FD2 Photon Detector System: Final Design Review Mechanical Design Overview

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4/18/23

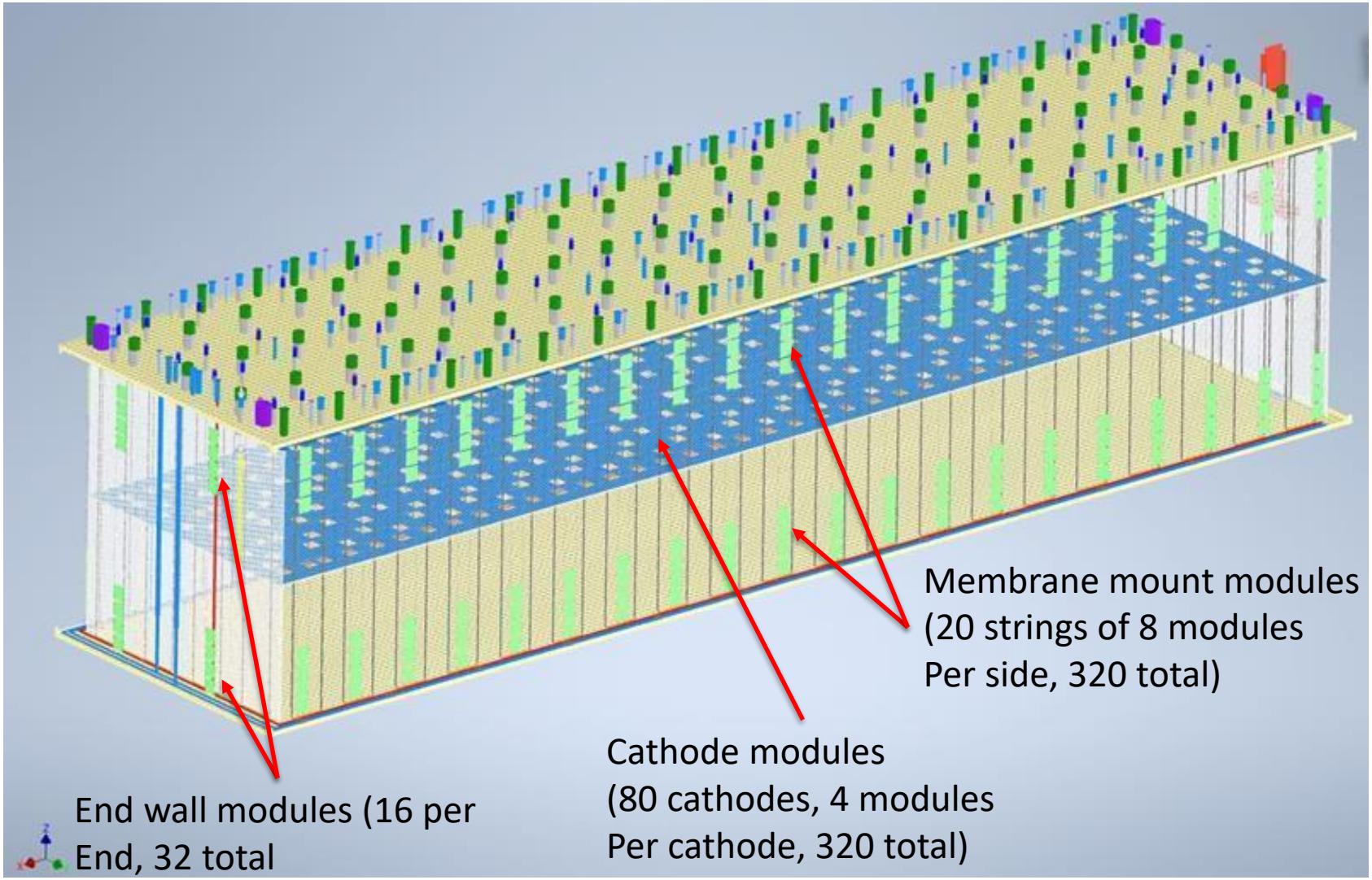
Outline

- History of mechanical development
- PD mounting in detector
  - Cathode mounting
  - Membrane mounting
  - Cable routing, monitoring system mounting
- PD module description
  - Module dimensions, general design outline
  - SiPM spring loading
  - Electronics housing
  - HV protection
  - Filter plate mounting
  - Assembly and shipping plan
- Monitoring system mechanics
- QA/QC/Manufacturing Summary
- Engineering analysis/Compliance office status
- Conclusion

Mechanical design evolution

- Module design
  - Evolution of successful FD1 PD design (60 X 12 cm^2 -> 60 X 60cm^2) active cells.
  - Similar to FD1 construction materials (FR-4 G-10 frames, Acrylic WLS plates, glass dichroic filter plates).
  - Similar common design for membrane and cathode modules.
  - Special FD2 module features include:
    - SiPMs spring-loaded to WLS plates to follow relative thermal contraction, improving optical contact.
    - 3-sided “Faraday cage” included to shield SiPMs from discharges of HV system.
    - Minimized support frame occlusion of optically active area.
    - Provision for simplified assembly at SURF.
  - Module frame design evolved through 5 design permutations and tested in CERN NP-02 cold box.
  - Internal consortium expert review to finalize design prior to Module 0.
- Monitoring system mechanics are well understood, building on dual phase and FD1 ProtoDUNE experience.
- Interface with Cathode and Cryostat for PD mounting closely controlled.

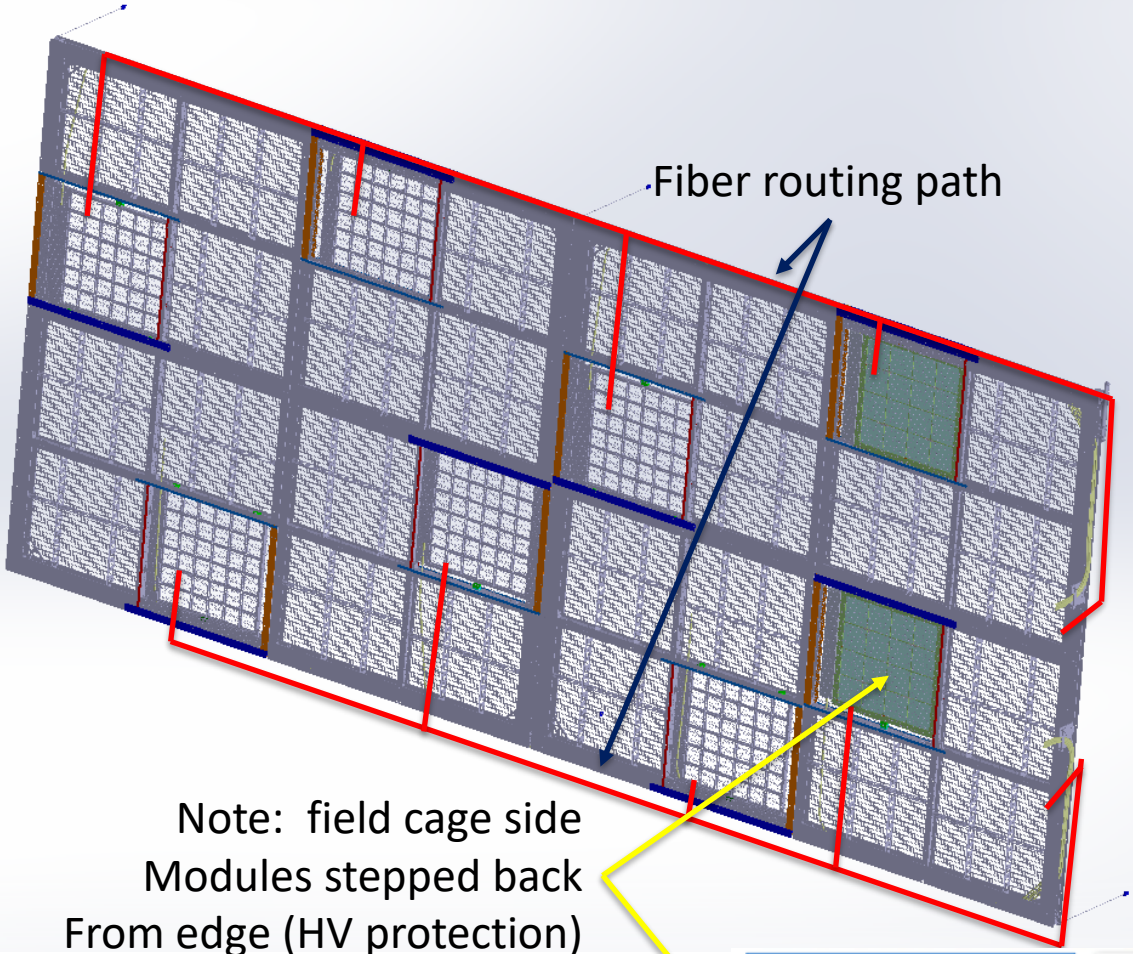
PD module arrangement on TPC

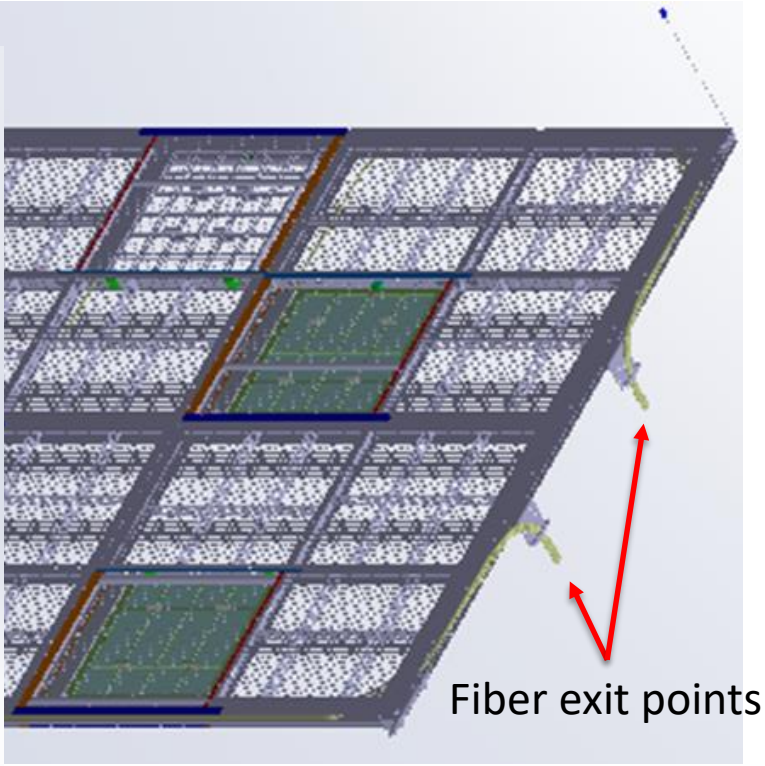


PD system layout (by the numbers)

