NP04 TPC CPA/FC/HV Electrical Design

Bo Yu

October 9, 2016

BROOKHAVEN NATIONAL LABORATORY

Outline

- Resistive cathode
- HV bus
- HV feedthrough receptacle cup
- HV filtering
- Modular field cage
  - Roll-formed field cage configuration
  - Ground plane
  - Drift field uniformity
- Resistive divider
- Overall schematic
- Risks
- Summary

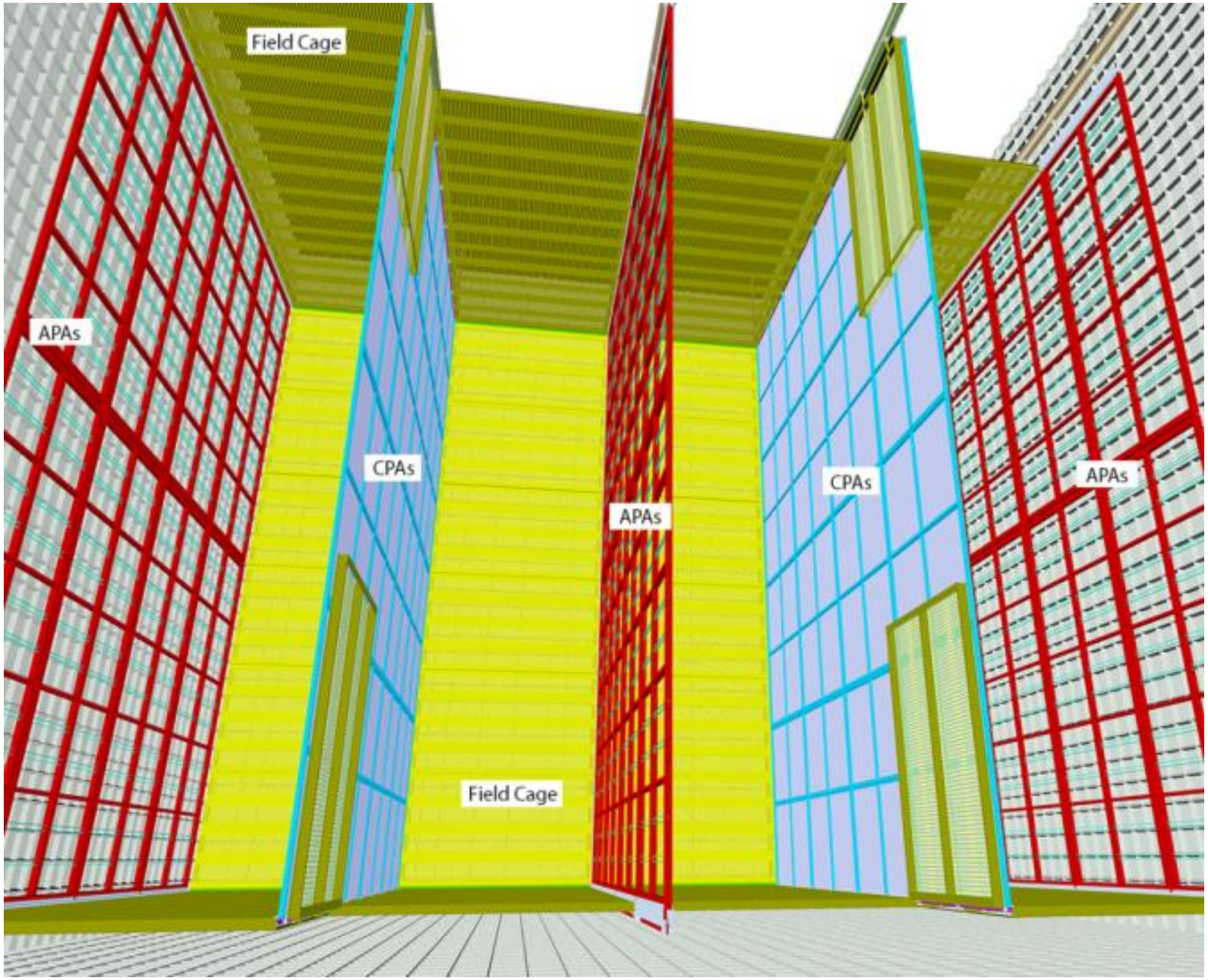
Please see the uploaded document: "ProtoDUNE E Field FEAs.pdf" for a collection of E field studies.

DUNE FD TPC (Single Phase)

10 kton fiducial cryostat.
Each has:
150 APAs, 200 CPAs
2000 m^2 field cage modules
385k readout channels

Active volume:
W: 14.5m, H: 12m, L: 58m

Installed under 5 mounting rails suspended under the cryostat ceiling.

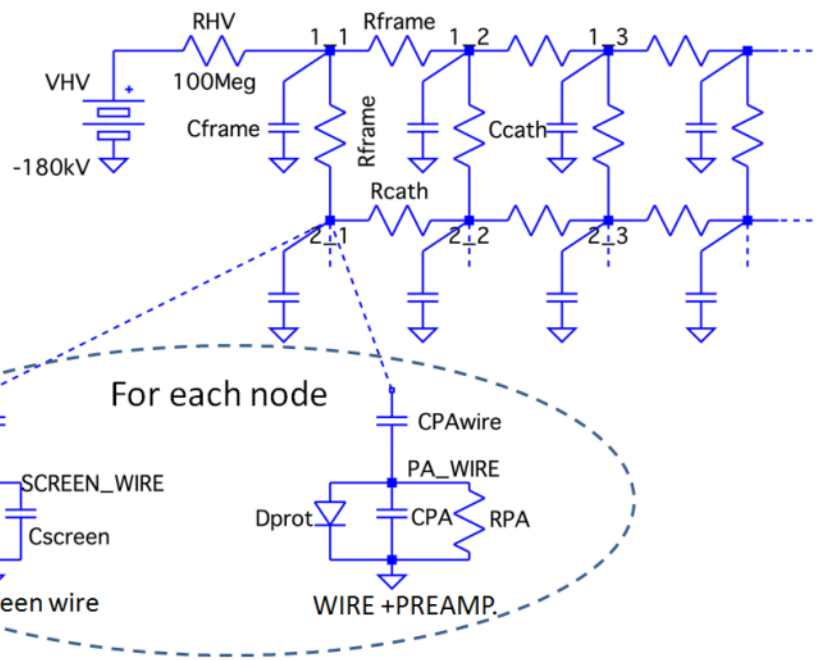


Cathode Plane

- Despite of placing the cathode planes away from the cryostat walls, there is still nearly 100 J of energy on each interior cathode when energized to 180kV due to the sheer size of the cathode planes in the DUNE SP FD.
- In the event of a discharge from a cathode edge to the facing cryostat wall, there is a risk of physical damage to either the cathode or the membrane. The voltage on an all metal cathode will collapse very quickly, injecting high current into the cold electronics through the APA wires, risking damage to the front end ASICs.
- This issue has been studied in detail. (see posted design paper on the section of Discharge Mitigation).
- To minimize these risks, we have developed several cathode designs that use nearly all highly resistive surfaces (1-100MΩ/☐). This will greatly reduce the peak power transfer to the cryostat and peak current injection into the front-end ASICs in a HV discharge.
- Several types of resistive surfaces have been investigated. The preferred solution is to use Dupont 100XC10E7 Kapton film (surface resistivity about 5MΩ/☐) laminated on FR4 substrates.

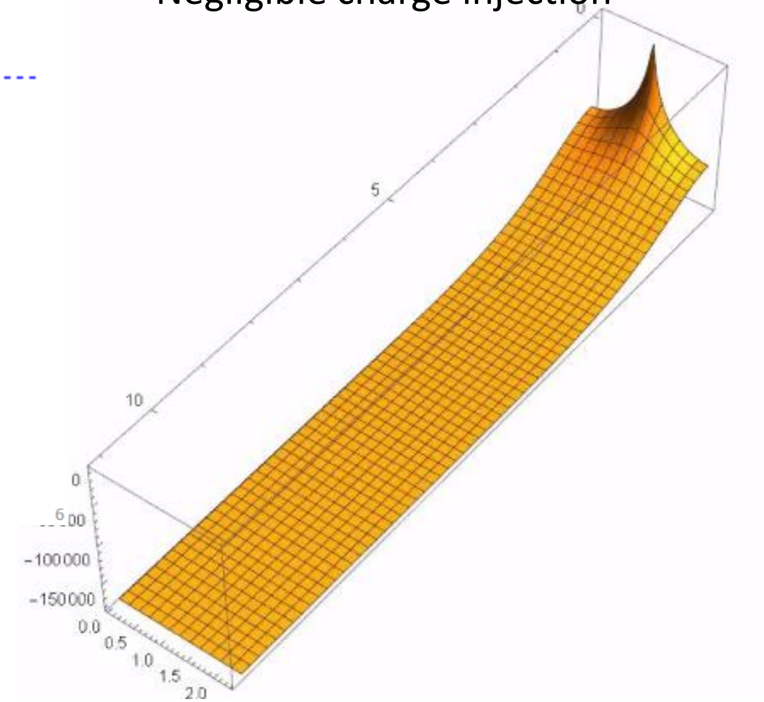
Study of the Charge Injection to the Electronics

- By Sergio Rescia (LBNE docdb 10749,10865)



R_{frame}=10GΩ/m
$R_{interior}$=1GΩ/sq

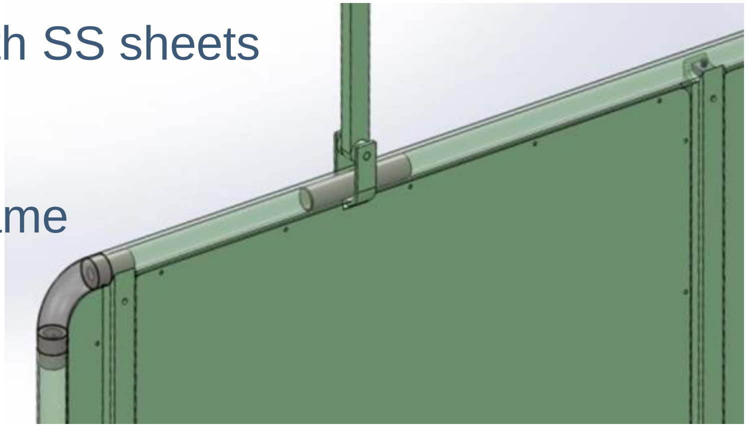
@200ms, 85% energy remains
Negligible charge injection



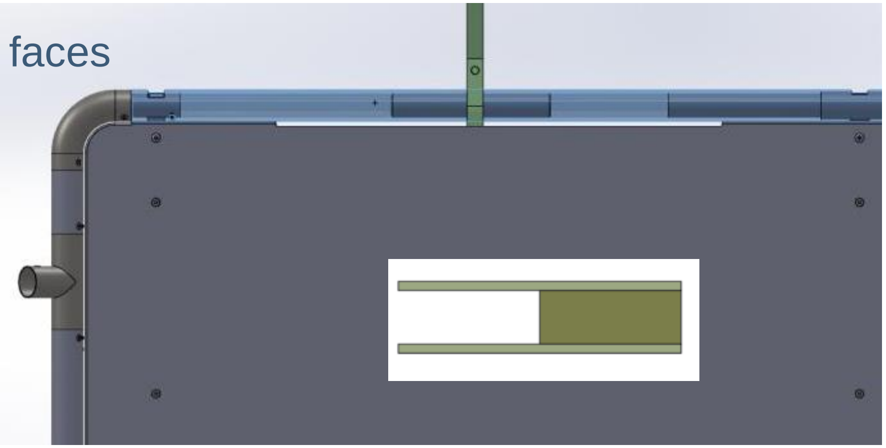
- Divide 12mx2.3m Cathode into 10cmx10cm “cells” i.e. 120x23=2760 (or 2904 nodes) Each cell modeled as resistors to neighbors and capacitor to ground
- SPICE simulation
  C: 8737, R: 5668, tot: 14419

Acceptable resistivity range:
1kΩ to 100MΩ/sq for NP04

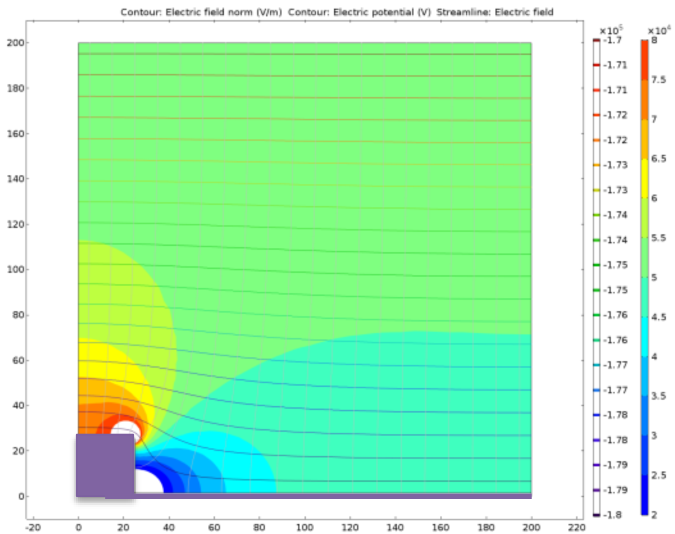
Evolution of the CPA Design



- LBNE Reference Design: stainless frame with SS sheets
  - Concerned about charge injection to CE
- DUNE CD-1R proposal: hollow fiberglass frame with resistive sheets
  - Light weight
  - Concerned about field uniformity near frame
- Flat resistive outer panels with internal frame
  - Entire cathode is flat on the outside, perfect E field
  - Large enclosed volume between cathode faces
  - Larger fiducial cut on the cathode
- Thin cathode on solid external frame, plus field shaping strips on frame

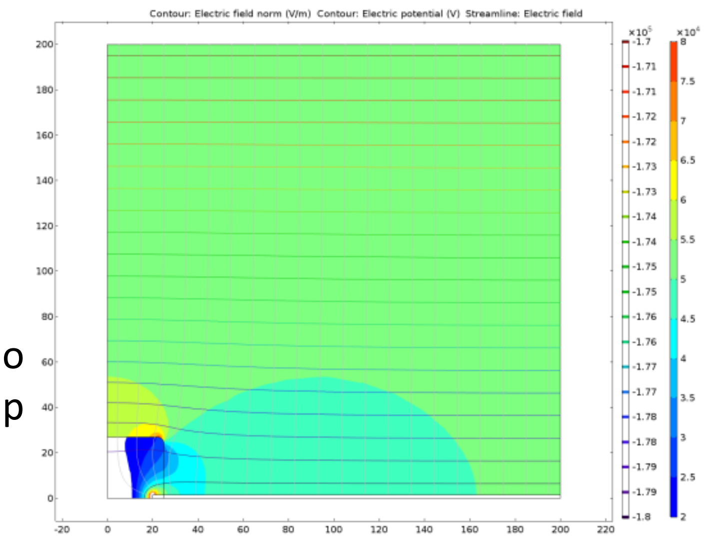


Minimizing E Field Distortion on the CPA

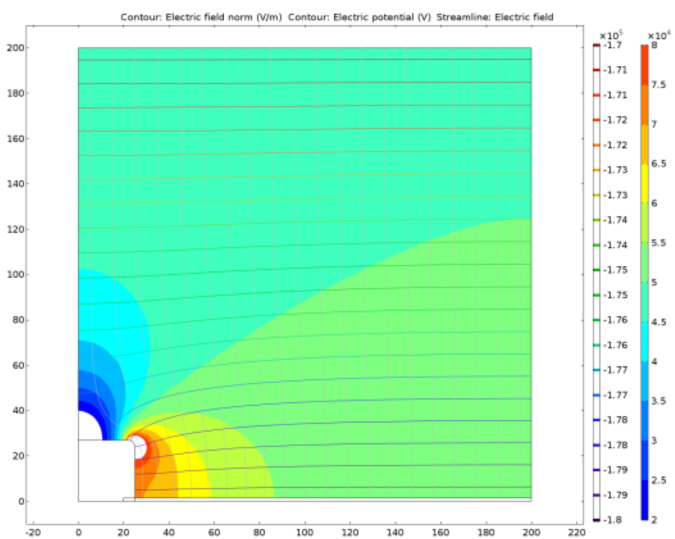


Conductive frame

G10 frame, no charge buildup

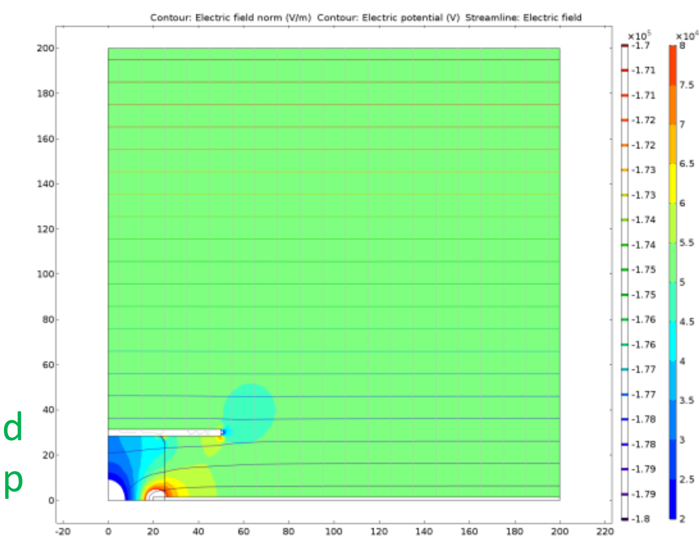


Each E contour step is 10% nominal drift field



G10 frame with charge buildup

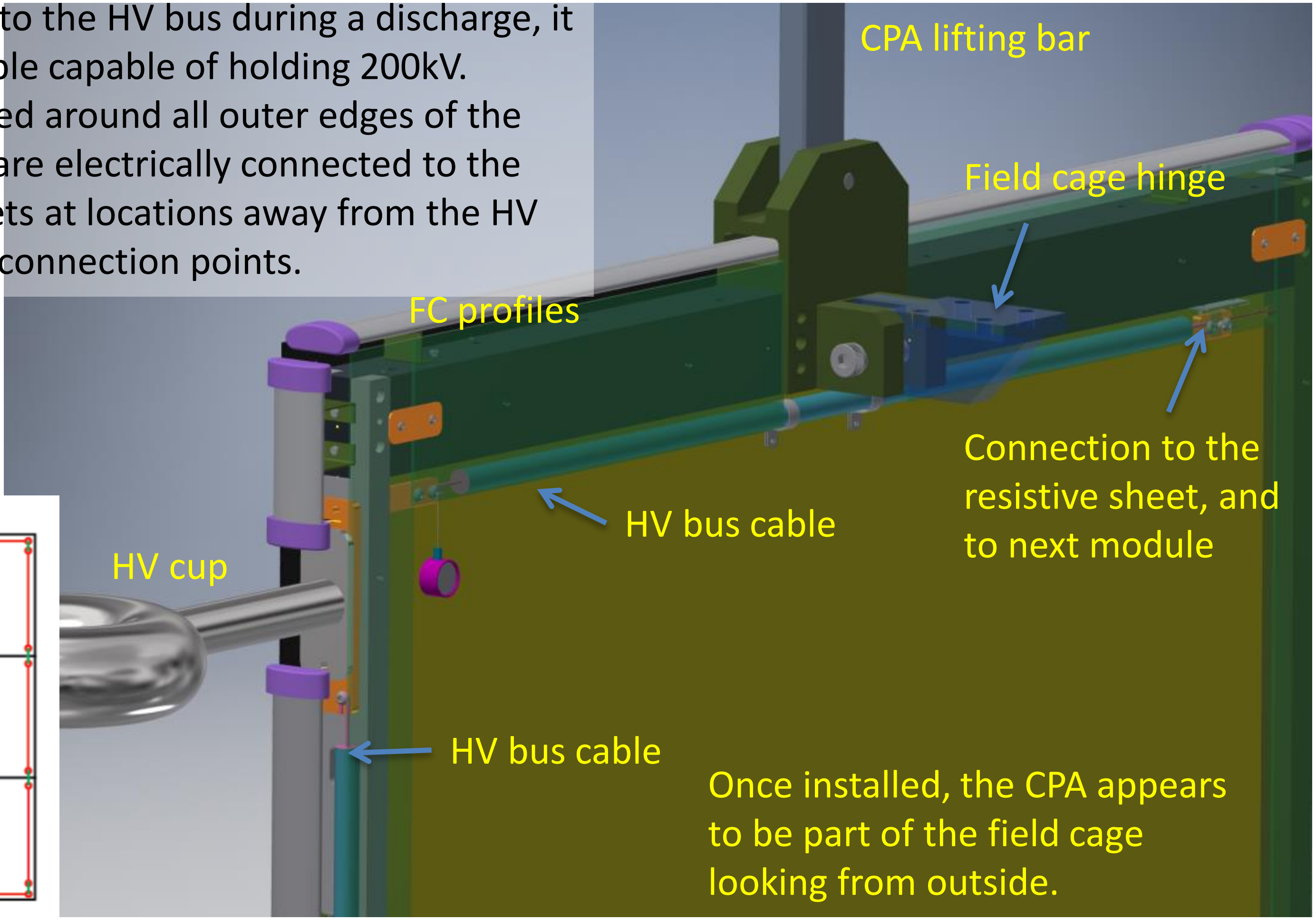
G10 frame + field shaping strip

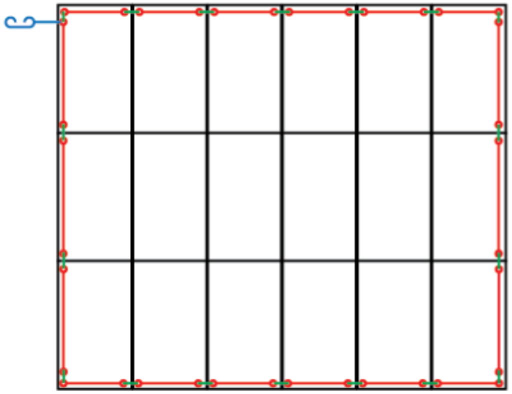


HV Bus Integrated into a CPA Module

Since the entire cathode is highly resistive, we must find a more conductive path to distribute the cathode bias voltage to all CPAs and all field cage dividers without significant voltage drop.

