The DUNE FD1-HD HV System: overview, status and plans

Francesco Pietropaolo (CERN)
on behalf of the HVS Consortium

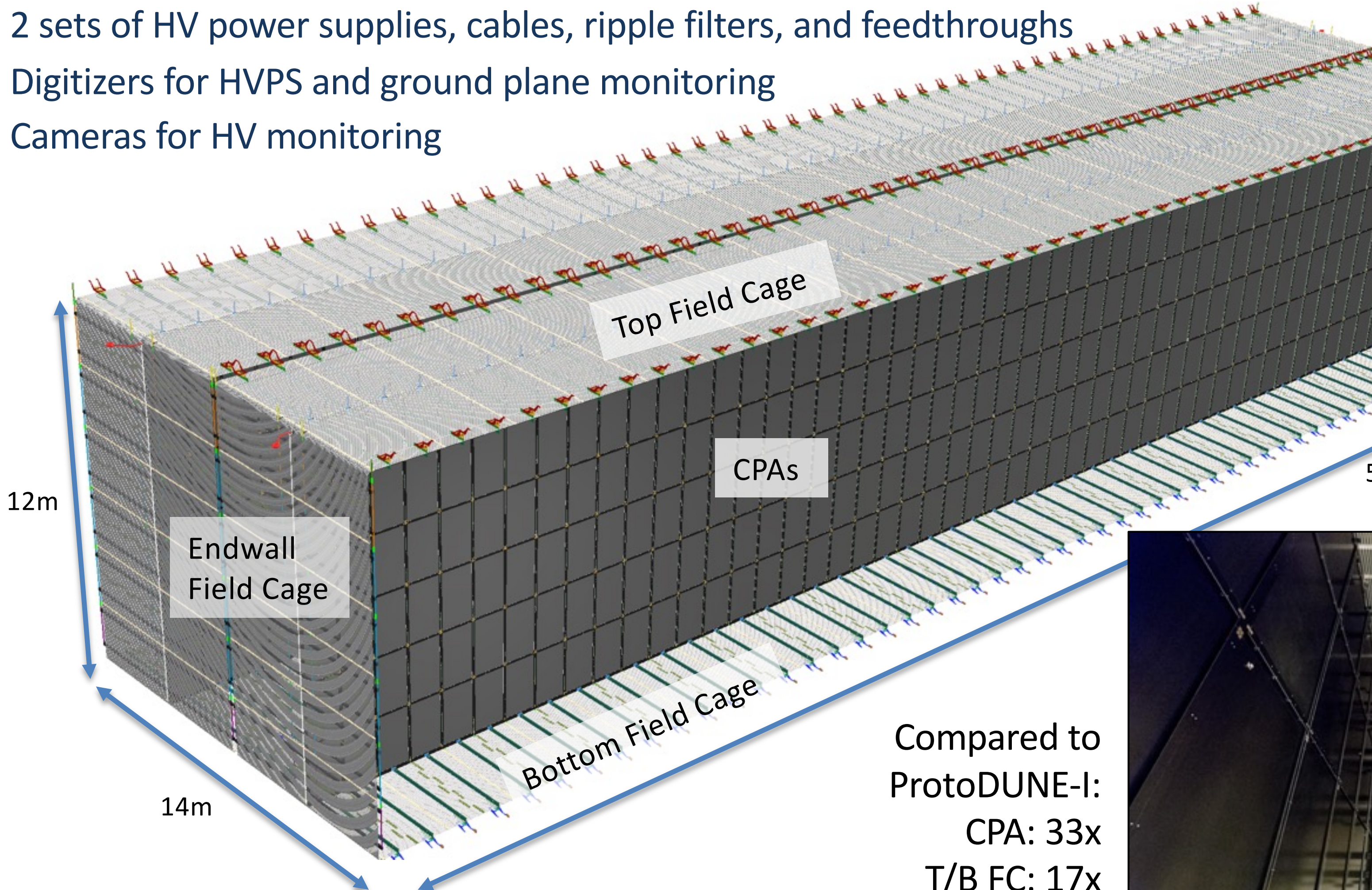
HVS Final Design Review, October 12th, 2022

Outline

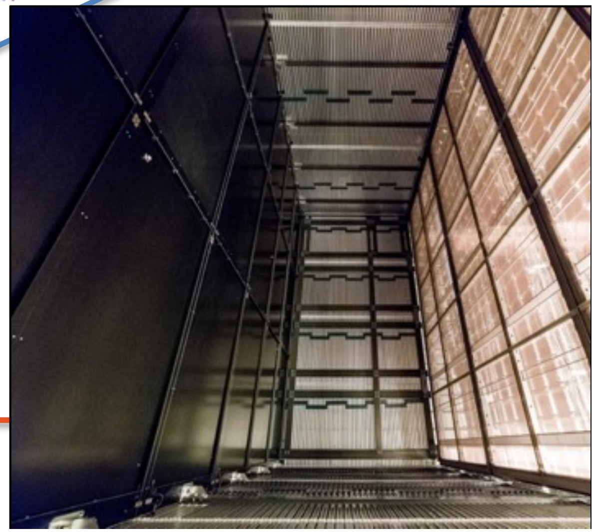
- FD1-HD HVS design update:
  - System overview
  - Evolution since the last PDR (June 2020) and TDR
  - Value engineering upgrades
  - Lessons Learnt from Ash River tests and ProtoDUNE-II installation
  - Structural Safety analysis
  - QA/QC plans, shipping/installation strategy, schedule
- Plans toward Production Readiness Reviews

HVS Consortium Scope for the FD1-HD

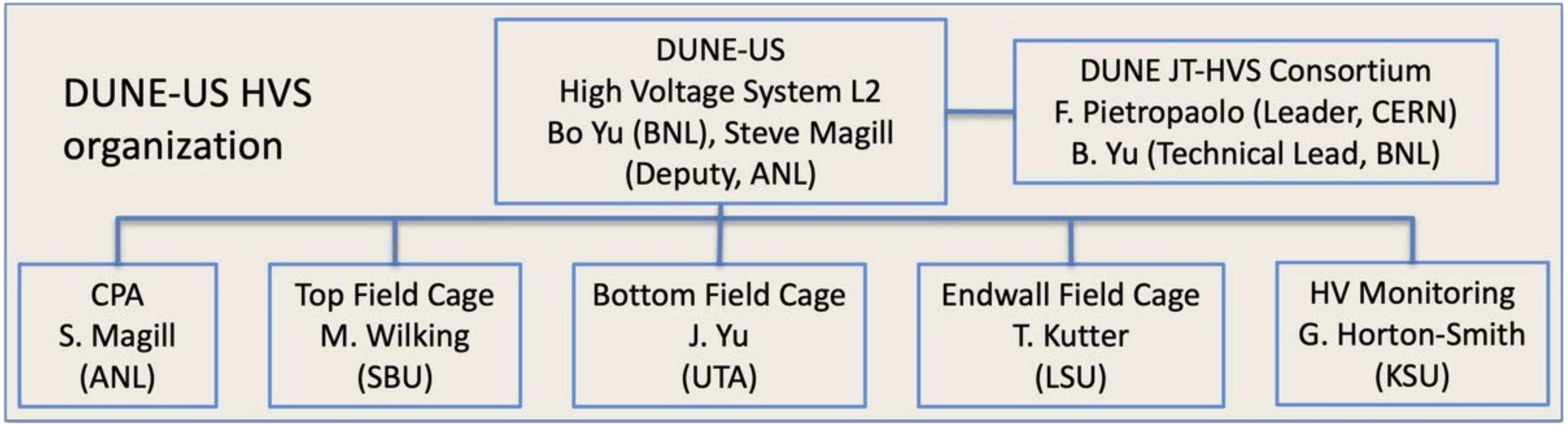
- Design, fabricate, test and assemble:
  - 100 CPA resistive panels forming two cathode arrays (1400m^2)
  - 100 top + 100 bottom field cage modules, 48 End Wall field cage modules (2000m^2)
  - 2 sets of HV power supplies, cables, ripple filters, and feedthroughs
  - Digitizers for HVPS and ground plane monitoring
  - Cameras for HV monitoring



Compared to
ProtoDUNE-I:
CPA: 33x
T/B FC: 17x
EW FC: 4x



HVS Institutional Responsibilities (FD1-HD)



Institutions	Deliverables
CERN	System Design, Requirements, R&D, Data Analysis, HV delivery installation and Monitoring, FC profiles, CPA resistive panels
ANL	System Design & Analysis, QA/QC, CPA production and installation
BNL	System Design & Analysis, Project Management, Interfaces, Cold Cameras
KSU	HV Bus & Interconnects, GP Monitoring System
LSU	Resistive Divider Boards, FC Termination Boards, End Wall Field Cage Production & Installation
SBU	Top Field Cage Production & Installation
UTA	Bottom Field Cage Production & Installation
W&M	CPA Production & Installation

Final Design Review charge questions

- The committee should consider:

ID	Description
1	How design choices satisfy the requirements
2	The completeness of the documentation of mechanical specifications, including 3D model and the 2D drawings for standard and custom components as well as the Compliance Office evaluation focusing on both safety and the proper application of design codes and standards.
3	The completeness of the documentation of electrical specifications, including system schematics, drawings, connections, and grounding details.
4	Whether transportation and installation plans are mature enough to provide assurance that the HVS components, as currently designed, can be safely transported and installed within the detector.
5	Plans for the further testing of HVS components in ProtoDUNE-II and whether lessons learned from ProtoDUNE-SP and other prototypes have been incorporated within the current design.
6	If draft documentation detailing plans for procurement, manufacturing, quality control, and part identifiers exists at a sufficient level of maturity for this stage of the design
7	If project planning materials including interface documents, risk assessments, schedules, and cost estimates exist at a sufficient level of development for this stage of the design.
8	Whether recommendations from previous reviews have been appropriately addressed.

- The HVS consortium believes that all questions have been fully addressed

Charge Question #1

HVS high level requirements (FD1-HD)

ID	Description	Spec (Goal)
SP-FD-1	Minimum drift field	250 V/cm (500 V/cm)
SP-FD-11	Minimum drift field uniformity	< ±1% [in 99.8% volume]
SP-FD-12	Cathode HV power supply ripple contribution to system noise	< 100 electrons
SP-FD-17	Cathode resistivity	> 1MOhm/sq. (1GOhm/sq.) [upper limit 10 Tohm/sq.]
SP-FD-24	Local electric field	<3.0 kV/cm (with specific exceptions to be tested separately (e.g. HV feed through)
SP-FD-29	Detector uptime	> 98% (> 99%)
SP-FD-30	Individual detector module uptime	> 90% (> 95%)
SP-HV-1	Power supply stability	> 95% uptime
SP-HV-2	Provide redundancy in all HV connections	Two-fold (Four-fold)

- No changes in the requirements list were requested since the 2020 PDR.
- Mostly fulfilled by ProtoDUNE phase-I.
- Confirmation expected from ProtoDUNE Phase-II assembly and operation.

