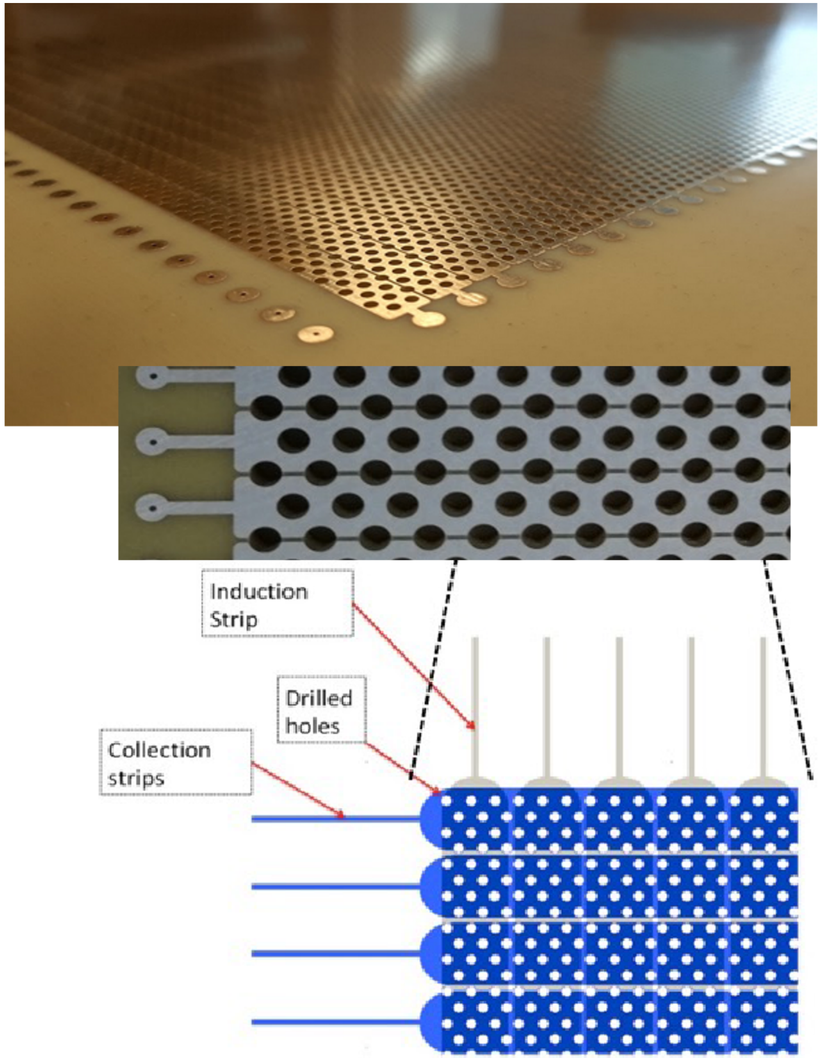
VD-LAr-TPC validation plan

- Staged approach started in late 2020 and continuing into 2022/3
- Small scale:
  - Tests of the perforated anode in the 50 Liter LAr-TPC at CERN
    Demonstration of the concept, study of the signal shape, optimisation of the geometry and the field configuration.
  - Standalone tests of HV components
    Test critical components (feed-through, top part of the extender, extender support structure) at full voltage in dedicated setups.
  - R&D on PoF and Photon Detector readout
    Various developments to demonstrate the feasibility of SiPM powered and readout optically.
- Large scale:
  - Demonstration of HV in NP02
    Full scale demonstration of stable operation at 300 kV and 6 m of drift.
  - Demonstration of full size CRP in NP02 “coldbox”
  - Full scale demonstration of final CRP prototypes, FE electronics and PD at HV operating in a TPC (NP02 module-0 for FD2)

CRP with perforated PCB anodes

Perforated PCB anode

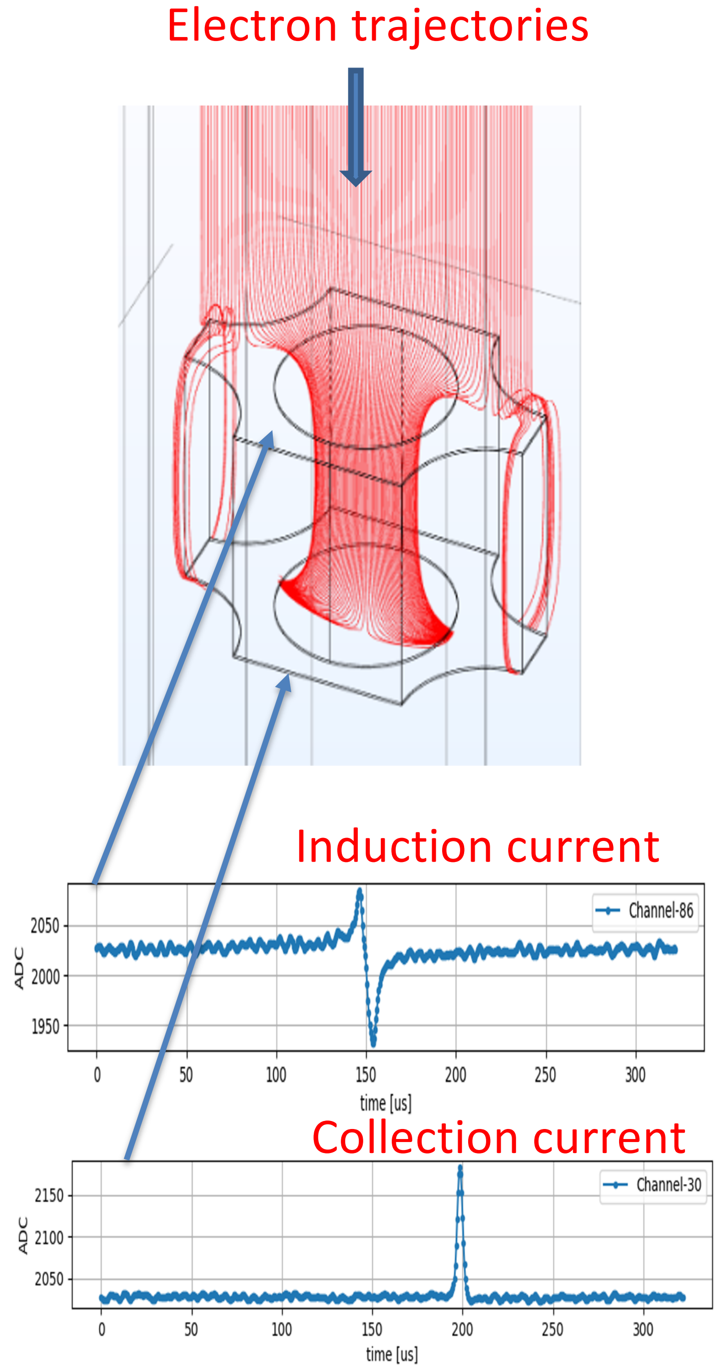
- In the past years a dedicated R&D program was carried out to develop a LAr-TPC with perforated multilayer printed circuit board (PCB)
  - Electrons are 2D focused in the PCB holes
  - Strips in the front sense induction signal
  - Strips at the back collect the ionization electrons
- The idea was driven 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
  - Integrating the FE electronics/ cable connectors on interface PCB's
- The design took advantage of the technological development of wide area Thick-GEMs at CERN (in particular the EP-DT-DD group)



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

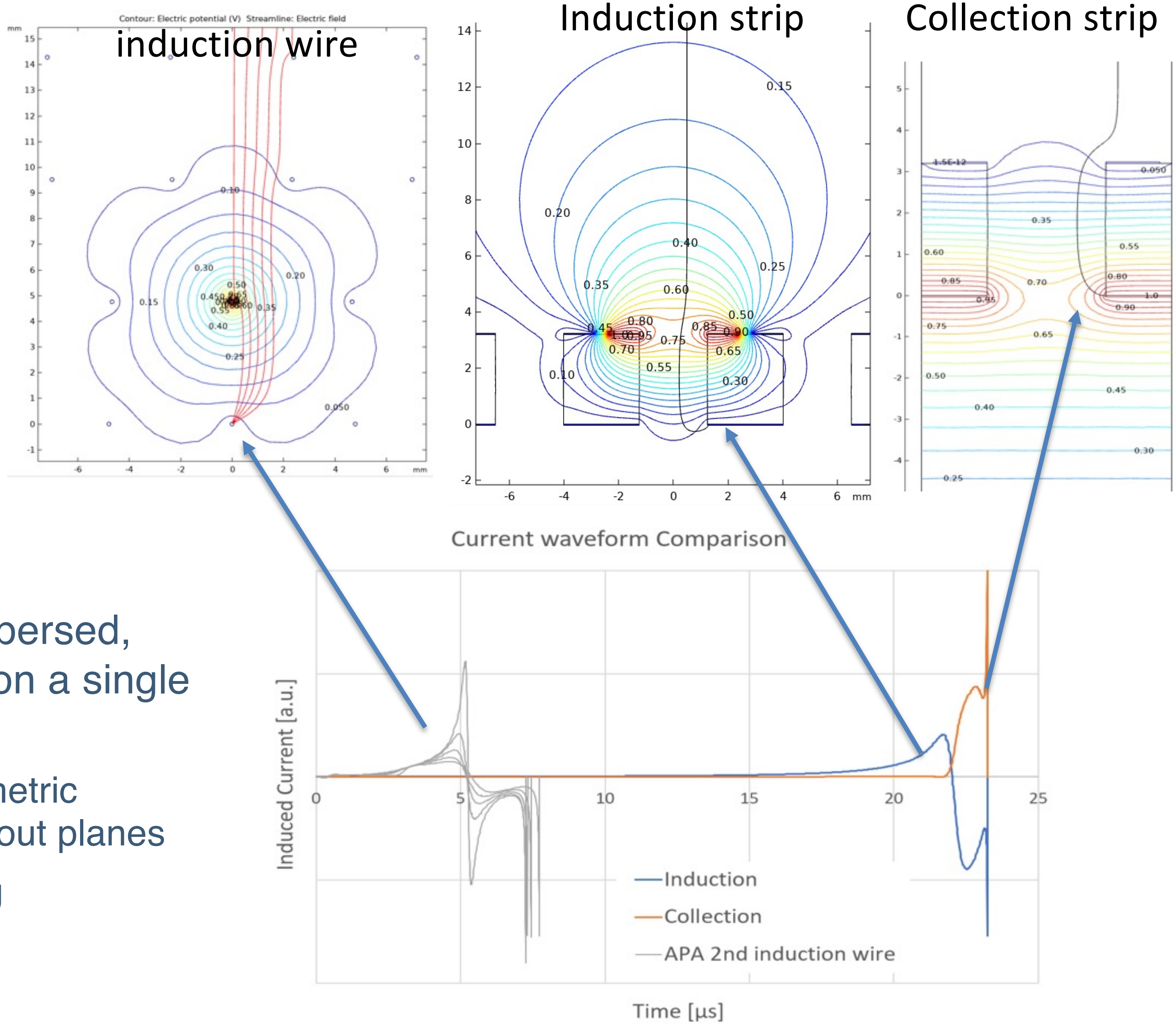
Basics and signal shapes

- Working principle
  - Electron trajectories are focused into 2D holes not in a "slice" like for wires. Focusing can be repeated on stacked PCBs for multiple readout views.
- PRO:
  - Electric and weighting field in the hole is more uniform.
  - Bipolar shape of induction signal is asymmetric with benefit for visibility of large dip angle tracks because "cancellation effects" are reduced
  - Induction signal is intrinsically larger than with wires and less blurred because the weighting field is confined to a single strip and not distributed on several wires
  - 3 views possible: PCB stack (preferred), multilayer, charge sharing
- CONS:
  - focusing EF ratio is high (> ratio of hole area to full area --> DV ~ kV)
  - Capacitance of strips (PCB dielectric constant and strip width) 4 to 6 times higher than wires at the same pitch: higher el. noise compared to same length wire



Wire vs strips signal comparison

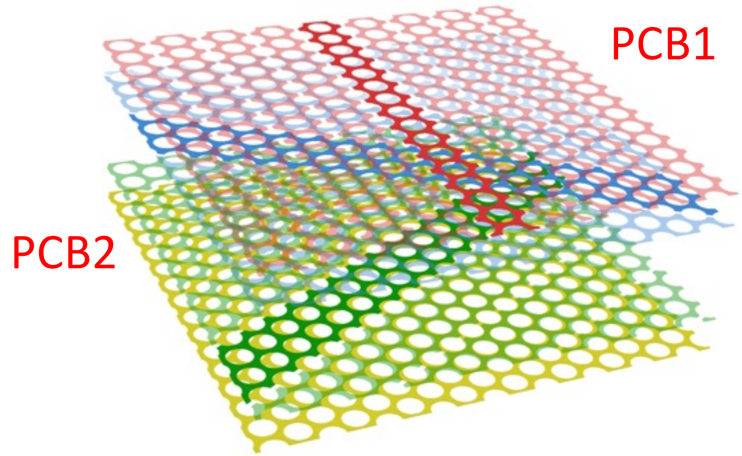
- Weighting potential used to derive induction current:
  - much more uniform in the case of strips vs wires



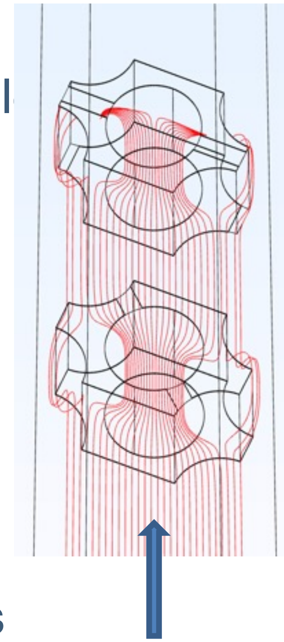
- The signal is less dispersed, mostly concentrates on a single electrode.
  - More uniform calorimetric response on all readout planes
  - Less blurred imaging

3-Views Perforated PCB Anode Concept

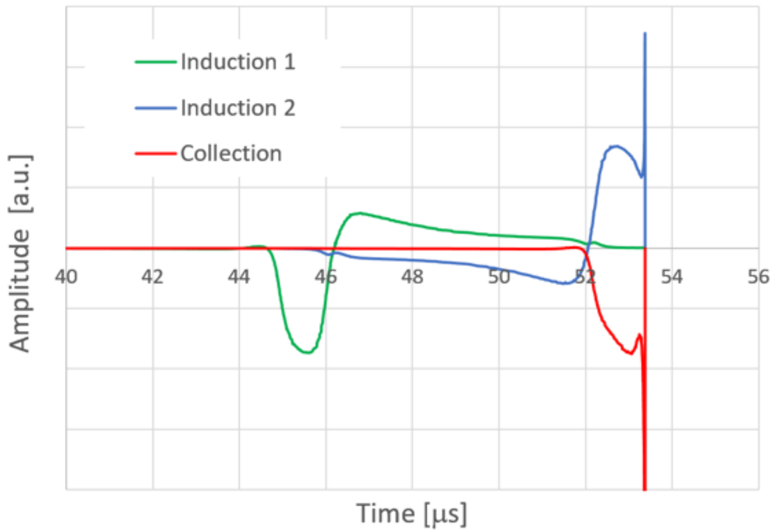
- Designed to reproduce the APA wire plane configuration:
  - Standard PCB thinkness ~ 3.2 mm
  - Bottom electrode on PCB2 is shield plane (no readout), followed by induction-1 on the top.
  - PCB1 is ~8-10 mm from PCB2, with induction 2 and collection readout.
  - Any strip orientation possible
- Shield plane effective to
  - Protects FE electronics from possibl HV instabilities and residual HV ripple noise
  - Sharpen Induction-1 signal start
- Defocusing between PCB's
  - No precision alignment of holes required
  - Asymmetric signals shape maintained for both induction layers



Electron trajectories

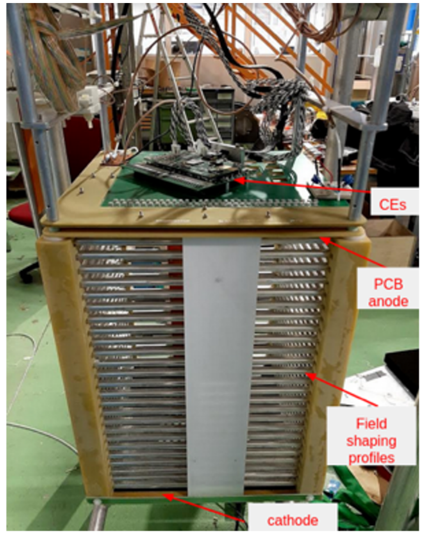


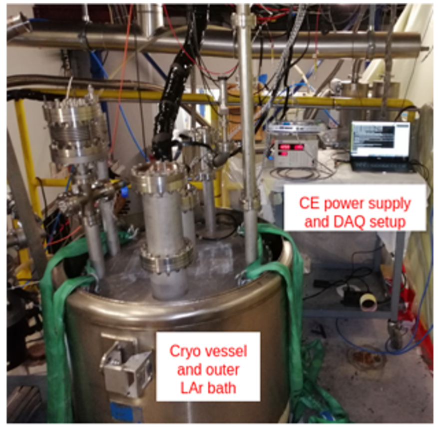
Induced current signal

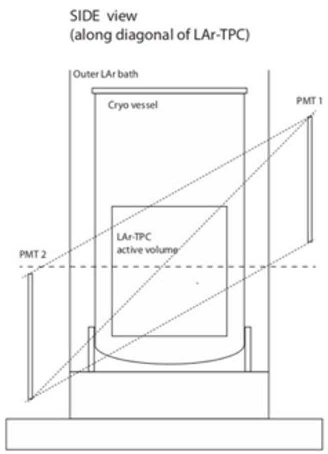


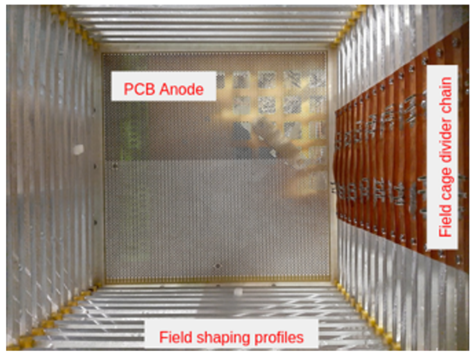
Small scale test

- Two and three view PCB anodes prototypes (32x30 cm2) built at CERN and implemented in the 50 liter LAr-TPC facility
  - Interface board biasing and ProtoDUNE/SBND Cold Electornics,
  - 52cm drift, Al field shaping rings, 500V/cm field
  - Cosmic muons triggers and Bi 207 source
  - Equipped with gas recirculation system for high purity (minimal signal attenuation)
- Two view goal:
  - signal vs hole size/pitch, transparency vs bias V, signal shapes and localization, energy resolution (comparison with wire chamber)
- Three view goals:
  - feasibility of stacked PCB layout, layer connection concepts, signal shapes and noise studies, strips orientation, feedback to signal simulations.

