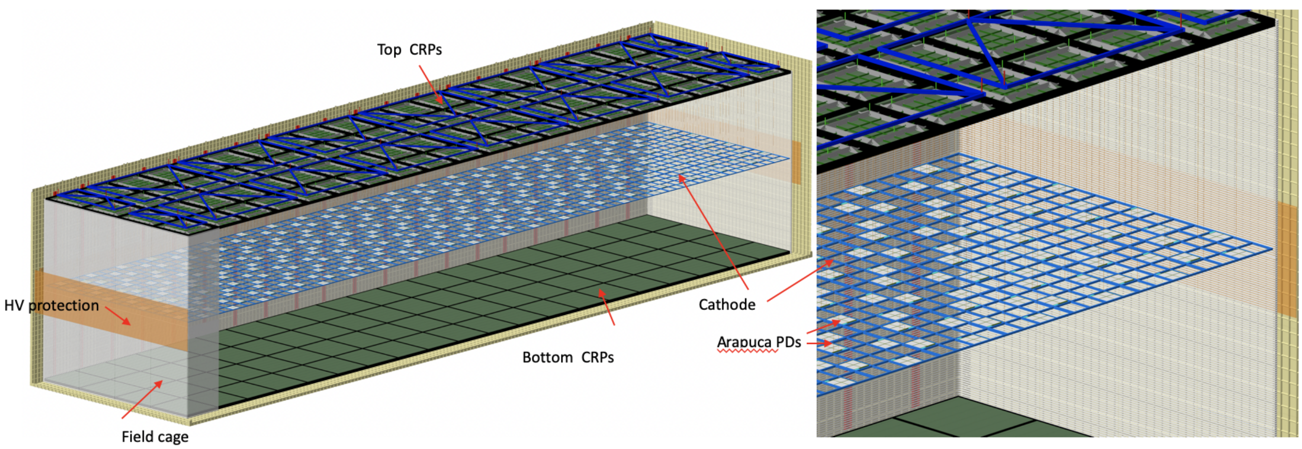
Deep Underground Neutrino Experiment Far Detector Conceptual Design Report

Single-Phase Vertical Drift Technology

June 4, 2021



DEEP UNDERGROUND NEUTRINO EXPERIMENT

Chapter 5

High Voltage System

5.1 Introduction

A LArTPC requires an equipotential cathode plane biased at high voltage (HV) and a precisely regulated interior electric field (E field) to drive ionization electrons traversing LAr to an anode sensor plane. The DUNE vertical drift detector module design, which assumes two drift volumes of equal drift distance 6.5 m and a nominal uniform E field of 500 V/cm, will have a horizontal cathode plane placed at detector mid-height and held at −325 kV, and horizontal anode planes at the top and bottom of the detector, as described in Chapter 3. The design features a 13 m full-height field cage (FC) along the vertical walls surrounding the detector volume to ensure a linear voltage gradient in the vertical direction, up or down as appropriate, from the cathode plane toward each anode plane. It consists of horizontal field-shaping electrodes stacked at regular intervals and interconnected by resistive voltage divider chains. The bias voltage to the cathode and FC is generated by a HV power supply located outside of the cryostat. A HV cable is routed from the output through a HV feedthrough mounted on the cryostat roof. The bottom of the feedthrough is attached to an extender, allowing the cable to reach 6.5 m down to the cathode plane. The key system components inside the cryostat are shown in Figure 5.1.

5.2 Specifications

One of the strengths of the vertical drift TPC is the large coverage (40% or higher)

BY: where is this 40% come from?

of the capable photon detection system (PDS). The mounting of these photon detectors in the cathode plane and on the surface of the FC with HV poses complications with the functionality and safety of the photon detectors as well as the impact to the uniformity of the field in the active volume. In this regard, the current reference design of high voltage system (HVS) is to insert photon detectors on the cathode plane to cover 14% of the surface, exposed to both the top and bottom active volumes. This design also employs the field cage with narrower aluminum

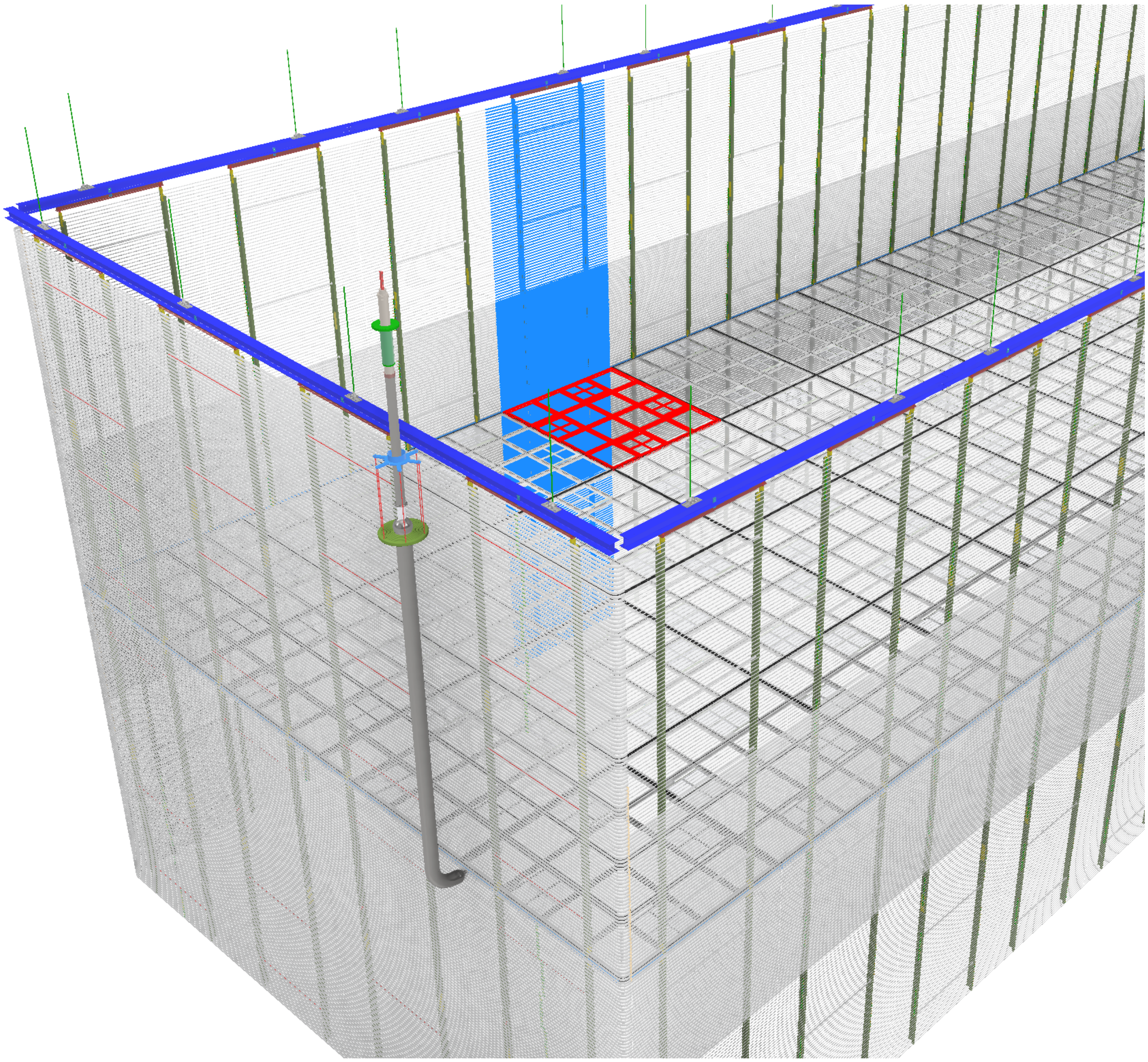


Figure 5.1: A view of the field cage (with one full-height FC column highlighted in cyan), the HV feedthrough and extender (in the foreground), and the cathode (with one cathode module highlighted in red). All of these drift field system components are inside the cryostat (not depicted).

profile electrodes which are 15 mm tall (compared to the 46mm in other areas) along the long wall, covering ±2.5 m to ±6.5 m of the each active volume, providing a 70% photo-transparency to the photon detectors mounted on the cryostat wall. Figure 5.2 shows a visualization of the field cage which employs the 70% transparent design.

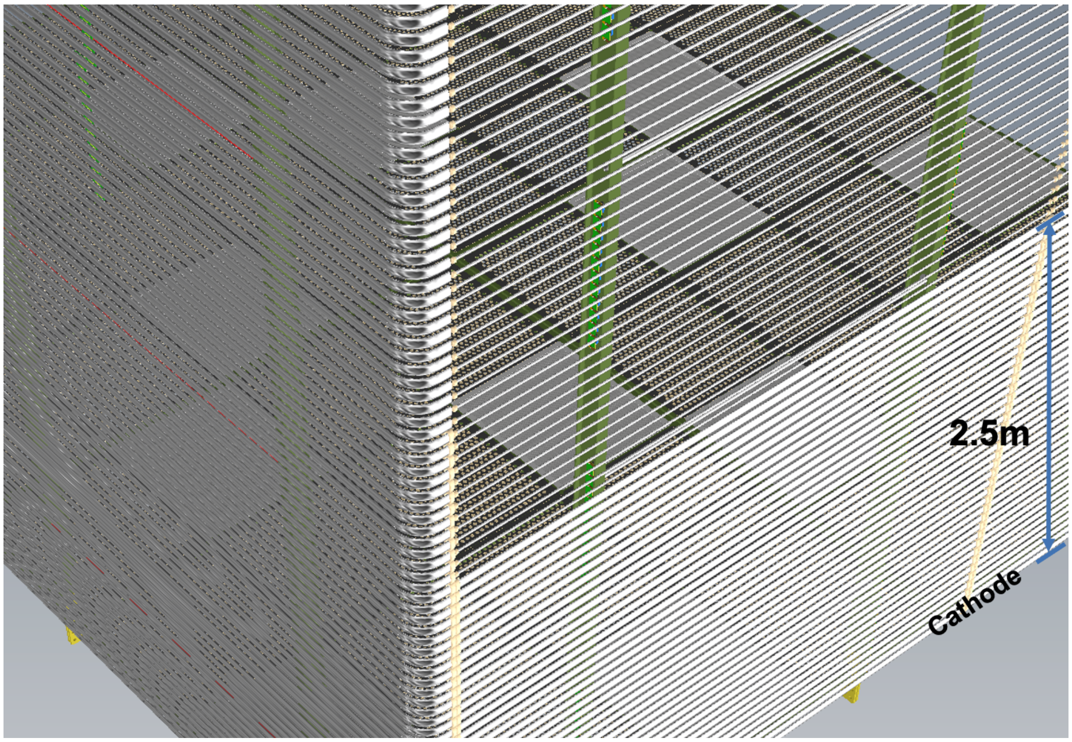


Figure 5.2: A depiction of the field cage with 70% optical transparency along the long wall.

The high level design requirements of the HVS are as follows:

- Minimum draft field: 250 V/cm (goal: 450 V/cm)
- Drift field uniformity: $< \pm 1\%$ over 99.8% of the active volume
- Cathode HVPS ripple contribution to system noise: $< 100e$
- Cathode resistivity: >1 MΩ/square, <10 TΩ/square (goal: >1 GΩ/square);
- Local electric fields: < 30 kV/cm, except for specific components with localized E field higher than 30 kV/cm, perform tests in pure LAr at least at 120% of the designed operating voltage;
- Detector uptime: > 98% (goal: > 99%);
- Individual detector module uptime: > 90% (goal: > 95%);
- Maximize power supply stability: > 95% uptime;
- Provide redundancy in all HV connections: two-fold (goal: four-fold);

Most of these requirements have been confirmed at the ProtoDUNE I, horizontal single phase TPC prototype.

