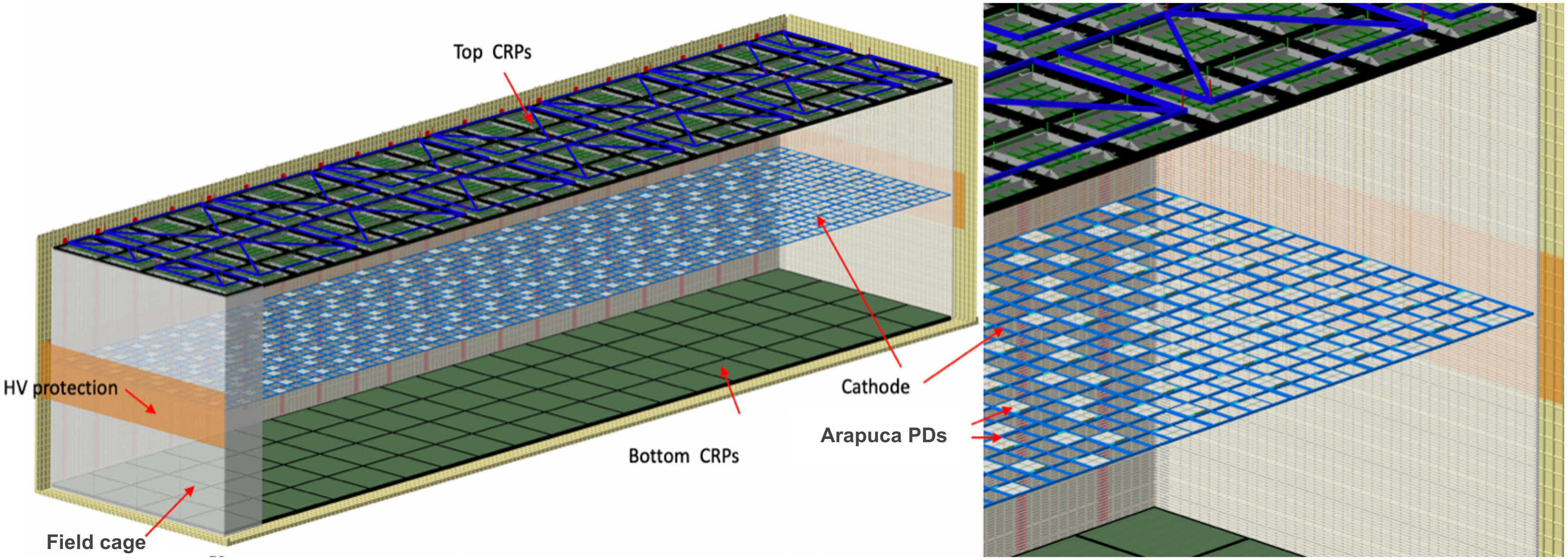
Status of the HV System Design



Bo Yu
Brookhaven National Lab

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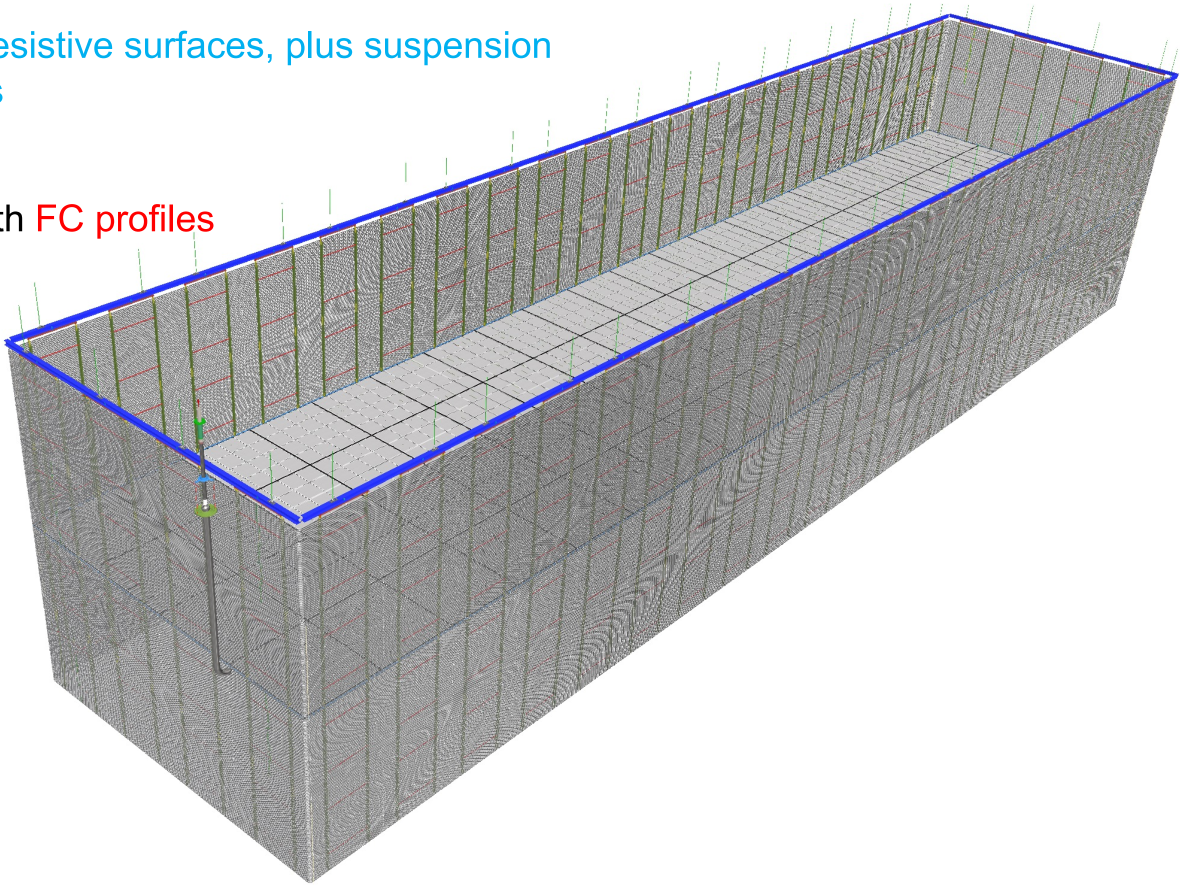
Scope

