Deep Underground Neutrino Experiment (DUNE)

Technical Proposal

Volume 3: The Dual-Phase Far Detector Module Design

May 16, 2018

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Contents

34

List of Figures

List of Tables

Todo list

Chapter 1

High Voltage System

1.1 High Voltage System (HV) Overview

1.1.1 Introduction

A liquid argon time-projection chamber (LArTPC) requires an equipotential cathode plane at high voltage (HV) and a precisely regulated interior E field to drive electrons from particle interactions to sensor planes. In the case of the DUNE dual-phase technology, this requires a horizontal cathode plane, held at negative HV; a horizontal charge-readout plane (CRP) in the gas phase as described in Chapter **??**; and formed sets of conductors at graded voltages surrounding the the central drift volume, collectively called the field cage as shown in Figure 1.1. The field cage (FC) consists of continuous field shaping rings that provide voltage degradation in the vertical direction and forms one continuous active volume.

The HV consortium provides systems that operate at the nominal voltages to provide the uniform 500 V/cm E field in the time projection chamber (TPC) drift volume. As a result, its systems constitute a large fraction of the internal structures of the TPC. Mechanical and structural concerns are taken into account, together with the electrical design to meet the requirements.

The design presented in this chapter is primarily based on the ProtoDUNE-DP design, which includes a set of basic elements (i.e., FC sub-modules, cathode and ground grid modules) that are deployed to build a TPC with a $6{\times}6{\times}6\,\mathrm{m}^3$ active volume. The extrapolation to the DP module structure with $12.0\,\mathrm{m}\ \times 12\,\mathrm{m}\ \times 60\,\mathrm{m}\ \ \mathrm{m}^3$ active volume requires some electrical and mechanical adaptations. The size of each element is kept within a roughly $3{\times}3\,\mathrm{m}^2$ envelope, matching the size of the CRP modules, which was optimized for underground transportation and assembly.

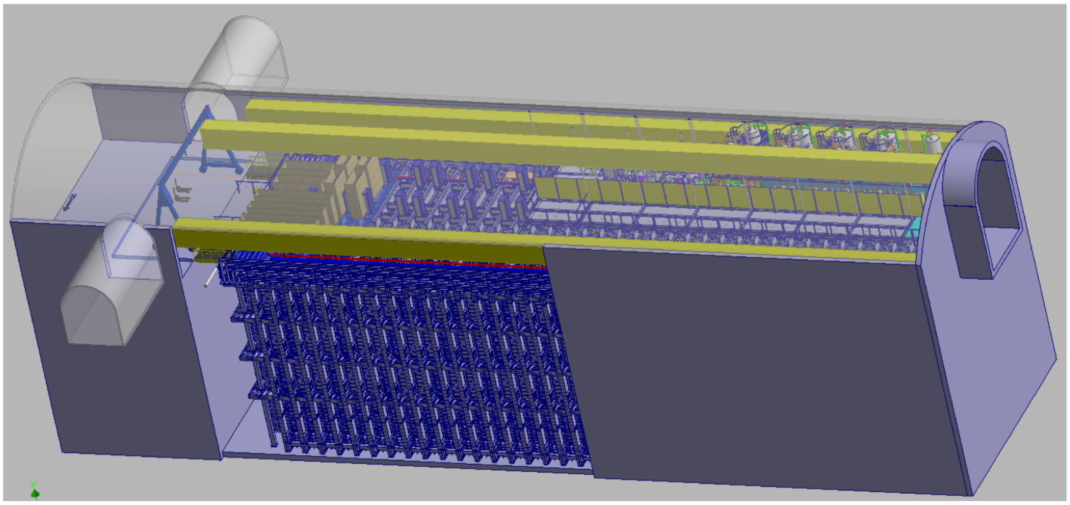

Figure 1.1: A cutaway showing an overview of a DP module, with the cathode plane and the PDS on the floor, the 12.0 m tall FC modules surrounding the active volume, and the anode plane, the only part of the CRP visible from this angle.

1.1.2 Design Considerations

The HV system is designed to meet the physics requirements of the DUNE experiment. This includes both physical requirements (e.g., an E field that allows robust event reconstruction) and operational (e.g., avoidance of over-complication in order to maximize data collection efficiency). A collection of essential requirements for the HV system is shown in Table 1.1.

1.1.3 Scope

The scope of the HV system includes the continued procurement of materials for, and the fabrication, testing, delivery and installation of systems to generate, distribute, and regulate voltages so as to create a precision E field within the detector module volume.

The HV system consists of components both exterior and interior to the cryostat. The HV power supply is located external to the cryostat. In the DP module, the HV power supply is expected to be located on top of the HV feedthrough. The HV is further distributed by interior components that form part of the TPC structure, as depicted in Figure 1.2.a. These components are:

- power supply,
- HV feedthrough
- HV extender and voltage degrader,
- cathode plane and ground plane (GP),

Table 1.1: HV System Requirements

No.	Requirement	Physics requirement driver	Requirement	Goal
1	Exceed minimum E field TPC drift volume	Maintain adequate particle ID, which is impacted by slower drift speed and increased recombination, diffusion and space charge effects.	$>$250 V/cm	500 V/cm
2	Do not exceed maximum E field in LAr volume	Avoid damage to detector to enable data collection over long periods.	30 kV/cm	as low as reasonably achievable (ALARA)
3	Minimize power supply ripple	Keep readout electronics free from external noise		
4	Maximize power supply stability	Maintain the ability to reconstruct data taken over long period. Maintain high operational uptime to maximize experimental statistics.		
5	Provide adequate decay time constant for discharge of the cathode plane and FC as well as cathode plane resistive segmentation	Avoid damage to detector to enable data collection over long periods. Maintain high operational uptime to maximize experimental statistics.	GΩ resistors per each connection of the $3 \times 3\,\mathrm{m}^2$ cathode units	
6	Provide redundancy in all HV connections	Avoid single-point failures in detector that interrupt data taking.	$>$2 voltage divider chains to distribute HV to the FC profiles	one voltage divider chain every four FC modules

sicsreqs

- field cage,
- HV return feedthrough and resistor box.

1.1.4 System Overview

A DP detector module has a single modular cathode plane that forms the bottom of the single 12 m (W) × 12.0 m (H) × 60 m (L) drift volume. It is constructed of eighty 3 m × 3 m contiguous units. The cathode units consist of stainless steel tube frames that hold a stainless steel grid. It is kept at a potential of −600 kV. A similar but highly transparent GP is placed just above the PDS, which is located near the bottom of the cryostat and below the cathode to shield it from the HV. The cathode bias is provided by an external HV power supply through a HV feedthrough and a voltage extender unit that reaches the cathode.

The FC surrounds the drift volume in a set of equidistant, stacked, horizontal, rectangular-shaped aluminum rings. Its function is to ensure a uniformity drift field of 500 V cm^{-1}. This is accomplished by gradually decreasing the voltage over the 12.0 m height from the cathode voltage of −600 kV to −10 kV at the top-most field shaping ring, to allow for electron extraction into the gas volume of the CRP. The FC consists of aluminum field-shaping rings, made up of mechanically and electrically connected 3 m long aluminum profiles. This is a cost-effective system for establishing the required equipotential surfaces.

1.2 HV System Design

1.2.1 High Voltage Power Supply and Feedthroughs

The HV delivery system consists of

- one power supply,
- HV cryogenic feedthroughs,
- HV cryogenic extender.