5.3 HV Supply and Delivery System

5.3.1 High Voltage Power Supply and Cable

Low-noise 300 kV HV power supplies and dedicated >300 kV cables are commercially available. While noise from the HV power supply was not an issue for the ProtoDUNE detectors, the requirement of low ripple on the vertical drift technology (FD2-VD) cathode and field cage is slightly more relaxed than that for the anode plane assembly (APA) based TPC due to the shorter strip lengths and a more effective shielding plane on the first anode plane facing the cathode. The optimization of a ripple filtering stage is part of the R&D activities described in Section 8, along with investigations into increasing the deliverable voltage of the existing HVPS to enable reaching the nominal drift E field goal of 500 V/cm. At the time of writing this report, two companies, Heinzinger and the FUG, have been contacted and discussion is ongoing for them to provide a HVPS capable of delivering -325 kV or higher.

5.3.2 HV Feedthrough and Extender

The high voltage feedthroughs (HVFTs) used by the ProtoDUNEs were tested at 300 kV. Following the lessons learned in operating the ProtoDUNEs, further improvements in the design, shown in the middle panel of Figure 5.3, are already being applied to ensure long-term stability. An HV extender is installed between the tip of the HVFT and the cathode plane to deliver the voltage, as shown in the left panel of Figure 5.3.

check that the ucla improvements are detailed somewhere. Anne

The extender is a 6 m long polished stainless steel tube with an outer diameter (OD) of 20 cm and a 2 mm wall thickness, mounted under the HVFT. Where it reaches the cathode it is welded to a 90 degree elbow that tapers to a smaller diameter and makes a flexible (spring-loaded) connection to the FC profiles. The elbow must have a gentle curvature to minimize any increase in the local E field.

The extender support structure shown in Figure 5.3 (right) allows the HVFT to be lifted up and out of the penetration without disturbing the extender assembly. A stainless steel sphere at the top of the extender opens or closes a hole in a G10 plate that serves as a receptacle for the tip of the HVFT. G10 rods connect this plate to a support bracket attached to the bottom of the HVFT penetration on the cryostat ceiling. This HVFT and extender interface is recognized as the most challenging part of the HV system and will be thoroughly studied and tested to ensure reliable operation as described in detail in section 8.

is this the ucla design?

fig 5.3 caption needs more detail. anne

This simplified version of the HV extender uses the LAr itself as the electrical insulation. Finite element analysis (FEA) has shown that a conductive cylinder at 300 kV with a diameter between

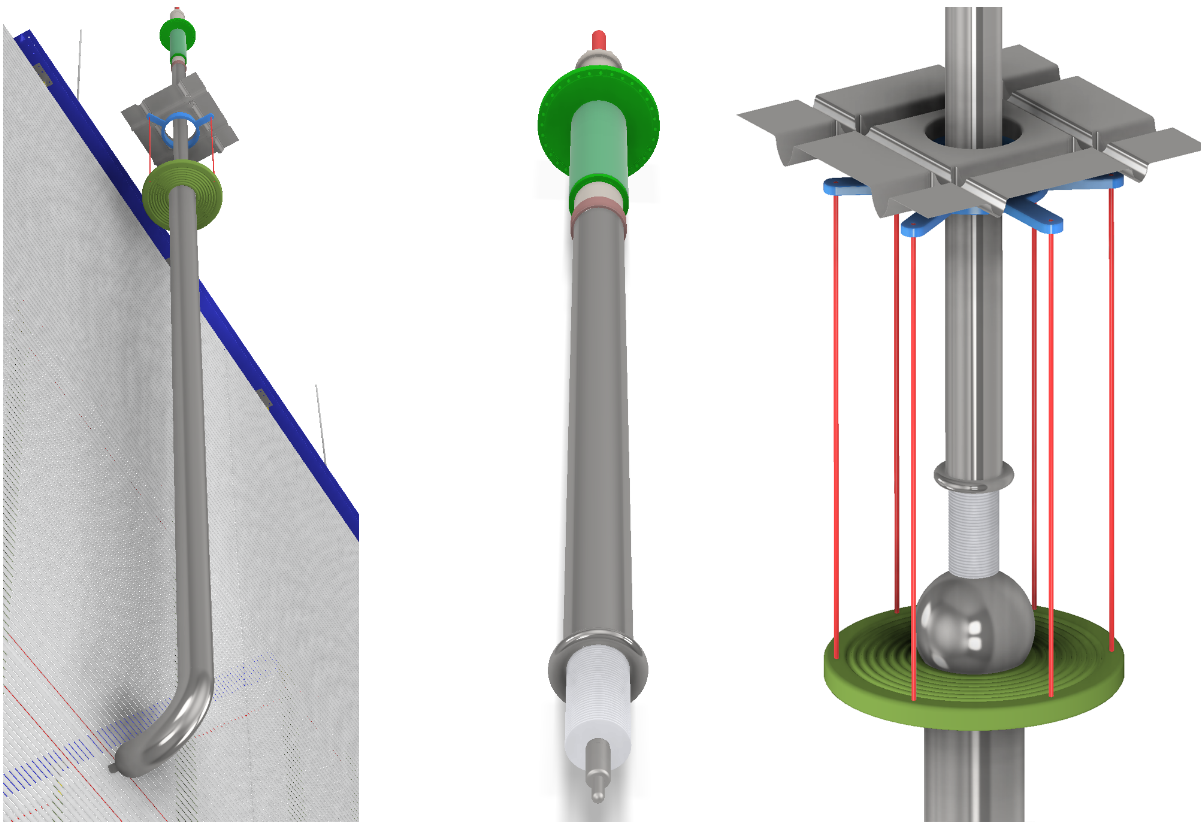


Figure 5.3: Left: Conceptual design of the HVFT and the simplified metal tube extender assembly connected to the FC at mid-height and to the cathode plane. Middle: Design of a HVFT by UCLA. Right: Details of the HVFT and extender interface. A small section of the ceiling membrane at the cryostat ceiling is shown to indicate the relative position of the support structure for the spherical HVFT receptor and the FR4 rods holding the support plate.

200 mm and 400 mm placed in the center of a 1 m gap between two grounded parallel planes will have a maximum surface E field of 17 kV/cm. This is well below the 30 kV/cm E field limit required for safe operation in LAr. The HVFT and extender will be placed on the side of the cryostat opposite the temporary construction opening (TCO) (Section **??**), where the distance between the FC profiles and the flat face of the cryostat membrane is 1.1 m. The knuckles and corrugations of the membrane have smaller radii of curvature and must be covered by a vertical band of flat conductive sheet. The internal cryogenic pipes on this end of the cryostat must also stay clear of the HV extender.

As an alternative solution, the possibility to cover the extender with high resistivity HV stress relief shrink-tube, similar to what is often used in HV cable terminations to quench corona-like current leakage, is also considered. Optimization of these details are underway mainly focusing at the minimization of local electric field on the surfaces of the electrodes and the insulating surfaces such as the extender supporting plates (see Figure 8.26 right).

Extender Assembly HV Testing The experience at the ProtoDUNE Dual Phase high voltage extender which developed a short at around 1.5m below the LAr surface and prevented operation of the full active volume, it is essential for the new extender design to be thoroughly tested. A testing of the essential HVS components, namely the connection of the HVFT receiver at the top of the extender and the 90° bend portion at the cathode level is being conducted at Fermilab. The details of this crucial testing is described in section 8.

5.4 HV Distribution System

The -325 kV HV is delivered to the cathode plane via the HVFT and the extender system. The field cage that surrounds the active volume is connected to the cathode plane and distributes the voltage uniformly throughout the active volume. The actual distribution of the voltage from the cathode to the field shaping rings is done via HV divider boards (HVDBs) which ensure uniform voltage drops between neighboring field-shaping rings. Multiple resistor boards and multiple resistors on each board guarantee redundancy. These are very similar to the boards used in the ProtoDUNEs. The current is returned through the HV return board, which is equipped with a voltage and current monitoring system. These components, depicted in Figure 5.1, are described below.

5.4.1 Cathode

The cathode plane, while modular like the ProtoDUNE cathodes, requires an all new design due to the unique requirements that the FD2-VD design imposes on it, for example that photon detectors (PDs) will be integrated into it. A conceptual design is shown in Figure 5.4.

Each cathode module has the same footprint as a charge-readout plane (CRP) module, with dimensions of 3 m×3.375 m×50 mm. A module's weight (including the PDs) is required to be less than 10 kg/m^2 in air to minimize deformations of the CRP superstructure from which it hangs from. To remain under the maximum bending constraint of 20 mm in LAr across the surface of each module, the cathode is constructed from the fiber reinforced plastic (FRP) I-beams of 50 mm height, 80 mm width and 8 mm thick central part. The frame forms 16 equally sized openings of 687 mm × 781 mm. The four openings containing a PD are covered with stainless steel wire-

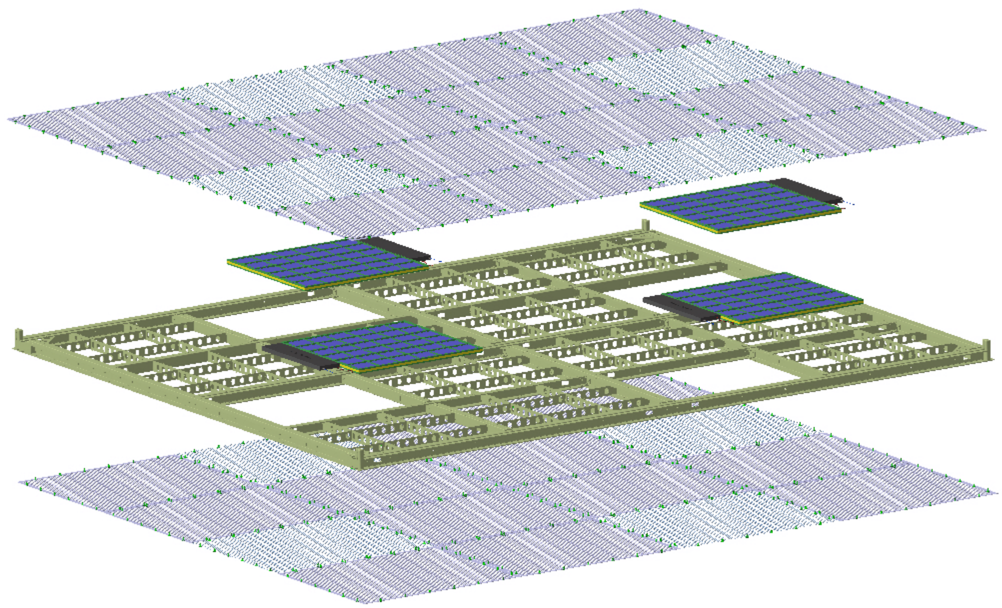


Figure 5.4: Conceptual design of a cathode module with integrated PD units. The top and bottom surfaces of the cathode module are tiled with highly transparent mesh panels. The mesh panels are interconnected by a FRP piece with a layer of resistive coating. Photon detector modules are embedded inside the cathode frame openings between the two layers of mesh panels.

mesh panels on both sides to ensure a transparency greater than 85% to maximize light collection. Standard stainless steel wire mesh that reaches an optical transparency above 86.5% and satisfies all the requirements is commercially available.