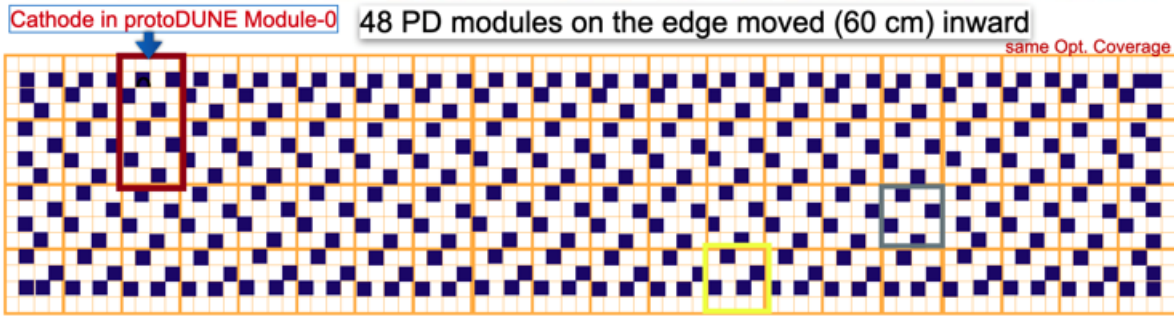
- 320 Cathode modules
  - 73.4 X 65.3 X 3cm^3
  - 8.8 kg (dry) 2.7kg (submerged)
  - 160 SiPMs (51,200 total)
  - 2 readout channels
  - 32 WLS plates (144 X 144mm^2)
  - 2-sided readout
  - 1 WLS plate
- 352 Membrane modules
  - 74.6 X 65.3 X 2.6cm^3
  - 8.8 kg (dry) 2.7kg (submerged)
  - 44 readout columns (8 modules each)
  - 160 SiPMs (51,200 total)
  - 2 readout channels
  - 16 WLS plates (144 X 144mm^2)
  - 1-sided readout
  - 1 WLS plate
- 44 Membrane mount module support assemblies
- 40 flange assemblies
- 88 monitoring system kits
  - 44 top, 44 bottom kits.
  - 176 light diffusers (mounted to field cage supports, one per membrane mount column).
  - 176 flasher channels.
- All inner module surfaces lined with Vikuiti reflective foil to increase light collection.

Cathode mounted modules





Note: field cage side
Modules stepped back
From edge (HV protection)



Cathode mounting points

- PD modules mounted in cathode with 3-point suspension.

- Two configurations: Perimeter and interior mounting.

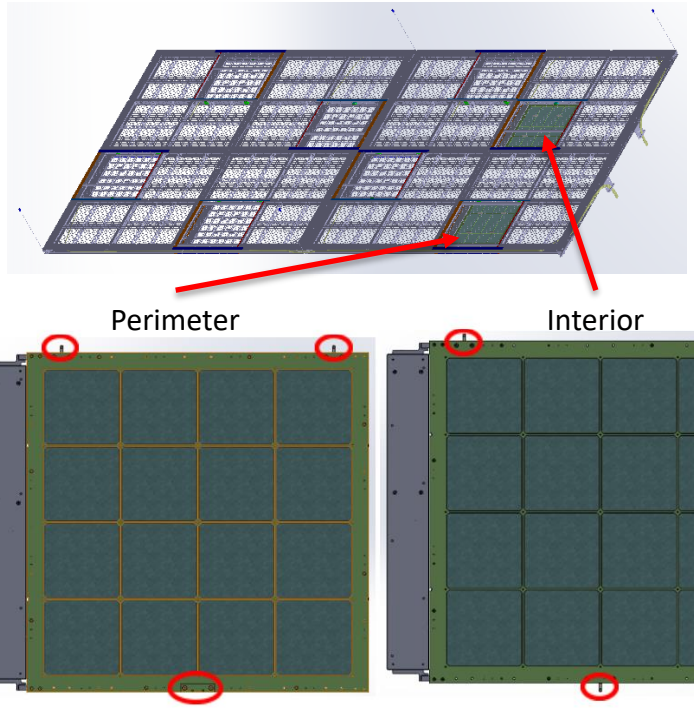
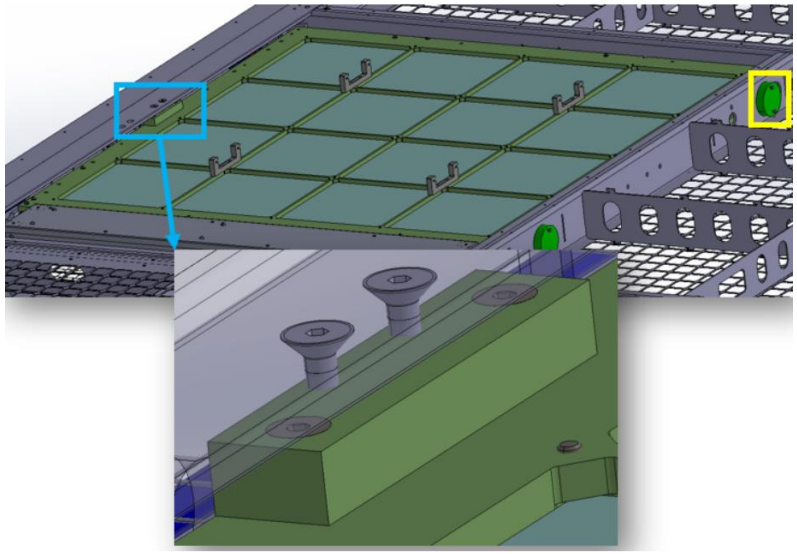
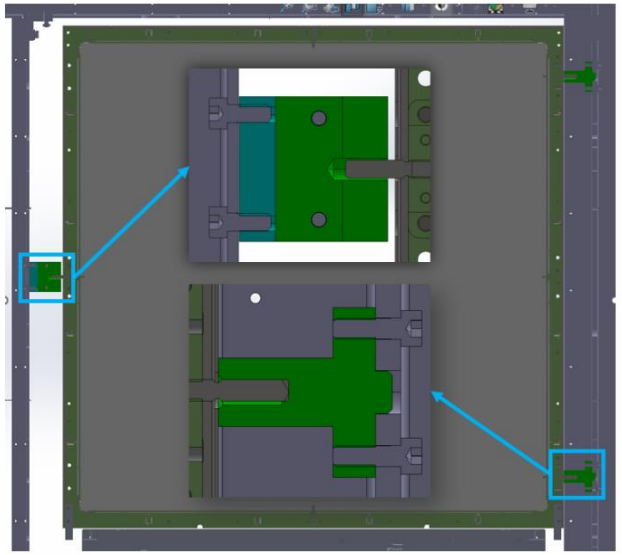
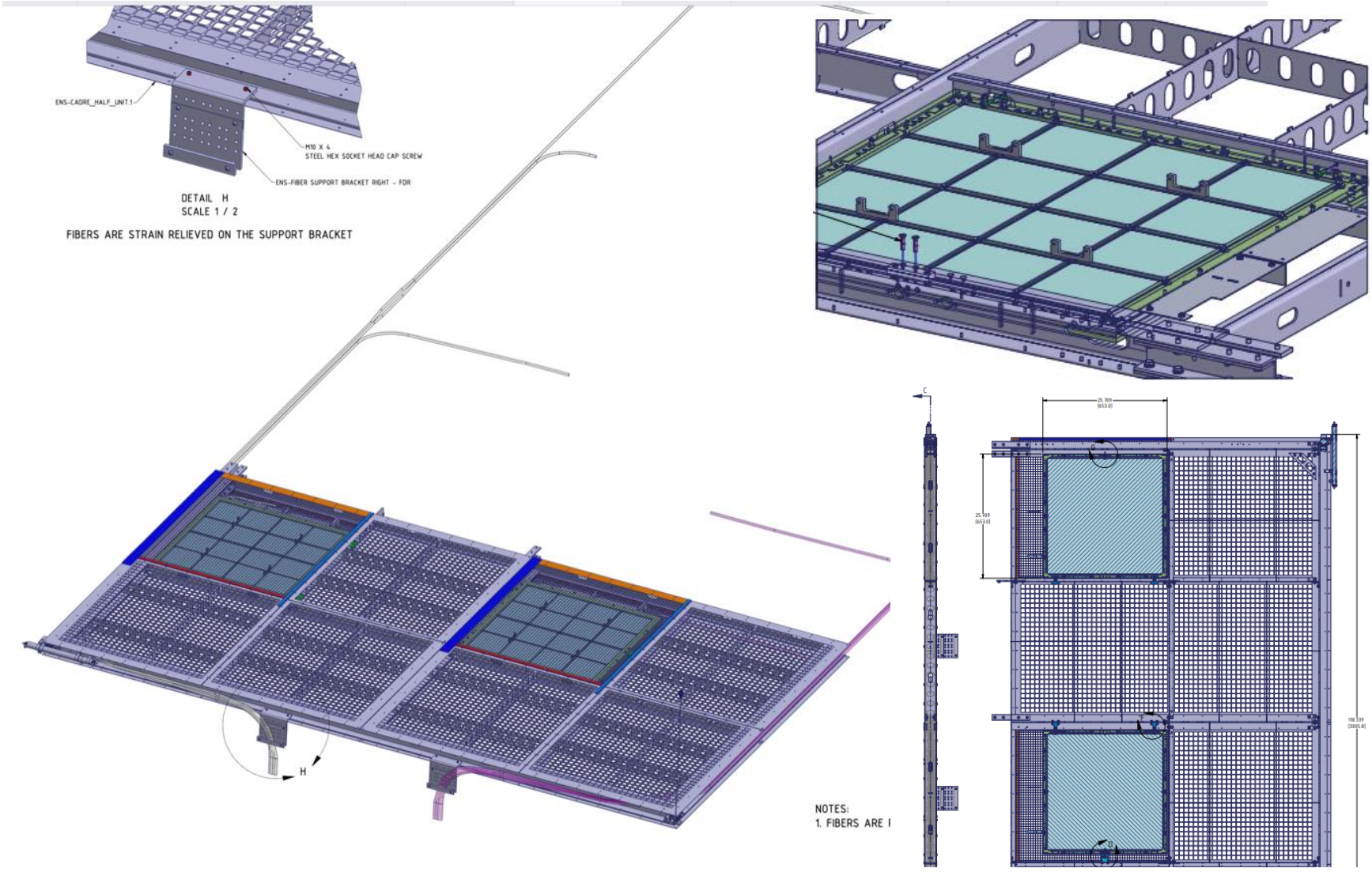