To ensure the nominal E field of 500 V/cm over the 12 m drift distance, an external power supply must deliver −600 kV to the cathode through one HV cryogenic feedthrough, with a maximum current draw of 0.5 mA. At present such a power supply does not exist, but Heinzinger, the industrial partner and leader in the production of HV power supplies, is executing a vigorous R&D program towards this goal, relying on the following facts:

- 600 kV power supplies are feasible, scaling from present industrial technology;

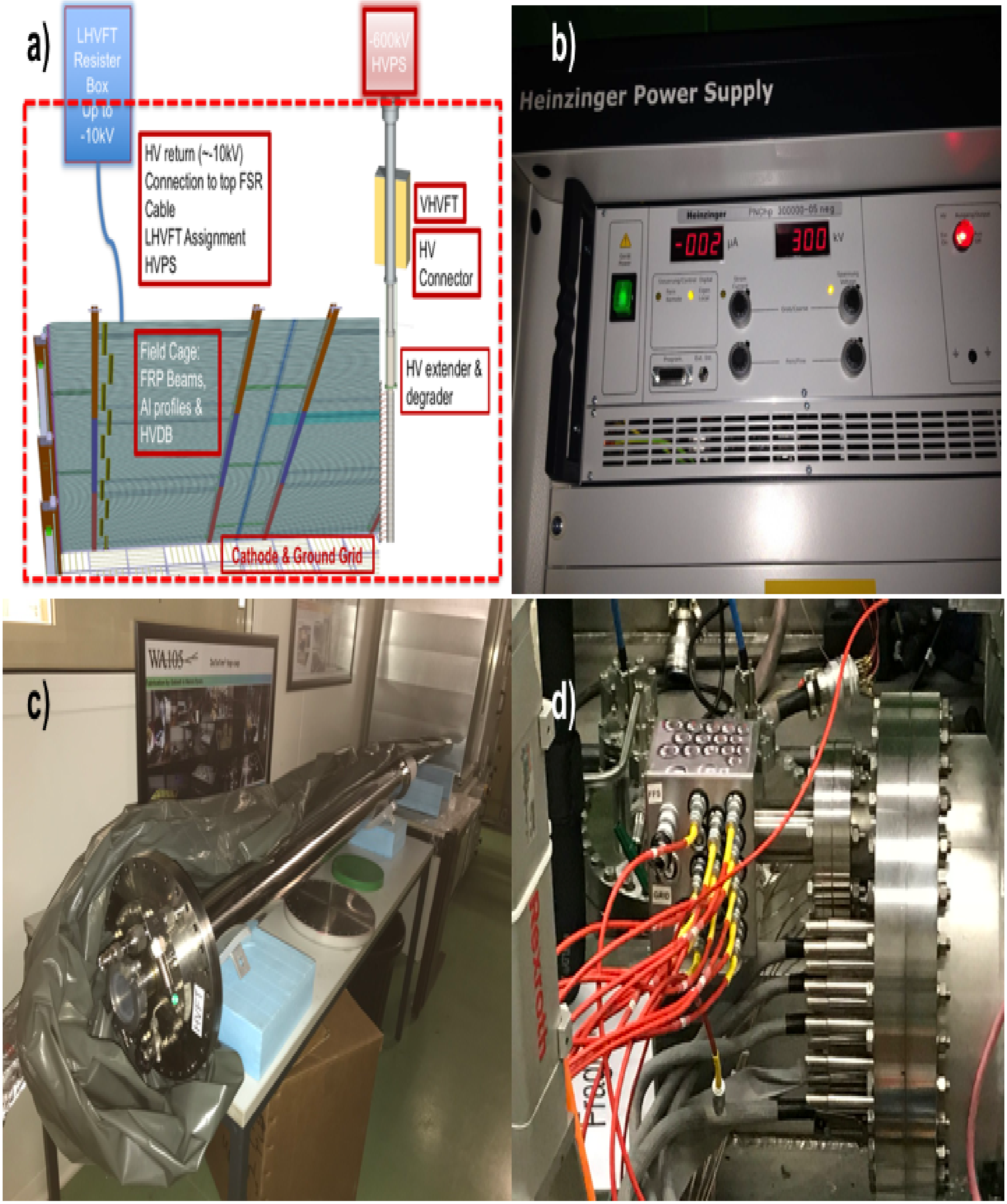

Figure 1.2: (a) Schematic overview of the VHV system for a DP detector module, (b) photo of the 300 kV Heinzinger power supply[2], (c) the VHV feedthrough, and (d) the VHV return connection. (All photos from the WA105 DP demonstrator.).

fig:dune

- The same is possibly true for the HV cryogenic feedthrough, scaling to large diameter and longer size with respect to the present 300 kV prototypes;

- The critical points of the HV distribution are then the cable and its connectors on the power supply and on the HV-feedthrough.

The joint R&D program between DUNE and Heinzinger aims to eliminate cables and connectors, and build a power supply that can be connected directly on the top of the HV-feedthrough. A sample schematic and some details are shown in Figure 1.3. Heinzinger is motivated to pursue this effort because of possible new industrial applications.

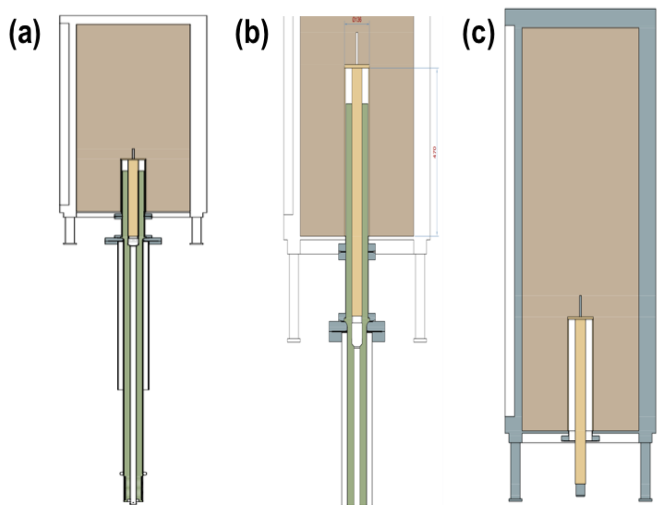

Figure 1.3: (a) Vertical cross section of the proposed VHV power supply inserted over the 750 kV HVFT for a DP detector module, (b) Insertion detail of the proposed VHV power supply inserted over the 750 kV HVFT. The female HDPE of the HVFT is indicated in green. The male plug of the HVPS, shown inserted, is a metallic conductor inserted in a HDPE insulating tube (indicated in yellow. The gap between male and female is filled, via a tube inside the HVPS (not indicated) by a silicone oil such as RHODORSIL 47 V1000. (c) Vertical cross section of the HVPS. The front panel is on the left. The HV multiplication and regulation (not indicated) is in the beige region.

Typical Heinzinger power supplies have ripples in the range of $\sim$30 kHz with an amplitude of $0.001\,\%\mathrm{V}_{\mathrm{nom}} \pm 50\,\mathrm{mV}$. A low-pass RC filter designed to reduce the voltage ripple could be integrated into the output of the power supply. It should be noted, however, that the required ripple suppression does not need to be as high as for the SP module due to the DP module's more effective shielding of the anodic structure, performed by the extraction grid and by the CRP signal amplification stage.

The HV feedthrough is based on the same successful ICARUS design that was adopted in both ProtoDUNE-SP and ProtoDUNE-DP. In this design, the voltage is transmitted along a stainless steel center conductor on the warm exterior of the cryostat, where this conductor mates with a cable end. Inside the cryostat, the end of the center conductor has a spring-loaded tip that contacts a receptacle cup mounted on the cathode, from which point HV is delivered to the FC. The center conductor of the feedthrough is surrounded by Ultra-High Molecular Weight Polyethylene (UHMW PE).

To first order, the upper bound of operating voltage on a feedthrough is set by the maximum E field on the feedthrough. Increasing the insulator radius reduces the E field. For the target voltage, the feedthrough uses a UHMW PE cylinder of at least 15.2 cm (6 in) diameter. In the gas space and into at least 15.2 cm of the liquid, a tight-fitting stainless steel ground tube surrounds the insulator. The ground tube has a CF-type flange of at least 25.4 cm (10 in) welded on for attachment to the cryostat. A prototype[3] has been successfully tested up to −300 kV in pure argon in a dedicated setup; two similar prototypes are currently being installed in ProtoDUNE-SP and ProtoDUNE-DP.