The remaining twelve openings of a cathode module are covered with the FR4 panels laminated with a resistive film (DuPont DR Kapton[1]) and perforated to ensure a transparency greater than 60% to the LAr flow. This scheme both reduces the peak current flow along the cathode in the event of a HV discharge and slows down the associated voltage swing, which reduces the noise into the readout electronics. Moreover, the pitch of the mesh wires must be set so as to preclude significant distortions of the E field, imposing a pitch lower than 30 mm. To ensure the planarity of the mesh, which is quite loose due to the transparency constraints, supports are provided in all the cathode frame openings. Cross ribs with holes to reduce the weight and allow the LAr flow are added in the openings without PDs, and supports are inserted across the PD dead zones in the openings housing the PDs (see Figure 5.5) to further strengthen the mechanical support.

PD modules are mounted to the FRP frame inside selected openings and are enclosed by the stainless steel mesh for both electrical and mechanical protection. The power and signal fibers for the PDs are routed inside the frame to the nearest FC modules. Electrical connections between the cathode modules and the FC are made by gold-plated spring loaded contacts on the cathode-facing edges of the field-shaping rings and through direct wire connection to ensure redundancy.

Six cathode modules are assembled together, forming a super module the size of a CRP super-

[1]DuPont®, https://www.dupont.com/electronic-materials/polyimide-films.html/

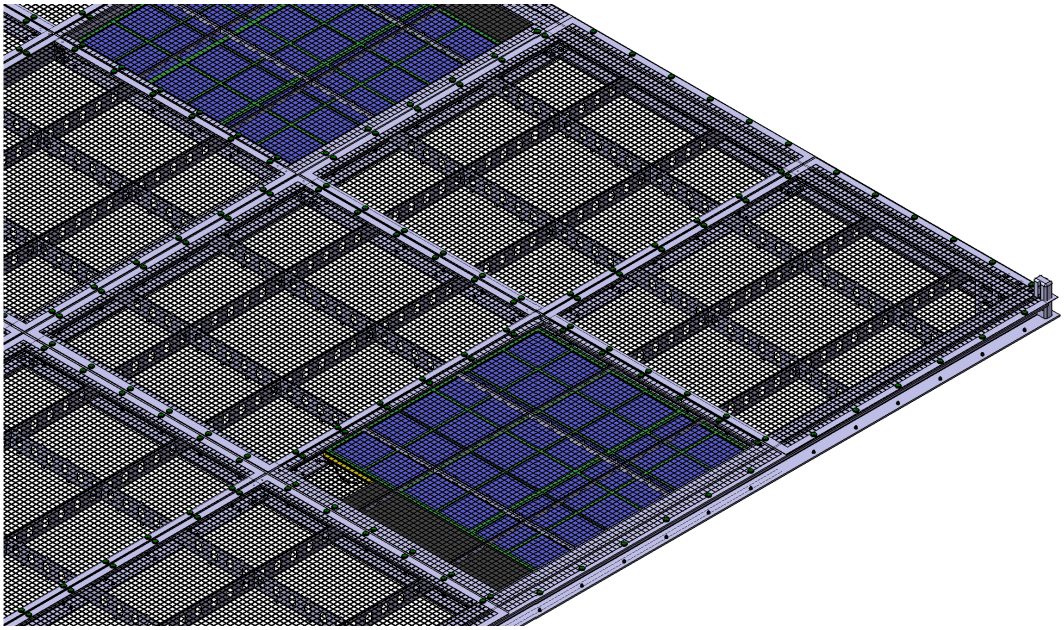


Figure 5.5: View of a quarter of a cathode module with the cross ribs supporting the mesh on both sides of the cathode. PD appear in blue with their associated electronic box in dark gray.

structure (including its extensions). A cathode super module is suspended from a superstructure's extensions and its center using 12 wires, as illustrated in Figure 5.6). This configuration limits the cathode distortion to about 15 mm in LAr and 32 mm in air across the surface of each cathode module. All 12 wires are strung in a vertical plane, 10 along the perimeter of the cathode super module at each junction of the cathode modules and one each at the two junctions in the center of the super module. The entire cathode plane consists of 20 cathode super modules.

5.4.2 Field Cage

ProtoDUNE-DP has demonstrated the simplicity of installing a FC in a vertical drift TPC. The ProtoDUNE-SP has operated successfully and collected lessons learned, leading to an updated FC design for the horizontal drift technology (FD1-HD) FC in which all insulating materials on the side of the FC facing the grounded cryostat wall have been removed to improve HV stability. The updated design also includes improved assembly fixtures. The FD2-VD FC design is adopting both of these improvements to benefit from both improved performance and even greater simplicity of assembly.

The FC modules for the long walls are 3.0 m wide × 3.24 m high, and for the end walls, 3.38 m wide × 3.24 m high, the widths of their al profile electrodes matching the CRPs' edges. Each FC module consists of 55 aluminum electrode profiles stacked vertically at a 6 cm pitch. They are mounted on two 10 cm tall 5 cm wide FRP I-beams of length 3.25 m spaced 2 m apart from each other. The end wall profiles that meet the four corners of the cryostat (one end per wall) are bent 90 degrees with a 10 cm bending radius to avoid charge buildup on the insulating caps at the corner. Figure 5.7 shows the proposed FD2-VD FC end wall module design.

Two columns of four FC modules each form an FC supermodule, 6.0 m(W) × 13 m(H) for the long walls and 6.76 m(W) × 13 m(H) for the end walls. The four walls surrounding the two active drift

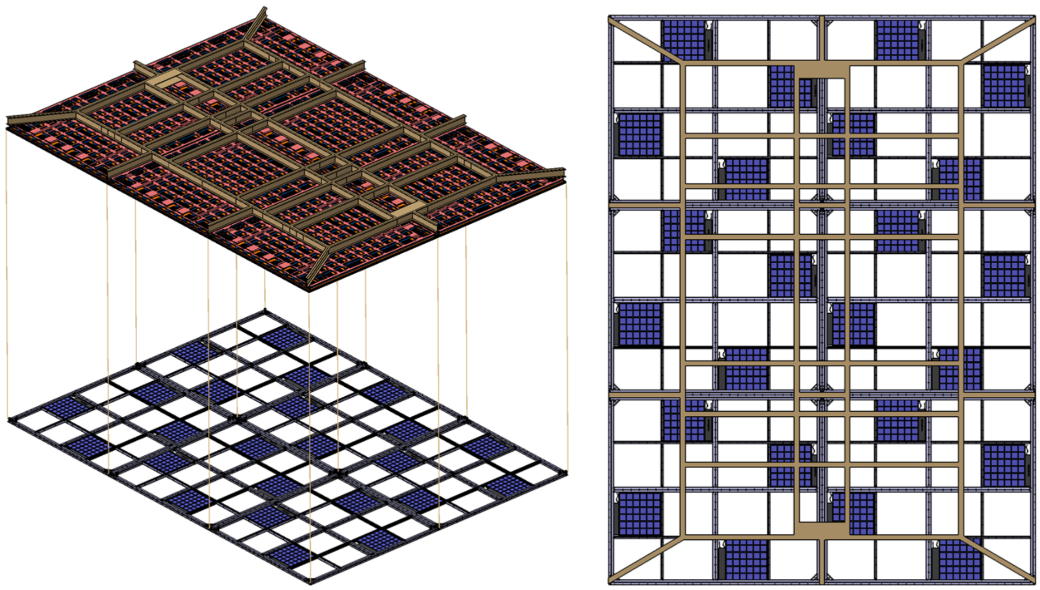


Figure 5.6: Conceptual View of six cathodes suspended to a CRP superstructure. Left: side view. Right: top view from the CRP superstructure (the mesh and the anode have removed for a clearer top view).

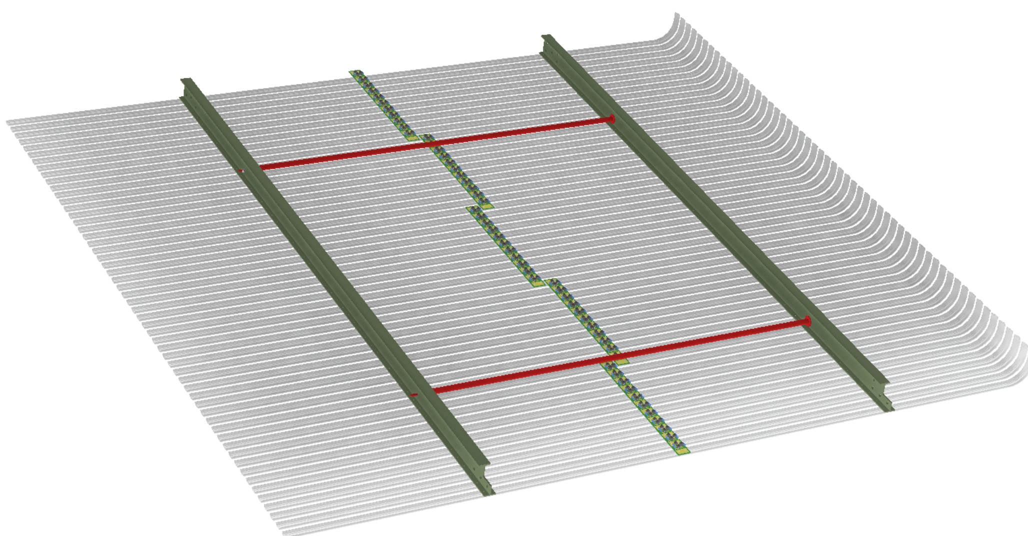


Figure 5.7: An end wall field cage module with its profiles with a 90° bend on one side to minimize the local field and to align with the FC module along the adjoining long wall.

volumes are formed by 10 supermodules each along the long walls, and two each along the end walls. Each supermodule hangs from a stainless steel I-beam with two lifting rods each going through a roof penetration (I&I scope). A total of 48 roof penetrations will be provided for the support of these field cage supermodules. Each mechanical feedthrough flange on top of these penetrations will be designed to allow the field cage lift rods, which are connected to the FC supermodule, to be pulled up and anchored on the flange. The FC support flange must also implement a mechanism to allow the FC supermodule to be moved laterally for a few centimeters to avoid interference with the CRP when during the FC installation.

The cryostat roof is expected to deform inward by about 1 cm after the cryostat is filled with LAr, causing some of the FC supermodule support I-beams to tilt a few millimeters, which would in turn cause a larger swing of the 13 m tall FC columns. To minimize lateral forces between modules, each top FC module is connected to its supermodule support I-beam through an intermediate yoke at a single point located directly above the center of gravity of the assembled FC column.

Unlike the FD1-HD, since most of the FD2-VD components are oriented horizontally and occupy narrow space in vertical direction. they are consequently less sensitive to vertical temperature gradients. The field cage, however, is an exception due to its orientation to provide a vertical drift field. To enable the FC to tolerate a greater vertical temperature gradient, the aluminum profile electrodes will be attached to only one of the two FRP I-beams on each FC module, allowing them to slide slightly on the other I-beam. The enhanced tolerance will reduce some constraints on the cryogenics system for cryostat cool-down and filling.