Figure 3: Perimeter Cathode Module Mounting Points (Left), Interior Cathode Module Mounting Points (Right)



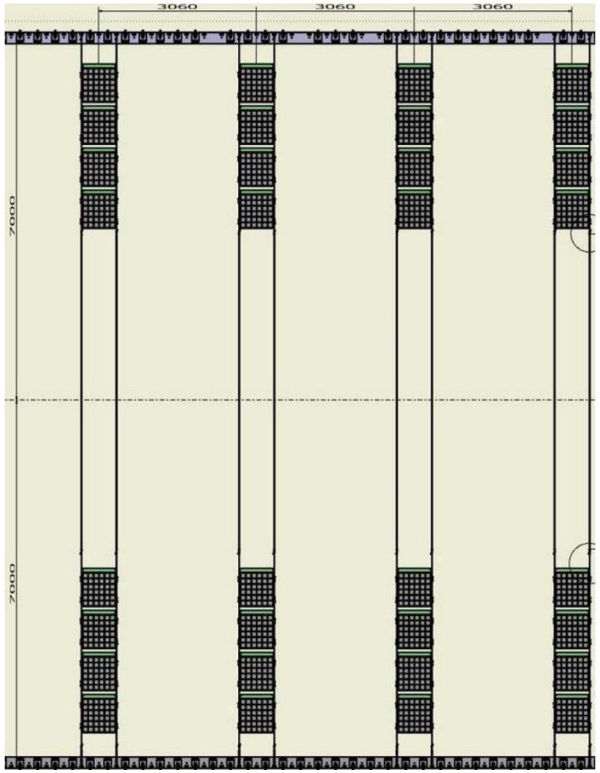


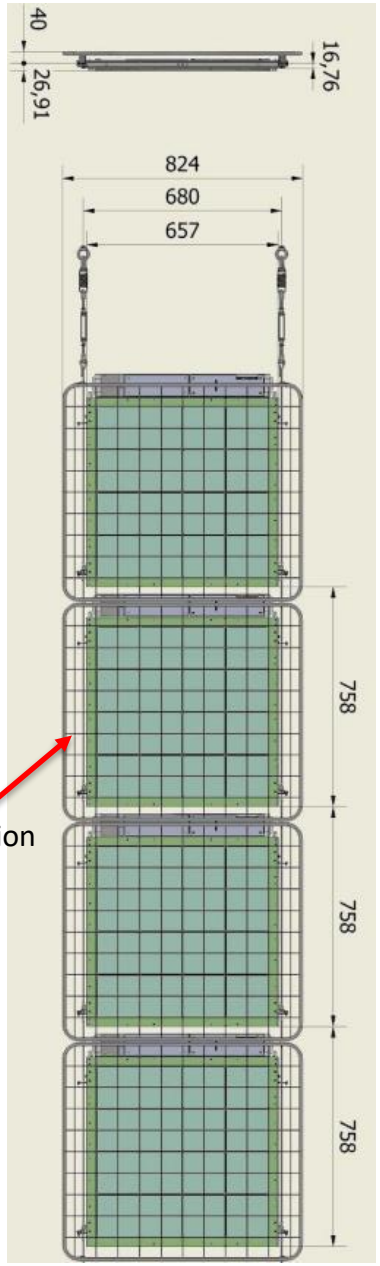
Module layout in cathode controlled in PDS/HV Interface control documents (https://edms.cern.ch/document/2619007/2)



Membrane mount

- PD modules are suspended in front of membrane wall.
- 2 stainless steel suspension lines anchored to membrane at top and bottom (M10 screw).

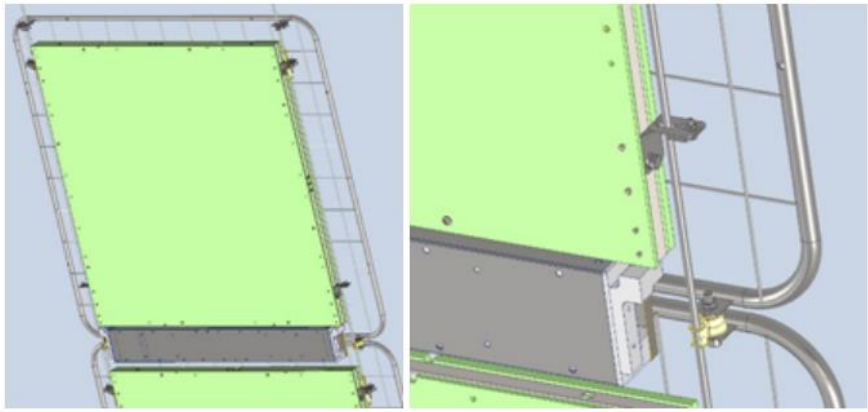




Module mounts to membrane suspension lines

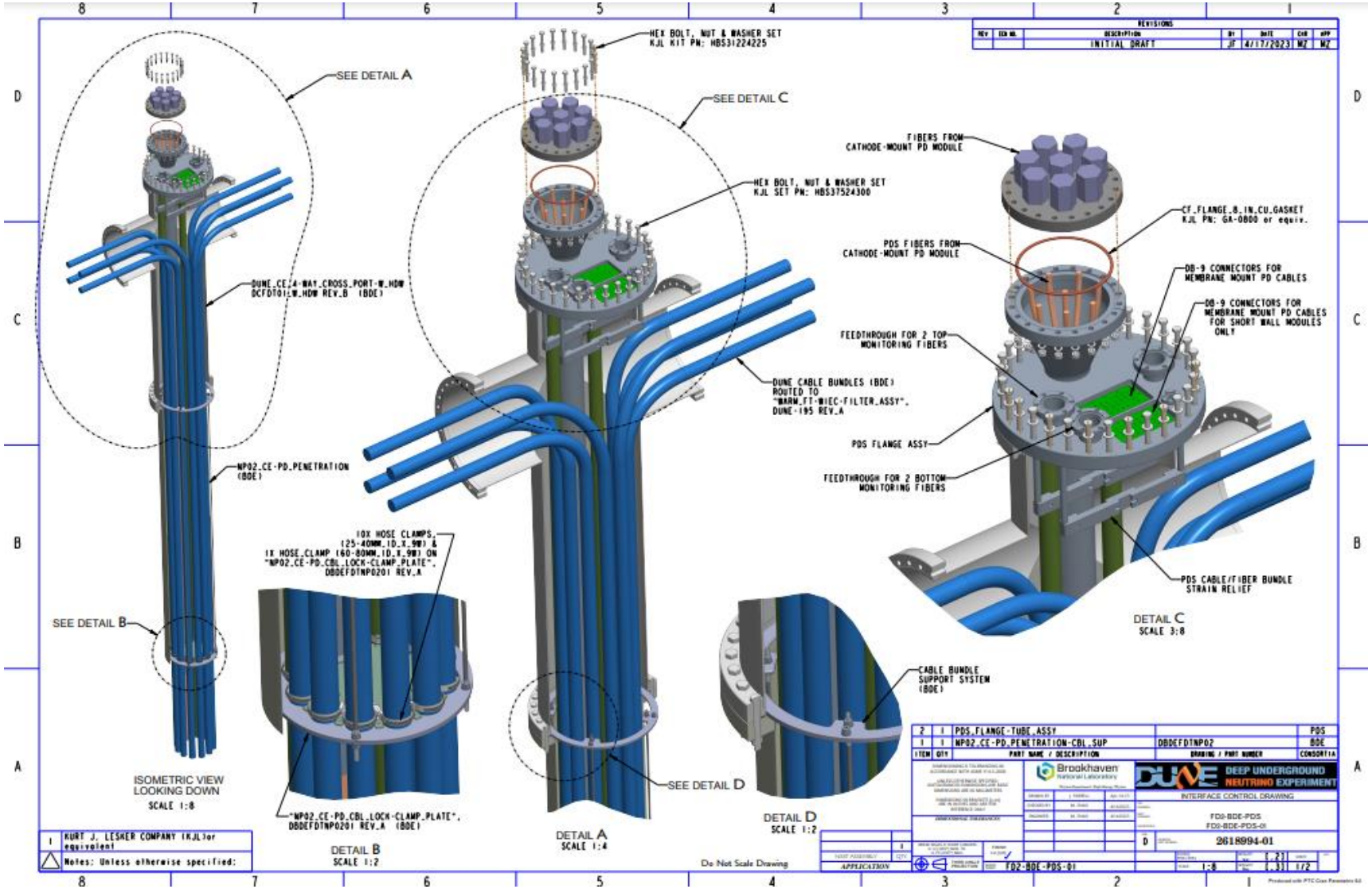
- Modules attach to suspension lines at 4 points using a single M5 screw for each support.
- Mounting system designed to address thermal expansion of module relative to suspension lines:
  - Upper supports carry weight, restricts motion in plane perpendicular to cable.
  - Lower supports allow motion along suspension line, restrict motion in plane perpendicular to cable.
- HV shielding meshes attach with similar supports.

