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Design, construction and operation of the ProtoDUNE-SP Liquid Argon TPC

ABSTRACT: Abstract...

KEYWORDS: Only keywords from JINST's keywords list please

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Contents

1 Examples

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Figure 1. DUNE Logo

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2 Detector component

2.1 Inner Detector: High Voltage

A liquid argon time projection chamber (LAr TPC) requires an equipotential cathode plan at high voltage (HV) and precisely regulated interior electric field (E field) to drift electrons from particle interactions to sensor planes. Thus the ProtoDUNE-SP LAr TPC consists of a vertical cathode plane assembly (CPA), vertical anode plane assemblies (APAs) and sets of conductors at graded voltages surrounding the drift volumes ti ensure uniformity of the E field, collectively called field cage (FC).

Figure 2 shows the TPC configuration. Six top and six bottom FC modules connect the horizontal edges of the CPA and APA arrays, and four endwalls connect the vertical edges (two per drift volume). Each endwall comprises four endwall modules. A Heinzinger -300 kV 0.5 mA HV power supply delivers voltage to the cathode. Two HV filters in series between the power supply and HV feedthrough filter out high-frequency fluctuations upstream of the cathode.

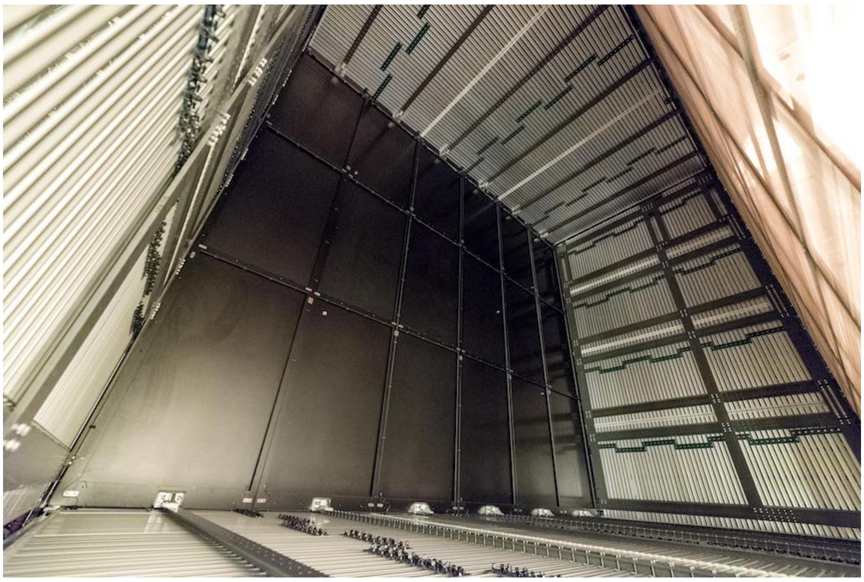

Figure 2. One of the two drift volumes of ProtoDUNE-SP. The FC modules enclose the drift volume between the CPA array (at the center of the image) and the APA (upper right). The endwall FCs are oriented vertically; the top and bottom units are horizontal. The staggered printed circuit boards connecting the endwall FC profiles are the voltage divider boards.

2.1.1 Cathode Plane Assemblies (CPA)

The cathode plane assembly (CPA), is located in the middle of the TPC, dividing the detector into two equal-distance drift volumes. The cathode plane's 7 m × 6 m area is made up of six *CPA columns*, each of which is constructed of three vertically stacked *CPA modules*.

The scope of the CPA includes:

- 18 CPA modules, each with a frame and resistive cathode panel,
- HV bus connecting the CPA columns and modules, and
- HV cup for receiving input from the power supply.

For a successful operation of the ProtoDUNE-HV system the CPA has to fulfill certain requirements briefly mentioned here. It should provide an equipotential surface maintaining −180kV nominal bias voltage. The flatness should be better than 1 cm while submerged in LAr, in addition the material used should have a similar CTE to that of stainless steel. Prevention of damage to the TPC and electronics through a HV-discharge as well as any exposed electric field strenght above 30 kV/cm in LAr are crucial. The provided bias voltage and current to the attached FC must be constant. Mechanically the CPA needs to support the full weight of the four connected top/bottom FC modules and a person during the installation, the cryostat roof movement between the warm and cold state needs to be considered too. Maintaining a modular construction form that is easily applicable in the cryostat is important such as the accomodation of the Photon Detection System (PDS) calibration items. Finally any possibility to trap a LAr volume should be avoided. The discussed requirements inspire the CPA design that is described in detail below.

CPA design

The cathode plane design has a surface made out of a resistive material, this measure was taken to prevent discharges potentially damaging the Cold Electronics (CE) or cryostat. In the event of HV breakdown at a given location on the cathode plane, the sudden change in voltage is restricted to a relatively localized area on the CPA module in question. The rest of the CPA maintains its original bias voltage, and gradually discharges to ground through the large resistivity of the cathode material. During the operational phase of ProtoDUNE-SP no event of discharge has been recorded. The resistive planes will be used in the DUNE-SP-FD design.