1.2.2 High Voltage Extender and Voltage Degrader

Since the HV has to be guided from the top of the cryostat to the cathode (12 m below the liquid argon (LAr) surface), an extension of the HV feedthrough is required, as shown in Figure **??**a, b and c. The extender contains an inner conductor at −600 kV surrounded by an insulator. Since the extension runs the entire height of the drift volume, metallic rings (degrader rings) are installed on the periphery of the extension close to the field-shaping ring. Each degrader ring is electrically connected to the field shaping ring at the same height thus guaranteeing that the E field in the LAr between the extender and the FC remains at 0.

fig:pd-hvft-exten

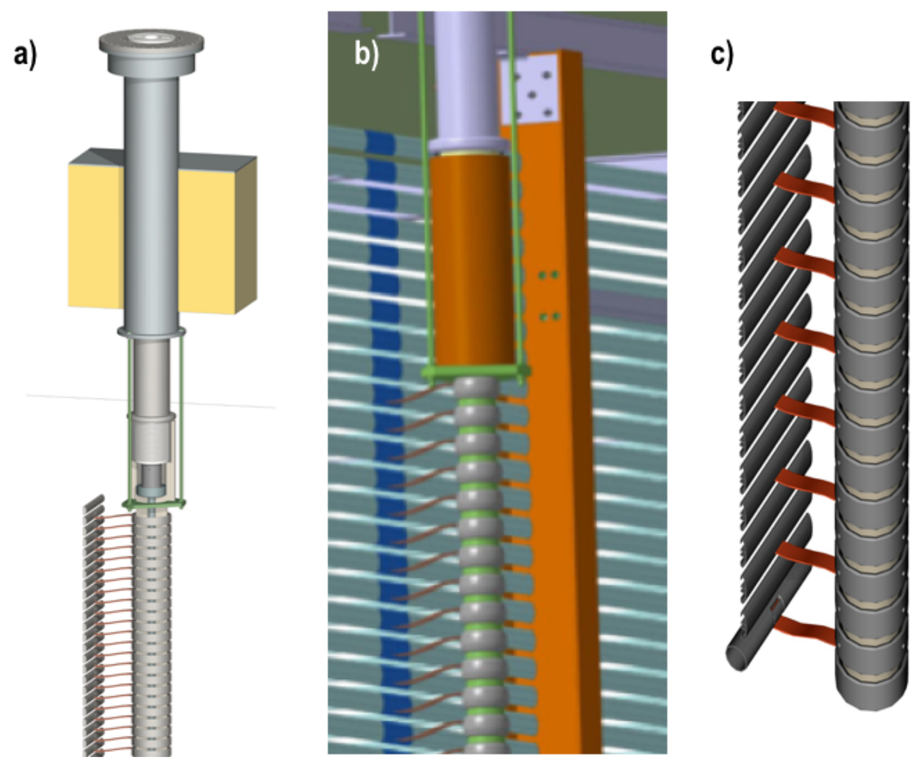

Figure 1.4: Pictures of HV feedthrough and HV extender-degrader; a) Overview of the HV FT, HV extender and the degrader chain, b) details of the top portion of the HV extender and its connections to the field shaping rings, c) detail of the HV extender and degrader connection to the bottom part of the FC, including the connection to the cathode plane.

fig:dp-h

[3]The prototype was manufactured by the company CINEL™ Strumenti Scientifici Srl.

1.2.3 Cathode Plane

The DP detector module's cathode plane forms the bottom of the single 12 m (W) × 12.0 m (H) × 60 m drift volume and provides a constant potential surface at −600 kV. It receives its HV from the central conductor of the extender that carries the voltage from the power supply through the HV feedthrough.

The cathode plane consists of eighty 3 m × 3 m modules. The cathode module design is based on the design used in ProtoDUNE-DP, for which the cathode consists of a stainless steel (316L) mechanical structure made from two types of tubes: an external frame made from 60 mm diameter tubes, and the internal portion is made from oval pipes of 20 mm × 40 mm with 1.5 mm thickness, as shown in Figure 1.5. This frame is filled with smaller tubes of 12 mm diameter (not shown in the figure), forming a grid, to provide a uniform equipotential surface, while ensuring 60 % optical transparency. All diameters are optimized to guarantee a uniform potential across the cathode, to satisfy the maximum local field requirement of 30 kV/cm, and to minimize the local E fields to ground. The cathode plane components are bolted together and fixed to the supporting fiber-reinforced plastic (FRP) I-beams of the FC. Modules of the same size as for ProtoDUNE-DP are foreseen for the DP detector module cathode. Some mechanical modifications will be performed in order to guarantee the flatness over the longer distance of 12 m compared to the 6 m of ProtoDUNE-DP. In addition, the shape of the conductors could undergo some slight modifications in order to lower the local E field values based on the ProtoDUNE-DP experience.

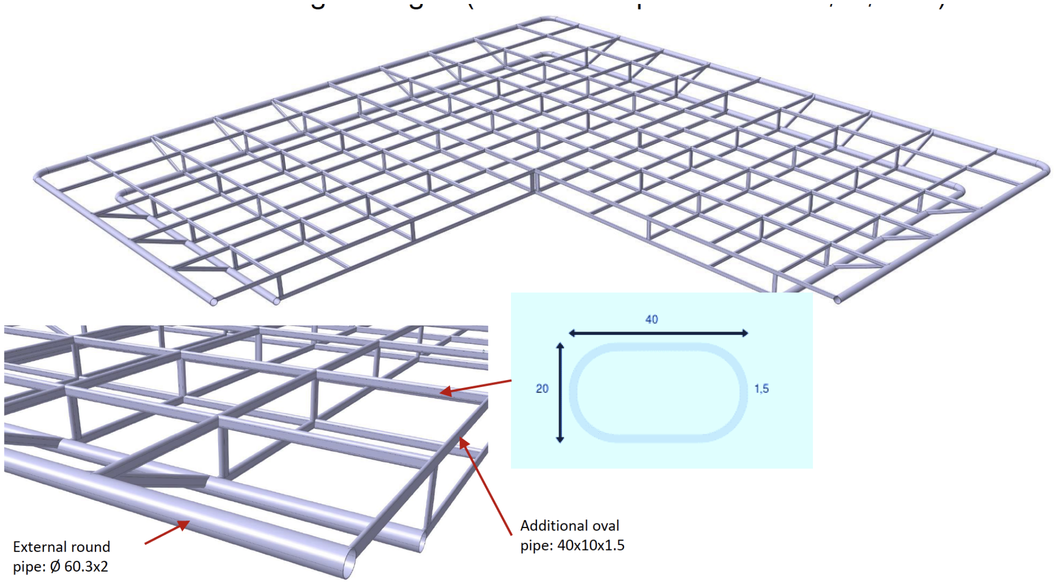

Figure 1.5: A cutaway view of ProtoDUNE-DP cathode(Credit: ETHZ)

The energy stored in the volume between the cathode plane and the ground grid (which sits under the cathode and above the photon detectors (PDs)) is estimated to be about 1.7 kJ over the 12 m × 60 m area, based on the cathode voltage and the distance of 1 m between the cathode and the ground grid described in Section 1.2.4. A sudden discharge from the cathode frame to the cryostat membrane could cause severe damage to the membrane. The modular construction of the cathode helps minimize this effect in case of discharge. During assembly in the cryostat, the cathode units are kept electrically insulated and connected to their adjacent neighbors through

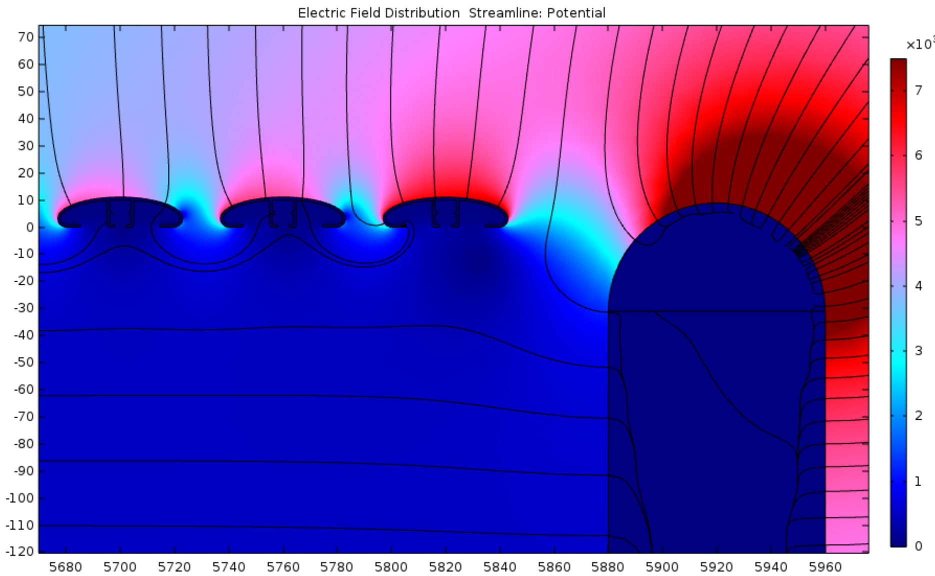

Figure 1.6: Place holder for field between cathode and the ground grid

GΩ resistors. Given the 100 pF capacitance of each cathode unit, any discharge occurring in one unit will release at most 21 J of stored energy while the discharge rate to the other units is slowed to the several-hundred-millisecond range.