HVS Electrical Design Specs

1	HV power supply ripple specification	<1E-5
2	HV cable/ low pass filter attenuation factor specification	<5E-4 in CE pass band
3	HV filter series resistance	<127MOhm
4	HV feedthrough test voltage in LAr	>250 kV
5	Resistive divider board resistor value	2 parallel of 5GOhm
6	Resistive divider board resistor value tolerance	+/-1%
7	Resistive divider board varistor resistance @ 1.5kV in LAr	>100GOhm
8	Resistive divider board varistor conduction voltage	>1.7kV
9	FC termination step down resistance, top/bottom modules	3750MOhm
10	FC termination resistance, top/bottom modules	227MOhm, +0/-20MOhm
11	FC termination step down resistance, endwall modules	625MOhm
12	FC termination resistance, endwall modules	38MOhm, +0/-4MOhm
13	Nominal FC termination bias voltage	-273V
14	Maximum resistance between any two points on the HV bus	<6 MOhm
15	maximum contact resistance to CPA resistive surface	<1GOhm
16	HVPS voltage and current digitization rate	>= 10 kHz
17	GP current digitization rate	>= 10 kHz

- All fulfilled by present design and validated by ProtoDUNE

HVS Mechanical Design Specs

1	Cathode array flatness	
1.1	Along drift direction, absolute	< +/- 10mm
	Along drift direction, relative misalignment between modules	< +/- 5mm
1.2	Along beam direction	< +/- 10mm, no gap > 15mm
1.3	Along vertical direction, absolute	< +/- 20mm
	Along vertical direction, relative between modules	< +/- 5mm
2	Field cage module	
2.1	Length	hold 57 profiles @ 60mm pitch, no interference with APAs, CPAs, and CEs in there installed positions
2.2	Width	2330mm +/- 5mm for middle rows
2.3	FC profile offset from active volume	>40mm
2.4	Field cage flatness, global	< +/- 20mm
	Field cage flatness, local	< +/- 10mm
2.5	Field cage profile placement accuracy along drift direction	
	absolute	< +/- 5mm
	relative between profiles	< +/- 2mm
2.6	Field cage profile placement accuracy normal to FC plane	
	Absolue	< +/- 10mm
	relative between profiles	< +/- 3mm
	Along the profile	No physical interference with neighboring module; maximum gap width with neighboring module <20mm
3	CPA/EWFC profile bending radius	
	maximum	flat flange face of profile is >40mm away from the TPC active volume
	minimum	> 50mm, or <30kV/cm surface E field
4	CPA panel to panel warm envelop clearance	5mm
5	CPA FSS outer edge offset from FC profiles	>10mm <40mm

- Fulfilled by present design: lessons learnt from ProtoDUNE applied
- Final validation with ProtoDUNE phase-II

Charge Question #8

Recommendations from last PDR (2020)

- Most recommendations (10/12) properly addressed
  - Solutions documented and incorporated into present FD1-HD and ProtoDUNE phase-II HVS designs
- Two remaining open issues
  - Validation of the EW installation procedures: final Ash river trial (row 25) planned in the next few months.
  - Removal of bottom GP requiring detailed definition of interfaces with TC, Cryo, CALCI: this is in progress and will be defined most likely within next January.
- PDR formally approved and closed by FD1-TC and FDC-DPD.

Fermilab Long Baseline Neutrino Facility, DUNE & CERN Neutrino Platform			
Document EDMS identifier: 2774172		Created: 24-Aug-22 Last Modified: 24-	Rev. No.: 1.0

FD1 HV PDR Closeout

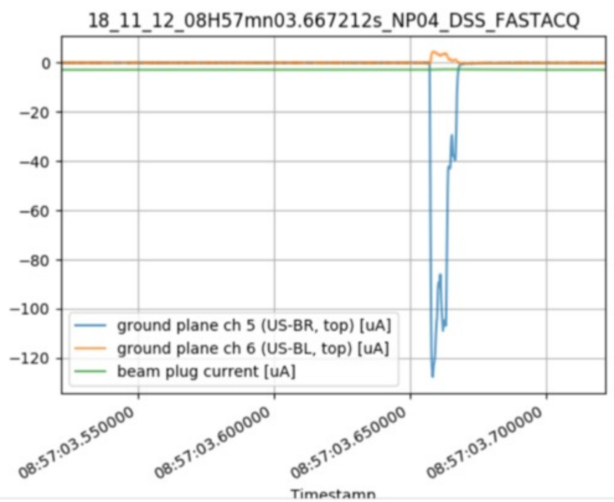
Abstract

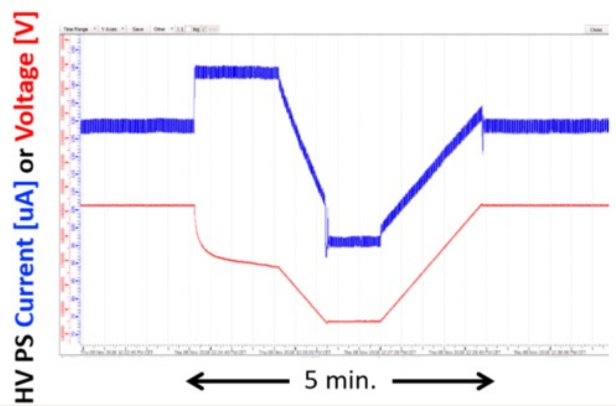
This document describes actions resulting from the Preliminary Design Review (PDR) of the High-Voltage System for Far Detector 1. We conclude that review recommendations have been properly addressed such that the review can be formally closed in anticipation of the upcoming Final Design Review (FDR) for this system.

Prepared by:	Checked by:	To be approved by:
E. James (FD1 TC)	**E. James (FD1 TC)** **M. Nessi (FDC DPD)** **J. Fowler (FDC CC)** **T. Shaw (FDC EE)** **O. Beltramello (FDC CO)** **M. Bishai (FDC RO)**	**M. Nessi (FDC DPD)**

Lessons Learnt from ProtoDUNE:

- The HVS goal of 180kV on CPA (the highest in a SP LAr-TPC) was reached and maintained soon after the LAr fill (Sept 2018).
- Remarkable uptime was achieved:
  - during beam run: > 98%,
  - during long term stability run: ~ 99.5%.
- Just two classes of instabilities recorded through out the detector live-time:
  - Fast discharges: O(10/day), ~10ms duration; self recovering
  - Sustained excessive current ("streamers"): nearly all from the same specific location. Recovered by lowering the voltage using an auto-suppression script.
- No system degradation observed over nearly two years of operation
- Adequate monitoring and HV controls allowed the remarkable uptime
- CPA alignment measured with cosmic muons shows tilts but mostly within requirement

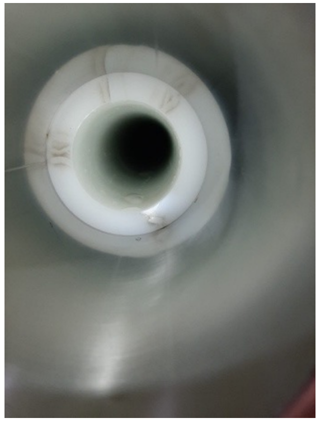




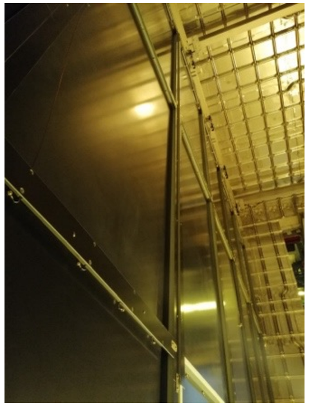
- *The behavior of the "streamers" possibly explained as a charging up effect of insulating materials in the strong e-field regions outside of the field cage*

Charge Question #5

ProtoDUNE-I Decommissioning: HV findings



- After termination of operations
  - HV-FT inspection :
    - thin traces of arcing found on the tip of the HV cable in HV–FT receptacle (most likely due to thin 200 kV cable)
    - thin layer of Ice accumulated (in two years) in the HV-FT receptacle making it difficult to extract HV cable.
    - *--> HV-FT design has been modified to cope with both issues (longer FT to avoid low temp. in receptacle, deeper cable receptacle)*



- After TCO opening
  - bowing of central CPA column (< 1cm) consistent with measurements made in LAr with cosmic rays
    - *Improved columns alignment system included in new design*
  - CPA lifting bars (facing GP-6) shows gray streaks; surface analysis indicates to be metal residuals that could be the cause of the « HV streamers » observed during operations.
    - *Improved surface quality control included in QA/QC procedures*
  - Not responsive EW current termination monitor due to disconnected SHV on the APA5 filter-panel (fail-safe varistors allowed EW biasing); similar problem with APA3 grid biasing.
    - *SHV panel accessibility may remain an issue for the APAs*

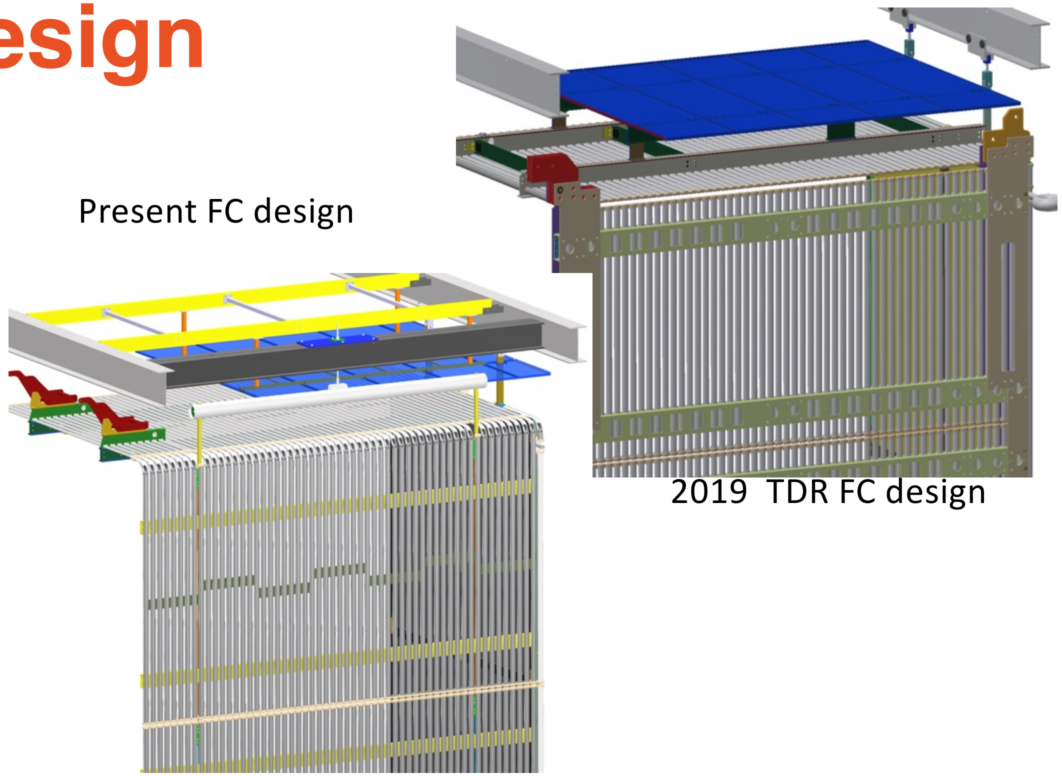
ProtoDUNE-I: HV decommissioning-recycling

- With the exceptions noted in the previous slide, **All HVS system components found in excellent conditions (from visual inspection)**
  - No oxidation of aluminum
  - No resistor / varistor damaged
  - No delamination of CPA resistive surface
  - No cracks on the PE endcaps
- **Material now reused in ProtoDUNE-II fully recovered and temporary stored in NP02 clean room**
  - All TBFC aluminum profiles 2.3 long (from 12 modules)
  - All Resistive Divider Boards: 5 GOhm version (from 7 modules) reused as is; 1 GOhm version (~100), replaced with 5 GOhm and mounted in PD2
  - All End Caps
  - The CPA panels (the two central ones dismounted and kept as spare parts)
  - All Ground Planes
  - HV Donut (arm rebuilt)
  - HV Feedthrough (as spare of the upgraded version under test)
  - HV Power Supplies (200 kV and 300 kV ones) & cables

Improving the FC Design

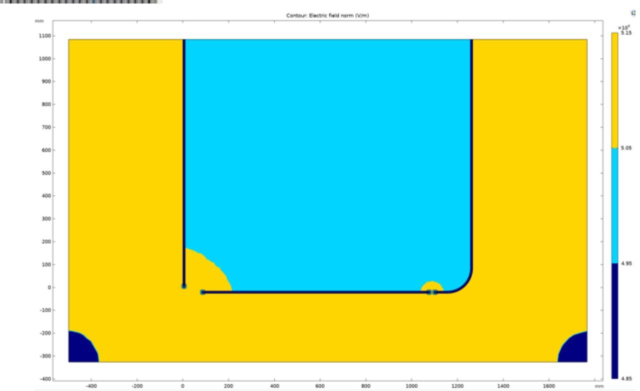
- Optimization of the field cage:
  - Eliminating nearly all insulating materials on the outside of the field cage to reduce the probability of surface charging in the high E field region
  - Increasing field cage to top ground plane distance, and remove bottom ground plane to further reduce E field, and stored energy (GPs moved out of HVS scope)
  - Introducing bent profiles at the End Wall field cage corner edges to improve drift field uniformity.