Upper constraint.



Lower Constraint

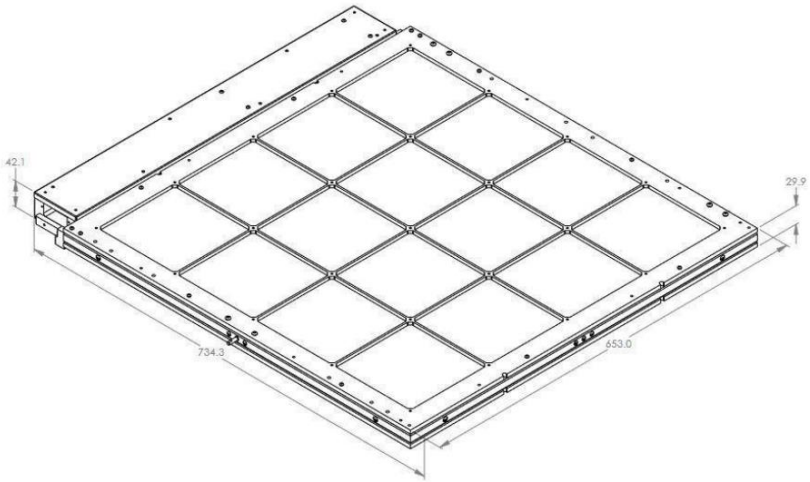
Shared BDE/PDS Crossing tube/cable/fiber routing

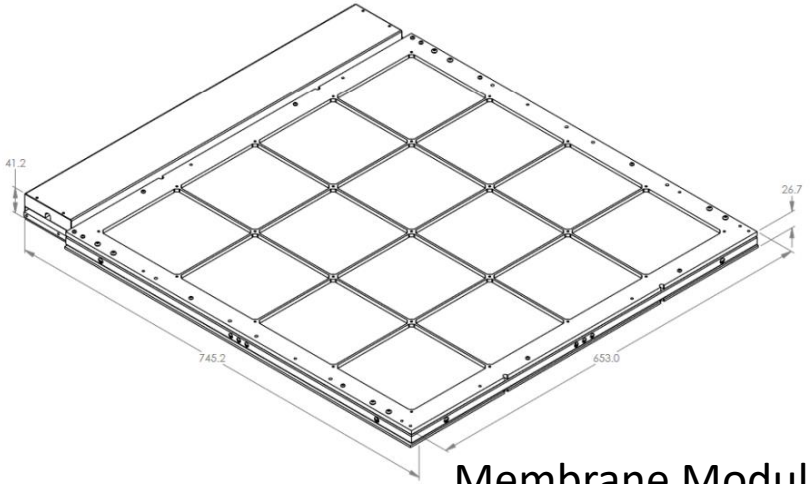


Module assemblies

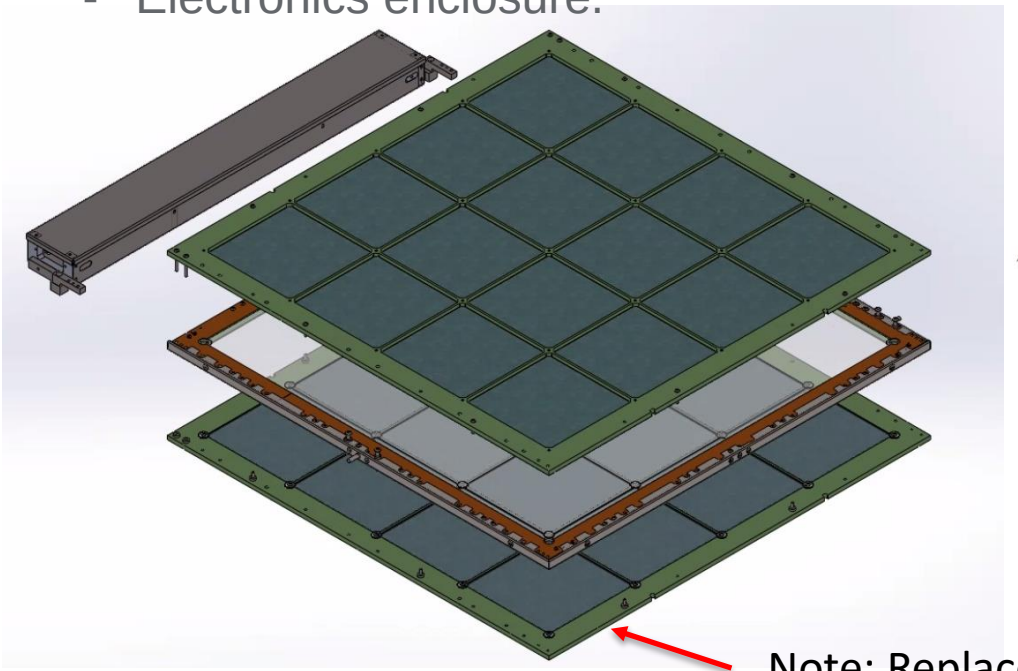
- PD modules are composed of 4 main components:
  - Core (SiPMs, WLS plate).
  - Filter frames (two, or one plus one backing plate for membrane module).
  - Electronics enclosure.

