The DUNE IN2P3 project and the evolution from the dual-phase to Vertical Drift

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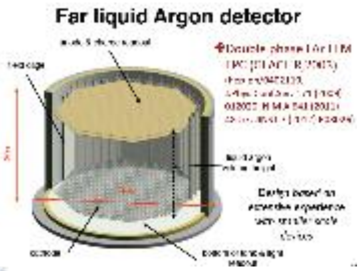
IP2I Lyon

DUNE TGIR kick-off meeting

25/5/2021

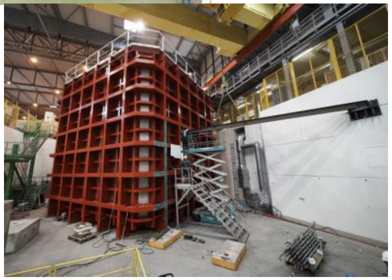
A little bit of history:



- LAr **R&D started at IN2P3 in 2006 for the charge readout electronics**, also supported by the LABEX LIO since 2012
- IN2P3 groups contributed to the **LAGUNA-LBNO program (2008-2014) and R&D** where the **dual-phase detector** technology was developed

- **IN2P3 project for the dual-phase R&D program at CERN** launched **at CS IN2P3 of June 2013 for LBNO-Demo**, then becoming **NP02/protoDUNE dual-phase in 2015**
- IN2P3 groups contributed in **2014** to the **fusion of the EU and US efforts** and to the birth of DUNE (**IIEB, LBNF/ELBNF EOI**)

- Since **2015 → DUNE/protoDUNE IN2P3 project**
- **2016-2017: construction and operation of the 3x1x1** detector. Provided: Charge Readout Electronics, suspension system of Charge Readout Plane
- **2017-2019: construction of NP02/protoDUNE dual-phase**. Provided: Charge Readout Electronics, Charge Readout Planes mechanics, DAQ system



- 2017 start of discussions for **DUNE IR project**, **2018 DUNE in TGIR roadmap**
- **2018 IN2P3 CS, start of discussions for TGIR project**, based on DP module: submitted summer 2019, on the way of approval in fall 2020
- **August 2019-September 2020: operation of protoDUNE dual-phase**
- **October 2020- December 2020: definition of Vertical Drift FD module #2**
- **January 2020-… preparation activities for Vertical Drift FD module #2**

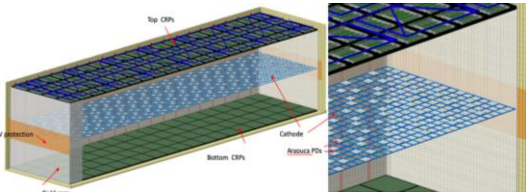
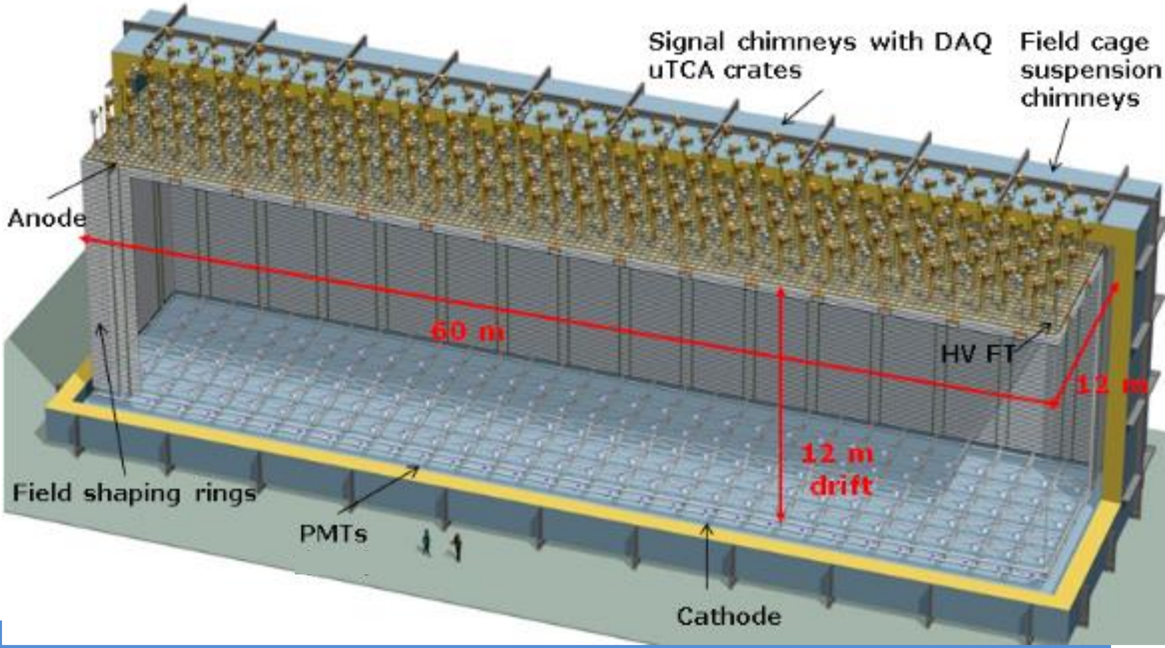


Table 1.2: Quantities of items or parameters for the 12.096 kt DP module

Item	Number or Parameter
Anode plane size	W = 12 m, L = 60 m
CRP unit size	W = 3 m, L = 3 m
CRP units	$4 \times 20 = 80$
LEM-anode sandwiches per CRP unit	36
LEM-anode sandwiches (total)	2880
SFT chimney per CRP unit	3
SFT chimney (total)	240
Charge readout channels / SFT chimney	640
Charge readout channels (total)	153,600
Suspension feedthrough per CRP unit	3
Suspension feedthroughs (total)	240
Slow Control feedthrough per sub-anode	1
Slow Control feedthroughs (total)	80
HV feedthrough	1
HV for vertical drift	600 kV
Voltage degrader resistive chains	4
Cathode modules	80
Field cage rings	197
Field cage modules	288
PMTs (total)	720 (1/m^2)

Dual-Phase DUNE FD: 20 times replication of Dual-Phase ProtoDUNE (drift 6m → 12m)   DUNE Conceptual Design Report, July 2015

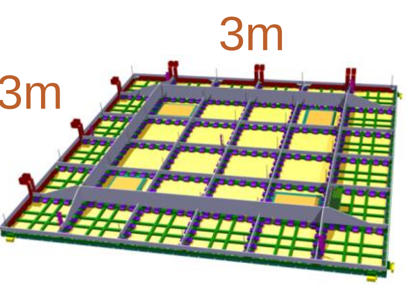
Active LAr mass:12.096 kton, fid mass:10.643 kton, N. of channels: 153600



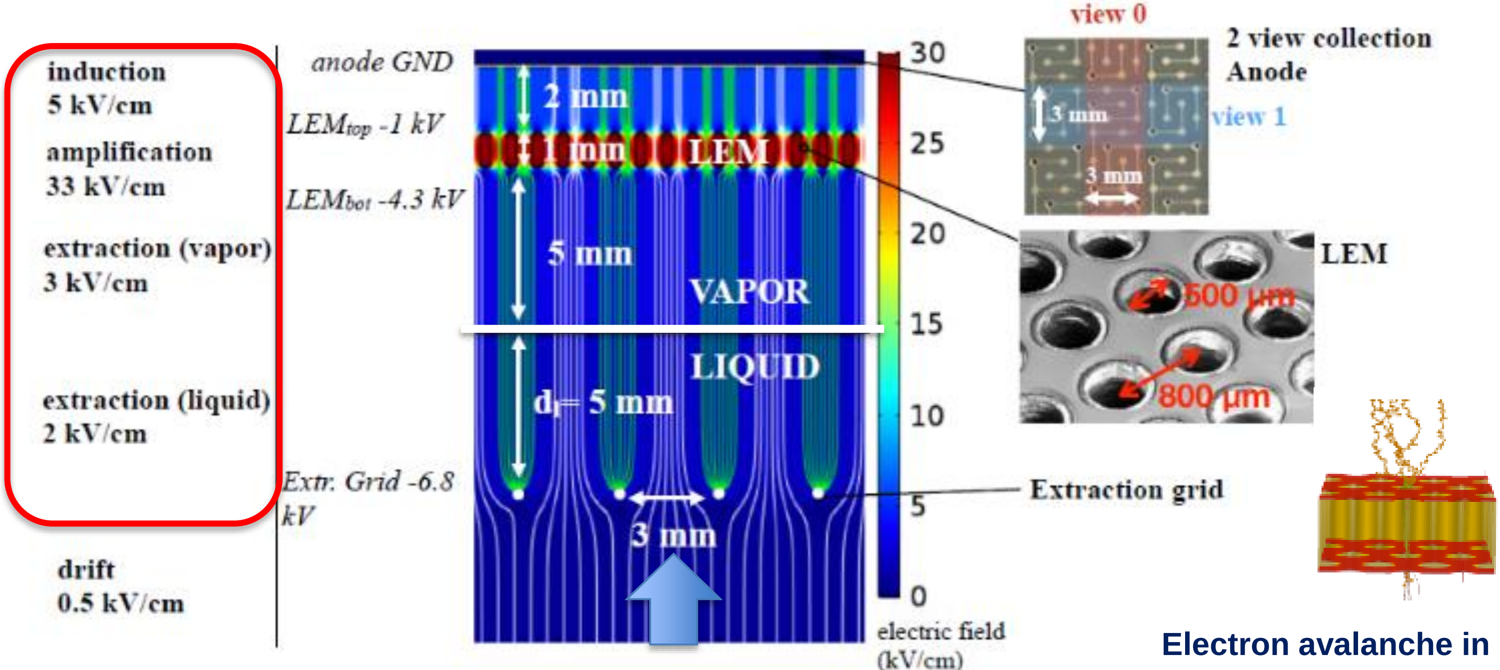
Advantages of dual-phase design:

- Gain in the gas phase → compensation for charge attenuation due to long drift paths, required gain 6 for 12 m drift (TDR requirement of gain 6 computed for 12m drift, 250V/cm drift field 300kV, and 5ms electrons lifetime)
- Simplified dual-phase detector design with vertical geometry→ cheaper production and installation costs, simpler and faster installation than single phase design
- Full accessibility to electronics and possibility of replacing also cryogenic front-end (FE) electronics during detector operation

Dual-Phase Charge Readout



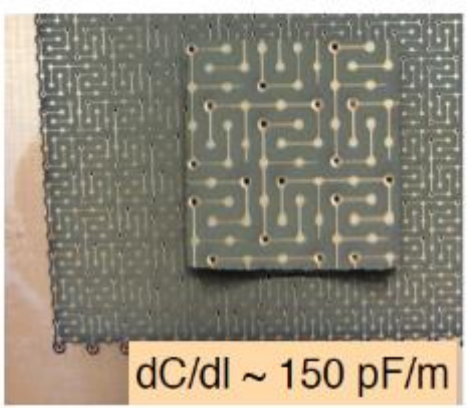
Charge Readout Plane integrating LEM-anode sandwiches