Present FC design



2019 TDR FC design

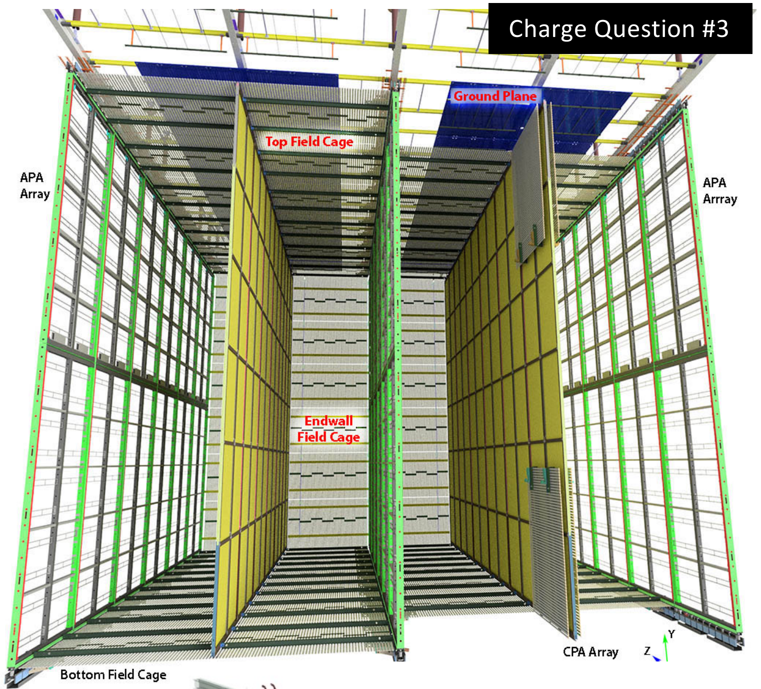
- Value engineering:
  - The changes result in simplified design, lighter, more robust construction, and significantly lower material cost.
  - All FC assembly and testing will be done underground; only shipping of the ”prepared and QC’ed components” of the field cage is required
  - *the EWFC support design ensures EWFC verticality regardless of the cryostat roof motion (NEW wrt last PDR)*



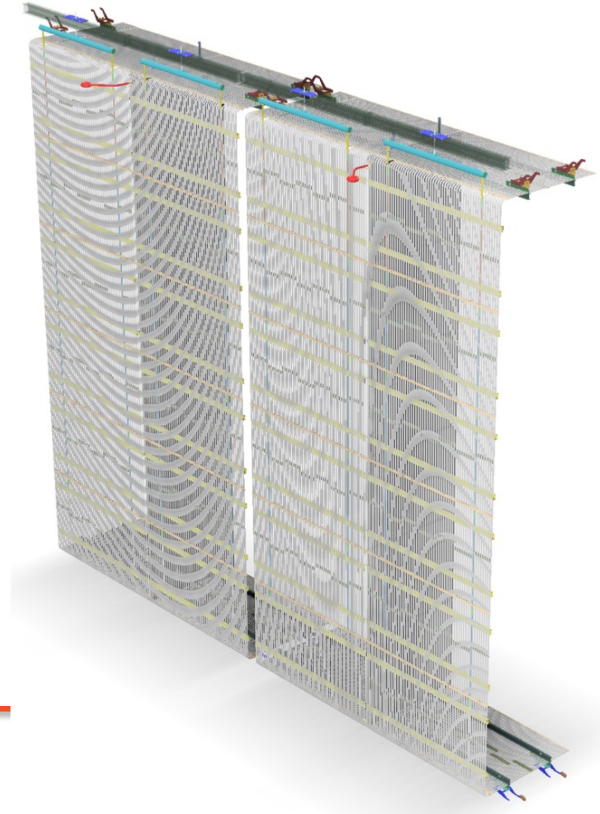
E-field uniformity in PD1 (lower left) and PD2 (lower right). Yellow (>1% nominal value)k , Blue (within 1%).

The New HVS Design

- 2 End Wall FC's each made of:
  - 24 2m x 3.5m EW modules (arranged in 4 identical columns, 6 modules tall) with top/bottom modules hosting bent aluminum profiles
- 25 mostly identical CPA/TBFC/GP rows, each made of:
  - 2 CPA's: 12 units each (1.15m x 2 m)
  - 8 Top/Bottom FC module (3.5m x 2.3m)
  - 4 Top Ground Planes (4 units each: 2.3m x 0.5m) hung independently to the DSS beams (NOT in HVS scope except for readout and monitoring)
- Assembly & Installation:
  - Performed fully underground (ProtoDUNE Phase-II experience on FC)
  - about 1 month for each EW
  - 1 week for each CPA/TBFC slice: deployment of FC at the end of installation.



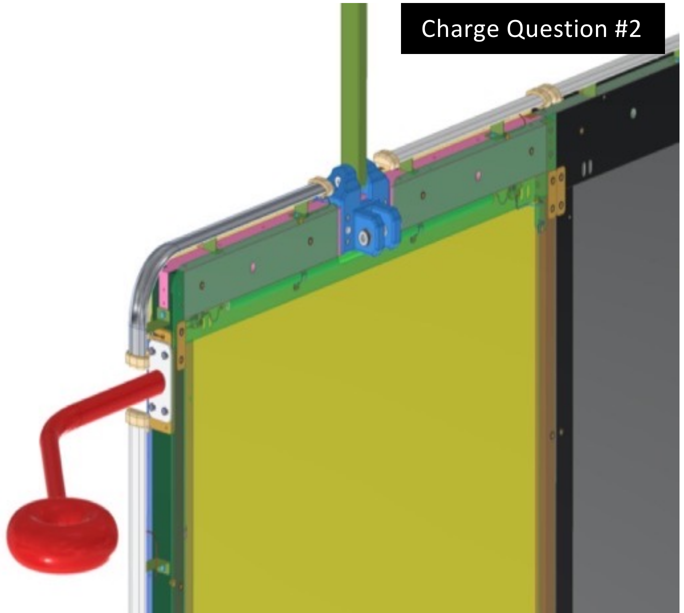
Personnel requirements and assembly times being validated at ProtoDUNE Phase II

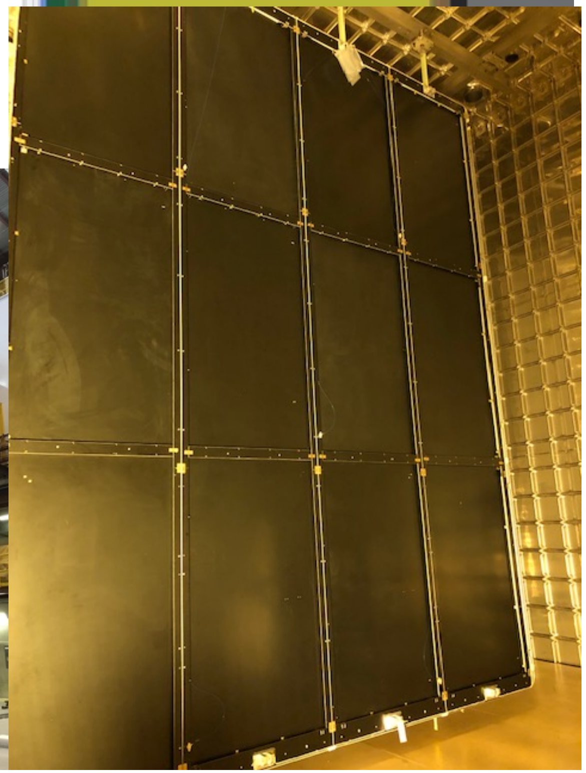


Charge Question #2

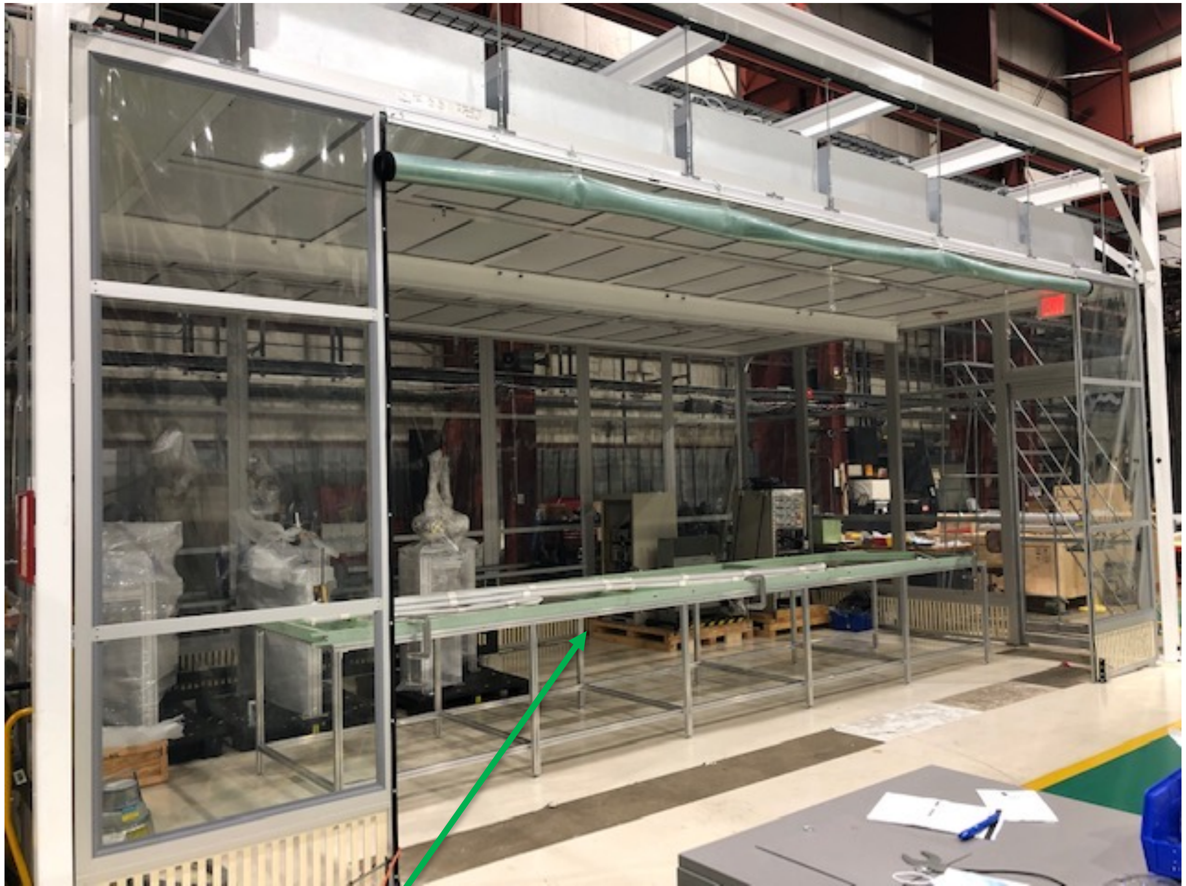
CPA

- Constructed from 50 side by side panels :
  - Each Panel is 1.15m in width and 12m tall, formed with 6 vertically stacked Resistive Kapton laminated modules
  - Hanging through a single link
  - HV bus is integrated in each CPA Panel for electrical interconnection between panels.
  - Resistive Field Shaping Strips to ensure E-field uniformity around the frame
  - “Donut” shaped receivers attached to the outermost CPA panels to receive HV feedthrough tip contact
- Minor modifications wrt TDR & last PDR:
  - bent profiles at corners,
  - FFS layout
  - New PD diffuser mounting scheme, implemented and to be validated at PD
  - More inter-panel alignment pins and slots
  - Anti-rotation feature to improve cathode plane planarity
  - Double sided HV bus for increased redundancy