The cathode plane design chosen for the ProtoDUNE-SP TPC is an array of 18 modules constructed from strong 6-cm-thick FR4 (the fire-retardant version of G10) frames. The frames hold 3-mm-thick FR4 panels laminated on both sides with a commercial resistive Kapton film. Each CPA module is 1.16 m wide and 2 m high, and they stack to form six CPA columns of height 6 m. The six-column-wide CPA has the same dimensions as each of the two APA planes.

The surface of the frame facing the APAs is covered by a set of resistive FR4 strips with a different bias voltage, set such that the frame itself causes no distortion in the drift field beyond the resistive surfaces.

The outer edges of the cathode plane facing the cryostat wall are populated with the same metal profiles, with insulating polyethylene caps, as used in the field cage (FC) described in Section 2.1.2. This limits high field strength (below 30 kV/cm, as specified in the requirements) in the surroundings

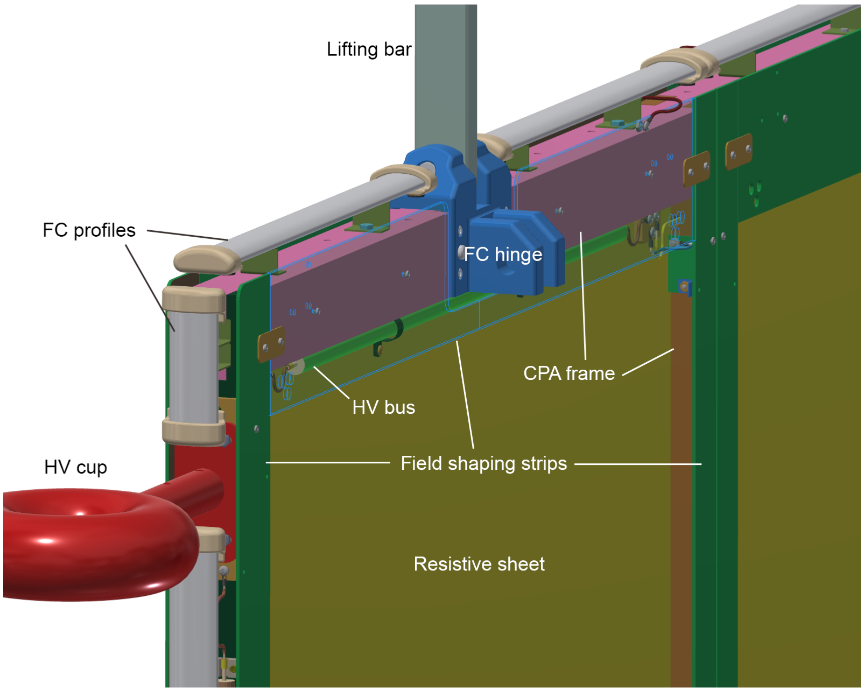

Figure 3. HV input cup connection to CPA array

of the CPA frame. This eliminates the need for a special design of the most crucial regions of the cathode plane: the edges of the CPA now look just like a continuation of the FC. Since these profiles are the only objects facing grounded surfaces, they are the most likely candidates to have HV discharges to ground. To limit peak current flow, these edge profiles are resistively connected to the field shaping strips. A completed CPA column is shown in Figure 4. A CPA plane is made up of two columns side-by-side.

The CPA is connected to the HV feedthrough through a receptacle, called the *HV cup*, at the back end of the cryostat (with respect to the beam entrance) and biased at -180 kV. It provides the voltage and the required current to all the FC modules (top, bottom and end walls) through electrical interconnects (Section 2.1.2).

Deformation and stress due to the pressure from the circulating LAr as well as shrinkage due to the temperature change have been taken into consideration for the design. For example to ensure contact between the CPA modules after cool down a gap of 0.7 mm has been introduced which corresponds to the calculated closing in after cool down. The joints between the FC and the CPA are also designed to accommodate an estimated shrinkage of 5.2 mm of the steel beam between CPA and APA.

Mechanical and electrical interconnections between modules

Three modules are stacked vertically to form the 6-m height of a CPA. The frames of these modules are bolted together using tongue-and-groove connections at the ends. The resistive cathode sheets and the field-shaping strips are connected using metallic tabs to ensure redundant electrical contact between the CPAs.