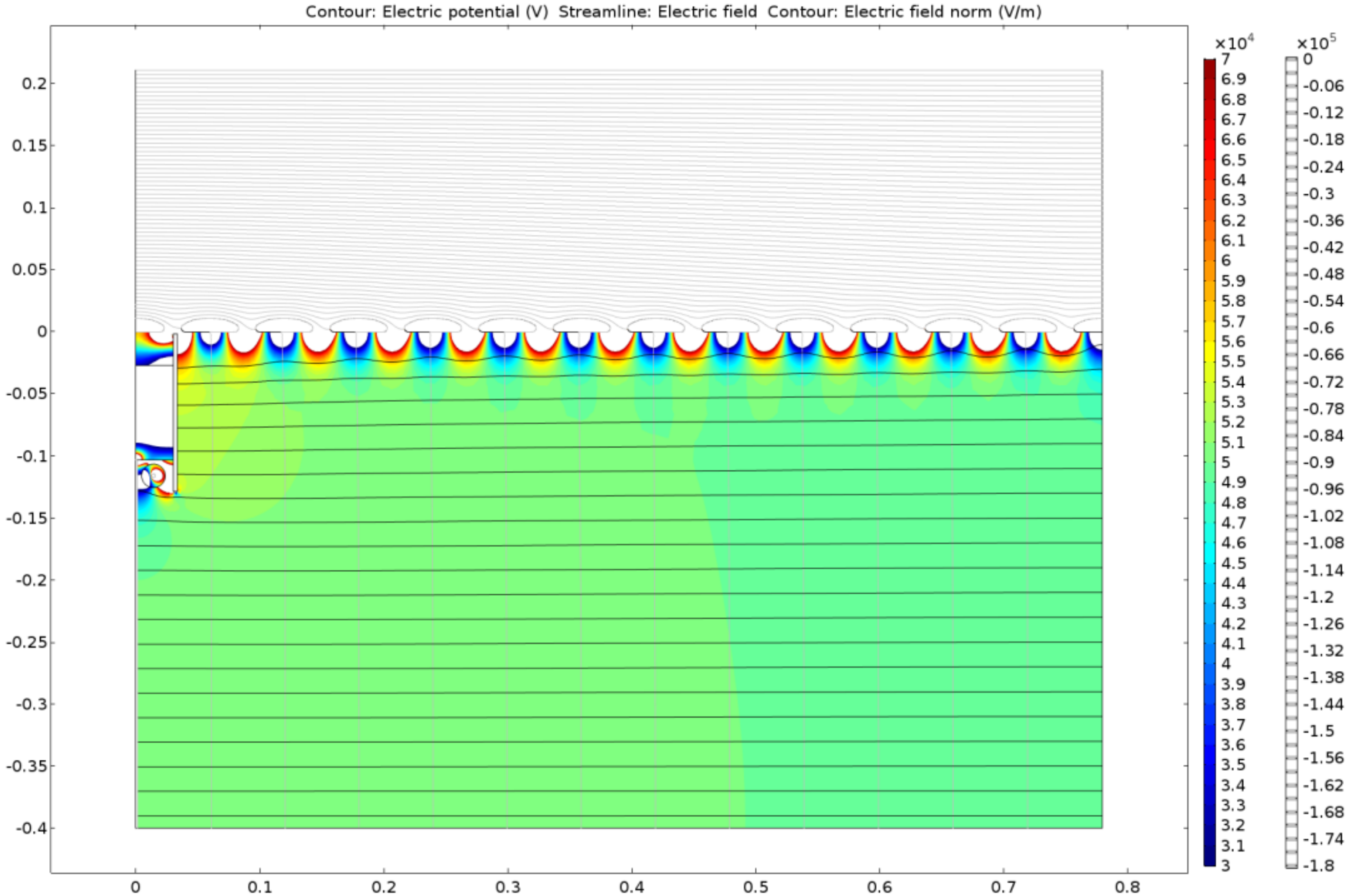
To avoid direct arcing to the HV bus during a discharge, it is made from a HV cable capable of holding 200kV.
FC profiles are mounted around all outer edges of the cathode plane. They are electrically connected to the cathode resistive sheets at locations away from the HV bus to resistive sheet connection points.





Drift Field Uniformity Near CPA Frame

- Color contours: E amplitude, 2% of nominal drift field
- Profiles at 6cm pitch, ground plane 20cm above
- Active volume starts 5cm below the inside surfaces of the field cage profiles

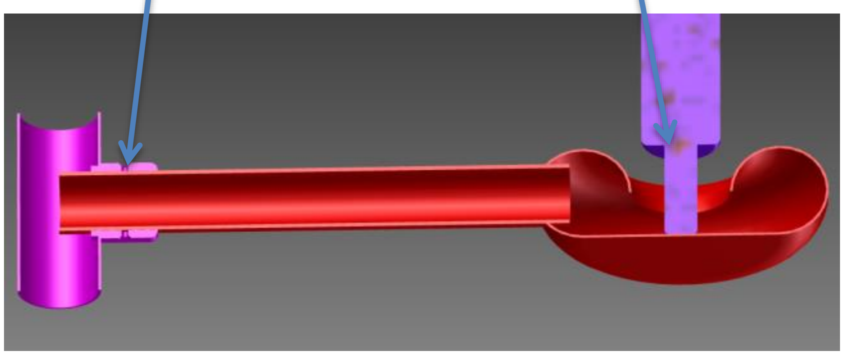


HV Feedthrough Receptacle

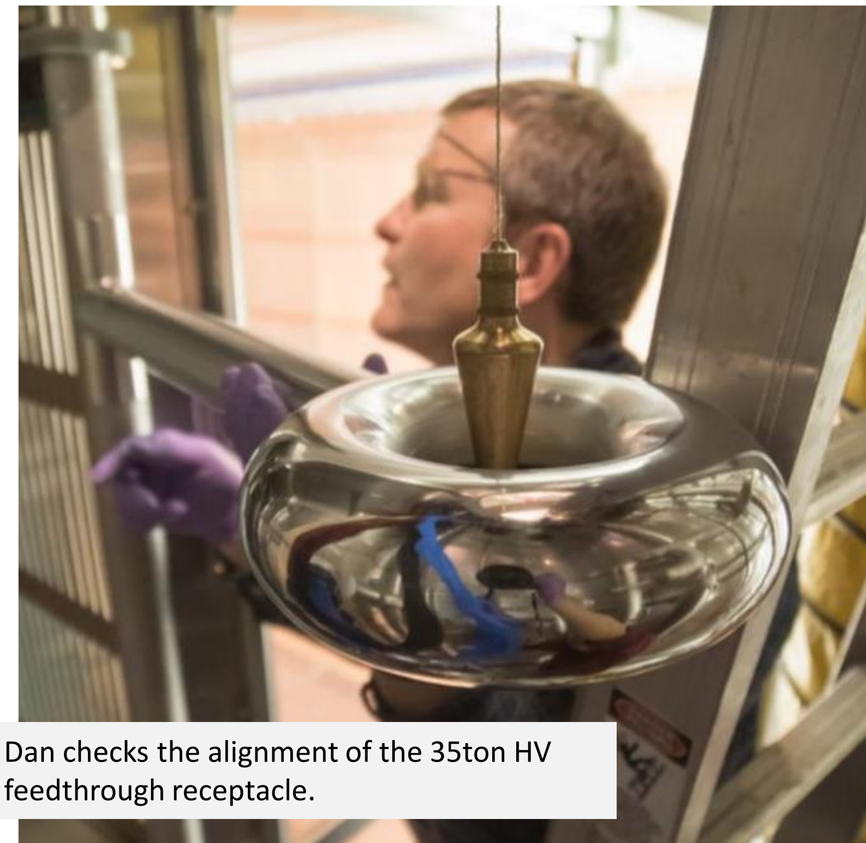
- The HV feedthrough receptacle is made from a stainless steel donut with a flat bottom plate. It has an edge radius of 38mm, and a inner diameter of 76mm.
- A slightly smaller version of it was used in the 35ton TPC.
- This HV receptacle may not work for the FD due to the +/- 10cm shrinkage between warm and cold.

The arm length can be a adjusted

We need to design a spring loaded tip to allow height tolerance



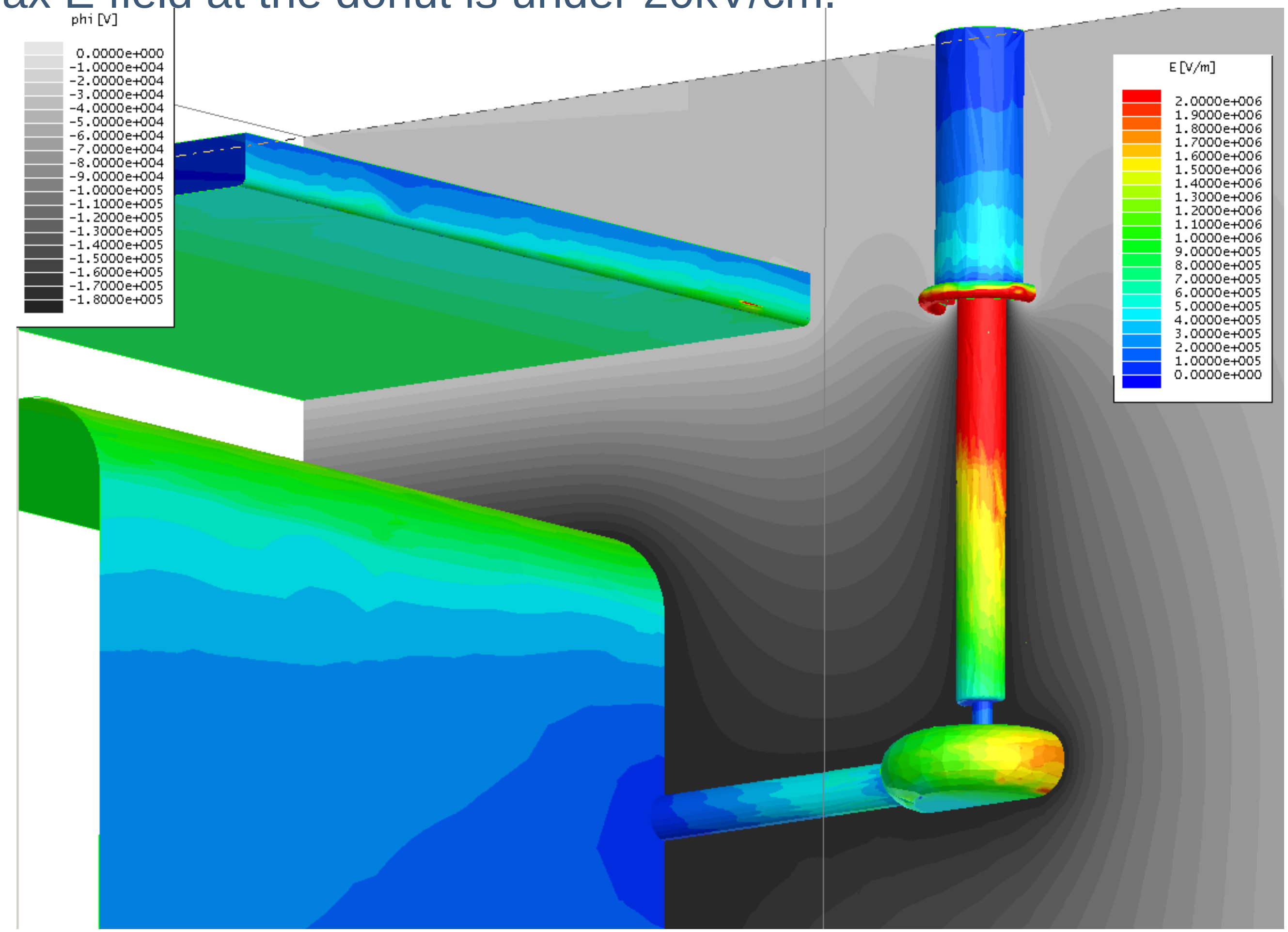
The donut is completely vented



Dan checks the alignment of the 35ton HV feedthrough receptacle.

Surface Field Near the HV Feedthrough

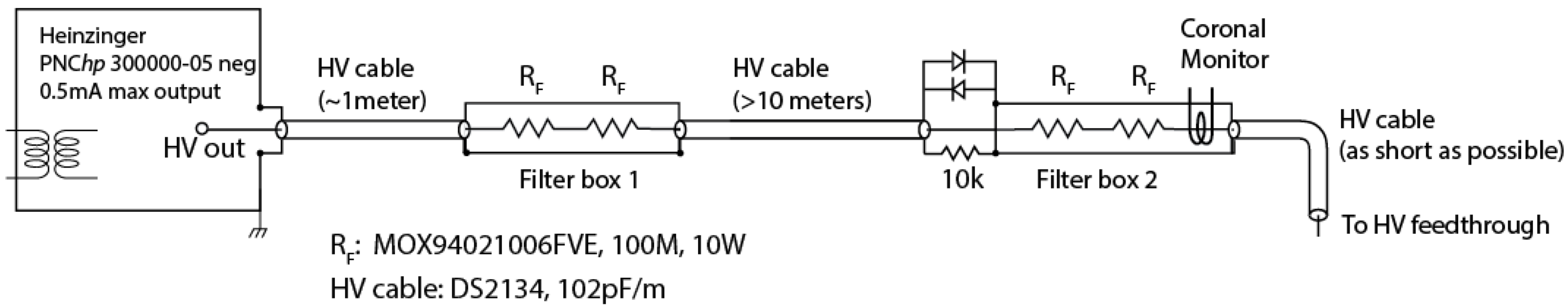
- Wall to FC distance 1m, FT center to FC: 44cm, FT shield rim lined up with ground plane. Max E field at the donut is under 20kV/cm.



HV System Filtering Requirements

- The Heinzinger PNChp power supply has a ripple spec of 10^{-5}. In order not to inject significant charge to the ASIC (<100e ENC), we need to have a filter network between the power supply and the HV feedthrough with an attenuation factor of >2000 at the ripple frequencies.

ENC of ASIC	600	e
max noise injection	100	e
	1.6E-17	c
capacitance of an APA to CPA	5.09E-11	F
capacitance of a G wire to CPA	8.48E-14	F
capacitance of a U wire to CPA	1.70E-14	F
maximum allowed ripple voltage	9.43E-04	V
Cathode Voltage	180000	V
Power supply output ripple @ 1E-5	1.8	V
attenuation factor needed in the filter	1908	



Modular Field Cage Design

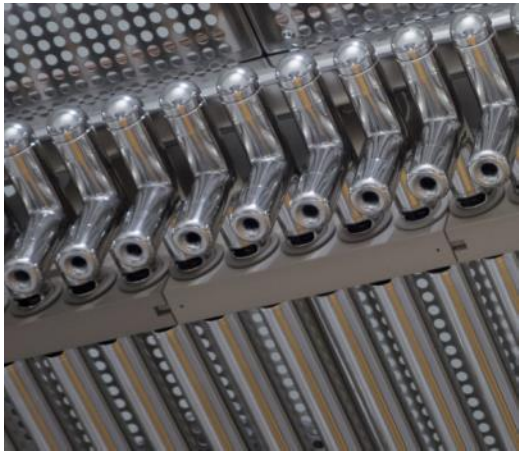
Previous large liquid argon TPCs (Icarus, MicroBooNE) have used stainless steel tubes as the field cage electrodes to form continuous mechanical and electrical “rings” or “race tracks”.

There are disadvantages to scale this design to multi-kiloton LArTPCs such as the DUNE Far Detector:

- mechanically, the field cage cannot be built as completely independent modules and therefore requires labor intensive steps to interconnect the electrodes, many at great heights inside the cryostat;
- electrically, linking electrodes spanning more than 100m in length also increases the stored energy each electrode has and increase the risk of damaging the field cage components in a HV discharge.

These considerations lead to the development of a field cage concept that is completely modular: both mechanically and electrically independent field cage modules tiled to form the entire field cage. Each module has its own resistive divider network, which provide greater redundancy against resistor failure.

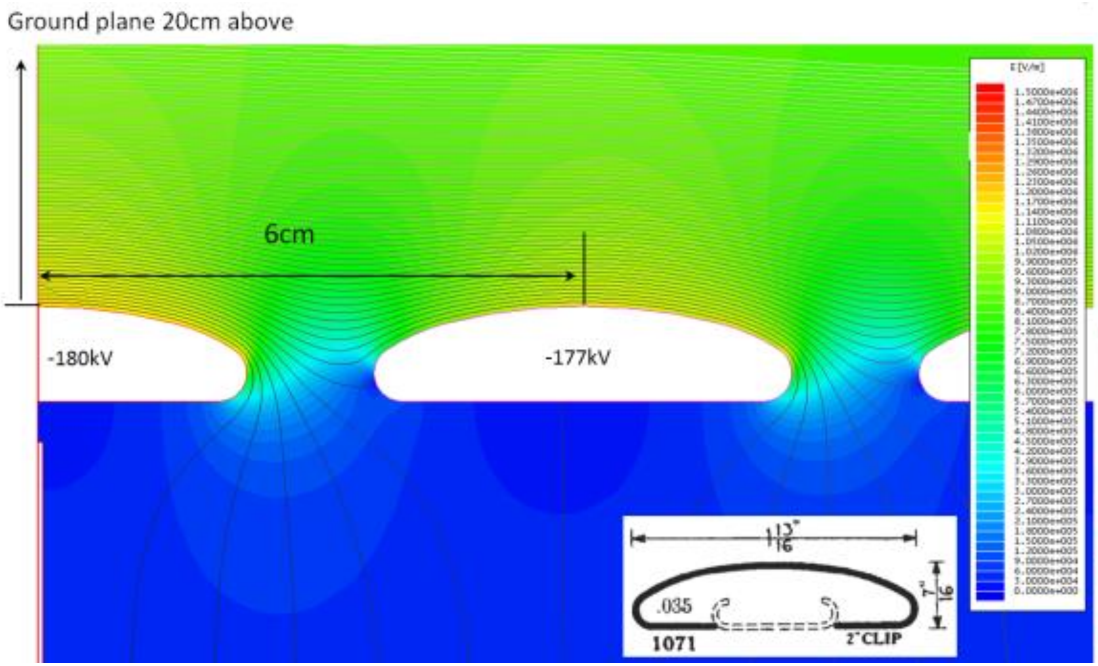
Instead of using tubes as the field cage electrodes, which must be vented frequently to avoid trapped volumes, roll-formed or extruded open profiles are investigated as potential electrode candidates.

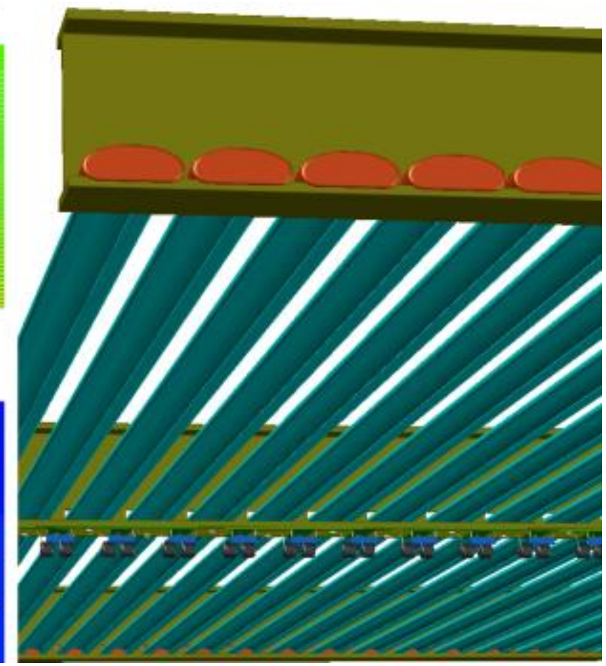


Field Cage with Roll-Formed Profiles

The example below shows the electric field on the highest biased field cage electrodes can be controlled to under 12kV/cm using the Dahlstrom #1071 profile even with only a 20cm ground clearance. If we can find a safe way of dealing with the ends of the profiles, this construction could allow a reduction in the top and bottom TPC clearance and make more efficient use of the LAr.

UHMW PE caps with wall thickness of 5-6mm are used to terminate each profile. The dielectric strength of the caps is capable of holding the full 180kV voltage.