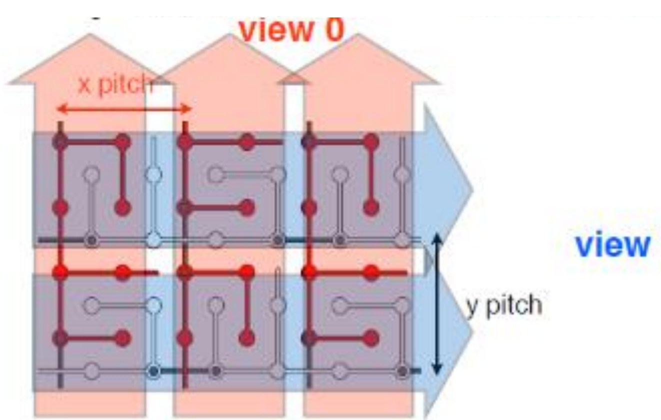


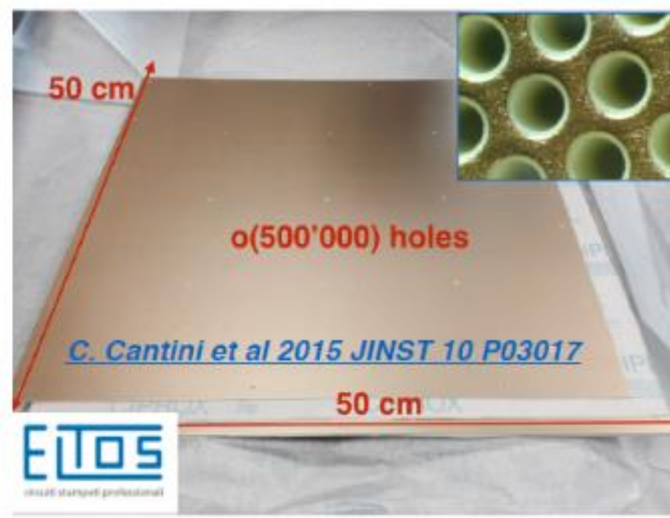
Electron avalanche in LEM hole

50x50 cm² LEM

50x50 cm² anodes with 2 collection views





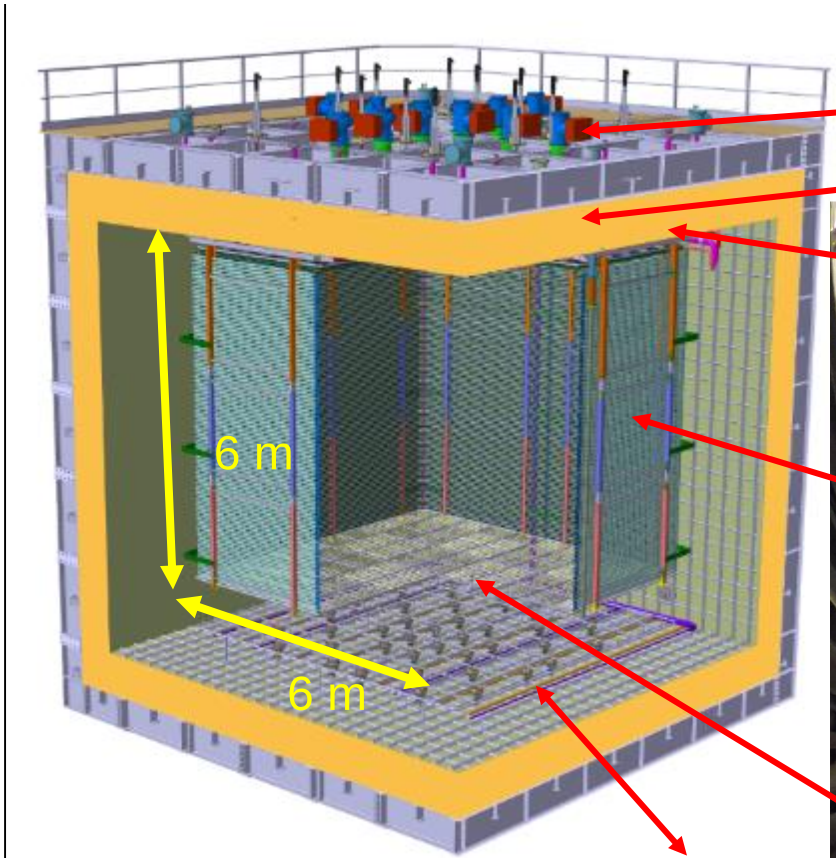


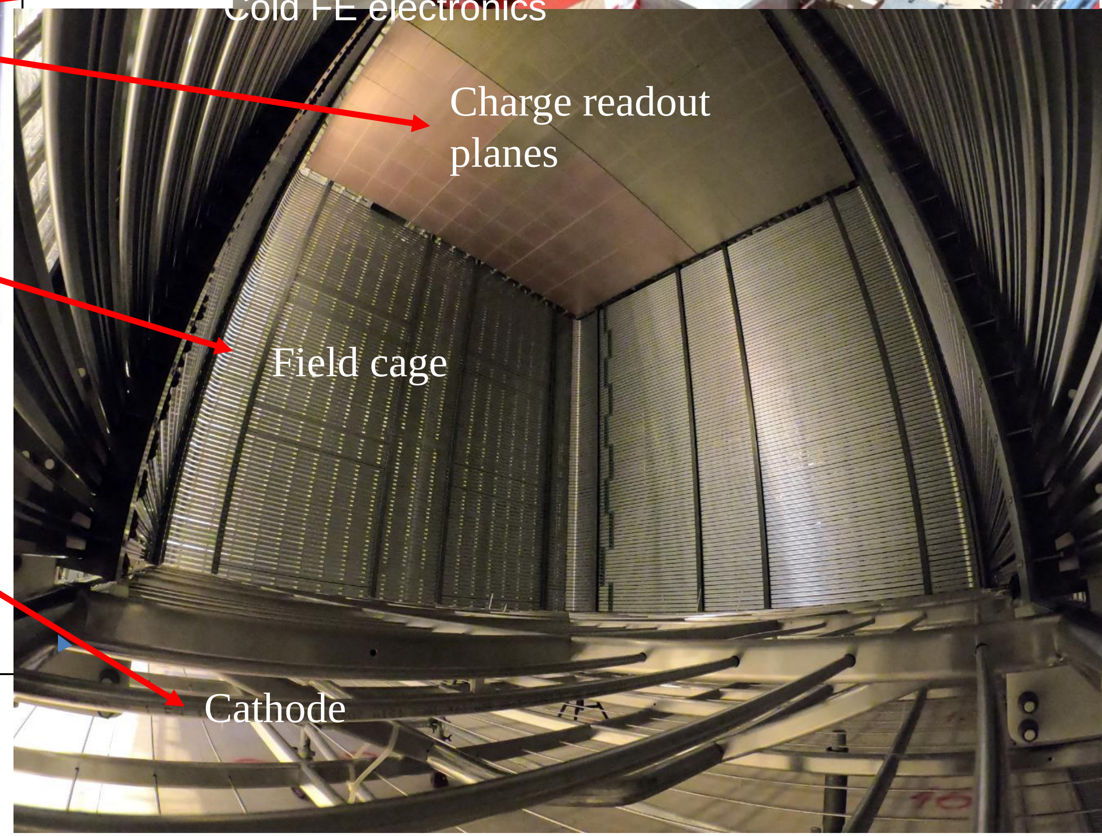
NP02/protoDUNE dual-phase

dual-phase FD design based on NP02:

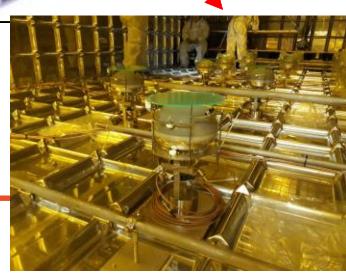
- 1/20 of active area of DP 10 kton
- NP02/protoDUNE DP 4 CRPs → DUNE 80 CRPs

Construction 2018-19 Operation 2019-20



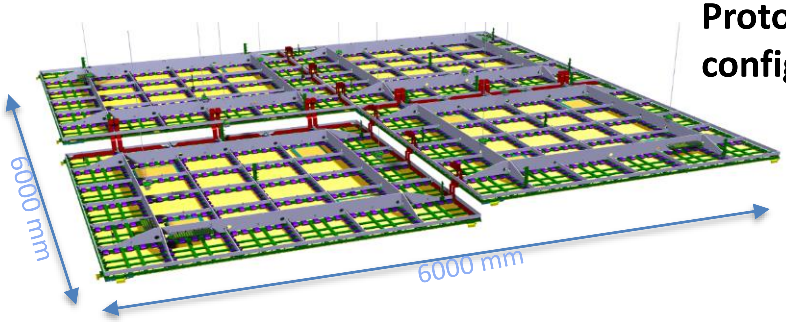


36 cryogenic photomultipliers
Hamamatsu R5912-02mod
with TPB coating

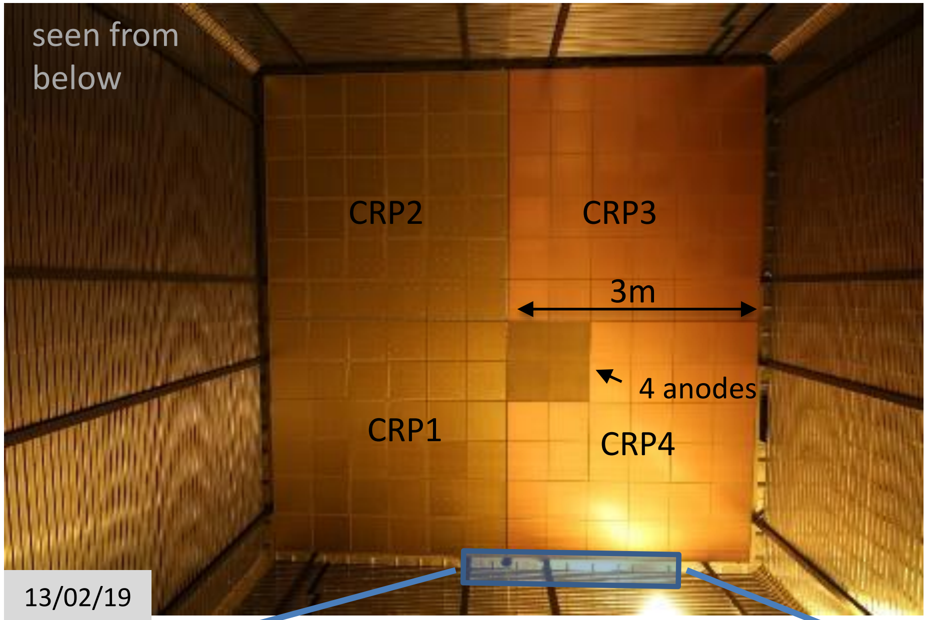


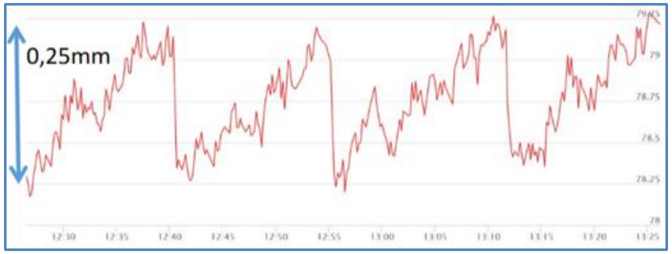
Charge Readout Planes
(LEMs CEA contribution)

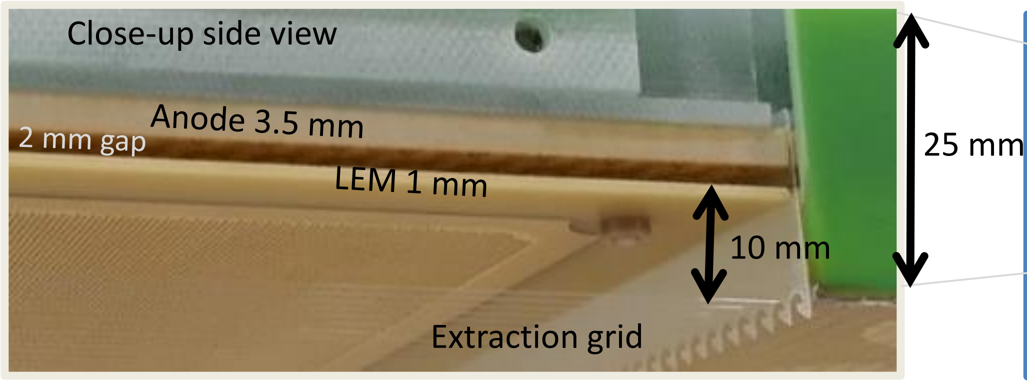
ProtoDUNE-DP configuration



4 CRPs







ProtoDUNE-DP accessible cryogenic front-end electronics and uTCA FE system

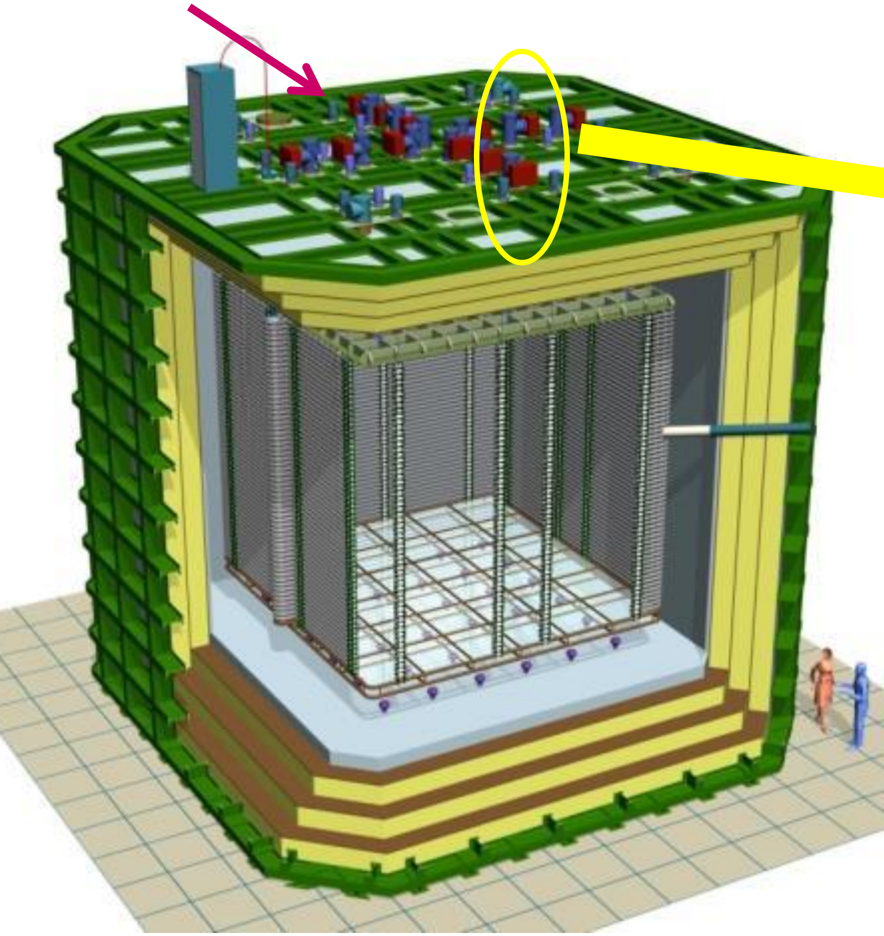
Full accessibility provided by the dual-phase charge readout at the top of the detector

➢ **Digital electronics <u>at warm</u> on the tank roof:**
- Architecture based on uTCA standard
- 1 crate/signal chimney, 640 channels/crate

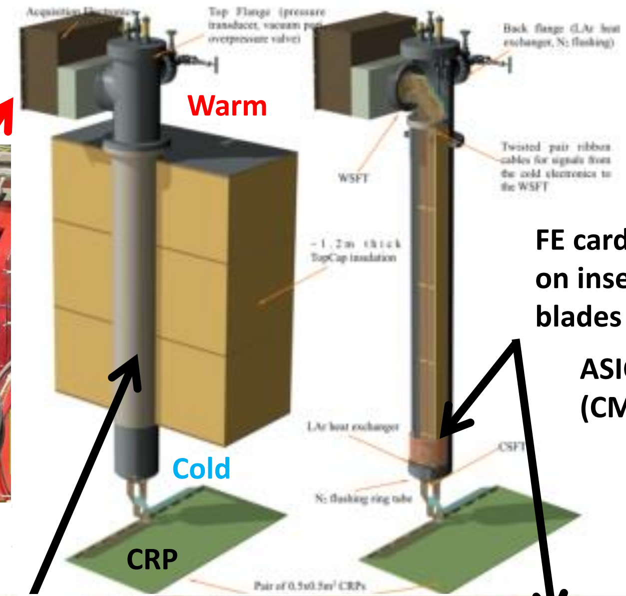
→ 12 uTCA crates, 10 AMC cards/crate, 64 ch/card

➢ **Cryogenic ASIC amplifiers (CMOS 0.35um) 16 ch <u>externally accessible:</u>**
- Operating at 110K at the bottom of the signal chimneys
- Cards fixed to a plug accessible from outside