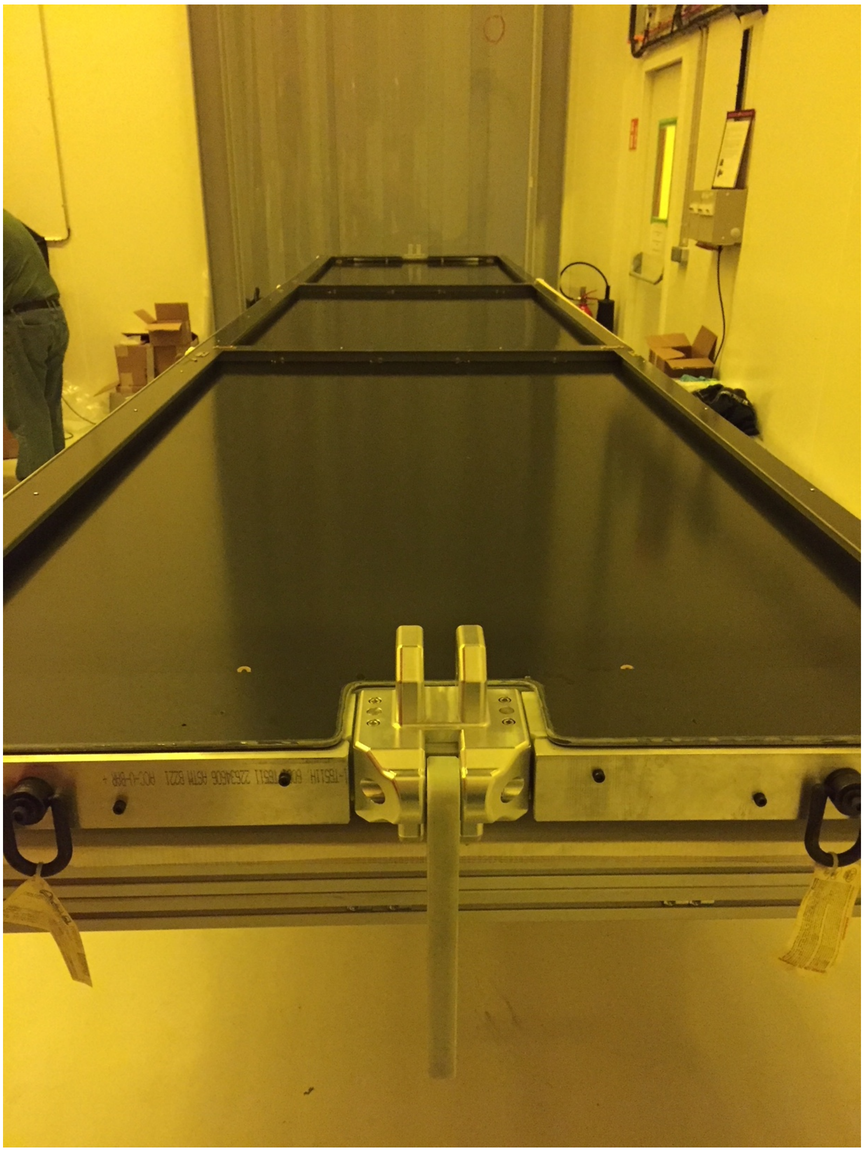

Figure 4. Completed 6 m long ProtoDUNE-SP CPA panel on production table. A CPA plane is made up of two panesl side-by-side.

Each CPA is suspended from the cathode rail using a central lifting bar. Due to the roof movement between the warm and cold phases of the cryostat as it is cooled, each CPA is expected to move ∼2 mm relative to its neighbors. Several pin-and-slot connections are implemented at the long edges of the CPA columns to ensure the co-planarity of the modules while allowing for a small vertical displacement.

The electrical connectivity of the resistive panels within a CPA column is maintained by several tabs through the edge frames. The voltage is passed from one column to another through embedded cables in the CPA panels referred to collectively as the HV bus as shown in Figure 3. Redundant connections in the HV bus between CPA columns are used to ensure reliability. The HV bus also provides a low-resistance path for the voltage needed to feed the FC resistive divider chains. The required connections to the FC modules are made at the edges of the cathode plane. Along the perimeter of the CPA, the HV bus cables are hidden between the field-shaping strip overhang and the main cathode resistive sheet. The cables are capable of withstanding the full cathode bias voltage to prevent direct arching to (and as a result, the recharging of) a CPA panel that discharges to ground. Connections are flexible in order to allow for FC deployment, thermal contraction, and motion between separately supported CPA components.

2.1.2 Field Cage (FC)

In the SP module the FC covers the top, bottom, and endwalls of all the drift volumes, thus providing the necessary boundary conditions to ensure a uniform E-field and shielding it from the cryostat walls. The FC is made of adjacent extruded aluminum open profiles running perpendicular to the drift field and set at increasing potentials along the 3.5m drift distance from the CPA HV (-180kV) to ground potential at the APA sensor arrays. Another element of the FC are the Ground Planes (GP) sitting on top and bottom FC modules. They confine the E Field in the liquid phase, avoiding high field in the gas phase (top) and close to the piping at the bottom of the cryostat. Apart from the profiles themselves, the nuts and bolts holding them, and the GP panels, all the FC components are made of insulating material fiberglass-reinforced plastic (FRP). FRP has good mechanical strength at cryogenic temperatures and low CTE. The FC modules come in two distinct types: the identical top and bottom modules, which are assembled to run the full length of the detector module and the endwall FC modules, which are assembled to complete the detector at either end.

Subdividing the FC into electrically isolated modules limits the stored energy in each FC module thereby minimising the risk of damage. Each FC module must have its own voltage divider network connecting the adjacent pairs of aluminum profiles along each FC module. The resistive chain provides the necessary linear voltage gradient.