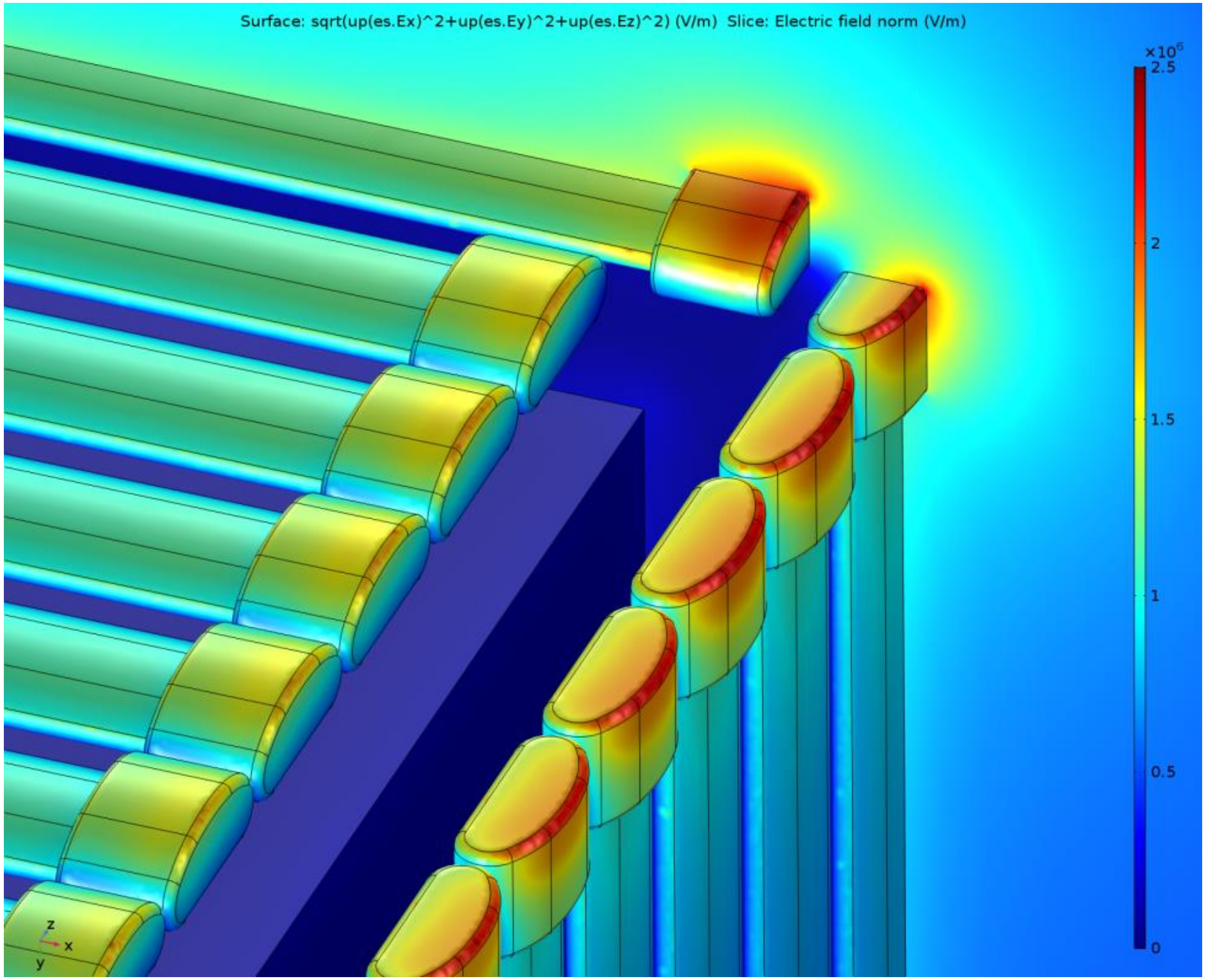


E Field at the Corner with PE Caps

Plot of the E field on the symmetry plane bisecting the metal profiles, as well on the surface of profiles and caps

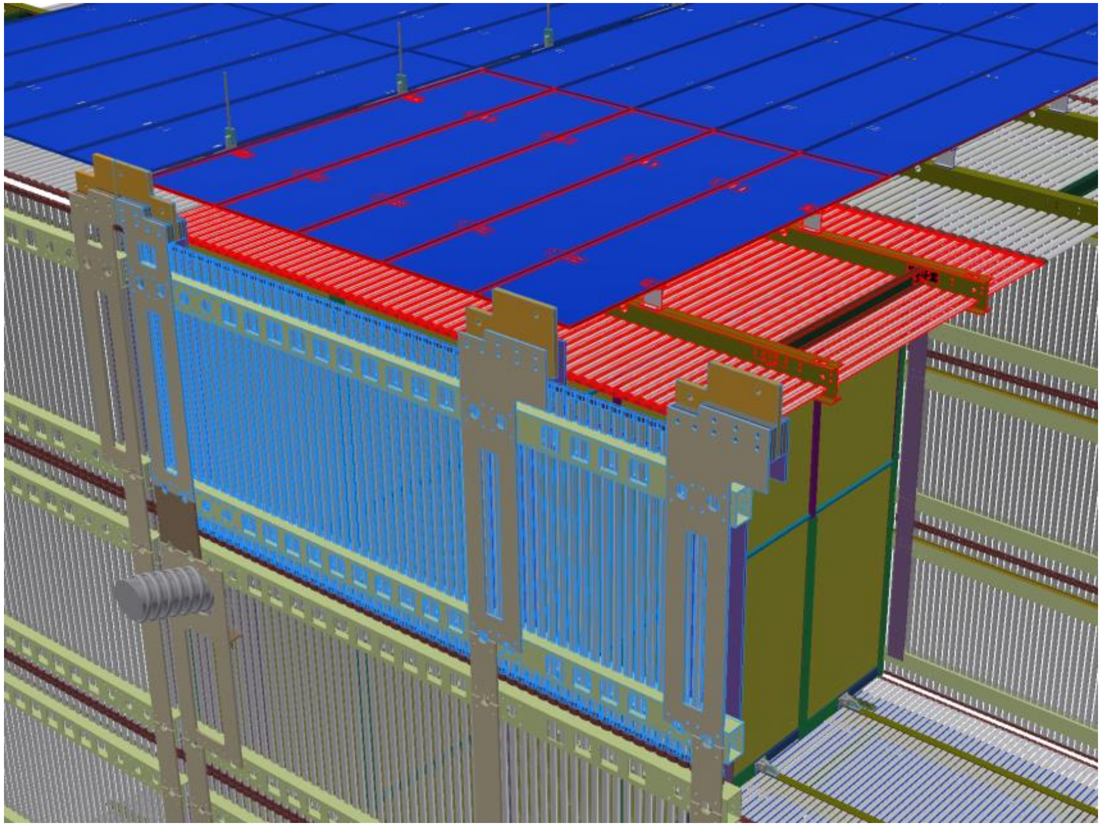
20cm ground clearance above, 40cm on the side, Cathode bias: -180kV, UHMW PE cap thickness: 6mm

The exposed field in the LAr is ~ 25kV/cm



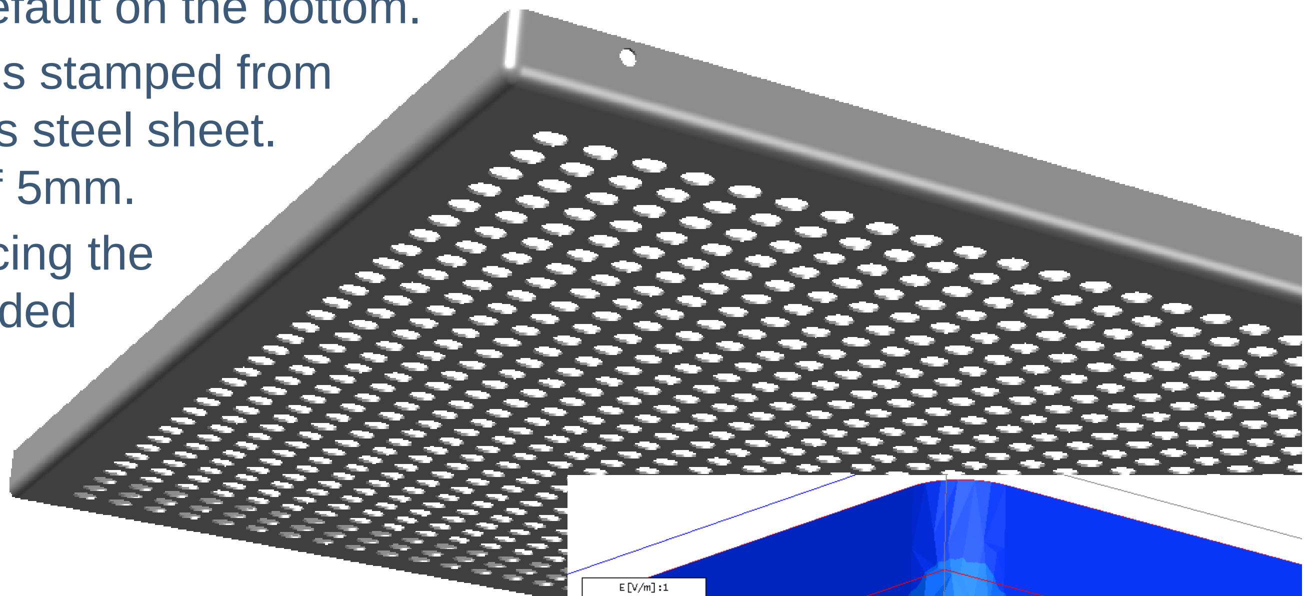
The Field Cage Components

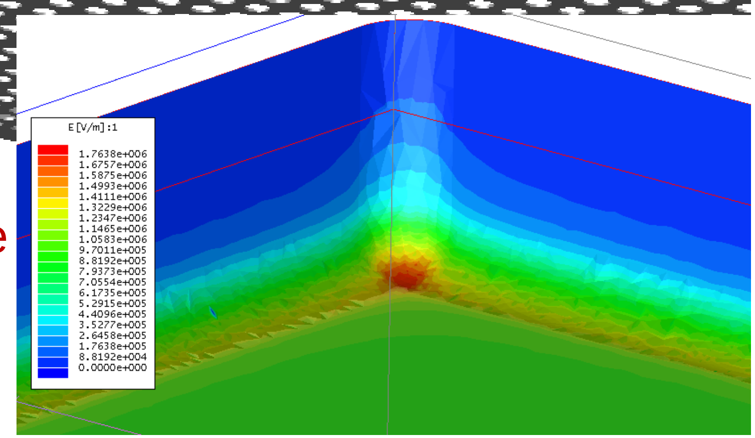
- Top and bottom field cage modules have integrated ground plane panels to shield the high field from leaking into the top and bottom service regions:
  - Top: gas ullage and rails
  - Bottom: cryogenic pipes
- End wall field cage modules have no accompanying ground planes due to larger clearance.
- Beam plug is integrated into one end wall modules
- Each field cage module has its own resistive divider network to maintain a linear voltage distribution along its length.
- The field cage profiles are electrically isolated between modules to minimize peak energy dump in case of sparks



The Ground Plane

- The purpose of the ground plane above the field cage is to shield the fringe field from the CPA/FC from entering the gas ullage to cause breakdown.
- The top and bottom FC modules are designed to be symmetrical: there is a ground plane by default on the bottom.
- The ground plane is stamped from 1mm thick stainless steel sheet. With corner radii of 5mm.
- The hole edges facing the field cage are rounded to ~ 0.5mm radius.

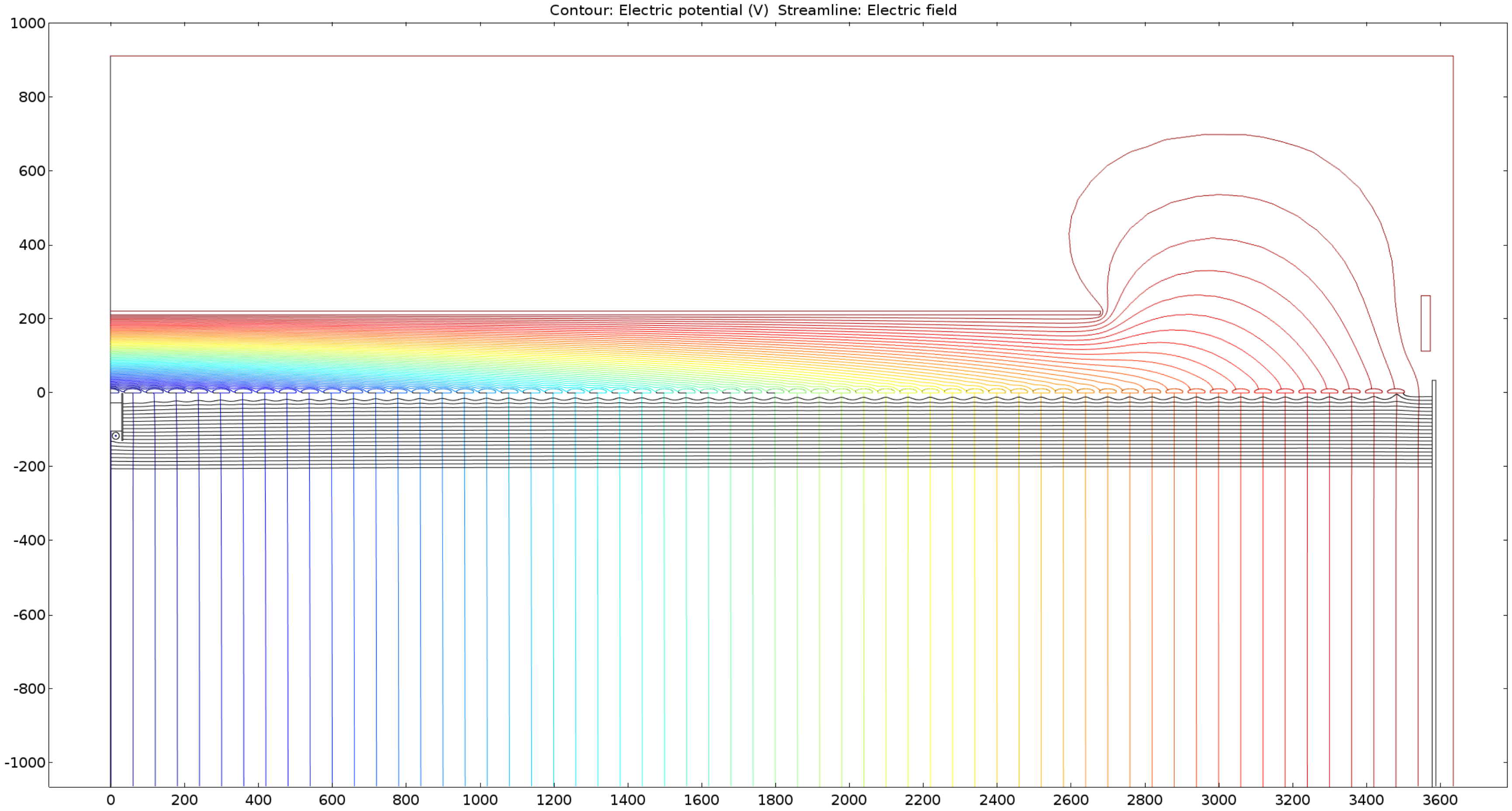




- The grounding of the ground plane should be made away from the APA/CE feedthroughs.
  - Top: to DSS feedthrough / rail
  - Bottom: to membrane

Drift Field Uniformity Near FC Edge

- 2D Model with full drift distance, half height (3m, mirror symmetry)



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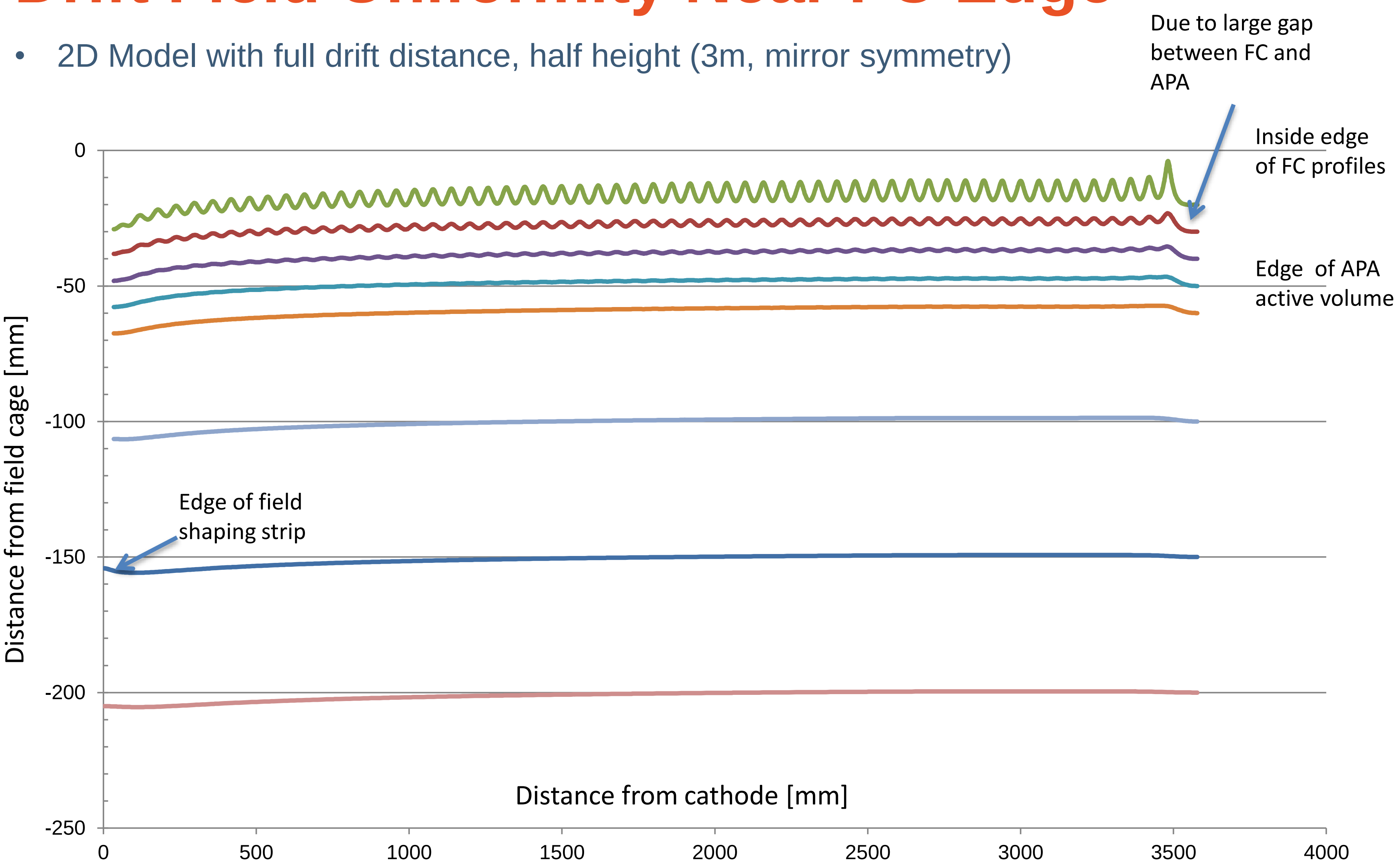
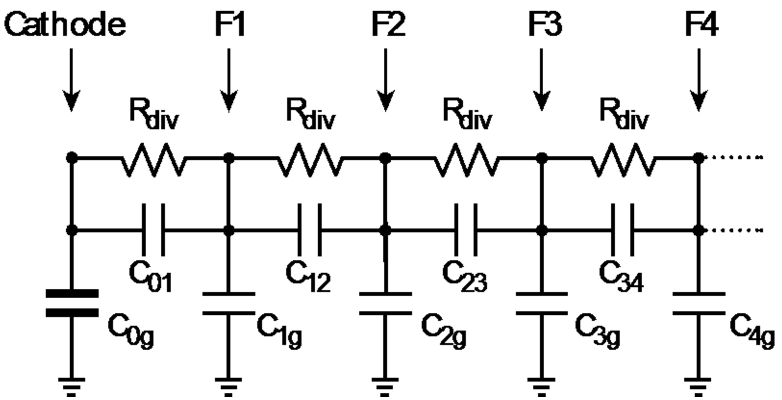


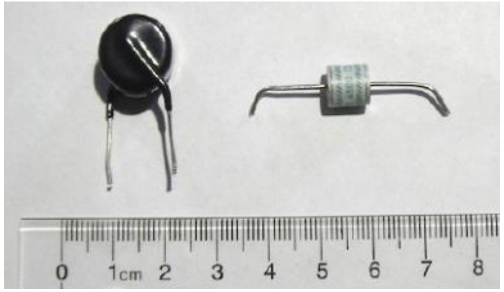
Field Cage Transient Response in a Discharge



- The resistors along the divider provide a linear DC voltage gradient.
- However, at shorter time scale (<<1s), the electrical behavior of the divider is determined by the varies capacitances on and between each electrodes. This divider is no longer linear at this time scale.
- A perfect capacitive divider requires the capacitance of each node to ground to be 0. In reality, there is always a finite capacitance from each node to ground. These capacitances "resist" change in the voltages on the nodes.
- In the event of a HV breakdown between the cathode to ground (cryostat), the cathode voltage quickly collapses to ground, but the first field cage strip to ground capacitance keeps its voltage from changing instantaneously to follow the cathode voltage, results in a momentary larger voltage differential between the cathode and the first field cage strip.
- This voltage differential can be a significant fraction of the cathode operating bias, large enough to cause HV breakdown between the two electrodes, or worse yet, destroy the resistors between the two electrodes.
- The natural solution to this problem is to add additional capacitance between the nodes of this divider.
- See MicroBooNE docdb 3307 for summary of the analyses

Surge Suppressor Studies

- An alternative to adding capacitance between divider nodes is to use surge protection
- Extensive tests have been done by MicroBooNE (docdb 3242, arXiv:1406.5216v2) on the use of varistors and GDTs (gas discharge tubes) as a mean of limiting the over voltage condition in the event of a HV discharge in the TPC.
- Both types will work for the purpose of restricting the voltage differential between field cage rings in LAr temperature.
  - A GDT quickly shorts the terminals when the voltage differential exceeds a threshold
  - A varistor changes its resistance to keep the voltage differential near the threshold voltage.
- The smooth transition and well defined clamping voltage of the varistors are preferred to the abrupt switching of the GDTs.
- The varistors would also function as redundant "resistors" in a divider chain.



Left: varistor
Right: GDT

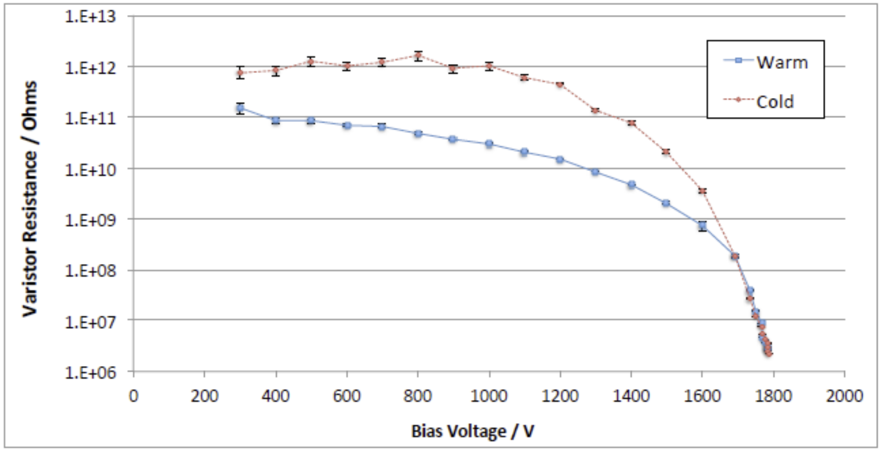


Figure 20: Effective resistance for the Panasonic ERZ-V14D182 varistor operated warm and cold, as a function of the voltage drop across the device.