I don't understand why allowing the sliding makes them more tolerant of temp gradients. Anne **(this is because the amount of contraction of the profiles differ near the cathode versus near the CRP due to the vertical temperature gradient. Thus, if the profiles are fixed on both the FRP frames over the entire height, the differences in contractions will distort the FC module. By tightening only to one FRP frame but leaving the other side lose, allows the profiles slides independently, leaving the FRP beams in their own places. –jy)**

The field cage profiles are positioned 5 cm away from the edges of the cathode modules. This buffer zone ensures the electric field is smoothed out at the boundaries of the active volume from a highly modulated pattern due to the discrete FC electrodes. Since the FC support I-beam is 10 cm deep, cutouts must be made on the FC I-beams to clear the cathode modules, and the top and bottom CRPs, which have the same footprint as that of the cathode.

This 5 cm vertical gap between the cathode and the field cage is in the transition region between two drift field of opposite directions. Due to the lack of well defined electrodes in this gap, non-uniform electric field extends into the active volume, as can be seen clearly in the left panel of Figure 5.8. To improve the field uniformity, a set of aluminum strips is mounted on the set of FC profiles at the cathode height, effectively extending the cathode surface to the field cage. The right panel of Figure 5.8 shows the improved field uniformity at the edge of the cathode plane. The additional field shaping strips essentially form a 5 cm×5 cm channel between the field cage and the outer perimeter of the cathode plane. A high voltage bus will be installed inside this channel to distribute the cathode high voltage to all the field cage columns. Similar to what has been done for FD1-HD, this high voltage bus will be constructed from segments of a HV cable, with periodic connections to the cathode panels.

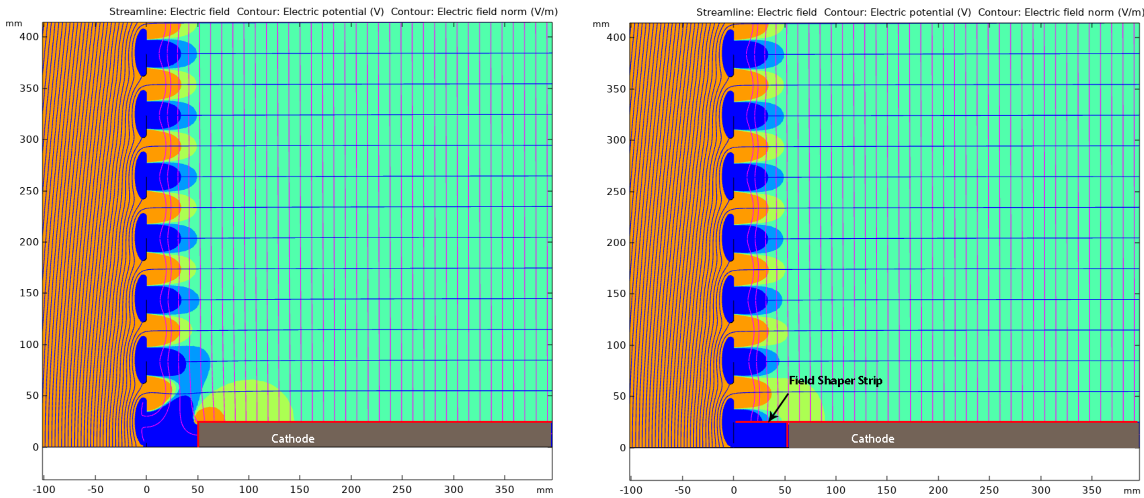


Figure 5.8: E field uniformity near the cathode and field cage intersection. Left: Cathode to FC gap (5 cm) open; Right: A field-shaping strip is installed in the gap to extend the cathode surface to the FC. The horizontal blue lines are equipotential contours, the vertical magenta lines are E field lines, and the color contours mark the regions that deviate ±1%, and ±5% from the nominal drift field.

in fig 5.8 where are the profiles themselves? seems like they're the left side of the dark blue areas. Please clarify. Anne

Transparent Field Cage: The reference design of the photon detector system has a large fraction of the photon detectors mounted on the cryostat wall, to collect photons transmitted through the field cage. However, the field cage design used in the two ProtoDUNE TPCs is only about 20% optically transparent. Naturally, a highly transparent field cage is desired to allow as much light as possible to reach the wall mounted PDs. But having a more transparent field cage requires either narrower FC profiles or larger profile pitch. Both of these options will increase the surface electric field on the profiles, therefore increase the risk of high voltage instabilities on the field cage. A hybrid solution is chosen to give 70% optical transparency to the PDs without causing additional increase in surface field on the profiles.

To increase the transparency of the field cage, a narrower extruded aluminum profile is designed. It has an elliptical shaped surface facing the outside of the TPC, yielding a relatively low E field on the surface even if positioned next to the cathode plane. The profile has a 15 mm width, at a 60 mm pitch, gives a maximum 70% transparency with the other field cage structures included. The cross section of this profile is shown in the top left of Figure 5.9. A comparison of this and the conventional profile is shown in the right.

The lower left of Figure 5.9 shows the E field distribution surrounding the narrow profile when it is positioned as the first profile immediately next to the cathode plane. The peak E field at this position is 13 kV/cm, well below the 30 kV/cm limit we imposed on all electrodes. Nevertheless, it is about 50% higher than that of the conventional wider profiles at the same position. To mitigate this potential risk of higher E field on the field cage surface, the narrowed profiles will only be used to cover field cage surfaces further away from the cathode plane where the bias voltages of the profiles are much lower. In the reference design of the field cage, the aluminum profiles for the FC in ±2.5 m to ±6.5 m range from the cathode along the long wall will have 15 mm width whereas the remaining profiles are of the width 46 mm.

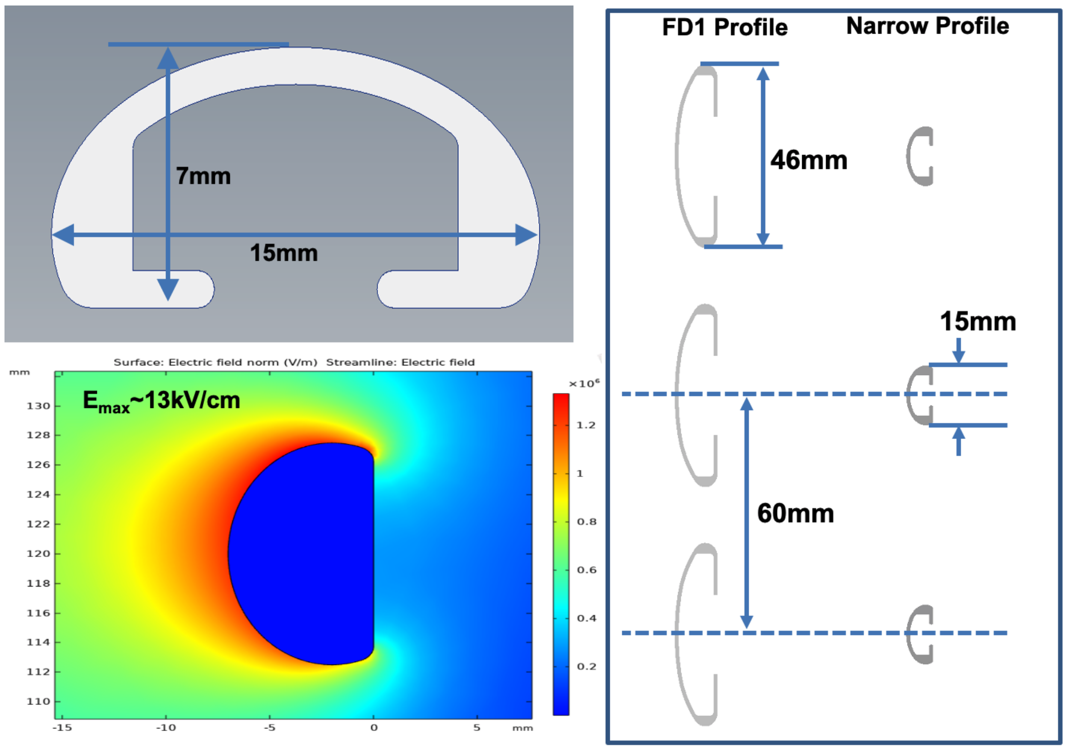


Figure 5.9: Top left: A cross section of a narrow aluminum profile, bottom left: local E field of a narrow profile when positioned next to the cathode plane, right: A comparison between the cross-sectional view of the FC configuration with wider profiles and that with the narrower profiles

the aspect ratios of the left pictures are wrong

Since the photon detector system only plans to install their detectors on the membranes along the long wall, the end wall FC can use the normal width profiles. Due to the 90° bend at the corners of the FC, the normal width profiles have a lower E field (17 kV/cm) than the narrow profiles would have (29 kV/cm). A 3D FEA E field of the corner section of the FC at the transition height is shown in Figure 5.10 left. In order to maintain the field at the 70% transparency transition height as uniformly as possible, a fine adjustment of the potential differences in the region is necessary as shown in Figure 5.10 right.

The distance of the FC profiles from the outer surface of the flat part of the membrane is estimated to be ∼700 mm. Once the height of the so-called knuckles in the membrane, where the vertical and horizontal corrugations cross and the depth of the cable trays for the bottom CRPs are taken into account, this distance is reduced to ∼620 mm. Extrapolating from the ProtoDUNE-SP HV experience, this is a safe separation for operation at 300 kV on the cathode. The hydrostatic pressure from the ∼7 m of LAr suppressing the formation of gas bubbles also helps the stability of the field. To further reduce any possible effect of high E field at the membrane knuckles, a flat ground panel will be added at the height of the cathode, extending ∼1.2 m both above and below the cathode plane along the full detector perimeter. Figure 5.11 shows a cross section of the

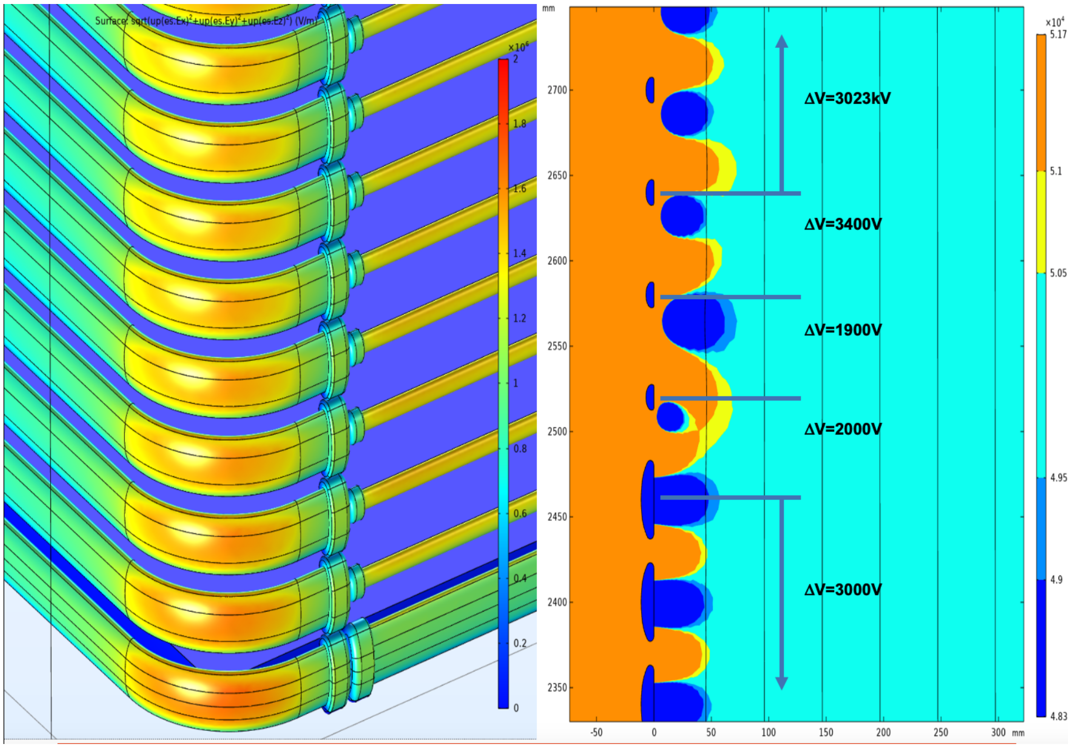


Figure 5.10: Left: A 3D FEA of the corner FC at the transition height, Right: 2D FEA E field map of the 70% transparent FC transition height

detector with the layout of the main elements described above.