The division of the FC into mechanically and electrically independent modules also eases the construction and assembly of the FC and greatly restricts the extent of drift field distortion caused by a resistor failure on the divider chain of a FC module.

Top/Bottom Field Cage and Ground Planes

In ProtoDUNE SP there are six top and six bottom FC assemblies as shown in Figure 5. The assemblies are constructed from pultruded FRP I-beams and box beams that support the afore mentioned aluminum profiles. The length and width are 2.3 m and 3.5 m respectively, each assembly comprising 57 aluminum profiles. A GP consisting of modular perforated stainless steel sheets runs along the outside surface of each top and bottom FC with a 20 cm clearance. The gas region of the volume, also referred to as gas ullage, is necessary for a safe and stable operation of the LAr cryogenic system. The ullage contains many grounded conducting components with sharp features near which the E field could easily exceed the breakdown strength of gaseous argon if directly exposed potential carrying FC. Also the bottom FC are equipped with GP to shield from cryogenic pipings and other sensors with sharp features on the cryostat floor.

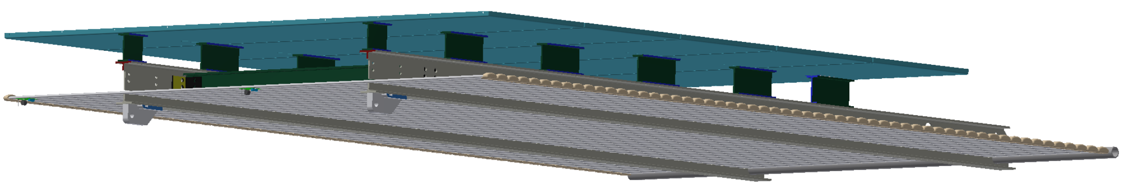

Figure 5. Drawings of a Top/Bottom FC module.

The connections between the top and bottom modules and the CPAs are made with aluminum hinges of 2.54 cm in thickness, that allow the modules to be folded in on the CPA during installation. The hinges are electrically connected to the second profile from the CPA. The connections to the APAs are made with stainless steel latches that are engaged once the top and bottom FC modules are unfolded and fully extended towards the APA. A top FC module being lifted for installation on the CPA panel is shown in Figure 6.

Figure 6. Lifting of a Top FC module. The latches that connect to the APA are at the bottom.

Endwall Field Cage

Each of the two drift volumes has two endwall FCs one on each end. Each endwall FC is in turn composed of four stacked endwall FC modules, the top most equipped with hanger plates. Each endwall FC module is constructed of two FRP box beams each 3.5 m long as shown in Figure 7. The endwalls are not equipped with GPs as there is enough clearance between cryostat wall and FC on the sides, avoiding high E field. In ProtoDUNE SP the endwall at the beam entry is constructed in a special way to accomodate the support of the beam plug described in section 2.1.3.

Field Cage Profiles

The top/bottom as well as the endwall FC modules consist of extruded aluminum field-shaping-profiles. The shape of the profiles allows to minimise the strength of the E field between a given profile and its neighbors and between a profile and other surrounding parts. The profile ends have a higher surface E field, especially those at the corners of the FC (boundary with APA or CPA). To prevent high voltage breakdowns in the LAr the ends of the profiles are encapsulated by custom

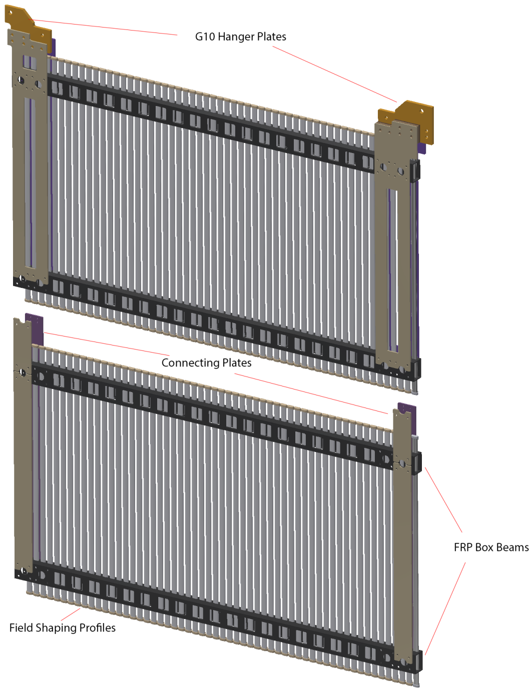

Figure 7. Top: uppermost module of the endwall FC. The two G10 hanger olates connect the endwall FC to the detector support system (DSS) beams above the APAs and CPAs. Bottom: regular endwall FC module. 3 such modules stack vertically with the top module to form the total height.

UHMWEP **get reference** caps. The caps are designed and experimentally verified to withstand the full voltage across their thickness.

Voltage Divider Boards & Terminations

A resistive divider chain interconnects all the metal profiles of each FC module to provide a linear voltage gradient between the cathode and anode planes.