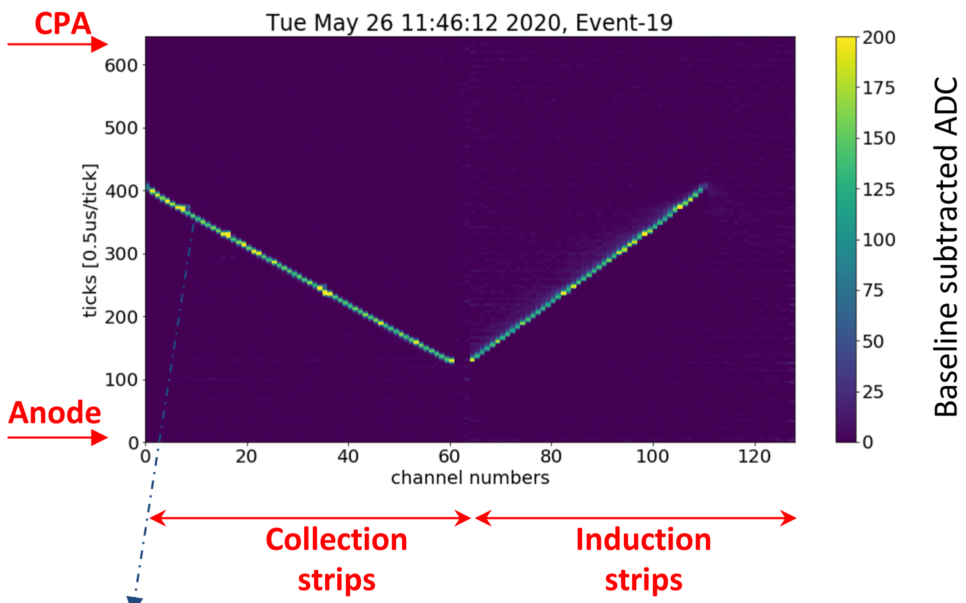


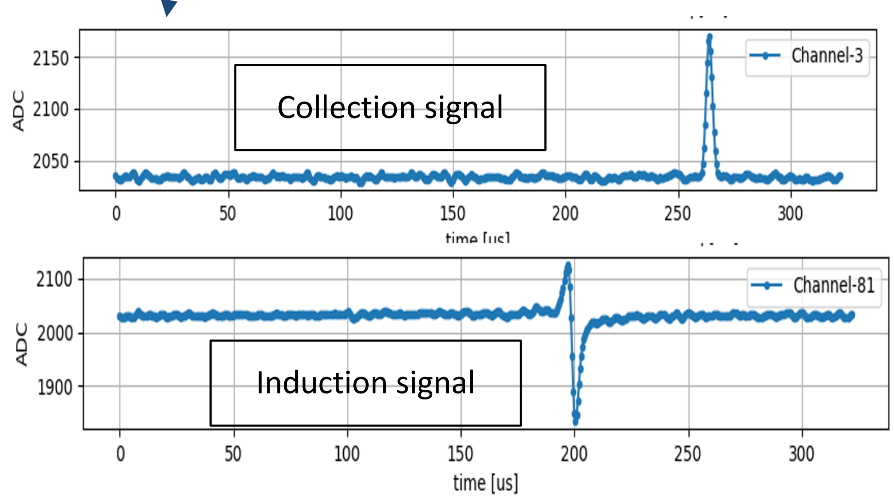






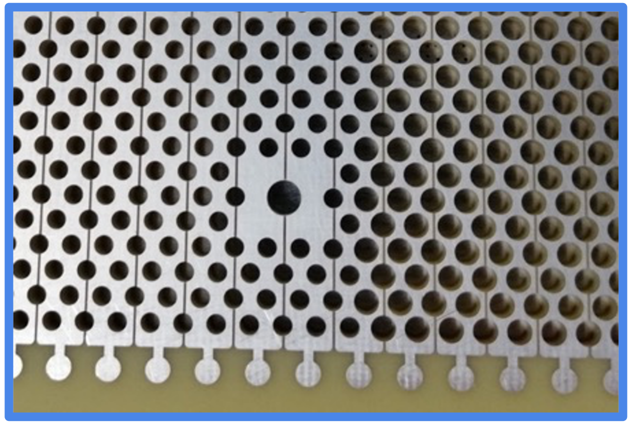
Two views



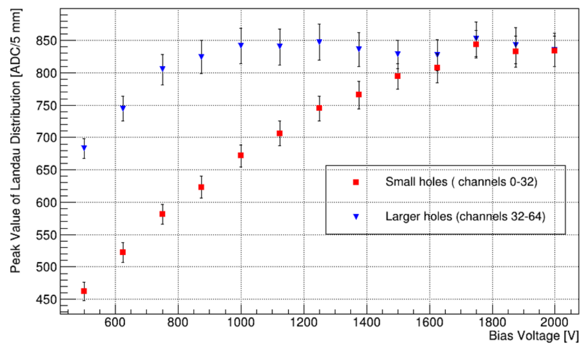


Sharp induction and collection signals
No spread of charge, no cross-talk!

Optical transparency: 38%, 59%



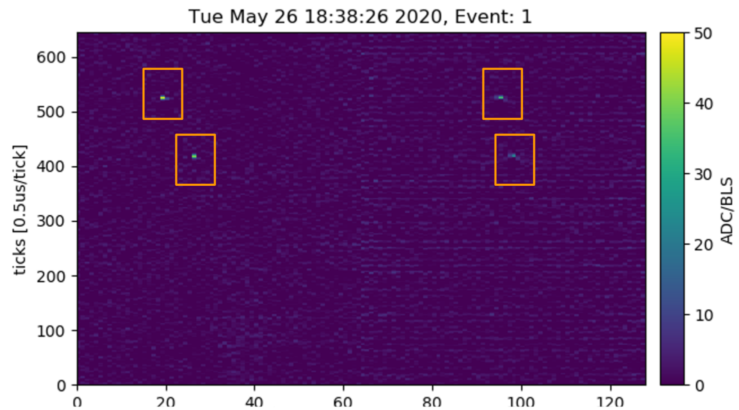
Electron trajectory transparency vs dV

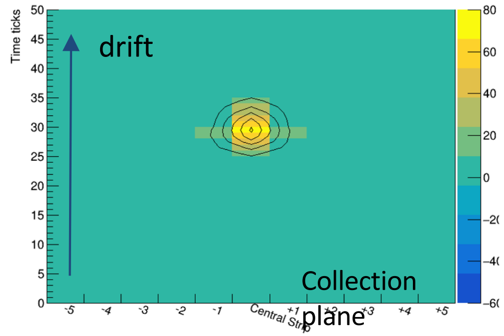


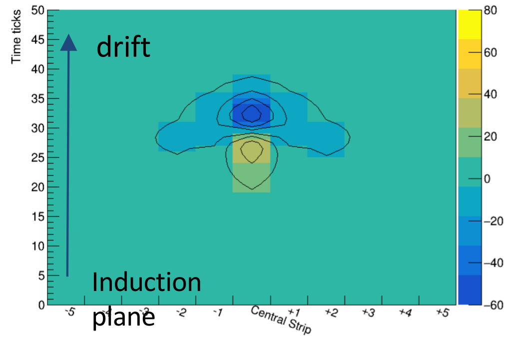
- ENC :
  - **Collection plane:** ~ 900e$^-$ at room temperature, ~ 320e$^-$ in LAr.
  - **Induction plane:** ~800e$^-$ at room temperature, ~355e$^-$ in LAr
  - Coherent noise removal improved noise level to 300e$^-$ for both layers
  - Consistent with expectation for strip caps

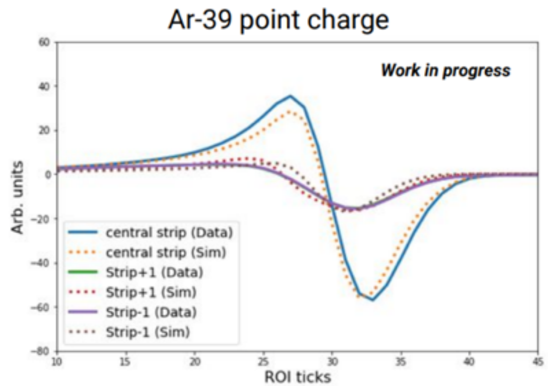
Two views Field response

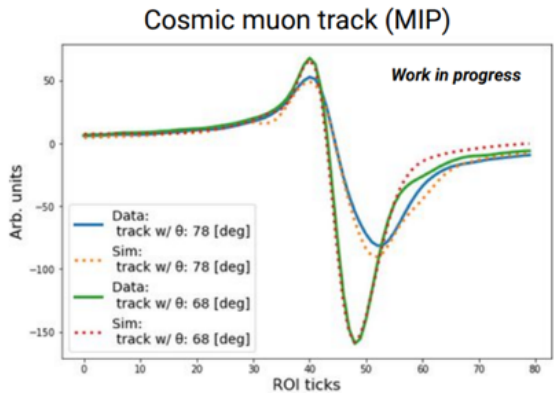
- single hits from Ar-39 calibration, Bi207 source
- Response confined mostly on the central strip ±1 neighbouring induction strips
- With direct measurements, the long-range induction effect can be properly dealt with with 2D signal processing procedure
- Useful to validate induction field simulations, input to data deconvolution
  - Nice agreement found



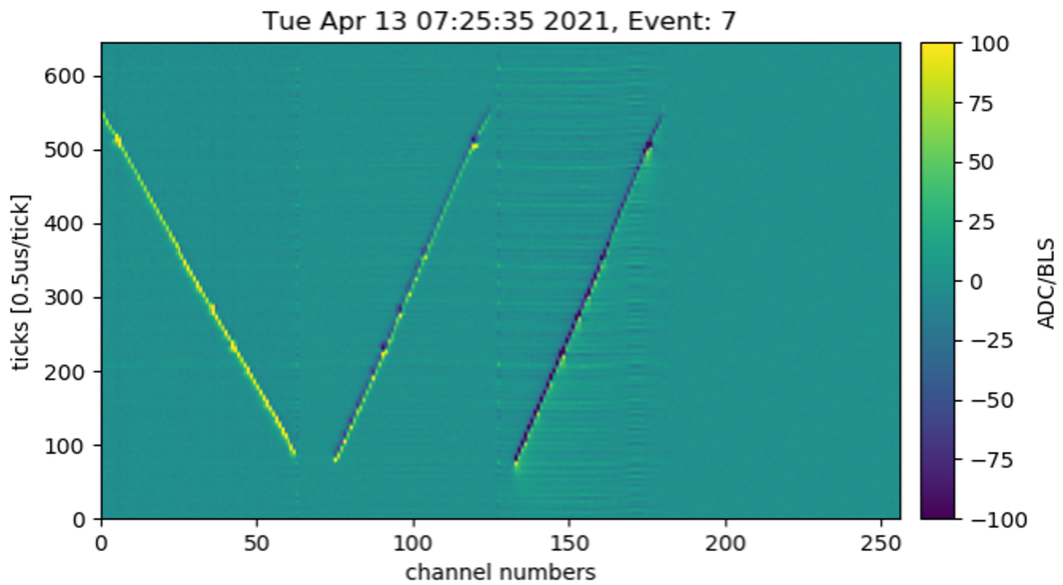


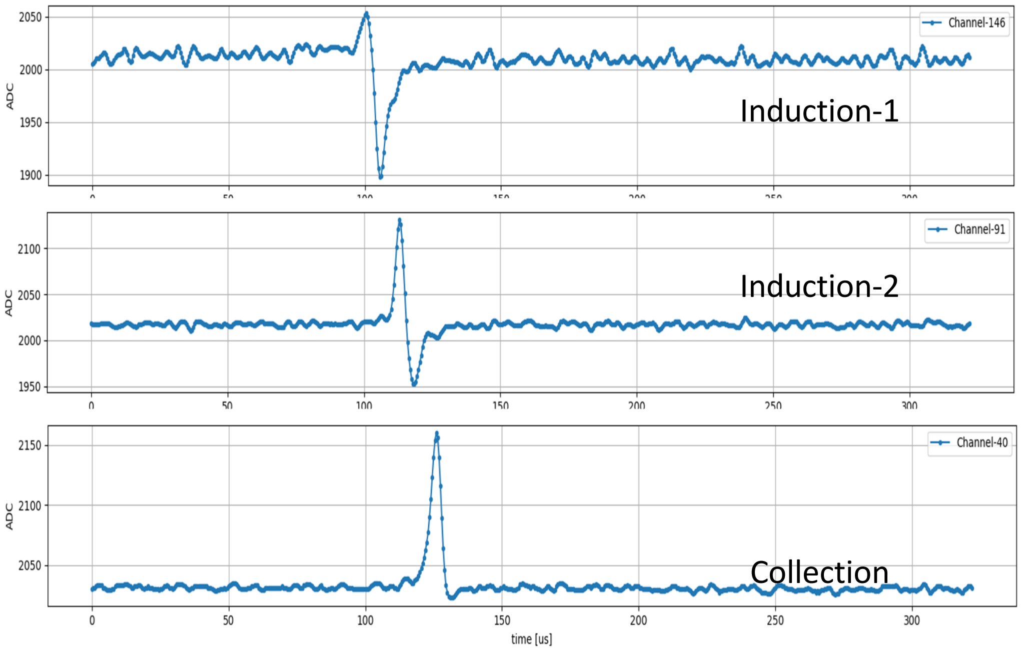




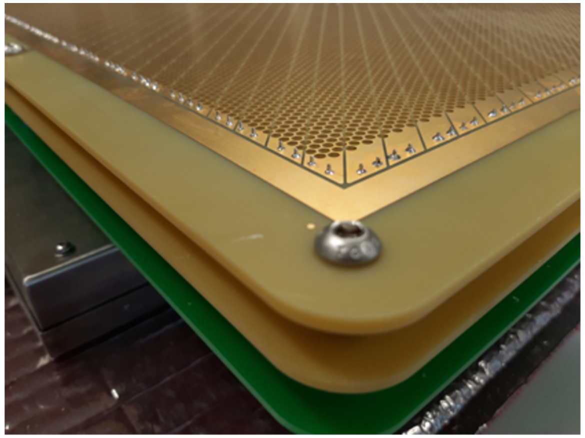


Three views

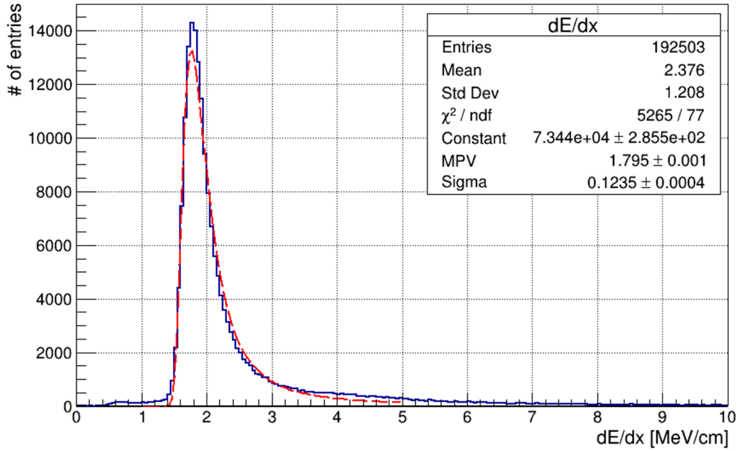




0° 90° 48° config
Collection/induction-2
5.2 mm pitch
induction-1
8.7 mm pitch
182 total channels
NO shield plane



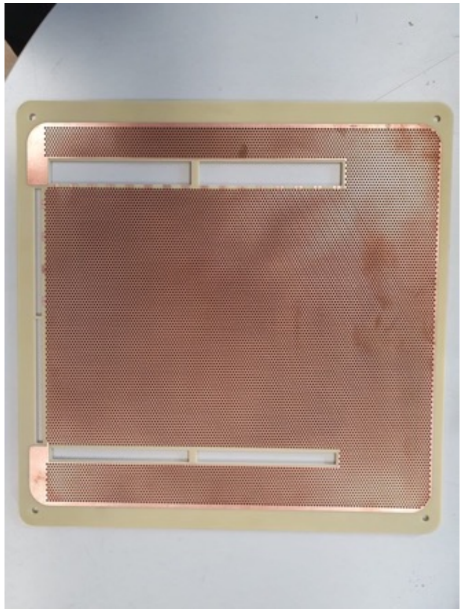
- Noise after coherent noise removal:
  - Floating FEMB channels: ~220e
  - Collection: ~300e
  - Induction-1: ~360e
  - Induction-2: ~300e
- Compatible with two-views

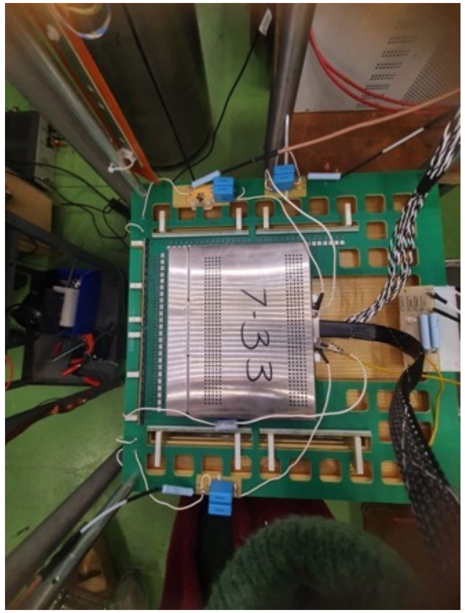


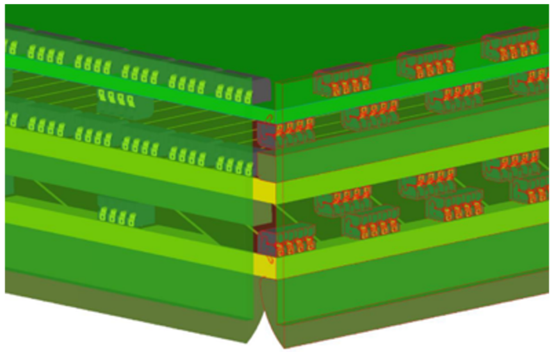
- Clear landau dE/dx from muons in collection. Attempts to extract it from induction ongoing

Three views ongoing

- Reference layout with 3 views + shield configuration
  - 3 views readout with 60 degrees orientation between views -30, 90 +30
  - 48 cannels collection, 40 + 40 inductions.
  - Slots introduced in the perforated PCB's to simulate gaps between CRP
  - New edge connectors towards the interface board.