→Short cables capacitance, low noise at low T

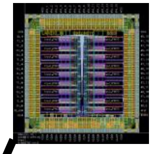


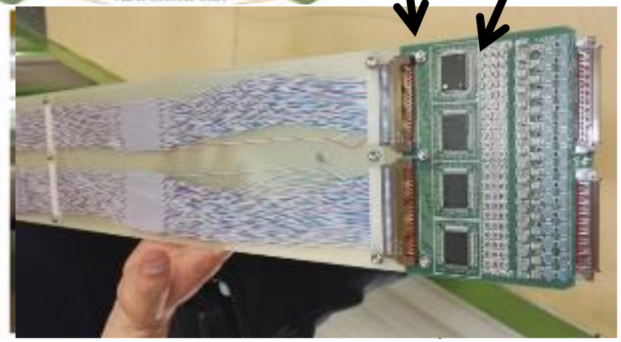
<50 cm



FE cards mounted on insertion blades

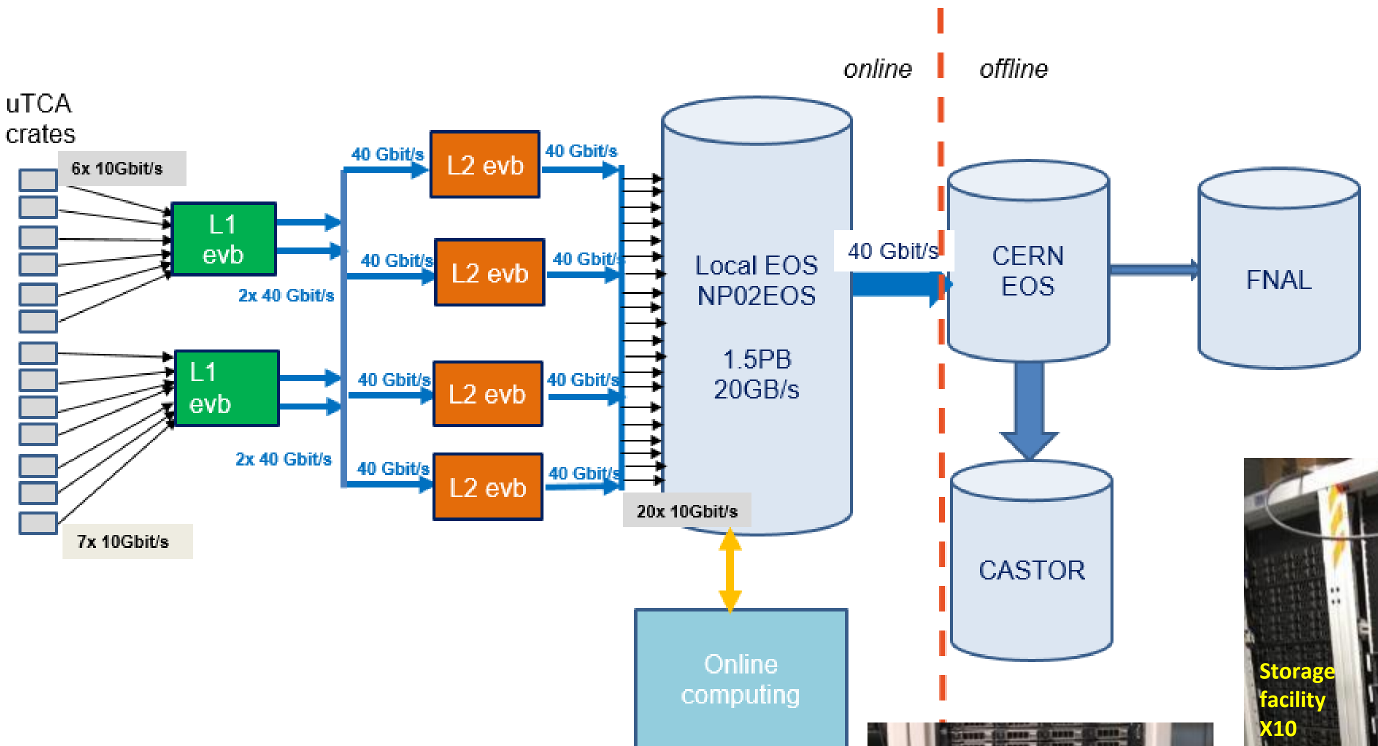
ASICs 16 ch. (CMOS 0.35 um)

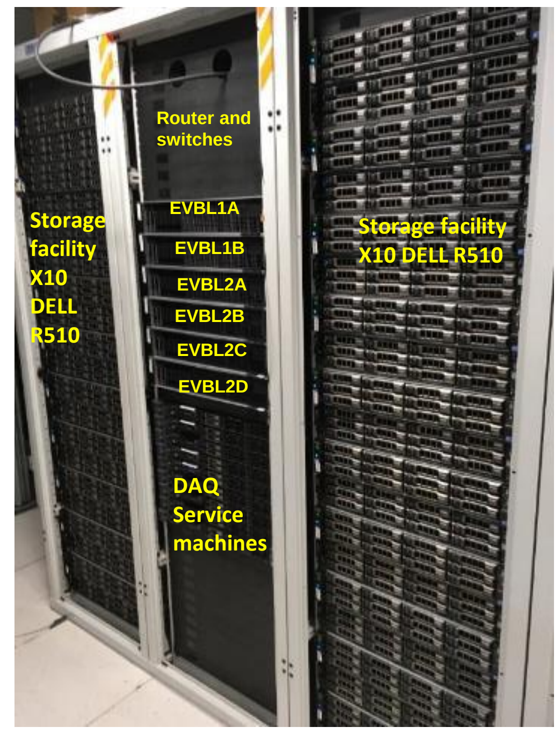




Signal chimney

NP02 DAQ/network infrastructure, 20 GB/s bandwidth

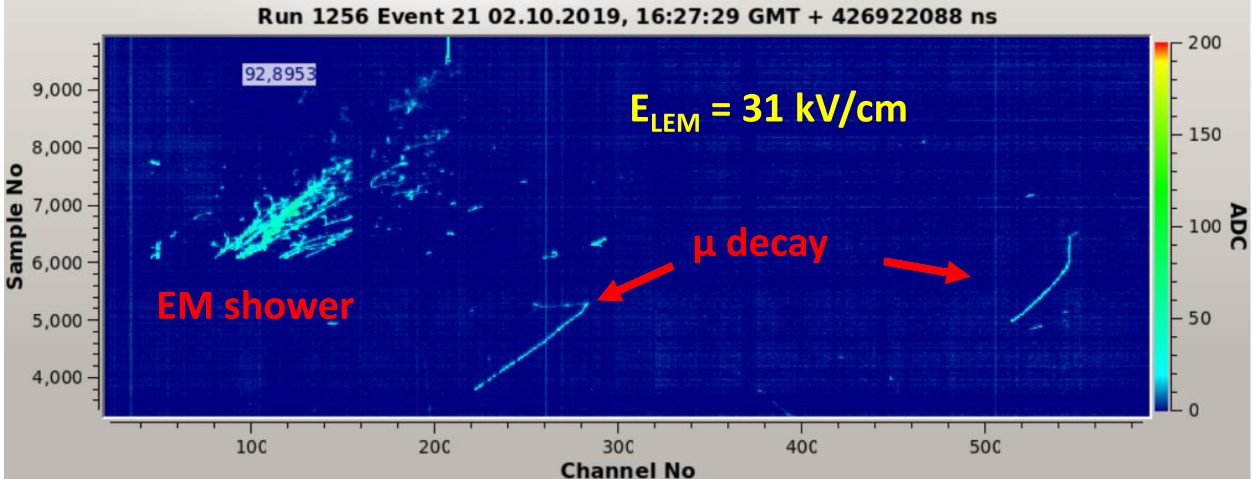




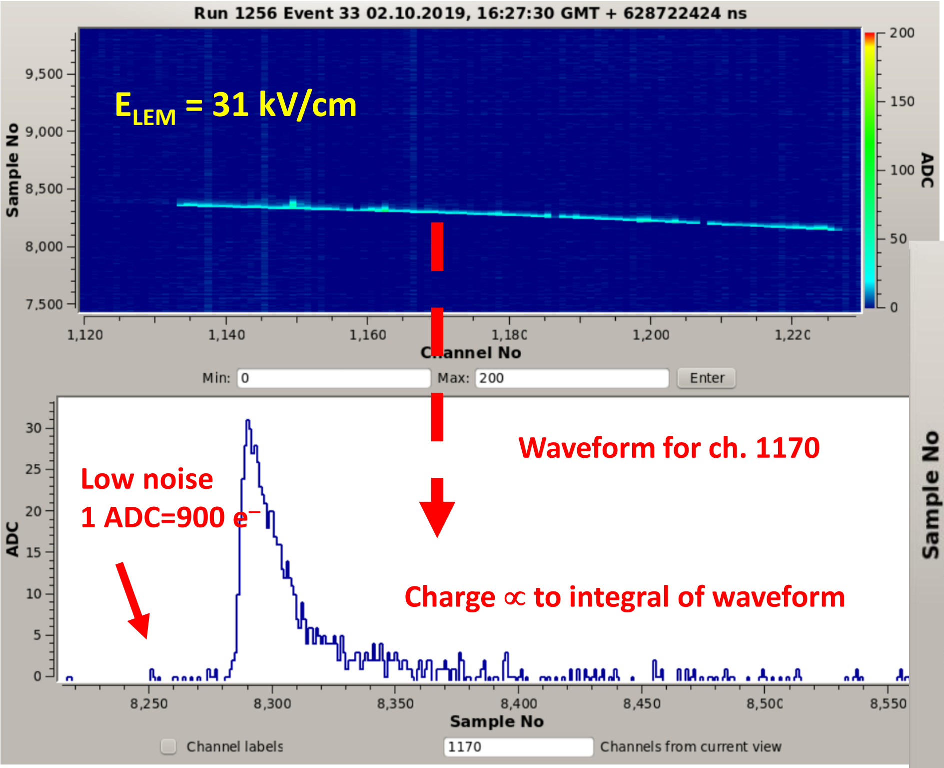
Online storage servers for distributed EOS system (1.5 PB) and online computing nodes (450 cores) provided by CCIN2P3

Cosmic ray events in protoDUNE dual-phase

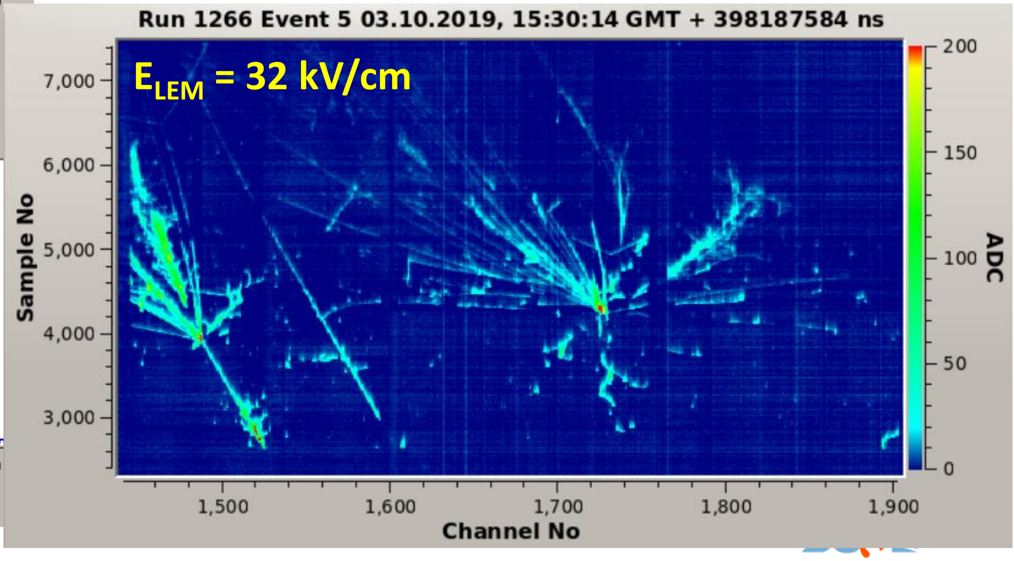
Electromagnetic shower + two muon decays



Horizontal muon track



*Multiple **hadronic interactions in a shower***



Experience from protoDUNE-DP 6x6x6 m^3 phase-I

- **NP02 6x6x6 m^3 construction 2018-2019**
- **All 4 CRPs tested in cold-box tests program in Summer 2018**
- **Start of detector operation in August 2019 → HV extender issue**
- **LEM and CRPs stability studies August 2019-April 2020**
- **HV surgery intervention (preparation + execution+ refilling) May-July 2020**
- **Continuation of the operation after HV surgery in August 2020**
- **Completion of dual-phase NP02 Phase-I operation period September 2020**
- **Cryostat inspection in February 2021**

Main features of what learned from operation period :

- Gain ~6 obtainable but LEMs performance tending to degrade over long time periods related to sparking

→ LEM design improvement program ongoing since spring 2020 at CEA,

→ Workshop with micro-pattern detectors community 6-7 April 2020: https://indico.fnal.gov/event/23774/

- Observed CRPs grid sparking instabilities
- Environmental cryostat aspects affect CRP stability: movements of LAr surface due to bubbling, presence of dust/debris
- Experience on HV system in protoDUNE-DP, short in August 2019 + result of surgery, R&D for 600 kV

→Foreseen LEMs and CRPs improvement program for Phase II running of protoDUNE-DP/NP02 (2020-22)
→Possible improvement of some environmental conditions from what learned from operation
→HV design improvements clear for 300 kV but parallel HV R&D launched for 600 kV to be completed

- **Very good LAr purity levels achieved (target 3-5 ms electrons lifetime → achieved >30 ms)**

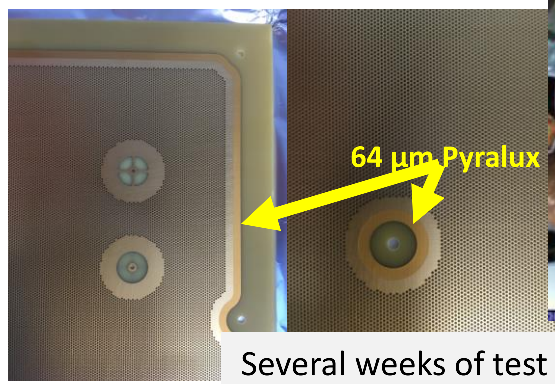
makes LEMs gain much less required to compensate for signal attenuation during drift

