Presentation of the global project and scientific stakes

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Fermilab & LAPP

Conseil Scientifique IN2P3
26-27 Oct 2021
The 1300 km baseline enables unambiguous measurement of the neutrino mass ordering

The detector’s on-axis location provides for a wide-band energy spectrum of neutrinos enabling detailed fitting of the oscillation parameters, including $\delta_{\text{CP}}$

The liquid argon technology for the Far Detector, at a depth of 1480 m, fully exploits the wide-band neutrino beam

The Near Detector complex provides control of systematic uncertainties
Liquid Argon Technology

• Use of LAr for the detection of high energy particles first suggested by L.W. Alvarez (1968)

• To mitigate the unsuccessful attempts to achieve charge amplification in LAr, B.A. Dolgoshein (1970) proposed and tested the main features of dual-phase argon detectors, in which ionization electrons produced in the liquid are extracted to the argon vapor on top and are there amplified.

• LAr TPCs proposed by C. Rubbia (1977) and H.H. Chen (1978)
  - Thanks to the high mobility and low diffusion of electrons in LAr, large LAr volumes can be operated as TPCs, providing high-quality imaging and high-resolution energy measurements from the detection of the ionization charge
  - The abundant scintillation light emitted by excited argon diatomic molecules can be used to determine the absolute event time (~10 ns resolution), to provide a self-trigger with no bias on the charge detection, and for calorimetry
  - High readout granularity, can sample electromagnetic showers down to a few % of a radiation length (as Gargamelle with Freon & NOMAD)
  - LAr TPCs overcome the deficiencies of both bubble chambers (limited in size and sensitive for short times) and large-size calorimetric detectors (coarser granularity)

  - **Ideal detectors for physics in the MeV to GeV range**
  - Many LArTPC detectors operating in the last ~15 years: ICARUS, ArgoNEUT, MicroBooNE, LARiAT, CAPTAIN, protoDUNE_SP, 3x1x1 m³, protoDUNE_DP
Events from LAr TPC detectors

(a) A 0.5 GeV/c electron candidate.  
(f) A 2 GeV/c pion charge exchange candidate.  
(e) A 1 GeV/c stopping proton candidate.

3x1x1 m³, dual phase
Particle Identification in protoDUNE-SP

\[ \zeta = \frac{1}{nT} \sum_j \frac{\left[ (\frac{dE}{dx})_j^{\text{Data}} - (\frac{dE}{dx})_j^{\text{MC Proton}} \right]^2}{\sqrt{\left[ \sigma (\frac{dE}{dx})_j^{\text{Data}} \right]^2 + \left[ \sigma (\frac{dE}{dx})_j^{\text{MC Proton}} \right]^2}} \]

Good $e/\gamma$ separation crucial for electron neutrino ID
The physics program of DUNE

- Long-baseline wide-band neutrino beam
  - Measurement of CP violation and determination of the mass hierarchy in a single experiment with spectral information

- Deep underground location allows access to astrophysical neutrinos
  - Supernova neutrino burst detection – sensitive to $\nu_e$ component
  - Atmospheric neutrino – capability for $\nu_\tau$ identification
  - Solar neutrinos – potential for detection of hep flux

- Massive detector with excellent tracking and calorimetric information
  - Search for proton decay – preferred channel $p \rightarrow \bar{\nu} K^+$

- Long baseline + higher energy neutrino beam
  - $\nu_\tau$ appearance, NSI searches
The LBNF Far Site Facility

2 x Detector caverns:
145m L x 20m W x 28m H
to house four 17.5 kt total mass modules

1 x Central utility cavern:
180m L x 20m W x 11m H
The ultimate DUNE detector will comprise 4 Far Detector (FD) modules.

The Collaboration currently focuses on delivering 2 FD modules by 2029:

- **FD1-HD**: single-phase horizontal drift detector with anode wire planes (APA) readout.
- **FD2-VD**: single-phase vertical drift detector with perforated PCB’s with segmented electrodes (strips) as Charge Readout Planes (CRP).

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**FD1-HD**

**FD2-VD**
LBNF Far Site Status

- Reliability Project upgrades completed
  - significant improvements, including new hoist system and refurbished shaft
- Pre excavation work completed
  - work to move excavated rock from one mile underground to the surface and deposit in the Open Cut
  - Excavation work construction of three DUNE caverns underway
    - Work stated in April 2021; will finish April 2024

Rock conveyor in operation

Drilling charge holes
Far Site Cryogenic Infrastructure

- In addition to the 1\textsuperscript{st} cryostat, CERN Council agreed to provide 2\textsuperscript{nd} cryostat module at June 2021 meeting
- Nitrogen system acquired via commercial contract (in initial award process)
- Argon system (receiving facility on surface, purification, recirculation and condensing systems, internal cryo systems) with in-kind contributions from international partners

- Warm structure final design completed in Nov 2018
- Membrane design for FD1-HD completed by GTT in April 2019
- Membrane design for FD2-VD in progress
The Near Site Facility