The HV system is funded jointly by CERN, DUNE-US, and IN2P3. It consists of

- The HV delivery system
  - HVPS, PS monitoring system, HV cable, ripple filters, HVFT, and HV extender
- The cathode plane
  - 80 cathode modules with resistive surfaces, plus suspension features to the super CRPs
- The field cage
  - 192 field cage modules, with FC profiles procured by CERN.



Requirements

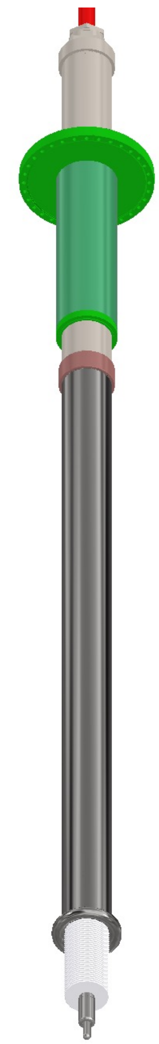
EB and TB held FD requirements:

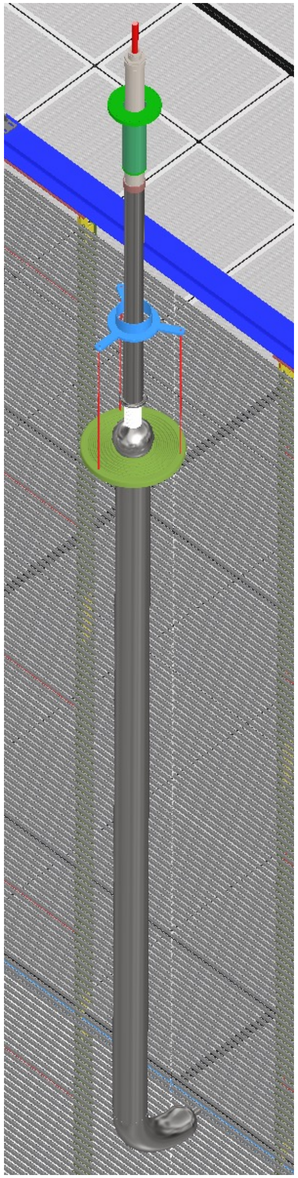
ID	Description	Spec (Goal)	Comment
SP-FD-1	Minimum drift field	>250 V/cm, (500V/cm)	Request change the goal to ~ 450V/cm to enable the use of existing 300kV HVPS. See Francesco’s presentation
SP-FD-11	Drift field uniformity due to HVS	< +/-1% in 99.8% of the active volume	Larger drift distance relaxes cathode flatness requirement
SP-FD-12	Cathode HV power supply ripple contribution to system noise	< 100 e	
SP-FD-17	Cathode resistivity	> 1MΩ/□, <10TΩ/□ (> 1GΩ/□)	
SP-FD-24	Local electric fields	< 30 kV/cm; Exceptions: for specific components with localized E-field higher than 30 kV/cm, perform test in pure LAr at least at 120% of the designed operating voltage	Request change of wording: voltage -> electric field
SP-FD-29	Detector uptime	>98%, (>99%)	
SP-FD-30	Individual detector module uptime	>90%, (>95%)	
SP-HV-1	Maximize power supply stability	> 95% uptime	
SP-HV-2	Provide redundancy in all HV connections	Two-fold, (Four-fold)	Request exception on single HVFT

Consortium held requirements and specifications under development.