The resistive divider chain is a chain of resistor divider boards each with eight resistive stages in series. Each stage (corresponding to 6 cm gap between FC profiles) consists of two 1 GΩ resistors in parallel yielding a parallel resistance of 0.5 GΩ per stage to hold a nominal voltage difference of 3 kV. Seven FC panels were equipped with voltage divider boards holding 5 GΩ, in order to test the nominal DUNE CITE DUNE TDR configuration. Each stage is protected against high voltage discharge transients by transient/surge absorbers (varistors). Bo, please rephrase this correctly :) The clamping voltage needs to be higher than the nominal voltage difference but not too high, as then local field distortions would become dominant: This is achieved with three varistors (with 1.8 kV clamping voltage each) are wired in series and placed in parallel with the associated resistors. A schematic of the resistor divider board is shown in Figure 8; an illustration of the resistor divider board used is shown as well. Each FC divider chain connects to an FC termination board in parallel to a grounded fail-safe circuit at the APA end. The FC termination boards are mounted on the top of the upper APAs and bottom of lower APAs. Each board provides a default termination resistance, and an SHV cable connection to the outside of the cryostat, via the CE signal feedthrough flange, through which we can either supply a different termination voltage to the FC or monitor the current flowing through the divider chain.

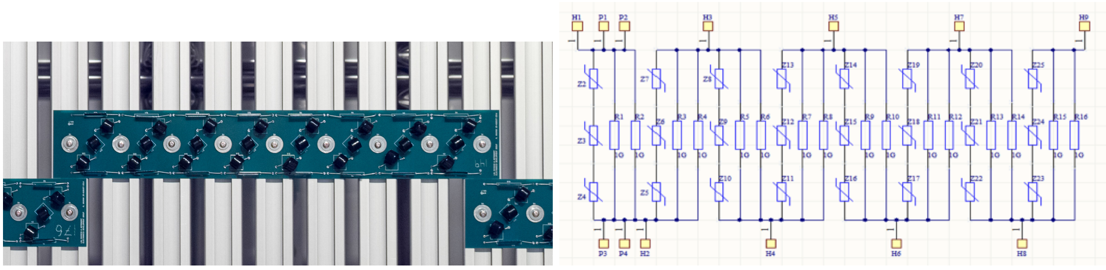

Figure 8.

2.1.3 Beam Plug (BP)

To minimize the material interactions of the particle beam in the cryostat upstream of the TPC, a volume of LAr along the beam path (between the cryostat membrane and the FC) is displaced, and replaced by a less dense volume of dry nitrogen gas. The gas is contained within the *beam plug*, a cylindrical glass-fiber composite pressure vessel, about 50 cm in length and 22 cm in diameter. It is illustrated in Figure 9. A pressure relief valve and a burst disk are installed on the nitrogen fill line on the top of the cryostat (externally) to ensure the pressure inside the beam plug does not exceed the safety level of about 22 psi. The nitrogen system schematic is shown in Figure 10.

The beam plug is secured to the endwall FC support structure as illustrated in Figure 9. The front portion of the beam plug extends 5 cm into the active region of the TPC through an opening in the FC. The FC support is designed with sufficient strength and stiffness to support the weight of the beam plug. The total internal volume of the beam plug is about 16 liters.

The requirements on the acceptable leak rate is between 7.8×10^{-5} scc/s and 15.6×10^{-5} scc/s. This is very conservative and is roughly equivalent to leaking 15% of the nitrogen in the beam plug over the course of a year. In the worst-case scenario in which all the nitrogen in the beam plug leaks into the LAr cryostat, the increase in concentration is about 0.1 ppm, which is still a factor of 10 below the maximum acceptable level, as specified by light detection requirements. Over the course of about 1.5 years of beam plug operations in LAr at ProtoDUNE, no detectable leak was observed.

At nominal operation, the voltage difference across the beam plug (between the first and the last grading ring) is 165 kV. To minimize risk of electrical discharges, the beam plug is divided into sections, each of which is bonded to stainless steel conductive grading rings. The seven grading rings are connected in series with three parallel paths of resistor chains. The ring closest to the FC is electrically connected to one of the FC profiles. The electrode ring nearest the cryostat wall is grounded to the cryostat (detector) ground. The maximum total power dissipated by the resistor chain is about 0.6 W.