- High intensity primary protons (60 - 120 GeV energy range) on a graphite target
- Designed for 1.2 MW initial proton beam power, upgradeable to 2.4 MW
- PIP II upgrade of the current LINAC necessary to reach 1.2 MW (with participation of IN2P3 and CEA)
- Presently achieved record beam power of 803 kW in March 2021 (no PIP II)
Neutrino Beamline

- Neutrino beamline at a slope of 5.8°
- Design optimized with a genetic algorithm using sensitivity to CP violation as input to the optimization process
- 3 horn focusing system, water cooled, peak current of 300 kA
- He cooled cylindrical graphite target, inserted in Horn 1
- \( \text{N}_2 \) filled target chase
- He filled decay pipe, 194 m long, 4 m \( \varnothing \)
Near Site Facility Conventional Facilities Status

- Final designs completed
- Proceeding with the contracting process

Site preparation for LBNF Beamline facilities completed on schedule in October 2020.
The Near Detector CDR Reference

- Measures the neutrino beam rate and spectrum to predict un-oscillated event rates in the far detector
- Constrains systematic uncertainties for oscillation measurements
The DUNE Collaboration

1347 Collaborators, 204 institutions in 33 countries

DUNE Collaboration Organization

Project: Funding Agency
- DUNE-US: DOE
- DUNE-UK: UKRI/STFC
- DUNE-Italy: INFN
- DUNE-France: IN2P3, CEA
- DUNE-Spain
- DUNE-Brazil: FAPESP
- DUNE-Swiss: Bern, SNF
- DUNE-CERN
+ ....

Institutional Board

Co-Spokespersons

Executive Board

Physics Coordinators

Authorship & Publication Board

Speakers Committee

Int. Resource Coordinator

Finance Board

Technical Coordinators

Technical Boards

Construction Consortia

Computing

Physics, Simulations and Analysis Groups

Define requirements

Design

Fabricate

Integrate Components

Install (with Project)

Commission

Operate

Analyze
DUNE Detector Consortia 1 of 2

Construction Management Group

Co-Spokespersons

FD1 Technical Coordinator

FD2 Technical Coordinator

ND Technical Coordinator

FD1 Technical Board

FD2 Technical Board

ND Technical Board

Consortia Leads and Technical Leads

Consortia Leads and Technical Leads

Consortia Leads and Technical Leads

DUNE Construction is supported by the JPO

JOINT PROJECT OFFICE

Project Controls
ESH
Quality Assurance
Procurement
Systems Engineering

Financial Management
Risk Management
Internal Reviews
Compliance
Legal
DUNE Detector Consortia 2 of 2

Consortia Leads/Technical Leads

Far Detector
- APA: C. Touramanis (Liverpool), TLs: B. Rebel (UW,FNAL), J. Evans (Manchester)
- Photon Detection System: E. Segreto (Campinas), TLs: D. Warner (CSU), F. Terranova (Milano Bicocca)
- TPC Electronics: D. Christian (FNAL), TL: M. Verzocchi (FNAL)
- CRP: D. Duchesneau (LAPP), TL: S. Tufanli (CERN)
- Top VD TPC Electronics: D. Autiero (IPNL), TL: T. Hasegawa (KEK)
- HV System: F. Pietropaolo (CERN), TL: Bo Yu (BNL)
- Calibration/Cryogenic Instrumentation: J. Maneira (LIP), TLs: S. Gollapinni (LANL), A. Cervera (IFC)

Near Detector
- Liquid-argon Detector (ND-LAr): M. Weber (Bern), TL: D. Dwyer (LBL)
- Beam Monitor – SAND: L. Stanco (INFN Padova), TL: C. Montanari (Pavia,FNAL)
- Argon Gas TPC (ND-GAr): A. Weber (STFC/Oxford), A. Bross (FNAL), TL: T. LeCompte (ANL)

Joint Near/Far
- DAQ/Slow Controls: G. Lehmann Miotto (CERN), TLs: A. Thea (RAL), A. Kaboth (RHUL)
- Computing: H. Schellman (Oregon State), TLs: M. Kirby (FNAL), A. McNab (Manchester)

*proto-Consortium
LBNF/DUNE summary schedule

- Schedule for FD2 is estimated
- Schedule is dependent on funding profile which will not be finalized until CD-2 baseline is approved by DOE
Long-baseline neutrinos: the measurements

120 kt MW yr

Neutrinos
1285 km
Normal Ordering

Antineutrinos
1285 km
Normal Ordering

DUNE $\nu_e$ Disappearance
$\sin^2 2\theta_{13} = 0.580$
$\Delta m_{13}^2 = 2.451 \times 10^{-3} \text{ eV}^2$
3.5 years (staged)
- Signal $\nu_e$ CC
- $\nu_e$ CC
- NC
- $\nu_e + \bar{\nu}_e$ CC
- $(\nu_e + \nu_e)$ CC

DUNE $\bar{\nu}_e$ Disappearance
$\sin^2 2\theta_{13} = 0.580$
$\Delta m_{13}^2 = 2.451 \times 10^{-3} \text{ eV}^2$
3.5 years (staged)
- Signal $\bar{\nu}_e$ CC
- $\bar{\nu}_e$ CC
- NC
- $\bar{\nu}_e + \nu_e$ CC
- $(\nu_e + \nu_e)$ CC