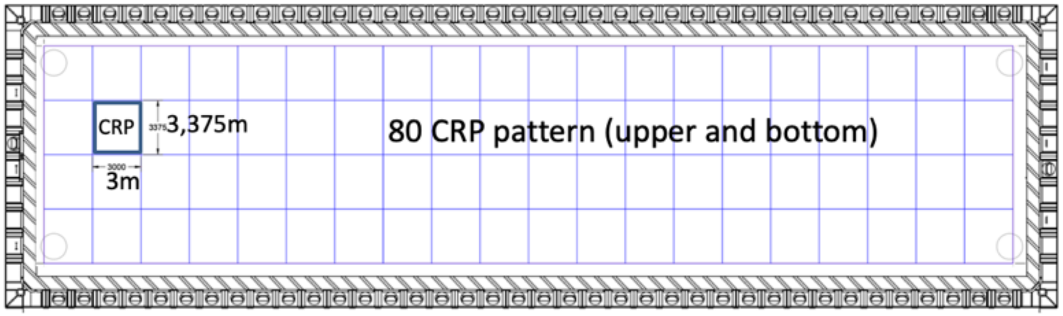


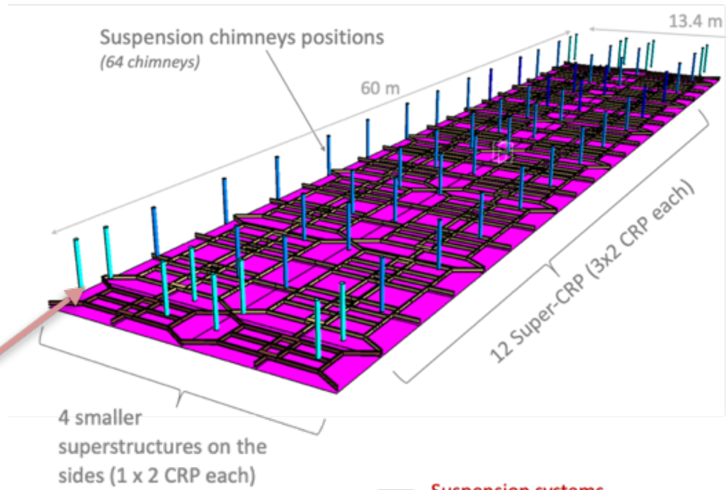


- Tested at warm for noise studies
  - Now being filled

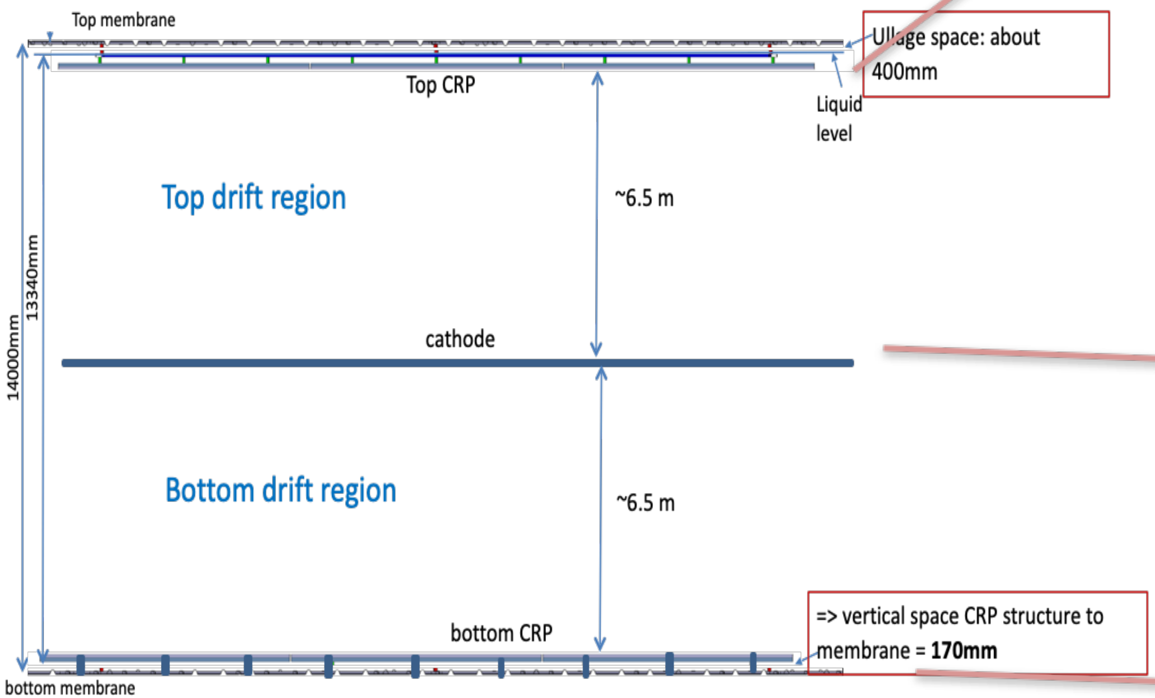
VD detector CRP arrangement

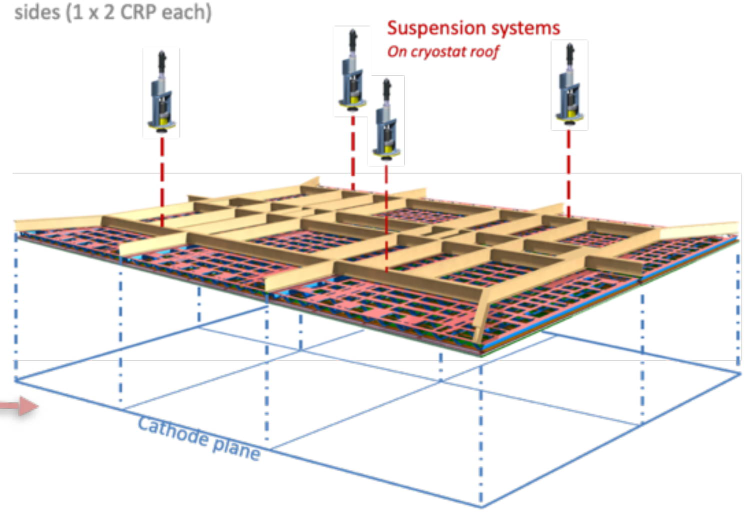
Top view:

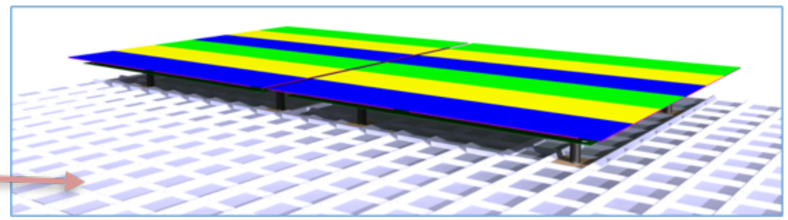




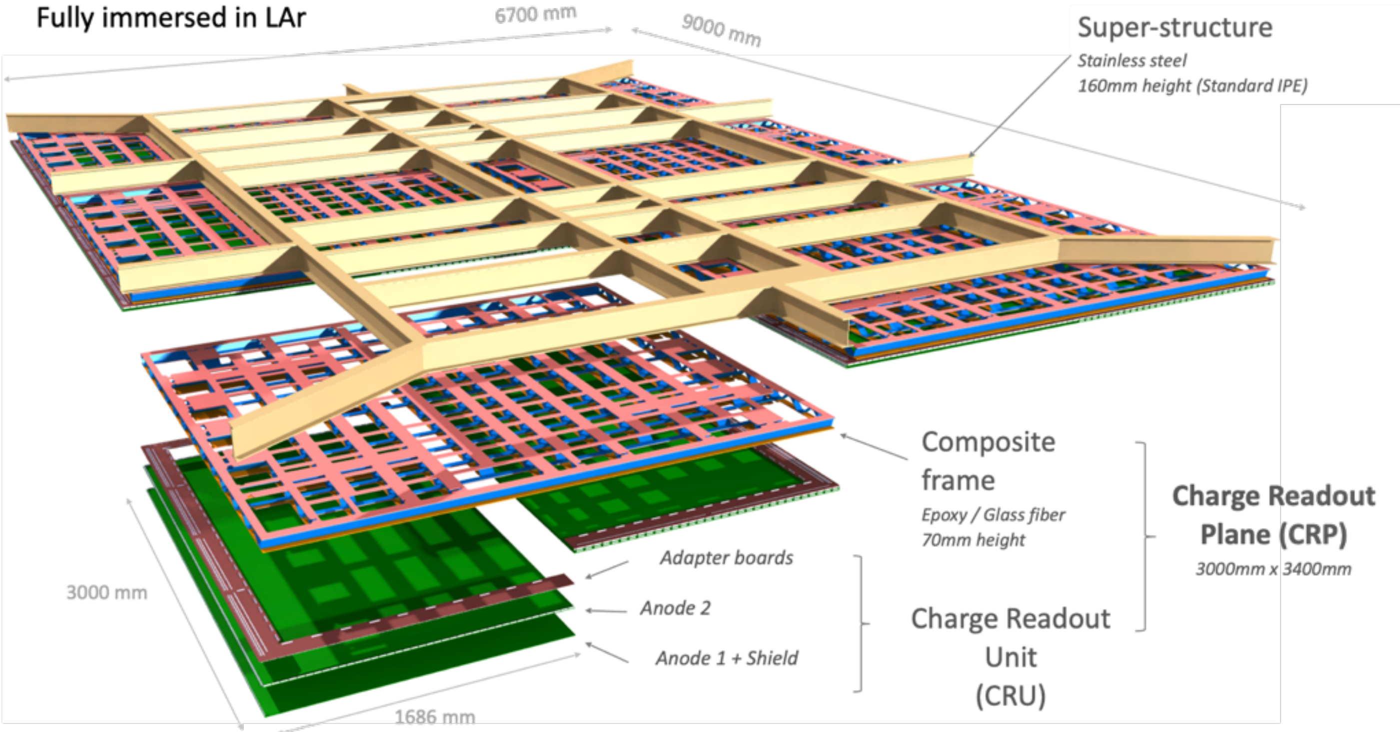
Side view :







CRP main components



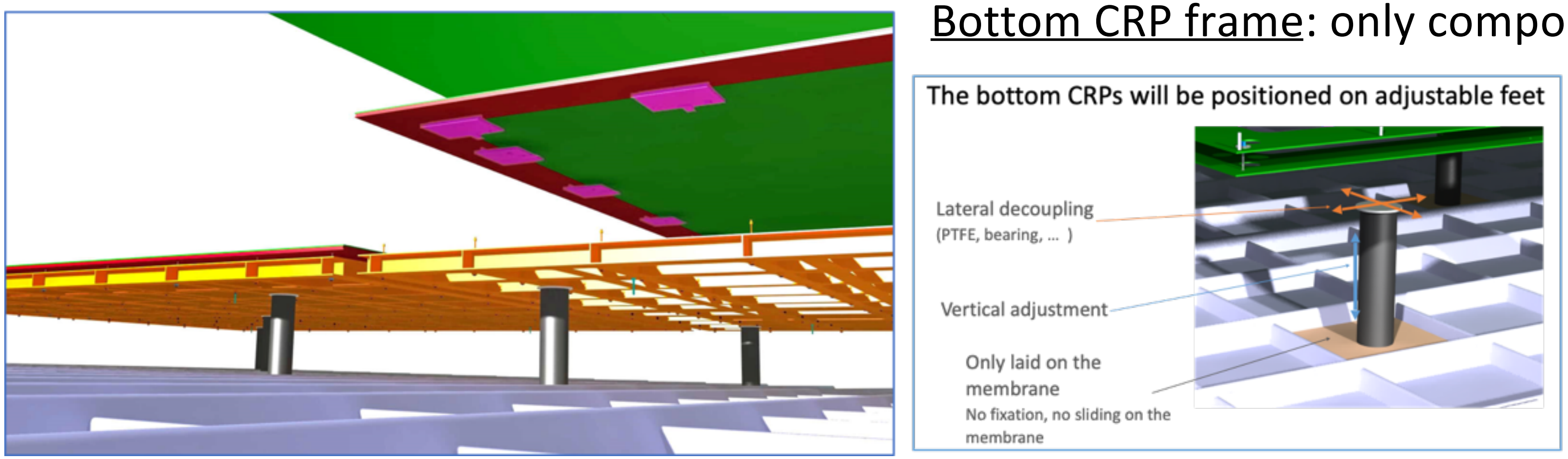
<u>Top CRP frame</u>:

Composite frames

Brings primary stiffness to electronic PCB

Thermo-mechanical behaviour close to PCB

<u>Bottom CRP frame</u>: only composite frame



Top CRP electronics (TDE)

- Evolution from dual-phase, optimized readout for CRPs suspended from cryostat roof.
- Signal feedthrough chimneys provide accessibility at any time also to cryogenic FE

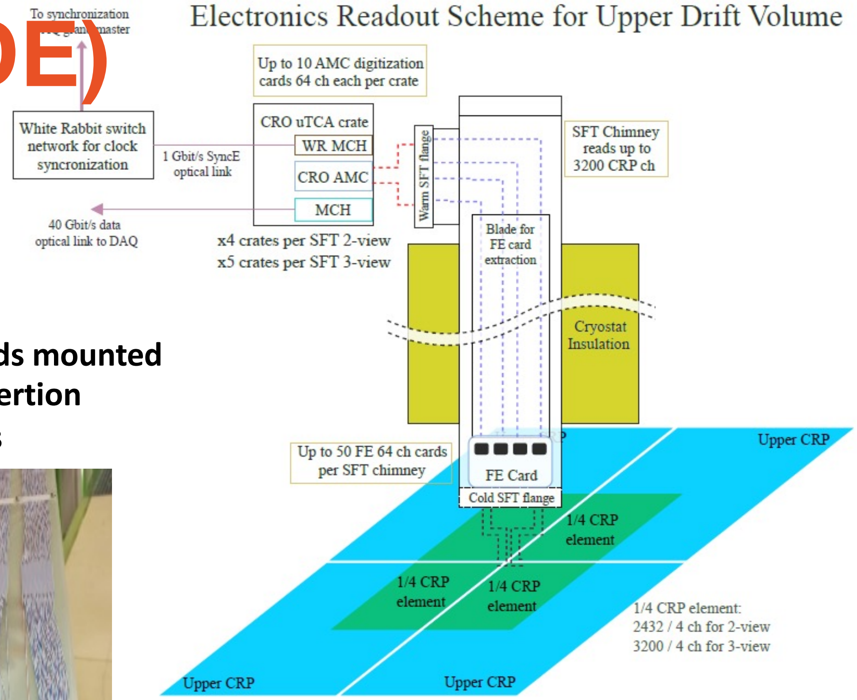
➢ **Cryogenic ASIC charge amplifiers (CMOS 0.35um) 16 ch <u>externally accessible:</u>**

- 64 channels FE cards operating at 110K at the bottom of the signal chimneys
- FE cards fixed to insertion blades handable from outside

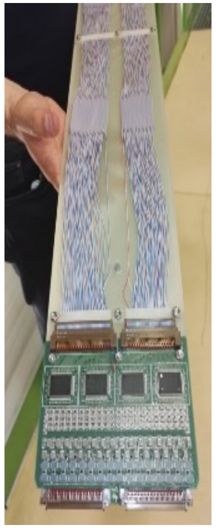
➢ **Digital electronics <u>at warm</u> on the cryostat roof:**

- uTCA architecture
- 64 channels AMC digitizer cards 10Gbit/s backplane connectivity
- White-Rabbit timing distribution

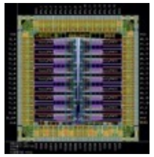
~256000 chs (3 views)

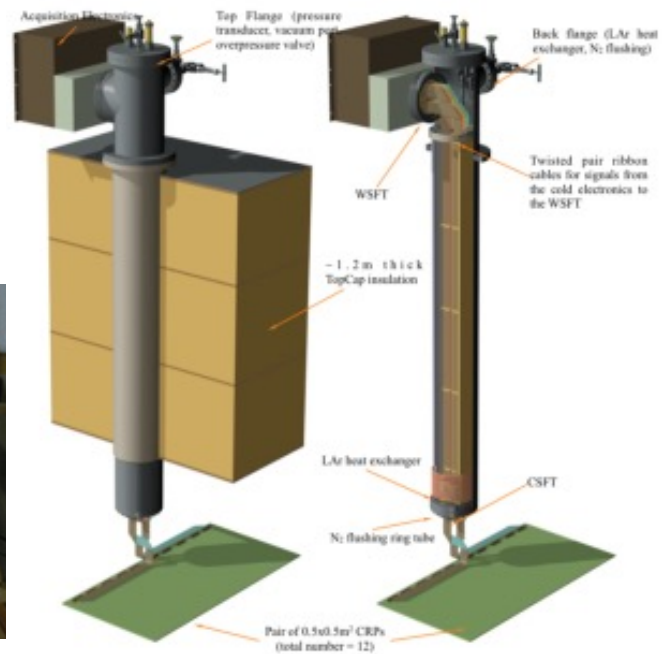


FE cards mounted on insertion blades



ASIC 16 ch. (CMOS 0.35 um)

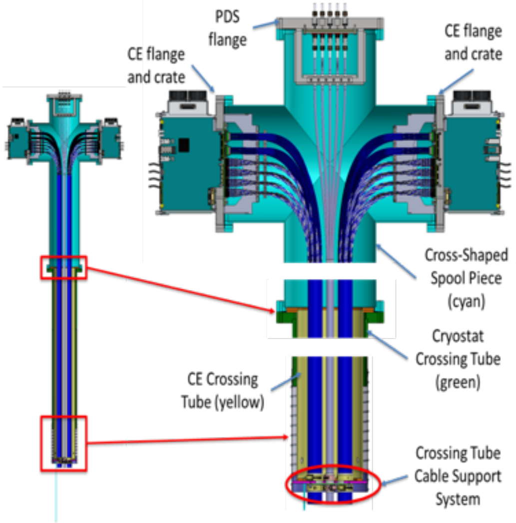


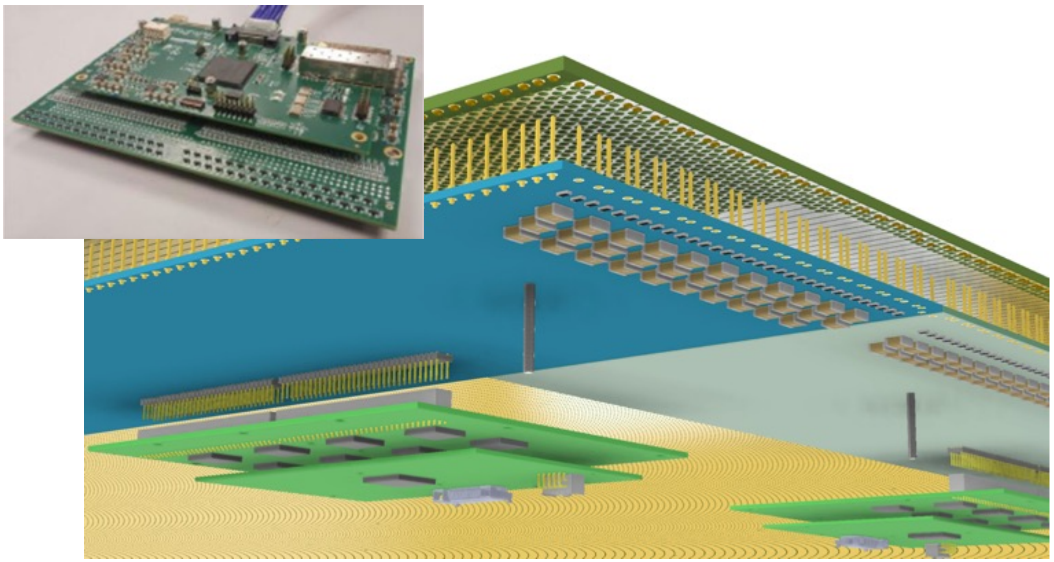


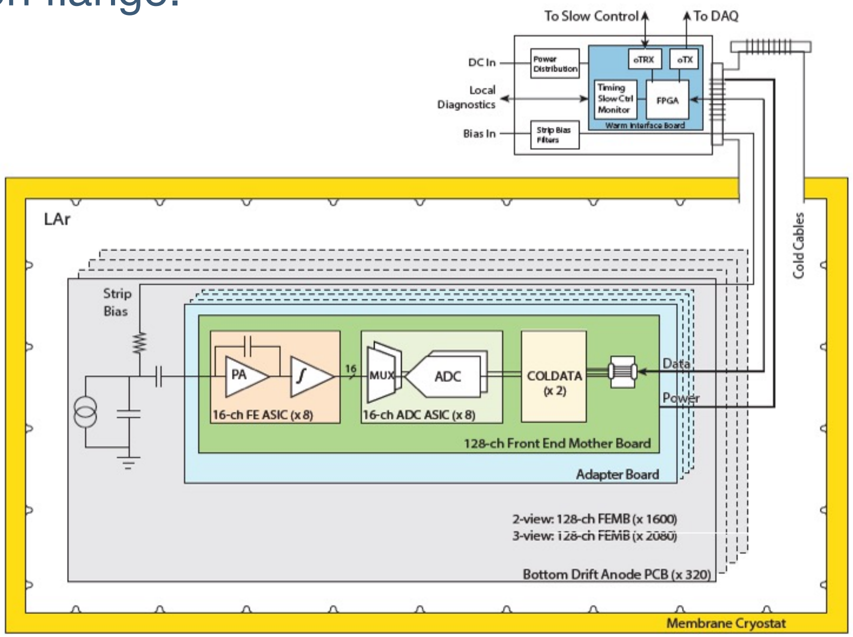
Bottom CRP electronics (BDE)

256000 chs (3 views)

- Same technology as NP04. Electronics designed to be immersed in LAr, very close to the pickup electrode
  - FE LArASIC charge amplifier and shaping (128 ch/board)
  - On board Digitization with ColdADC (2 MHz, 12 bit)
  - 30-year operation in cold certification
- Routing of cables (digital signals) on the floor, vertical cable trays close to the cryostat wall
- 40 cryostat penetrations (20 on each long side)
  - Warm digital interface boards crates mounted on flange.