Clean Room @ANL for CPA Production

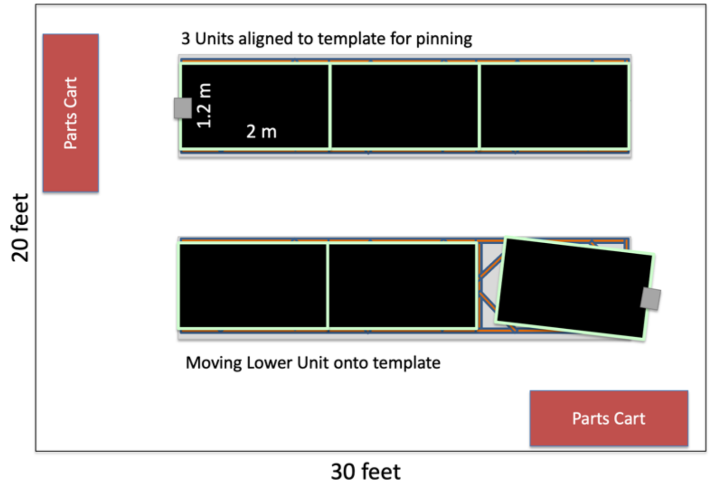


8020 Al table with 3-unit CPA template made from spare frame parts

- Already used for PD2 CPA assembly
- Ready for FD1 production

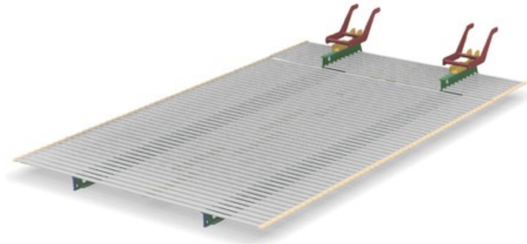
- Clear plastic walls
- Ceiling fan units create positive pressure air system
- Ceiling lighting
- Size fits 2 – 20 foot long tables plus room for carts containing all parts and hardware needed for a single CPA panel production (6 CPA Units – 12 m tall

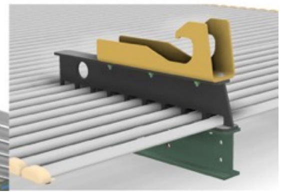
Factory Configuration



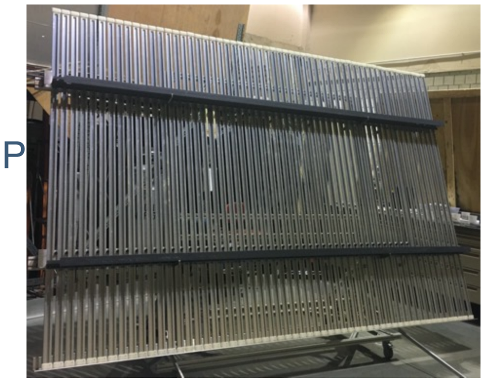
Charge Question #2

Top/Bottom Field cage modules





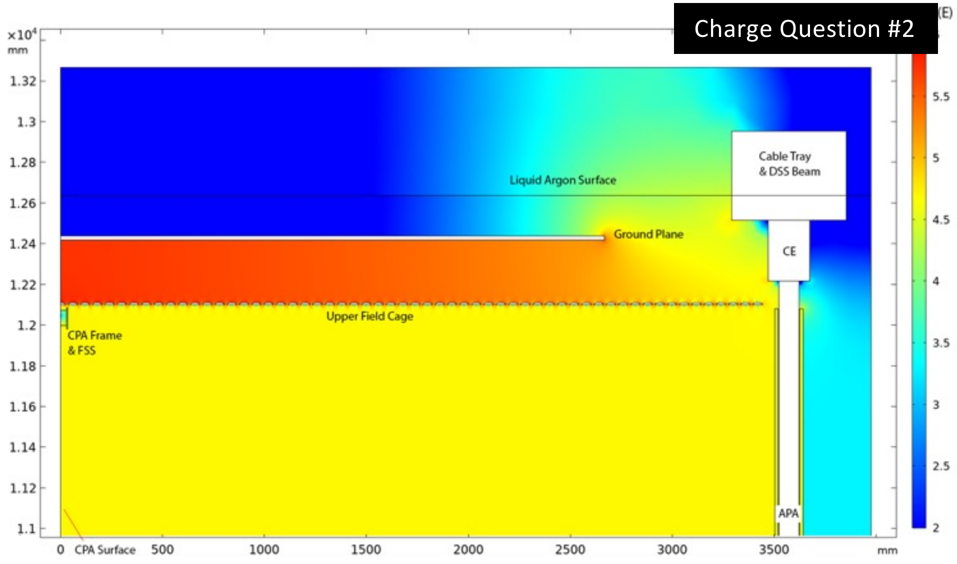
- **Very simplified structure wrt TDR solution (no change from last PDR)**
  - No change in dimensions (2.3 x3.5 m2).
  - Same electrodes shape and 6 cm pitch
  - No standoffs for Ground Planes
  - Lighter FRP 4 inches I-beams
  - Profiles sitting outside the beams
  - Non-metallic hinge on FC for CPA connection
- Simpler aluminum latches to APA
- Activities at production sites (SBU/UTA)
  - FC assembly procedures developed via test assemblies:
    - Several iterations of assembly cart modifications performed to optimize assembly procedure
    - QA/QC finalized procedure for newly designed FRP parts, including the QC jig development
  - TBFC for PD2 fully assembled at CERN
    - With assembly tools and storage cart shipped to CERN

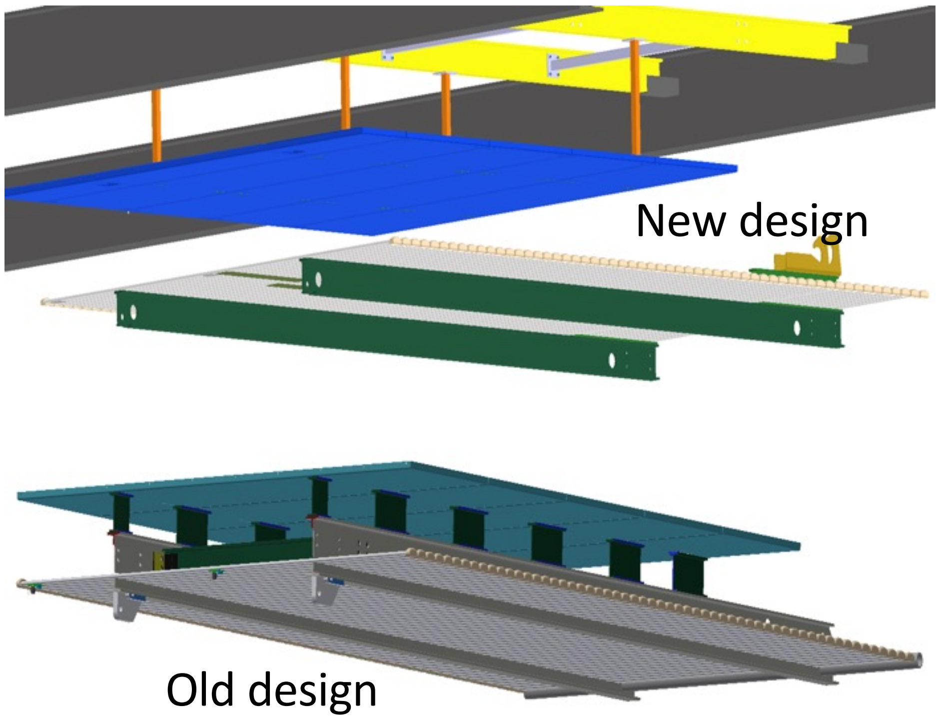


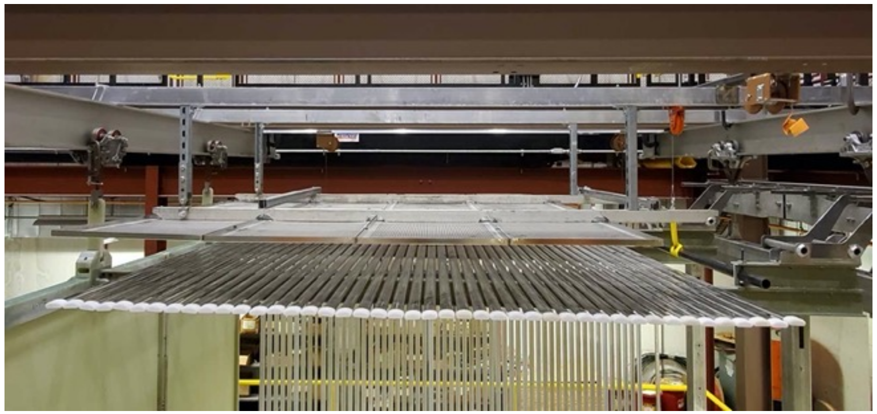
Ground Planes

- Used to confine the E-field below the Liquid Argon surface
- **New wrt TDR**:
  - Hanging from DSS
  - No GP's at the bottom (cryo pipes have been moved away from under the TPC)
  - 30 cm distance above Top field cage Modules (50% increase from PD1 and TDR)
  - No insulators connecting FC to GP
  - Moved out of HVS scope except for current monitoring system
- Layout and Installation tested in Ash River and being validated in ProtoDUNE-II

Charge Question #2

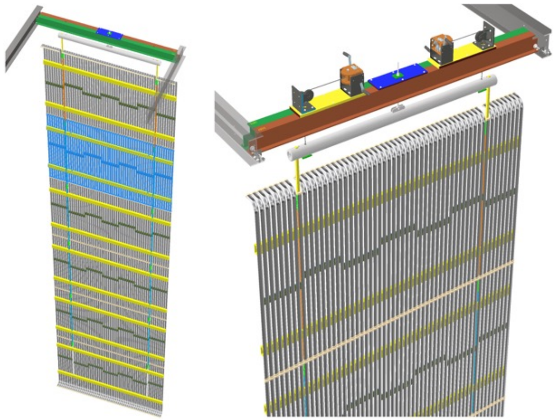


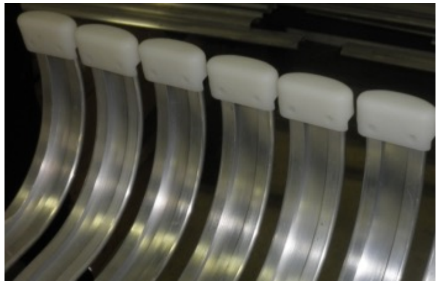




End Wall Field cage modules

- **Significant modifications with respect to ProtoDUNE-I (and TDR)**
  - Panel height 2m (it was 1.5 m)
  - Aluminum profiles sittings outside of smaller cross section FRP box beams
  - Aluminum holding bars for easy connection of 6 panels forming a wall.
  - Bent profiles (tool successfully prototyped at LSU production site) in the top & bottom most panels to minimize E-field distortions at the edges of the FC
  - New: Yoke to hang on a single point to DSS to guarantee verticality also in case of DSS/Roof deformations.
- Full panel assembly to be performed underground with dedicated tooling and supporting structures
  - Validated by LSU team at CERN for ProtoDUNE-II
    - Bending and QC procedures
    - Modules assembly and installation