5.4.3 HV Divider Boards (HVDB)

The resistive chain for voltage division between the profiles provides a linear voltage gradient between the cathode and the top-most and bottom-most field-shaping rings. This chain is critical because it determines the uniformity of the E field inside the active volume of the TPC. The PCBs with ten nodes (nine gaps) called high voltage divider boards (HVDBs), provides the voltage divisions to the entire field cage. Each gap of a HVDB consists of two 5 GΩ resistors in parallel for inter-board redundancy and three variable resistors (varistors) of threshold voltage 1.7 kV each to protect the resistors in case of a sudden discharge. With each stage having a 3 kV voltage differential, the total expected current is, therefore, $\sim 1.2\mu$A along each HVDB chain on a 6.5 m high FC column. With the total forty eight 6.5 m high columns, surrounding the active volume, the total current per each active volume is $\sim 57.6\,\mu$A. Given the two drift volumes in parallel, the FC for the entire FD2-VD will draw $\sim 115.2\,\mu$A.

Figure 5.12 shows a section of a HVDB board mounted on a section of the field cage (partially transparent). The boards can be mounted either directly on the field cage profiles, or through a set of right angle metal brackets such that the boards are edge on to the field cage surface, To further improve the light transmission through the field cage, the voltage divider boards can also be positioned such that the components are recessed into the FRP I-beams. The HVDB for the FD2-VD will have only two varistors per stage since the maximum expected drift field is 500 V/cm.

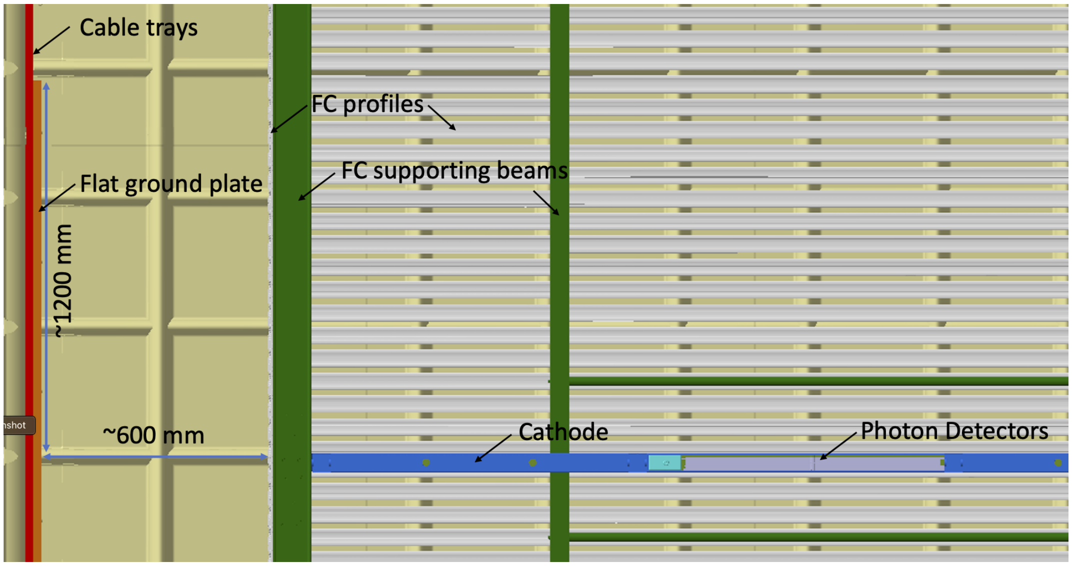


Figure 5.11: Detector cross-section at the cathode height, also showing the cable trays running along the membrane and the ground panel.

BY: are we ready to do this? it may mess up the RT measurements. JY- What do you mean?

The transition from the wider conventional FC profiles to the narrower version to increase the transparency introduces a discontinuity in the distribution of field cage electrodes. As a result, some minor modifications on the voltage differential between FC profiles at this transition region are needed to maintain a uniform electrical field inside the active volume. Preliminary analysis has shown (see Fig. 5.10) that the voltage drops in this region need to be: $V_n = 2000\,\mathrm{V}$, $V_{n+1} = 1900\,\mathrm{V}$,$V_n + 2 = 3400\mathrm{V}$, where n is the gap between the last wide and the first narrow profiles. The resistor values across these gaps must be adjusted accordingly.

The field cage voltage divider chains for both the top and bottom active volumes are terminated through wired connections outside of the cryostat, to a set of power supplies that can both control the termination bias voltages, as well as measure and record the current flowing through each divider chain. The voltage adjustment gives us the capability of fine tuning the drift field near the edges of the CRPs, while recording the current recording, proven to be a valuable diagnostic tool. These termination wires will be connected to the SHV connectors on the bottom electronics signal feedthroughs.

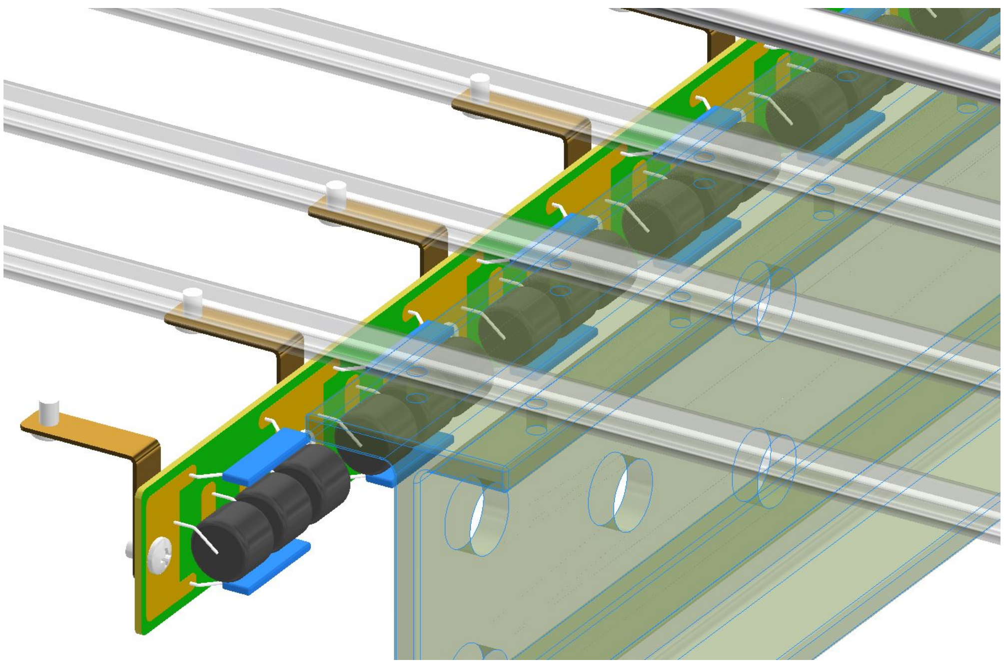


Figure 5.12: Illustration of the resistor divider board mounted edge on to the field cage to improve the light transmission through the field cage to the wall mounted photon detectors.

Chapter 8

Prototypes and Demonstrators

8.1 A Phased Approach

The vertical drift technology (FD2-VD) prototyping program will follow a phased approach with an aggressive but realistic schedule that aims to commission full-scale component prototypes before the end of 2021. The prototyping strategy comprises several phases taking place at the European Laboratory for Particle Physics (CERN) and Fermi National Accelerator Laboratory (Fermilab):

1. proof-of-concept tests in the 50 L liquid argon time-projection chamber (LArTPC) facility at CERN for the PCB-based anode design (two views);

2. further tests in the 50 L LArTPC with improved three-view geometry to optimize operating conditions (biasing voltages, peaking times) of the perforated PCB anode readout and the electronic components of the readout chain;

3. stand-alone tests of individual components of the high voltage (HV) system, using facilities both at CERN and Fermilab;

4. tests of a full-scale charge-readout plane (CRP) prototype in the modified cold box used for ProtoDUNE-DP to validate the devices and develop the integration steps;

5. test of full-scale HV components in the NP02 cryostat (the cryostat previously used for ProtoDUNE-DP).

Success of the full-scale CRP prototype test (item 4, above) along with stable operation at the nominal HV of 300 kV (item 5) should lead to baselining the FD2-VD as the second DUNE far detector (FD) module. This HV test will use the new HV extender design (Section 5.3.2) and will be performed in ultra-pure liquid argon (LAr) provided by the NP02 cryogenics system.

Once baselined, the module 0 prototype for the FD2-VD detector will be constructed and installed inside the NP02 cryostat in 2022–2023. Long-term operation and full characterization with a

8.3 Standalone HV Tests at CERN and Fermilab

It is planned to validate the most critical HV system components, namely the new HV feedthrough and the new HV extender, in standalone mode.

Three NP04/NP02 HV feedthroughs were built, and all functioned properly at 300 kV on a short-term basis in dedicated test stands. However, at the end of the (longer) NP04 run, the HV system was raised above the nominal 180 kV to 234 kV and operated for several days, at which point a sudden current trip occurred. During decommissioning of NP04 (after two years of continuous operation), ice formation in the cable receptacle was noticed

only in NP04? No, in both of them

; this could explain the 234 kV cutoff. The same ice formation was observed during the decommissioning of NP02 (as expected, given the identical layout of the HV FT and the similar N2 distribution system).

The new feedthrough, designed and built at UCLA, is similar in concept, but is about one meter longer on the warm end, and the cable receptacle remains in the warm section of the HV feedthrough. It is designed to be interchangeable with the NP04/NP02 HV feedthrough and should prevent ice formation.

The new HV feedthrough has already been extensively tested at 200 kV. Tests at 300 kV are underway in May/June 2021 at CERN. Assuming that these tests complete successfully, we will have obtained price quotes for building new HV feedthroughs for the NP04 phase II.

The new HV feedthrough will be tested in a dedicated 2 ton cryostat at CERN for an extended period of time to validate the functionality and stability at 300 kV under purity, cryogenic and electrical conditions that are similar to the conditions expected in the DUNE FD module.

anne to here Fri 5/28

For this purpose the full warm HV supply chain, including the 300 kV power supply, HV cables, and ripple filter, similar to those of ProtoDUNE NP04 and NP02, will be assembled and connected to the to the HV feedthrough. Figure 8.15 shows a 3D model of the test stand (left) and the actual HV feedthrough (right) when it was tested at 200 kV after manufacturing.

The test setup at CERN will include monitoring of the excess leakage current on the GP's (as successfully implemented in NP04); in addition, cryogenic cameras and temperature probes will help to closely monitor the cryogenic and HV stability during several weeks of continuous operation (Figure 8.16).