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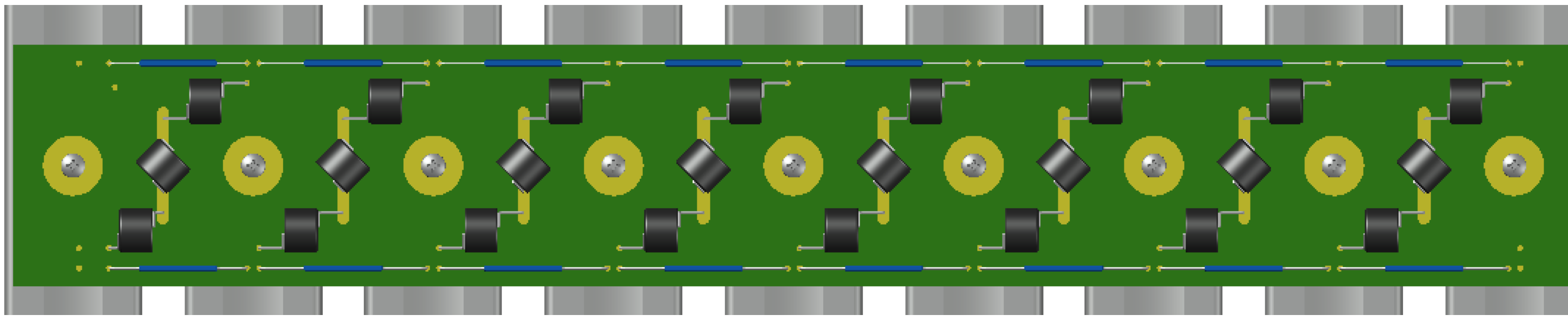
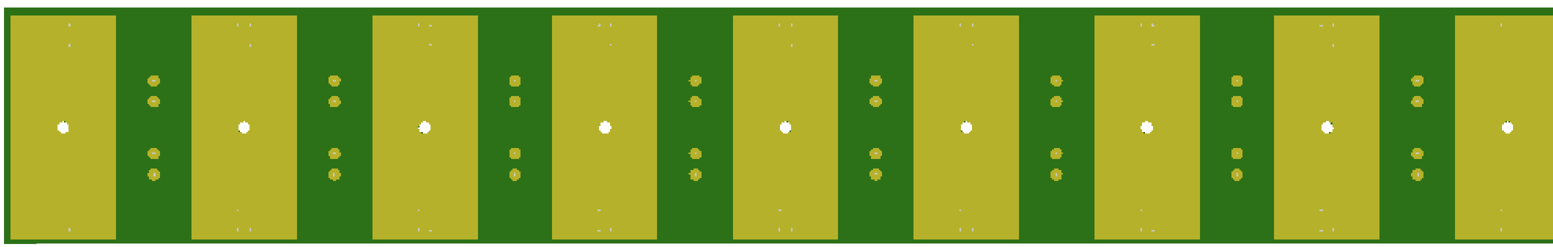
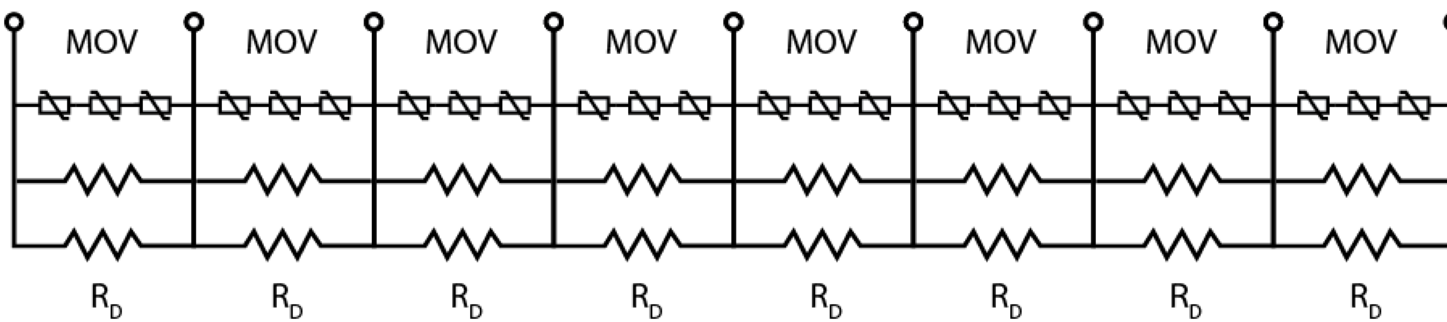
Resistive Divider Board

- We need to use 3 such varistors in series between profiles if we want to have the ability to reach more than 500V/cm drift field in ProtoDUNE.
- Two resistors in parallel to provide redundancy.



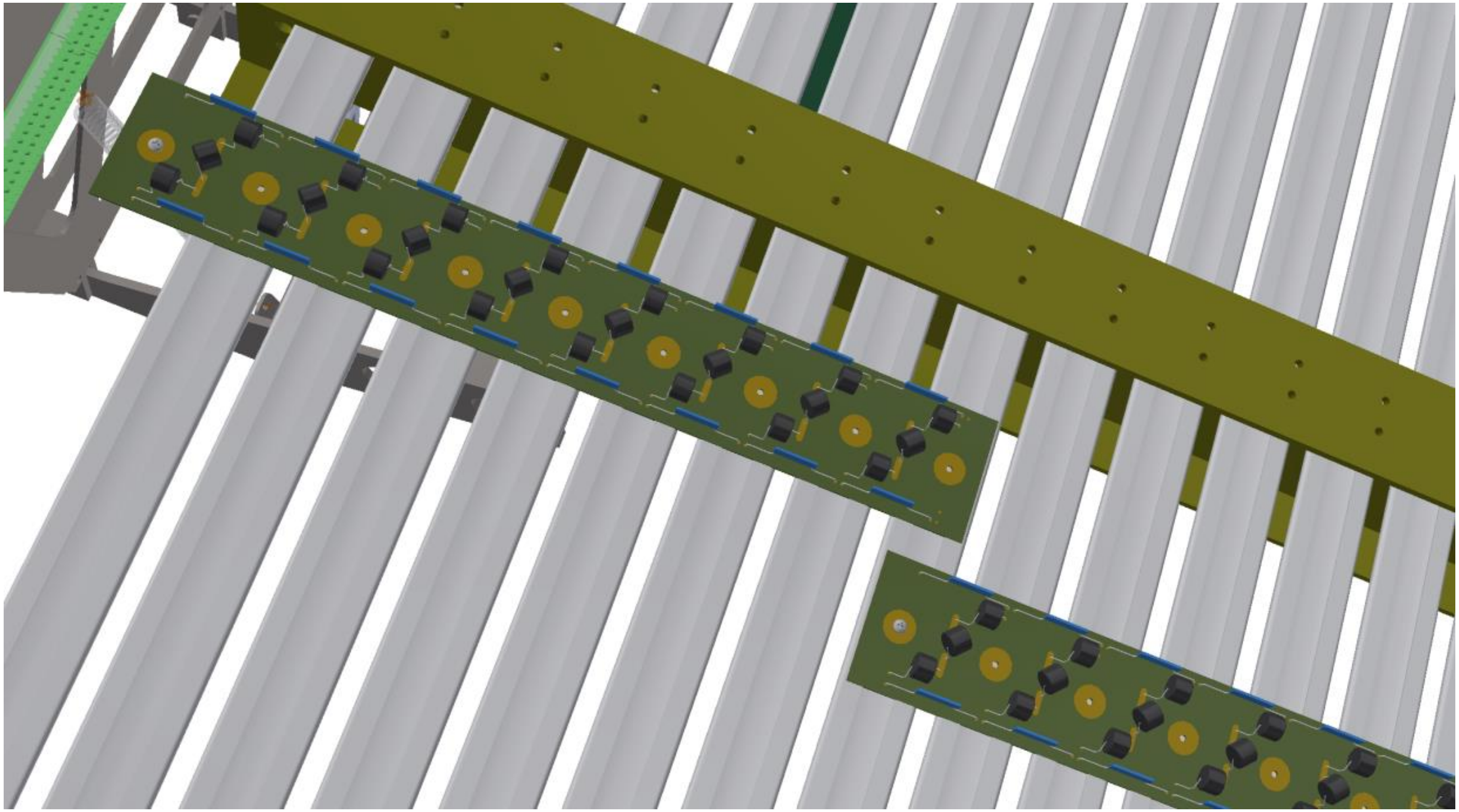




RD: SM104FE-1000M, MOV: ERZ-V14D182

Placement of Divider Boards

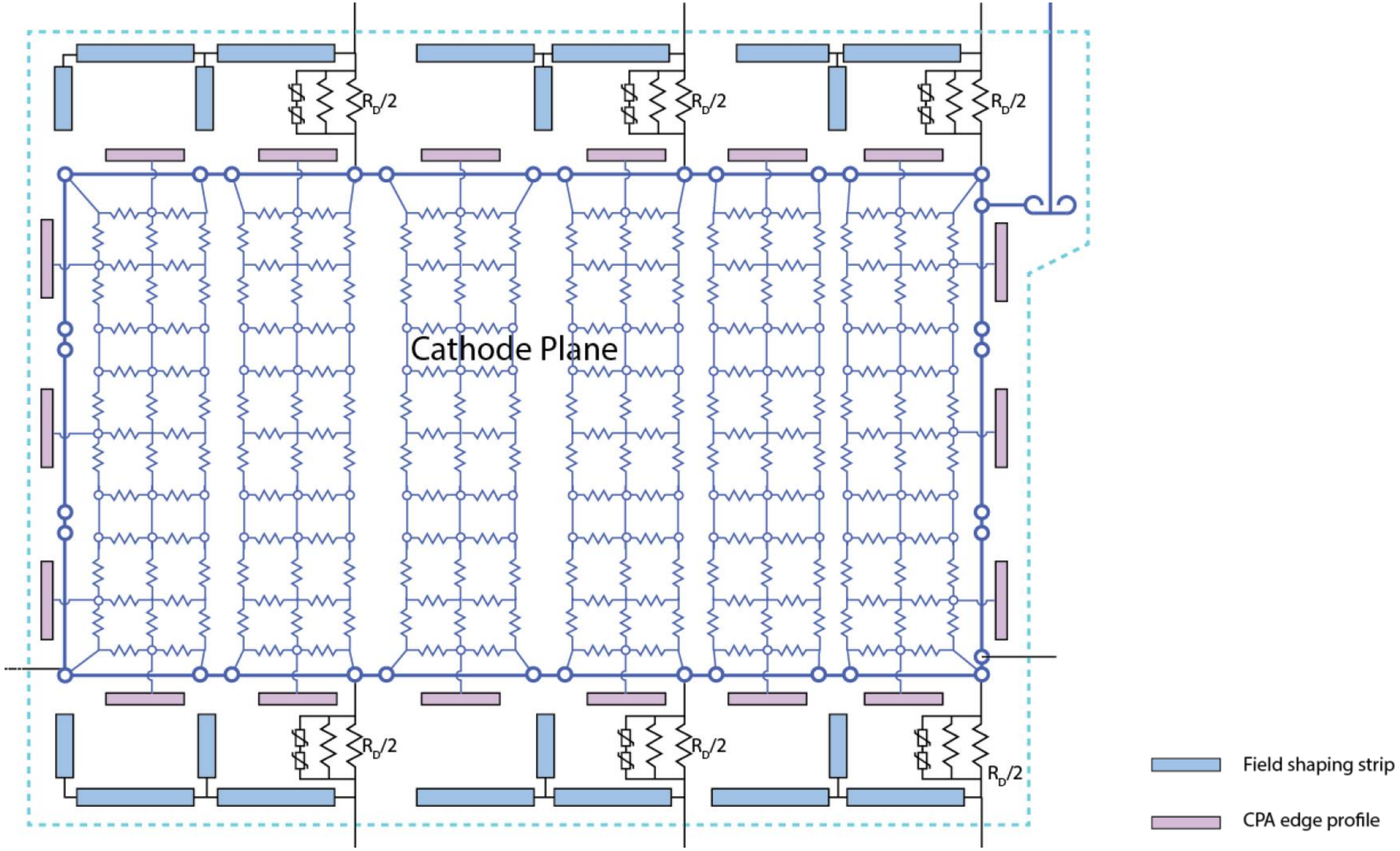
These divider boards can be mounted anywhere along the metal profiles. They are staggered to provide a continuous chain. Avoid putting them very close to the I-beam allow room for installing locking floor planks.



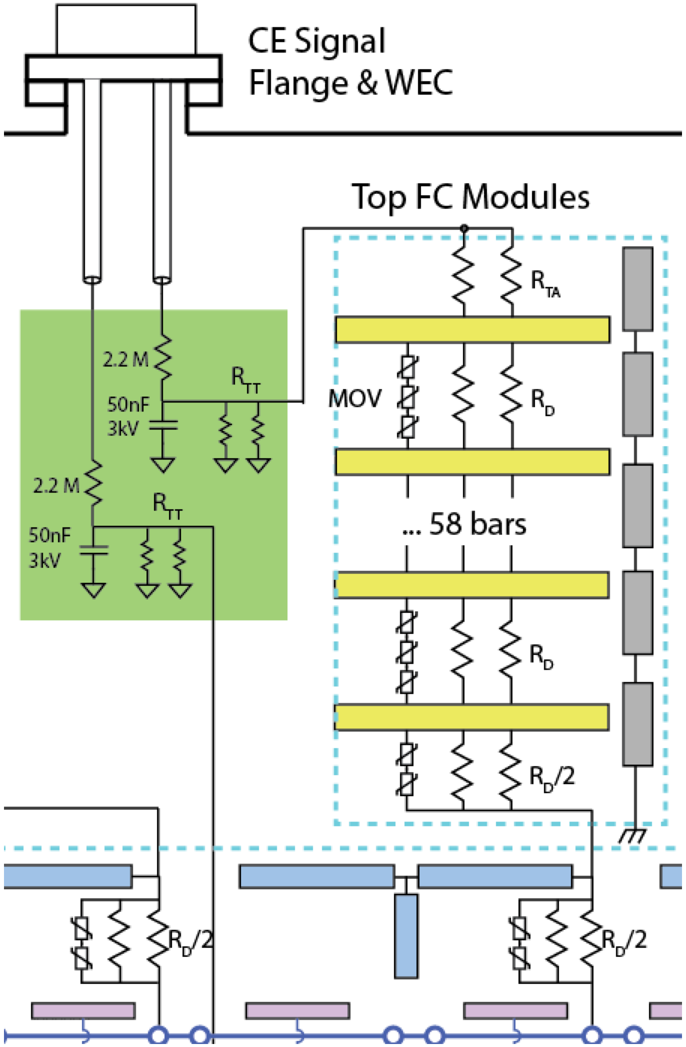
Divider Resistivity Range

LAr TPC signal current due to surface cosmic rays (ProtoDUNE SP)			
length of CR tracks	7452	m/s	100/m^2 muon flux, 2.3mx6mx3.6m
total energy loss	1579824	MeV/s	2.12MeV/cm
total charge deposition	1.07107E-08	C/s	23.6eV for Argon
equivalent current	1.07107E-08	A	11nA
let the divider current be 100 times	1.07107E-06	A	
total resistance over 3.6m is	1.7E+11	ohm	170Gohm
field cage strip pitch	6	cm	
number of divider	60		
resistance per divider	2.8E+09	ohm	this is the upper limit
Power supply side limitation (DUNE FD)			
HV power supply current limit	1	mA	
number of field cage panels in parallel	124		middle CPA, double field cage
max allowed current on each panel	8.06	uA	
total resistance	2.2E+10	ohm	
resistance per divider	3.7E+08	ohm	lower limit

CPA System Schematic Diagram

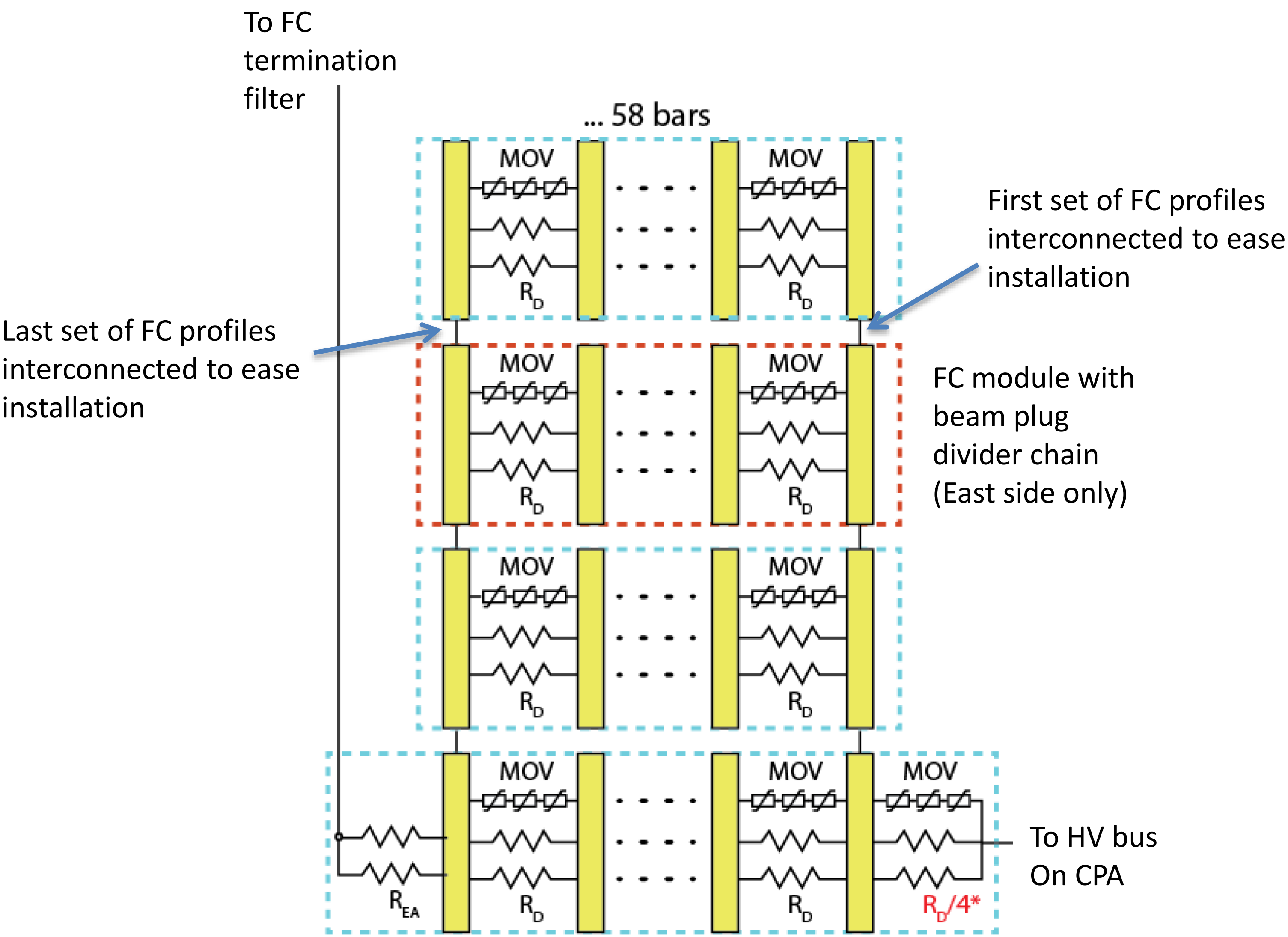


Top/Bottom FC Schematic Diagram



We might choose to use redundant wire connections between field cage and the filter board to avoid single point failure.

End Wall FC Schematic Diagram



CPA/FC System Schematic Diagram

NP04 Field Cage Schematic
11-1-2016

R_{TT} Top/Bottom termination
R_{TE} End wall termination
R_{TA} Top/Bottom APA
R_{EA} End wall APA

Ground plane panel

Field cage profile

Field shaping strip

CPA edge profile

FC module with beam plug
It has additional dividers

* RD/4 in parallel with beam plug divider resistor

Circuit common is the APA frame, which is connected to the detector ground through the returns of the power supplies.

Cables from flange:
RG316 with SHV connectors

Wires from filter board:
Dielectric Science 6905

R_D: SM104FE-1000M
MOV: ERZ-V14D182

HV bus: Dielectric Science 2134

Risks and Mitigations

https://fermipoint.fnal.gov/collaboration/PM-Tools/Pages/Risks-by-WBS.aspx

<table>
<tr><th>Risk ID</th><th>Title</th><th>Mitigation</th></tr>
<tr><td>RT-131-FD-058</td><td>The required High Voltage cannot be achieved</td><td rowspan="2">Validate key component (HVFT) at full/over voltage; Test small assembles at higher E field; Test small prototype assemblies at full voltage (35ton)</td></tr>
<tr><td>RT-131-FD-079</td><td>Field Cage design <s>using printed circuit boards</s> on a large scale not demonstrated</td></tr>
<tr><td>RT-131-FD-080</td><td>Damage to field cage resistors/electrodes in event of discharge</td><td>Segmented field cage modules; Redundant resistor networks; Adding varistors to protect resistors</td></tr>
<tr><td>RT-131-FD-081</td><td>Stored energy in the CPAs is suddenly dumped</td><td>All resistive cathode is developed to significantly slow down the charge injection into the FEE, as well as reduce the peak power of the discharge.</td></tr>
</table>

Charging of insulators on the field cage may rise as a risk, particularly for ProtoDUNE due to its higher ionization background. We are evaluating if the fiberglass materials have sufficient conductivity to avoid complete charging up. If significant charging up is suspected, we must impose large rounding radii for most insulating structures near the cathode.

Summary

- A new all resistive cathode has been developed using a commercial resistive film solution in order to mitigate the risk of high current injection into the cold electronics
  - The design achieves good E field uniformity at the cathode, and minimal fiducial cut due to mechanical structures
- A new design of independent, modular field cage using open metal profiles has been developed.
- The HV system electrical schematic is nearly complete. Some component values related to the voltages at monitoring points are under discussion
- Field shaping at the beam plug window is still under development

Review Charge Questions

1. Does the CPA/FC/HV design meet the requirements? Are the requirements/justifications sufficiently complete and clear?

Yes; need further work

2. Are CPA/FC/HV risks captured and is there a plan for managing and mitigating these risks?

Yes

4. Does the documentation of the CPA/FC/HV technical design provide sufficiently comprehensive analysis and justification for the CPA/FC/HV design adopted?

Yes

5. Are all CPA/FC/HV interfaces to other detector components (APA, detector support system and beam plug) and cryostat documented, clearly identified and complete? Does the TPC integrated 3D model adequately represent the mechanical interfaces to the CPA/FC/HV and between adjacent CPA/FC?

Yes

7. Is the grounding of the FC ground planes and to the APA and shielding/filtering of the HV understood and adequate?

Yes

8. Are the design radii, surface finish, cleanliness and QC standards adequate to support operation at the design HV?

Yes

9. Is the HV system design comprehensive and integrated? Are appropriate safety concerns incorporated into the design? Is the HV system monitoring properly integrated in the Detector Safety System? Is appropriate HV filtering in place to effectively reduce noise on cold electronics and photon system?