High Voltage Delivery System

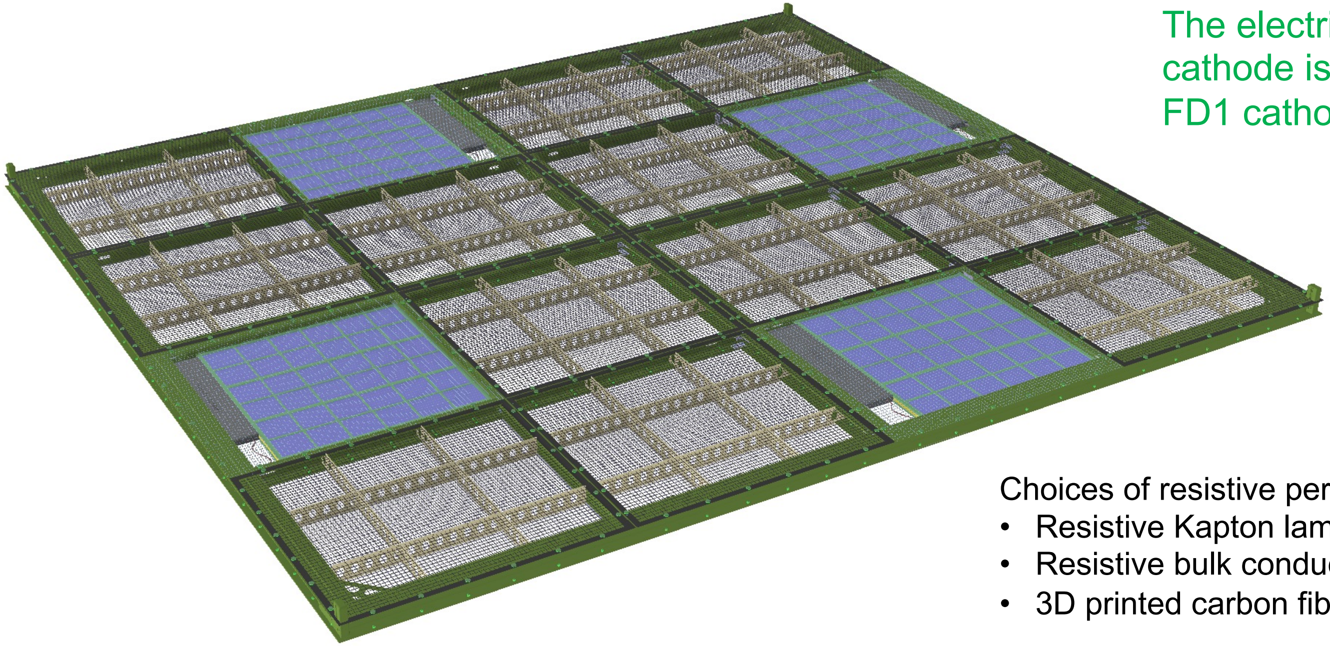
- The high voltage delivery system is comprised of a HVPS, HV cable, ripple filters, HV feedthrough, and an HV extender inside the cryostat to deliver the voltage to the cathode and field cage at the mid height of the TPC.
- The reference design plans to use the Heinzinger PNChp 300kV power supply to power bias the cathode at ~293kV. These HVPSs have been successfully deployed in the ProtoDUNEs with good performance.
- A 300kV rated ripple filter will be designed and constructed based on the successful design of the NP04 ripple filter with moderate voltage drop to allow a higher voltage at the cathode.
- The HVFTs used in ProtoDUNEs have been tested to 300kV before deployment in the large cryostat. The HVFT in NP04 worked well for more than 2 years. Both HVFTs developed ice buildup at the HV cable connection on the air side: a shortcoming in the FT design. An existing HVFT built by UCLA for the 35ton TPC is being evaluated at CERN for 300kV operations. This feedthrough is free from the cold connection problem, and is our reference design
- A new HV extender has been designed and the critical section (HVFT to extender interface) is under construction at FNAL and will be tested at Iceberg (presentation by Sarah L.). A full-size extender will be built at CERN and tested in NP02 in the fall (presentation by Francesco P.)





Cathode Plane

- Each cathode module is constructed from a 3m x 3.4m x 0.05m FRP I-beam frame with 16 openings. Modules are suspended to the super CRP structure above the top anode plane using insulating ropes (Dyneema).
- Double sided x-arapuca PD modules are installed in 4 of the openings (PDS scope), encased by highly transparent (~80%) metal wire mesh panels on both sides.
- 12 pairs of perforated resistive panels are mounted on the top and bottom faces of the frame, reinforced by light-weight rib structures. These and the wire mesh panels are electrically interconnected to form two highly resistive surfaces with sufficiently slow discharge RC time constant to reduce harmful charge injection to the FEE connected to the anodes. The porosity of the resistive panels is to be determined by CFD.