In parallel with the HVFT test, a prototype of the cryogenic HV extender will be constructed and tested at Fermilab, where cryogenic testing facilities exist that can accommodate larger HV components. The most critical elements to be tested are the suspension mechanism connecting

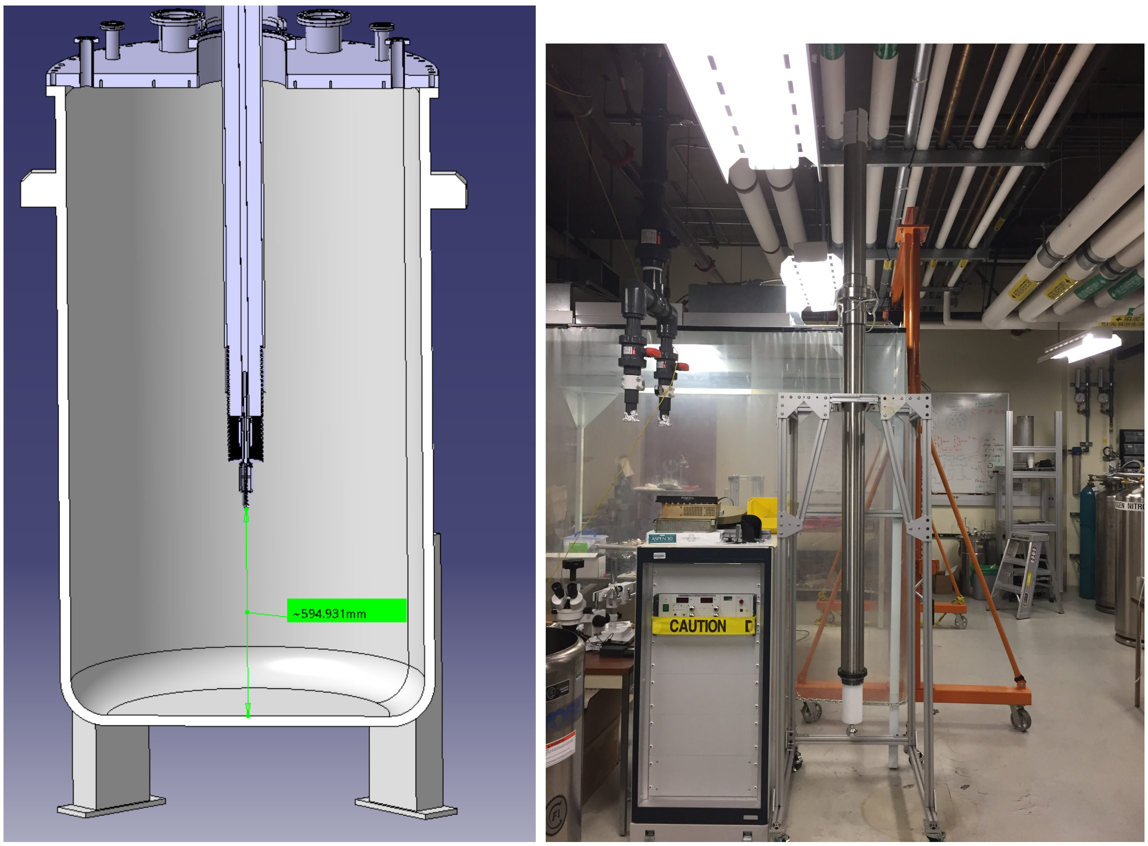


Figure 8.15: Left: 3D model of the HV feedthrough in the 2 tom cryostat. Right: the manufactured HV feedthrough after it was tested at 200 kV.

Figure 8.16: Left: test stand of the HV feedthrough. Right: details of the HVPS, the cryo-camera view and the new HVFT semi-spherical tip specifically mounted for the HVFT test.

the HV system to the HV feedthroughs on the cryostat roof and its heat dissipation in cryogenic conditions as well as the mechanical and electrical connections to the HVFT located at the top of the HV extender. For this reason, tests of the HV extender's reliability and stability at the nominal HV of ≈ 300 kV will take place at Fermilab using a one-meter-long test extender. It will be surrounded by a ground wall placed at the same distance as planned for the FD2-VD far detector module. This extender length should be sufficient since the highest local E fields are expected at the location where the HVFT makes a contact to the extender

near the grounded wall?

and bubble formations from potential heat transfer would occur at most a few tens of cm below the LAr surface on the HVFT.

Given the size of the full HV extender, a reduced test of the critical features at full voltage is planned for the Iceberg cryostat at the PAB. The test consists of the receptacle sphere, the G10 support disk and rods for roof suspension, and a lower stainless steel section with similar weld treatments of the full extender. The sphere and G10 supports are identical to those for the full extender, and the lower tube has a similar diameter**(similar diameter not the same? –jy)**. A model of the test and a photo of the test piece being installed are shown in Figure reffig:HVExtTestFNAL.

8.4 Test of the 70 % transparency field cage

The field cage design solution partially implementing narrower FC electrodes seems to be safely complying with the maximum local surface electric field requirements (<30 kV). A long term HV test at nominal E field, however, is important to gain confidence that there are no hidden flaws. We plan to perform this test at CERN in the two ton cryostat, where the HV feedthrough is presently under validation, adding a mini field cage between the HV feedthough and the ground planes.

The cryostat, 1 meter diameter and 1.8 m depth, is being equipped with an efficient purification / circulation systems to achieve high purity LAr (subject to safety validation and approval). Dedicated monitoring systems (ground plane current pick-off, LAr PM, cameras and temperature/level meters) will be integrated in the new layout.

The mini field cage will include aluminum profiles mimicking the shape of the 70% transparent field cage solution (a preliminary sketch is presented in Figure 8.18). The actual layout (electrode segmentation, distance from the cryostat walls, maximum voltage, etc) is under optimization:

- The whole FC will sit at the potential of the HV-FT;
- Ground planes are added at the four sides for an outer E-field uniformity similar to the Vertical Drift layout;
- With a 10/11 cm field cage to ground plane distance, an actual outer E-field as in VD is reached with 60-70 kV on the HV-FT;

A similar test was successfully performed in 2016 with the CERN 50 L test stand to gain experience

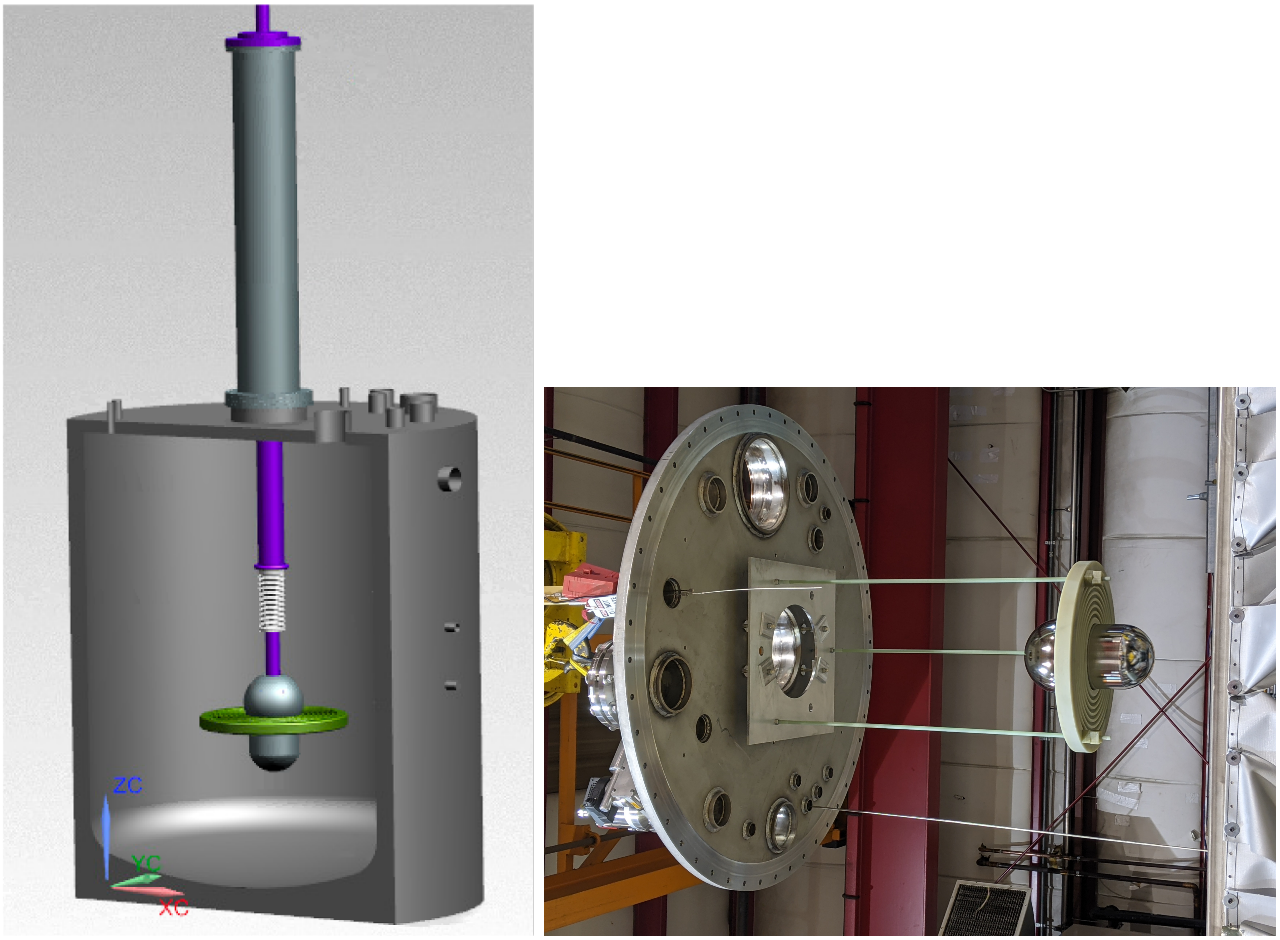


Figure 8.17: Left: 3D model of the HV feedthrough and extender test in the test cryostat. Right: the HV extender test piece being installed into the cryostat.

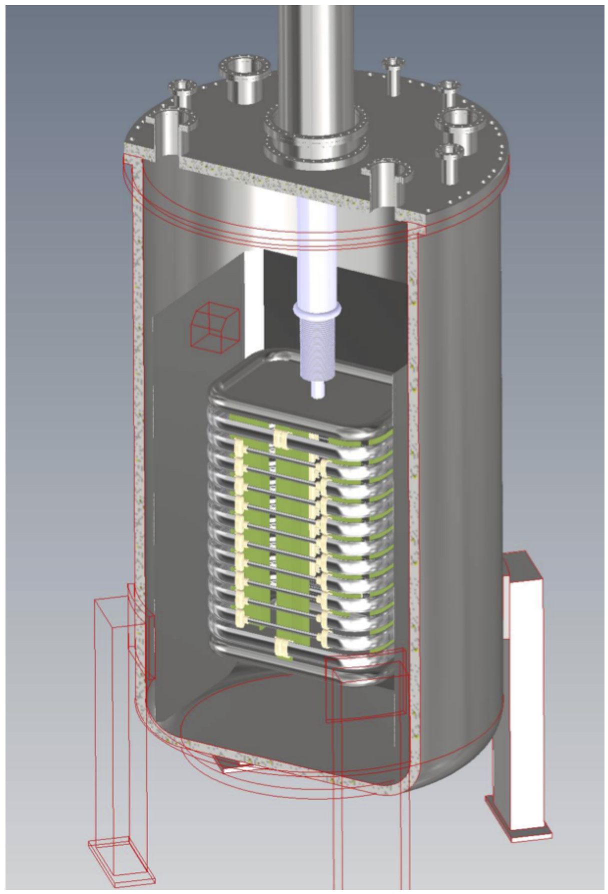


Figure 8.18: Sketch of the mini field cage embedded into the 1 ton cryostat at CERN. All electordes of the cage are short-circuited together at the High Voltage value delivered by the HV-FT. The field cage is surrounded by four ground planes read out independently to allow detecting the location of possible current instability. One side of the cage will be equipped with narrower profiles as in the 70% transparent layout.

with the Horizontal Drift layout.