Yes

Backup slides

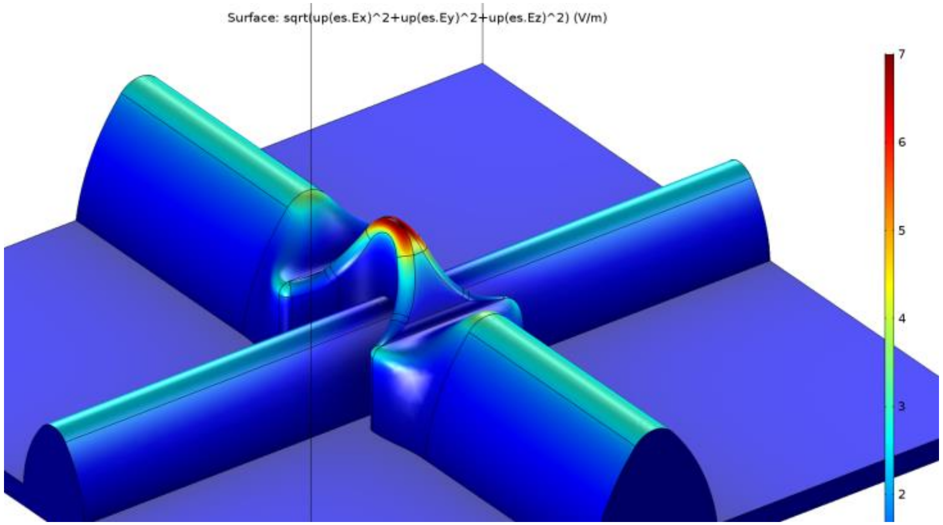
E Field on the Membrane Knuckle

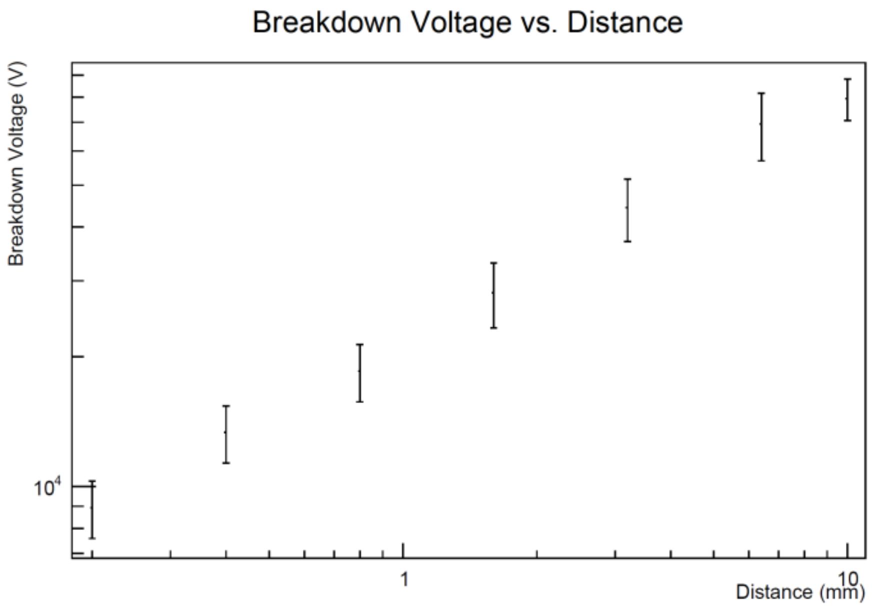
This is an approximate model of the GTT membrane. The knuckle principle radii (16 and 4.5mm) were fitted from a scan of the membrane.

With 1V at 1m above the flat the membrane, the field enhancement factor on the knuckle is 7.

Scale this to the end wall of the cryostat (west), where the maximum E field is 180kV/43cm, the field at the knuckle is 29kV/cm.

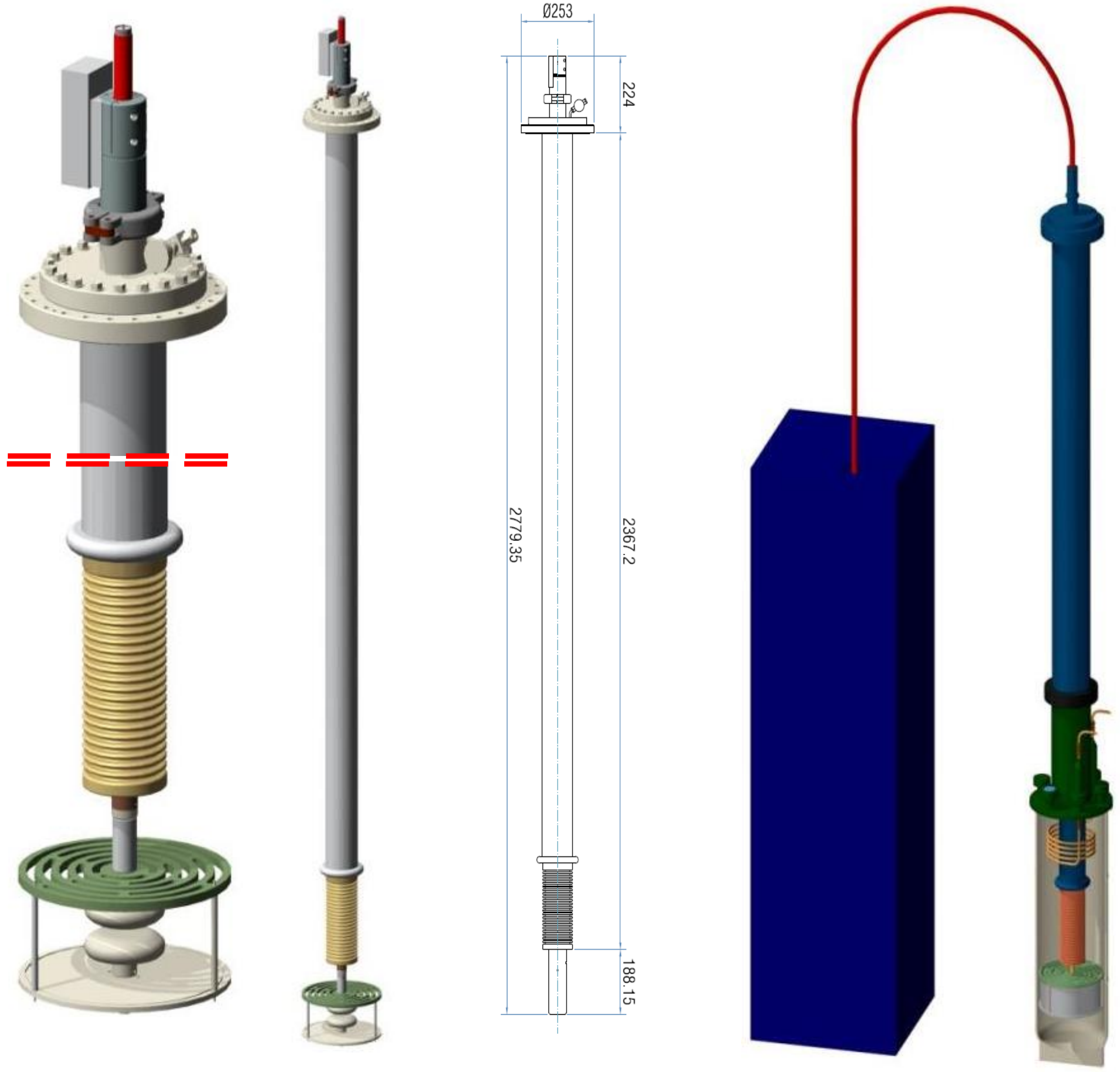
Sarah Lockwitz has tested a piece of the GTT membrane against a flat electrode and found that the breakdown voltage is 80kV over a 1cm gap at the tip of the knuckle.





WA105 HV Feedthrough Design

HVFT for 300kV with Rogowsky profile electrodes



Proposed design of DUNE HV FT (UCLA)

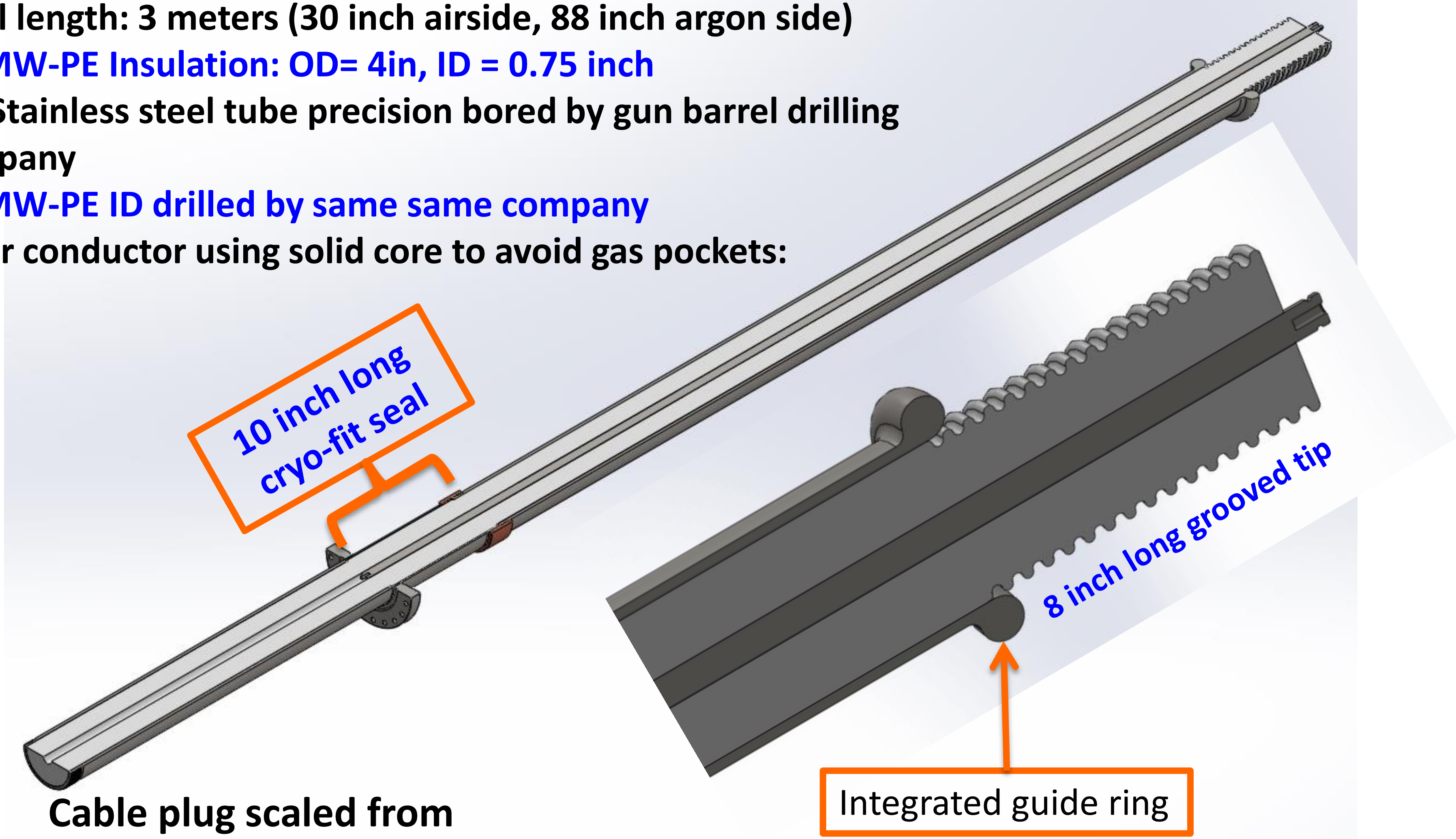
Total length: 3 meters (30 inch airside, 88 inch argon side)

UHMW-PE Insulation: OD= 4in, ID = 0.75 inch

OD Stainless steel tube precision bored by gun barrel drilling company

UHMW-PE ID drilled by same same company

Inner conductor using solid core to avoid gas pockets:



Cable plug scaled from existing plug design (not shown)

Evaluation of Resistive Materials

- Carbon loaded Micarta
- Zelec ESD powder mixed with polyurethane binder
- ESD surface conducting G10 from Current Composite
- Screen printed resistive ink on G10 substrate
- DuPont resistive Kapton film on G10 substrate

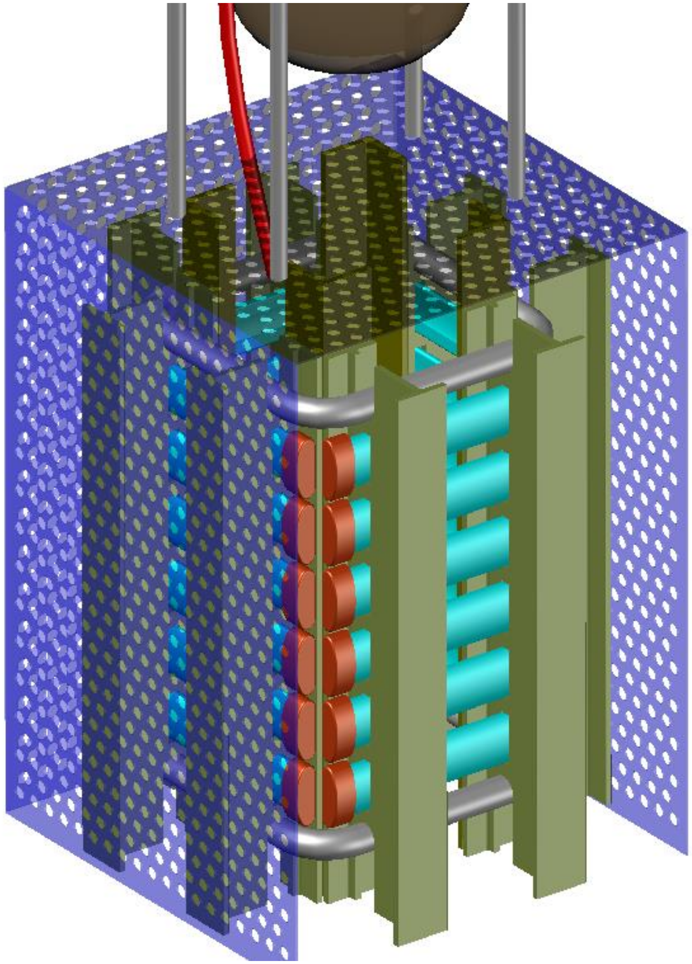
- Bonding strength
- Resistivity uniformity, stability
- Resistance to sparks, abrasion

- See summary by Francesco Pietropaolo: https://indico.fnal.gov/getFile.py/access?contribId=35&sessionId=10&resId=0&materialId=slides&confId=11632

Roll-Formed Field Cage Test Setup

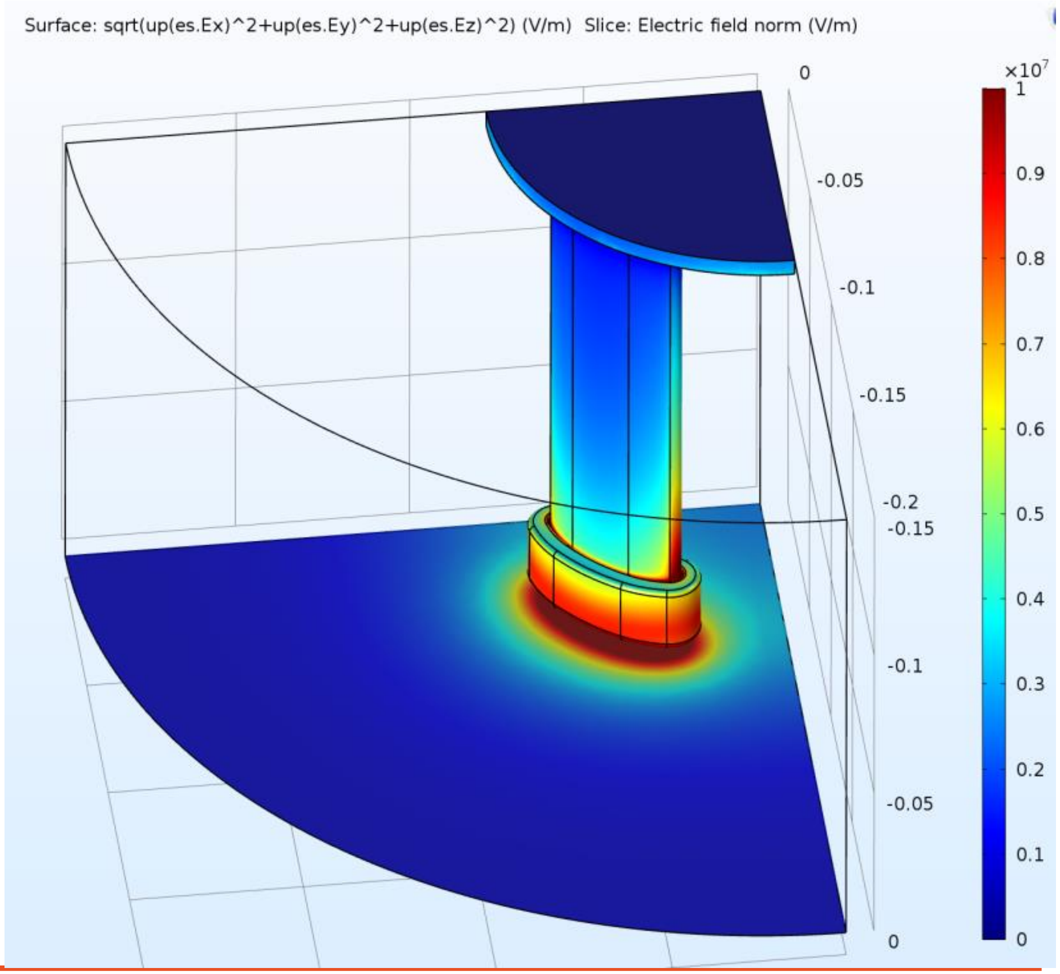
- To validate the field cage concept in pure LAr
- Designed to fit in the ICARUS 50 liter cryostat
- Roll-formed metal profiles with UHMW PE caps
  - Choice of metal (Al, SS) and surface finish
- Pultruded fiberglass I-beams form 4 mini panels
- All profiles are at same potential to simplify HV connection
- Ground planes only 66mm away
- Requires 1/3 of FD bias voltage to reach same E field
- Ground planes can be connected to external amplifiers to monitor micro-discharges
- Video camera to monitor bubbles and sparks

- Holding 100kV (see Francesco's talk)



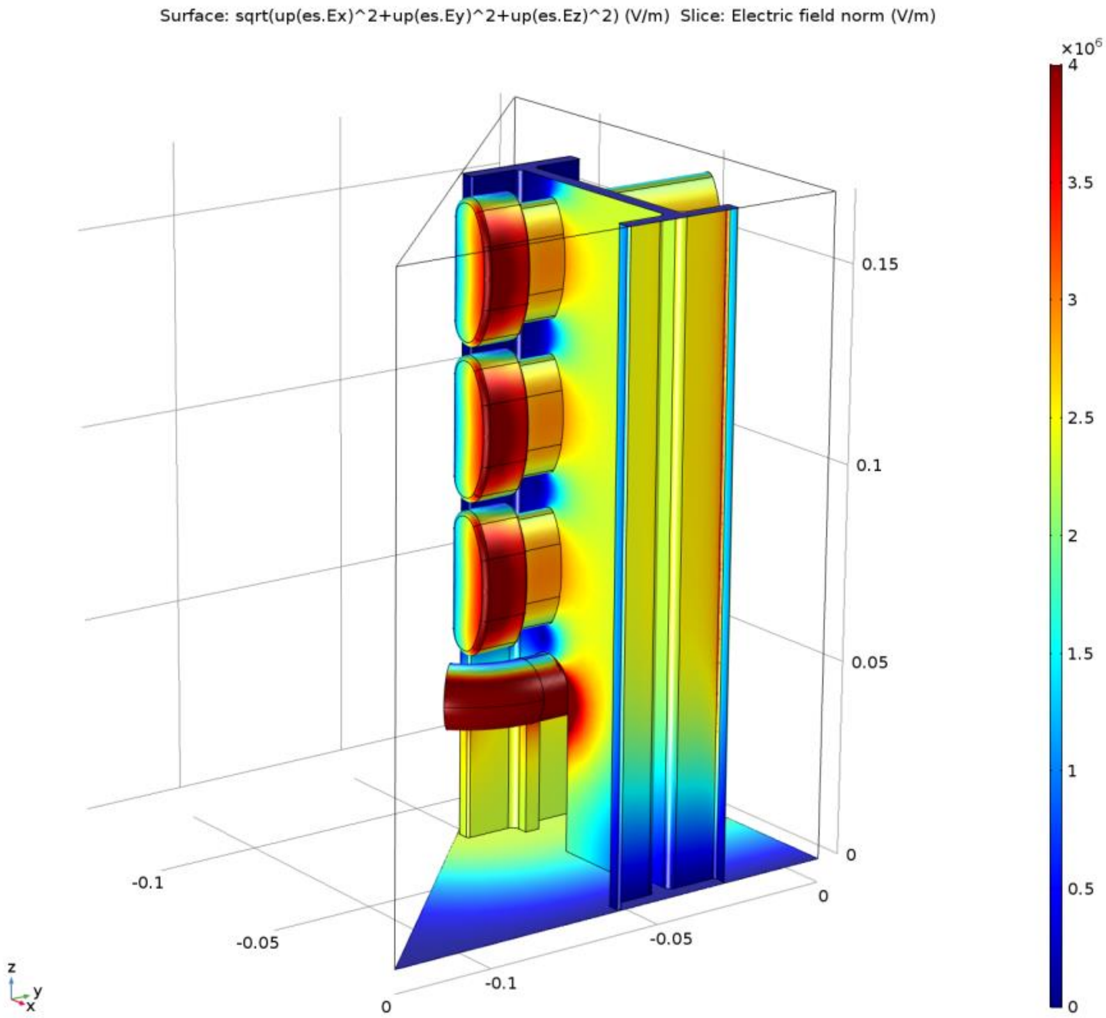
Small Field Cage Tests

-150kV through the caps and 5mm of LAr in an open Dewar



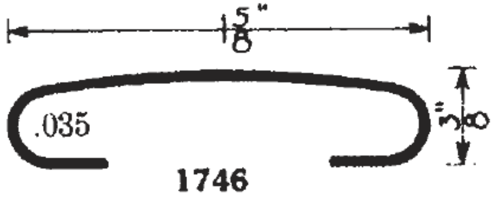
Small Field Cage Tests

-100kV on the profiles, 6.6cm to ground plane. Clean argon.