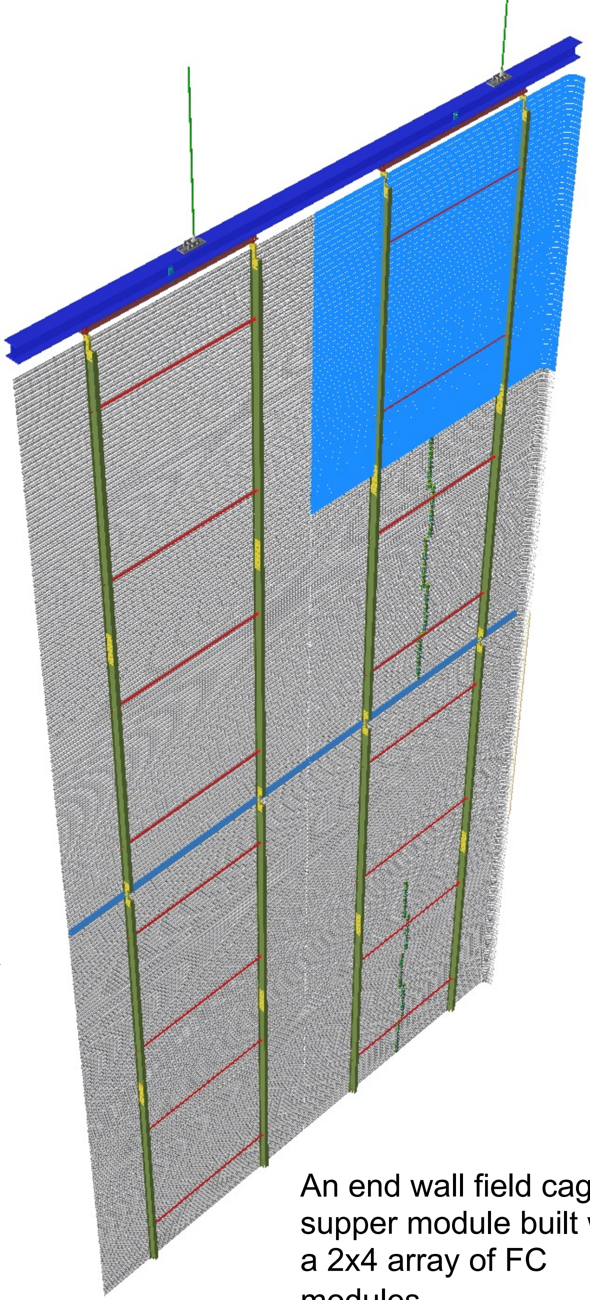


The electrical characteristics of this cathode is very similar to that of the FD1 cathode planes.

Choices of resistive perforation:
- Resistive Kapton laminated FR4 sheet (FD1 CPA)
- Resistive bulk conducting FR4 sheet
- 3D printed carbon fiber + PEEK grid.

Field Cage

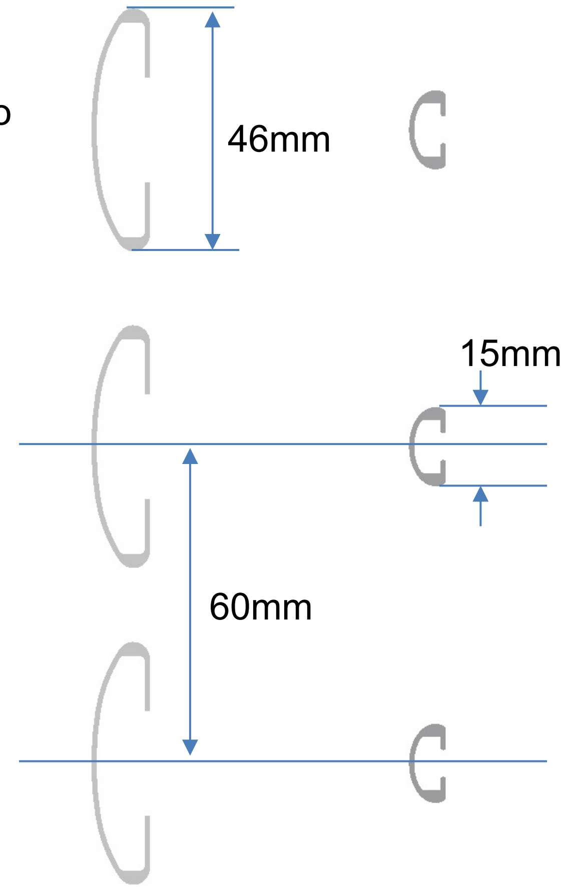
- The field cage will be constructed from arrays of FC modules surrounding the LAr volume between the top and bottom anode planes. The design is based on experiences gained from both NP04 and NP02 installation and operations. The electrical characteristics of this design will be validated in the ProtoDUNE II. Its key features in assembly and installation have been demonstrated in NP02.
- The field cage module uses the existing ProtoDUNE extruded aluminum profiles mounted on the outer flanges of FRP I-beams. The ends of each profile are terminated in UHMWPE caps to prevent the exposure of high E field to the bulk liquid argon. Each module has its own resistor divider chain to eliminates the need for lateral electrical interconnect between modules.
- Along the 4 vertical edges of the field cage, the profiles are bent at 90° to provide smooth conductive surfaces to reduce field enhancement. The 13m double drift depth is covered by a column of 4 FC modules. Two FC columns are supported by a common stainless steel I-beam to form a supper FC module, which is suspended through two roof penetrations.
- A study on improving the optical transparency of the FC modules has been conducted with encouraging outcome, providing more flexible placement for the PDs.