The present plans is to start procuring the required materials as soon as the VTPC field cage design is ready and validated, in order to perform the tests in early 2022.

8.5 Full-Scale Readout System Test in NP02 Cold box

The aim of the test in the NP02 cold box, described in Section 8.5.2, is to characterize and validate the design and the construction procedures of a full-scale CRP, the electronics chain and the photon detectors (PDs), as well as to validate the design and the construction procedures of the various non-standard feedthroughs, which will be built to be as similar as possible to those for the FD2-VD FD module. To achieve these goals, the setup must accommodate a detector of the size that is representative of the final DUNE readout module.

The NP02 cold box, shown in Figure 8.19, is the most suitable cryostat available at CERN to facilitate cost-effective, rapid turnaround, which will allow multiple tests to be performed in series. This cold box was successfully used to test the CRP modules for ProtoDUNE-DP. It holds about 13 t of LAr.

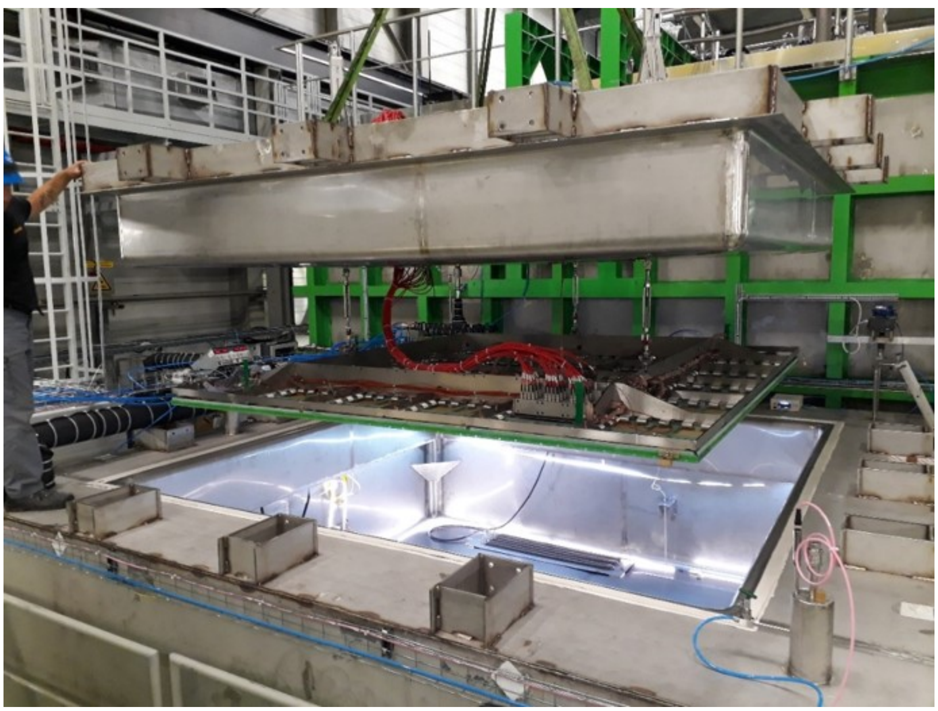


Figure 8.19: Cold box where the CRPs were tested prior installation in ProtoDUNE-DP; shown open with dual-phase (DP) components hanging from the top.

8.5.1 The Test Program

The test program will include:

- a mechanical test of the CRP in cryogenic conditions,

8.5.5 Components Procurement

The success of the large-scale test in the cold box relies on contributions from a number of institutions according to the following delivery scope:

- anodes and electronics support structure (CRP mechanics), provided by LAPP (IN2P3)
- top FD2-VD electronics (40×64 channels), provided by Lyon (IN2P3)
- bottom electronics (40×64 channels), provided by BNL
- top feedthroughs (2x??), provided by Orsay (IN2P3)
- bottom feedthrough (1x??), provided by BNL
- cathode module, provided by Orsay (IN2P3)
- X-ARAPUCA units (2-4) provided by FNAL, Brazil and Italy
- X-ARAPUCA fiber power and readout system at 300 kV, provided by FNAL
- HV system and feedthrough, provided by Fermilab and CERN
- DAQ system provided by UK, CERN and Lyon
- LAr and LN_2, provided by CERN
- CRP, provided by CERN

what are 1x and 2x? just 1 and 2? Anne

8.6 High Voltage Demonstration in NP02 Cryostat

A full-scale, integrated test of the FD2-VD HV distribution is one of the essential milestones to demonstrate its feasibility. The NP02 cryostat offers the best available environment for this test, since it has detector components from ProtoDUNE-DP installed that can be reused, the infrastructure for filling with ultra-pure LAr is in place, and its size will allow for a realistic evaluation of the HV system performance at 300 kV.

In particular, the high voltage system of NP02 closely resembles the one of the Vertical Drift layout: the field cage and the cathode hang from roof for a 6 m drift; the FC profile shape and spacing, the bent FC corners and the resistive divider boards are also very similar; the CRP structure is decoupled from the field cage and holds the anode (DP) read out units with minor interference with the FC hanging structure.

A recent inspection (February 2021) confirmed that the whole detector in NP02 is in good shape (apart from the HV extender) and can be reactivated as it is (Figure 8.25): the readout and the biasing systems are all available; the PMT's are working (including WLS layers); the monitoring system are active (except for a few cameras that need to be replaced with existing spare ones).

Several aspects of the HV system will be tested, i.e., connection of the extender to the cathode and the HVFT, HV discharge protection, the upgraded extender performance, HVFT and the overall HV stability short and long term.

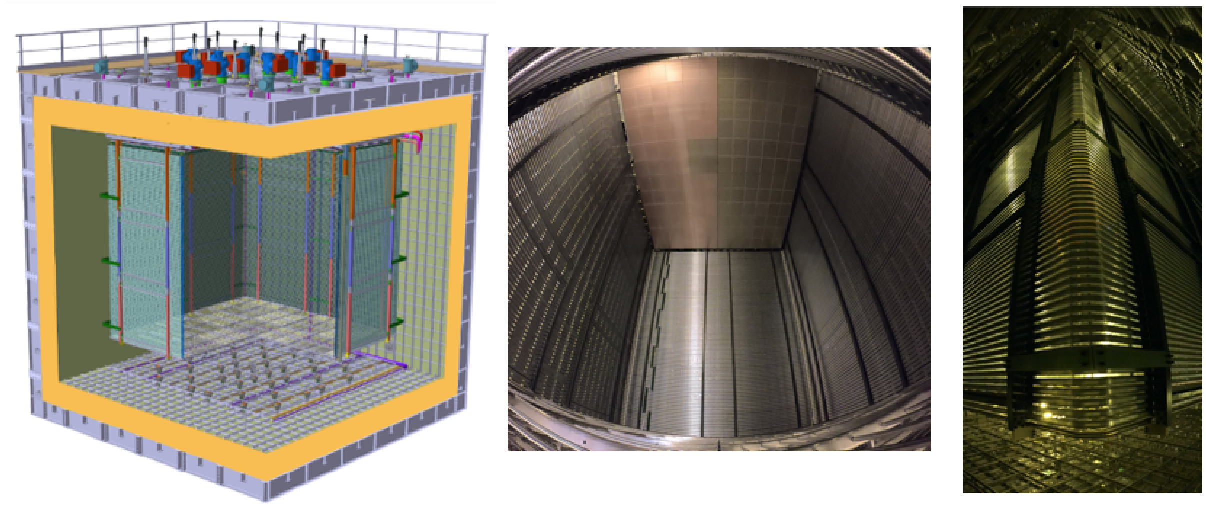


Figure 8.25: (Left) Schematics of the NP02 cryostat. (Center) Fish-eye picture of the CRP and FC structure taken from the cathode. (right) Detail of a FC corner.

We are collecting and preparing the components for the test. The 300 kV HV power supply and its cable are already at CERN and have been tested in the past few months. A new, longer HVFT, based on a design from UCLA and described in Section **??**, is also at CERN and is undergoing tests. The HV extender location in the Vertical Drift Far Detector is at the equal distance from the surrounding surfaces, namely the cryostat membrane and the field cage electrodes. To simulated this feature in NP02, a spare flange along a corner of the cryostat will be exploited. The opening matches to HVFT requirement (Figure 8.26). The electric field distribution at the surface of the extender is expected to be similar to that at the location in the straight section as in the Vertical Drift Far Detector. The extender elbow will be connected to the cathode via simple spring-loaded wires (more than one for redundancy) to keep the field cage stable against the potential HV extender movement. No special requirement on precision alignment of field cage to HV extender is foreseen due to the anticipated weak E field in the surrounding volume.

Optimization of the HV extender design is underway mainly focusing on the minimization of the local electric field on the surfaces of the electrodes and the insulators such as the extender supporting plates (see Figure 8.26 right).

The commissioning of the NP02 detector for the HV extender test requires few installation steps. The present extender will be removed and replaced with the new one together with the newly designed, built and tested HV feed-through. It is important to note that the extender exchange can be accomplished without reopening the cryostat structure; access for personnel and material will be through the standard manhole. This will speed up the test preparation significantly. During operations of NP02, bubbles formation at the LAr surface were observed in steady state cryogenic conditions (Figure 8.27), originated from the HV feedthrough (gas trapped below the ground donut) and from the topmost field cage rings (gas trapped in the C-shaped profiles and escaping from connecting clips). Thermodynamic model, supported by additional cameras observations, indicates that the bubbles are present in the top $\sim$20 cm below the LAr surface.

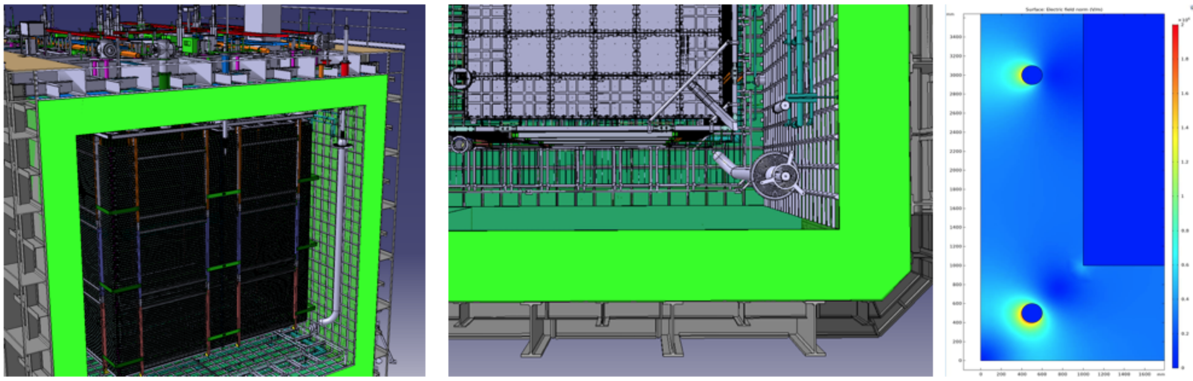


Figure 8.26: (Left) 3D drawing of the new HV feedthrough and extender concept in the NP02 cryostat. The chosen penetration is on a corner of the cryostat, where the distance from the membrane and the field cage is similar to the proposed layout in the full FD module. (Center) Same but seen from the top. (Right) Comparison of the surface electric field for the extender located at the cryostat corner or near the straight wall.

add as reference:(see the presentation at LBNC in 2019: https://indico.cern.ch/event/857610/sessions/331374/#20191205).