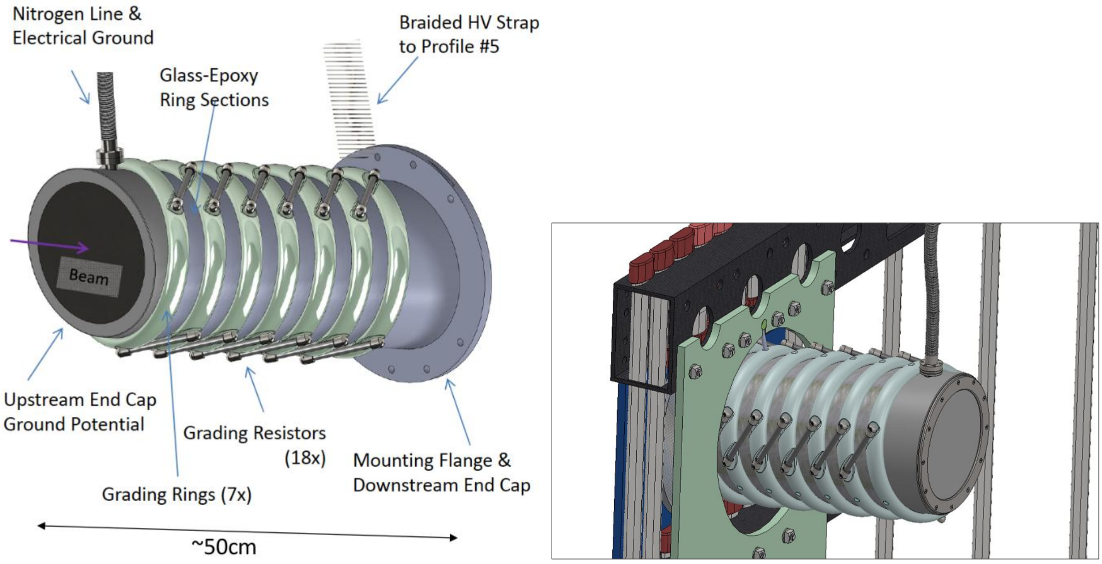

Figure 9. The beam plug is a composite pressure vessel filled with dry nitrogen gas. Left: The vessel is about 50 cm in length and about 22 cm in diameter. The pressure vessel is divided into sections with each section bonded to a stainless steel grading ring. The grading rings are connected by three parallel paths of resistor chain. Right: Beam plug to field interface.

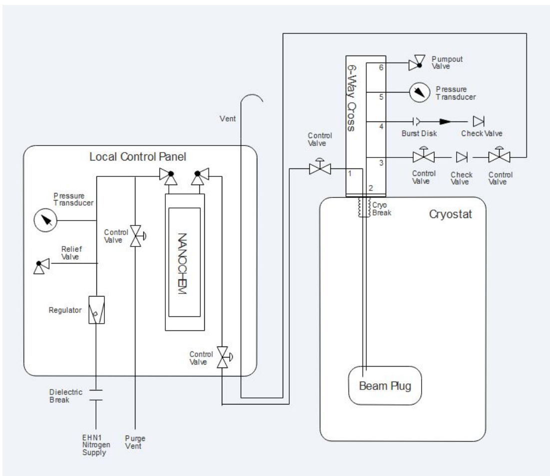

Figure 10. Beam plug nitrogen gas system schematics. The Local Control Panel is mounted on top of the cryostat near the DN160 flange feedthrough. The nitrogen line enters the cryostat via the 6-way flange which also has a burst disk for emergency pressure relief and temperature/pressure sensors.

2.1.4 HV components

The TPC high voltage (HV) components include the HV power supply, cables, filter circuit, HV feedthrough, and monitoring for currents and voltages (both steady state and transient).

The -180 kV that are necessary to produce the required electric field of 500 V/cm are delivered by the power supply through an RC filter and a HV feedthrough to the CPA. The design of the HV feedthrough is based on the very successful construction technique adopted for the ICARUS HV feedthrough [2] and shown in Figure 11. Before installation the feedthrough was also successfully operated for several days in a test stand at up to 300 kV. The design is based on a coaxial geometry, with an inner conductor (HV) and an outer conductor (ground) insulated by ultra-high-molecular-weight polyethylene (UHMW PE) as illustrated in Figure 11. The outer conductor, made of a stainless-steel tube, surrounds the insulator, extending down through the cryostat into the LAr. In this geometry, the electric field is confined within regions occupied by high-dielectric-strength media (UHMW PE and LAr). The inner conductor is made of a thin-walled stainless steel tube to minimize the heat input and to avoid the creation of argon gas bubbles around the lower end of the feedthrough. A contact, welded at the upper end for the connection to the HV cable, and a round-shaped elastic contact for the connection to the cathode, screwed at the lower end, completes the inner electrode. Special care has been taken in the assembly to ensure complete filling of the space between the inner and outer conductors with the PE dielectric, and to guarantee leak-tightness at ultra-high vacuum levels.