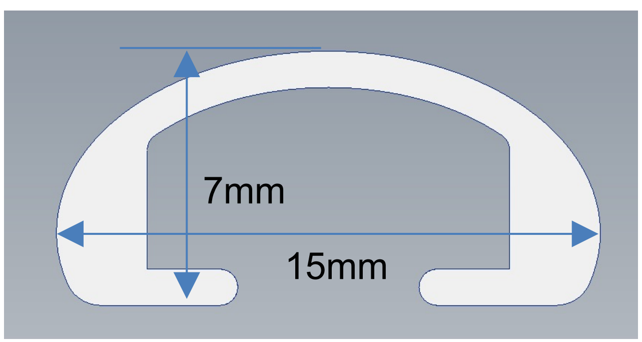


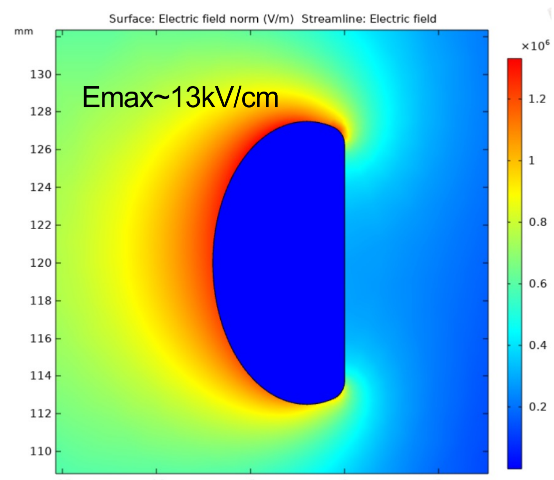
An end wall field cage supper module built with a 2x4 array of FC modules

Choosing a Narrower Elliptical FC Profile

- To build a more transparent field cage, we can either increase the pitch of the existing profiles, or reduce the width of the profiles while maintaining the same pitch.
- Increasing the profile pitch will necessitate an increase in the field cage to active volume clearance to avoid the non-uniform field near the profiles, and therefore a reduction in active volume.
- An ellipse with 3:2 aspect ratio gives a lower surface E field compared to circle of the same diameter, and also has a better transparency at larger incident angles.
- This ellipse is flattened on the side facing the active volume as a stable mounting surface to the support beams.
- The profiles are mounted on the FC modules with the same 60mm pitch used in the ProtoDUNE TPCs, providing a ~70% maximum transparency at normal incident angle with support structures included.



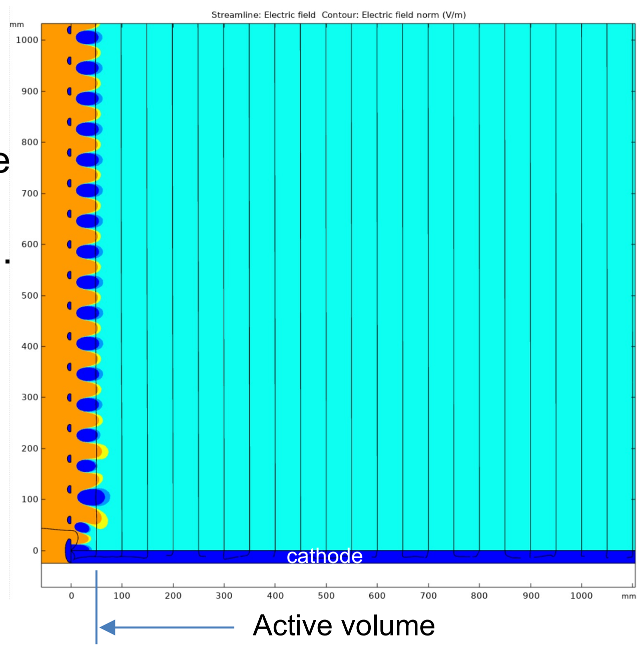




Simple and Effective Correction to the Drift Field Distortion

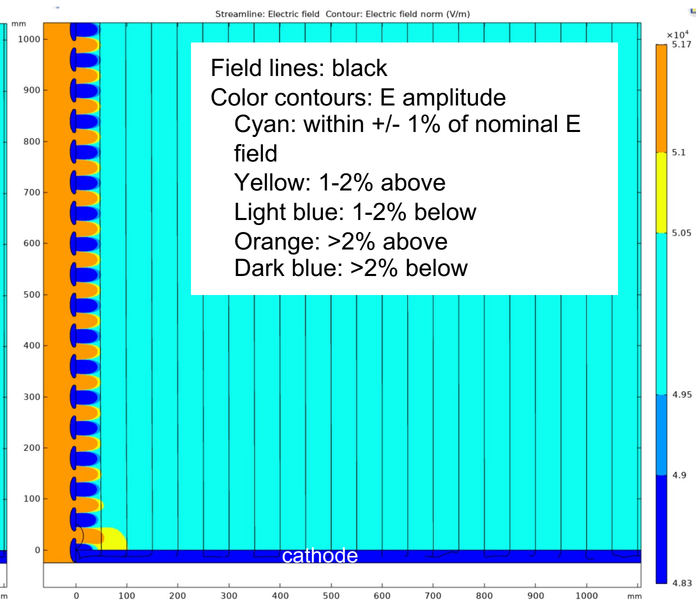
- If the thinner FC profiles are biased with a constant voltage drop between profiles and on a constant pitch, about 3% of the active volume would have drift field deviating from the nominal value by more than 1%, and the field lines diverge as electrons leaving the cathode up to 10cm.
- A simple and effective correction to the non-uniformity can be achieved by adjusting the bias voltages on the first 3 FC profiles near the cathode surface while maintaining a constant voltage drop on the rest of the profiles.
- This correction requires a set of resistive divider boards with non-standard values at the first 3 gaps near the cathode.