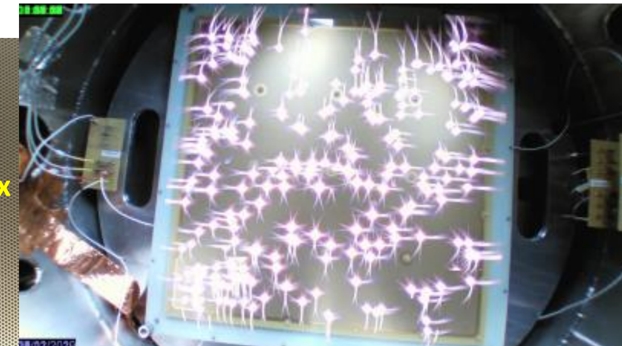
ProtoDUNE-DP R&D activities: (SPSC April 2020)

Goals: (1) Improve LEM stability over time in terms of HV, spark rate and increase the active area >95%
(2) Improve CRP planarity and robustness with respect to any liquid argon surface instabilities
(3) Eliminate all risks linked to grid sparking onto the charge readout electronics

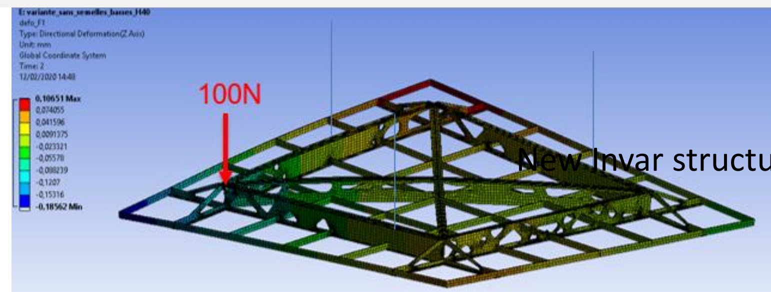
LEM and anode improvement plan is in progress at CEA/Saclay:

- Improving LEM design with high quality rims using a micro etching technique developed by CERN
- Adding an insulating material in the dead regions of LEM using 64 um thick Pyralux coverlay (successful tests at Saclay) very effective to eliminate sparks in those regions
- For the anodes: new design to incorporate a guard ring on both faces of PCB





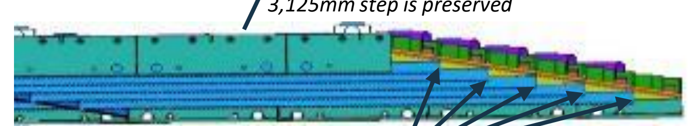
Several weeks of test at 3.4 kV, no spark on the insulated area



For the CRP structure and extraction grid:

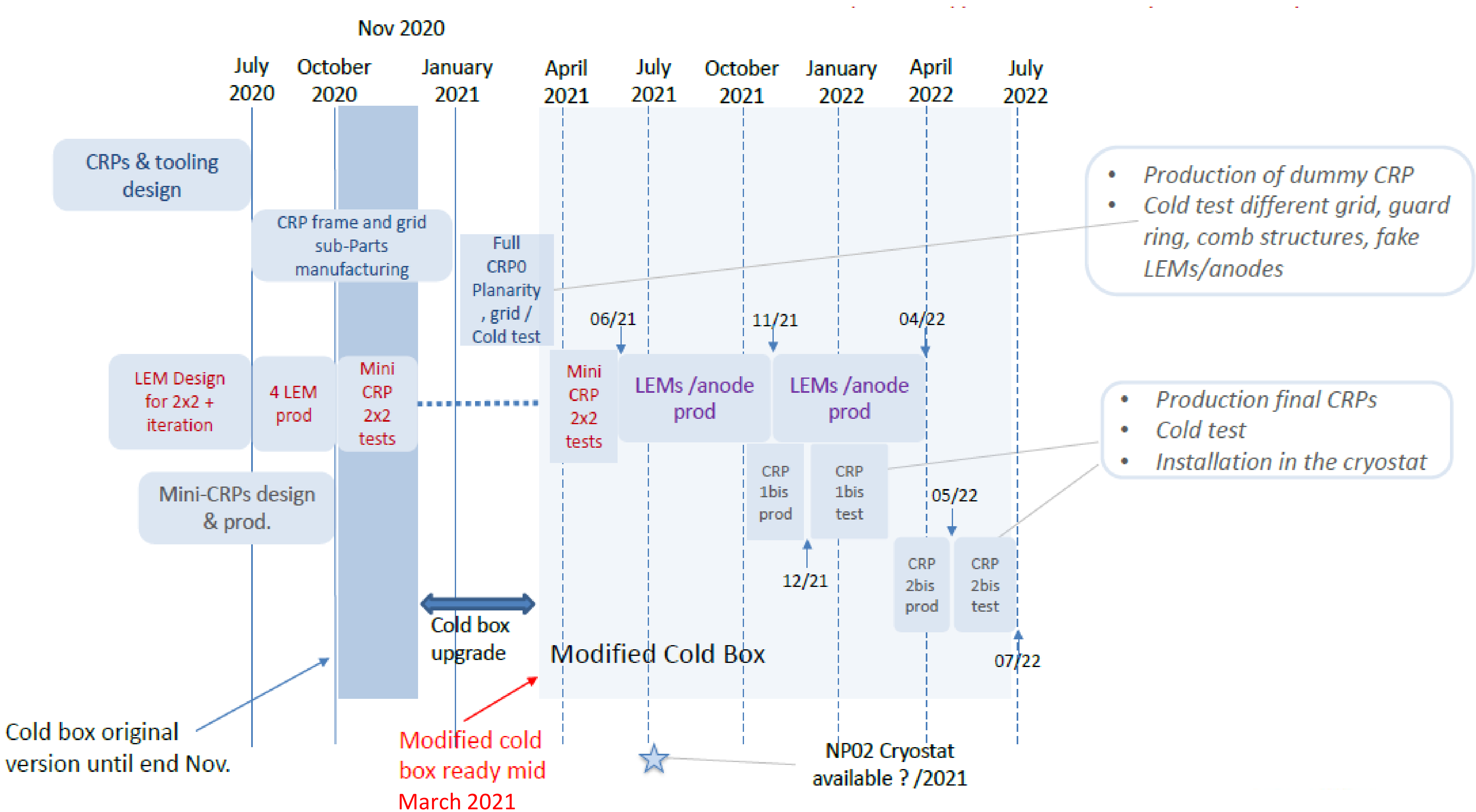
Modifications of the design are being validated to incorporate:

- a more stiff structure (20 times less deformations)
- A guard ring in the extraction grid support structures to guide the possible discharges
- Modifying the combs with resistive material
- Add 2mm to the grid-LEM distance



ProtoDUNE-DP Phase II planning (small scale tests + cold-box + Module-0):

(Activities schedule presented at April 2020 SPSC meeting, updated on September 2020)

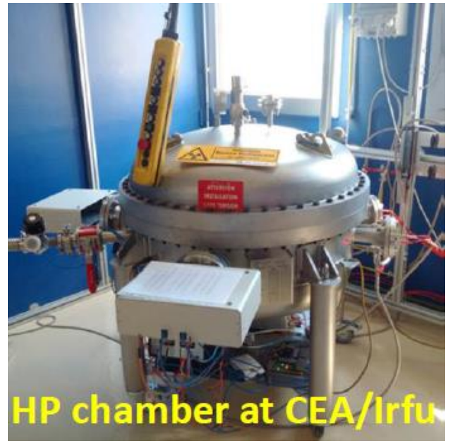


Schedule now replaced by Vertical Drift integration tests 2021-2023

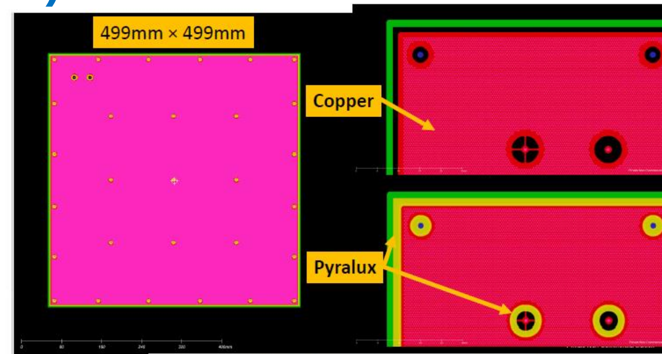
Progress on small tests R&D activities: (Summer 2020)

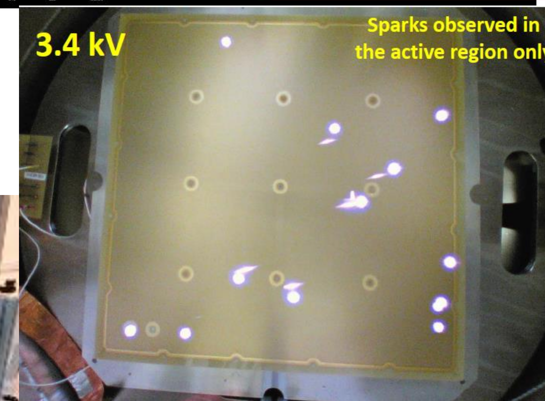
Tests of new LEMs design at CEA to reduce sparking

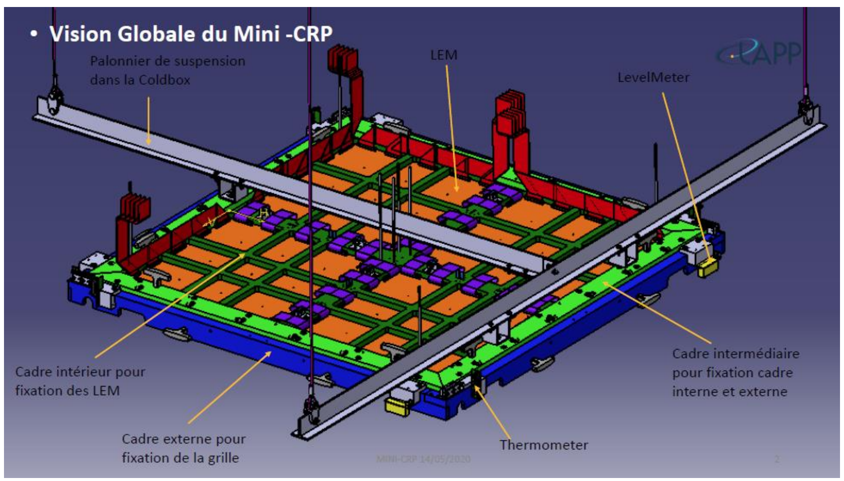
- Pyralux insulator on edges and pads
- Increased active area to 93-95%
- Studies on segmented and resistive LEMs and on RIMs optimization

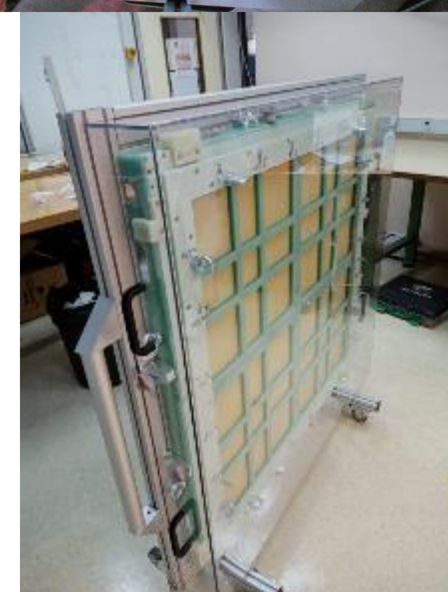


LEM design with 95% active area







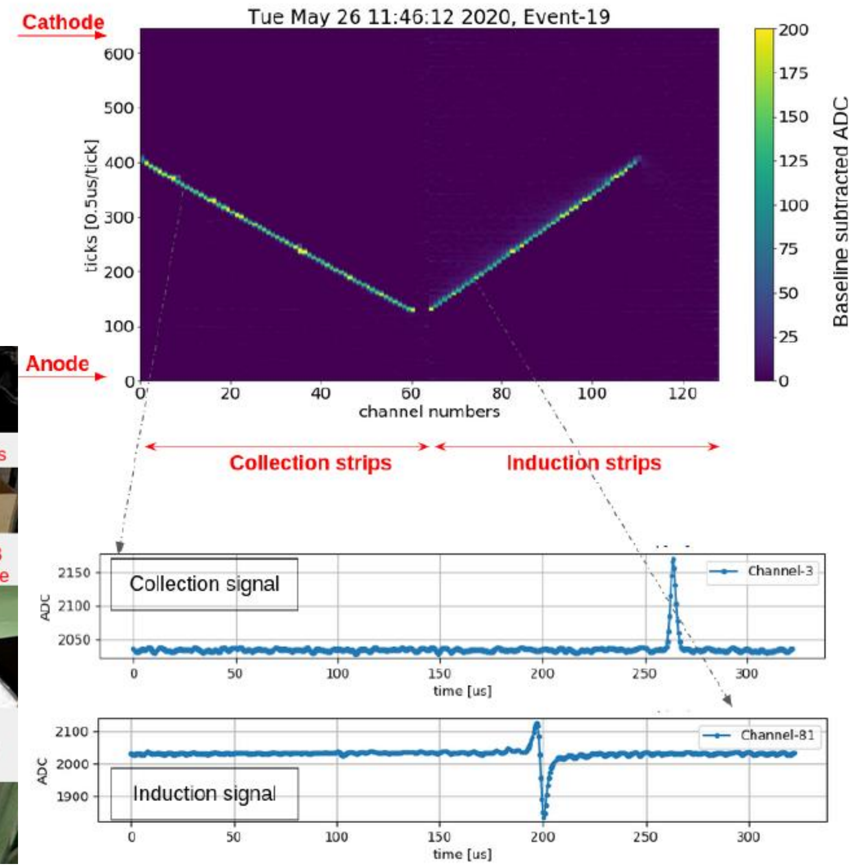


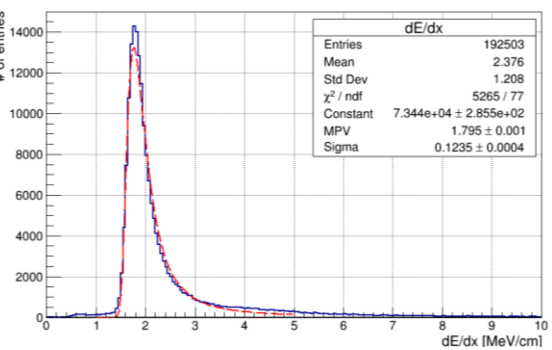
New design developed for 3x3 m² CRPs following the CRPs improvement program:

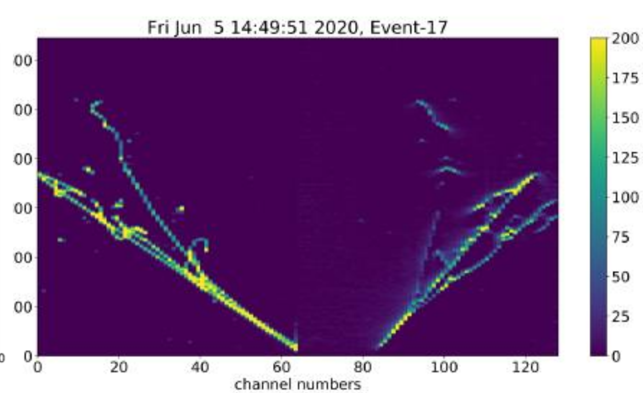
→ First design implementation on a MiniCRP structure (1x1m²) made following the CRP improvement program to test 4 LEMs from new design

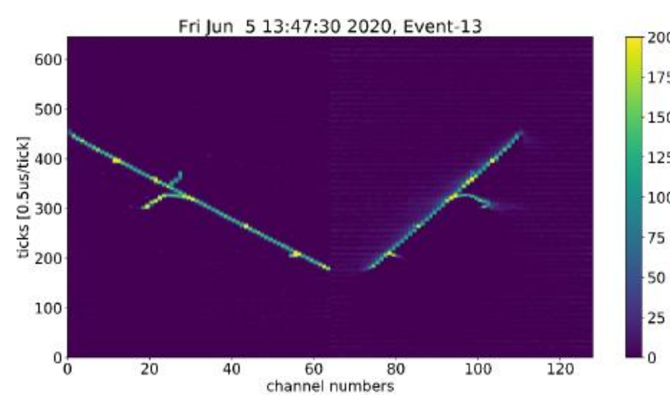
- New extraction grid + grid sparks prevention system

Perforated anodes tests at CERN Neutrino Platform with the 50l TPC test stand (Summer 2020)









Can we think of a simplified DP detector without LEMs (w/o the extra time needed to complete LEMs/CRP developments) which could be immediately built for DUNE, quickly and at affordable costs ?

→ Yes, the so called « **Vertical Drift** » :

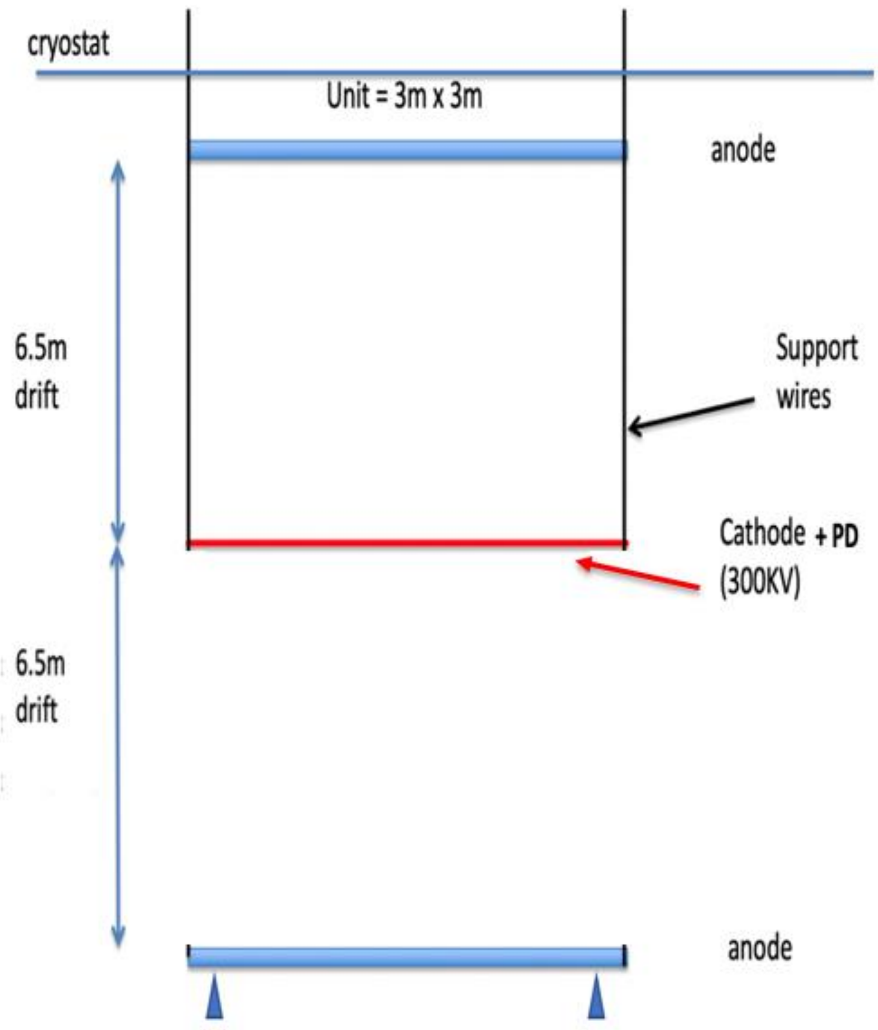
- **No LEMs → CRP evolution to perforated anodes**
- **No further changes in the cryostat needed to ensure better stability of LAr surface, can work with current performance**
- **No 600 kV → ~300 kV operation**
- **All detector components developed for dual-phase (CRPs, electronics, field cage, cathode, HV system) and associated investments maintained**
- **Geometry optimized to increase the sensitive volume, very much needed for physics → 15 kton**
- **Large cost and time reductions from the point of view of installation costs in South Dakota**

- **Tests at CERN on Vertical-Drift perforated anodes, since beginning of summer 2020 and continued in more complicated configurations (3 views test also performed in April-May 2021)**
  →confirmed the idea of evolving from the LEM design

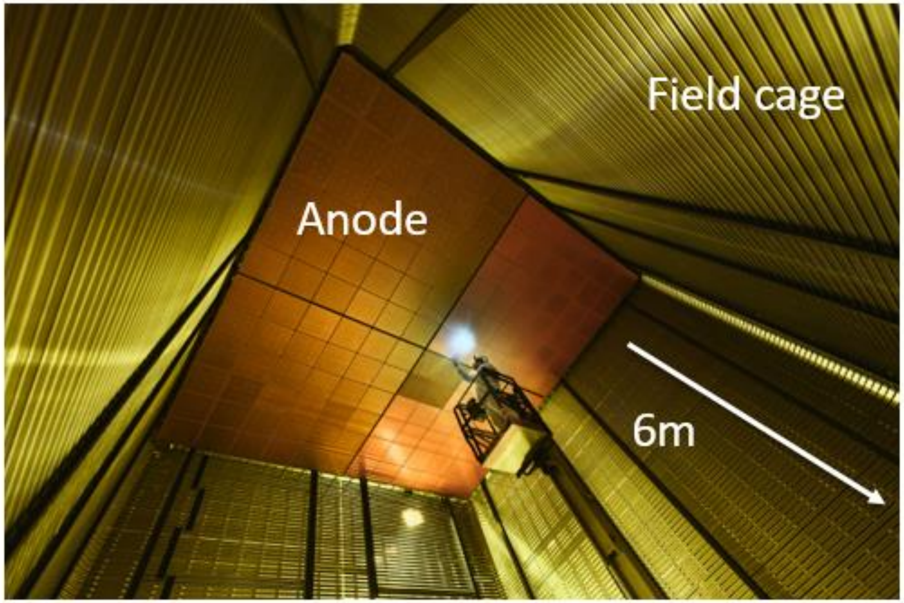
- **Developments since September 2020 to optimize the geometry and engineering of the detector and to reach a convergence with the collaboration and funding agencies**
  → process completed in December 2020

- **DOE IPR concluded in January 2021 → very strong support to this evolution of DUNE far detector configuration**
- **VD became preferred option by the DUNE collaboration to build the 2nd FD module**

Vertical Drift layout

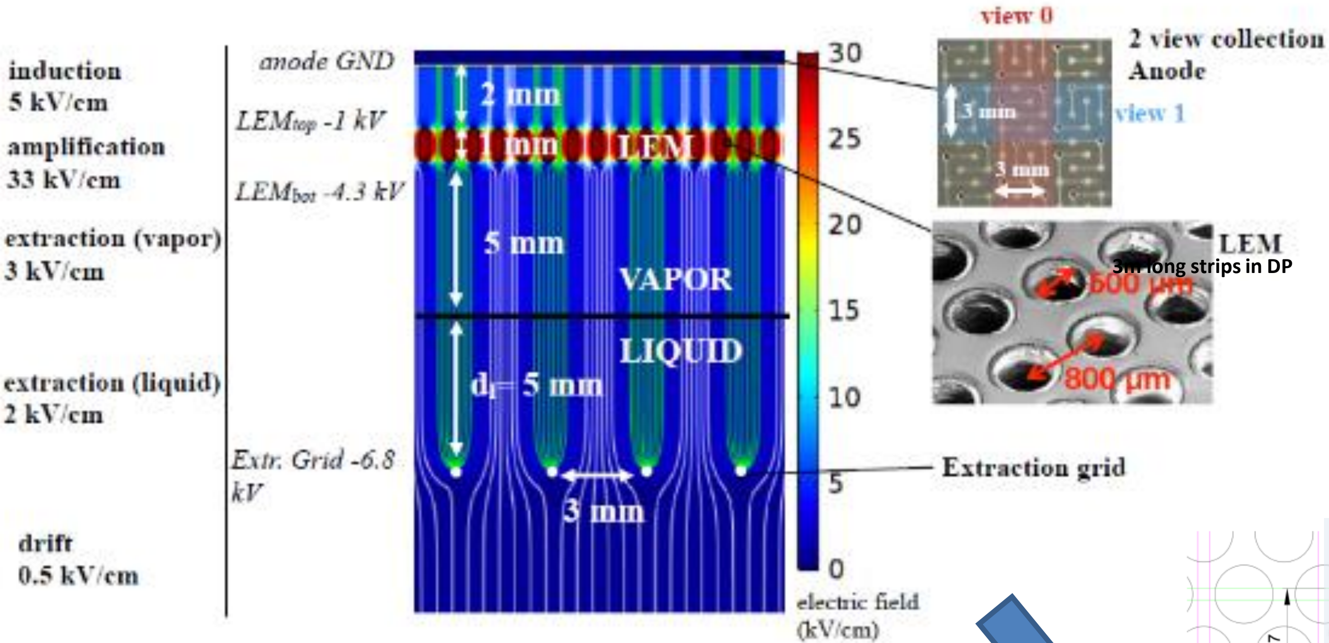


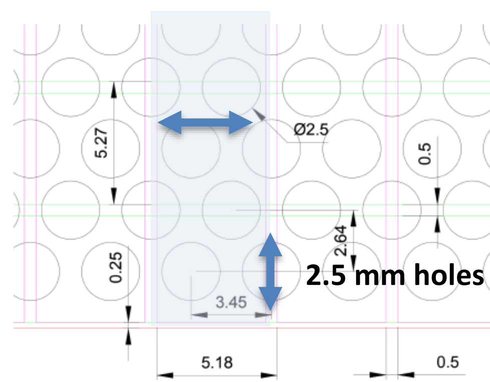
NP02 layout

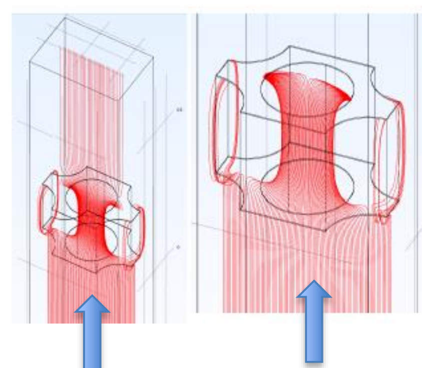


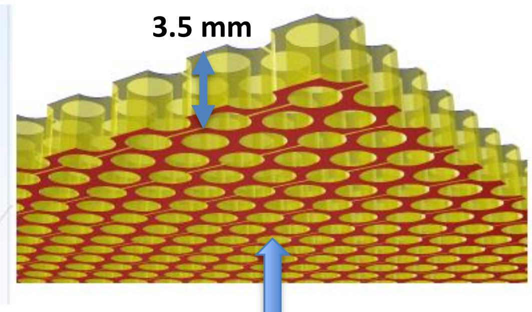
cathode

Evolution of CRP charge readout stack: Dual-Phase → Vertical Drift









Vertical drift:

- Anode PCB (3.2 mm thick) directly immersed in LAr, 2.5 mm holes
- Perpendicular strips on the top and bottom faces of the PCB: 5.2 mm pitch, 1.5 or 1.68 m long
- Bottom strips induction signals, top strips collection, 1kV across for full transparency

Vertical Drift vs Dual-Phase

Signal reduction related to **unitary gain in VD is compensated by a few favorable differences with respect to the DP configuration:**

a) factor 2 is gained by not having to share the charge among two collection views
b) factor 1.7 is given by the strips pitch increase (5.2mm instead of 3.1 mm for DP)
c) factor 1.6 is gained by the absence of the DP extraction/collection efficiencies (0.63)

- **VD overall signal increase factor (x5.3) similar to the DP TDR requirement (gain=6)**

- In addition **DP gain requirement was defined for a more unfavorable** drift length and drift field **configuration present in DP (250V/cm, 12m drift, 5ms lifetime)**

→ requirement relaxed by a factor 4 (equivalent gain 1.5) for 500V/cm: 6.5m drift, 6 ms lifetime or by 5.2 (equivalent gain ~1) for 500V/cm, 6.5m drift, 6 ms lifetime (~300kV at cathode)