Detailed calculations are in progress to determine the final shape and the size of the cathode and ground grid frames to limit the maximum E field to 30 kV cm^{-1} throughout the LAr volume (Figure 1.6), as per requirement 2 (Table 1.1). Structural calculations are also in progress to verify the planarity of the cathode as it hangs on the FC supports. Value and voltage characteristics of the connecting resistors will also be defined according to results from dedicated simulations of the cathode electrical model.

1.2.4 Ground Grid

The ground grid is installed between the PD and the cathode plane to shield the PMTs from a discharge.

The ground grid consists of 316 L stainless tubes, as does the cathode. It is made of eighty 3 m × 3 m modules. Unlike the cathode, the ground grid has a single layer supported by a set of feet resting on the membrane floor. Detailed studies on the grid geometry are ongoing to ensure that the requirement on the maximum local field is satisfied.

1.2.5 Field Cage

1.2.5.1 Mechanical Structure

The field shaping rings of the FC are made up of extruded roll-formed aluminum open profiles. The profiles are stacked horizontally and constructed into continuous rectangular rings that form the vertical sides of the drift volume. The aluminum profiles are attached to structural elements made of pultruded FRP.

FRP is non-conductive and strong enough to withstand the FC loads in the temperature range of −150 C to 23 C. This material meets the Class A International Building Code classification for flame spread and smoke development, as characterized by ASTM E84.

Each of these modules is composed of three styles of submodules of dimensions 3 m (W) × 2 m (H). These submodules are supported by two 15.2 cm (6 in) FRP I-beams (with profile slots cut out) and two 7.62 cm (3 in) cross bar I-beams that form a rectangular frame.

The FC is modular, each module covering a vertical area of 3 m (W) × 12.0 m (H). There are two types of modules, straight section and corner, both types having the dimensions 3 m (W) × 12.0 m (H). A total of 72 straight section modules (i.e., with straight profiles) and eight corner section modules, with profiles bent 45 degrees at one corner to allow straight connections via clips at the corner, as shown in Figure 1.7.c. A photo of the ProtoDUNE-DP FC is shown in Figure 1.7.d.

Each FC module is made of six submodules of three distinct types: top, bottom and middle. The dimensions for all submodules are 3 m (W) × 2 m (H). Each module has one top submodule with 33 profiles, four middle submodules with 33 profiles each, and one bottom submodule with 32 profiles, for a total of 197 profiles per module. The voltage of the top-most field shaping ring is −9 kV. The top submodules make the mechanical connection to the ceiling of the cryostat from which the entire FC hangs, as shown in Figure 1.10, left. The bottom modules make both mechanical and electrical connections to the cathode.

A railed rib runs along the length of the aluminum profiles at the center of the profile. The rib provides mechanical strength and acts as the rail for the slip nuts that hold the profiles onto the supporting FRP frame. The rib also serves as the rail for the nuts that hold the HV divider boards and the slip nuts for inter-module profile connections. All profiles at a given height are electrically connected via an aluminum clip screwed onto the slip nut across two neighboring profiles. A resistive divider chain interconnects the aluminum profiles to provide a linear voltage gradient between the cathode and the top field-shaping ring.

The extruded aluminum profiles are mounted to the 15.2 cm (6 in) I-beam via two stainless screws and aluminum slip nuts in the center enforcement rail of the profile. The mounting is only on one of the 15.2 cm I-beams to allow contraction on either side of the profile. The top submodule has an extended 15.2 cm FRP beam with holes to connect it to the stainless steel I-beam hanging from the ceiling. The bottom submodule has a cutout to hold the cathode plane onto it. The four middle submodules are symmetric, and thus interchangeable. FC modules are horizontally interconnected

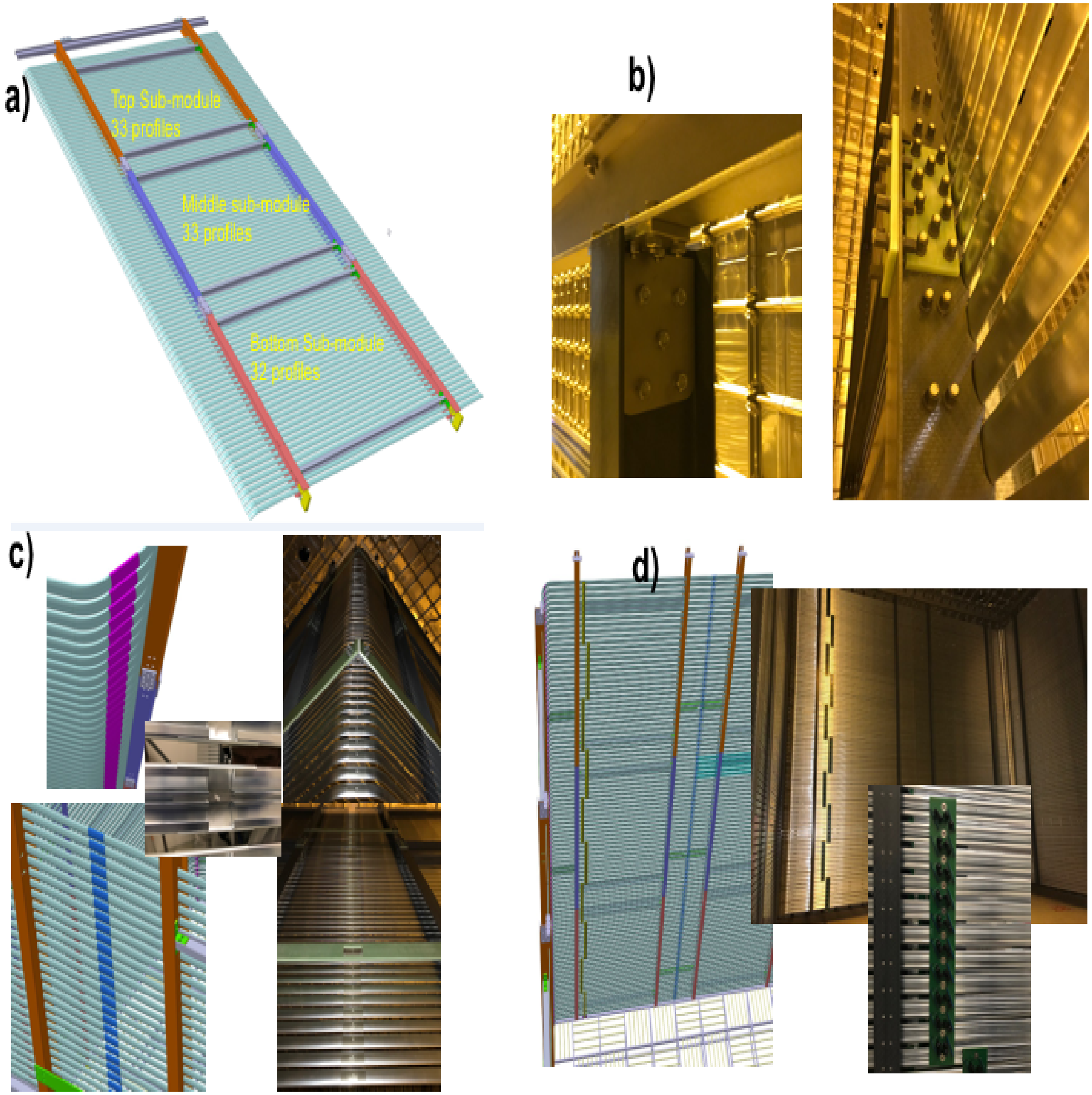

Figure 1.7: FC parts and connections for ProtoDUNE-DP. a. One ProtoDUNE-DP FC panel consisting of three submodules. The DP module has virtually the identical structure, except for the number of middle submodules, which is four, b. A photo of the top module connection to the stainless steel I-beam and an inter-submodule connection, c. Aluminum clip connection at the corner and at the straight sections, d. HV divider boards and their connections on ProtoDUNE-DP FC.

fig:dune

with six G10 bars screwed to the vertical FRP I-beams at positions evenly distributed along the 12.0 m height. This interconnection guarantees the required alignment of the adjacent aluminum profiles for clipping. Given this interconnection, the full FC can be considered as single skeleton that is mostly composed of FRP, which will shrink by about 12 cm over 60 m once the cryostat is filled with LAr. To compensate for this, the G10 bars are designed to be slightly longer than their final length in the LAr.