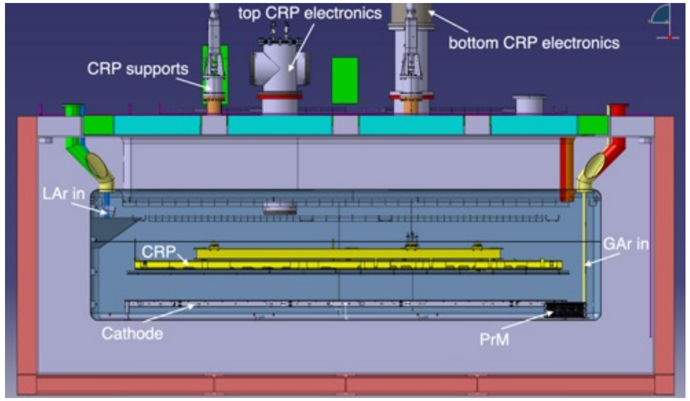


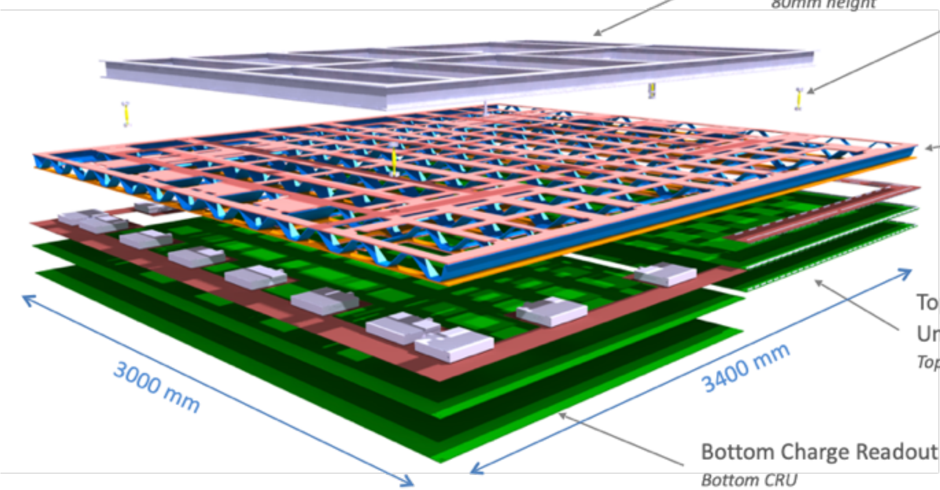




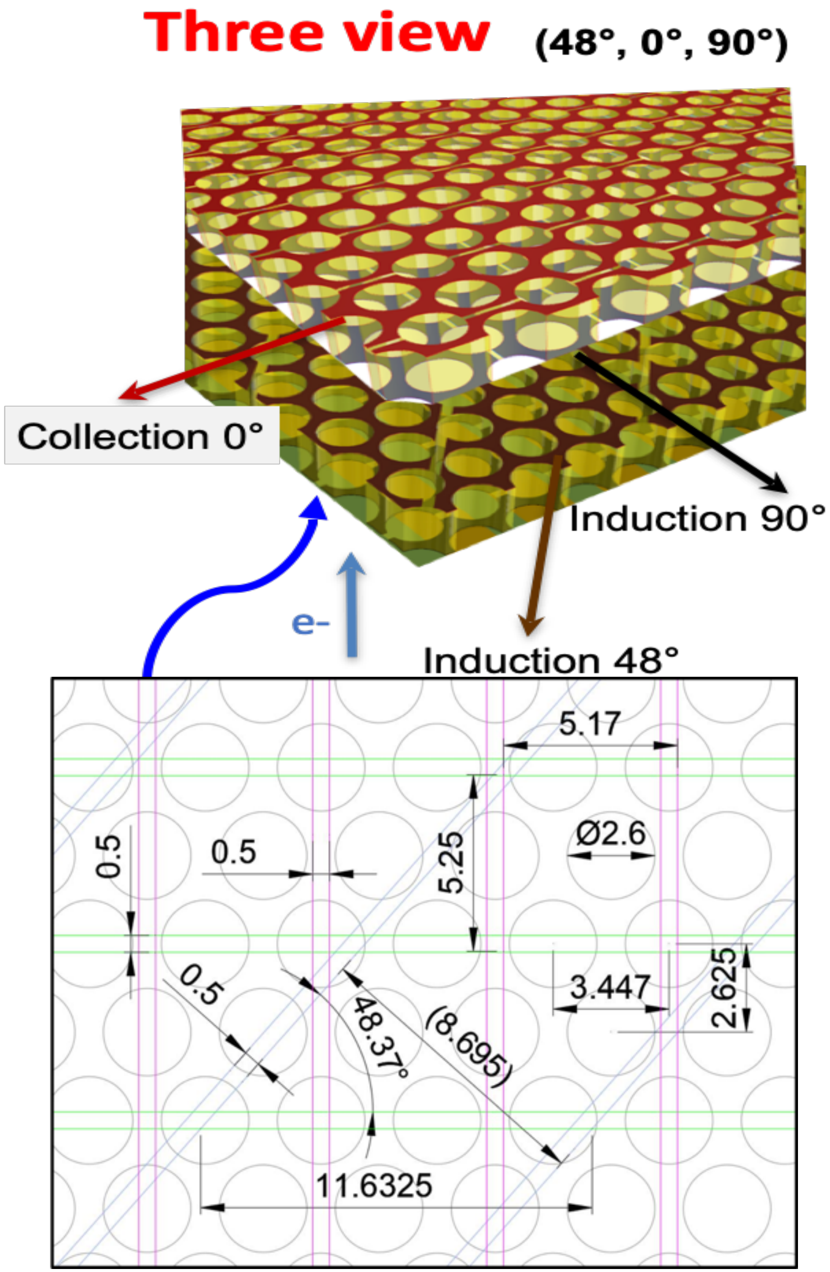
Test program of CRP in NP02 cold box

- Facility refurbished and made operational EHN1 in August 2021
- Shares the cryogenic system of NP to guarantee pure Argon filling and gas recirculation
- Roof adapted to hang the new CRP
- CRP Prototype made of 2 CRU's with Top and Bottom Electronics respectively
- *Top penetrations layout adapted to specific electronics requirements (different for TDE and BDE)*
- *Cathode sitting on feet on the floor (25 cm drift)*





PCB reference design layout



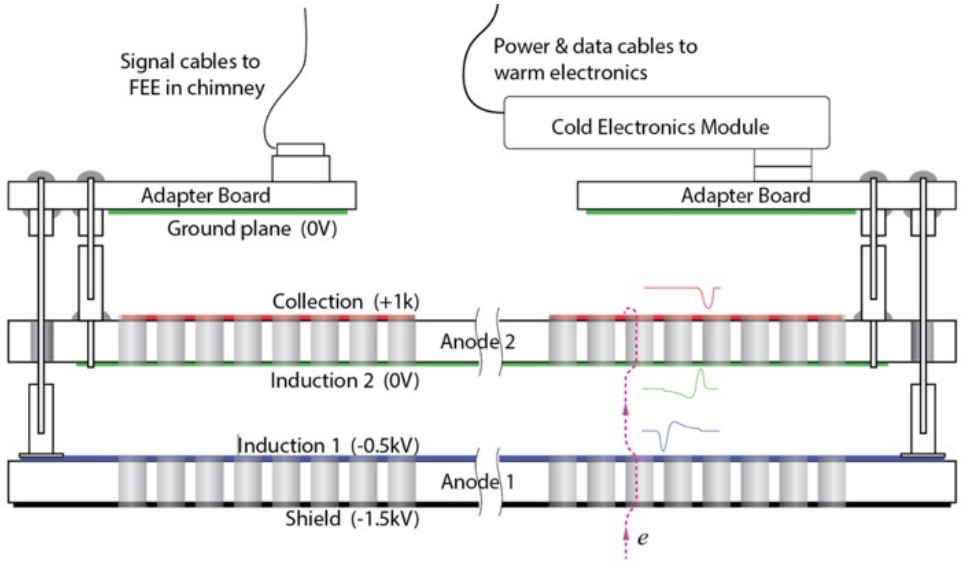
3rd view at ~48°
Induction1 strip pitch: 8.7mm
Collection and Indidcution 2: ~ 5 mm
8.5 mm PCB spacing

Three views layout with strips at 0 °, ±30 ° also an available option
Final design choice depends of physics, reconstruction arguments

Biasing voltage for 450 V/cm drift
Collection +900V
Induction2 0V
Induction1 -340V
Shield -1240V

CRP 3-View Prototype for cold box

3-view option with a diagonal view (48°) on 1st induction and 3200 channels per CRP



Basic readout unit (CRU) is 1/2 of CRP

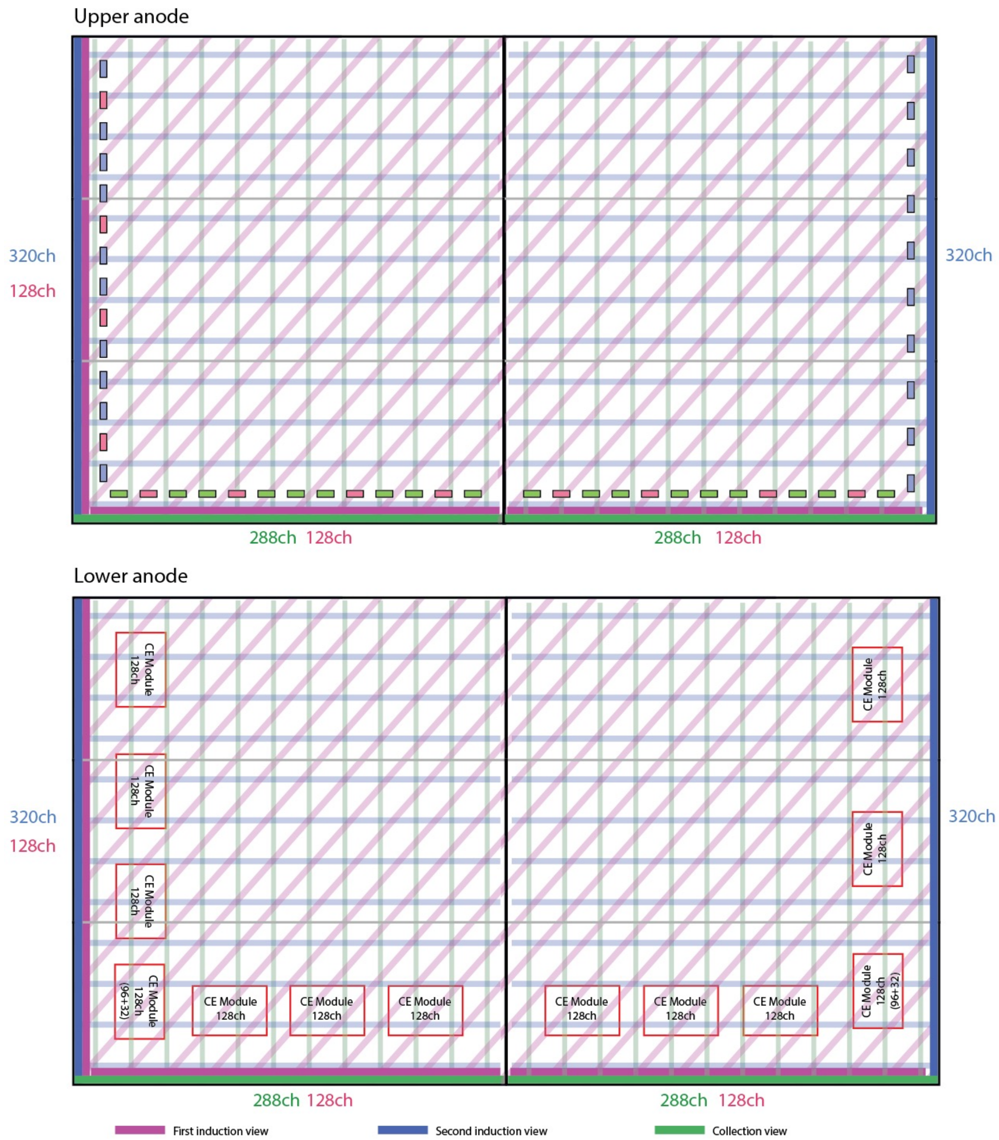
Channel count per CRU pair

1st view: 384

2nd view: 640

3rd view: 576

Top electronics



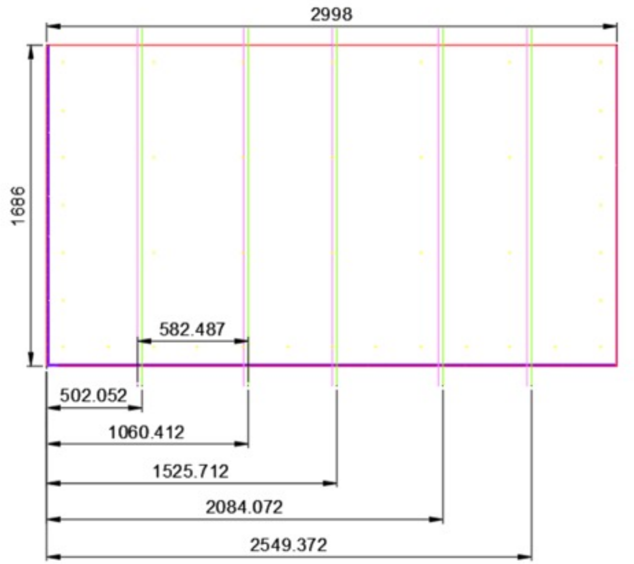
Bottom electronics

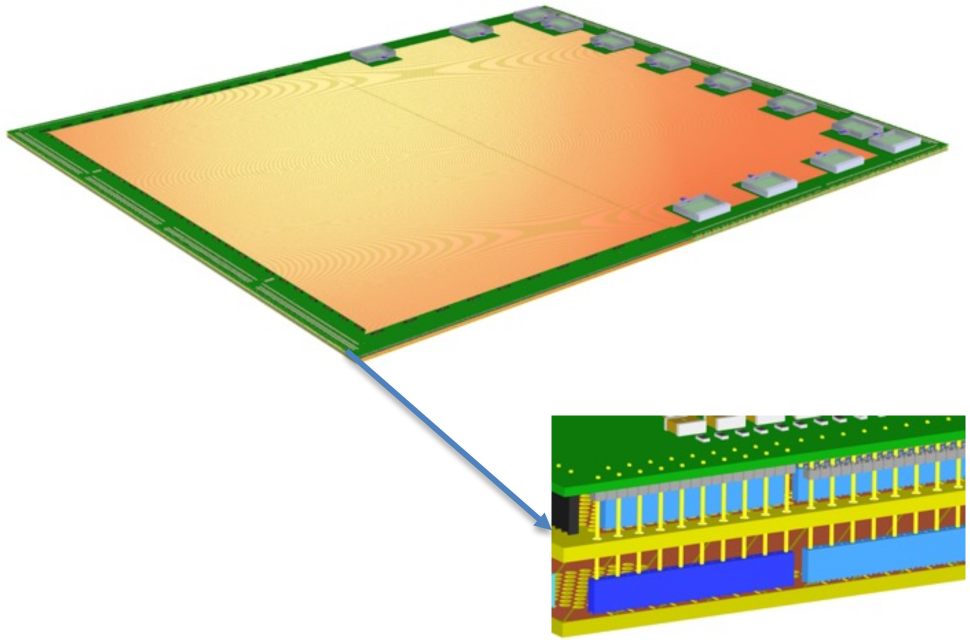
Large PCB Design Assumptions

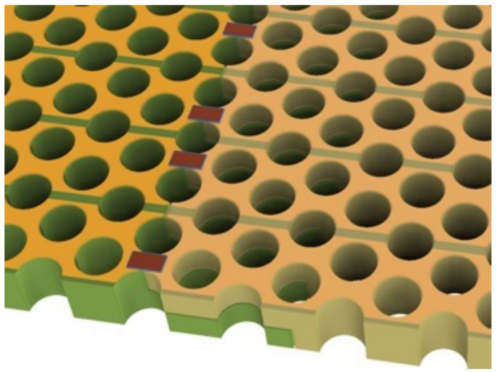
- Use existing DUNE/ProtoDUNE SP/DP readout electronics
  - Limit input capacitance to that in the current APAs ~150pF (~1.5m strip)
- Practical boundary conditions
  - Common PCB core thickness: 3.2mm or less
  - Typical PCB fabrication limitation (commercially available): ~ 1.7m x 0.6m in plating.
  - Drilling speed goes linearly with board thickness
  - Estimated time to perforate the whole CPR plates with a single fully dedicated drilling machine (24/24) is about 2 years
  - Larger dimensions drilling machines available but requires heavy tuning of whole production process
  - PCB gluing process to reach required CRP unit dimension developed in house (with EP-DT-DD group)
- 3-view layout based on Stack of two perforated PCB's:
  - Additional multilayer interface board to host biasing network and connectors to FE electronics
- Minimize dead areas between modules
  - *Edge connectors between PCB layer also developed in house*

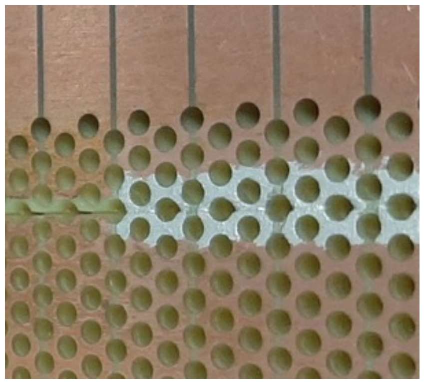
Anode Interconnect Technique

- Procedure :
  - join 6 pieces of 1.7m x 0.5m PCBs into a single assembly using a half lap joint technique.
  - Epoxy to glue the joint without blocking the holes.
  - Screen-printed conductive ink patches bridge the strips across the gap.
  - Proposed and successfully tested at the CERN PCB workshop.
- For large-scale production, vendors identified able to fabricate PCBs up to 1.5m x 1.7m in size, to require one joint for CRU sized anode.
- Manual edge connector mounting (to be optimized)