Cathode Module



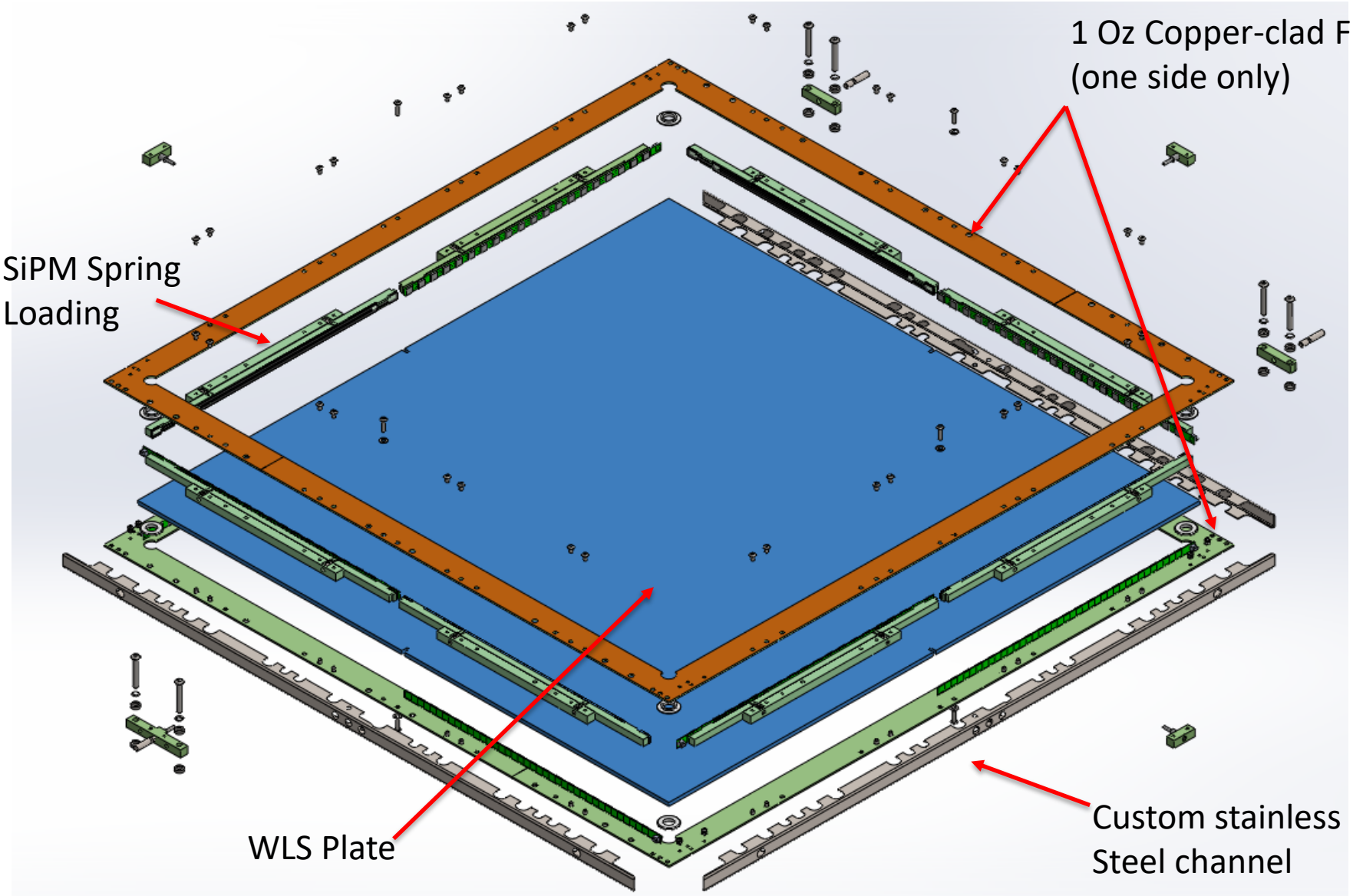


Membrane Module



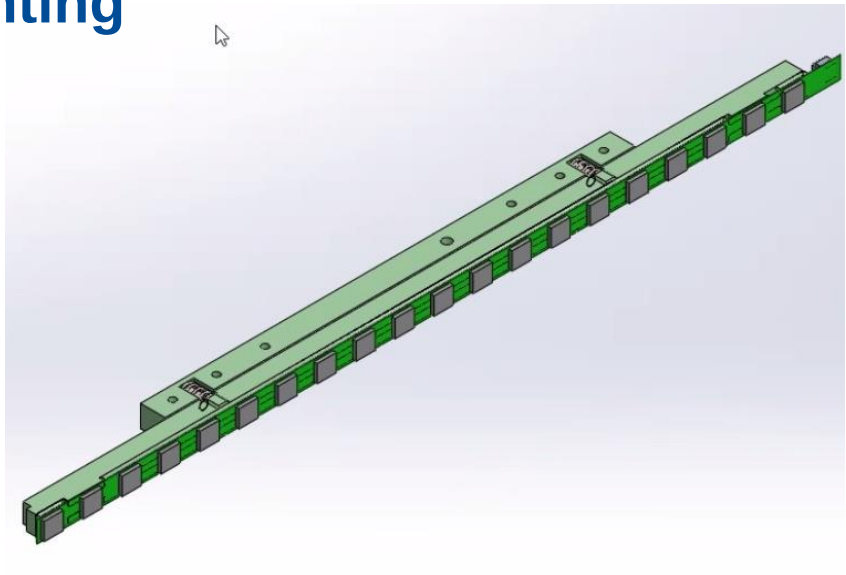
Note: Replaced with FR4 backing plate (Vikuiti lined) for membrane module

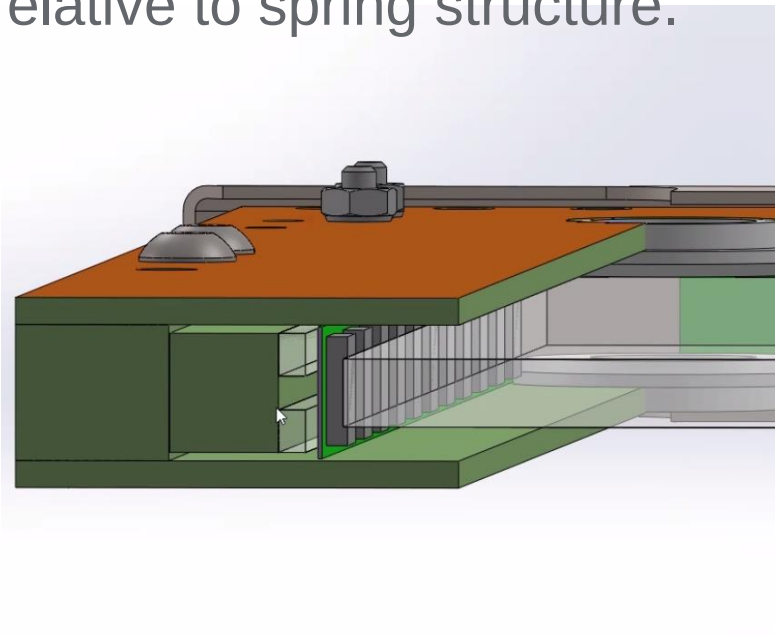
Core- Exploded view

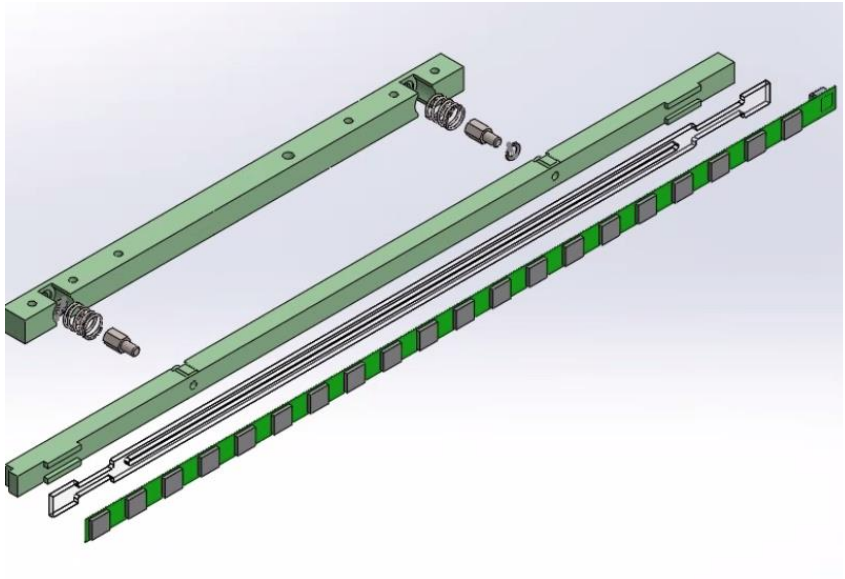


Core- Spring-loaded SiPM mounting

- 2 springs push SiPMs against WLS plate
- Designed to accommodate full relative WLS plate motion during cooldown (~6mm total)
- Acrylic shoe behind flexi PCB to manage contraction of PCB relative to spring structure.

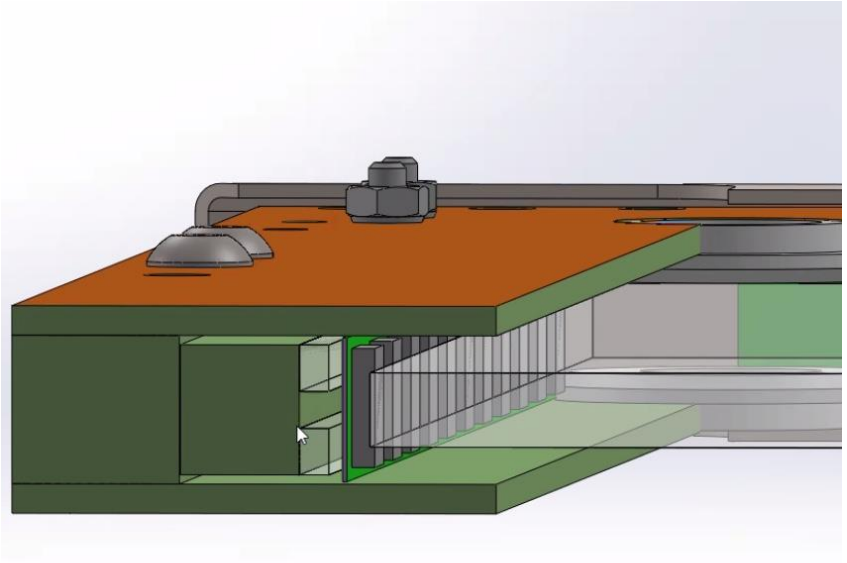


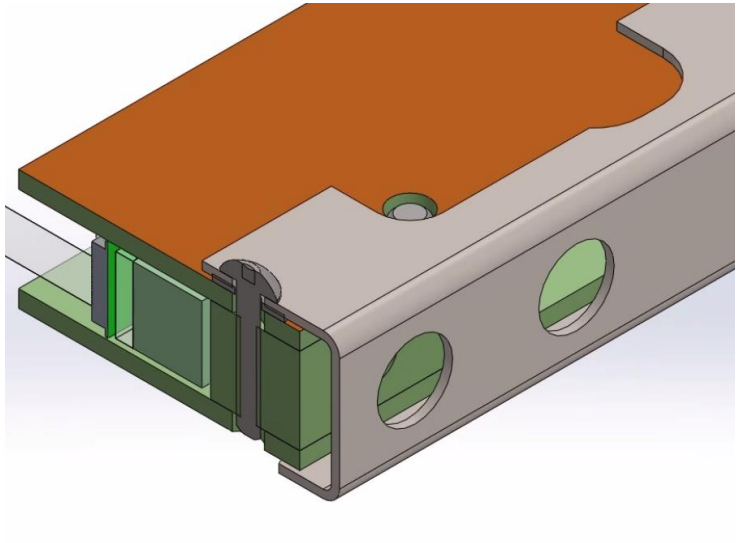


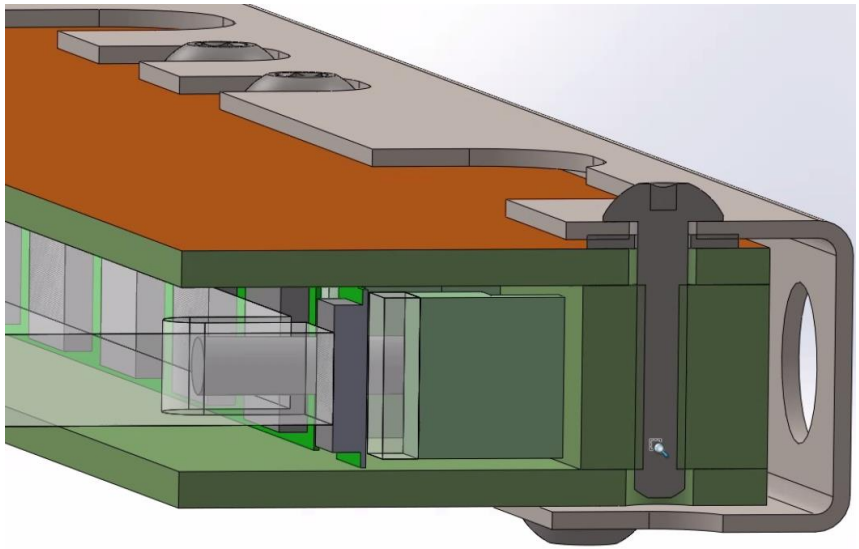


Core- Cathode HV breakdown protection

- 3-sided Faraday cage (single-sided copper-clad FR4, stainless steel backing channel) provides protection for SiPMs and cables.
- Connected to electronics box ground.
- Enclosure designed to protect SiPMs after thermal contraction of WLS plate.
- Validated by simulations at FNAL, BNL.