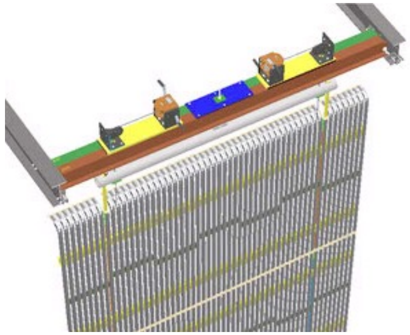
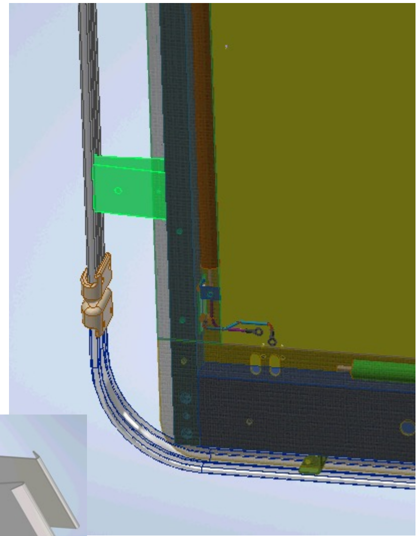
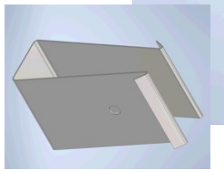
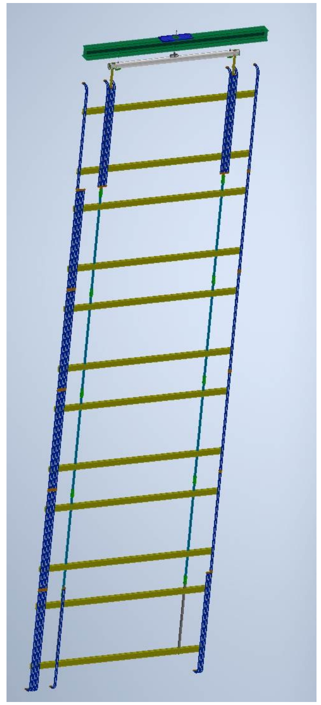
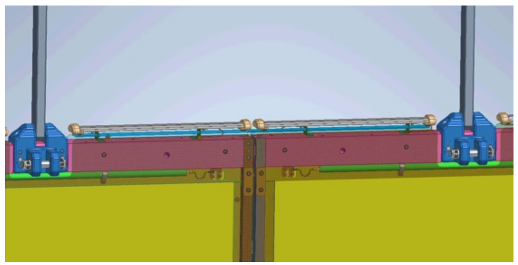
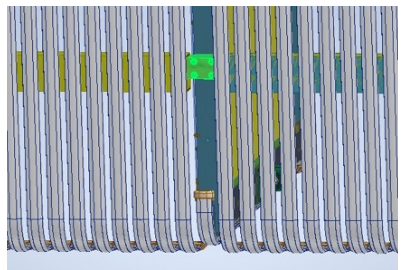



Charge Question #2

Changes to Design Since Last PDR

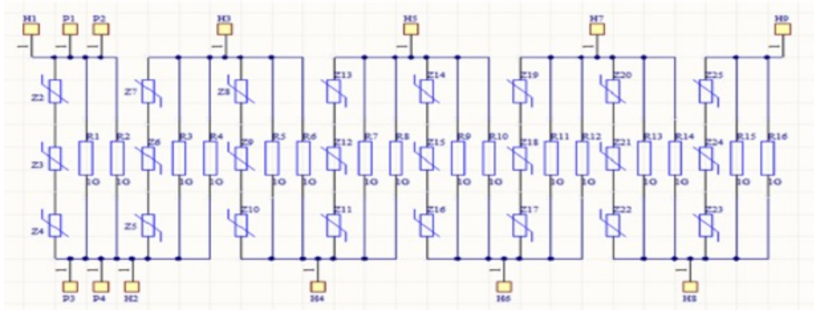
- EW support from DSS changed to double FRP I-Beam
- Single point EW hanging system
- Winch system for assembling EW has been updated
- Design of diffuser attach on CPA being updated
- FSS Geometry has been updated and optimized
- Snap clips for profiles on CPA added
- EW/APA and EW/CPA restraints updated
- Latch system od TBFC to APA optimized
- Updated tolerances on dwgs
- Added redundant HV bus and connections to CPA
- Added anti-rotation rods to top and bottom of CPA

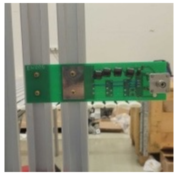







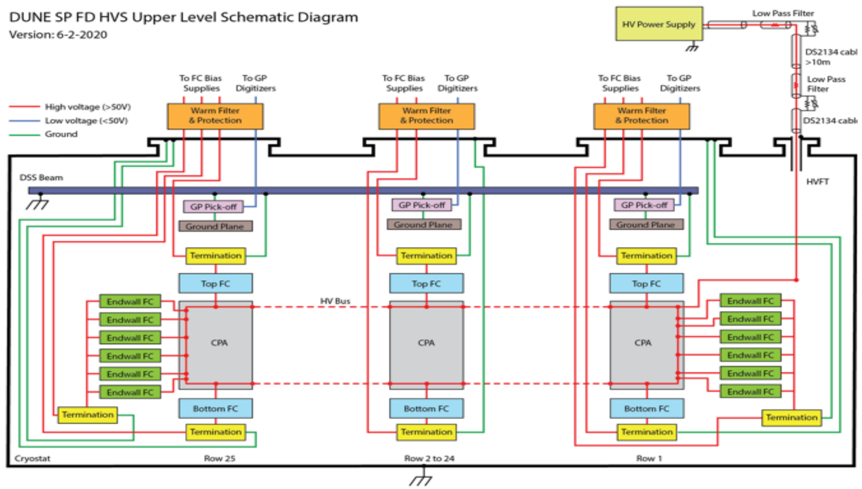
Charge Question #2

Divider boards & electrical interconnections

- **NO change with respect to TDR and PDR**
  - Two 5 GOhm resistors in parallel in each step of 3 kV / 6 cm
  - For redundancy: 3 varistors in series (opening at 1.7 kV each), in parallel with the resistors
  - In case of resistor failure, DeltaV goes from 3kV to ~5 kV
  - Well defined QA/QC plans (LSU)
    - Applied and successfully tested for the ProtoDUNE-II assembly
  - Termination boards for both EW and TBFC also designed and produced for PD2
- Similar interconnection scheme as for ProtoDUNE and TDR

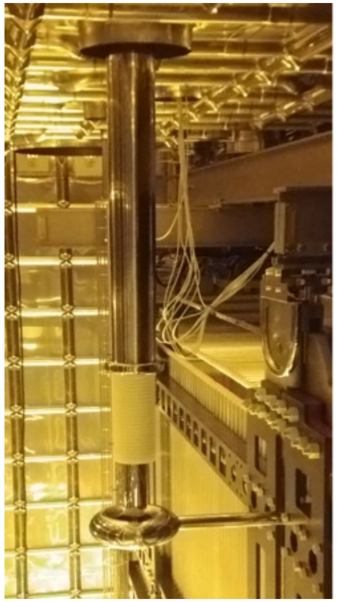


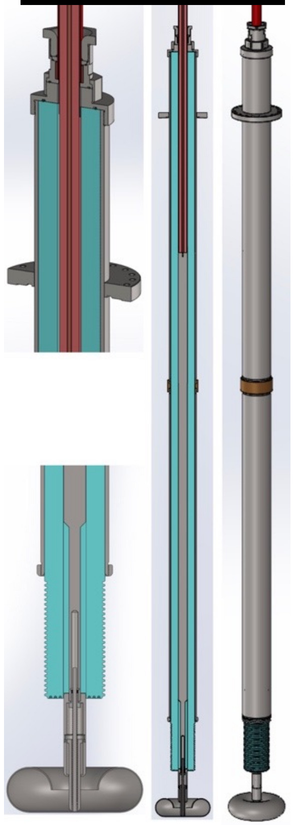


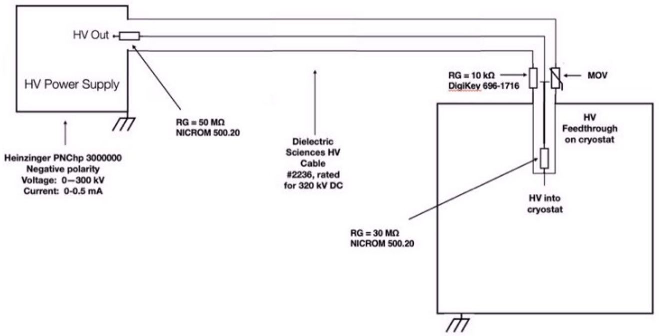


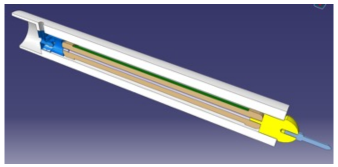
HV delivery

- Main differences wrt TDR & 2020 PDR:
  - HV FT: unified design with FD2-VD (300 kV rated)
    - Scaled up version of the ones successfully tested in PD1 (NP04 and NP02) -> 4m length, 150 mm diameter.
    - 1 m long warm section to avoid the ice formation issue in the cable receptacle
    - Accepts 320 kV rated HV cable (200 kV option with termination adapter)
    - Under construction at CINEL (same as previous FT's)
  - Simplified ripple filtering system
    - Commercial HV Resistor located in cartridges integrated into the cable terminations
    - Tested at 300 kV in NP02 HV stability run





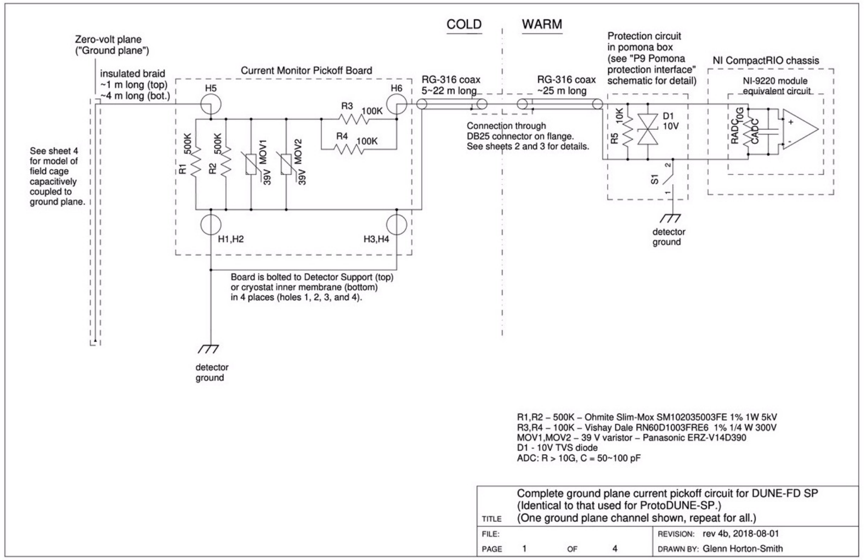




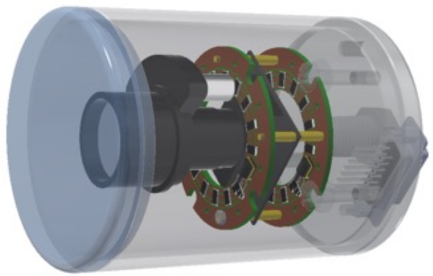
- if no E-Drift > 500 required)

HV monitoring & grounding

- **Similar to TDR & PDR**
  - Ground planes current pickoff monitors (100 channels)
  - Termination current on each voltage divider chain (208 channels)
  - HV-PS voltage/current and ramping up/down features
  - (discharge monitors on HV filters)



- Also in HVS scope:
  - Cold cameras (~16) similar to those used in ProtoDUNE-SP and DP to visually monitor critical spots: HV feedthrough, end wall edges



- Grounding scheme follows DUNE prescriptions, as successfully applied in ProtoDUNE-I