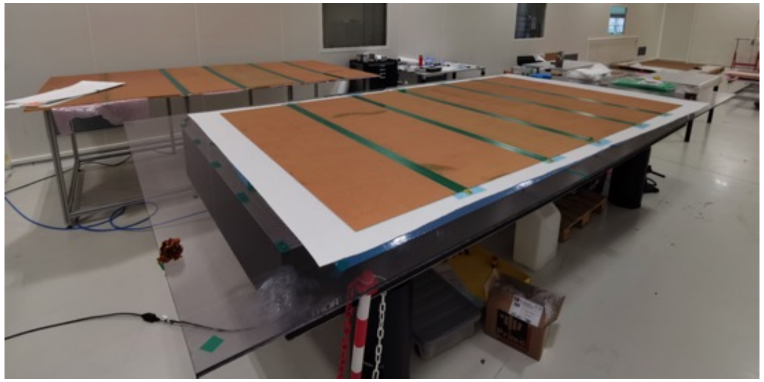






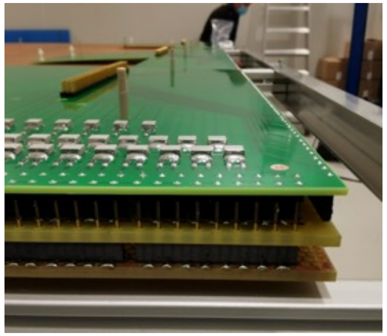
CRP layers construction

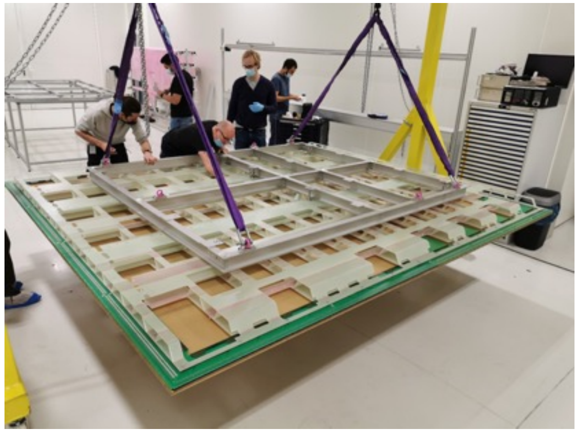
- PCB slices produced by ELTOS, received in July and August. Total of 36 (for 1 CRP + spares)
- Perforated Anode PCB treatment and process procedures carefully applied (quick learning curve):
  - Gluing PCBs
  - Cleaning the PCB surface
  - Silver printing
  - Heating/polymerisation procedure
  - Continuity tests at cold
- During this period, several lessons learned and implemented for the anode production
- Construction performed in clean room environment (CERN-B185)
- Typical construction time, 1day/CRU



CRP assembly

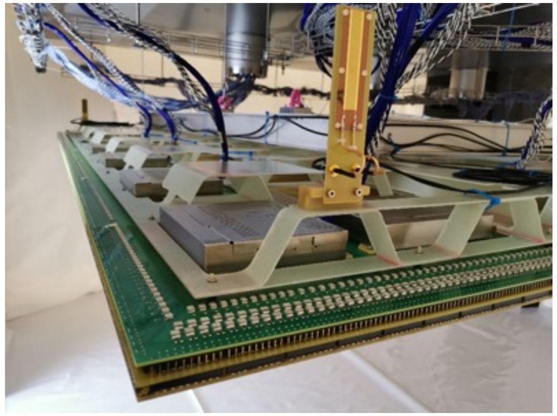
- Procedure:
  - Stack the CRU layers and the interface boards (spacers, connectors)
  - Mount the bottom FE boards + cold testing
  - Align the CRU's boundaries
  - Couple with the composite frame and the metallic support structure
  - Packaging for transportation to EHN1
- Lot more lessons learned and implemented for the CRU/CRP assembly
- Full assembly (1 CRP) in one working week (mid October)

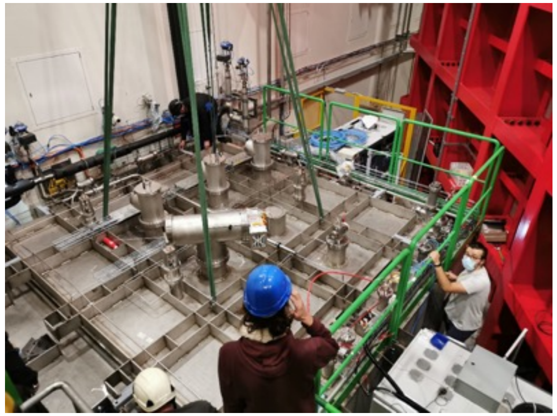




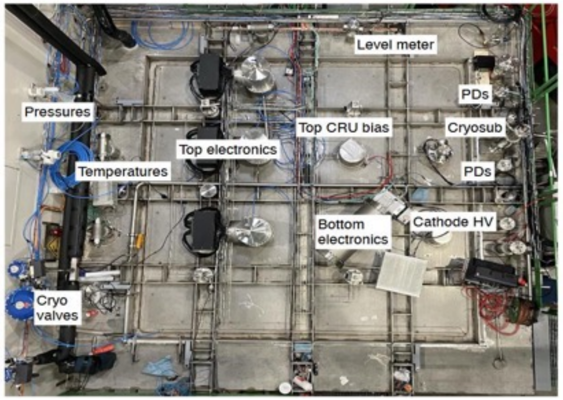
CRP Installation in Coldbox at EHN1

- Cold box equipped with the cathode on the floor (integrating photon detectors) and monitoring instrumentation
- Procedure:
  - Hang and instrument the CRP under the Coldbox roof
  - Route FE cables (TDE and BDE), bias lines and service probes (temperature, levels)
  - Install the BDE warm interface crates and test FE boards
  - Lower the roof and close the coldbox
  - Install Top Electronics
    - blades with the cryo-FE cards in the chimneys
    - cabling of uTCA crates
  - Install connectivity to networking and timing and DAQ



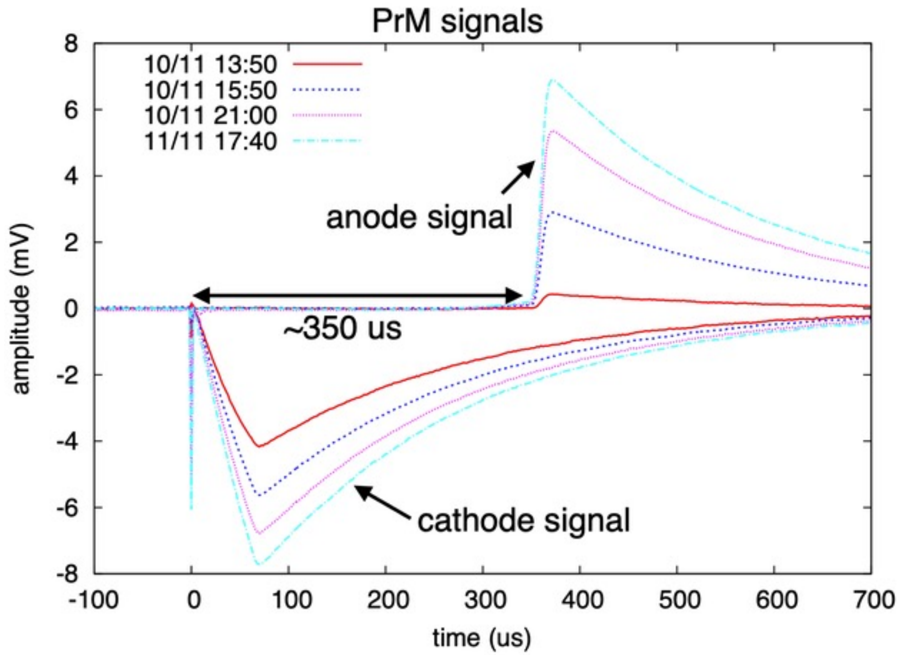


October 25



Coldbox commissioning and run

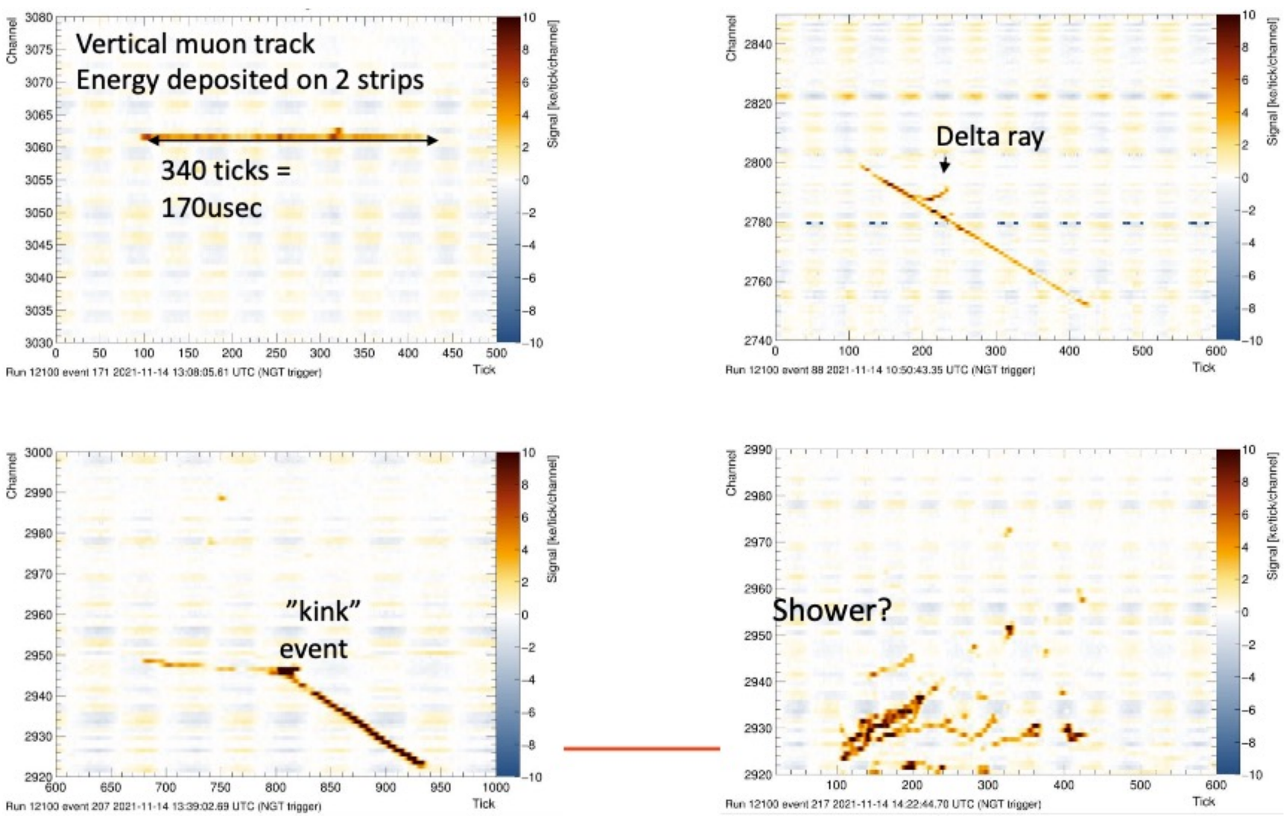
- Ar-Gas purging for one day.
- LAr filling performed on 10th November.
- LAr taken from NP02 (much faster) Filling completed in ~6 hours.
- LAr purity increasing while filling. Purity after filling > 1 ms
- Expected negligible loss of signal from the TPC cathode *O*(150 us drift time)
- Re-condensation not activated (boil-off exhausted to the atmosphere)
- LAr level decrease 2 cm/day (filled 5 cm above the nominal)
- Minor loss of purity from the filling to last day of run (~1week)
- Cathode HV (~10 kV) and nominal bias voltages on CRP layers immediately set after filling
- Data taking with random trigger immediately started



First Data from BDE in LAr

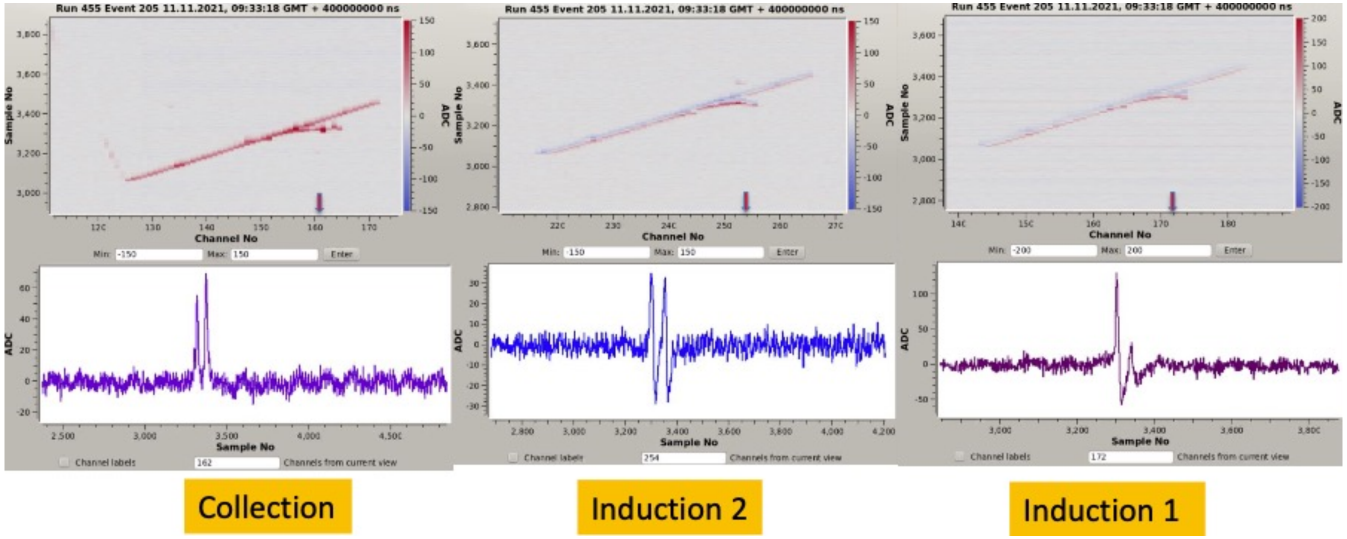
- All 1600 channels online soon after LAr filling
- Strong effort from the DAQ group to provide online monitoring and initial raw data treatment (coherent noise removal)
- Cosmic ray tracks observed right away after turning on cathode and CRP bias voltages
- Origin of large coherent noise (~24 kHz) under investigation

(events after coherent noise removal)

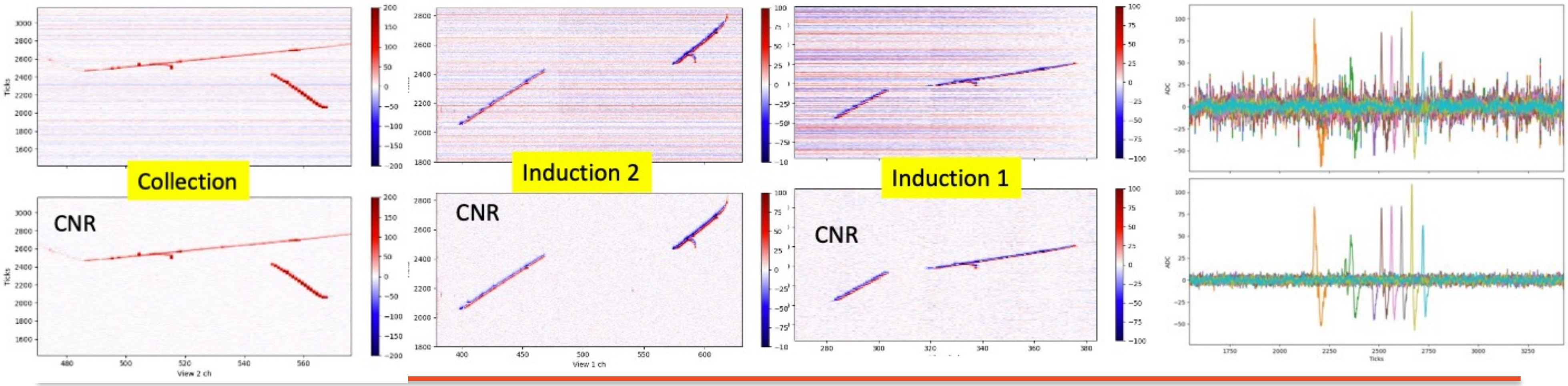


First Data from TDE in LAr

- Very good raw data quality (S/N)



- Some coherent noise present depending on strip/board geographical location. Coherent noise removal allows reach nominal noise expectation (< 600 el.)