DUNE $\nu_e$ Appearance
Normal Ordering
$\sin^2 2\theta_{13} = 0.088$
$\sin^2 2\theta_{13} = 0.580$
3.5 years (staged)
- Signal $(\nu_e + \nu_e)$ CC
- $\nu_e + \bar{\nu}_e$ CC
- $(\nu_e + \nu_e)$ CC
- $(\nu_e + \nu_e)$ CC
- $\bar{\nu}_e + \nu_e$ CC
- $(\nu_e + \nu_e)$ CC
- $(\nu_e + \nu_e)$ CC
Long-baseline neutrinos: sensitivities at low exposures

- DUNE will unambiguously resolve the neutrino mass ordering at a 3σ (5σ) level, with a 66 (100) kt-MW-yr exposure

- DUNE can measure CPV at a 3σ level with a 100 kt-MW-yr exposure for the maximally CP-violating values $\delta_{CP} = \pm \pi/2$
Long-baseline neutrinos: ultimate sensitivities
DUNE and Hyper-K

• An important similarity between DUNE and Hyper-K
  - Very large neutrino detectors are only feasible by instrumenting the surface of the detector and not the volume
  - DUNE FD2-VD is the optimized solution for single-phase LAr, derived from the main concepts of the dual-phase LAr TPC

• Hyper-K (shorter baseline, off-axis beam & Water Cerenkov detectors) and DUNE (longer baseline, wide band beam & LAr detector) are more complementary than competitive, both for neutrino physics and proton decay searches
  - Higher statistics & lower details vs Lower statistics & higher details
  - DUNE sensitivity to the shape of the oscillation spectrum and the larger matter effects allow simultaneous measurements of $\delta_{CP}$ and mass ordering
  - Systematics are very different, which is a good thing for difficult measurements like CP violation with neutrinos and proton decay searches

• Healthy competition is very welcome. “To be the first is good, but to be first and to be right is better” (S. Ting)
Conclusions

• LAr technology has seen an incredibly large growth in the last ~15 years
  - while 2 DUNE detectors are defined, the remaining 2 may still take advantage of new developments

• LBNF/DUNE well in progress
  - Excavation of the far site caverns is in progress
  - Module 0 components for FD1-HD are being constructed (1\textsuperscript{st} APA delivered at CERN)
  - FD2-VD finalizing configuration with a focused test plan

• Long baseline + wide-band $\nu$ beam + LAr detector allow simultaneous measurements of $\delta_{CP}$ and mass ordering. Unique sensitivity to $\nu_{\tau}$ appearance

• DUNE & HYPER-K: two approaches with very different systematics
Gargamelle Bubble Chamber
3 ton sensitive mass
Heavy Freon

Bubble $\varnothing$ (mm) 3
Density (g/cm$^3$) 1.5
$X_0$ (cm) 11.0
$\lambda_T$ (cm) 49.5
dE/dx (MeV/cm) 2.3

2.7 tons drift chambers target
Density (g/cm$^3$) 0.1
2% $X_0$/chamber
0.4 T magnetic field

TRD detector
Lead glass calorimeter

Resolution (mm$^3$) $3 \times 3 \times 0.2$
Density (g/cm$^3$) 1.4
$X_0$ (cm) 14.0
$\lambda_T$ (cm) 54.8
dE/dx (MeV/cm) 2.1

C. Rubbia,
CERN Report 77-8,
May 1977
LBNF/DUNE Organization

LBNF/DUNE Project Organization

Host Laboratory
- Laboratory Director
- Chief Research Officer

DUNE Collaboration Management
- Co-spokespersons
- Technical Coordinators
- Resource Coordinator

Project relationship to DUNE

Deputy Project Director for Facilities
- FSCF SP
- FSCF PM
- NSCF+B SP (DPDF)
- NSCF PM
- Beamline PM

Deputy Project Director for Far Detectors
- FD1+C SP
  - Shared Technical Coordination
  - Facility Support and Services
  - FD1+C DOE PM
  - FD1+C DOE Dep PM
- DUNE FD1 TC (FD1+C DOE PM)
  - DOE Comp PMs
  - Install PM
  - LAr PM
  - Infrastructure PM

Deputy Project Director for Near Detectors
- ND SP
  - Shared Tech Coord Support
  - DUNE ND TC
  - ND DOE PM
  - DOE Comp PMs
  - Install PM
  - Cryo Sys PM
  - Infrastructure PM