1.2.5.2 Electrical Interconnections

An aluminum clip connects the ends of each set of two end-to-end FC profiles, forming continuous equipotential rectangular rings 144 m long. Rows of HVDBs, consisting of two resistors and a series of four surge-protection varistors in parallel, bridge the gap between the two neighboring stacked profile rings. The total number of rows will be determined based on the redundancy and the current-limit requirements; one row of HVDBs is in principle sufficient to provide the required potential difference of 3 kV between neighboring rings, but more are desirable for redundancy.

The resistive chain for voltage division between the profiles provides a linear voltage gradient between the cathode and the top-most field shaping ring. It is critical as it determines the strength of the E field between one profile and its neighbors, as well as between the profile and other surrounding parts, e.g., the grounded stainless steel membrane. The E field needs to be kept well below $30\,\mathrm{kV\,cm^{-1}}$ at all points in the LAr bath to enable safe TPC operation.

The identified profile, Dahlstrom Roll Form #1071 [4] is estimated to lead to E fields of up to $12\,\mathrm{kV\,cm^{-1}}$, for the planned FC configuration and operating voltage. Figure 1.8 illustrates results from an E field calculation.

Two distinct types of HV divider boards are used for ProtoDUNE-DP: 10 stage and 8 stage boards. Each stage consists of two $2\,\mathrm{G\Omega}$ resistors in parallel and four varistors of threshold voltage 1.28 kV to protect the resistors in case of a sudden discharge. The total expected current at 600 kV is therefore $3\,\mathrm{\mu A}$ per row. Since multiple rows, which are connected in parallel, are used for redundancy, the expected current in the entire system is simply the number of rows times the current per each row. For optimization purposes, one DP module HVDB will connect 11 stages. This enables one 12.0 m tall module to be covered by fifteen 11 stage HVDB and one 10 stage HVDB at the bottom to make the final connection.

Figure 1.9 shows one HVDB board and Figure 1.7.d. shows the connection of one row of HVDB along the entire height of the FC as installed in ProtoDUNE-DP. The 12 m (W) × 60 m (L) ground plane consists of 80 unit planes (each 3 m × 3 m). The cathode plane is mounted to the bottom of the FC, together forming one contiguous unit of field-providing structure. The bottom-most HVDB makes the connection between the cathode and the bottom-most field-shaping ring. For redundancy, a total of two HVDB rows are used in ProtoDUNE-DP. The DP detector module will use one HVDB chain every four FC modules, providing an ample redundancy. However, the final number of rows of HVDB must take into account the impact of the underlying current through the FC due to the particle interactions.

[4] Dahlstrom Roll Form #1071, Dahlstrom™.

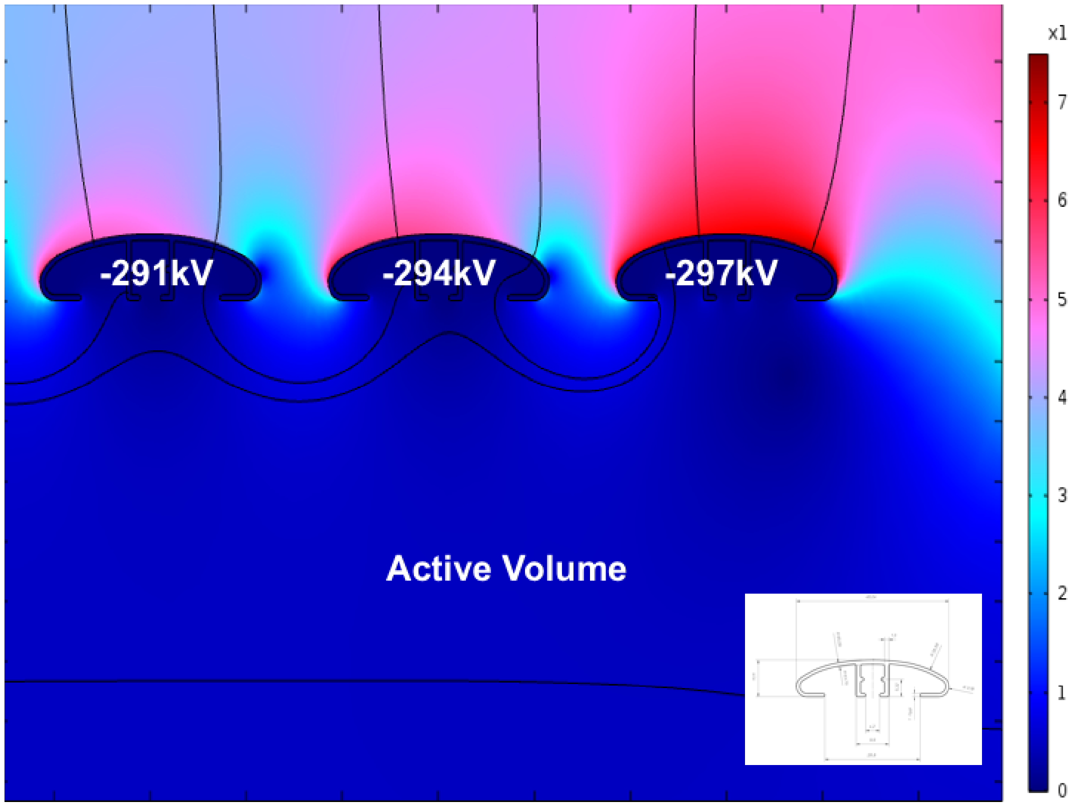

Figure 1.8: E field map (color) and equipotential contours of an array of roll-formed profiles biased up to −300 kV and a ground clearance of about 100 cm in ProtoDUNE-DP (CAD model) fig:prof

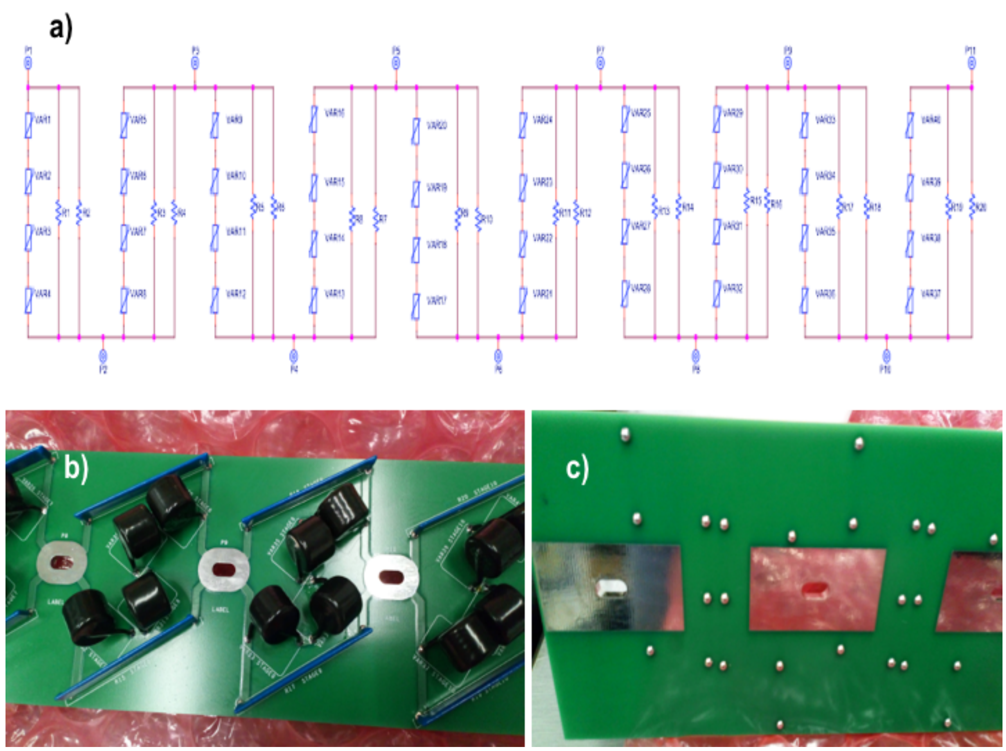

Figure 1.9: ProtoDUNE-DP HV divider board (a) schematic circuit diagram, (b)photo of the top of the board, (c) photo of the bottom of the board fig:dp-