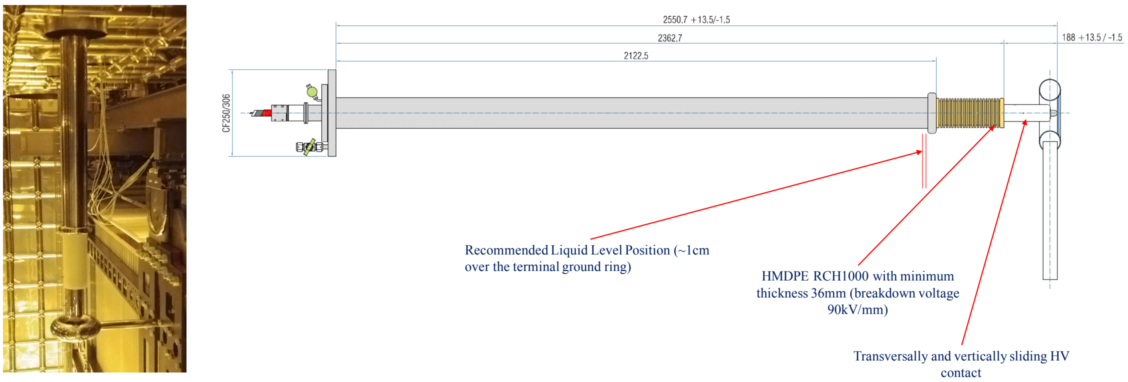

Figure 11. Photograph after installation and drawing of the HV feedthrough. The distance from the cup to the top surface is approximately 1.3 m.

Filter resistors are placed between the power supply and the feedthrough. Along with the cables, these resistors reduce the discharge impact by partitioning the stored energy in the system. The resistors and cables together also serve as a low-pass filter reducing the 30 kHz voltage ripple on the output of the power supply.

The filter resistors are of a cylindrical design. Each end of a the HV resistor is electrically connected to a cable receptacle. The resistor must withstand a large over-power condition. A cylindrical insulator is placed around the resistor.

Outside the cryostat, the HV power supply and cable-mounted toroids monitor the HV. The power supply has capabilities down to tens of nA in current read-back and is able to sample the current and voltage every 300 ms. The cable-mounted toroid is sensitive to fast changes in current;

the polarity of a toroid's signal indicates the location of the current-drawing feature as either upstream or downstream of it.

Inside the cryostat, pick-off points near the anode monitor the current in each resistor chain. Additionally, the voltage of the ground planes above and below each drift region can diagnose problems via a high-value resistor connecting the GP to the cryostat. The instrumentation provided useful information on HV stability.

HV Commissioning, Beam Time Operation and Stability Runs

During cool-down and LAr filling, a power supply was used to supply −1 kV to the cathode and monitor the current draw of the system. As the system cooled from room temperature to LAr temperature, the resistance increased by ∼10%, consistent with expectations. Once the LAr level had exceeded the height of the top GP, the voltage was ramped up to the nominal voltage.

Two types of instabilities emerged in the cold side of the HV system. The first type are the so-called current blips, during which the system draws a small excessive current that persists for no more than a few seconds. The magnitude of the excess current during such events increased over the subsequent three weeks from 1% to 20%. The second type of instability, labeled "current streamers," exhibited persistent excessive current draw from the HV power supply with accompanying excessive current detected on a GP and on the beam plug. These two types of instabilities were experienced periodically throughout the duration of the beam run. The frequency of both types increased over time after the system was powered on, until a steady state of about ten current blips/day and one current streamer every four hours was reached. These effects are consistent with a slow charging-up process of the insulating components of the FC supports, which then experience partial discharges that are recorded as HV instabilities. This process restarts after every long HV-off period.

In addition, these processes seem to be enhanced by the LAr bulk high purity, which allows the electric current to develop. At low purity electronegative impurities act as quenchers, blocking the development of the leakage current. During the 2018 beam run periods, priority was given to operating the PDSP detector with maximal up-time in order to collect as much beam data as possible at the nominal HV conditions. In some cases, mostly outside of the beam run period, we turned off the HV system momentarily to allow the HV system components to discharge. This is reflected as larger dips in the uptime plot shown in Figure 12. During moments when the rest of the subsystems (including the beam) were stable, the moving 12-hour HV uptime fluctuated between 96% and 98%. Automated controls to quench the current streamers were then successfully implemented in an auto-recovery mode. These helped significantly to increase the up-time, by optimizing the ramping down and up of the HV power supply voltage, which was performed in less than four minutes. The process of the auto-recovery mode is shown in Figure 13.

Investigating the long-term behavior of the HV instabilities and understanding their origin became goals of the long-term operation of ProtoDUNE-SP in 2019. As mentioned above, it appears that the current streamer effect is a charging-up process with its frequency increasing with time after a long HV-off period. This behavior has been repeatedly observed and confirmed in 2019. The current streamer rate stabilized at 4-6 per day, and the location was essentially always on the same single Ground Plane (GP#6) out of the 12 monitored GPs. Their rate and location were approximately independent of the HV applied on the CPA in the 90 kV to 180 kV range.