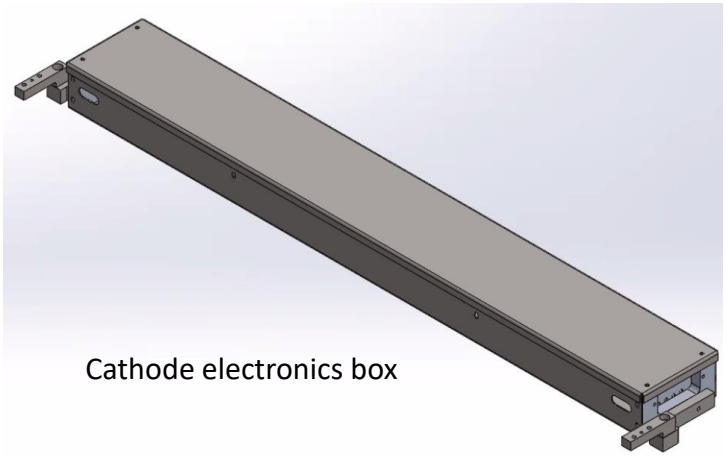




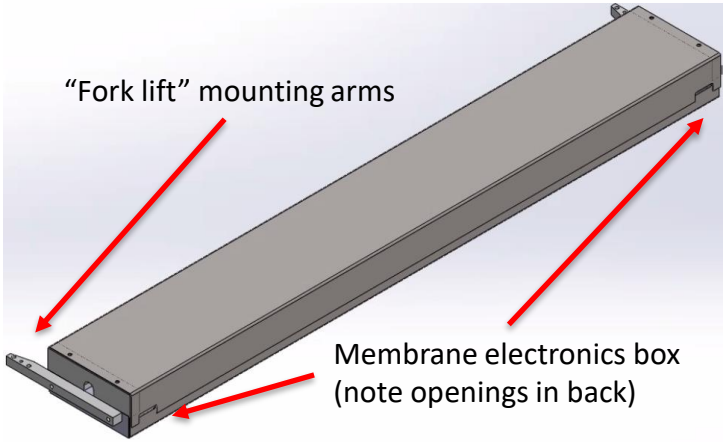


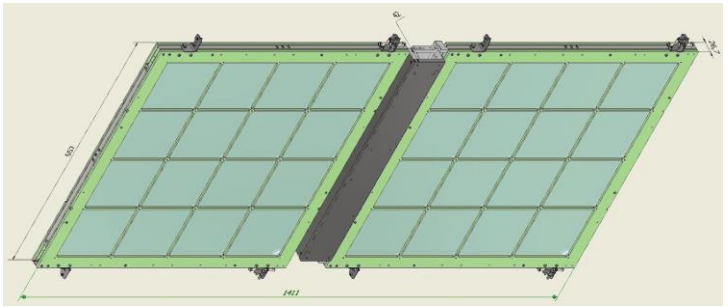
Electronics enclosures

- Folded stainless-steel sheet metal box.
- Top cover can be removed after assembly to allow electronics hookup following installation in cryostat.
- Extends module Faraday cage around electronics.
- Provides light shield around POF and SOF to protect module
- Baseline: Two membrane mount modules share one electronics enclosure, one box per membrane module (single-box membrane option still under review),



Cathode electronics box

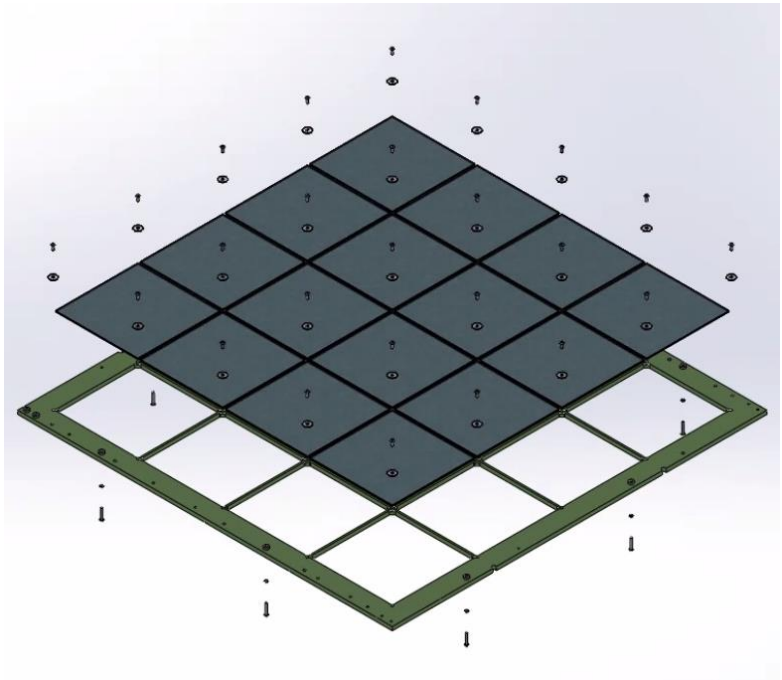


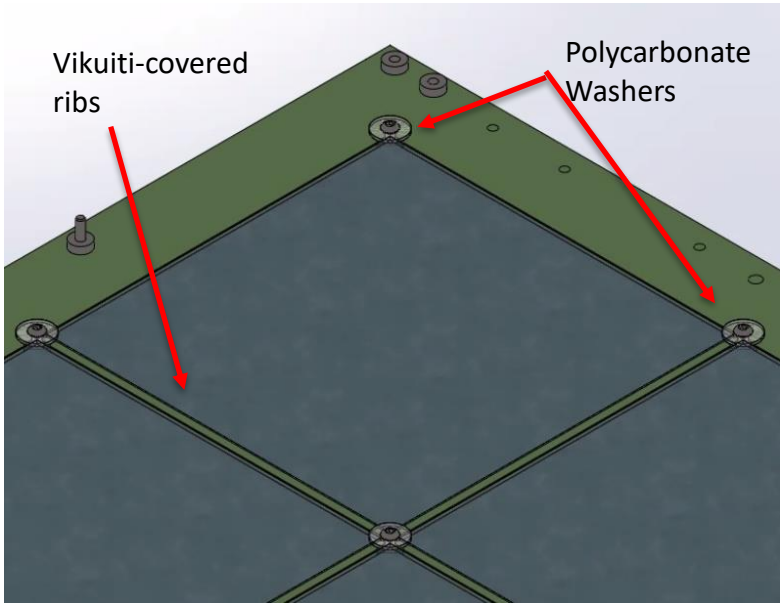


Membrane module shared electronics box

Filter Frame Assembly

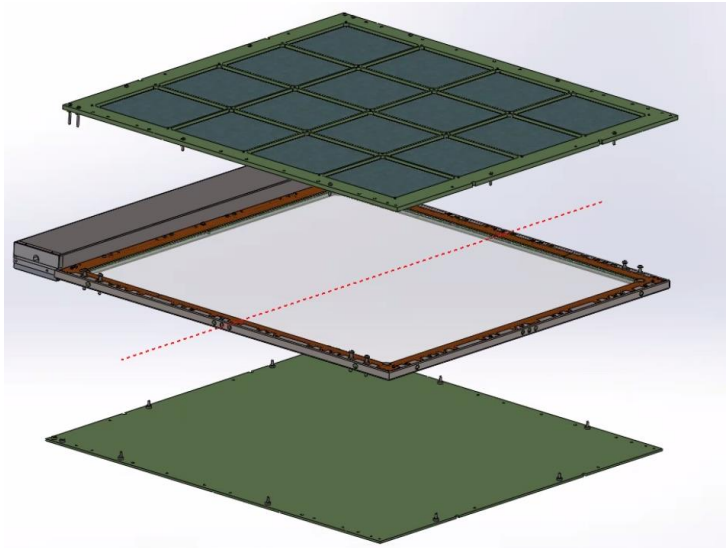
- Dichroic filters are supported in pockets in FR-4 G-10 frames (16 per frame).
- Held in place by polycarbonate washers with M3 screws.
- Assembly time is approximately 30 minutes per frame.
- Frame ribs covered with Vikuiti to increase light collection.
- Filters flush with inner surface of frame (optimize ARAPUCA effect).
- Rib height minimized to avoid light loss.



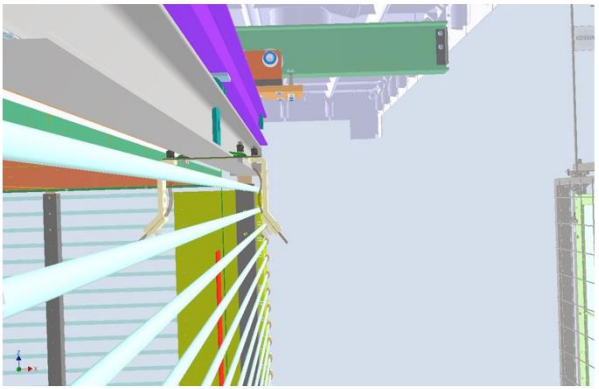


Shipping/ underground assembly plan

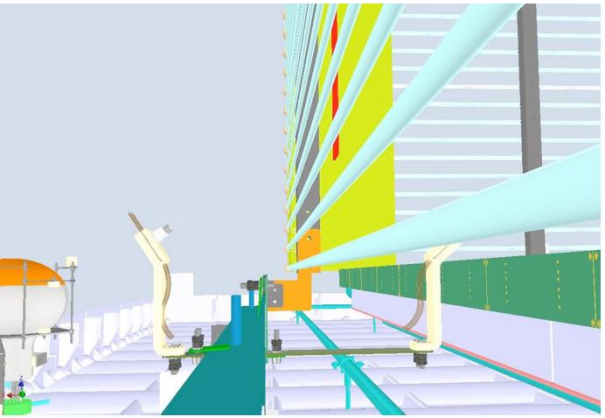
- PD modules were designed to be shipped in 3 pieces:
  - Core assembly (including SiPMs, WLS, electronics box, Faraday cage) pre-assembled at assembly sites.
  - Filter frame assemblies (or filter frame and backing plate for membrane module.
  - Dichroic filter plates
- Assembly at SURF will consist of:
  - Loading filters into frame (~ 30 minutes per frame.
  - Screwing frames to module core (~10 minutes per frame).