DUNE Consortia

DUNE consortias
Electron neutrino appearance rates

<table>
<thead>
<tr>
<th>Sample</th>
<th>Expected Events</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$\delta_{\text{CP}} = 0$</td>
</tr>
<tr>
<td></td>
<td>NO</td>
</tr>
<tr>
<td>$\nu$ mode</td>
<td></td>
</tr>
<tr>
<td>Oscillated $\nu_e$</td>
<td>1155</td>
</tr>
<tr>
<td>Oscillated $\bar{\nu}_e$</td>
<td>19</td>
</tr>
<tr>
<td>Total oscillated</td>
<td>1174</td>
</tr>
<tr>
<td>Beam $\nu_e + \bar{\nu}_e$ CC background</td>
<td>228</td>
</tr>
<tr>
<td>NC background</td>
<td>84</td>
</tr>
<tr>
<td>$\nu_\tau + \bar{\nu}_\tau$ CC background</td>
<td>36</td>
</tr>
<tr>
<td>$\nu_\mu + \bar{\nu}_\mu$ CC background</td>
<td>15</td>
</tr>
<tr>
<td>Total background</td>
<td>363</td>
</tr>
<tr>
<td>$\bar{\nu}$ mode</td>
<td></td>
</tr>
<tr>
<td>Oscillated $\nu_e$</td>
<td>81</td>
</tr>
<tr>
<td>Oscillated $\bar{\nu}_e$</td>
<td>236</td>
</tr>
<tr>
<td>Total oscillated</td>
<td>317</td>
</tr>
<tr>
<td>Beam $\nu_e + \bar{\nu}_e$ CC background</td>
<td>145</td>
</tr>
<tr>
<td>NC background</td>
<td>40</td>
</tr>
<tr>
<td>$\nu_\tau + \bar{\nu}_\tau$ CC background</td>
<td>22</td>
</tr>
<tr>
<td>$\nu_\mu + \bar{\nu}_\mu$ CC background</td>
<td>6</td>
</tr>
<tr>
<td>Total background</td>
<td>216</td>
</tr>
</tbody>
</table>

120 kt MW yr integrated rate between 0.5 and 10 GeV
Le projet DUNE à l’IN2P3 : contributions, responsabilités et partenariat

D. Autiero

IP2I Lyon

CS IN2P3

26/10/2021
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 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 2021-... preparation activities for Vertical Drift FD module #2
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

50x50 cm² anodes with 2 collection views
NP02/protoDUNE dual-phase

- Dual-phase FD design based on NP02:
  1. 1/20 of active area of DP 10 kton
  2. NP02/protoDUNE DP 4 CRPs → DUNE 80 CRPs

Construction 2018-19 Operation 2019-20

- 36 cryogenic photomultipliers
  - Hamamatsu R5912-02mod with TPB coating

- Digital electronics in uTCA crates
- Cold FE electronics
- Charge readout planes
- Field cage
- Cathode

6 m x 6 m
Charge Readout Planes (LEMs CEA contribution)

ProtoDUNE-DP configuration

seen from below

4 CRPs

13/02/19

Close-up side view

Anode 3.5 mm

2 mm gap

LER 1 mm

Extraction grid

Side view

25 mm

10 mm

CRP2

CRP3

CRP1

CRP4

4 anodes

3m
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 at warm 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 externally accessible:
    - 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

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[Diagram and images illustrating the setup and accessibility features.]
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**

- Electromagnetic shower: $E_{LEM} = 31 \text{ kV/cm}$
- Muon decay
- Low noise: 1 ADC = 900 e
- Charge $\propto$ to integral of waveform

**Waveform for ch. 1170**

**Charge** $\propto$ to integral of waveform
Experience from protoDUNE-DP 6x6x6 m³ phase-I

- NP02 6x6x6 m³ 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
- NP02 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/](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

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
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

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

Field cage

Cathode + PD (300KV)

Anode

Cryostat

Unit = 3m x 3m

Support wires

6.5m drift

6m

cathode
Evolution of CRP charge readout stack: Dual-Phase $\rightarrow$ 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 CDR draft reviewed this summer by the LBNC and in Dominique’s presentation.

Vertical Drift reuses many dual-phase developments for the CRPs, top-drift e cage/cathode

CRP = 3x3.375 m² readout units (anode)

- 160 CRP units (80+80 on top/bottom, readout with DP/SP electronics)
- Drift active volumes 2*5’265 m³ = 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, Bernard Courty, Jaime Dawson, Camelia Mironov, Dariusz Nita, Sabrina Sacerdoti, Camille Sironneau, Pierre Prat, Alessandra Tonazzo, Thomas Patzak

- **IJCLAB Orsay:**
  Fabien Cavalier, Gilles Ferry, Alexandre Gallas, Thibaut Houdy, Yoann Kermaidia, Rodolphe Marie, Christopher Magueur, Philippe Rosier, Laurent Simard

- **IP2I Lyon:**
  Dario Autiero, Clement Barbarin, Edouard Bechetoille, Bruno Carlus, Quentin David, Fabien Doizon, Claude Girerd, Cyrille Guerin, Slavic Galymov, 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, Alberto Marchionni, Fabrice Peltier, Laura Zambelli

- **LPSC Grenoble**
  Johann Collot, Joel Dai, Thomas Kosc, 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

- 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 Fabien’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 Alberto’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 VD CRP installed this Monday → first cold-box cycle soon.
  - Tests activity continued in 2022 in preparation for Module-0.