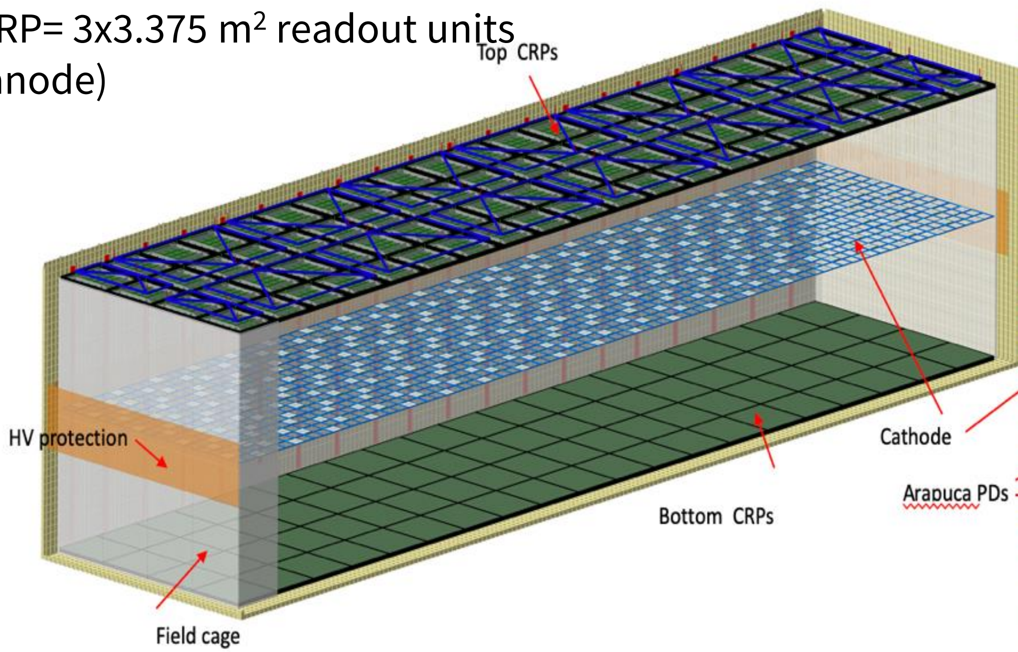
- **Signal in VD with 300 V/cm (500V/cm) is stronger than in DP requirements (gain=6) by a factor 3.5 (4.6)**

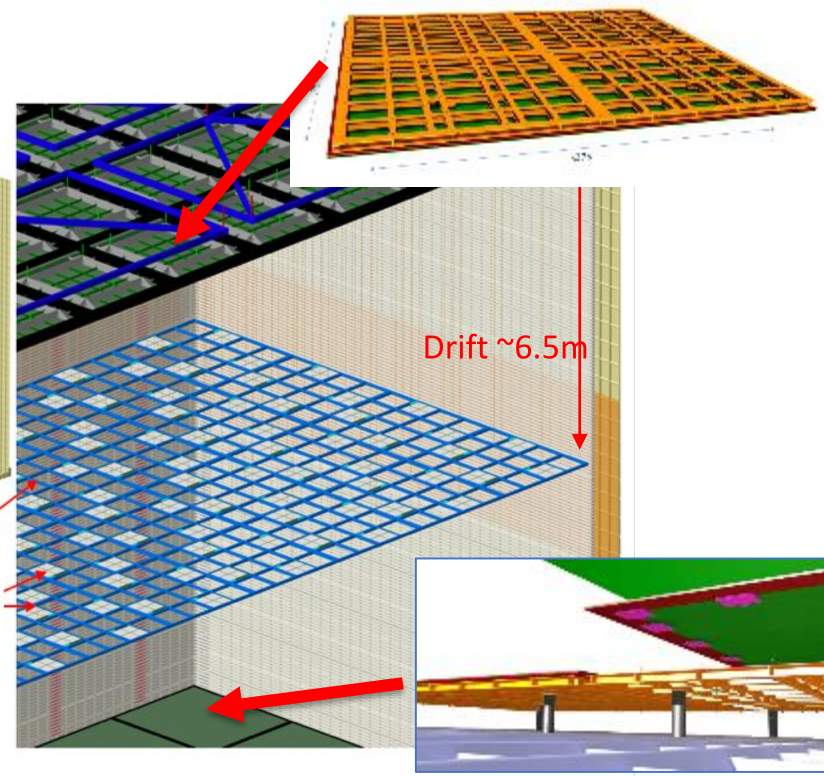
- **Strips capacitance is also lower for VD**: (<100 pF/m) over about 1.5 m length to be compared to 160pF/m x 3m length in case of DP configuration.

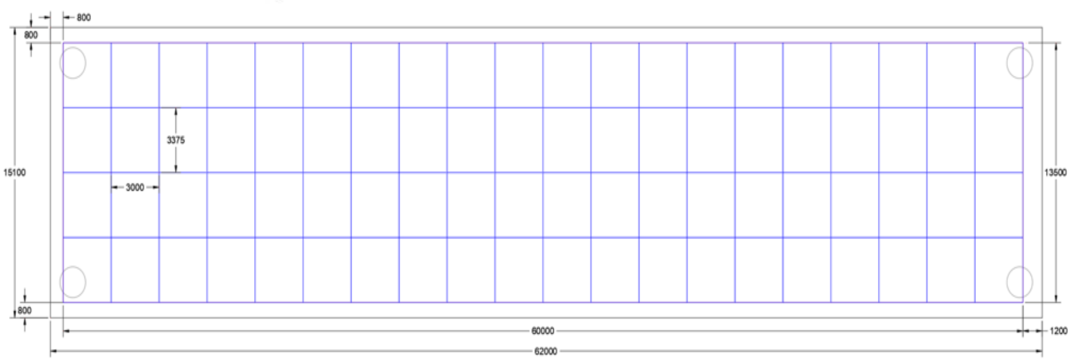
Vertical Drift far detector module

Detailed description in Vertical Drift proposal document and in Dominique's presentation.
Vertical Drift reuses many dual-phase developments for the CRPs, top-drift electronics, field cage/cathode

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







- ✓ 160 CRP units (80+80 on top/bottom, readout with DP/SP electronics)
- ✓ Drift active volumes 2*5'265 m^3 = LAr 14.74 kton

Teams:
(people so far involved. More people are in the process of being hired and expected to add in the next months)

- **APC Paris:**

Joao Coelho, Etienne Chardonnet, Bernard Courty, Jaime Dawson, Dariusz Nita, Andrès Munoz, Sabrina Sacerdoti, Camille Sironneau, Pierre Prat, Riccardo Dallavalle, Alessandra Tonazzo, Thomas Patzak

- **IJCLAB Orsay:**

Fabien Cavalier, Gilles Ferry, Alexandre Gallas, Eric Lavaut, Rodolphe Marie, Philippe Rosier, Laurent Simard

- **IP2I Lyon:**

Dario Autiero, Clement Barbarin , Edouard Bechetoille, Bruno Carlus , Quentin David, Fabien Doizon, Claude Girerd, Cyrille Guerin, Slavic Galymov, Thomas Kosc, Hervé Mathez, Elisabetta Pennacchio, Denis Pugnere, Konstantin Shchablo , William Tromeur
+ Electronics service of CENBG (contributing to Top drift electronics production and QC)
Frederic Druillole, Patrick Hellmuth

- **LAPP Annecy**

Benjamin Aimard, Isabelle Debonis, Guillaume Deleglise, Dominique Duchesneau, Nicolas Geffroy, Pablo Kunze, Oliver Lantwin, Fabrice Peltier, Laura Zambelli

- **LPSC Grenoble**

Johann Collot, Jean-Sebastien Real, Jean-Stephane Ricol, Arnaud Robert

Involvements of the IN2P3 groups:

- TGIR project focusing on construction contributions to the 2nd FD module based on the Vertical Drift. Funding accessible via TGIR program of the order ~50% M&S costs of 2nd FD module (39.5M$)
- CERN LBNF contribution to second cryostat consolidated
- CERN + UK + US groups contributing to 2nd FD, US funding being consolidated (see Steve's presentation)

- Current IN2P3 teams: APC Paris, IJCLAB Orsay, IP2I Lyon, LAPP Annecy, LPSC Grenoble
  ~50 people

- Foreseen/foreseeable IN2P3 contributions:
- ✓ Top Drift CRPs and mechanical structures: LAPP + LPSC (instrumentation + contribution to construction)
- ✓ Top Drift Electronics: IP2I + E. Serv. CENBG (sharing of production and QC) + IJCLAB (Chimneys)
- ✓ Cathode: IJCLAB
- ✓ High Voltage system: LPSC
- ✓ Light readout electronics: APC (PD system design under definition)

Involved Consortia: CRP, Top-electronics, HV, PD

IN2P3 contribution to leadership of CRP and top-electronics Consortia

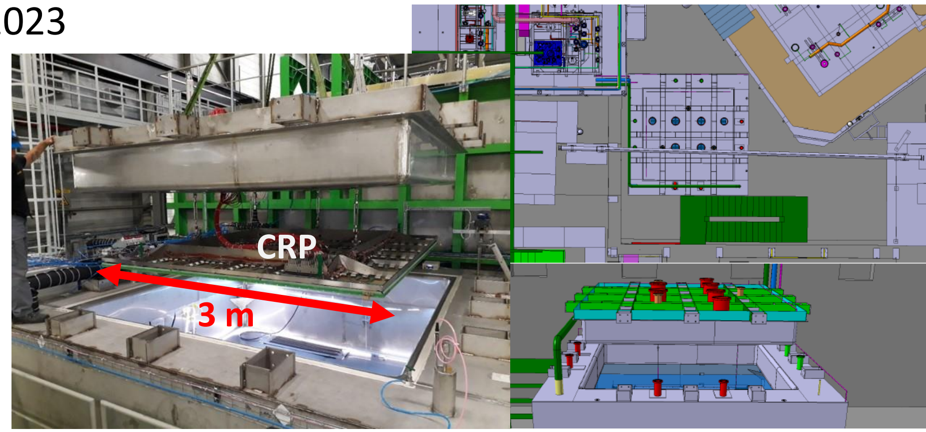
- Going full steam ahead for the test campaign of VD elements (CRPs, electronics, HV, PD) at CERN (see Marzio's presentation) with cold-box, NP02, NP02 module-0: 2021-2023
- Production of detector elements: 2023-2026
- Installation at SURF: 2026-2027

→ See schedule and organization details in Steve's presentation

- Parallel strong efforts by the groups on analysis, software developments and computing

Vertical-Drift 2021 activities at the CERN Neutrino Platform in 2021-2023

- Substituting the already planned DP Phase II tests activities foreseen with the cold-box built in 2018 for individual CRP tests. → Cold-box modified and upgraded from the DP configuration and moved to EHN1.
- Parallel tests of new simplified HV extender design in ProtoDUNE dual-phase/NP02.
- Continuation of the cold-box tests campaign in 2022 to define final CRPs for module-0
- Module-0 operation in NP02 cryostat foreseen in 2023



➢ **Cold-box tests of new CRPs**

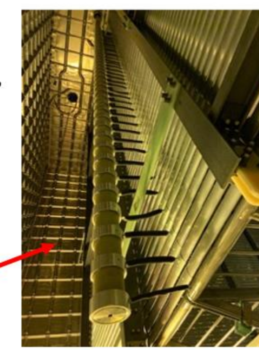
- Dual-phase cold box refurbished and installed at EHN1 side by side to NP02 by April 2021
- Since June 2021 integration at CERN of all components and commissioning
- First cold-box cycle of a CRP since the end of September 2021
- Tests activity continued in 2022 in preparation for Module-0

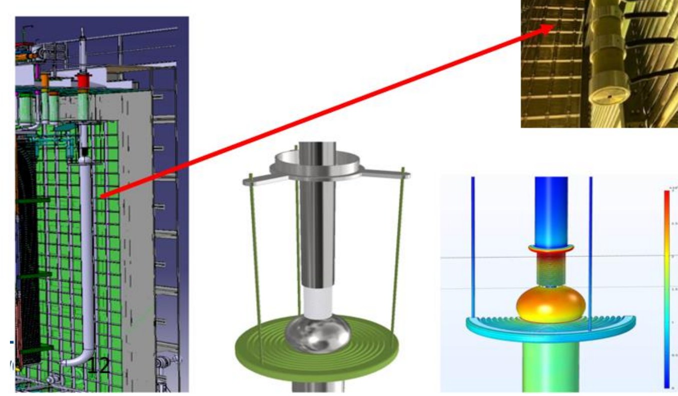
➢ **protoDUNE-DP/NP02 HV test:**

- Access to NP02 after warming up February 2021
- Removal and insertion of new HV extender March-June 2021
- Cool-down and filling of NP02 July-August 2021
- Operation and HV test September-November 2021

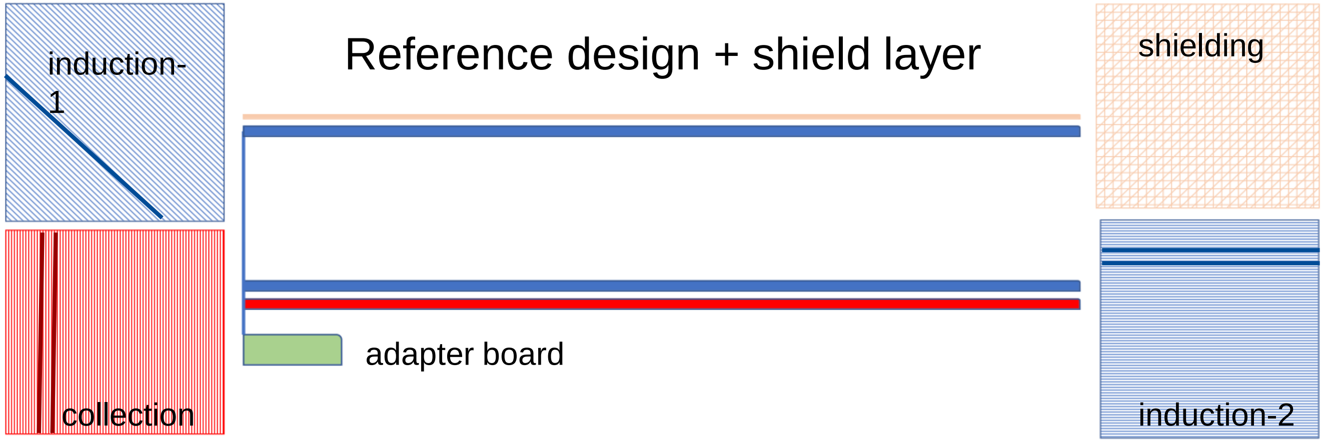
300kV test in NP02

- ✓ New HV system (300KV supplier, feedthrough, extender, DAQ, ..)
- ✓ Fill NP02 and get purity
- ✓ 2-3 months operation
- ✓ No need to open the cryostat, insertion via man hole