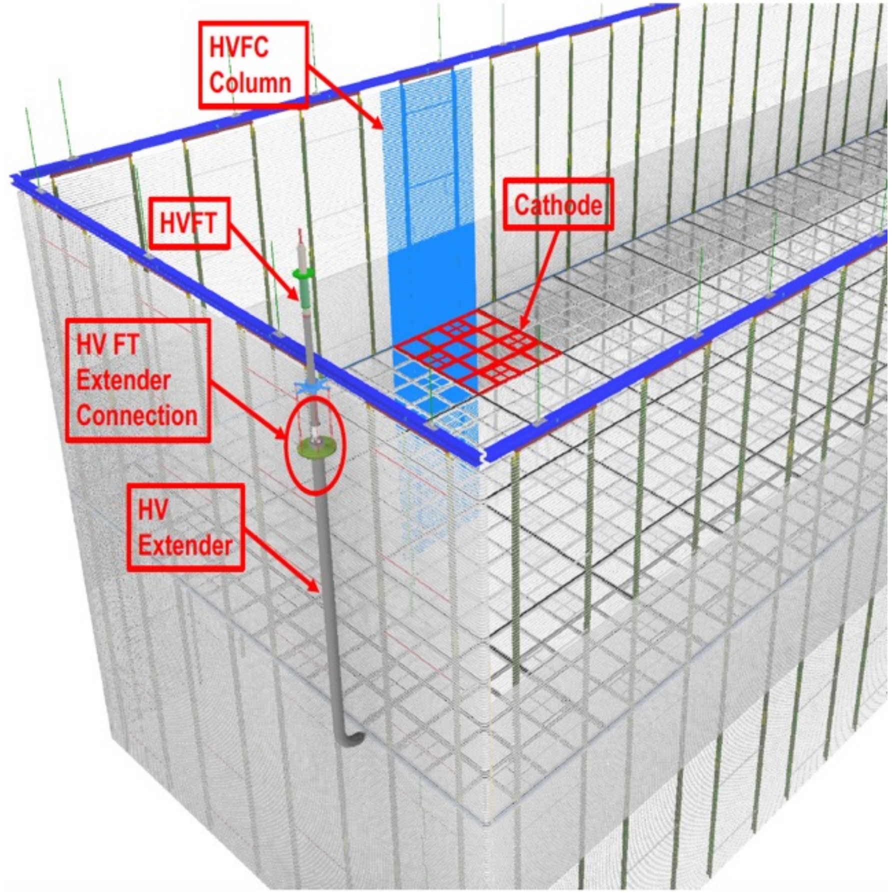
Next steps

- First CRP construction and coldbox test with integrated BDE and TDE successfully achieved.
- Large sample of triggers O(10^6) with nice cosmic / beam halo tracks acquired, exploitable for detailed Vertical Drift CRP performance study and noise understanding. Event reconstruction and analysis in progress. Preliminary results on CRP signal response are in line with 50l tests but extended to full scale.
- After opening of the coldbox, grounding improvements have been performed on the CRP interface boards to mitigate the coherent noise issue. A new run is starting this week.
- In view of the NP02 Module-0 final test, several cold box run are foreseen next year for the three new CRPs with the final strips orientations (90, ± 30°), the final edge connectors choice and equipped with the homogeneous set of electronics (full BDE or full TDE)

High Voltage / 6 m drift demonstrator

High Voltage system for the drift volume

- **Three main components**
- Cathode plane:
  - 80 modular units 3x3.4 m2 integrating PD's
  - Hanging from CRP superstructure
- Field cage
  - derived from the DP design with Lessons learned from NP04
- The HV delivery system:
  - HV extender: improved version of the one implemented in NP02.
  - HV Feed-through HV cable and HV Power Supply as for NP04/NP02

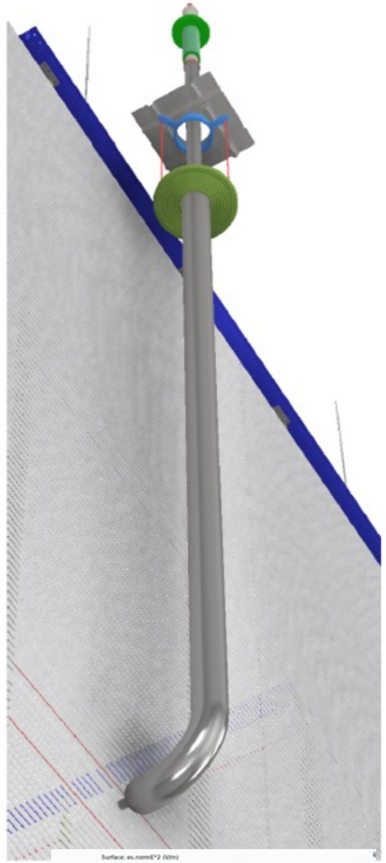


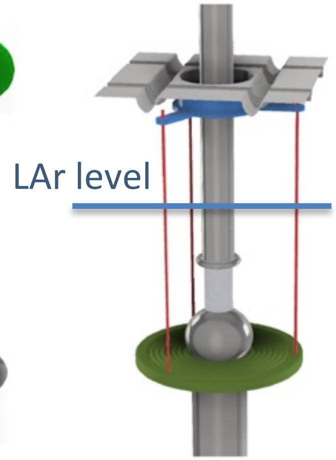
- **Main challenge**
  - *Demonstrate long term HV stability at 300 kV on the cathode in pure LAr. Recording of 6 m long drift events. Being presently performed on NP02 equipped with the DP detector*

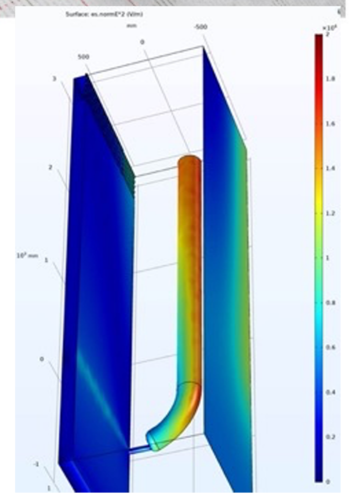
HV Delivery system

- Present understanding from ProtoDUNE and R&D experience is that insulating materials are to be avoided in high E-Field regions such as the space between FC and cryostat walls
  - Insulators can charge up due to ionization radiation in pure LAr, thus distorting the E-field and inducing unpredictable HV instability or failures
  - Rely instead on LAr dielectric rigidity (MV/cm): drifting electron do not have enough energy to trigger discharges.
  - Avoid heat input that can produce gas bubbles, (mostly present in the first 20-30 cm below LAr surface, elsewhere suppressed by hydrostatic)
- New extender complies with these rules
  - Diameter (20cm) and distance from walls and FC (40 cm) and curvature of “elbow” safe for LAr at 300 kV
  - Coupling of extender to HV Feed-through >30 cm deep in LAr
  - Only insulating material in the extender support

New extender

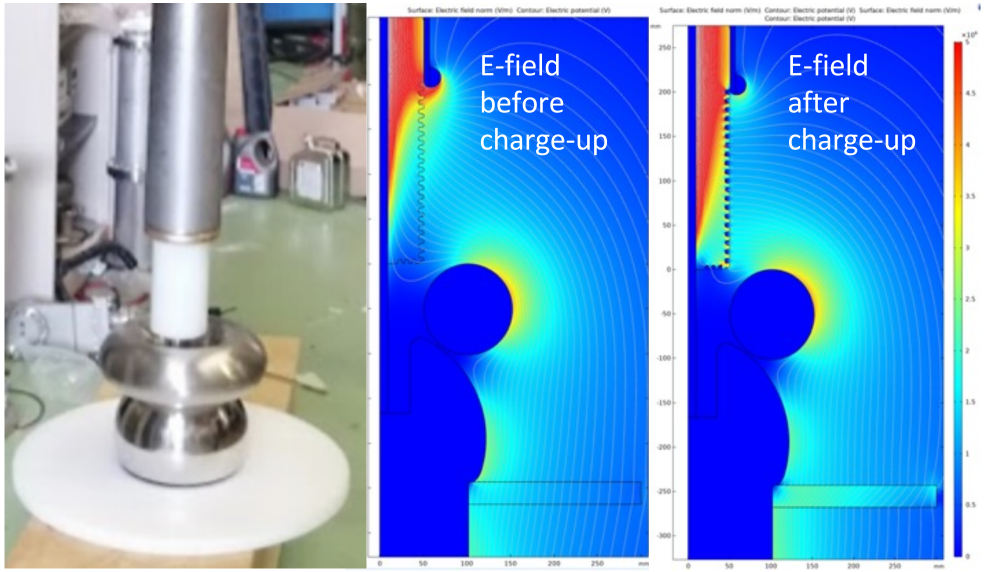




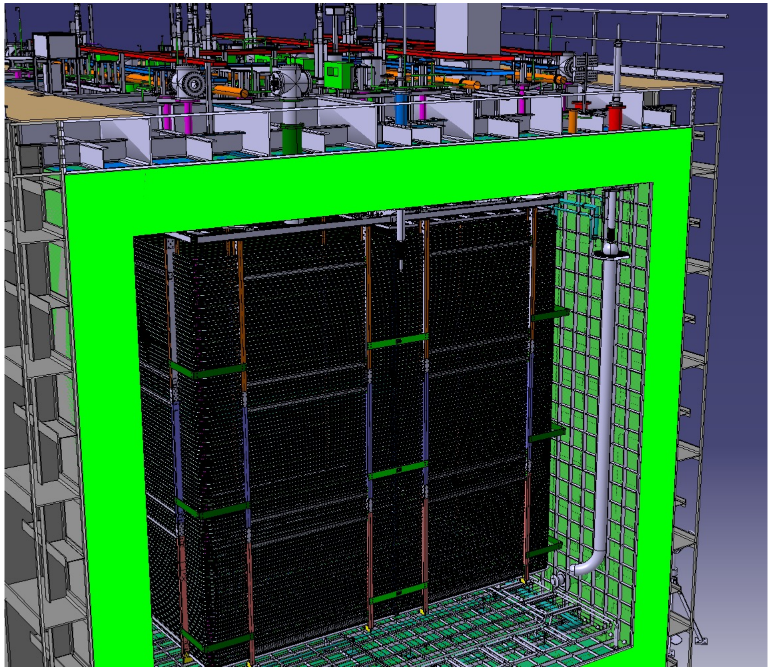


Validation of HV delivery system

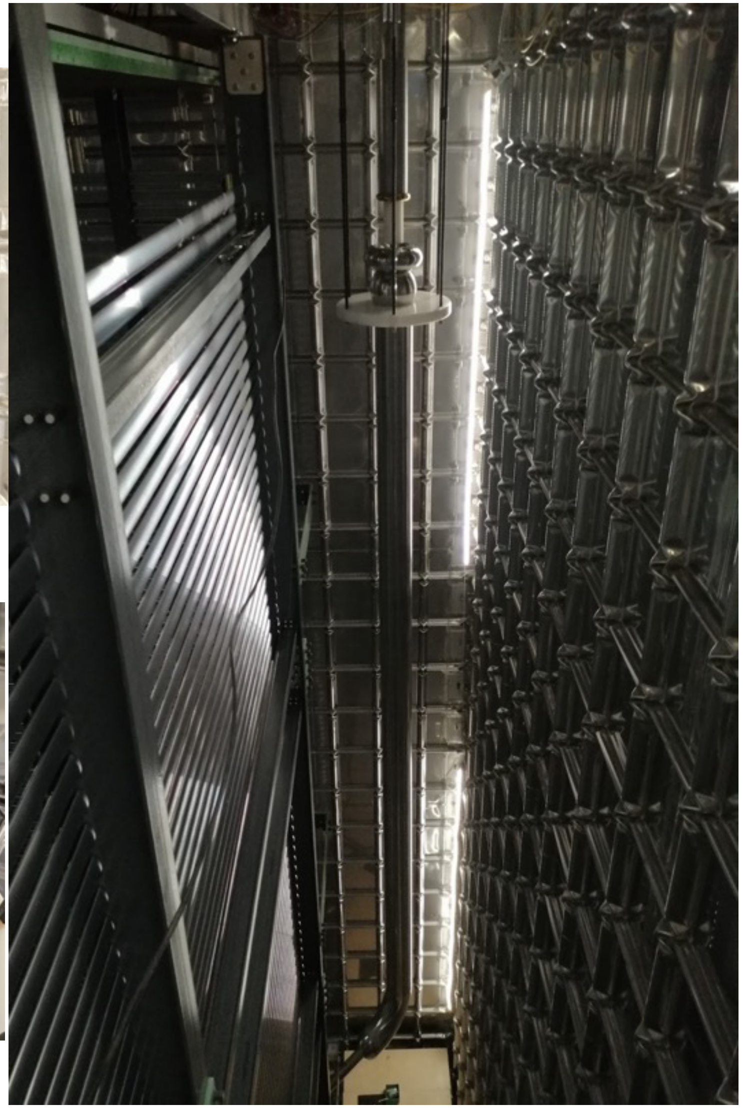
- First step (spring 2021)
  - Multiple small scale tests (2ton cryostat) in pure LAr and 300 kV of the extender coupler-to-HVFT:
  - optimize the shapes against HV stability by minimizing critical high E-field regions before and after charging up of FT insulators and extender support



- Second step (summer to present)
  - Replace the NP02 old extender with new one connecting it to Cathode and FC
  - Fill the cryostat with 750 ton of LAr, activate recirculation
  - Ramp up the HV at 300 for long term stability run
  - Monitor HV stability with cameras, PMT's HV-pPS controls.
  - When El-lifetime exceed ~3 ms, activate the DP extraction/readout CRP and electronics to record 6 m long track

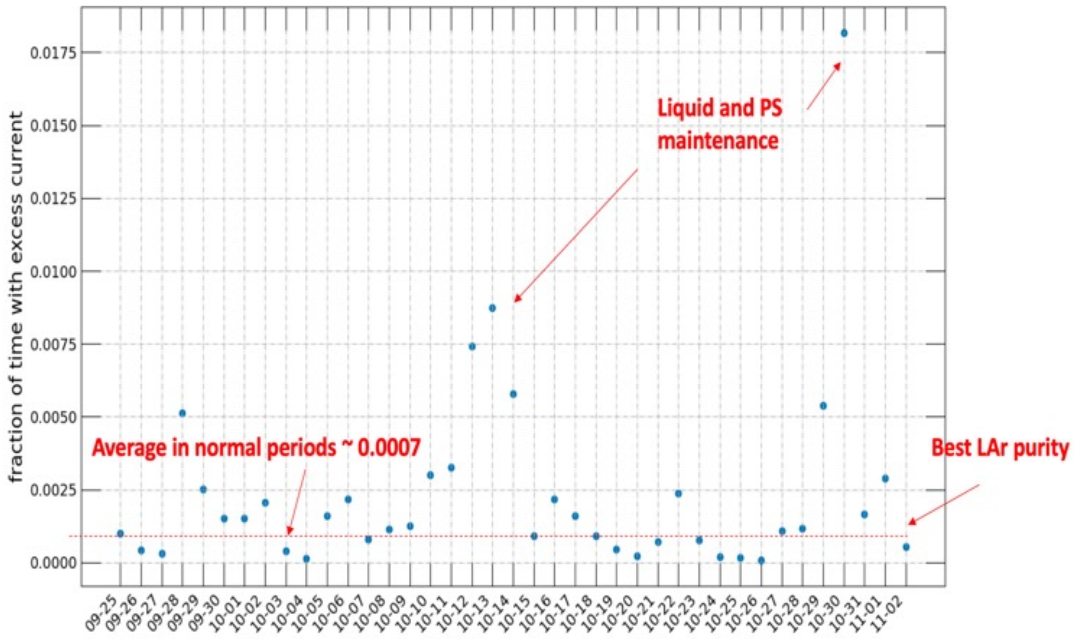


NP02 HVS with new extender



NP02 HV long term stability

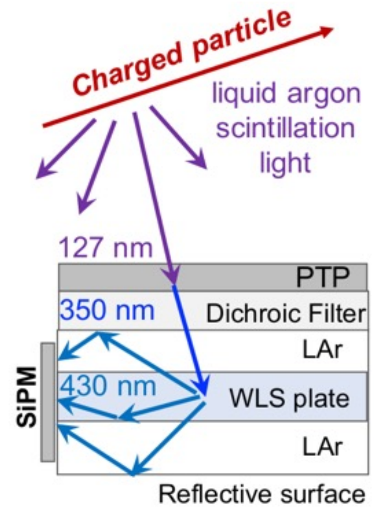
- Test started on September 20
- Up-time at 300 kV > 99.9% over more than 40 days of continuous operation with LAr purity exceeding 1ms.
- Stainless steel extender body very stable over the full 6 m length, including elbow termination and coupling with the Field cage; 40 cm distance from corrugated membrane enough to hold 300 kV.
- Coupling between extender and HV-FT not showing charging up instability issues.
- *Rare HV instabilities (excess current and visible sparks) localized around the extender coupler and the support disk (residual charging up effects)*
- An external cable-FT failure interrupted the test for 2 weeks. Now restarted. CRP activation foreseen for early next year



Large area photon detector at HV

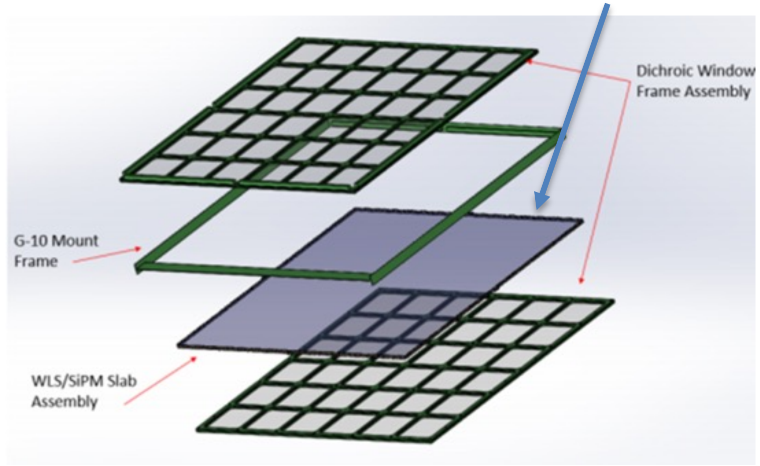
Large Area Photon Detection concept

- Based on the x-ARAPUCA technology, leveraged HD experience. New design (“tile”):
  - WLS plate 600 x 600 x 3.8mm3
  - Double sides
  - Active area 3380 cm^2
  - Estimated mass 5.5 kgSiPMs on flex circuits board (hybrid passive ganging) around perimeter glued or spring loaded to WLS plate
  - 160 SiPMs into 2-channels
  - (80 SiPMs/ch = 20 Passively Ganged x 4 Actively Ganged)
- R&D ongoing on dichroic mirror, WLS plate and optical coupling to SiPM in LAr:
  - improve overall quantum efficiency (reaching ~ 3%)

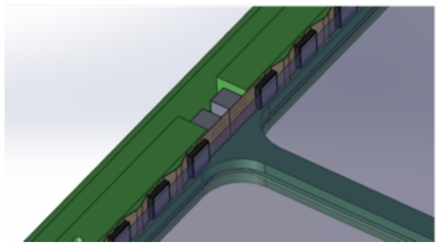


Not to scale.

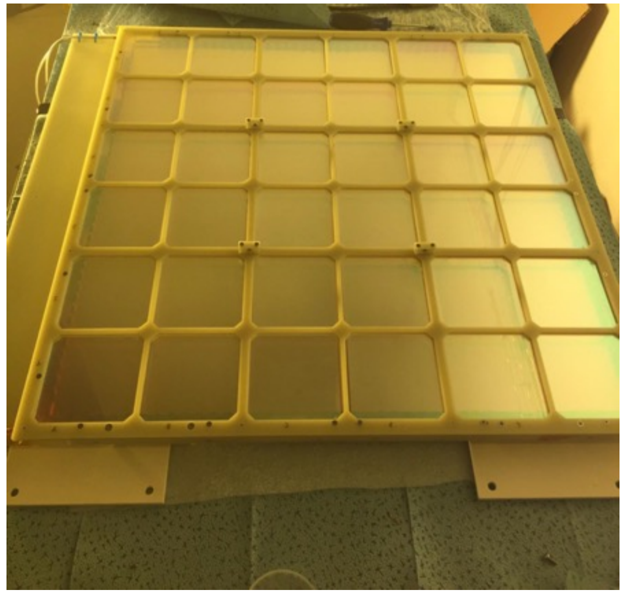
(new) HQE WLS plate (60x60 cm2)