- **protoDUNE-DP/NP02 HV test:**
  - Access to NP02 after warming up February 2021.
  - Cool-down and filling of NP02 August 2021.
  - HV operation at 300 kV started in September 2021 for a few months.
Anode PCB for the first cold-box tests in 2021

Reference design + shield layer

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
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.
- 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 achieved 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 DUNE IN2P3 project now benefits of the support of the TGIR (now IR*) 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 DOE/FNAL/LBNC/SPSC reviews and a CDR review 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 effort has made large progress in 2021 with the HV test and the cold-box preparation. Production activities for FD2 expected to start at the end of 2023.
Perforated anodes tests at CERN Neutrino Platform with the 50l TPC test stand (recent 3 views test)
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

3/4 of a CRP (TOP) Readout electronic identical to Dual Phase

Cold electronic like for Single Phase

Upper anode

Collection: 3 m

Induction: 3.375 m

2432 ch per CRP

1680 mm

1500 mm

2432 ch per CRP

1680 mm

Top drift electronics from Dual-Phase design

Upper Electronic Feedthroughs

Top chimney topology: connexion at each CRP corner

Total 105 feedthroughs
The peripheral one can be of smaller radius!

Connexion similar to DP6

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
Vertical drift LAr TPC design overview

D. Duchesneau
LAPP

Outline:
- General layout and dimensions
- Anodes and CRP
- Cathode, Field cage and HV
- Photon detection system
- Summary
Liquid Argon TPC:
- To detect ionisation charge and scintillation light

- Designed to maximize active volume
  - Charge Readout units close to LAr surface and cryostat floor.
  - Cathode at middle height

- Perforated PCB’s with segmented electrodes (strips) as readout units with integrated electronic interfaces
  - 2 or 3 view using 2 perforated PCB layers
  - Optimizable strip orientation, pitch, length and PCB modularity

- Modular supporting structures for readout planes
  - Derived from CRP design of DP Incorporates cathode hanging system

- Single field cage surrounding entire active volume derived from DUNE-DP design

- Photon detectors based on X-ARAPUCA technology (same as DUNE-HD)
  - integrated on cathode plane and on the cryostat walls.
  - decoupling from HV, achieved with optical fibers for signal and power transmission.
General dimensions and cryostat for the Vertical Drift detector

- The Cryostat layout will mostly remain the same as the one foreseen for the horizontal drift DUNE detector with internal dimension: 62m x 15m x 14m

- Differences: the roof penetrations (signal and detector support) and the size of the TCO (Temporary Construction Opening)
General detector geometry arrangement

Top view:

Side view:

Cathode is suspended to the general CRP top support structures

6 cathode units suspended to SuperCRP by 12 points with dyneema (Kevlar) wires
**Perforated PCB Anode:**

**Principles:** Strips on perforated PCB 3.2mm thick

**Three view** (48°, 0°, 90°)
- ✔ 2.5 mm holes
- ✔ Collection strips in the transverse direction, 5.2mm width
- ✔ Induction2 strips along beam, 5.2mm width
- ✔ Adding 3rd view at ~48°
- ✔ Induction1 strip pitch: 8.7mm
- ✔ 8.5 mm PCB spacing

Adding a ‘shield’ layer facing the cathode to reduce the risk of charge injection to the FEE

Design for the 1st CRP and cold box test in 2021

All drift electrons are passing through the holes in the 2 layers before being collected.
Charge Readout Plane and anode assembly

- 160 CRP units (80 on top, 80 on the bottom)
- 1 CRP = $3000 \times 3375\; \text{mm}^2$
- Charge Readout Units (anodes + adapter boards)
- 1 mechanical frame

Readout by CE

Readout by DP electronics

Composite frame

Readout geometry foreseen: Identical for top and bottom:

- An anode PCB unit is 3 m x 1.7m in size, constructed by bonding several PCBs side by side.
- A CRP is made of 2 CRU

Composite frame

Top CRU

Bottom CRU

CRU

CRU

Cold electronic FEMB cards
Top CRP plane layout

Each superstructure is suspended by 4 cables and position controlled from the top of the cryostat like for Dual Phase

Top plane: 80 CRPs

Anode planarity specification: <10 mm @ cold
Design of the bottom CRP frame: 
No metallic frame, only composite frame

With the bottom CE boxes attached below the anode plane + planarity can be controlled by the supporting feet to keep each anode plane within the 5 mm deformation range

⇒ Bottom frame can be made more transparent than top frame and 
⇒ Lighter thanks to the adaptable supporting feet distribution

The bottom CRPs will be positioned on adjustable feet

- Lateral decoupling (PTFE, bearing, …)
- Vertical adjustment
- Only laid on the membrane
- No fixation, no sliding on the membrane

Cryostat membrane floor
Charge readout electronics and Adapter Board interface

Top CRP: Readout electronic identical to Dual Phase completely accessible from cryostat roof

1/2 of a CRP (TOP)

Bottom CRP: Cold electronic like for Horizontal Drift

For the \((48^\circ, 0^\circ, 90^\circ)\) => 3200 channels / CRP

Channel count per ½ CRP
1\textsuperscript{st} induction: 384
2\textsuperscript{nd} induction: 640
collection: 576

Each CRU has 8 unique FEE adapter boards, carrying 50 cable connectors to the FEE inside the roof chimneys.