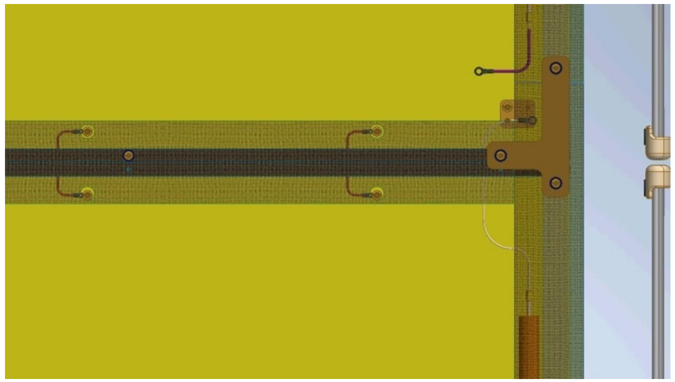
Charge Question #2

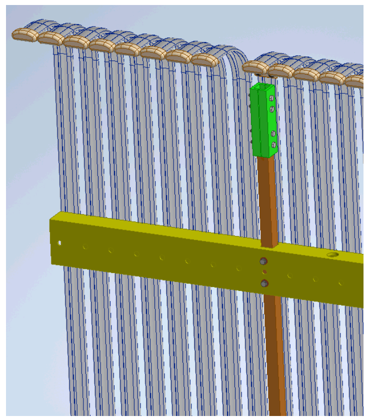
Advances following the last PDR in 2020

- Design
  - Modified the end-wall support structure to avoid impact from cryostat roof deformation
  - Changed the warm FC lengths to ensure cold length is 3574mm between APA-CPA beams.
  - Added EWFC-CPA and EWFC-APA interconnect features
  - Updated safety analysis plan and completed the analysis
- Prototyping
  - FD TBFC modules, two rounds of assembly table
  - FD EWFC modules, assembly and profile bending tools
  - FD CPA modules: 2 columns of 12m high assembly with mobile QC
  - Ash River ProtoDUNE II phase 1 beam left
  - ProtoDUNE II assembly and installation (ongoing): mobile QC adopted of all HVS components
  - FD1 row 25 trial installation

Open Design Issues (to be settled before PRR)

- Camera signal feedthrough flanges have not officially been assigned (proposed to tee off 4 DSS penetrations).
- Mounting hole pattern for the GP pickoff boards and EWFC support beams have to be agreed upon by DSS
- Based on lessons learnt from PDII experience, the following changes are to be made
  - Updated Diffuser design (provided by PDS) has to be finalized and implemented on CPA.
  - Holes for the HV jumpers between panels need to be enlarged to ease the installation
  - Enlarge holes on FSS to allow for more adjustment (flatness)
  - Update dimensions and tolerance on EndWall C-clamp connectors
  - FC and EW assembly tooling and fixtures need to be optimized and finalized according to ProtoDUNE Phase-II experience





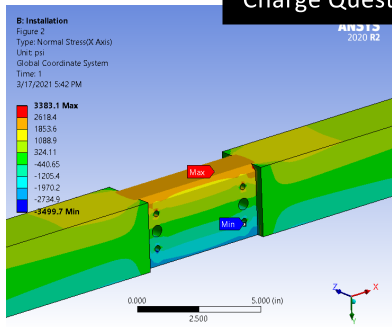
Charge Question #2

Structural Safety Analysis

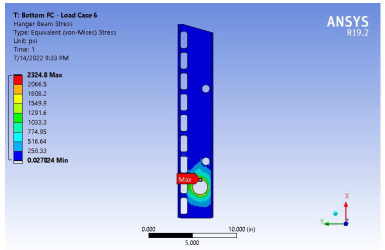
EDMS#2579744

- Guided by approved Analysis Plan #2520669
  - Installation and gravity loads during dry and wet operation
  - Incorporated material properties for orthotropic behavior
  - CPA
    - Lifting individual modules
    - Full structure with Field Cage loading
  - End Walls
    - Symmetric model looking at one column
  - Field Cage
    - Lifting FC onto CPA
    - Lifting FC to deployment
    - Operational cases
- Notable Analysis Result
  - CPA Top beam bending stress was critical section for operation case
  - EW pipe stress concentration for lifting case was important to investigate, c-clamp was critical section
  - FC lifting onto CPA was investigated and stresses were below limits

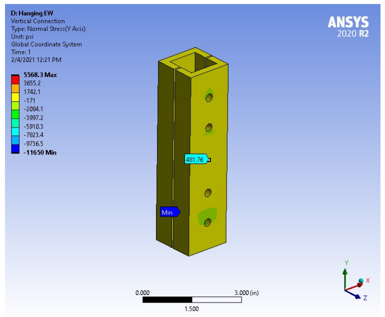
CPA Top Beam Bending During Installation



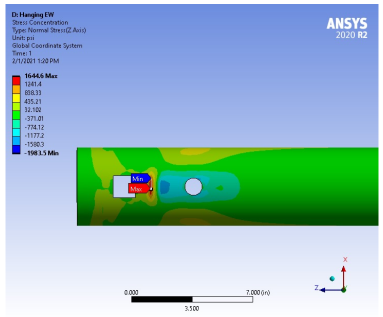
FC Hanger Beam Stress Lifting onto CPA



C-Clamp Stress Plot



EW Pipe Stress Concentration for Lifting Case



Charge Question #2

Structural Safety Analysis: CO validation

- Validation Process performed with frequent and efficient feedback between HVS and CO
- *The main outcomes are:*
  - *The HVS was verified for all load cases defined in the Analysis plan and some others identified during the review of the documents.*
  - *The frame members strength and stability as well as the connections were verified for all LCs in accordance with the relevant standards (appropriate safety factors were used).*
  - *The utilization ratios are within the acceptable limits*
- *The following considerations remain to be addressed* (to be finalized before PRR):
  - *Strategies and checks for the management of deformations (during cooldown and operations) to ensure the squareness of the HVS* → in progress, TC also involved (for the definition of the DSS beam distances at warm and cold)
  - *An envelope study (nominal dimensions plus deformations and tolerances) of the system in operational dry and wet configurations:* → *in advanced stage, close contact with CO*

EDMS No.: 2382749
Date: 26.07.2022

LBNF / DUNE Compliance Office
System Structural Validation document – DESIGN

DUNE High Voltage (HV) System

From O. Beltramello, M. Zimbru

Project Leaders: F. Pietropaolo, B. Yu
Project Engineers: V. Garino, N. Wozniak

1. System identification:
HV system composed of CPA, FC (field Cage), EW (end Wall)

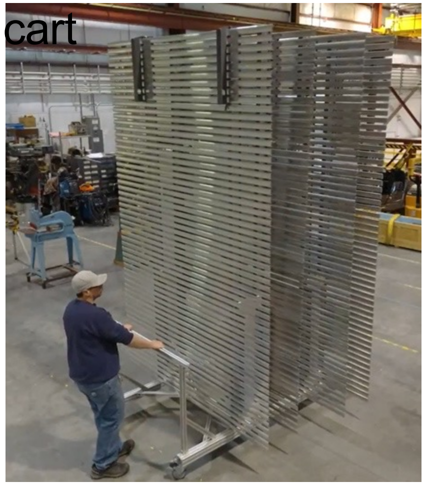
2. Provided documentation:
EDMS 2520669 v.1 – HVS Analysis Plan
EDMS 2579744 v.1 - HVS Strength Analysis

Charge Question #5

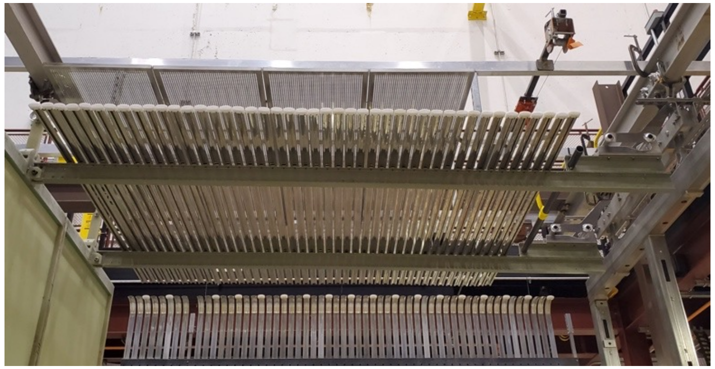
Ash River Trial Assembly

- Throughout the early part of the Covid pandemic, while most of the facilities were in full or partial lockdown, the Ash River crew continued their work on fabrication, assembly, and installation trials of key TPC parts.
- Officially not part of the HV Consortium, the Ash River crew, led by Bill Miller and Tom Wieber made invaluable contribution to the development of the HV system for FD1

Spring 2020: FC assembly and storage cart



Spring 2020: Initial ProtoDUNE II CPA/FC/APA trial Installation

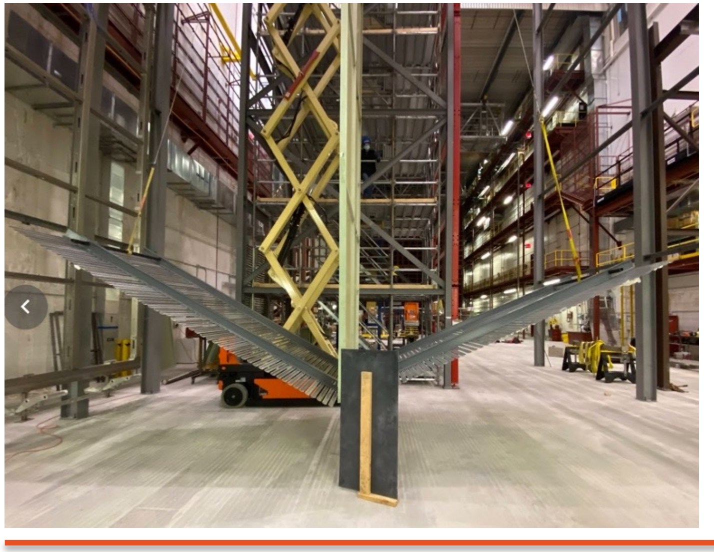


Fall 2020: 12m tall FD1 full height CPA installation

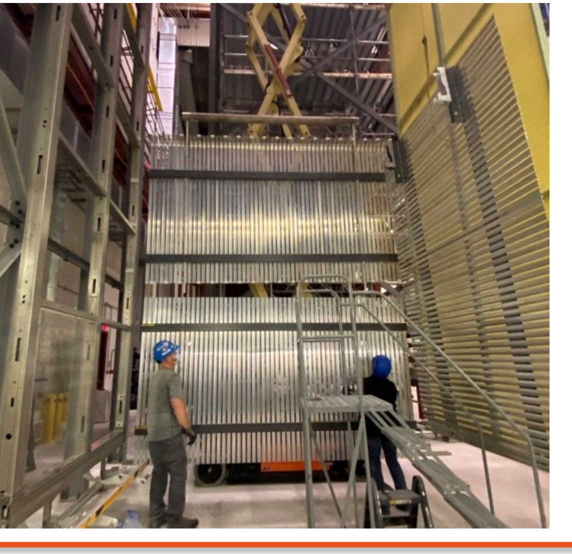
Ash River Trial Assembly: FD1 row 25

- A first installation workshop was held at Ash River in Dec 2021 to demonstrate the installation of the row 25 TPC, which is the most challenging part of the FD1 HVS installation due to limited access and floor space.
- This exercise addressed the current FD1 HVS installation plan.
  - Lessons learned compiled during the trial led to several improvements in the procedures and tools, which are being successfully implemented in ProtoDUNE II
  - Further AR validation tests planned in late 2022