70% transparent field cage



The voltage drop across the first gap (cathode to FC #1) is 900V
The voltage drop across the 2nd gap is 1650V
The voltage drop across the 3rd gap is 3520V
The voltage drops between profiles from #3 and up is 3023V.

Standard (HD) field cage

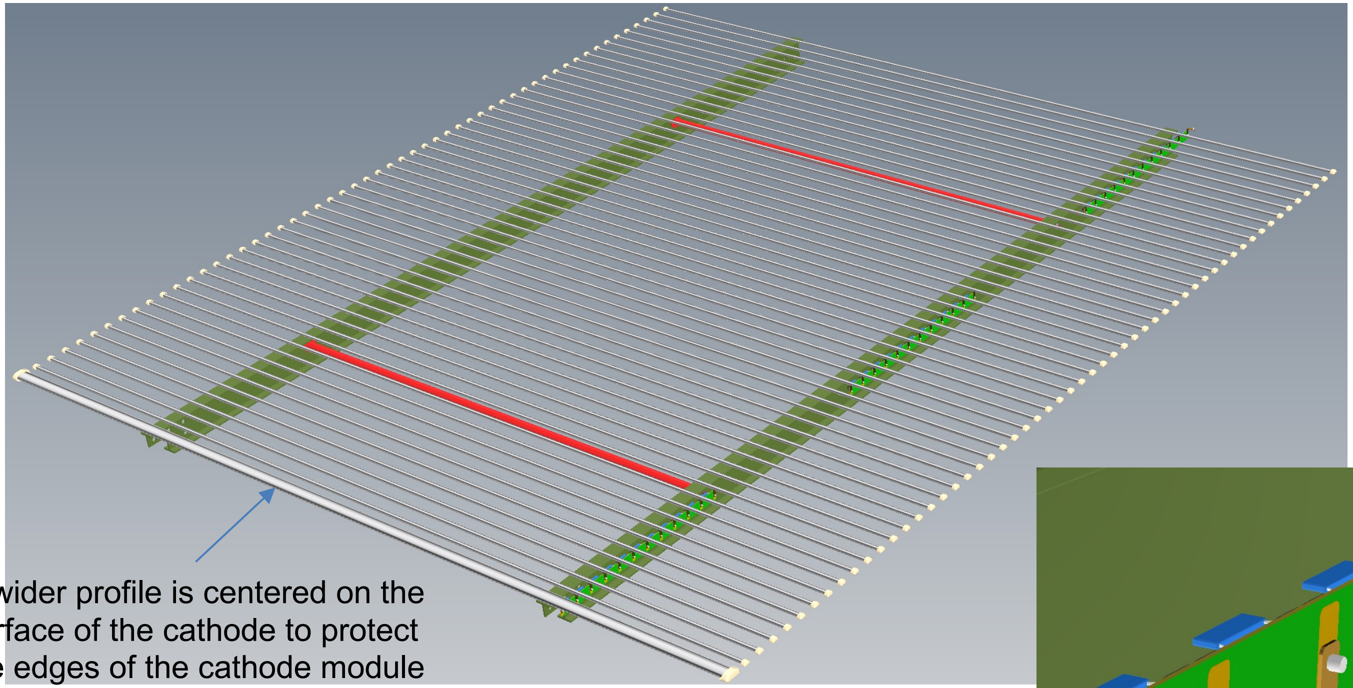


A “standard” field cage design uses the wider aluminum profiles designed for FD1. The profiles have a constant voltage drop of 3000V.

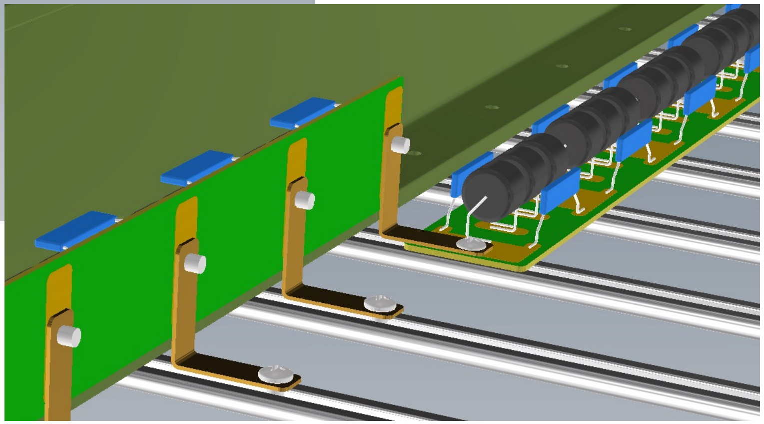
FC Module Construction (3m x 3.3m nominal size)

Regardless of the type of FC profiles used, the module construction is basically the same: 2 vertical FRP beams support 50+ profiles at a constant pitch. The profiles are locked onto the outer flange of the FRP I-beams by slip nuts inside the profiles.