8 unique CE adapter boards carries 13 CE modules, in addition to the high voltage coupling capacitors and current limiting resistors.
Requirements for the top and bottom drift electronics are the same as commonly defined in the DUNE design reports for the FD1-HD and ProtoDUNE-DP electronics.

Top and bottom drift volumes implement different CRO electronics in order to take maximal advantage of the different configurations of the two drift volumes.

Top drift electronics: use same design as for Dual Phase

- Analog cryogenic FE cards accessible in the chimneys
- AMC digitization cards in uTCA crates

Charge readout electronics

- Analog cryogenic FE cards accessible in the chimneys
- AMC digitization cards in uTCA crates
Bottom drift electronics:

Use same FEMB cards and Warm Interface Board design than the Horizontal Drift detector

- 1 chimney for 2 bottom CRPs = 5120 ch/chimney
- Chimney runs along the long side of the detector,
- Cables run vertically on trays attached to the primary membrane
- 20 cable trays per side, total 40 chimneys
- 25m long cables

FEMB in LAr for amplification, pulse-shaping and digitization

System architecture of the TPC readout electronics in the bottom drift volume.
Field cage and HV distribution

The HV system consists of:

- The HV delivery system
  - HV power supply (>300 kV)
  - PS monitoring system, HV cable, ripple filters,
  - HV Feedthrough, and
  - HV extender

- The field cage
  - 192 field cage modules, with FC aluminium profiles

- The cathode
HV Feedthrough and extender

- HV of ~300 kV entering with a vertical penetration at one extremity of the cryostat in the region where FC and the cryostat wall distance is larger than a meter
- Max drift field over 6.5m ~500V/cm
- Extender has a simplified technology compared to NP02: based on a highly electropolished metallic pipe of 20 cm in diameter.
- LAr used as insulator from FC and membrane (40 to 50 cm distance)
- Spherical extender coupling to HV-FT
- Insulating extender suspension disk and rods

The HVS distribution system largely derived from the DP layout with upgraded design

→ The whole HV distribution chain is integrated and tested at full scale in the NP02 cryostat this year
Field cage

• Field cage surrounds the two active volumes (60mx13mx6.5m each) and provides a uniform electric field to LAr for ionization electrons to drift

• Modular construction with two 5cm wide, 10cm tall, 3.25m long FRP I-beam frames and 55 extruded aluminum profiles in 6cm pitch
  - FC along the long wall : 3.0m (W) x 3.24m (H)
  - FC along the end wall : 3.38m (W) x 3.24m (H)
  - Profiles mounted on outside toward the cryostat wall, minimizing charge-up in insulator

• Along the 4 vertical edges of the field cage, the profiles are bent at 90° to provide smooth conductive surfaces to reduce field enhancement

A study on improving the optical transparency of the FC modules is being conducted, providing more flexible placement for the arapucas on the cryostat walls

• The vertical installation scheme established and validated at NP02 PDDP
  - Further optimization ongoing

An end wall field cage supper module built with a 2x4 array of FC modules
Cathode structure and interface with CRP superstructure

Cathode specifications:
- Planarity of the cathode plane: <20mm
- Weight: less than 10kg/m2
- Width: 50 mm
- Field distortion: < 1%

- Arapucas encased by highly transparent (~80%) metal wire mesh panels
- + perforated resistive panels to form two highly resistive surfaces with sufficiently slow discharge RC time

Structure: FRP beams

Assembly of 6 cathode modules with same size as CRP

Suspension systems On cryostat roof

Dyneema insulating ropes
Photon detector system

• Based on X-Arapuca tiles (like in Horizontal Single Phase detector)
• Arapucas are embedded in the cathode frame at -300 kV (4*80= 320 double sided tiles. Total surface 230 m²)
• Challenging situation => power distribution over fiber for the SiPM boards and fiber readout; R&D in progress to demonstrate connectivity in presence of HV
• Reflector on the anode surface (material to be identified)
• X-Arapuca optimized for 10 ppm of Xenon

Requirements:
• Average Light yield > 20pe/MeV
• Minimum LY > 0.5 > pe/MeV
• Time resol < 1us

The reference design: to equip also the top and bottom cryostat walls with Arapucas

Readout: SiPM signal is transmitted over fiber (both analog and digital transmission is under evaluation)
Photon detector system

Photon Detection System reference design (4π):

- 320 xArapuca (60x60cm$^2$) on cathode (2x115m$^2$) with analog readout
- 320 xArapuca (60x60cm$^2$) on cryostat membrane (115m$^2$) at 3m from cathode and standard FD1 readout
- 70% transparent field cage

Backup design:

All arapucas on cryostat walls (no HV)
- 720 x-Arapuca (60x60cm$^2$) on cryostat membrane (260m$^2$). Standard FD1 readout with no PDS at 300kV.
- Xe doping, 70% transparent field cage