Plan to mitigate this issue includes: cutting and removal of the two-three topmost FC rings; addition of gas escape paths in the HV feed-though design (this feature already present in new HV-FT under test).

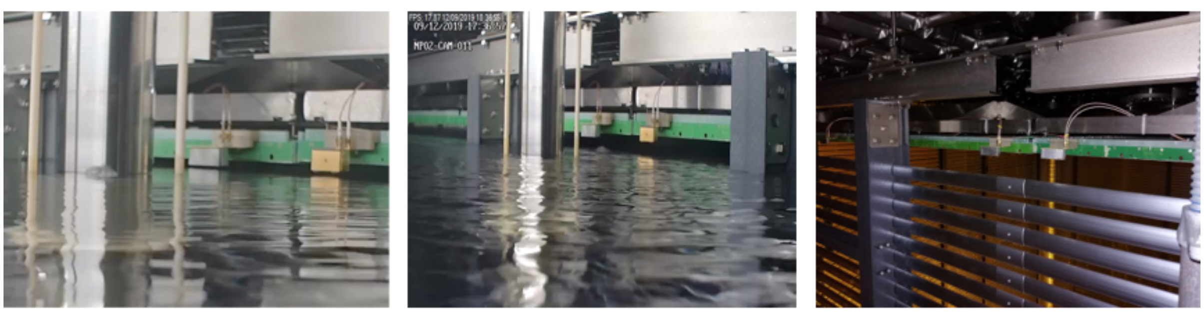


Figure 8.27: (Left) Gas bubbles formation from the HV FT ground donut ring. (Center) Same but from the clips location of teh topmost FC rings. (Right) FC view without LAr: the top two-three rings will be removed to avoid bubbles formation in the HV test run.

The possibility to cover the extender with high resistivity HV stress relief shrink-tube, similar to what is often used in HV cable terminations to quench corona-like current leakage, is also considered.

The sequence of operation required to prepare this test are summarized as follows:

1. access inside the cryostat and remove the periphery ground grid

2. install the false floor where the ground grid was removed

3. install the scaffolding for ease of access from the manhole

4. install the scaffolding for the access around the existing ProtoDUNE DP extender

5. cut the field cage connections to the degrader ring around the extender and change/repair the field cage clips as needed

6. remove the present extender from its penetration with crane

7. cut and remove the two to three topmost field cage rings (this requires moving the scaffolding around the field cage)

8. dissemble the scaffolding and reinstall it where the new extender will be (at the north corner of the cryostat).

This overall procedure resembles very much to what was already done to install the ProtoDUNE DP extender; details are being finalized.

Before the installation, the new HV extender will be assembled at CERN (parts are shown in Figure 8.28). The extender head parts **(what do you mean by the "head" the HVFT receptor and the ceiling suspension system? –jy)** and the 90° bend elbow will be shipped by Fermilab to CERN; CERN procures electro-polished tube of proper dimensions (about 20 cm diameter and 6 m long) and build the stainless steel suspension system; assembly of HV extender modular parts, cleaning and surface quality control will be performed at EHN1 close to the NP02 cryostat. In the cryostat, the extender suspension system to the cryostat penetration rim, built at CERN, will be welded on the rim of the penetration (similar to what was done for old extender).

The actual installation procedure is also quite well defined (and it is also similar to one of the old extender): the HV extender is inserted vertically through the manhole until reaching a first trolley on the false floor; the HV extender is lowered with the crane, helped by the trolley, it is pulled towards the correct position; the HV extender second extremity is placed on a second trolley and the HV extender is rotated and shifted into the position; the HV extender is hung at its top extremity to be lifted with the crane through the HVFT penetration; the FR4 supporting disc is attached to the suspension system with FR4 rods; the elbow tip is connected to cathode with spring wires; the new HVFT is inserted and electrical continuity checks are performed. Figure 8.29 visualizes the procedure.

Finally we are also evaluating the possibility to study the creeping behavior of cathode suspension strings under cryogenic conditions, by suspending from the roof of the cryostat 6m long ropes of the selected materials terminated with a weight equivalent to that of the Vertical Drift Cathode. Their length will be monitored (with cameras or other appropriate systems) throughout the whole operation of the NP02 HV test. **(This test will be done at one of the corners where the local field is minimal? –jy)**

The NP02 commissioning will follow closely the sequence adopted for the first run in summer 2019.

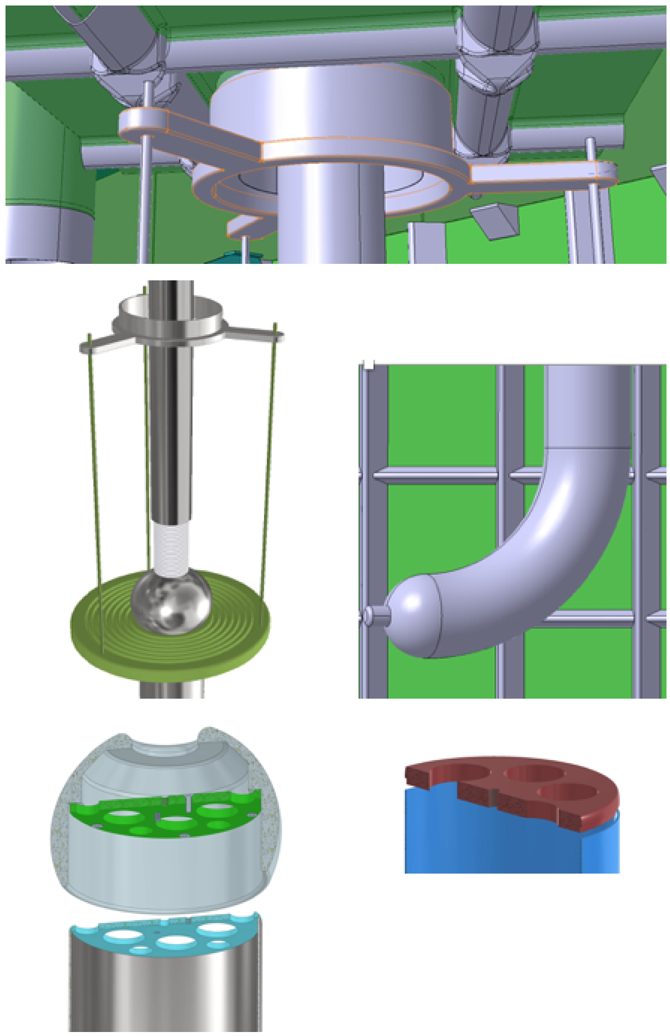


Figure 8.28: (Top) Extender suspension structure welded to the cryostat penetration rim. (Center) FR4 bars with the FR4 disk supporting the extender, and the extender elbow. (Bottom) Mechanical elements required to assemble together the extender top spherical head, the 6 m long pipe and the elbow at the bottom.

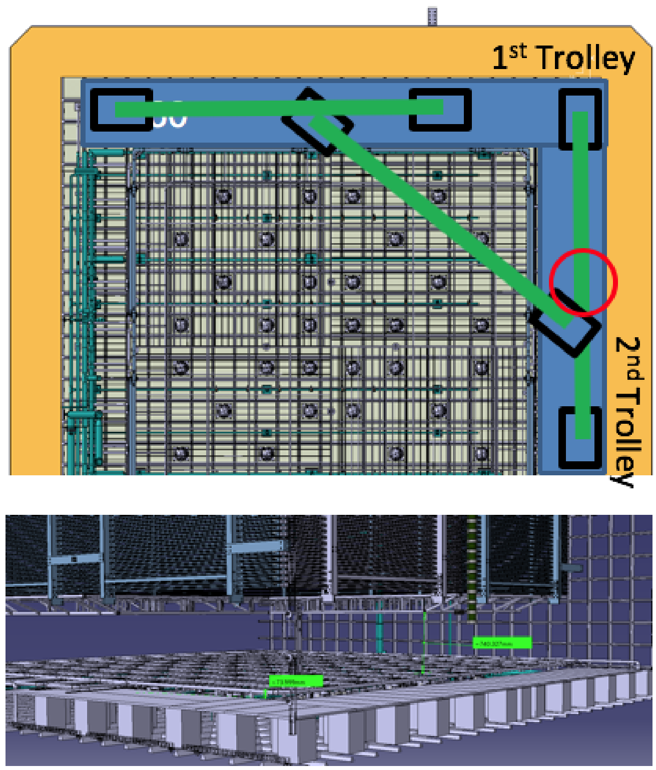


Figure 8.29: (Top) Sketch of the new HV extender installation sequence in NP02 seen from above. The extender is the green bar. The manhole is the red circle. The trolleys are the black rectangles. The final extender position in in the top left corner. (Bottom) The empty space between the false floor and the cathode, needed to rotate the extender, is shown.

- LAr will be available for filling in August 2021;
- Detector operation could start in September with HV ramping up CRP R/O operation at various stages of the the HV ramping up can be envisaged to evaluate HV stability, induced noise and possibly LAr purity (through attenuation along muon tracks, and with Purity Monitors);
- When the maximum HV is reached (hopefully 300 kV), start long term stability run (several weeks) in steady state conditions;
- HV monitored, by sensing analogue PS output and FC current termination (20 kHz sampling rate) allowing the detection of current / voltage instability (proven effective in NP04/NP02);
- CRP readout (not necessarily always on) to monitor possible induced ripple or spike noise, electric field instability, Argon purity.

8.7 Schedule of Tests

This section lays out the schedule for completing the tests in 2021.

CD2 IPR no longer in Dec; do dates need to change?

Small-scale tests:

- Integrate and operate a SiPM array, powered with PoF technology, into the 50 L cryogenic test stand at CERN by December 2020;

  accomplished?
- Proof-of-principle for the three-view readout: finalize PCB

  PCB or CRP design?

  design by December 2020; start production, assembly and operation in the 50 L test stand in January 2021;

  accomplished?
- Start HV feedthrough long-term test in 2 t cryostat at CERN in January 2021; and
- Test of the top part of the HV extender at Fermilab starting February/March 2021.

Cold box test:

- Refurbish and install cold box at EHN1 by April 2021;
- Commission cryogenics for the empty cold box in May 2021;
- Receive all the FD2-VD module components at CERN by June 2021;
- Integrate the components in the NP02 clean room in July 2021;
- Insert the FD2-VD module into the cold box in August 2021;
- Run tests on the FD2-VD module in the cold box from September to November 2021.

HV test in NP02:

- Access and inspect NP02 as soon as it is empty and warm in March 2021;
- Remove the present ProtoDUNE-DP HV extender in March-April 2021;
- Receive new HV extender at CERN by May 2021;
- Install the new extender in June 2021;
- Cool and fill NP02 July-August 2021;
- Operate HV system in NP02 September-November 2021;
- Report on stability and performance December 2021.

Importantly, this schedule is compatible with the use of the ~ 750 ton of LAr to fill NP04 for the horizontal drift technology (FD1-HD) Module 0 validation runs in 2022.