Symmetrical deployment of the bottom FC modules



Installation of the full height EW FC modules



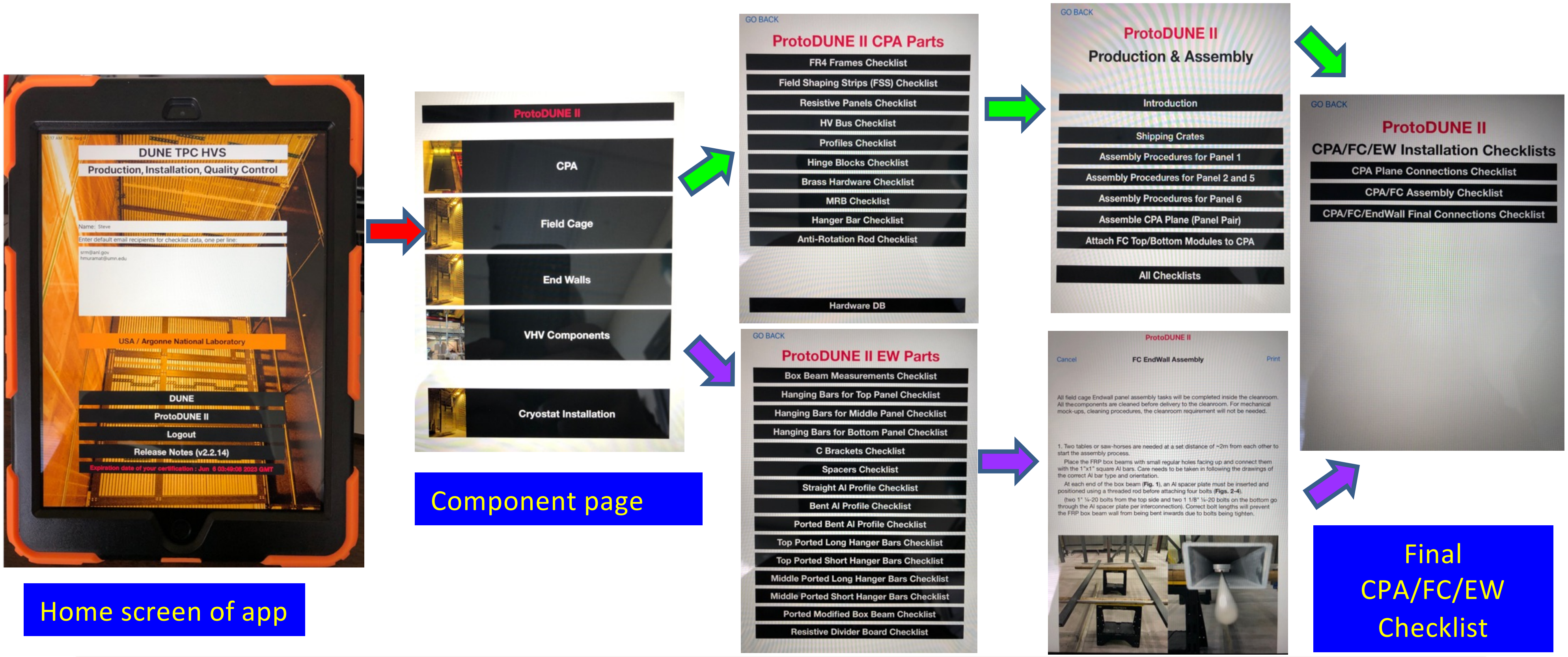
Complete one drift cell of row 25

QA/QC

- HVS coordinator working closely with production sites and DUNE QA/QC representatives.
  - Co-leading the development of mobile app integrating checklist / traveler system for accurate, real time recording of QC information
- Procedures finalized (based on ProtoDUNE-I experience, being validated in ProtoDUNE-II) for all the HV system construction phases:
  - development and design
    - Electrical/mechanical analysis; material testing in cold; small scale test validation
  - prototyping
    - Ash River trial assemblies (modules, ProtoDUNE scale, FD scale)
    - ProtoDUNE–II / Module 0
  - production
    - screening of critical components;
    - tagging components & implementation of electronic checklists / traveler documents
  - Installation
    - planned checklist to ensure correct function and interconnect of installed components

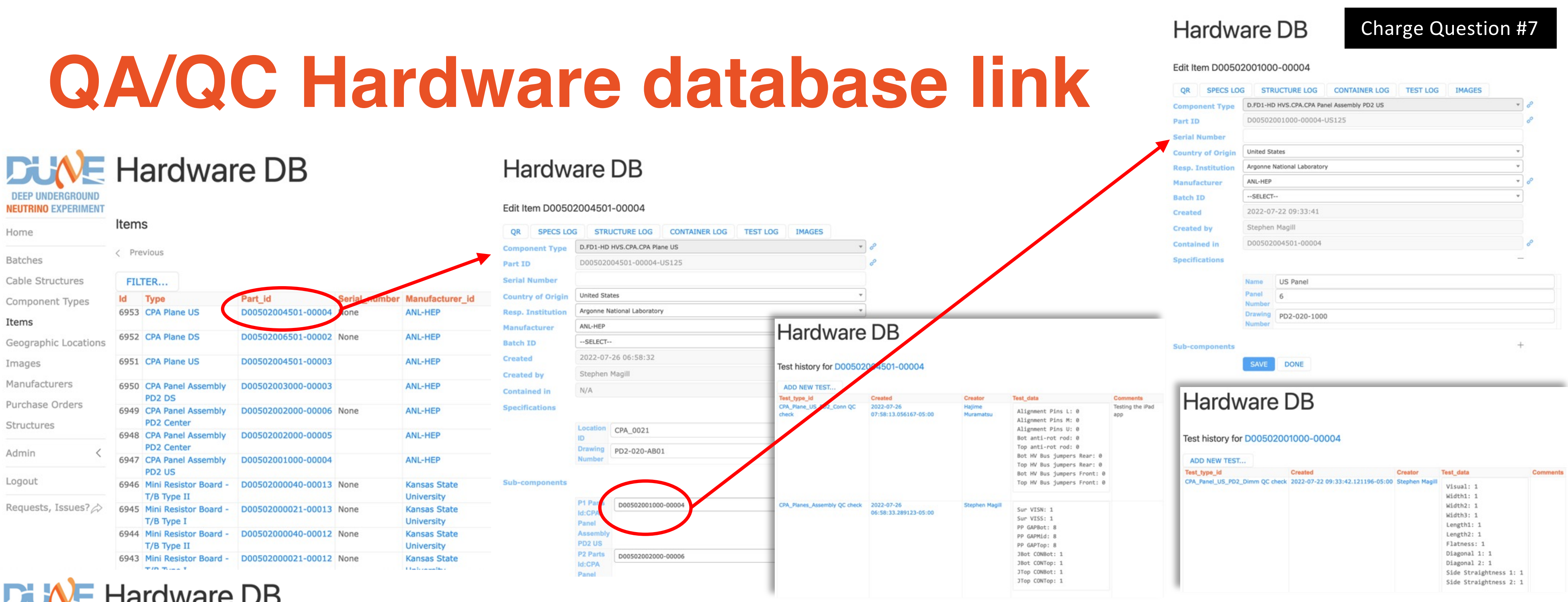
QA/QC – iPad app

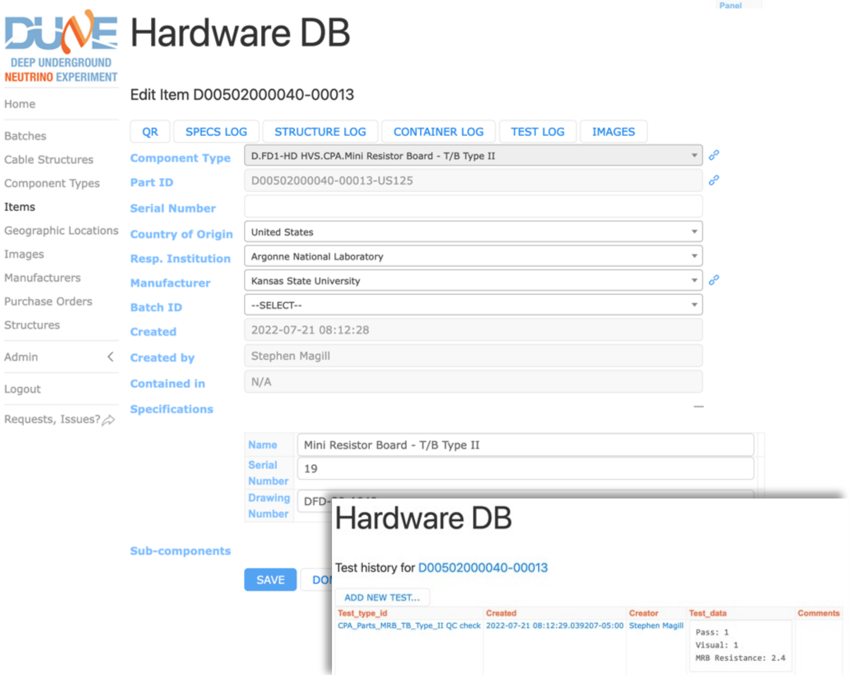
- Plan for QC on all parts, production modules, assembly and installation procedures for DUNE.
- Procedures and Checklists contained in an iPad app with automatic uploading of data to DUNE Hardware Database.
- Unique Parts IDs for HVS components allow tracking of parts through production, assembly, installation and detector operation.



Charge Question #7

QA/QC Hardware database link





- Screenshots from DUNE Hardware Database (for CPA in PD2)
- Top left: Listing of some of the database entries for CPA.
- Top middle: Contents of entry for CPA Plane US (upstream CPA Panel pair).
  - Inset shows test logs from checklist for this Plane
  - Note subcomponents of this Plane are the 2 CPA Panels
  - Test log data includes gap size (8 mm) between Panels
- Top right: Contents of Panel 6 (most upstream of the panel pair) subcomponent with its inset checklist test log.
- Bottom: Entry for CPA component part – Mini-resistor Board (MRB)
  - Inset shows test log from checklist for this MRB
  - Data stored is the board’s resistance (2.4 Gohms)

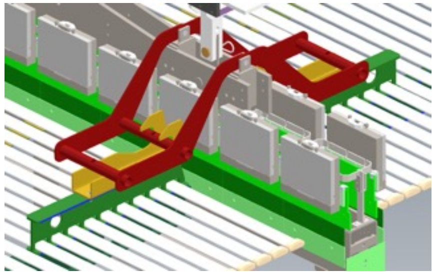
Interface Requirements

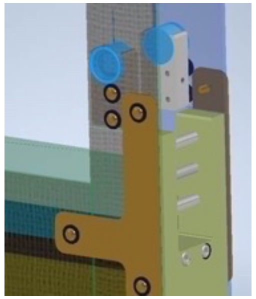
1	The mechanical connections between the top/bottom field cage modules and the APA shall not impart moment loads to the APA frames.
2	The end wall FC modules shall be constrained to the APA and CPA arrays.
3	The top field cage shall maintain a clearance of at least 30cm from the bottom surface of the ground plane
4	The top field cage shall have openings large enough to allow the calibration laser periscope heads to penetrate through the plane of the field cage profiles.
5	The CPA shall provide attachment points for the PD calibration diffusers to be mounted on both sides with clear view of the APA arrays.
6	Each FC termination circuit shall have an additional failsafe current return path to detector ground to guard against FC termination cable failure.
7	The FC termination bias power supply specifications: maximum output voltage: -1kV, maximum output current: 1mA, output voltage ripples: <0.1V, minimum V/I readout freq: 1Hz
8	FC termination and failsafe current return paths shall avoid the APAs

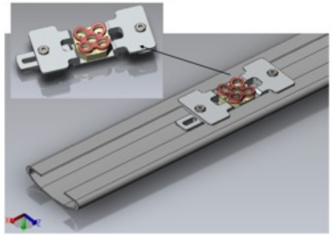
Interfaces with other consortia

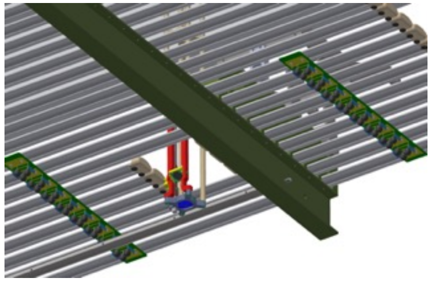
- Essentially finalized with most detector consortia.
- Interface documents with DSS, facility, installation in advanced development.