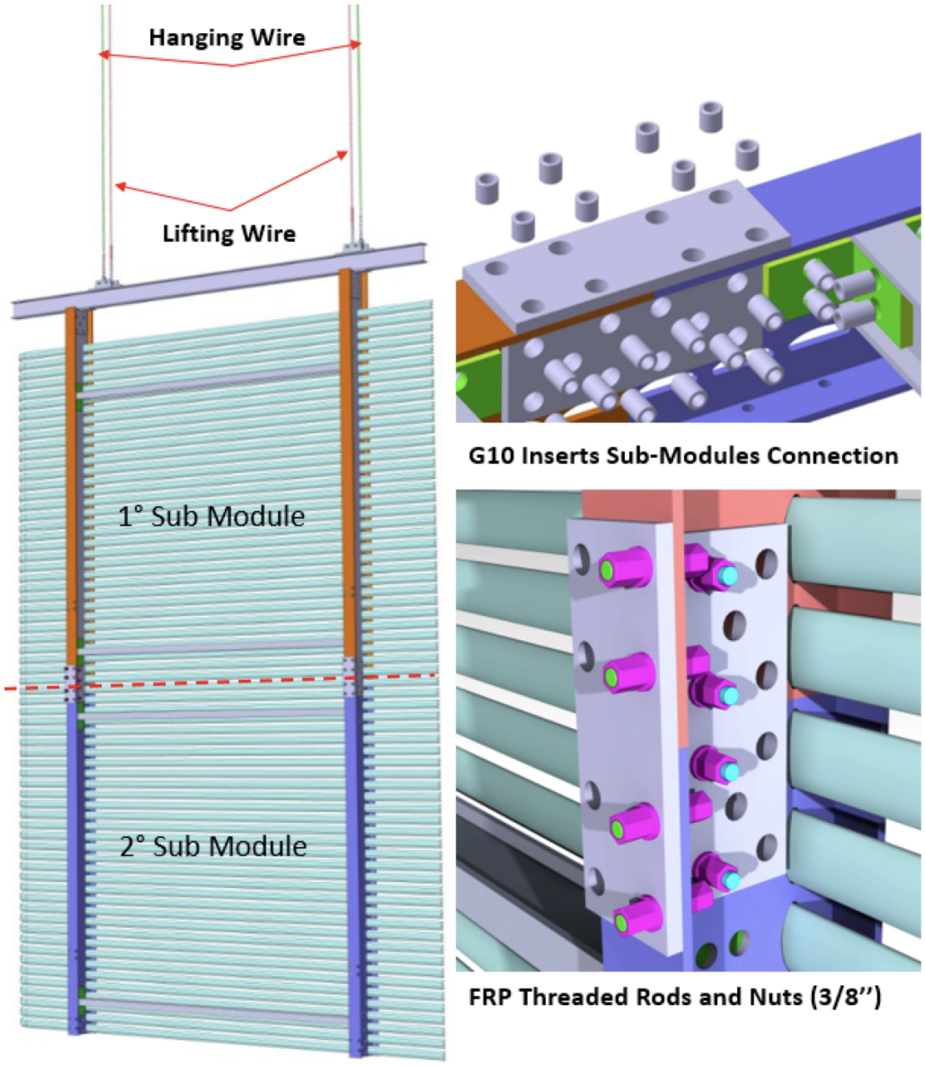

Figure 1.10: Left: Two submodules connected and hanging from the two sets of stainless steel cables on the ceiling. The lifting wires are used to raise the module to its position as submodules are connected; the hanging wires keep the fully integrated module in its final position. Right: Inter-submodule connections. Each connection is made by two 1cm thick G10 plates along the height of the I-beams and one 1cm thick G10 plate on the flange.

fig:dp-f

1.2.6 HV Return and Monitoring Devices

In order to maintain the potential difference between the top-most field shaping ring and the extraction grid of the charge readout plane, either a dedicated HV supply and an adjustable resistor chain is used in the HV return outside of the cryostat. This requires an independent 10 kV feedthrough similar to those developed for the extraction grid.

Multiple devices are planned for monitoring the HV.

- The Heinzinger units have typical sensitivities down to tens of nanoamperes with current readback capability. The units are able to sample the current and voltage every few 100 ms.
- Inside the cryostat, so-called pick-off points near the anode will monitor the current through the HVDB resistor chain.
- Additional pick-off points could be implemented on the ground grid below the cathode to monitor possible stray currents.

1.3 Quality Assurance

dp-hv-qa

Field Cage FRP Parts Upon delivery of the FRP I-beams and other parts, all parts undergo a visual inspection process to look for defects, in particular those affecting structural integrity, such as cracks, air bubble holes, depression and flatness. The parts are sorted into three preliminary categories: category 0 (pass), category 1 (problematic but could be repairable) and category 2 (severe and unusable) .

The visual inspection is followed by critical dimension measurements to verify individual submodule assembly and module interconnection integrity. These measurements focus on cross sectional dimensions for rods, plates and bars, and on the length, straightness, flatness and camber of the beams and flanges. All measurements must satisfy the mechanical tolerance provided by the design drawings and the standard industry quality criteria.

The FRP I-beams and parts in category 1 undergo a repair process during the preparation stage through defibering, deburring and sanding. Another set of measurements is performed after the repair to redetermine the part's category.

Those in category 2 are returned to the vendor for replacements.

HV Divider Board All resistors used for board production are numbered and undergo a three-stage quality assurance (QA) test for final selection. Resistance is measured at voltages up to 4 kV in 500 V steps for each stage. The first stage is done at room temperature, the second at LN temperature, and the third again at room temperature after warming up. The measured values are histogrammed for the final selection, in order to look for groupings of values. It is more important that the resistance values be close to each other than that they be at any particular value (unless they are too far from the design values). The resistors for which the resistance values are within 1% of each other are selected.

All varistors for board production are also numbered for QA purposes and undergo a three-stage QA testing program for the final selection. Each stage is a clamping voltage measurement, first at room temperature, then at LN temperature, and again after warming back up up to room temperature. The measured values are histogrammed for the final selection; those for which the clamping voltage is closer to the design values are selected, to ensure proper protection.

Once the electrical parts are mounted on the HVDB by the vendor, they undergo a three-stage QA testing program. Each stage involves a resistance measurement, first at room temperature, then at LN temperature, and again after warming back up up to room temperature. The measured values are histogrammed for the final selection. The boards can fall into three categories: 0. Pass, 1. Repairable and 2. Rejected. If at any testing stage the resistance is more than 0.5 % away from the mean, the part does not fall into category 0, pass. Boards in category 1 are sent back to the vendor with the selected resistors so that the parts in the failed stages can be replaced.

Aluminum Profiles and Clips The QA testing of the aluminum profiles and clips is done on prototype production samples prior to full production. The samples are visually inspected for their shape and their adherence to the design drawing, the surface smoothness, the surface-coating quality, and the smoothness of the bend (for the profiles with the 45° bend). Clip samples are visually inspected for their shape and their adherence to the drawing, their edge smoothness, their mechanical fitness, and how tightly they fit to the profiles.

Cathode, HVFT and the Extender The QA for other components is under development as part of the ProtoDUNE-DP construction efforts.