(new) SiPM-WLS plate optical Contact

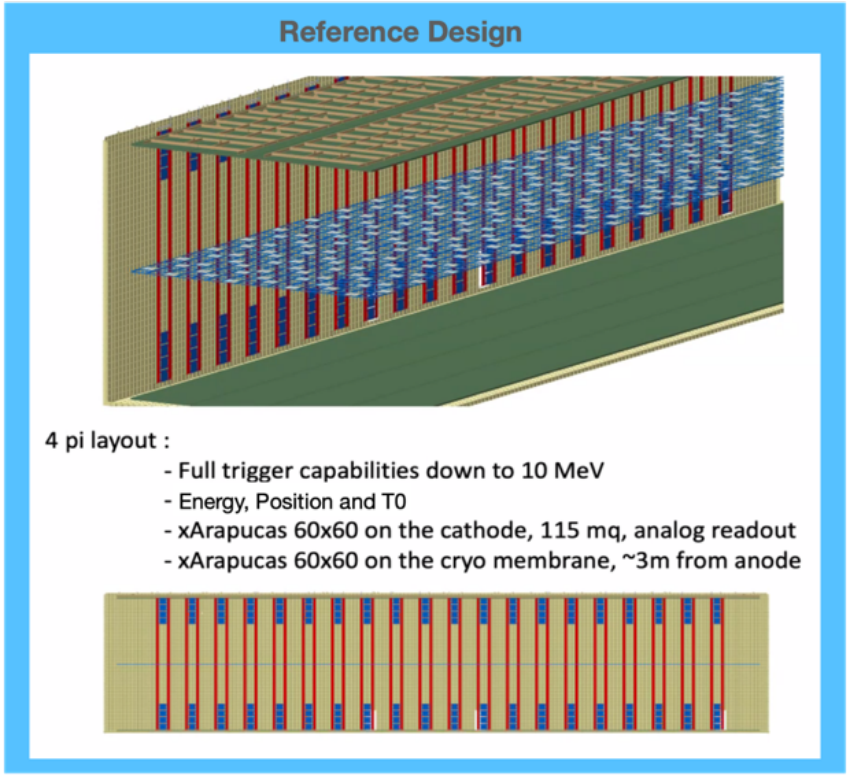


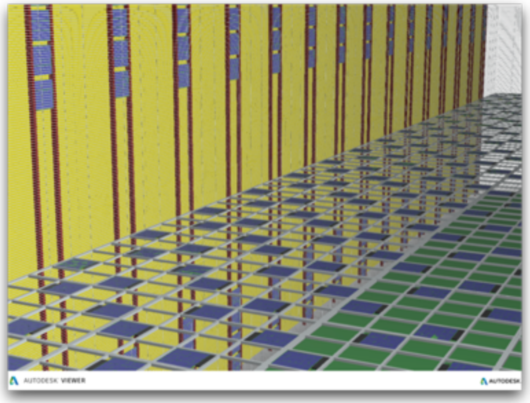
x-ARAPUCA tile prototype

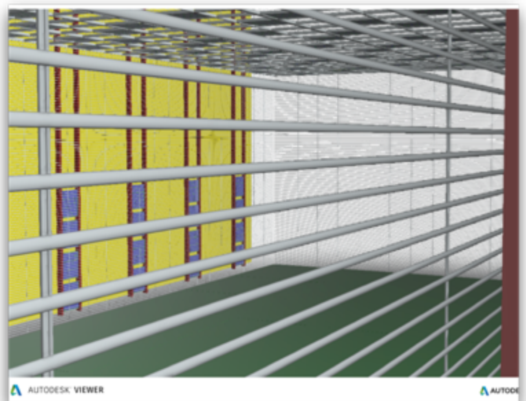


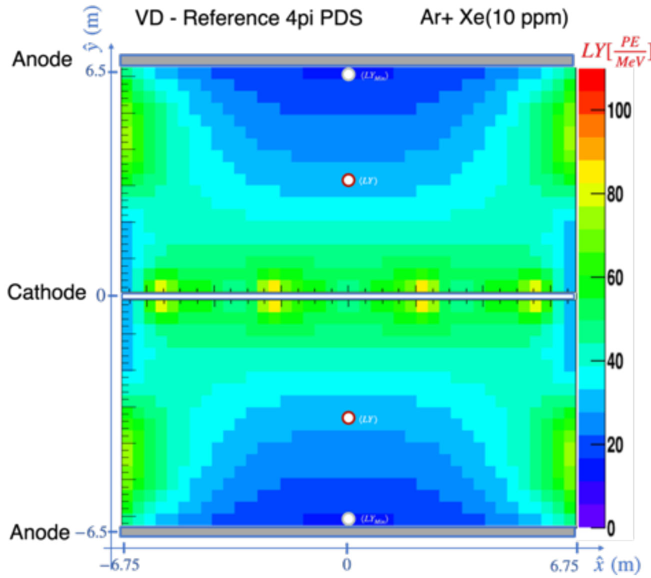
Light readout system

- PD Active Optical Coverage distributed onto 3 sides of the LAr Volume
  - Cathode side and the 2 Long Membrane Cryostat sides, 70% Transparency FC
  - Optional PD Passive Optical Coverage (reflector) on the Anode side
  - Xe doping (minimize Rayleigh scatter for light at far distance)
- *The Reference design endorses ~14% coverage:*
  - *good uniformity of response, very low detection & trigger threshold, energy resolution and position resolution capability*





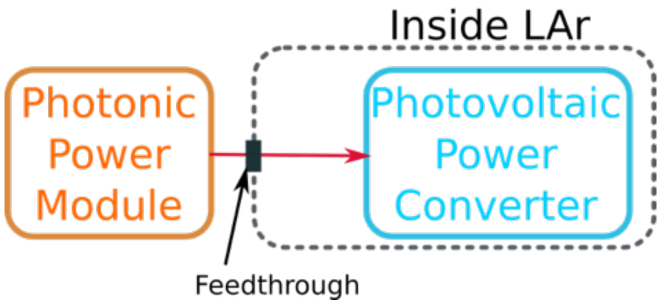




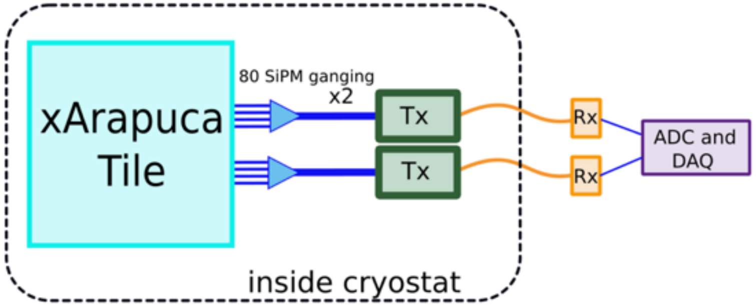
Operating PD’s on HV surface (cathode)

- Electrically floating ***Photo-sensors*** and ***r/o Electronics***
  - Power (IN) and Signal (OUT) transmitted via non-conductive cables (e.g. optical Fibers)
- PoF and SoF *(optolinks)* technologies commonly employed for voltage isolation between source/receiver and embedded electronics in high voltage or high noise environments.
  - None are rated to operate at LAr Temperature)
- Highly specialized R&D launched (mid Mar 21) to validate/customize COTS PoF and SoF technology for Cold applications or to thermally isolate from Cold environment and operate COTS technology in Warm
- Fall back solution also available with PD’s only on cryostat walls (double area): less uniformity
  - Still viable for time stamp and trigger

Power over Fiber



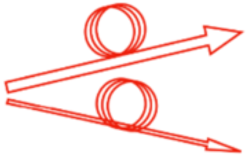
Signal over Fiber: cryogenic analog transmitter



Digitization in cold also under study: FPGA, digital transmitter and receive

R&D for Power Over Fiber in LAr/LN2

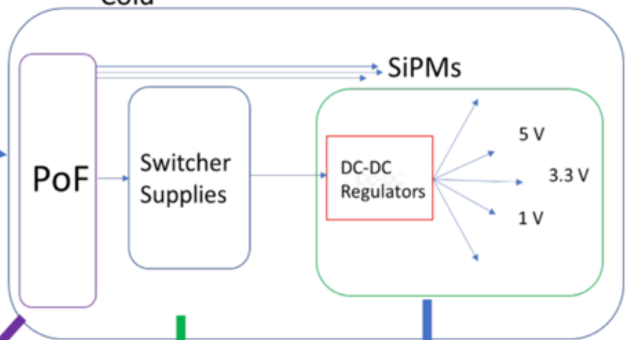
Lasers Transmitter+ Fiber



+ *Low Volt/High Current* Receiver (CE)

+ *High Volt/Low Current* Receiver (SiPMs)

Lasers – Deliver Power

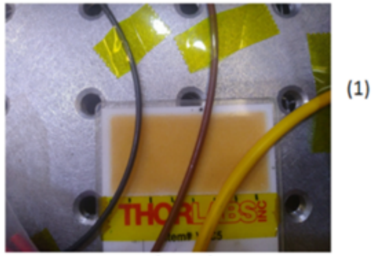


2 Systems:

SiPM: 48 Volts @ <1 ma

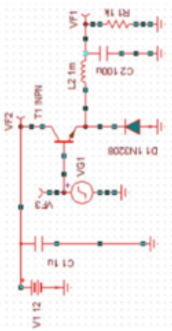
Electronics:
Communication Systems:
5, 3.3, 1 Volt @ Amps

(3) (2)

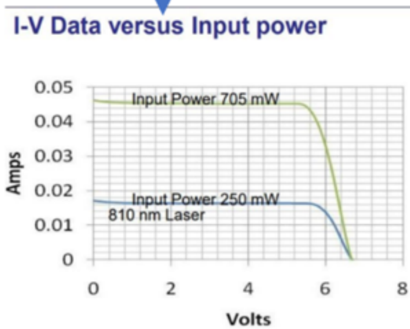


Fibers Testing

Light Receiver

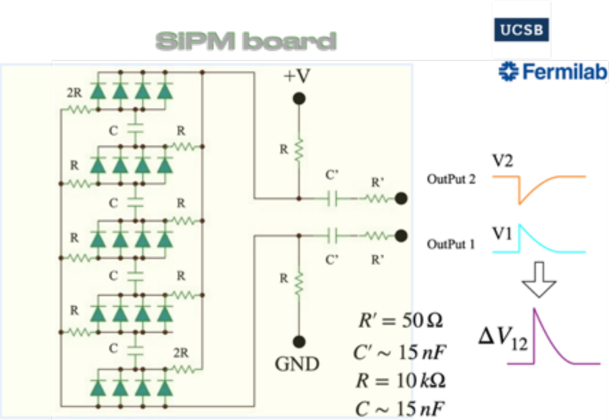


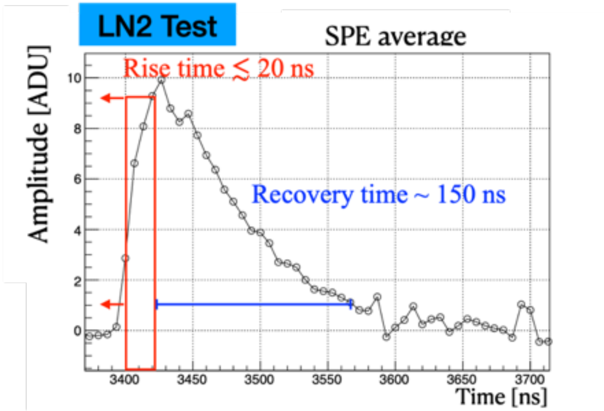
High Voltage/vLow Current Light Receiver



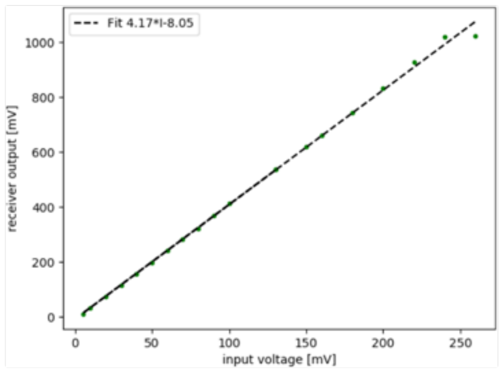
Low Voltage/High Current Light Receiver

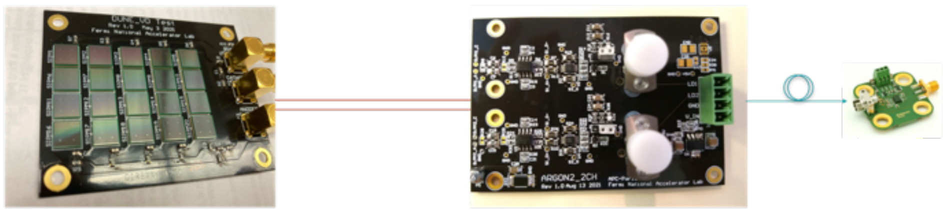
R&D for Signal Over Fiber in LAr/LN2

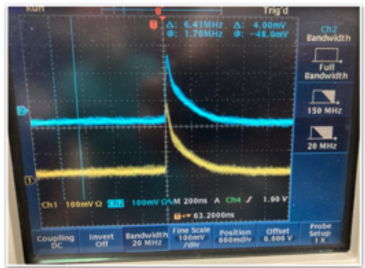


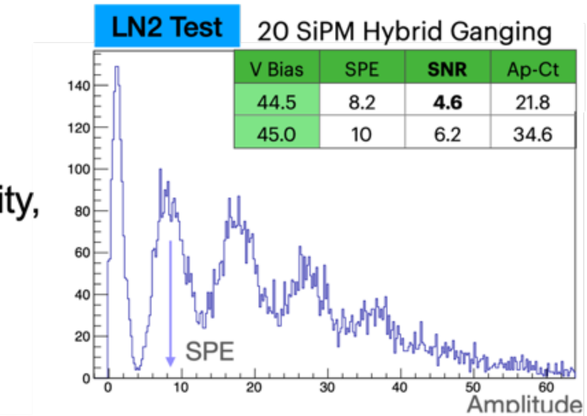


Short(er) SiPM Recovery Time from Hybrid Passive Ganging (Smaller Capacitance & Common Bias Voltage)

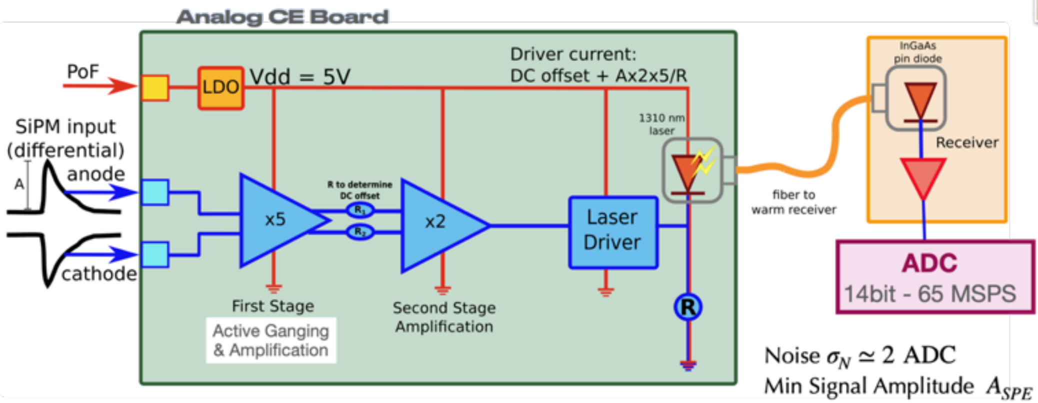








V Bias	SPE	SNR	Ap-Ct
44.5	8.2	**4.6**	21.8
45.0	10	6.2	34.6



- board+laser linearity, noise spectrum, small signal transmission

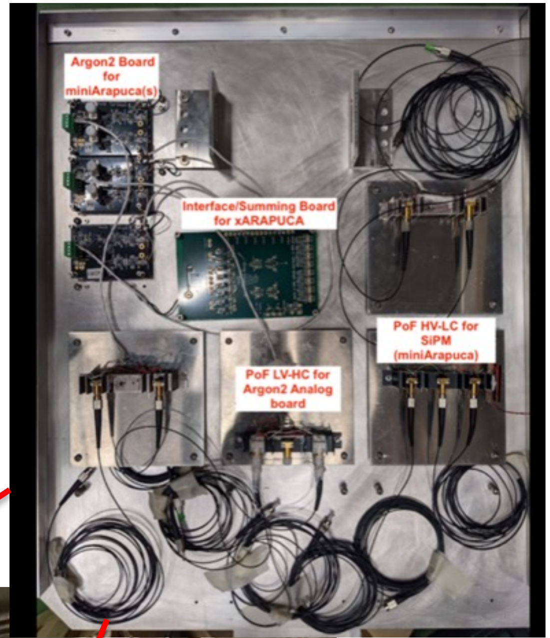
Noise $\sigma_N \simeq 2$ ADC
Min Signal Amplitude $A_{SPE} \simeq 10$ ADC (4 to 5 bits)
Max Signal Amplitude $A_{Max} \geq 1000$ PE (amplitude of 1000 PE piled up in one - *first 15 ns* - time bin, **below 14-bit ADC saturation)**

PD's at HV for coldbox test

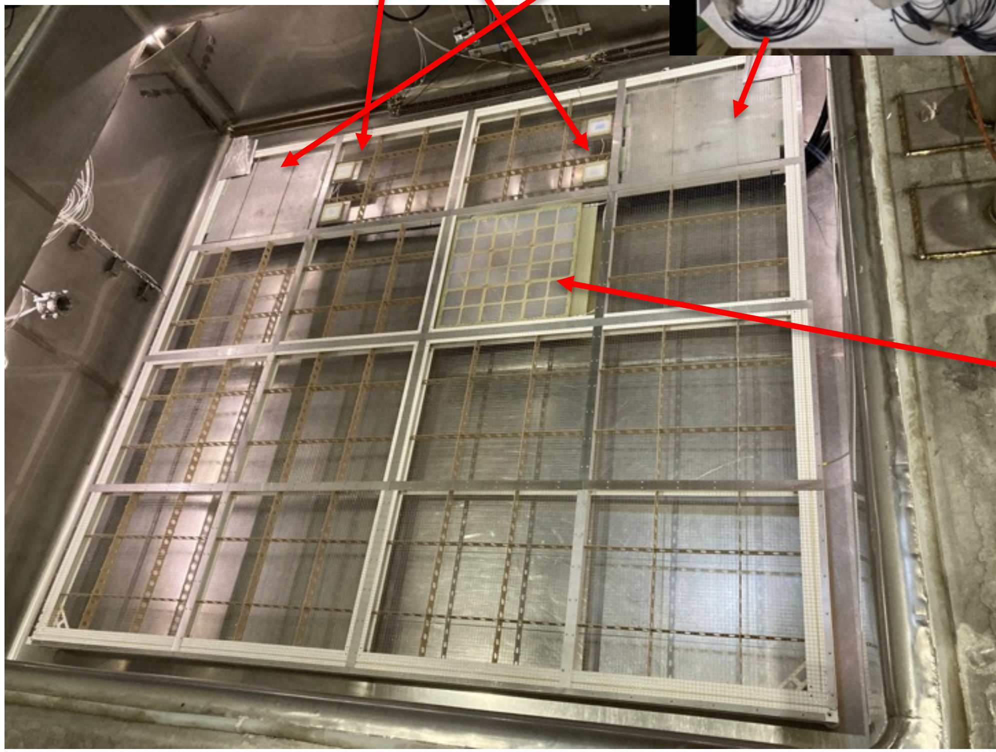
- Full chain of electrically isolated (optically connected through fibers) Photon Detector system installed in the Cathode Frame, inside the ColdBox
- Cathode: first prototype of VD concept

- First operational test in upcoming week
  - PoF & SoF readout reliability/stability at HV
  - Power dissipation
  - Possible interference with HV and/or CRP readout