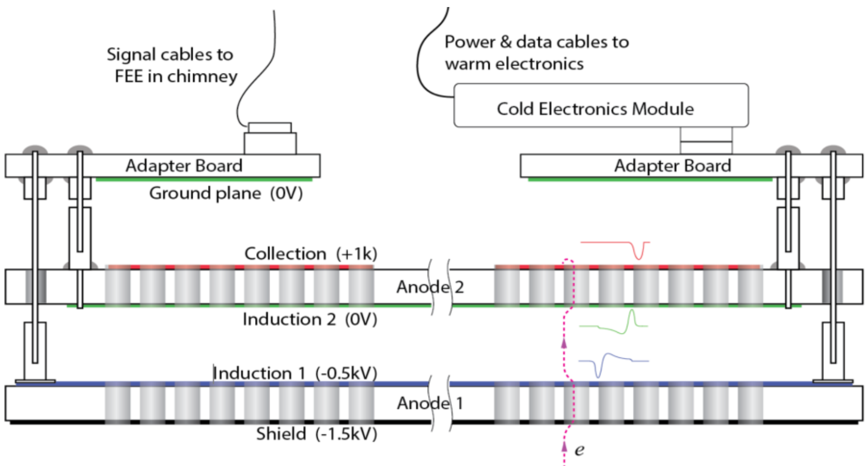


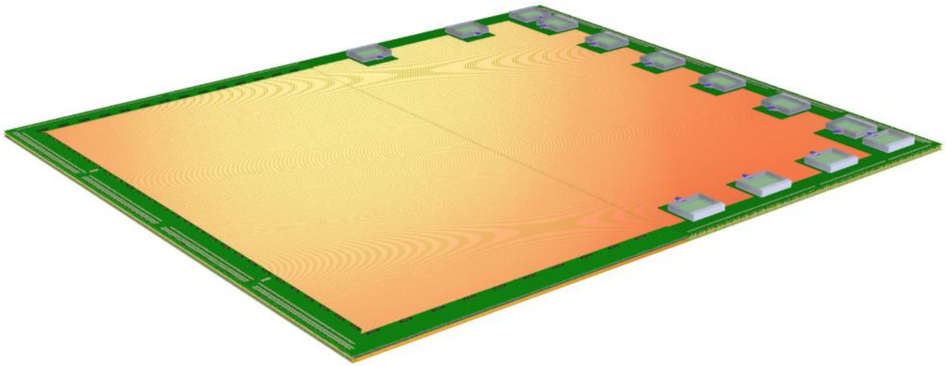


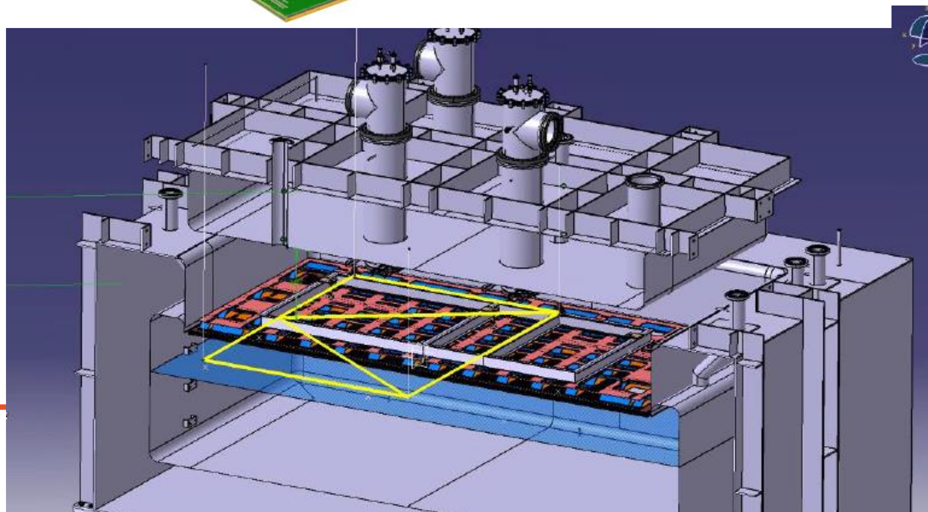
Anode PCB for the first cold-box tests in 2021



Induction-1: -48 degrees
Induction-2: 0
Collection : 90 degrees







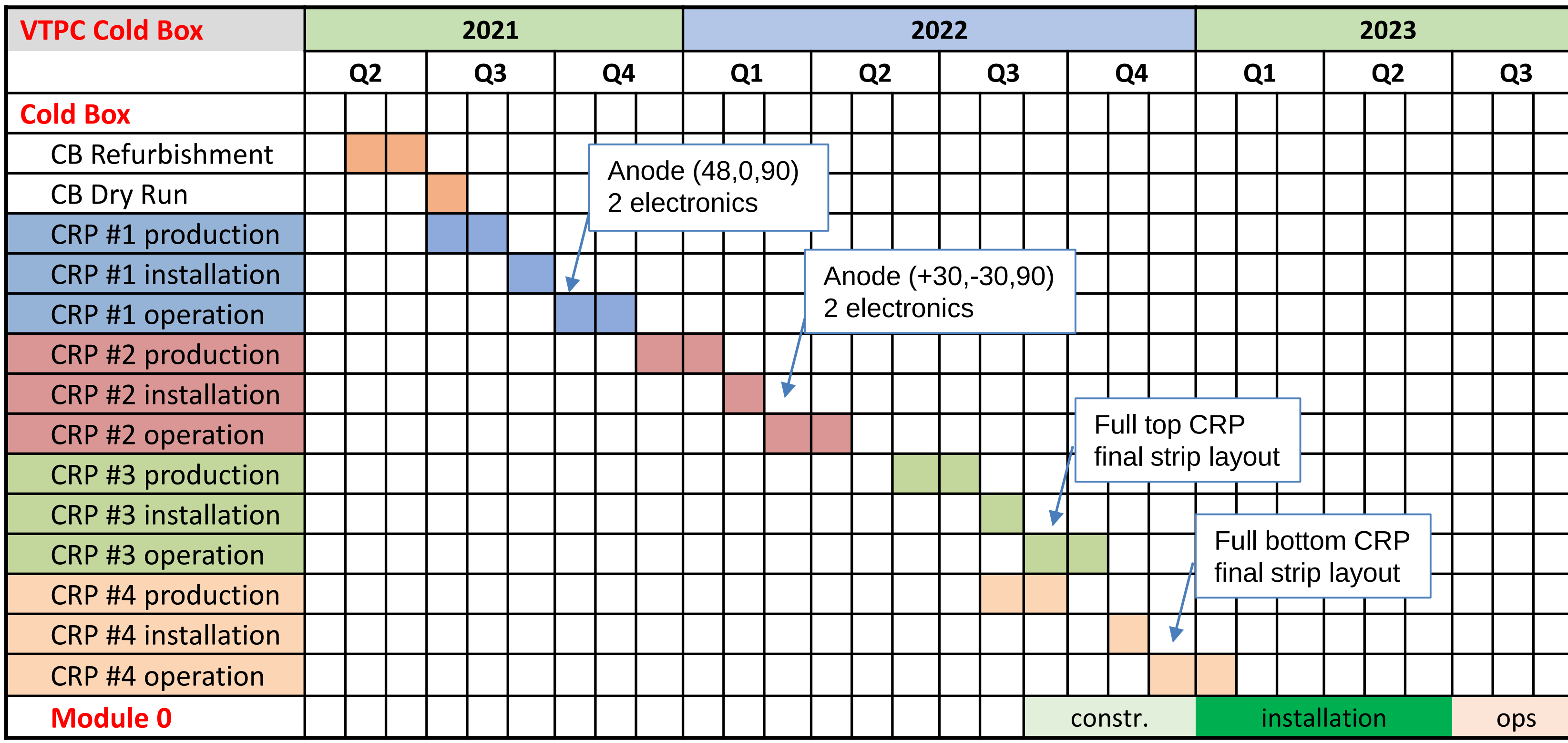
Configuration allowing assessing simultaneously the 2-views and 3-views performance in the same anodes setup to be used for the first CRP tests in 2021 → CRP shared as ½ top, ½ bottom CRPs

CRP test plan for Cold Box and Module 0

Preliminary plan given in the answers to LBNC after April 28th review

The CRP plan for 2022 includes:

- ❑ Construction and installation of a second CRP to test different strip orientation in March 2022
- ❑ Followed by a third final top CRP after decision on strip orientation in May 2022.
- ❑ A fourth (final bottom CRP) is expected possibly from US by fall 2022.



These tests will allow a complete definition and fully instrument module-0.

Conclusions:

- The IN2P3 project for DUNE is a long-standing project, started with the R&D phase in 2006 and prototyping activity at the CERN Neutrino Platform since 2014 (contributing to the 3x1x1 and protoDUNE dual-phase detectors). Completion of the foreseen 1 year operation program of ProtoDUNE dual-phase was done following expected schedule.

- We have been then evolving in 2020 the dual-phase design to Vertical Drift the basis of the operation experience, lessons learned and new developments

→ This turns into a simplified and more robust CRP design based on the perforated anodes and included an improved design of the HV extender, based on the acquired experience.

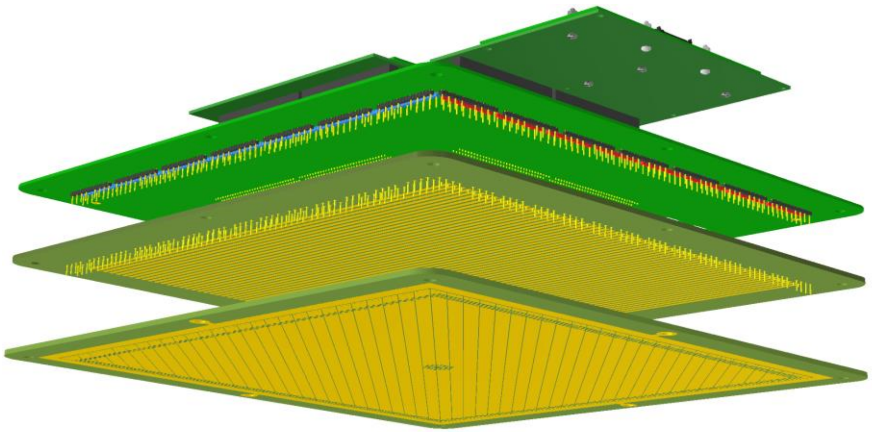
- The IN2P3 project now benefits of the extraordinary support of the TGIR which was prepared since 2017 and which will allow to contribute significantly and advance towards construction of the 2nd DUNE FD together with the convergence of several favorable international factors in the US and at CERN

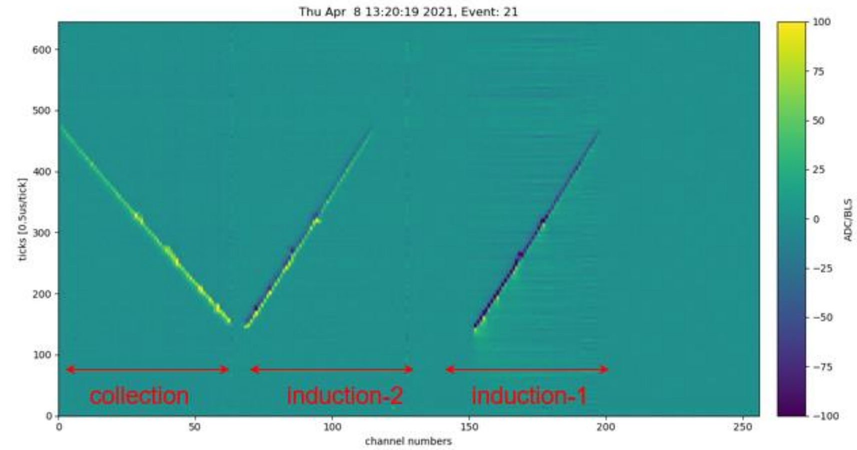
- Detailed engineering aspects of the DUNE far detector module have been worked on the basis of the vertical drift design, which has already passed several reviews and it is now the preferred choice of the DUNE collaboration for the 2nd FD.

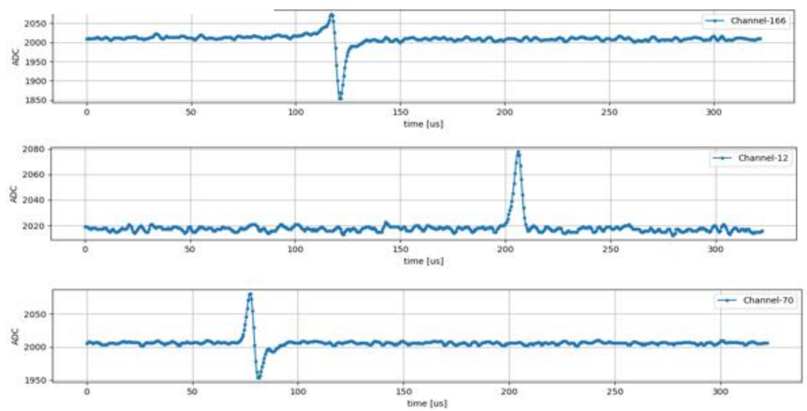
- The experimental activities and cold-box tests program (2021-2023) have been redefined to support the integrations tests for the Vertical Drift. This is a crucial effort now. Production activities for FD2 expected to start in 2023.

- This kick-off event starts an exciting period in front of us !