Power Supply and Feedthrough The power supply is tested extensively along with the controls and monitoring software. Capabilities to test include:

- Ramp and change the voltage; including rate change and pause capabilities and settings.
- Accept user-defined current limit. This parameter sets the value of current at which the supply reduces the voltage output in order to stay below it. The current limiting itself is done in hardware.
- Accept a setting for the trip threshold current. At this threshold the software would reduce the voltage output. In previous experiments, the trip function in software would set the output to 0 kV.
- Record the current and voltage readback values with a user-defined frequency, and also to record any irregular current or voltage events.

1.4 Production and Assembly

1.4.1 Field Cage Submodule Frames

All FRP parts that pass the QA process undergo the preparation process, which involves quality control (QC) at each step. Each of the parts is first defibered, deburred, sanded to smooth the edges, and then varnished to suppress any remaining fibers. Once the part completes the preparation process, it is stored in a humidity- and temperature-controlled drying area for 24 to 48 hours to fully cure the varnish. Upon full curing, each module is laser-engraved with a unique part number and recorded in a QC database.

At this point the submodule is pre-assembled on a table prior to packaging to ensure fitness of all parts, including inserts, screws and slip nuts. When the fitness is verified, the submodule is disassembled and packaged into a 2 cm×20 cm×2 m compact package with the edges wrapped with a thick plastic layer to protect the parts from mechanical damage, e.g., from a fall. This package includes all necessary parts to assemble the given submodule along with 10 to 20% spare parts. This ensures that each package is self-sufficient for the final assembly. Each package is given a submodule number for further tracking purposes. This submodule number stays with it throughout assembly at SURF and final installation so that the submodule can be assigned to its specific module and in its proper location within the module.

These packages are shipped to SURF and transported underground for final assembly prior to the installation. The 3 m long aluminum profiles are produced and shipped to SURF separately for final assembly. The final QC of the profiles is conducted during submodule assembly. Profiles with deep scratches and sharp protrusions that could cause excess charge concentration will be rejected. This process must be done underground at the time of submodule assembly because of the delicate nature of the coated surface and the smoothness requirement.

Assembly of submodules from the parts is carried out inside the cryostat. An assembly table with a precision alignment bar for rapid profile alignment is used for this task. The package is opened on the table and the FRP frame is assembled with four L-brackets and sixteen 5.61 cm (2.21 in) threaded rods through the G10 insert and eight 5.77 cm (2.27 in) threaded rods through G10 inserts held by the plastic nuts. These nuts are first hand-tightened and then set with a torque wrench.

Once the frame is assembled, aluminum profiles are inserted through the corresponding slots on the 15.2 cm (6 in) on either side. One slip-nut is inserted onto the center rib rail prior to the profile insertion. Care must be taken to ensure that the profiles are not scratched during the insertion process.

Once all profiles are inserted into the frame, each of the profiles is mounted onto the I-beam using two 45 mm M4 button head hex drive stainless steel screws into the aluminum slip nut. When all screws are hand-tightened as much as possible, the final torque is applied using a torque wrench. The final alignment of the profiles is then made by hand, tightening only one or two screws, as necessary. A wheel base made of unistrut bars is then mounted to the bottom of the submodule and the entire unit is placed in a designated area to await installation. The wheel is clearly labeled with the submodule number for tracking purposes.

1.4.2 Cathode Plane

Each cathode module is assembled off-site and shipped to SURF in its transport container. The containers are transported underground to the cryostat and opened in front of the cryostat. The cathode module is then inserted into the cryostat for installation.

1.4.3 Ground Plane

Each ground grid module is assembled off-site and shipped to SURF in its transport container. The containers are transported underground to the cryostat and opened in front of the cryostat. The ground grid module is then inserted into the cryostat for installation.

1.4.4 Electrical Interconnections

The HVDBs are mounted on the profiles as the submodules are built. For optimization purposes, one DP module HVDB connects 11 FC stages. One 12.0 m tall module is covered by fifteen 11-stage HVDBs, and one 10-stage HVDB is at the bottom to make the final connection. One row of HVDBs is mounted every four FC modules. All connections and electrical functionality must be checked with a high-sensitivity electrometer.

1.5 Interfaces to the HV System

1.5.1 Cryostat

Each FC module is suspended and raised by two ropes hung from the cryostat roof through the FC suspension feedthroughs, by winches as in ProtoDUNE-DP.

Once an FC module of the full height is completed for DP module, it will be hung from the cables attached to the final suspension hook and the the suspension feedthrough is then fully sealed. A possible improvement on the ProtoDUNE-DP interface is to use remote-controlled electrical winches (as opposed to manual) to ensure synchronized lifting of the modules.

1.5.2 Charge Readout Plane

No direct hardware interface exists between the HV and CRP systems. The cryostat penetrations and feedthroughs for the two systems are completely independent, as are their control electronics. The only interface envisaged includes a system for maintaining the proper distance between the top-most field-shaping profile and the extraction grid in order to maintain the proper extraction field and to ensure the physical separation between the two systems.

1.5.3 Photon Detection System

No direct hardware interface exists between the HV and PD systems. The cryostat penetrations and feedthroughs for the two systems are completely independent, as are their control electronics. The only interfaces envisaged include (1) maintenance of a safe minimum distance between the PDs and the −600 kV cathode; and (2) definition of the PD power dissipation limit (production of bubbles would compromise the HV stability). The power dissipation depends on the final PD density chosen, which is awaiting simulation results. Aspects of the cathode design are also awaiting simulation results to determine its impact on the PDS. These interfaces are effectively at the level of design requirements.

1.6 Transport, Handling and Integration

The FC FRP beams and G10 parts are shipped in a standard wooden crate. Parts for each submodule are packed into one flatpack of dimensions 0.2 m×0.2 m×2 m sealed in multiple layers of shrink wrap and a thick soft cushion of plastic for edge protection. Due to the compact size of each submodule package and since a total of 530 or so submodules are expected, including 10% spare, the total number of crates for FRP parts to be transported down the shaft will be small. Given the dimensions of the hoist cage, an optimal crate size could be 1.2 m×1.5 m×2.3 m, each containing 30 flatpacks of FRP parts.

The extruded aluminum profiles for FC are shipped separately in standard wooden crates. A total of 197 profiles are needed for each 12.0 m module. Therefore, the total number of profiles to be transported down underground would be of the order 18,000, including 10 % spares. The same number of aluminum clips are also shipped in standard wooden crates and are transported underground separately.

The cathode modules of dimension 3 m×3 m are assembled off-site and shipped to SURF in their transport containers. Given the paucity of storage space at the 4850L, the cathode plane is assembled as each unit cathode plane arrives at the cavern – in its assigned order – and is unwrapped. The cathode plane is assembled inside the cryostat by connecting the cathode units mechanically and electrically, taking into account the constraints imposed by the installation of the ground grid modules and the photomultiplier tubes (PMTs).

The integration starts from the cryostat end opposite to the temporary construction opening (TCO). The field cage modules covering the 12 m long side of the cryostat are installed first. This installation is followed by the CRP installation, which requires access to the cryostat floor. Once a $3{\times}12\,\text{m}^2$ strip of CRP modules is installed, the corresponding field cage side modules are installed followed by the installation of the four cathode modules. The four ground grid modules are initially attached to the cathode modules allowing access for the removal of the false floor and the subsequent installation and cabling of the photomultipliers below the cathode modules. After the installation of the photomultipliers, the ground grid modules are lowered to their final positions. This installation sequence is repeated until the entire detector is complete. The field cage modules covering the endwall on the TCO side are installed before the installation of the last 3×12 m^2 cathode strip.

The power supply, feedthroughs and HV extender are sent to SURF in standard shipping crates. Unwrapping requires clean areas and careful handling. Surfaces can be cleaned with alcohol and allowed to dry.

1.7 Quality Control

The assembly, testing, transport, and installation procedures required to ensure adequate QC of all HV system components are being defined, tested and documented during the construction of ProtoDUNE-DP.

The FC submodules are assembled inside the cryostat on an assembly table with a precision alignment bar, as in ProtoDUNE-DP. Each submodule-FRP part package is visually inspected for external damage and is opened carefully to avoid damage to the FRP parts. The bags of hardware are removed and set side. The two 15.2 cm (6 in) I-beams, two 7.62 cm (3 in) I-beams and connecting L-brackets are visually inspected for damage during transport. Once the FRP parts pass the inspection, they are assembled into the frame on the table.