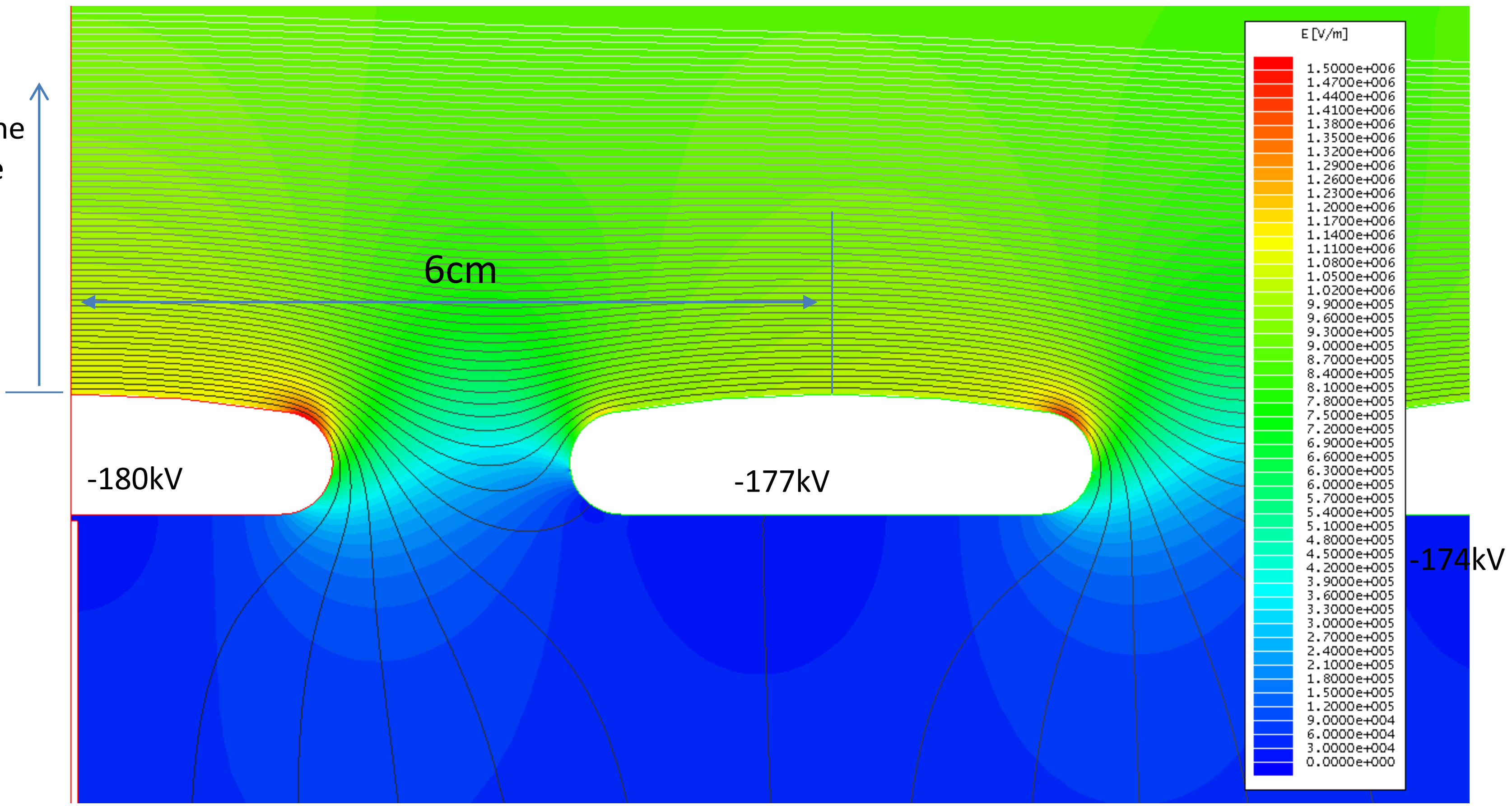


Field Cage with Profile # 1746

Pitch 6cm (3kV)
Max. E field ~15kV/cm



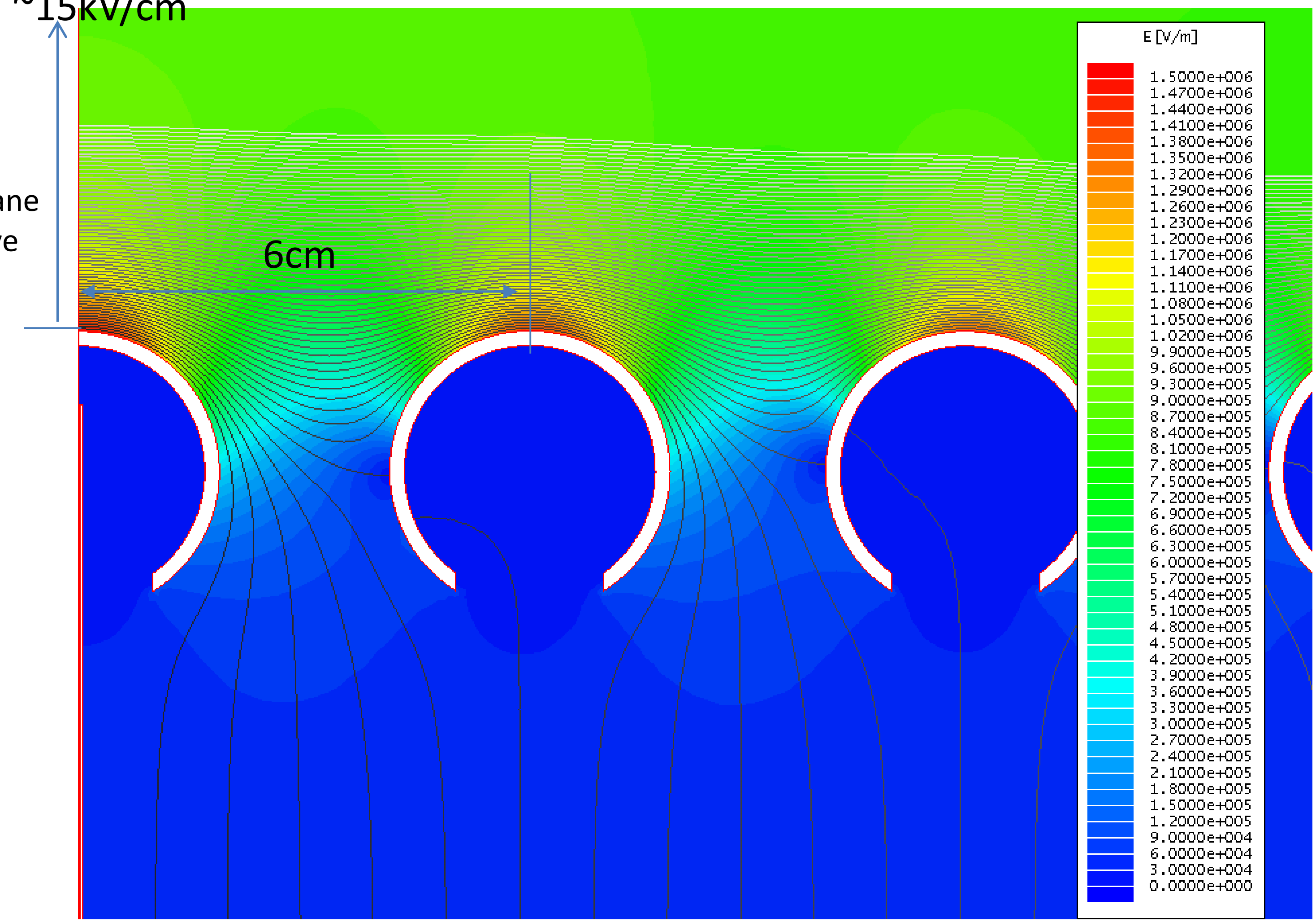
Ground plane
20cm above



Field Cage with 38mm tube (1.5”)

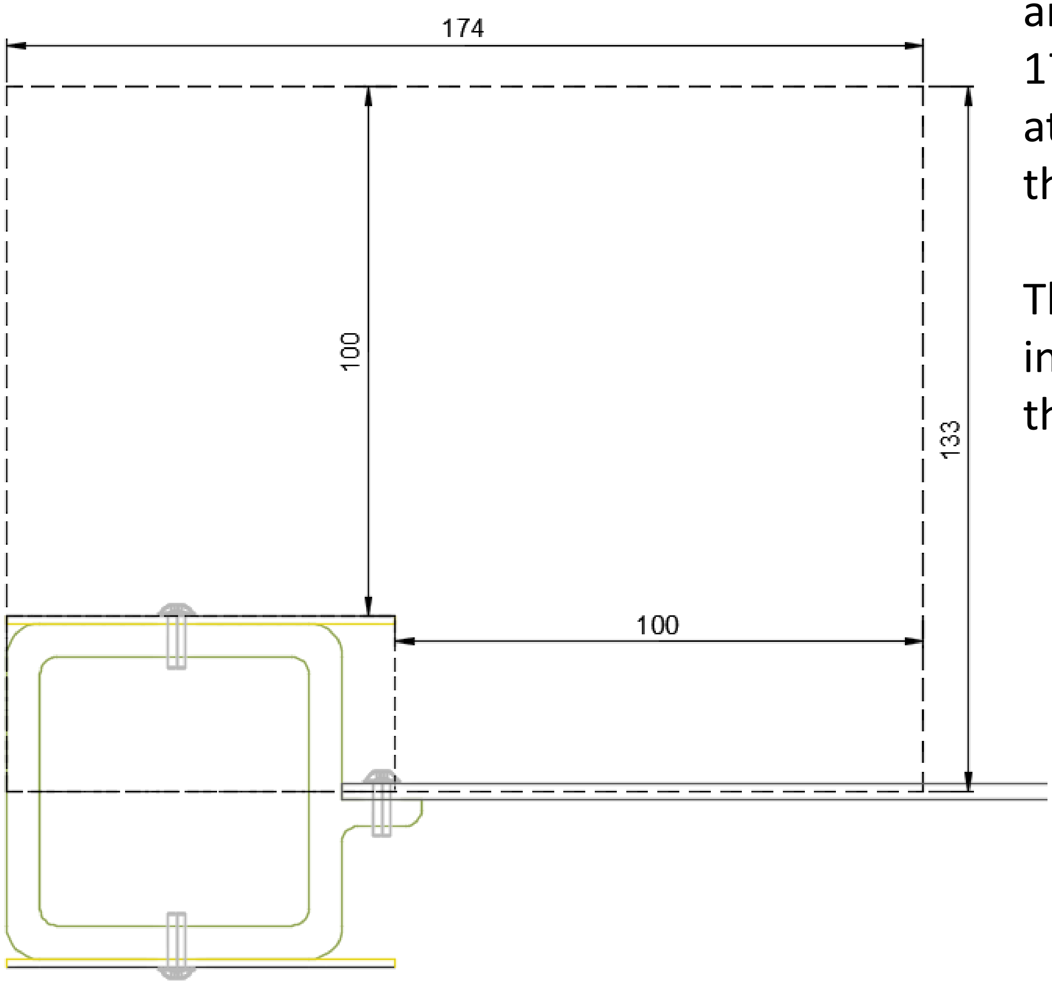
Pitch 6cm (3kV)
Max. E field ~15kV/cm

Ground plane
20cm above



BROOKHAVEN NATIONAL LABORATORY DUNE

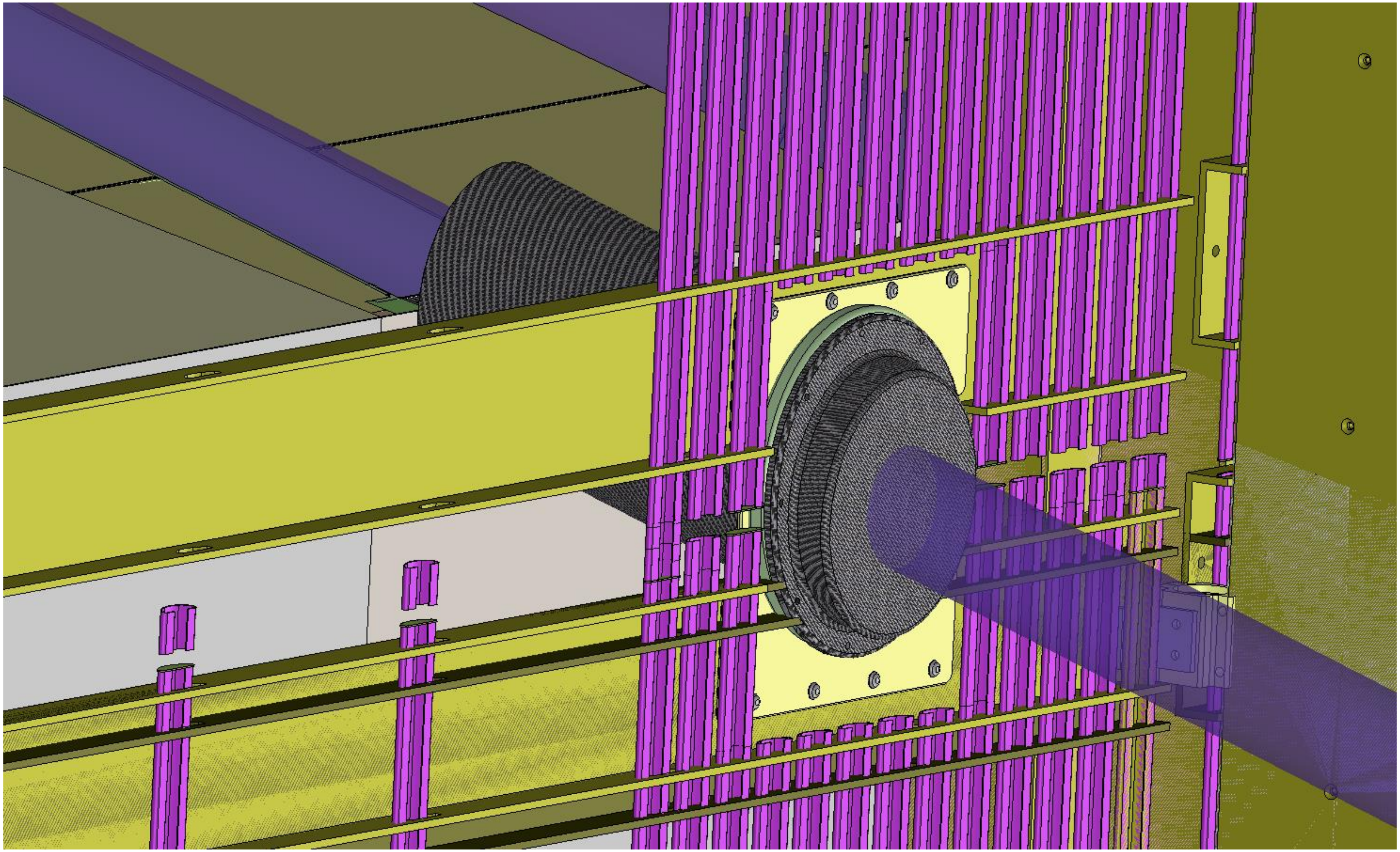
Fiducial Cut on the Thin CPA Design



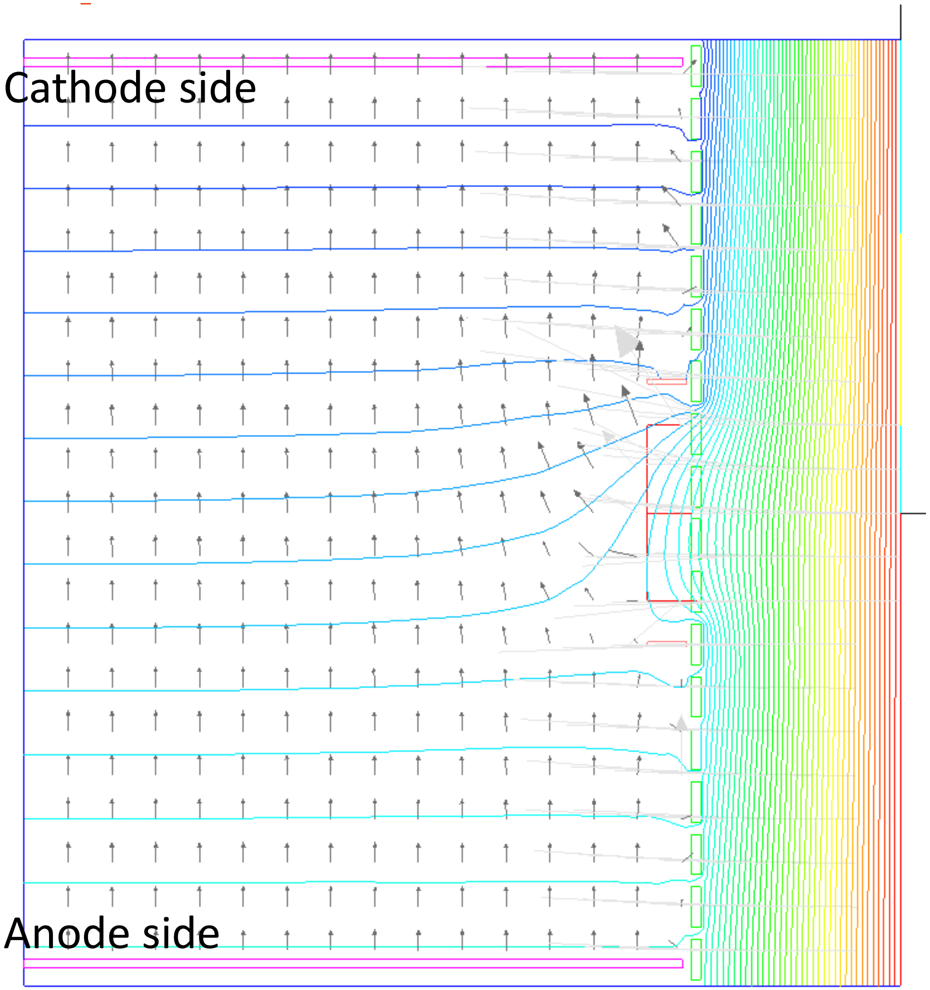
If we apply a fiducial cut of 100mm around the frame, the area of 174mm x 133mm would be the cut at the cathode every 0.58m (half of the new half width CPA).

This averages to ~40mm over 0.58m instead of ~110mm in the case of the double walled configuration.

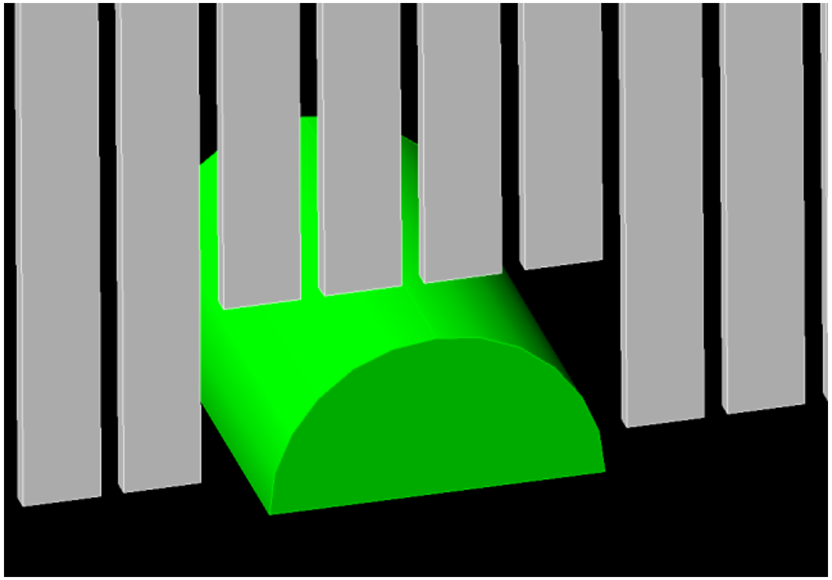
The Current Design of the Beam Plug



Potential Contours at Beam Window Center

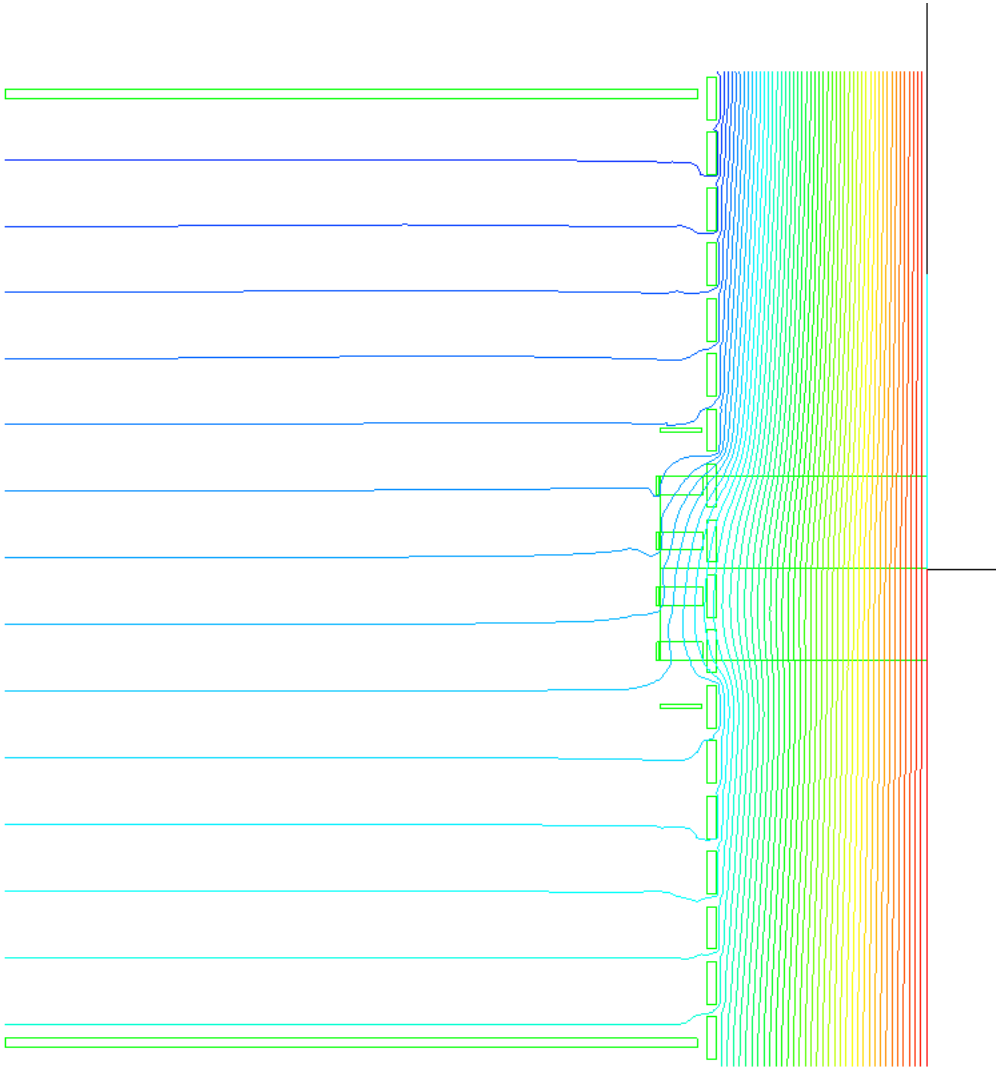


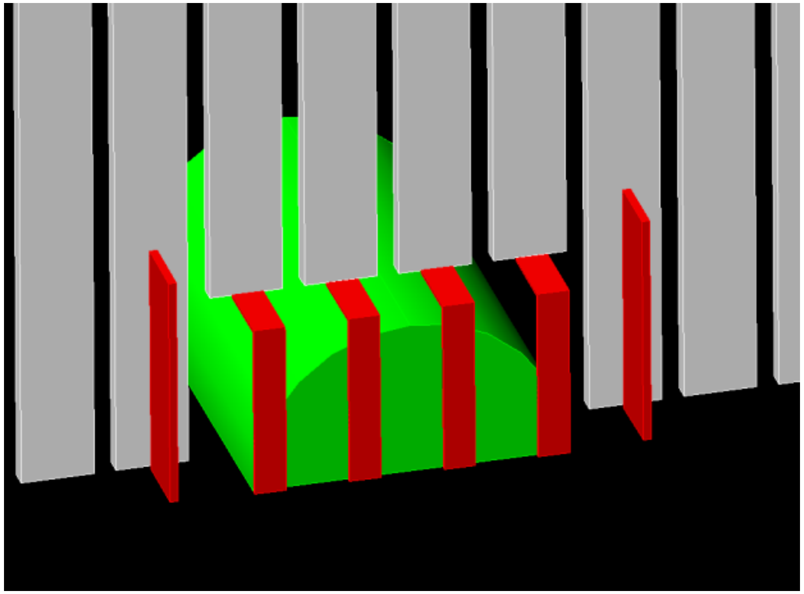
The field cage has a cutout, and the 20cm beam window (insulating plug) is placed through this opening, 5cm into the field cage.
This plug is assumed to be air (thin wall ignored) in this model.