Perforated anodes tests at CERN Neutrino Platform with the 50l TPC test stand (recent 3 views test)



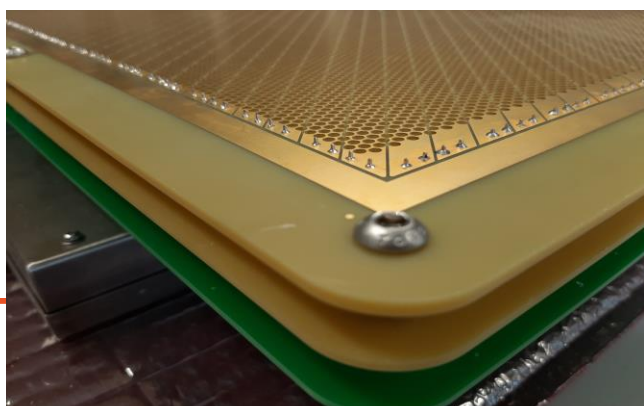


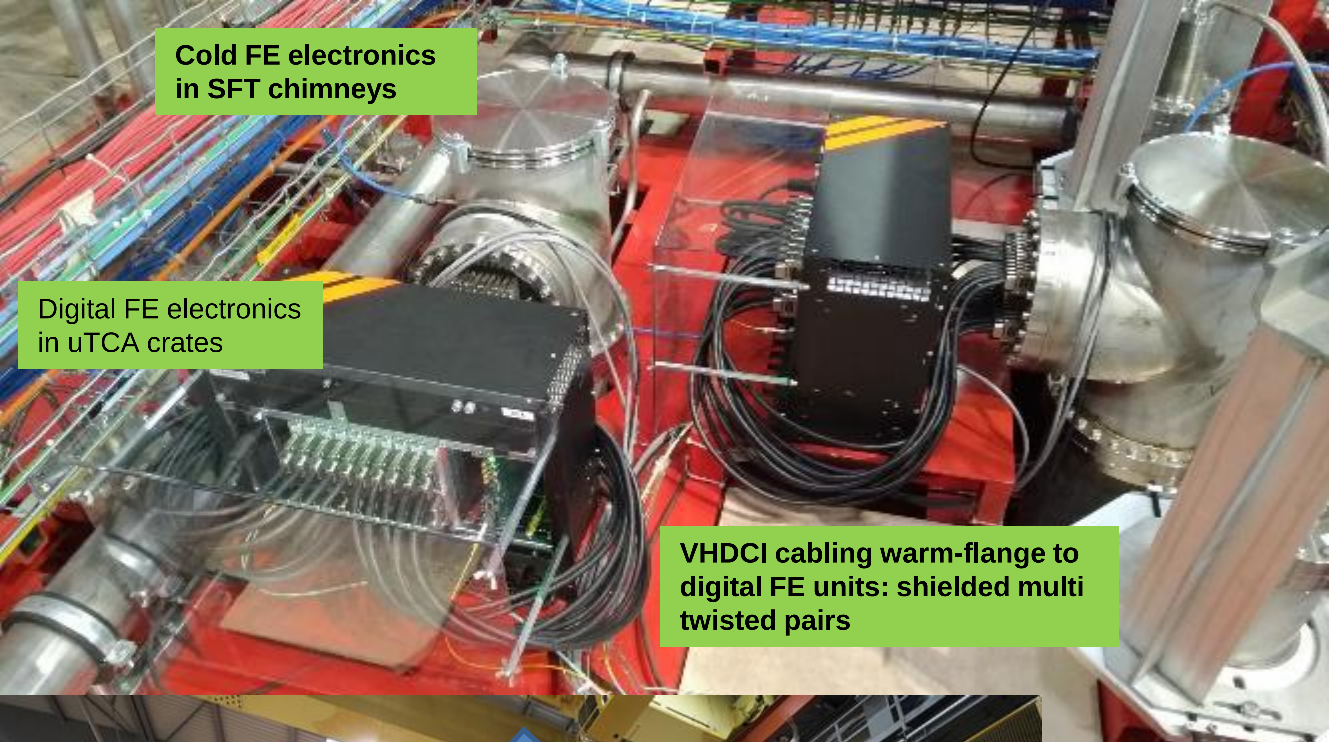


induction-1

collection

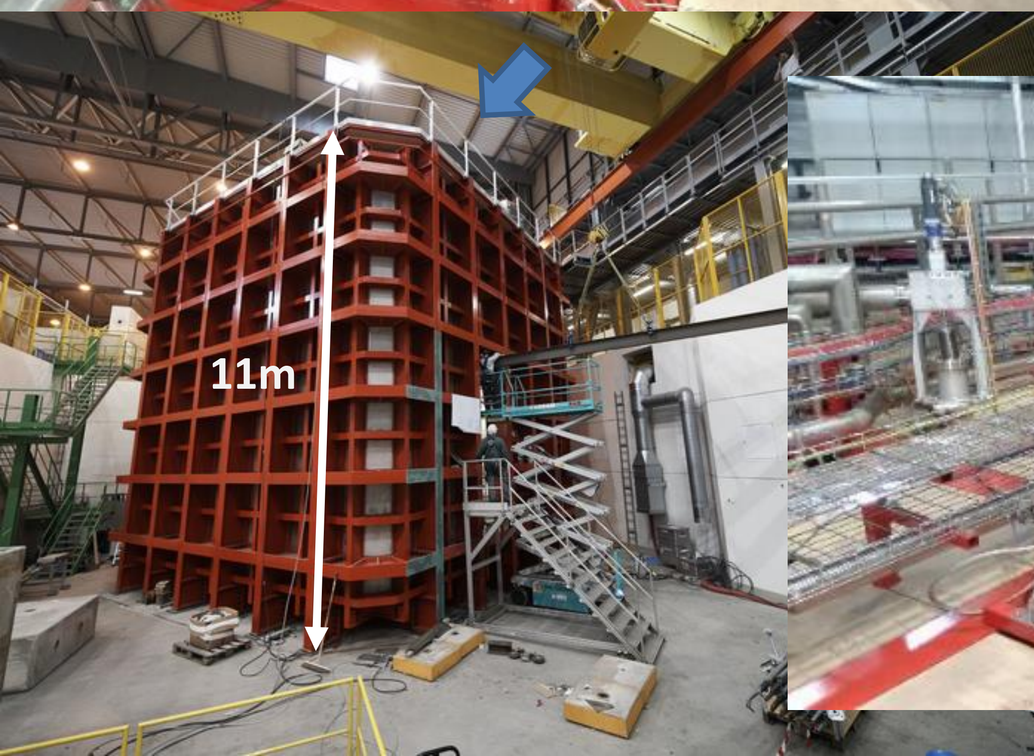
induction-2





ProtoDUNE dual-phase view of the cryostat roof with:

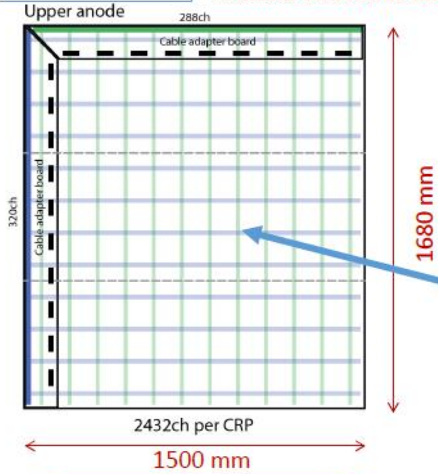
- **FE digitization electronics in the uTCA crates**
- **Signal feedthrough chimneys with cold electronics**

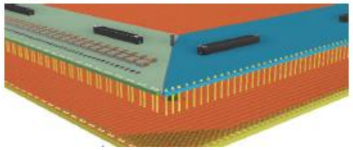


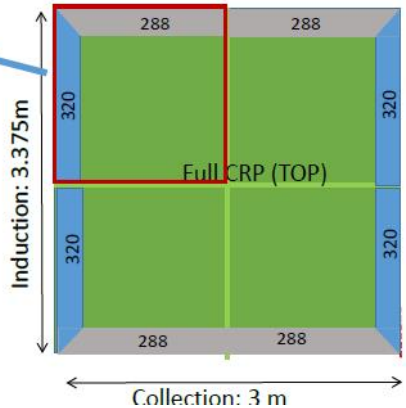
Anode electronics and Adapter Boards

¼ of a CRP (TOP)

Readout electronic identical to Dual Phase

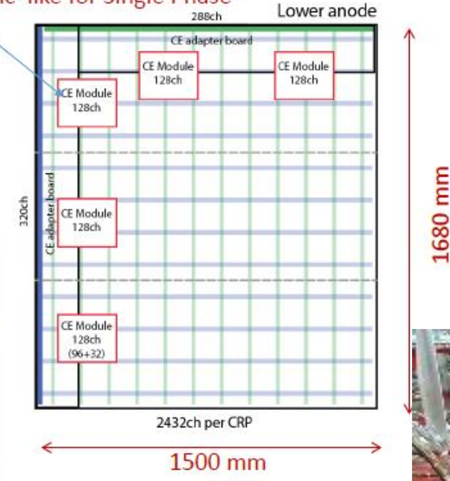


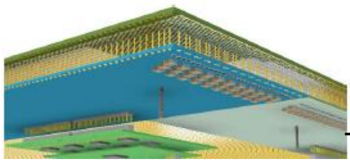




¼ of a CRP (Bottom)

Cold electronic like for Single Phase

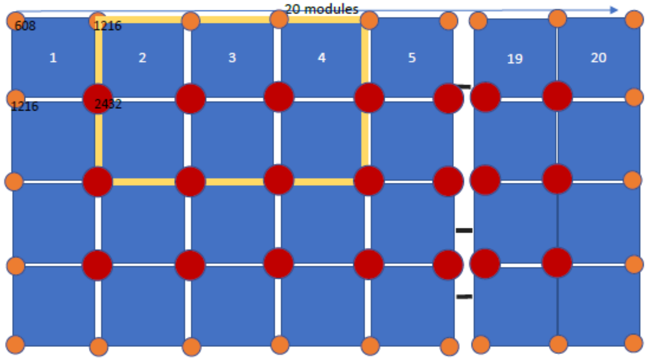




Top drift electronics from Dual-Phase design

Upper Electronic Feedthroughs

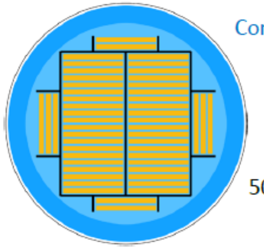
Top chimney topology: connexion at each CRP corner



Total 105 feedthroughs

The peripherical one can be of smaller radius!

Connexion similar to DP C

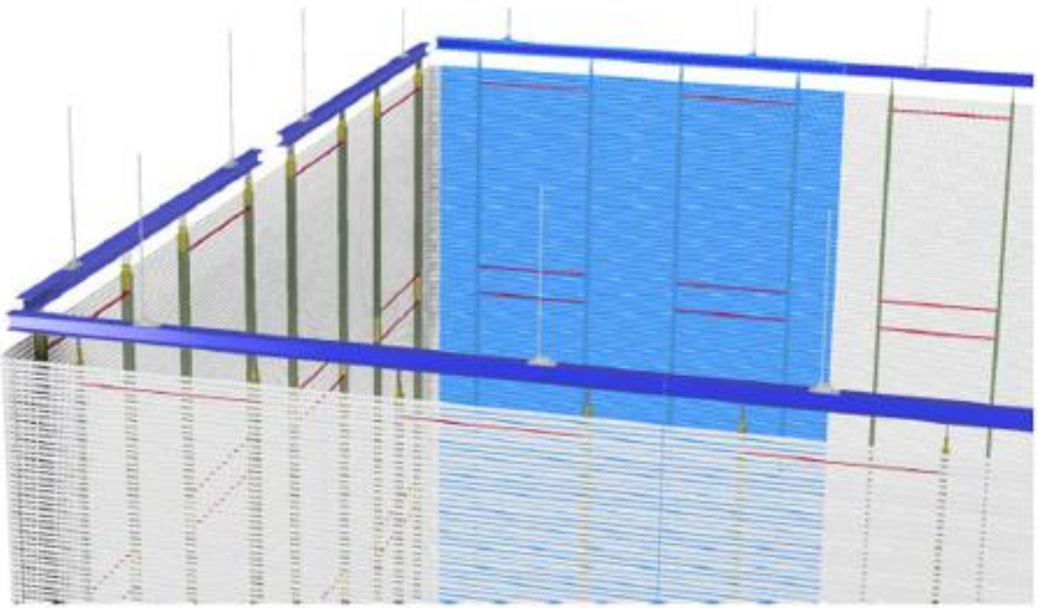


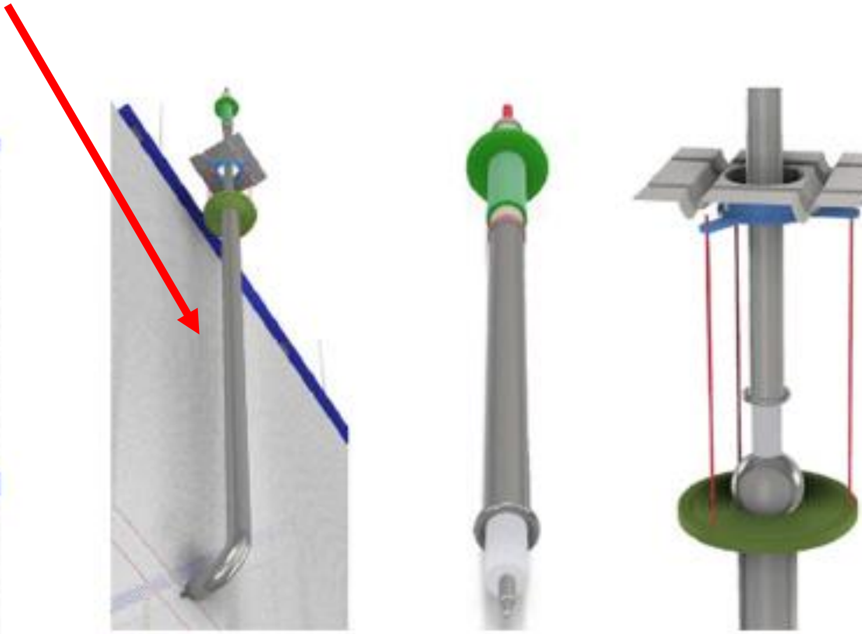
50 cards can fit inside!

Pipe internal diameter : 48 cm

Field cage and HV system

- ~300 kV applied to the cathode at the middle of the detector, max drift field ~6.5 m
- Field cage as in NP02 supported by DSS beams, using the same penetrations as bottom CRPs signals
- HV entering from the roof of the detector with a vertical penetration with the extender made with a simplified and more robust design compared to NP02: a simple round pipe of 20 cm diameter using LAr itself as insulator





Cold-box preparation for the tests in 2021

- Cold-box used in 2018 for DP CRPs tests moved from Bld-182 to EHN-1
- Mechanical reinforcements, top-cap modifications has started (additional feedthroughs for electronics and HV)
- Cold box modifications will be completed in May
- Cryogenic modifications to achieve necessary purity (~0.5 ppb, ~600 us) will be completed by July