The aluminum profiles are visually inspected and felt by hand for severe scratches and any excess sharp points. The profiles that pass are inserted into the profile slots on the FRP submodule frame, with one alignment-fixing slip nut inserted into the rail on the reinforcement rib, and follow the assembly and alignment process described in Section 1.4.1. The alignment of the profiles is checked using a straight-edge along one end of the profile. The submodules that pass are put on the wheel base and stored for installation.

The HV divider boards are tested on-site for resistance of each stage at room temperature to ensure the integrity of the board and each electrical connection of the resistors before installation onto the submodule.

At SURF, cathode and GP modules are checked for the required planarity and mechanical integrity. Also during the installation phase the electrical continuity between the modules is checked.

The feedthrough and the HV extender are tested simultaneously at the testing facility site (possibly at CERN or the integration and test facility (ITF)), preferably with the planned power supply. To pass, the feedthrough must hold the goal voltage (−600 kV) in ultra pure LAr (TPC-quality purity corresponding to a free electron lifetime, $\tau \geq 7$ ms) for at least 24 hours. The ground tube submersion and E field environment of the test setup must be comparable to the real FC setup or more challenging. Additionally, the feedthrough must be UHV-grade leak-tight.

Upon arrival at SURF the power supply used in the DP module HV system is tested before installation, with output voltages and currents checked on a known load.

1.8 Safety

v-safety

In all phases of HV system development of the DP detector module, including fabrication, installation, and operations, safety is the highest priority. As for ProtoDUNE-DP, assembly, testing, transport, and installation procedures will be documented. Explicit attention is paid to the transferability of the ProtoDUNE-DP procedures to the DP detector module; the most critical of these are noted in the preliminary ProtoDUNE-DP risk assessment document[5].

make a citation later

The structural and electrical designs for the dual-phase (DP) HV system are based on designs that are vetted and validated in the ProtoDUNE-DP construction, which is currently in its final phase of deployment at CERN. In parallel with the ProtoDUNE-DP contruction and operation, HV tests at CERN are planned using a full-voltage and full-scale HV feedthrough, power supply, and monitoring system in dedicated HV test facilities. This also provides an opportunity to complete full safety reviews.

Operating the FC at its full operating voltage produces a substantial amount of stored energy. The modular design of the cathode specifically addresses this safety concern: in the event of a power supply trip or other failure that unexpectedly drops the HV, the charge stored in the segmented cathode structure limits the power dissipated. This design will be tested in ProtoDUNE-DP at 300 kV voltage over 9 m^2 surfaces segmented in four cathode modules.

Integral to the DP FC design, both in ProtoDUNE-DP and the DP detector module, is the concept of pre-assembled modular panels of field-shaping conductors with individual voltage divider boards. The structural design and installation procedures used in ProtoDUNE-DP were selected to be compatible with use at the far detector (FD) site and were vetted by project engineers, engineering design review teams, and CERN's safety engineers. Some revisions to these designs are expected based on lessons learned in installation and operations; these revisions will be reviewed both within the DUNE project and by Fermilab EH&S personnel. The overall design is on solid footing.

Assembly of the FC panels and resistor-divider boards involves labor on the part of the collaboration members, technical staff, and students, and does not present unusual industrial hazards.

[5] CERN EDMS document number 1856841.

The HV consortium will work closely with each assembly site to ensure that procedures meet both Fermilab's and institutional requirements for safe procedures, personal protective equipment, environmental protection, materials handling, and training. The vast majority of part fabrication will be carried out commercially and shipping will be contracted through approved commercial shipping companies. Prior to approving a site as a production venue, the site will be visited and reviewed by an external safety panel to ensure best practices are in place and maintained.

1.9 Organization and Management

1.9.1 HV Consortium Organization

At present, the HV consortium is gathering institutions to participate in the design, construction and assembly of the HV systems for both SP modules and DP modules. The consortium needs to grow in the near future, and it hopes to attract new institutions, in particular from EU to balance USA participation with additional international participants.

Table 1.2: HV Consortium Participants

Institution	Investigator	Contact
EU: CERN	Francesco Pietropaolo	francesco.pietropaolo@cern.ch
USA: Argonne National Lab	Steve Magill	srm@anl.gov
USA: Brookhaven National Lab	Bo Yu	yubo@bnl.gov
USA: University of California (Berkeley)	Cheng Ju Lin	cjslin@lbl.gov
USA: University of California (Davis)	Emilija Pantic	pantic@ucdavis.edu
USA: Fermi National Accelerator Lab	Sarah Lockwitz	lockwitz@fnal.gov
USA: University of Houston	A. Renshaw	arenshaw@central.uh.edu
USA: Kansas State University	Glenn Horton-Smith	gahs@ksu.edu
USA: Lawrence Berkeley National Lab	Cheng Ju Lin	cjslin@lbl.gov
USA: Louisiana State University	Thomas Kutter	kutter@phys.lsu.edu
USA: South Dakota School of Mines and Technology	J. Reichenbacher	Juergen.Reichenbacher@sdsmt.edu
USA: Stony Brook University	Micheal Wilking	michael.wilking@stonybrook.edu
USA: University of Texas (Arlington)	Jaehoon Yu	jaehoonyu1@gmail.com
USA: Virginia Tech.	Jon Link	jmlink@vt.edu
USA: College of William and Mary	Jeff Nelson	jknels@wm.edu

The consortium has the following management structure:

- Consortium Leader: Francesco Pietropaolo (CERN)
- Technical Leader: Bo Yu (BNL)
- TDR/TP Editors for DP: Francesco Pietropaolo and Jaehoon Yu (UTA)

In the current HV consortium organization, each institution is naturally assuming the same responsibilities it had for ProtoDUNE-DP. The consortium is organized into six working groups (WG) that are addressing the design and R&D phases, and the hardware production and installation.

- WG1. Design optimization for SP and DP; assembly, system integration, detector simulation, physics requirements for monitoring and calibrations. Conveners: Jeff Nelson, Vic Guarino, Bo Yu, Dimitar Mladenov;
- WG2. R&D activities and facilities. Conveners: Francesco Pietropaolo, Ting Miao;
- WG3. SP-CPA: Procurement, in situ QC, resistive panels, frame strips, electrical connections of CPA modules, QC, assembly, shipment to assembly site / QC. Conveners: Stephen Magill, Francesco Pietropaolo;
- WG4. DP Cathode. Convener: Jaehoon Yu;
- WG5. FC modules. Conveners: Thomas Kutter, Michael Wilking, Jeff Nelson, Jaehoon Yu;
- WG6. HV supply and filtering, HV power supply and cable procurement, R&D tests, filtering and receptacle design and tests. Conveners: Franco Sergiampietri, Sarah Lockwitz.

Merging of SP and DP groups is envisaged for the working groups where synergies are being identified: HV feedthroughs, voltage dividers, aluminum profiles, FRP beams, and assembly infrastructures.

1.9.2 Planning Assumptions

The present baseline design for all elements of the HV system for DP module strictly follows the ProtoDUNE-DP design as it has been produced and is being assembled. It is also assumed that no major issues in the HV system operation of ProtoDUNE-DP will be encountered and therefore that the basic HV system concepts are sound.

However some design modifications and simplifications must be implemented to take into account the doubled drift distance, implying an increase in HV delivery to the cathode from -300 kV to -600 kV.

The DP HV system distribution and the related cathode structure still require intense R&D, given the unprecedented value of the required HV (-600 kV). The related results could lead to revision of design details such as the shape of the cathode elements and of the GP structures, the distance from the cryostat walls, the distance between the cathode and the GP protecting the PDs, and resistive connections of the cathode modules. It is important to ensure that the E field intensity in the LAr is below the critical value of about 30 kV/cm everywhere and that the energy stored in the FC is not released catastrophically to the detector membrane.

As for the SP module, ProtoDUNE-SP serves as the test-bed for understanding and optimizing detector element assembly, installation sequence, and integration as well as requirements in human resources, space and tooling, and schedule.