The estimated weight of such a module is about 70kg with the FD1 profiles, and half as much using the thinner profiles.



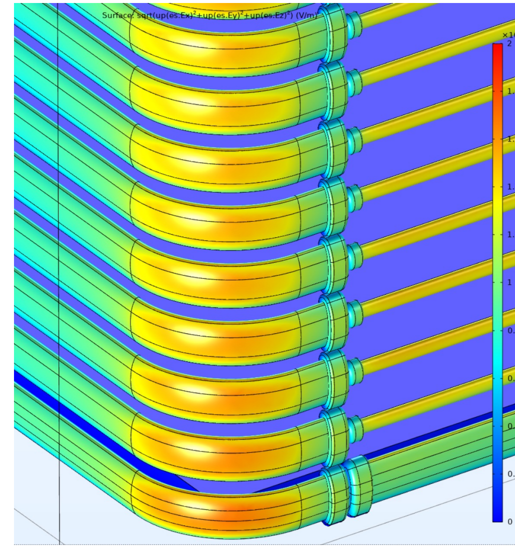
A wider profile is centered on the surface of the cathode to protect the edges of the cathode module

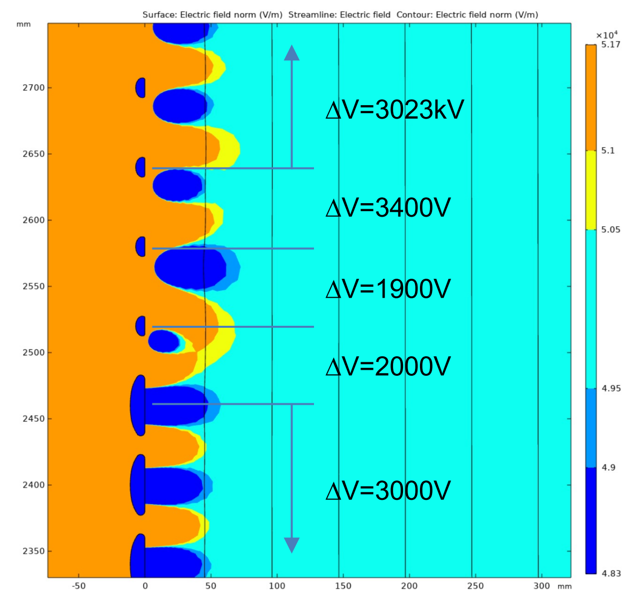


The resistor divider boards have a narrower width (35mm) compared to the FD1 version (80mm) and can be mounted edge on to increase light transmission.