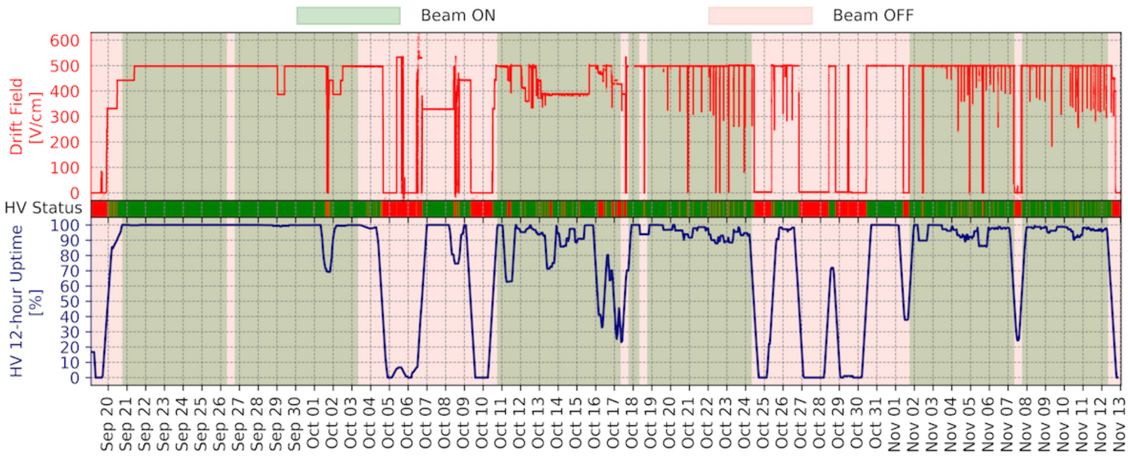

Figure 12. The performance of the HV system across the test beam period, Sep-Nov 2018. The top panels shows the drift field delivered to the TPC the middle panel indicates HV cuts during periods when the system is not nominal (some periods not visible due to their short timescale), and the bottom panel shows the moving 12-hour uptime of the HV system based on these HV cuts.

More recently, after a change of the LAr re-circulation pump (April 2019), the detector was operated for several months in very stable cryogenic conditions and with very high and stable LAr purity (as measured by purity monitors and cosmic rays). During this period, the HV system was set and operated at the nominal value of 180 kV at the CPA for several weeks without interruption. A significant evolution in the behavior of the HV system was observed.

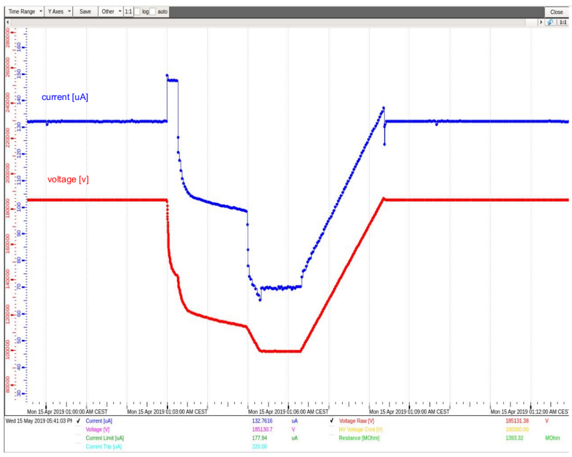

Figure 13. Example of the HV automatic recovery procedure developed to detect and quench the current streamers. Whenever an excess sustained current from the HV power supply is detected in the monitoring of the total detector resistance, the HV from the power supply is lowered in discrete steps. At each step the total resistance is checked and if it agrees with the nominal detecroor resistance the HV is ramped up again to its nominal value, if it isn't the case the HV is lowered to the next step.

To better understand the current streamers phenomenon, the HV system was operated for about fifty days without the auto-recovery script, and the current streamers were left to evolve naturally. They typically lasted 6 to 12 hours, exhibiting steady current and voltage drawn from the HV power supply and they eventually self-quenched without any intervention. The repetition rate was highly reduced to about one current streamer every 10-14 days; this rate can be compared to the 4-6 per day in the previous periods with auto-recovery on.

The auto-recovery script was then re-enabled and the current streamer rate stabilized at about one in every 20 hours; in addition, the intensity of the current streamer on the GP was reduced with respect to the previous periods. As in the previous runs, the current streamers occurred always on the same GP (GP#6) with a small leakage current on the beam plug hose, which is close to GP#6.

This behavior is a further indication that the current streamers are in fact a slow discharge process of charged-up insulating materials present in the high-field region outside of the FC. The auto-recovery mode does not allow a full discharge, so the charging up is faster, and the streamer repetition rate is shorter.

The LAr purity loss experienced at the end of July, 2019, was accompanied by the complete disappearance of any HV instabilities. They gradually reappeared when the electron lifetime again exceeded 200 microseconds, and their intensity constantly increased as purity improved. This behavior replicated that observed after the initial filling, and supports the hypothesis that the HV instabilities are enhanced by the absence of electronegative impurities in high-purity LAr.

The effects of the current streamers on the front-end electronic noise and the PD background rate have been investigated. We have not observed any effect of the current streamers on the FE electronics. On the other hand, recent analysis of the data collected by the PDS during active current streamers has indicated a high single photon rate on the upper upstream part of the TPC. This is consistent with the activities recorded on GP#6, which is located exactly at this upper upstream area.

References

[1] D. Newbold, *ProtoDUNE-SP Timing System: Interfaces and Protocol*, tech. rep., Bristol, 2016.

[2] ICARUS collaboration, S. Amerio et al., *Design, construction and tests of the ICARUS T600 detector*, *Nucl. Instrum. Meth.* **A527** (2004) 329–410.