Monitoring system mechanicals



Top monitoring-system kit



Bottom monitoring-system kit

- For every X-ARAPUCA membrane column (44 total columns) two **monitoring-system kits** are installed at the top/bottom beams that support the field cage:
  - Top fiber with a 1-to-2 fiber bundle. Fiber end-points attached at the support structure pointing one fiber towards the cathode X-ARAPUCAs and the other one towards the membrane X-ARAPUCAs.
  - One long fiber down to the bottom connected to a 1-to-2 fiber bundle with the Fiber end-points attached at the support structure with the same configuration than for the top.
- Fibers are **routed** towards the flange: bottom fibers through the cryostat wall and top fibers through the cryostat top.
- Fibers are attached to the **flange**: 2 SMA feedthroughs are required per column (88 total feedthroughs).
- **Light source:** External pulsed UV-light system on a rack-mount light calibration module at warm temperature. FPGA based control logic unit coupled to an internal LED pulser module and an additional bulk power supply.

Monitoring-system kit installation in ProtoDUNE-VD

ProtoDUNE-VD flange

Possible fiber end diffusers

QA/QC/Manufacturing summary (Details in https://edms.cern.ch/document/2730720/2

- Remaining QA/Validation for mechanicals:
  - All major design decisions for the FD2 PDS mechanics have been taken.
  - Final PRR preparation (“Module 1”) modules to be fabricated in summer 2023 for autumn 2023 testing in NP02 cold box.
    - Minor changes for ease of fabrication implemented- no conceptual changes.
  - ProtoDUNE-II VD represents extremely valuable QA/Validation opportunity!
- Manufacturing plans under development.
  - Fabrication assembly sites selected (US for cathode, Spain for membrane).
  - Manufacturing/contracting will follow local procurement procedures in the US and Spain.
- QC testing planned in detail, described in QA/QC document.
  - Warm scans at fabrication sites prior to shipping.
  - All modules tested in LN2 cryogenic test stations (US and Spain).
  - Warm scan prior to installation in cathode/membrane mounting.
  - Final installation verification procedure (in-situ test).
  - All QC data stored in DUNE QC database.

Compliance Office Analysis Documents

- Analysis plan submitted to compliance office. https://edms.cern.ch/document/2883231/1
- Analysis report submitted to compliance office. https://edms.cern.ch/document/2883232/1
- All loads and deflections within reasonable safety factors
- Compliance office preliminary reply at https://edms.cern.ch/document/2883233/1

Deflection (mm)	Minimum	Average	Maximum
Horizontal Mounting, Cold Load Condition	0	0.2	0.7
Vertical Mounting, Warm Load Condition	0	0.01	0.025
Horizontal Mounting, Warm Load Condition	0	0.33	1.1

Table 9 - Results

Stress (MPa)	Minimum	Average	Normalized Maximum *(Loading Local Maximum)*	Safety Factor $(\frac{Directional\ UTS}{Shear\ Stress})$
Horizontal Mounting, Cold Load Condition	4.00E-04	3.40E-01	4.5	14.4
Vertical Mounting, Warm Load Condition	1.70E-06	7.40E-02	1.2	137
Horizontal Mounting, Warm Load Condition	8.10E-05	0.7	5.62	11.5

Analysis results for module deflections in cathode support

Analysis results for membrane mount supports

Element	Acceptable Mass (kg)	SF
Eye Bolt	230	>4
Shackles	250	>4
Straining Screw	300	>5
5mm Rod Bar	1344 (672MPa)	>24
12/10mm dia. Tube	968 (275MPa)	>17
Tested: 2-pt. welded rod bar	100	1.83
Final: 4-pt. welded rod bar	200	3.67

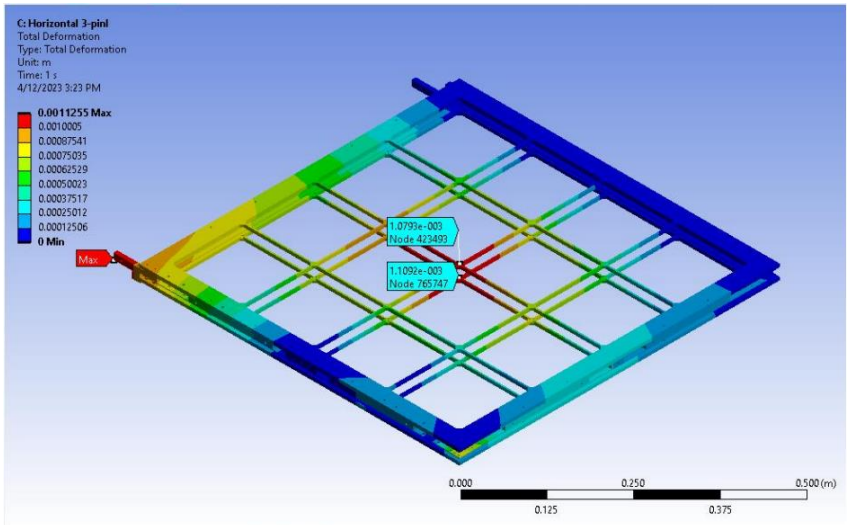


Fig. 35: Deflection: Warm condition, horizontal loading

Compliance Office Analysis
Documents PRELIMINARY assessment

6. CO Conclusions for the Final Design Review

The structural analysis of the Photon detector system for the DUNE Far Detector 2 (FD2-PDS) has been provided by the lead engineers. Due to the short amount of time available before the review, the documents received have been only **PRELIMINARILY assessed**.

The verifications of the structural components are considered satisfactory, considering applicable design codes and project requirements. Nevertheless, a more in-depth analysis of the engineering documents is necessary and shall be performed in the next month, resulting in a final validation.

The main outcomes of the preliminary review process are:

- The components of the PDS were verified for the load cases defined in the analysis plan.
- The strength of the structure and the connections were verified, and appropriate safety factors were obtained.
- The utilization ratios are within the acceptable limits for all structural elements.

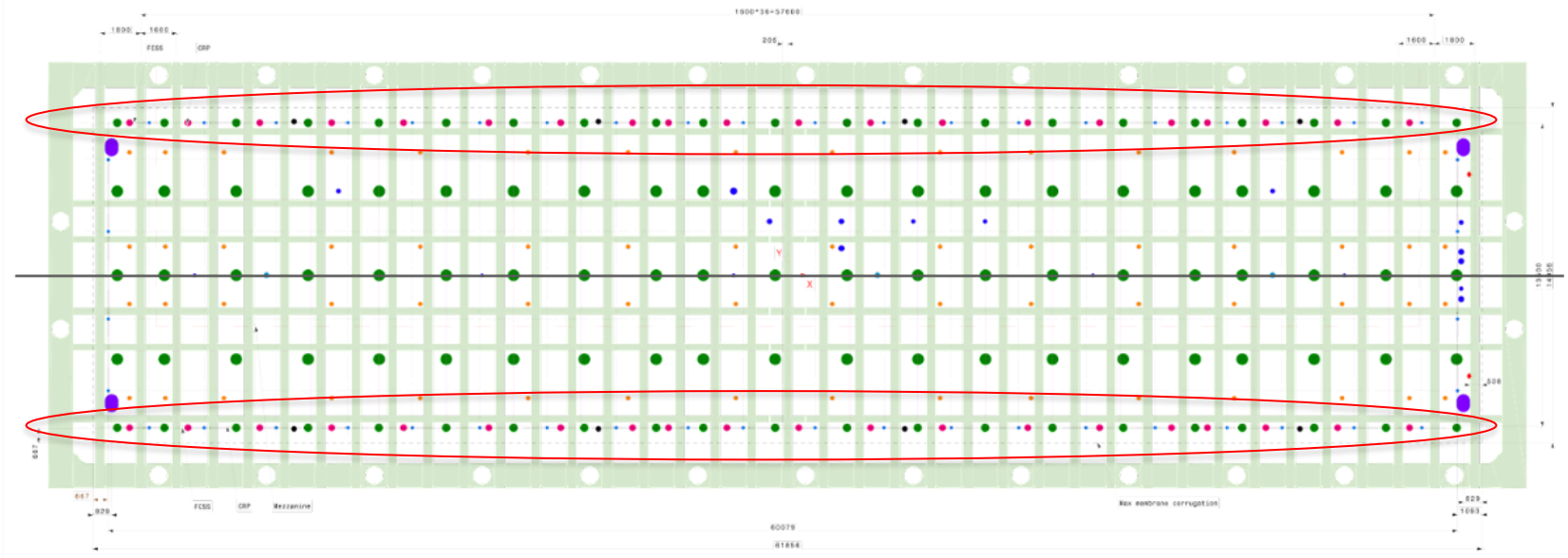
Conclusions

- Extensive testing in the NP02 cold box and Module 0 have resulted in a well-proven mechanical system.
- Multiple phases of design evolution and internal reviews have led to an easy to assemble, reliable module design.
- Manufacturing and QC plans are well advanced and reasonable.
- Engineering analysis show that the support systems are reliable and meet required safety factors.
- The PD mechanical system is well advanced and ready to prepare for the Production Readiness Review.