- 70% transparent field cage design concept is being demonstrated in the NP02 cryostat in parallel to the 300kV test now.
- An high E field test in a small setup is planned early next year to validate if the full height transparent field cage is safe to operate
Summary:

Vertical Drift detector advantages:

- Extended drift distance, profiting from excellent LAr purity, allows to maximize the fiducial mass by reducing dead material in the active volume
- Highly modular concept of each detector component
- Simplified installation and QA/QC procedures, not requiring large in situ infrastructures
- Simplified anode structure based on standard industrial techniques
- Field cage structure completely independent from the other detector components
- R&D on photon detection system at high voltage in progress
- Possibility for a Photon detection system with improved light detection coverage and trigger efficiency wrt Horizontal Drift; equivalent to HD if only cryostat wall instrumented
The END
Activities on the Neutrino Platform at CERN

- Vertical Drift HV system test in NP02 cryostat
- Cold-box tests
- Vertical Drift Module-0 in NP02 cryostat
Neutrino Platform @ CERN

- **Provide** to the $\nu$ community a **test beam infrastructure** (charged particles)
- Bring **R&D** at the level of **technology demonstrators** in view of major technical decisions
- **Support** the short & long baseline **activities** (infrastructure & detectors)

**TPC Prototypes** at the scale 1:20, with **modules at the DUNE scale**
Two technologies originally investigated (LAr single phase (NP04), LAr double phase (NP02))
Main Goals of tests @CERN

- Demonstrate the continuous operation of a 300 kV distribution system
- Test of the 70% Transparency Field Cage

Characterize and validate the design and the construction procedures of:

- Mechanical tests of the perforated PCB anode assembly (CRP) in cryogenic conditions
- Characterization of the performance of the perforated anode and of the full electronics chain (top and bottom) in terms of signal to noise ratio and its stability
- Mechanical test of the cathode module in cryogenic conditions
- Test the light readout system concept running in an HV environment
- Test the integrated system as a whole and evaluate the interplay between the powering scheme, the charge readout electronics and the light readout system
• HV extender for Double Phase developed an issue (short path connection to the field cage)
• **New Simplified Design**
  • 6m long, 20cm diameter, 2mm thick polished SS tube main-body HV extender w/ a 90° elbow
  • Uses LAr as the insulator instead of completely confining the electric field in the extender itself
  • Placed in the middle of 1m gap between Field Cage and the cryostat wall
  • Spherical HV FeedThrough receptor of 25cm diameter

**Vertical Drift HV system test in the NP02 cryostat in 2021**
• Tests and validations at FNAL and CERN (May-July)

• Modification of the HV-FT and extender coupling mechanism until successful operation at 300kV in standalone test setup

• New series of tests at CERN in July before NP02 installation
Current Status

- HV running at 300 kV till mid-September in NP02

- Stable Voltage but current blips (duration < 1s) with rate of one event per 1 to 2 hours => origin under investigation
Current Conclusions

- The stainless steel extender body is very stable over the full 6 m length and the elbow termination.

- 40 cm distance from corrugated membrane is enough to hold 300 kV even with LAr purity exceeding 1 ms.

- The new HV Feedthrough seems perfectly adequate for operation at 300 kV.

- The cable termination, including the 50 Mohm filtering resistance, is also working properly.

- Any optimization of the HV distribution design should involve only the extender head and can be tested in smaller cryostat.

- Understanding in progress of the geometry and the origin of the sparks from the extender head to the polyethylen plate.

- External telescope to study coincidence with large cosmic ray showers.

- Data taking foreseen with Double Phase detector.

=> IN2P3 effort for DAQ (duplication with ColdBox) and running the detector (CRP, readout status …)
ColdBox Tests

- Cryostat able to host cathode and CRP of dimension $3 \times 3,375 \text{ m}^2$
- Refurbished version of previous ColdBox for Double Phase
- LAr level stability maintained within +/- 5 mm
- Liquid argon purity compatible with electron drift over 20 cm
- Absolute vapor pressure stabilized to a few mbar around the nominal value
- Drift distance of at least 20 cm with a drift field of 500 V/cm $\Rightarrow$ Cathode at $-10 \text{ kV}$
The ColdBox content (Photodetector not shown)
ColdBox Planning

- Huge effort of IN2P3 groups for design, production and installation

- Dry run: sufficient purity achieved for >20 cm drift (lifetime about 200-300 μs)

Here we are (~ few weeks of delay compared to April planning)
Top electronics readout and DAQ

- **Top CRP readout** based on the completely accessible electronics (cryogenic ASICs and Front-End cards, uTCA digitization cards, timing system and DAQ) successfully operating on **NP02/protoDUNE dual-phase**
- **Adaptations** and **developments** for the Vertical Drift: new FE cards with decoupling components for VD anodes, change of digitization cards dynamics for bipolar signals of VD induction views, development of 40 Gbit/s uTCA connectivity/DAQ
- Need to preserve integrity and operation of NP02/protoDUNE-DP for HV test → readout electronics, DAQ and ancillary systems. Sharing of NP02 DAQ back-end/storage. **new system independent on NP02**
- Components for the ColdBox test for a full top-drift CRP (3200 channels) procured with **new productions in spring 2021** (ASICs, front-end cards, digitization cards, timing cards and distribution, uTCA crates, low voltage system, calibration system and DAQ system) and **extensively tested** by the beginning of the **summer 2021**
- **Dedicated production** of 5 mini-chimneys for the cold-box tests.
Chimneys integration with Top electronics and DAQ