PoF & SoF Electronics



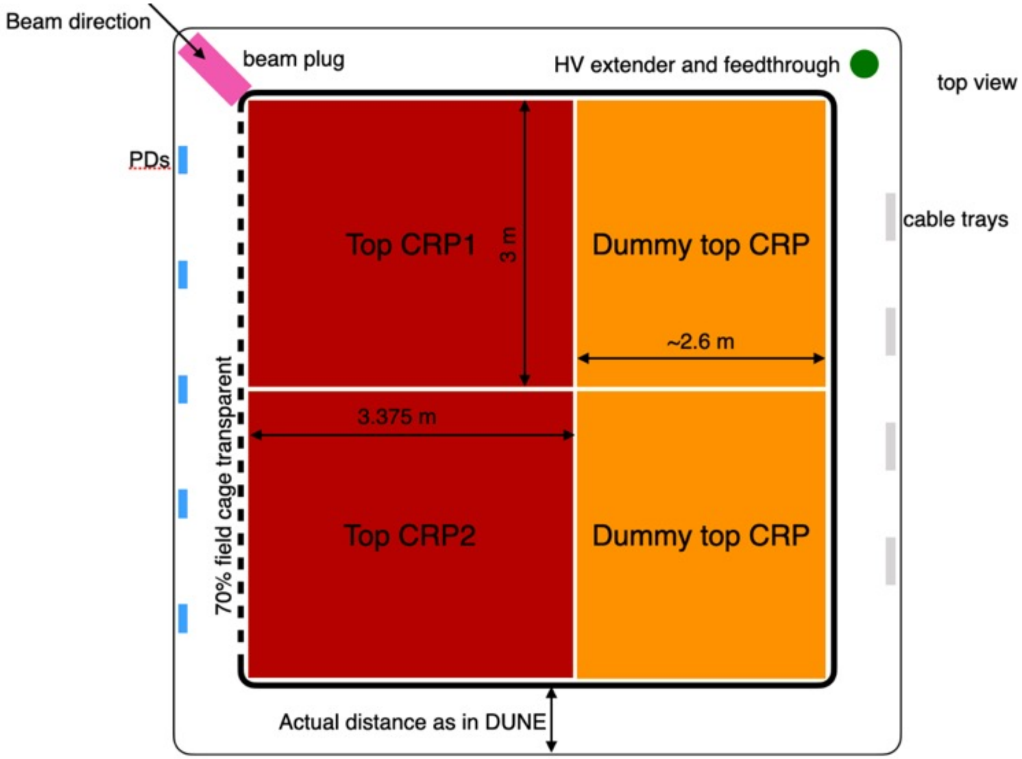
PD-miniArapuca's

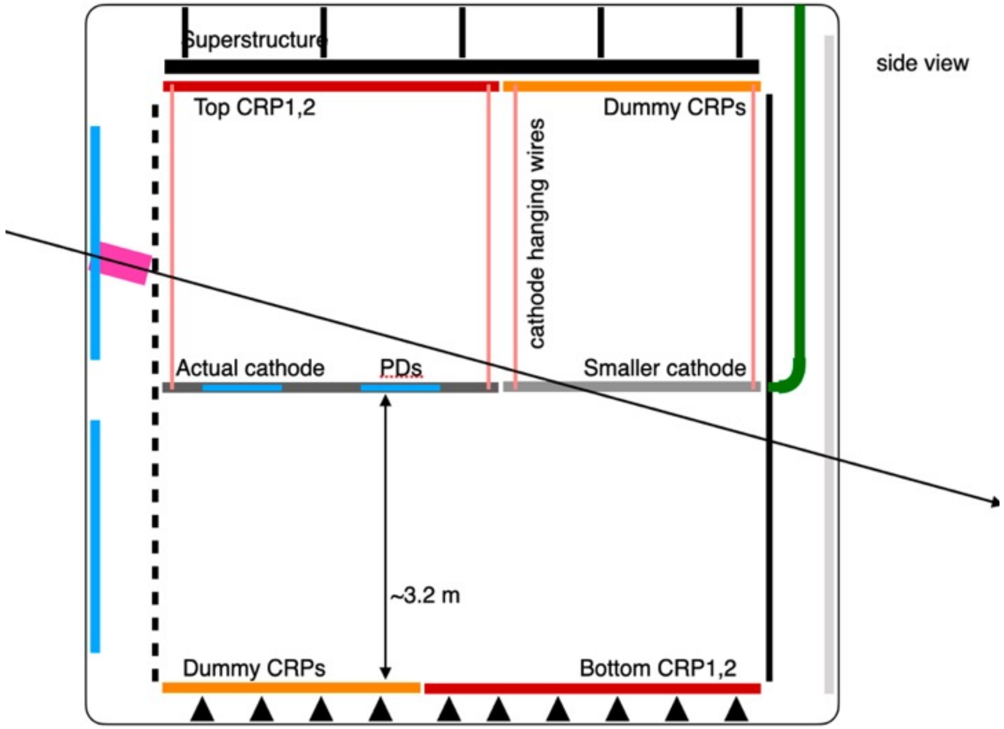


x-Arapuca

Vertical Drift Module-0

- Final validation of the integrated detector components (in 2023)
  - Two top and two bottom CRP's fully equipped with TDE and BDE
  - Suspended cathode at mid height: 3.2m drift (possibility to reach ~1kV/cm)
  - 70% transparent field cage
  - X-Arapucas on Cathode and on cryostat wall
- Detailed engineering of the module-0 layout is ongoing
- Beam exposure for both drift volume possible





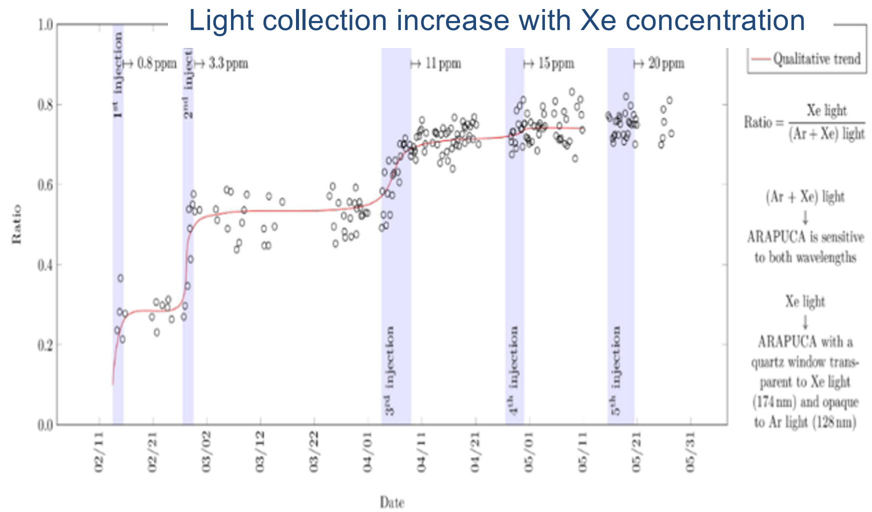
Summary and outlook

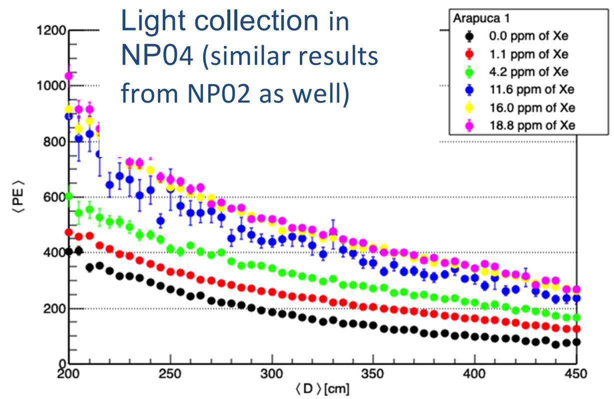
- The Vertical Drift LAr-TPC design relies on experience gained with NP04 and lessons learned from NP02 (DP) with the goal of:
  - maximizing the active volume
  - optimizing the construction/installation costs and schedule
  - maintaining reliability and detector performance wrt to the HD design
- An intense R&D effort is ongoing within the DUNE collaboration to validate the main detector components:
  - *the read-out planes, the High Voltage, the Photon Detection system*
  - exploiting same cryostat design, cryogenic/purification system, FE electronics and DAQ already well established for the HD and the former DP design
- Encouraging results with 1:1 scale component prototypes are being obtained at the CERN ν-platform, opening the way to:
  - finalize the DUNE FD2 design
  - validate it in the NP02 cryostat (Module-0) in 2022/23
  - plan the construction and the assembly of FD2 for operation at SURF in 2029
- A Conceptual Design Report has been written and is now under review.

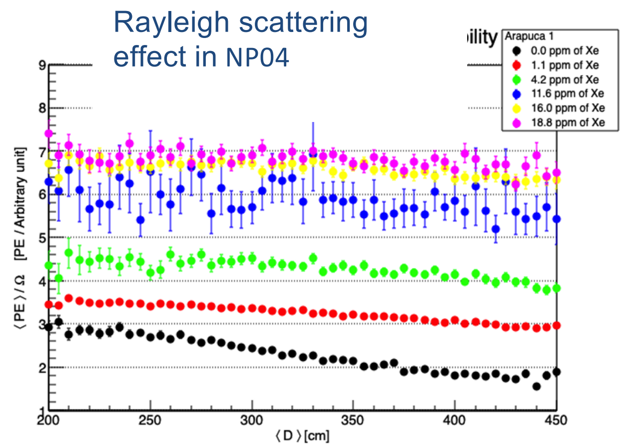
Additional slides

Xenon doping for long distance light collection

- Xe-injection Successfully demonstrated in ProtoDUNE-SP/DP
  - Up to ~20 ppm in mass, injected into the cryostat
  - Effective ArAr* to XeXe* dimers energy transfer resulting in xenon scintillation at 175 nm for the full Ar slow component (3/4 of the total light) already at tens of ppm of Xe concentration
  - The effects of N_2 contamination recovered with a small amount of Xe
  - ~ 2 times increase in the total collected light observed
- Benefits of Xe-doping
  - Mitigation of nitrogen contamination risk
  - Increase in scattering length: 6m instead of 0.9m (effective improvement in uniformity)
  - Increase in average detection efficiency across detector volume
  - Reflectivity to Xenon light of metallic surfaces helps improving light collection uniformity
- Simplify the use of PDS in longer drift TPC
  - Higher detector efficiency at 175 nm: possibly no need of wave shifter on PD, further increasing collected light (~x2)



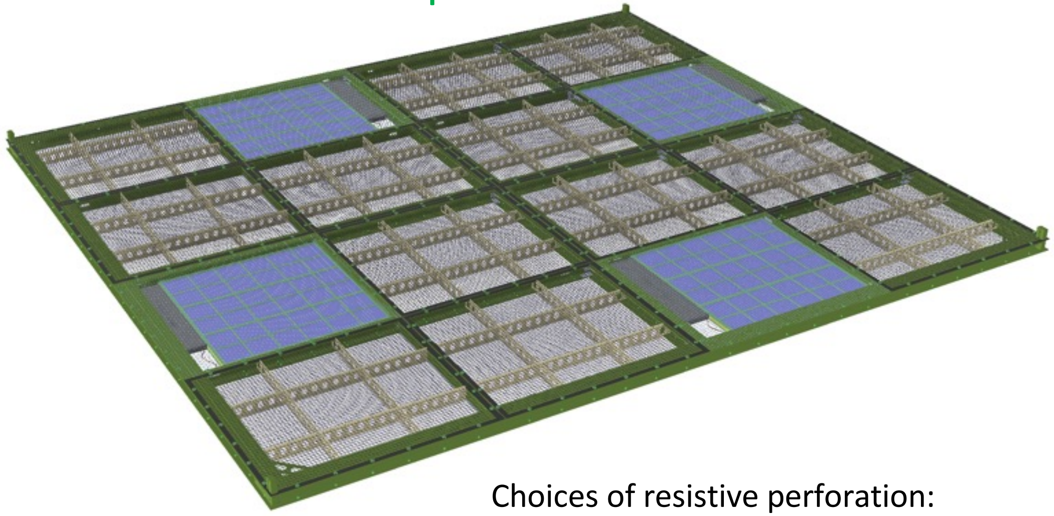




Cathode Plane

The electrical characteristics of this cathode is very similar to that of the FD1 cathode planes.

- 80 modules of 3m x 3.4m x 0.05m FRP I-beam frame with 16 openings.
- Suspended from the corners to the super CRP structure using insulating vertical ropes (Dyneema/Kevlar).
- Double sided X-Arapuca PD modules installed in 4 of the openings (PDS scope encased by highly transparent (~80%) metal wire mesh panels on both sides.
- 12 pairs of perforated resistive panels (10^6 Ohm/square) mounted on the top and bottom faces of the frame.
- Cathode resistive surfaces allows slow discharge time constant to reduce harmful charge injection to the FEE connected to the anodes in case of HV discarges
- The porosity of the resistive panels allows Liquid Argon convection



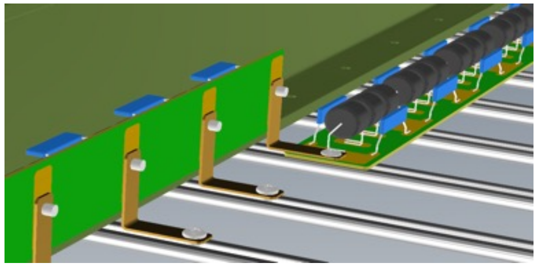
Choices of resistive perforation:

- Resistive Kapton laminated FR4 sheet (FD1 CPA)
- Resistive bulk conducting FR4 sheet

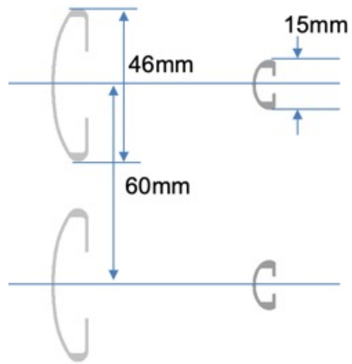
- Total weight. Less that 100 kg including PD's
- Planarity better than a few cm in LAr
- First prototype with integrated PD's under test in the NP02 cold box
- Elongation/creeping of ropes in Lar under study

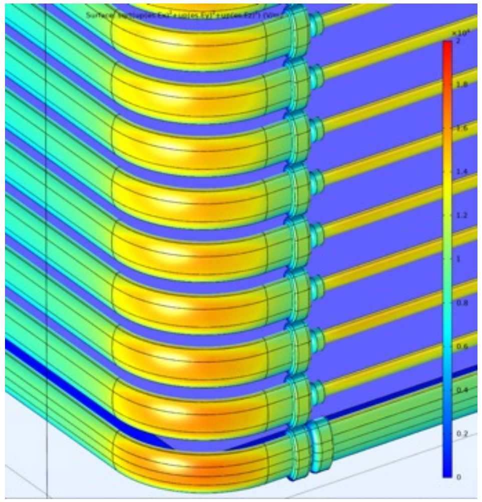
Field cage

- Thick profile shape and spacing proven in NP04/NP02: nominal DV = 2.7 kV.
- Thin shape (70% transparency) required only in front of X-Arapucas on cryostat wall.
  - Drift field uniformity not much affected, but higher field gradient toward cryostat.
  - within 30 kV/cm (safe field against HV instabilities) corners where thick profiles are mandatory
- Resistive divider board similar to NP04

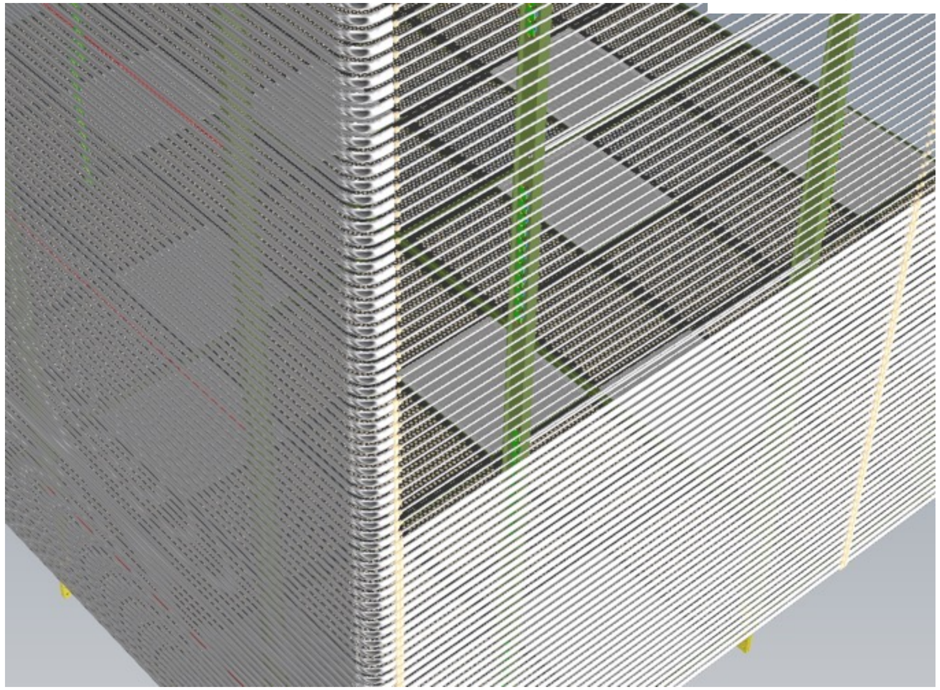


- Under test:
  - Mixed shapes FC window introduced in the NP02 coupled to NP04-Arapucas on the walls
  - Full implementation foreseen in NP02 Module-0





Cathode plane

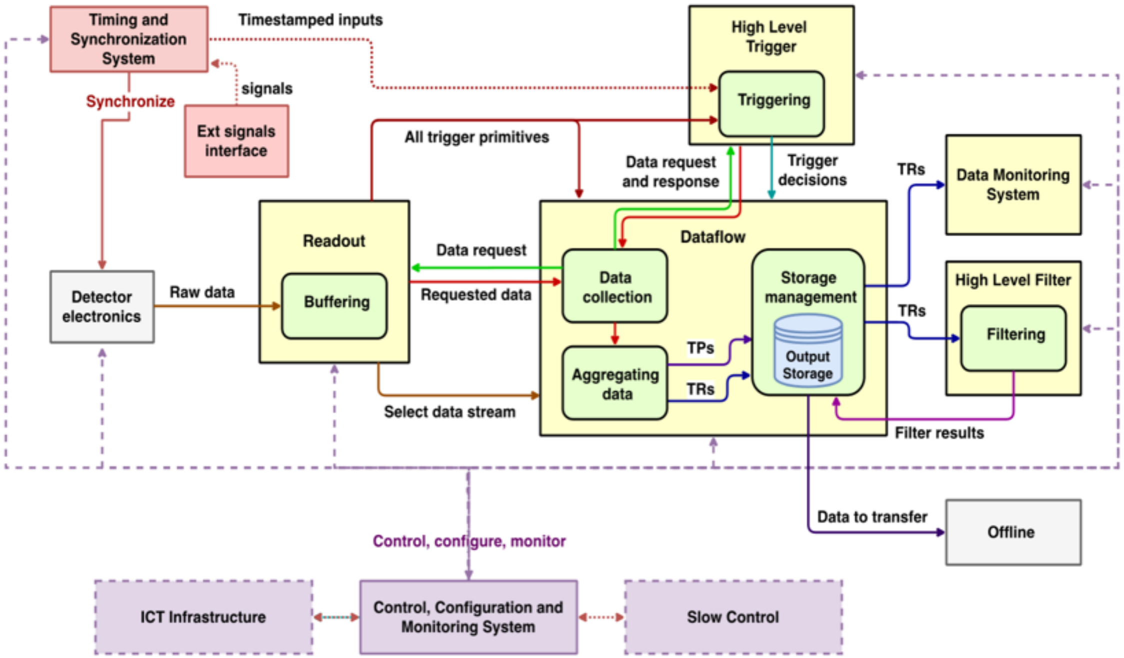


Thick FC profiles along the end walls, wrapping around corners, and cover the long walls within 2.5m of the cathode plane.

70% transparent portions of the field cage are along the long walls of the cryostat, and cover the areas 2.5m from the cathode and beyond.

DAQ and trigger

- DUNE DAQ consortium already tuned to a SP and DP readout
- Work on interfacing with SP electronics (CE + PD) is presently well advanced, in preparation for the 1st detector module. Work reused for the VD together with expertise from the DP community to develop the interfaces to the VD top electronics



- The number of TPC channels, i.e. the data volume, for the DAQ for the VD is very similar to the SP detector (~400k TPC channels) -> ~1.5 TB/s (+ ~50 GB/s PDS)
- The VD has a longer drift, thus the event size is larger for those events for which the whole drift (4.25 ms) is taken. The same (HD) approach to data reduction is foreseen