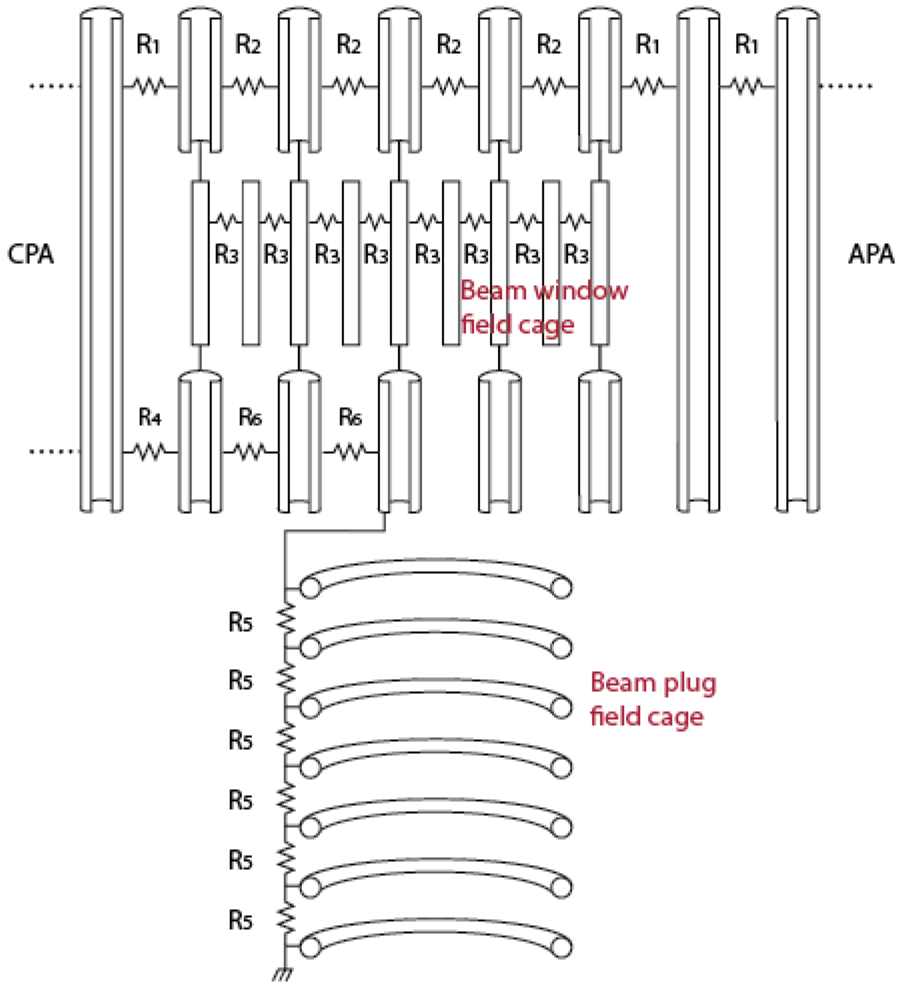
Due to the ground plane (cryostat wall, ~30cm away in this model) and the hole in the field cage, there is a strong E field pushing electrons toward the face of the plug. If the plug penetrates much deeper, the distortion near the beam window face diminishes. However, there could be surface charging on the side wall of the insulating plug, causing other kind of field distortion.

Potential Contours at Beam Window Center Plane with Field Shaping Strips over the Beam Plug





Schematic for Resistive Dividers with Beam Plugs



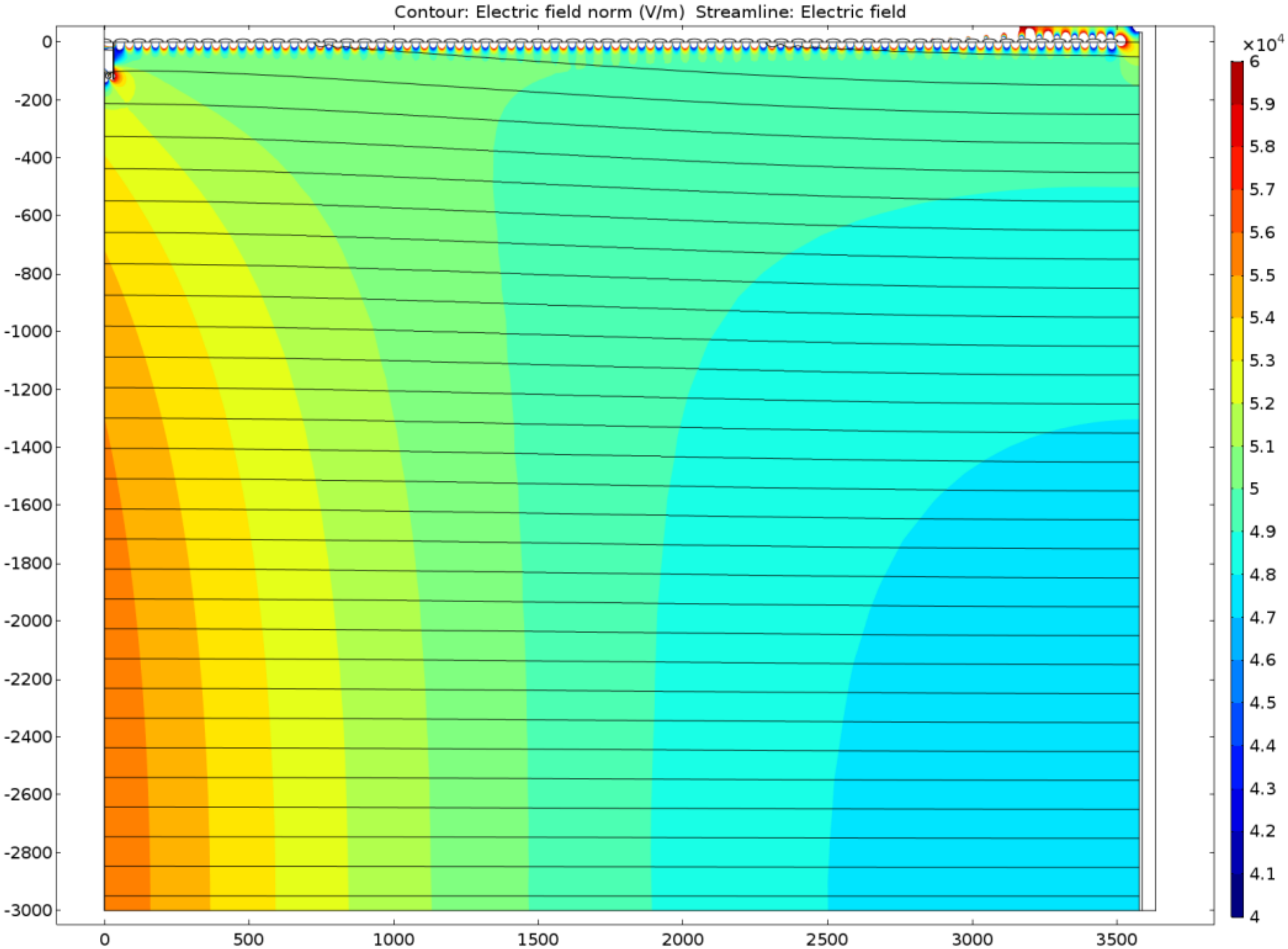
Need to make electrical connection to the cryostat wall

Impact of Space Charge (2D)

Peak charge density @ cathode: 71nC/m^3, assuming 110/m^2/s

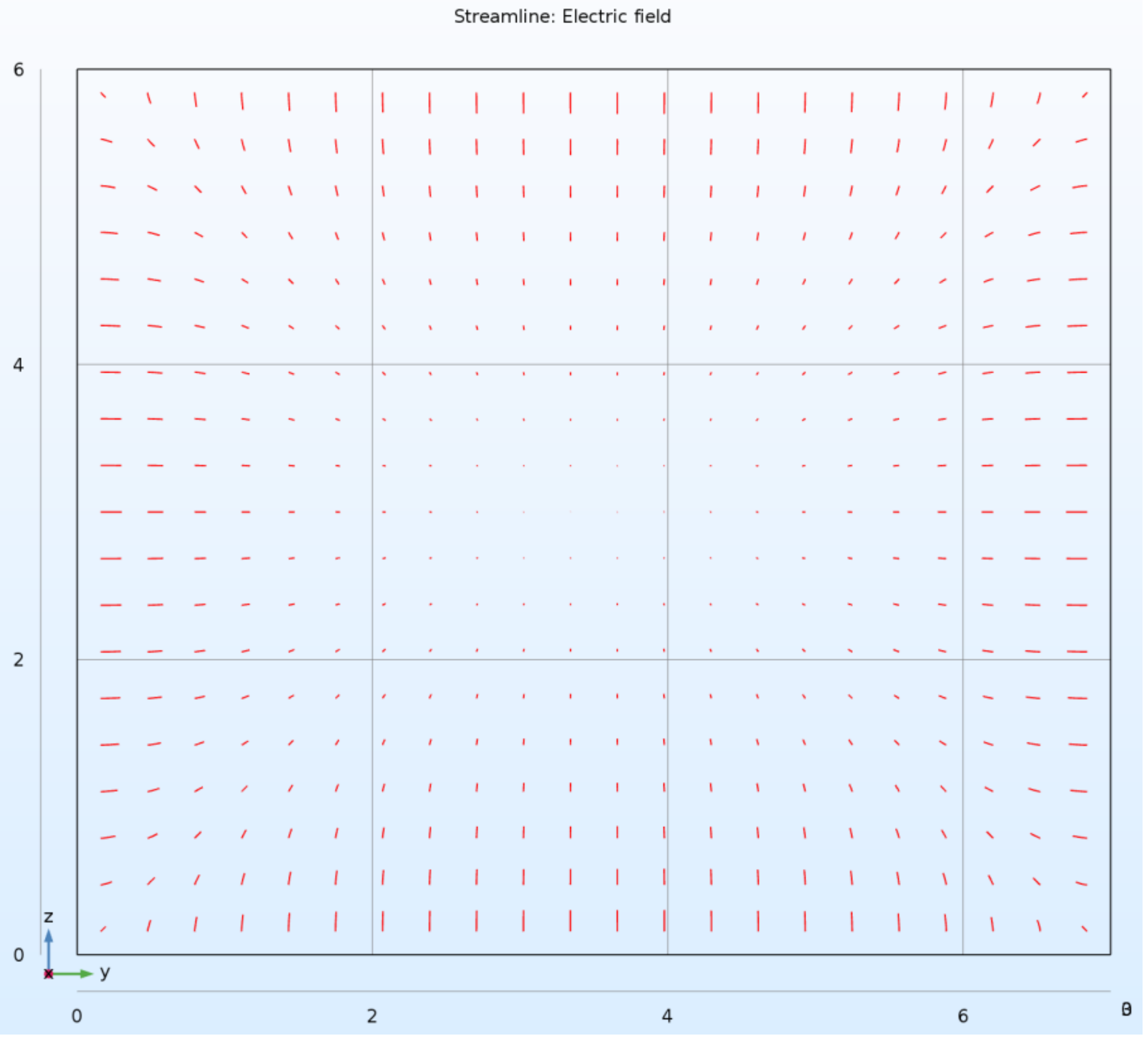
Max deflection ~ 15cm.

E contours: 2% per step



Impact of Space Charge (3D)

Projection of field lines on the wire plane



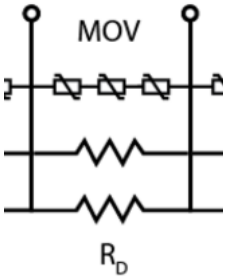
Peak charge density @ cathode: 71nC/m^3, assuming 110/m^2/s

Max deflection ~ 15cm.

Broken Resistor in a Field Cage Module

Between two adjacent nodes of the resistor divider chain are two 1GOhm resistors in parallel, and 3 serially connected MOVs in parallel. The nominal voltage drop is 3kV.

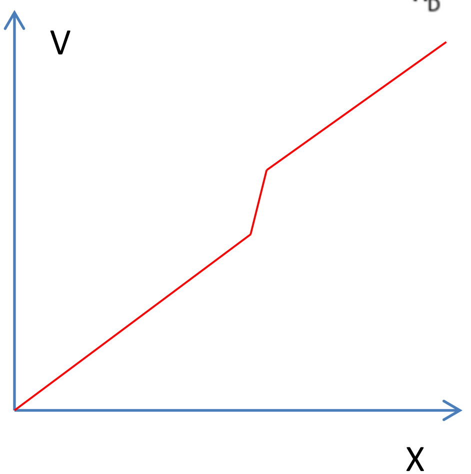
An open resistor on the divider chain would approximately double the voltage cross the remaining resistor to 6kV. This will force the varistors in parallel to that resistor into conduction mode, results in a voltage drop of roughly 5kV (1.7kV x 3), while the rest of the divider chain remain linear, with a slightly lower voltage gradient.



This voltage profile on one field cage module is modeled in 3D, with the rest of the "FC modules" in ideal linear form. Instead of using discrete electrodes on the field cage, plates with perfectly linear voltage distribution are used. This gives the "ideal" behavior and can then be superimposed with the effect of the discrete electrodes.

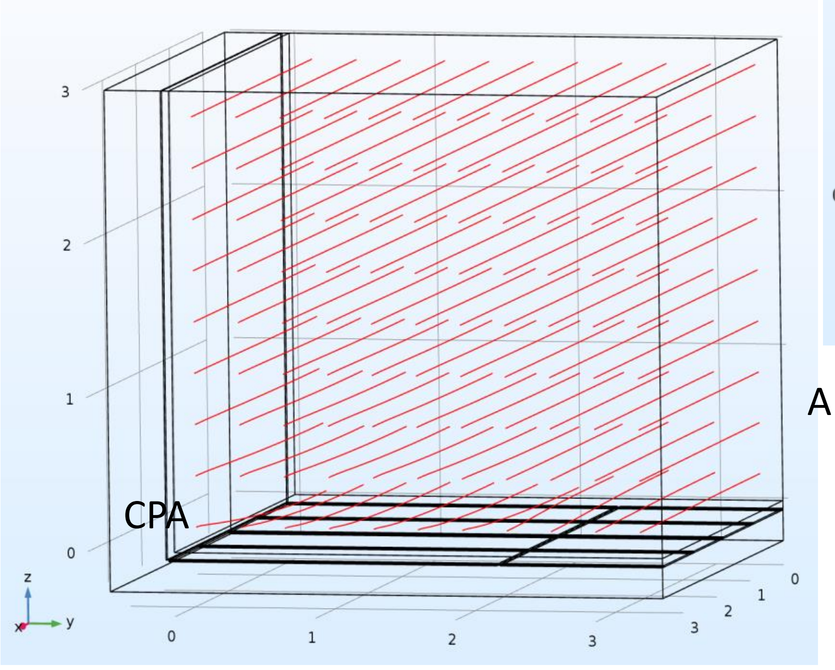
Because the damage to the divider is local to one module, its impact to the TPC drift field is limited to region near this module. This is part of the intention of this modular design.

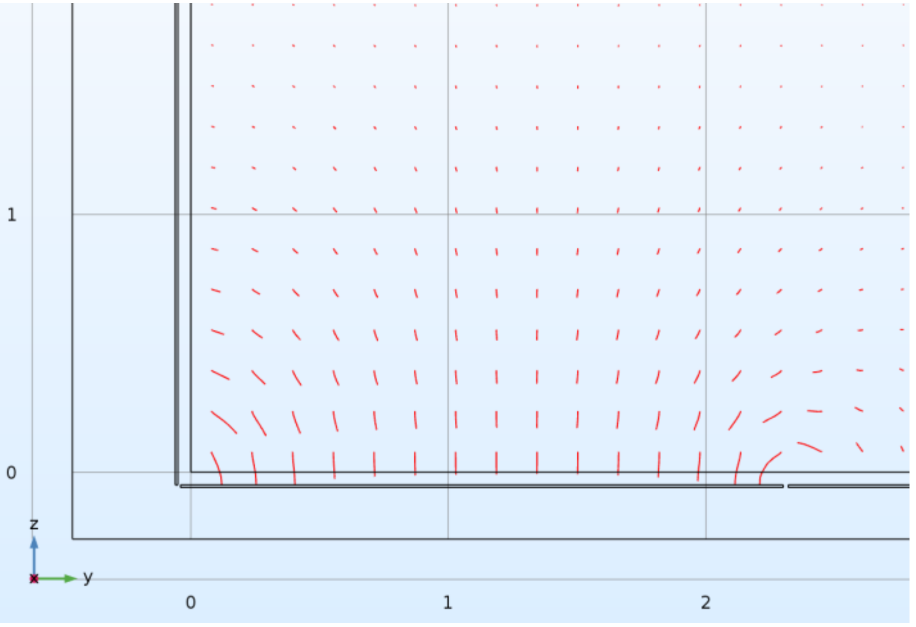
The effect of the resistor values can be scaled from this study. A 2% change in a resistor value (1% change from the 2R in parallel) will give ~1.5% of the distortion from a broken resistor.