- **Full integration test performed in July** in a dedicated area at EHN1 for one chimney, including all elements produced for the cold-box (chimneys, low-voltage system, timing system, pulsing system, uTCA crates, DAQ, data fibers infrastructure) → **validation of all readout chain elements and noise in agreement with expectations**
- Three chimneys fully tested with DAQ in the integration setup: September-October
- Integration setup dismounted and **needed material moved to ColdBox area last week**
- **Chimneys installed** on ColdBox roof **last week**
- **CRP cabling** to chimneys performed **last week**

FFT noise spectrum:
- Good noise conditions despite temporary setup not connected to cryostat ground but to EHN1 building ground
- Very little coherent noise contamination present
Cathode

- Designed in April
- Produced in the industry in June-July
- Assembled at CERN in September
- LAr tests end of September
- Bending about 15 mm within the requirements
• **Photon Detector fully integrated** last week

• Several possible solutions for the electronics have been installed

• **One solution provided by IN2P3**
Cathode installed in ColdBox last Thursday
Charge Readout Plane

- 2 PCB
- 3 views with different angles

Reference design + shield layer

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

Hole alignment between PCB’s allows to minimize biasing voltage on four electrode layers
Charge Readout Plane

- Mechanics is an evolution from Double Phase design
- Need to handle top and bottom electronics
- New design last spring
- Production this summer
• Composite Frame assembly

• Link to metallic structure
Bottom and Top Charge Readout Unit assembly
Fully assembled CRP seen from below
Fully assembled CRP seen from above
CRP Integration last week

Attachment to the cold box roof

Instrumentation installation (level meters, temperature probes)

CE cable routing and connection through the flange

Top electronic routing and connection to the chimneys and on the CRP
• CRP Insertion in the ColdBox yesterday

• Start of commissioning this week in gas phase before LAr filling
Vertical Drift Module-0 in NP02

- Almost a scale 1:1 test
- Mandatory step to validate integration of all elements before mass production
- Production Readiness Review foreseen at the end of 2023
- Same activity for HD in NP04

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Anode (48,0,90) T/B electronics
Anode (+30,-30,90) T/B electronics
final anode strips, full top CRP/electronics
final anode strips, full bottom CRP/electronics

Legend:
- Cold-Box: production
- Module-0: construction, installation, operation
Module-0 in NP02

Tunable HV from 75 kV (same drift time) to 300 kV (same max HV) passing by 150 kV (same drift field)
Conclusion

- Intense program of tests (2021-2023) at the CERN neutrino platform in view of launching the mass production for the second VD FD module at the end of 2023
  => IN2P3 teams deeply involved with strong responsibilities and visibility

- New, simpler, extender design holding 300 kV => valid design for the VD HV layout

- Commissioning and tests for ColdBox will start in the coming days
  => very strong effort performed in 2021 to keep the planning. Exciting period with tests results of the first fullscale VD CRPs in front of us

- ColdBox runs will allow if needed in several iterations perfecting final design in view of production

- VD Module-0 will arrive soon almost in parallel to HD Module-0 => Sufficient scientific and technical staff needed to insure the success

From the closeout report of the LBNC September 2021 meeting reviewing CDR and activities at the CERN Neutrino Platform:

"A year ago the Vertical Drift concept was a glint in a few peoples eyes. We have observed an ambitious R&D program which is enjoying amazing success. We have reviewed the technical aspects in the Spring of the year and recently reviewed a complete Conceptual Design Report. DUNE has our comments, and we have discussed their path to what we anticipate will be a recommendation for approval of the CDR by the end of the year"
BACKUP
- Original extender had very complicated design using a G10 cylinder to insulate the central conductor and bring the HV to cathode. The G10 cylinder was surrounded by equipotential rings connected to the field cage in order to contain locally the electric field (very strong in the first rings).

- A short between the second equipotential ring (connected to field cage) and extender conductor developed in August 2019 during commissioning at 250 kV due to a crack developed in G10.

- In situ repair attempt in June 2020 (cut with external surgery first 3 connection links of equipotential rings to field cage) → short path deported to 4th connection due to surface current developing on G10.

- Extender removal May 2021 → localization of the short in a fault in G10 material below the second ring.
E field simulation

E field on the surface of the left nut (conductor): 12kV/cm in gas.

E field under the CRP extraction grid: 900V/cm

E field in the liquid under the surface: 600V/cm
Charge accumulation at the surface (-1μC/m²)

E field on the surface of the left nut (conductor): 17kV/cm in gas.

E field under the CRP extraction grid: 2kV/cm

E field in the liquid under the surface: 540V/cm