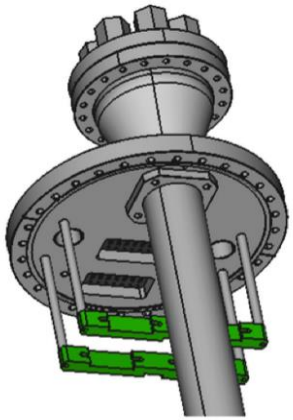
Backups

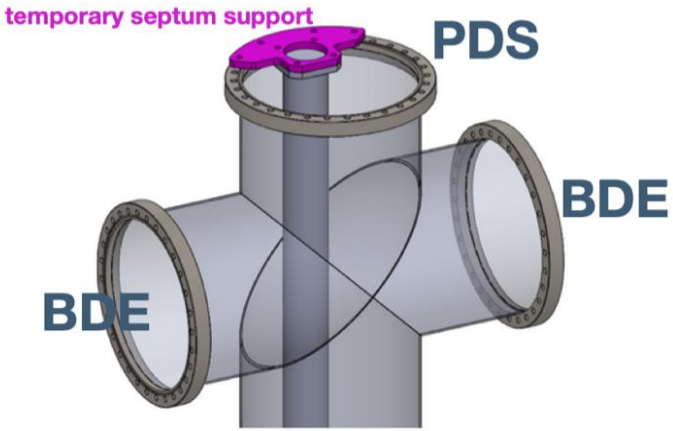
PDS Port Assignments

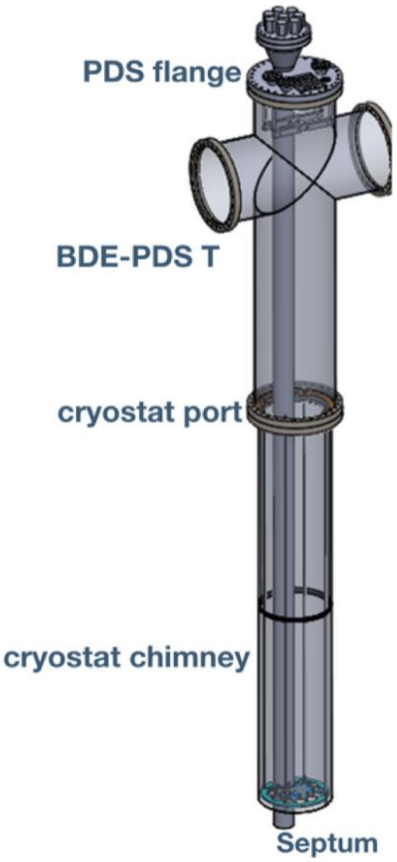
Pos.	Diameter [mm]	Quantity	Description
1	Ø200	64	CRP Supports
2	Ø526	63	Top Center CRP Cables
3	Ø381	42	Top Side CRP Cables
4	Ø304.8	40	Bottom CRP Cables + PDS
5	Ø250	2	High voltage
6	Ø250	8	Spare and Laser
7	Ø800	4	Manholes
8	Ø150	48	FC Supports
9	Ø250	4	CALCI NtS



FD2 PDS flange/cable/fiber routing







Consortium-Held Requirements (I, General)

TDR ID	PD Subgroup	Specification number	Spec. or Req.?	Name	Primary Text	Value	Status
General							
	Cathode-mount PD						
		1	R	Electric Isolation	Cathode-mounted modules must be electrically isolated - no copper cable connection to/from TPC cathode (at HV)		Met
		2	R	Double sided	Light sensitive areas facing up and facing down must be provided for light collection from upper LAr volume above central cathode and from lower Volume below cathode		Met
	Membrane-mount PD Module						
		1	R	Electric Isolation is NOT required for membrane modules	Membrane modules can be connected with copper cables.		Met
		2	R	Single sided	Light sensitive areas facing inward to the active LAr volume of the TPC - through Field Cage		Met
	Monitoring/Calibration						
		1	R	LED Flasher/Diffuser system	A Monitoring and Photosensor/Electronics response calibration system based on LED Flasher (warm) and Diffuser (cold) equivalent to FD1 PDS is required	Allow for monitoring of SiPM gain, stability, and timing integration.	Met

Consortium-Held Requirements (ii, Integration, cathode mount)

TDR ID	PD Subgroup	Specification number	Spec. or Req.?	Name	Primary Text	Value	Status
Integration							
	Cathode-mount PD						
		1	R	Cathode-mount Module dimension	Module must fit inside mechanical envelope in cathode-module	maxima: 740mm x 650mm x 50mm (inside	Met
		2	R	Cathode-mount Module weight	Cathode-module shape deformation must remain within bounds set by HVS. Cathode-mount PD module weight must not induce cathode-module deformation	Module mass <15 kg, goal 12 kg (Dry) ==> Wet <10kg, goals 8kg (buoyancy in LAr)	Met
		3	R	Maintain cathode-to-PD clearance at LAr temperature	The cathode-mount PD fiber system must not limit the separation of the cathode during thermal expansion/contraction. The specification is driven by engineering to ensure no damage occurs.	>2mm (at least 1mm per side including all tolerances)	Met
		4	R	Faraday shield protection of sensors and electronics for cathode-	Faraday shield protection of sensors and electronics must be implemented to minimise	SiPMs contained inside 3-sided Faraday cage to	Met
		5	R	Cathode-mount modules position on the cathode plane	No cathode-mount modules must be positioned at the edges of the cathode plane to minimise	>60cm clearance from cathode edges (and any	Met

Consortium-Held Requirements (iii, Integration, membrane mount)

TDR ID	PD Subgroup	Specification number	Spec. or Req.?	Name	Primary Text	Value	Status
	Membrane-mount PD Module						
		1	R	Mechanical holding structure for Membrane-mount modules (behind FiedCage)	Independent holding structure supported by existing anchoring points of the membrane cryostat for Membrane-mount modules (behind		Met
		2	R	Membrane-mount modules position behind Field Cage	Membrane-mount modules must be positioned at vertical distance from cathode plane, behind	> 2.5 m vertical distance from cathode plane	Met
		3	R	Ground mesh in front of membrane-mount modules	Ground mesh must be positioned in front of membrane-mount modules	mesh should make no EF> 30kV/cm	Met
	Cathode- and Membrane-						
		1	R	PD Module deflection	Module frame must not deflect under load and at any point dry or immersed in LAr.	Module deflection <5mm under standard	Met
		2	R	Cable conduit for fibres and cables	modules fibers and cables must use conduits shared on the cryostat membrane with TPC bottom drift electronics, with no mutual interference		Met

TDR ID	PD Subgroup	Specification number	Spec. or Req.?	Name	Primary Text	Value	Status
	Monitoring/Calibration						
		1	R	LED "warm" fiber jacketed	LED fiber at the cryostat top	Teflon or other plastic	Done
		2	R	LED "cold" fiber jacketed	LED fiber inside the cryostat	Protects fiber (teflon or	Done
	`	3	R	LED fiber Optical feedthrough	LED fiber Optical feedthrough must be located at PDS signal flange.	Multiple feedthroughs will be installed	Done
		4	S	LED Calibration Module	LED flash module supplies 12 diffusers	12-ch form factor combines 12 light	Done

Consortium-Held Requirements (iv, Design)

TDR ID	PD Subgroup	Specification number	Spec. or Req.?	Name	Primary Text	Value	Status
Design							
	PD Modules						
		1	S	Material selection - cryo-resilient	materials already selected for FD1 PD modules (XARAPUCA super-cell) should be used for FD2 PD modules (XARAPUCA mega-cell) where possible. Main components: mechanical frame, dichroic filter, WLS-1 film,		Done
		2	R	XARAPUCA mega-cell design and max photo-collection efficiency	New XARAPUCA mega-cell design should maximise photo-collection efficiency. Minimal dead space or shadow by mechanical frame, maximal exposed surface of dichroic filter area and WLS plate,		Done
		3	S	Materials selection for Mechanical Frame	FR-4 G-10 and Stainless steel alloy 304 shall be the primary structural materials for PD	Structural material FR-4 G-10 or Stainless	Done
		4	R	FR-4 G-10 Warp Plane Alignment	specified as to the warp(glass-fiber mat) plane orientation to allow better thermal expansion control	aligned to mose sensitive expansion plane	Done
		5	S	Stainless steel hardware	All PD fasteners shall be stainless alloy 18-8 or 304 unless otherwise specified	Stainless alloy 18-8 or 304 for fasteners	Done
		6	S	Anti-vibration fasteners	Lock washers (where possible), lock-tight thread, lock adhesive shall be used to protect against vibrational loosening	Thread locker or adhesive required for all fasteners.	Done
		7	S	Dichroic filters cutoff	Dichroic filters cutoff optimised for pTP emission stoctrum transmission and WLS-2 doped PMMA emission spectrum reflection inside the supercell.		Done
		8	R	Dichroic filters refraction index	Dichroic filters refraction index optimised for liquid Ar to improve light collection efficiency		Done
		9	R	Optical contact WLSplate-to-SiPM	SiPM mounting must be dynamic to preserve SiPM location through relatice material contraction during cooldown to 87 K.		Done
		10	R	Non-conductive high reflective layer	mechanical frame must be coated with non-conductive high reflective layer - VIKUITI ESR foils should be used to improve light collection efficiency		Done

Consortium-Held Requirements (v, Fabrication, Installation)

TDR ID	PD Subgroup	Specification number	Spec. or Req.?	Name	Primary Text	Value	Status
Fabrication							
	PD Modules						
		1	R	Assembly Clean Room	PD module assembly shall be conducted in a clean assembly area	Class 100,00 (ISO 8)	Met
		2	S	Environmental control/Temperture	PD module assembly shall be conducted in a clean assembly area	<30 Deg. Celsius	Met
		3	R	Environmental control/Humidity	PD module assembly shall be conducted in a clean assembly area	RH between 15 and 85%, dewpoint <9C	Met
		4	R	Environmental light exposure.		Filtered lighting >400nm for all integrated exposures up to 2 weeks.>520nm for longer exposures	Met

TDR ID	PD Subgroup	Specification number	Spec. or Req.?	Name	Primary Text	Value	Status
Installation							
	Modules						
		1	R	Self-fixturing module installation	No external fixtures shall be required to install PD modules into cathode modules in their final orientation	No installation fixtures required	Met