Avoid High E Field at the Field Cage Corners

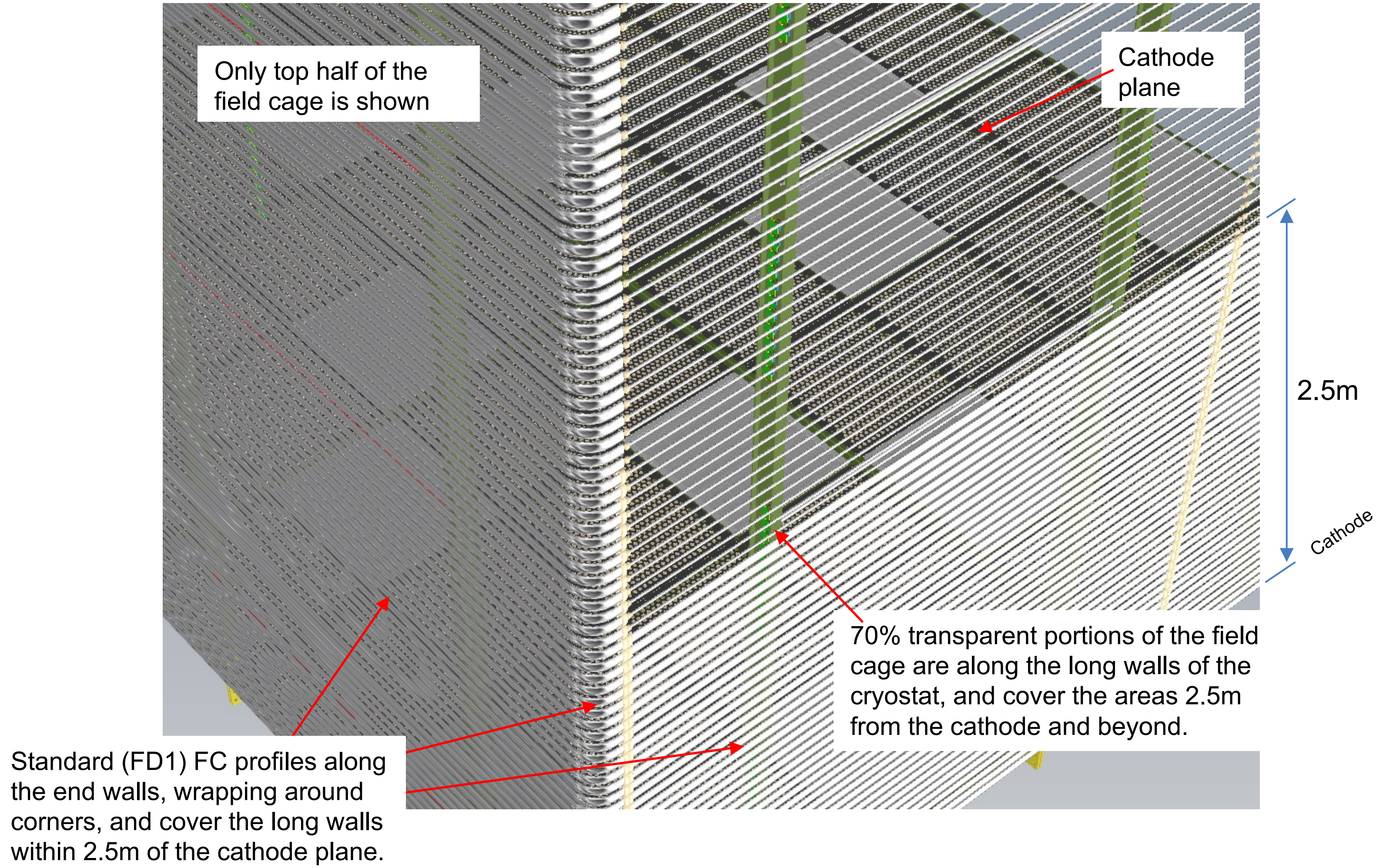
- Since PDS only planned to install PDs on the long walls of the cryostat, the FC modules along the end walls can use the wider profiles as in FD1.
- The 90° bent profiles at the corners of the FC have a lower E field (17kV/cm) than narrow profiles would have (29kV/cm).
- Nevertheless, the thin profiles along the long walls of the TPC have ~ 50% higher E field than that on the wider profiles at the same locations.
- To further reduce the higher E field on the thin profiles to the level comparable to that of the wider profiles, we need to mount the wider profiles within ~ 2.5m of the cathode, and mount the thin profiles from +/- 2.5m to +/- 6.5m from the cathode plane.
- This is the FC reference configuration to match the cathode + wall mounted PD option from PDS where the wall mounted PDs are far away from the cathode plane.
- With the tailored voltage distribution on a few thin FC profiles, we have the flexibility of moving the wide to thin profiles transition height anywhere between the anode and cathode planes, providing the required transparency to PDs without incurring unnecessary risk in HV instabilities.





Near the transition point between the two types of profiles, tailored voltage distribution on a few profiles can correct most of the field non-uniformities

Appearance of the Reference Design of the Field Cage



Key Interfaces

Consortia	Interfaces
CRP	Mechanical support of the cathode plane
Bottom CE	Field cage termination cables, and bias supplies
PDS	PD integration inside the cathode modules Cable routing along the cathode Transparency requirement on field cage modules PD PoF and readout module attachment on FC Fiber routing along the field cage
Slow control	Monitoring of HVPS and FC terminations
CALCI	TBD
LBNF I&I	FC top support beams, and roof penetrations HVFT port, HVPS location, HV cable routing Cold camera signal feedthrough ports and anchor points Design of the ground plane Integration and Installation

Ongoing and Planned Technology Development

Topics	Status
300kV HVFT with warm cable interface	An existing HVFT is being evaluated
HV extender without solid insulation	Key sections under construction, test within weeks. Full scale test in NP02 in the fall.
300kV ripple filter	Planned this year
Perforated resistive cathode surface	Multiple options are being evaluated
Choice of cathode suspension cables	Under evaluation for CTE, elongation, and creep.
70% transparent field cage	Conceptual design exists, small scale demonstration is planned for this year
RDB component semi-automated testing stands	Planned for later this year

Summary

- The conceptual design of the HV system components have been developed, with some detailed parameters and material choices under evaluation.
- Most of the operating principles and design features are evolved from the FD1 counterparts, and have been validated by the ProtoDUNEs operation, with further improvements.
- We recognize a number of new challenges, such as the HV extender, and have planned a series of development activities and small to large scale tests to validate the designs, and mitigate the risks.
- A 70% transparent field cage design is taking shape. It appears that we have the flexibility of mixing the more transparent FC configuration with the conventional design to accommodate the wall-mount PDs while minimizing HV risks.
- The SPVD HVS is expected to meet the same high level requirements from FD1. We are performing cost and benefit analysis to see if we need to set the drift field goal to 500V/cm.
- The SPVD HVS has a distinctively different set of interfaces with other subsystems compared to FD1. The interface with PDS is very complex and must be closely coordinated.

BACKUP