Broken Resistor on First Gap (CPA Side)

Electrons leaving the cathode are deflected toward the field cage module with the broken resistor

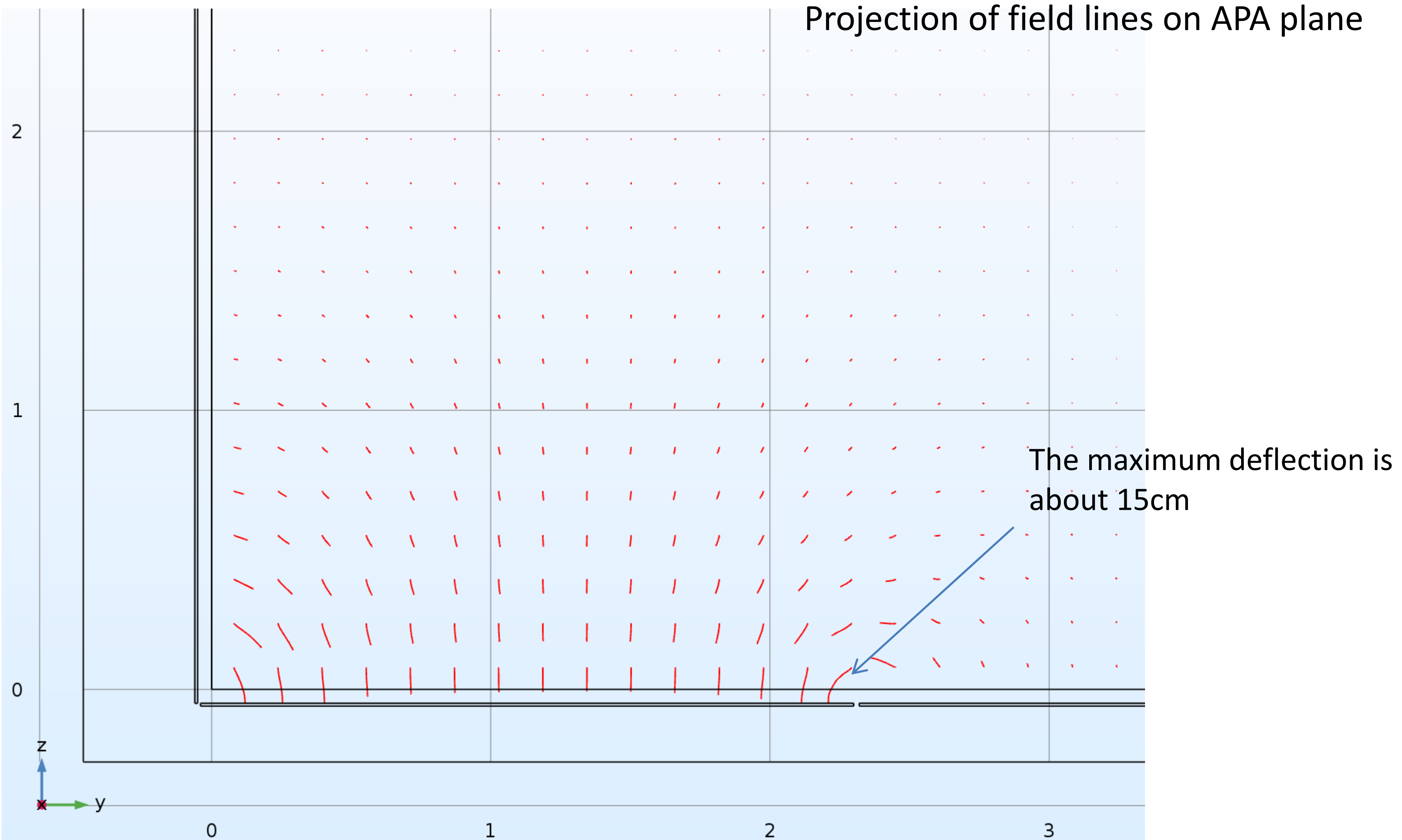




Projection of field lines on APA plane

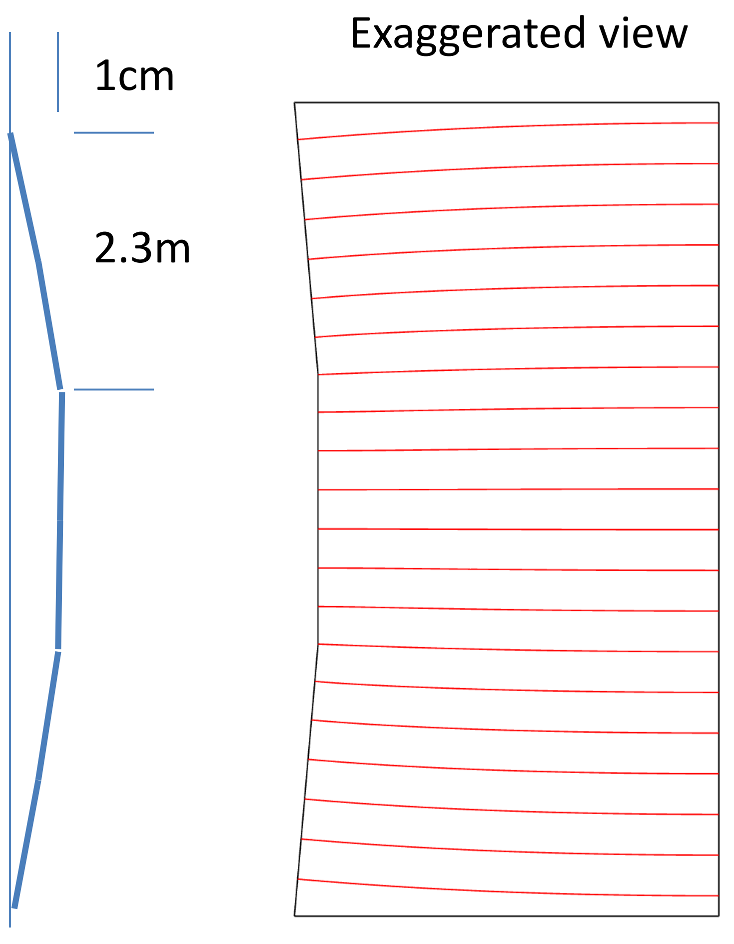
The maximum deflection is about 15cm

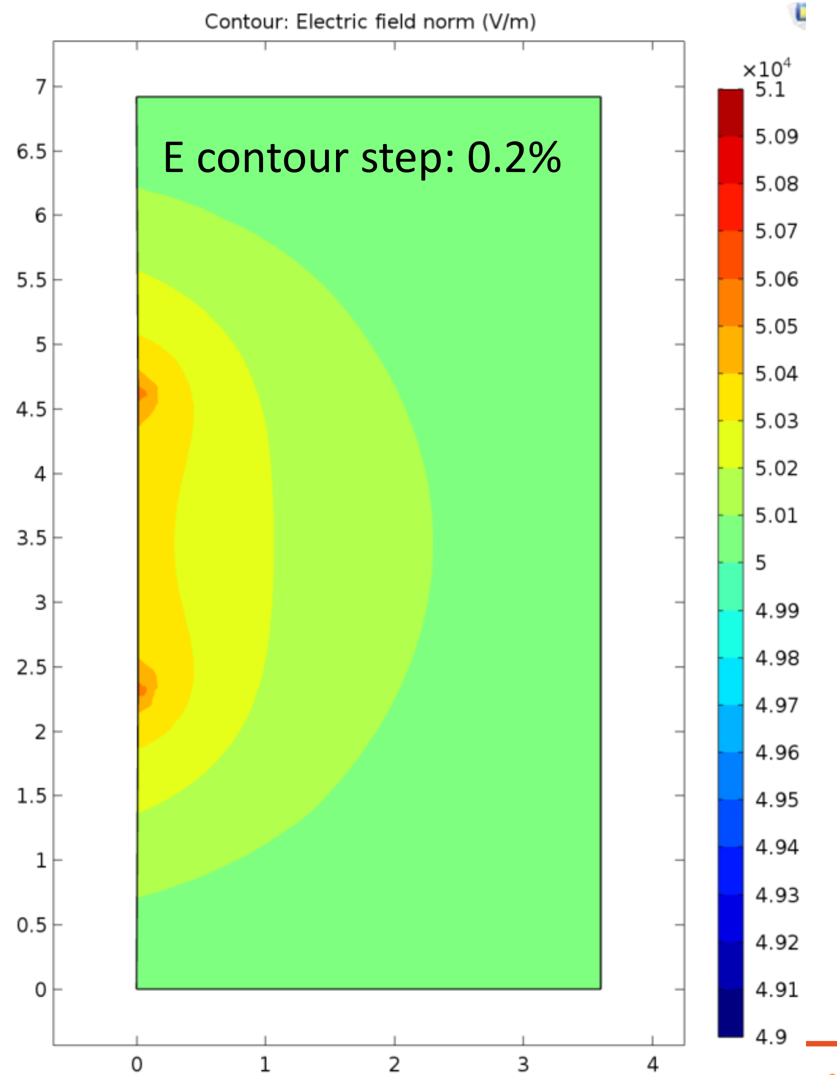
Broken Resistor on First Gap (CPA Side)



Cathode plane bows in

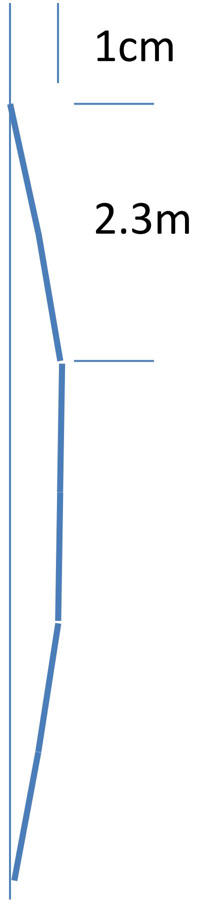
- Central 2.3m x 2m tile bows in by 1cm.

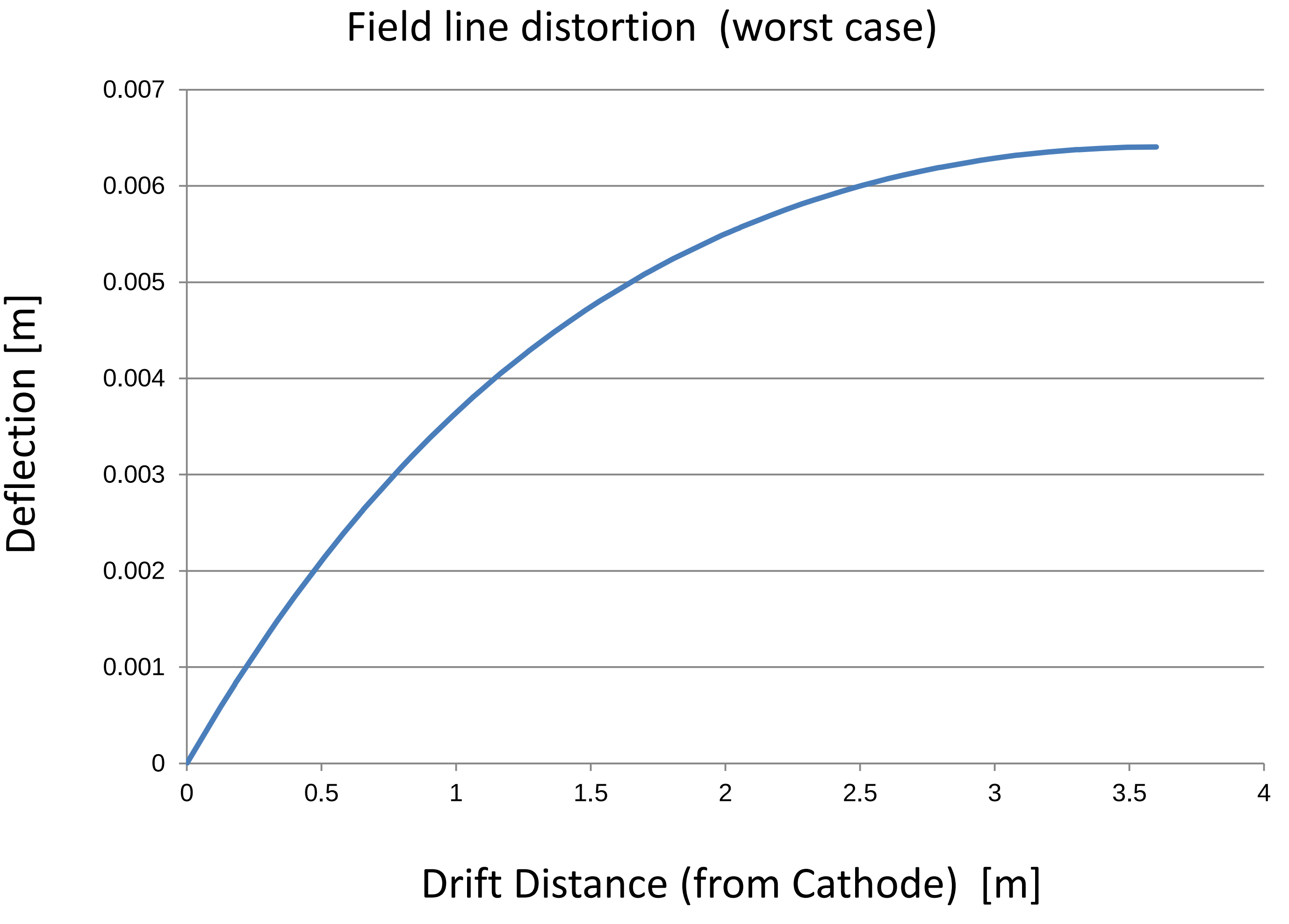




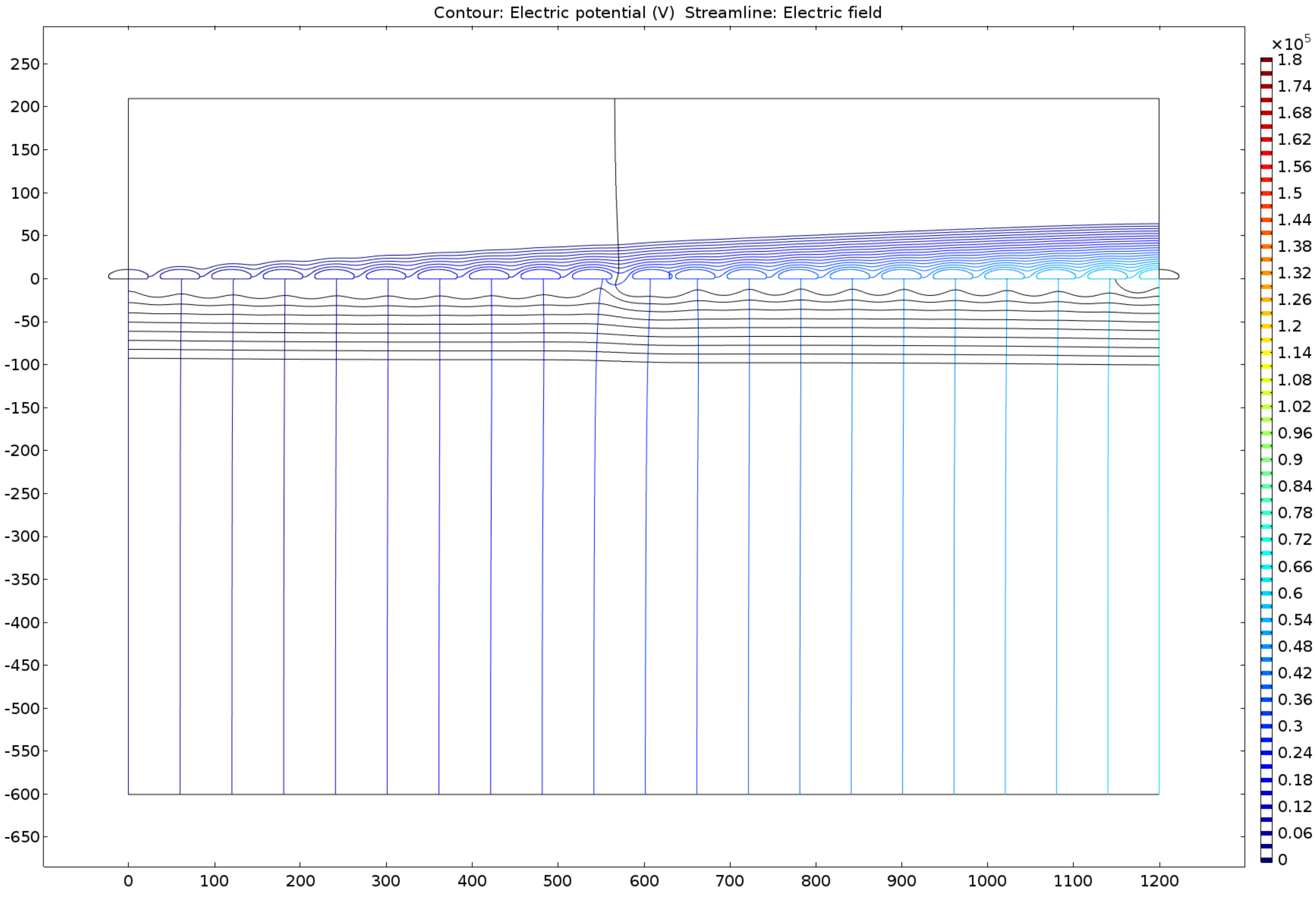
Cathode plane bows in

- Swing: +/- 1cm

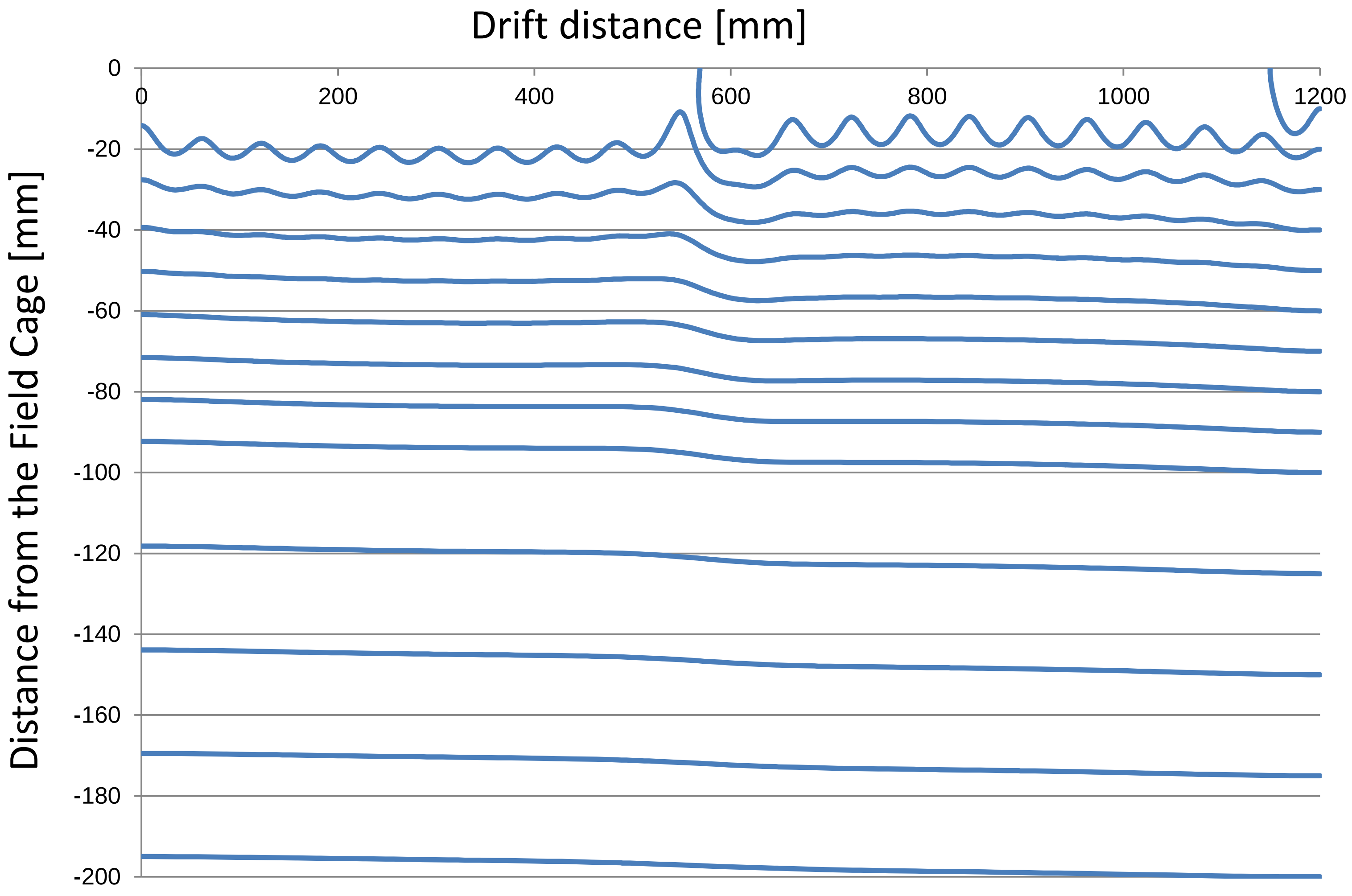




FC profile shift on plane by 10mm

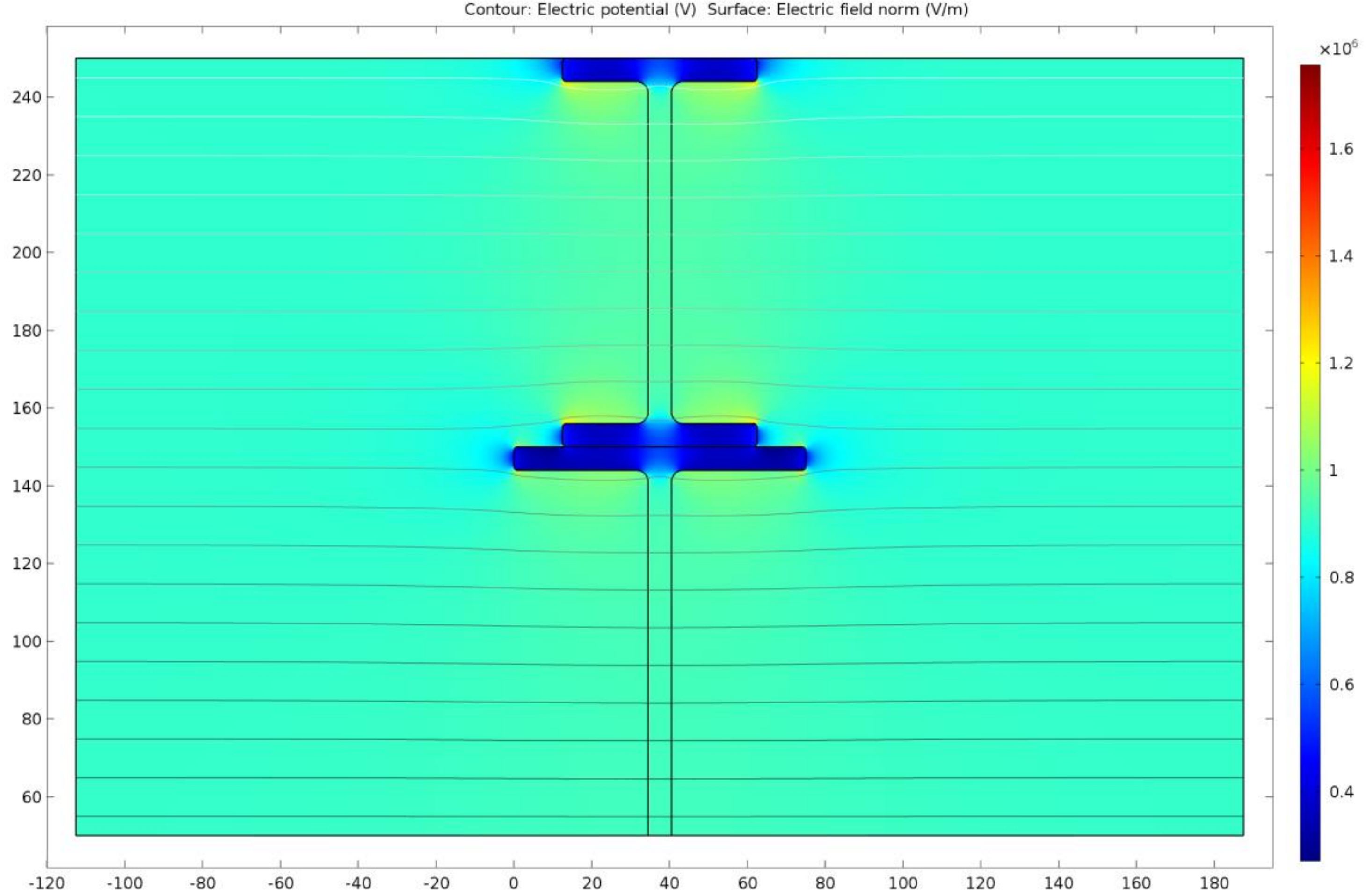


FC profile shift on plane by 10mm



No charge build up

- 2 I-beams stacked between the ground plane and field cage profiles.
- Corner radius of the I-beams is 1mm. 180kV over 20cm



With charge build up

- Applied “zero charge” boundary condition to all surfaces of the I-beam except the top and bottom flat faces.
- White contour lines: V
- Black contour lines: E