Consortia	EDMS number	Key Interface Items
APA	2088738	Field cage support on APA frames
PDS	2088721	PD calibration flashers and fibers on CPA
CE	2088706	FC termination and ground plane monitor cable routing, warm filters on SHV feedthroughs, termination bias supplies
CALCI	2145142	FC openings for lasers, target mirror assemblies on FC profiles
DAQSC	2145154	HV vs. LAr level interlock, ground plane and HVPS digitizers, cold camera power supplies
Installation	2145184	Installation activities in UG cleanroom, cryostat
Facility	2145170	HV feedthrough locations; rack and cable trays; liquid and gas flow in cryostat
DSS	2339392	Support of the CPA/FC modules on DSS; ground plane design, support, and installation; cable routing









Transportation Requirements

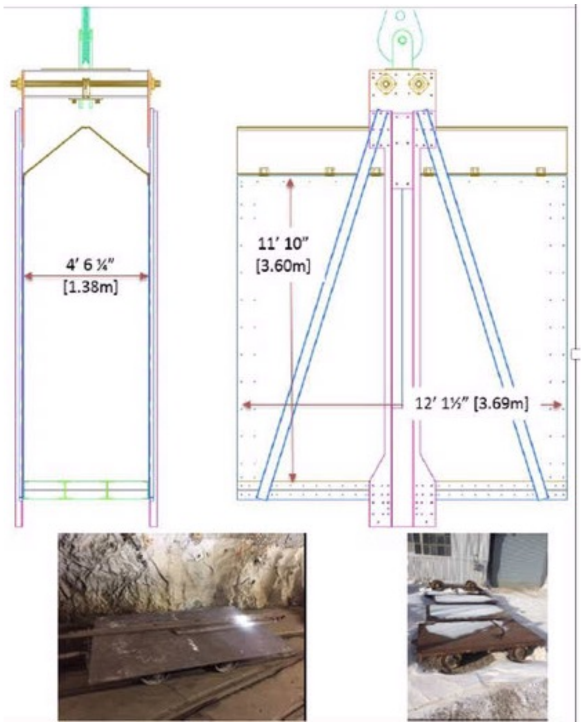
1	The shipping crates and packing material shall not release particulates inside the UG cleanroom under normal operating conditions. If such construction is not economical, the content shall be transferred to a clean container before entering the cleanroom
2	All shipping crates with length greater than 3.65m (inner length of the Ross cage) shall be compatible with lifting in both horizontal and vertical orientations, including inverted from normal shipping orientation, and shall provide all necessary lifting points for both orientations.
3	Contents of all shipping crates shall be double bagged before reaching the UG cleanroom

Installation Requirements

1	The temporary EWFC support beams shall be able to move along the DSS beams for at least 20cm with the full load of the EWFC modules.
2	The attachment features between the EWFC and the APAs and CPAs shall be accessible from either inside or outside of the TPC
3	The HVFT receptacles shall accommodate the shrinkage of the TPC to maintain good electrical contact to the tips of the HV feedthroughs without interference
4	The EWFC storage cart shall not interfere with the existing TPC components when positioned to installation positions.
5	The design and installation of the field cage shall allow the final FC deployment to be as late and as quick as possible to enable maximum TPC component access

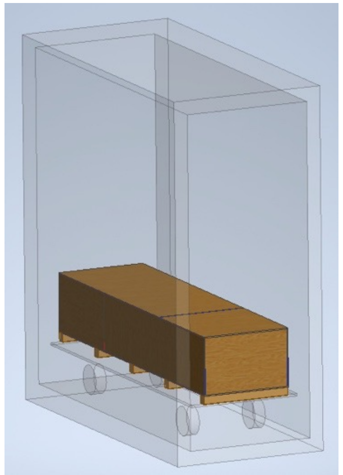
Shipping of the HVS components

- No major changes from 2020 PDR
- Main parts to ship: CPA modules, FC profiles, FC beams, HV delivery, divider boards, assembly tools.
  - All crates fulfill shipping requirements (size and weight for shaft lift transportation, cleanliness for clean room).
  - All crates designed to fit on the underground transport cart and within the lift cage
  - All parts wrapped in plastic bags and placed in wooden crates at production sites
  - Possible visual inspection at SDWF
  - Crates to be delivered outside FD1 assembly area, sides removed before entering the Clean Room (only parts in plastic bags)
- Prototype crates produced: shipping to CERN successfully tested for all the equivalent ProtoDUNE-II HVS parts.



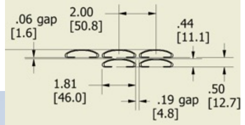
- Height-11' 10" (3.60)
- Depth-12' 1" (3690)
- Width- 4' 6" (1380)
- Weight- 13,000 lbs. (5900kg)

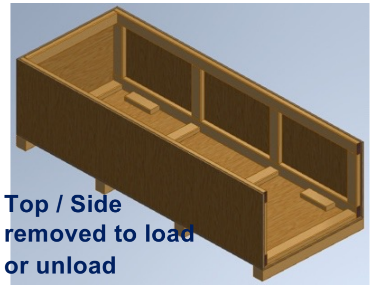
Standard cart (18" height)that rolls in and out of cage is which minimizes the height of the total load to 10' 4"



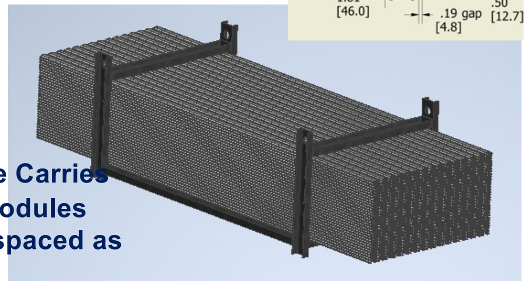
Shipping of the HVS components

- FC profiles
  - 96” x 38.3” x 29”, 1000 LB
  - 25 Loads of FC, 6 Loads of EW
- FC beams
  - 139” x 38.3” x 29”, 1400 LB
  - 2 EW Loads, 8 FC Loads
- CPA modules
  - 95.” x 52” x 68”, 1400 LB
  - 50 Crates/Loads down shaft
- HV delivery tools
  - HVP, HVFT and HV cable transport crate provided by vendors (shipping tested from CERN to FNAL)
- Shipped in dedicated crates
  - Parts for EW FC assembly tables, EW bending tools
  - Deployment tools

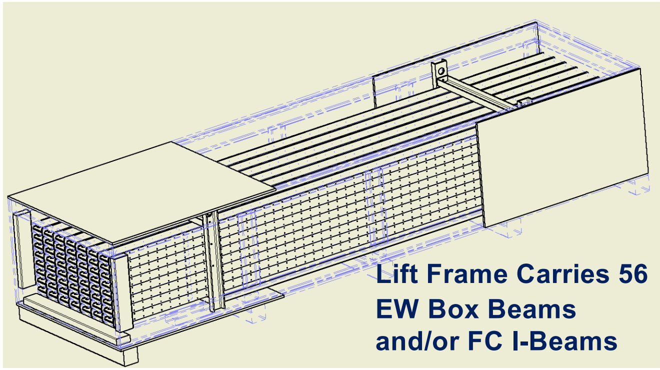




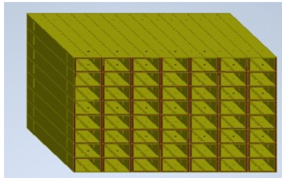
Top / Side removed to load or unload

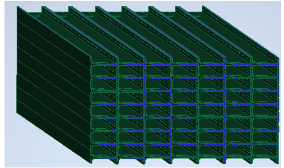


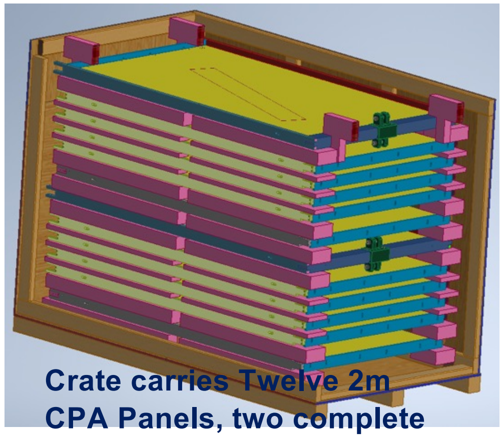
Lift Frame Carries 480 = 8 modules Profiles, spaced as shown



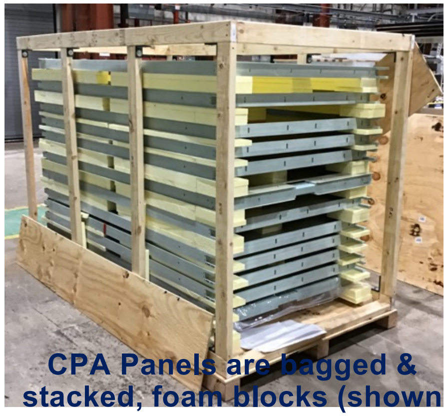
Lift Frame Carries 56 EW Box Beams and/or FC I-Beams







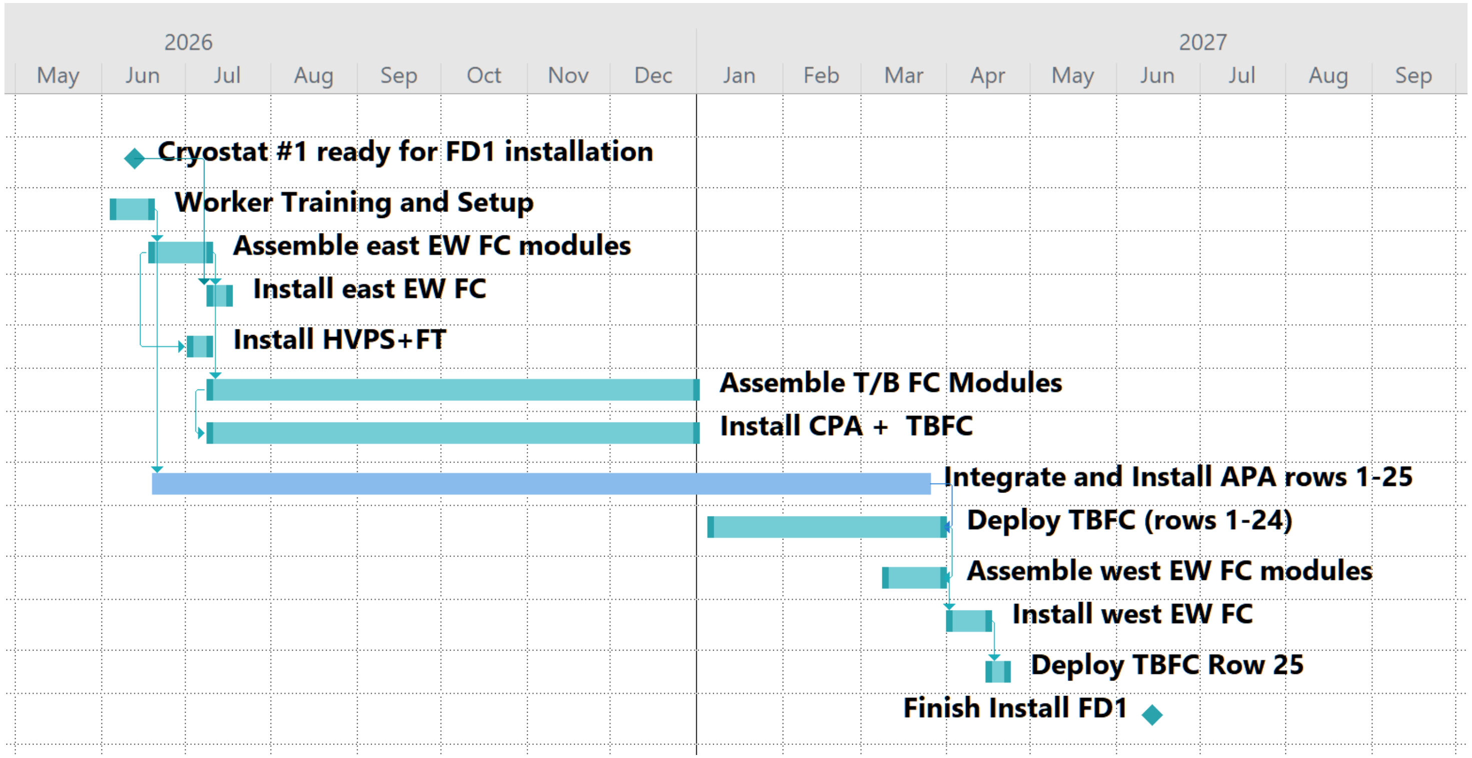
Crate carries Twelve 2m CPA Panels, two complete 12m Assemblies, sufficient for one CPA/CF Module



CPA Panels are bagged & stacked, foam blocks (shown in pink, drawings provided) are used to separate panels & prevent damage

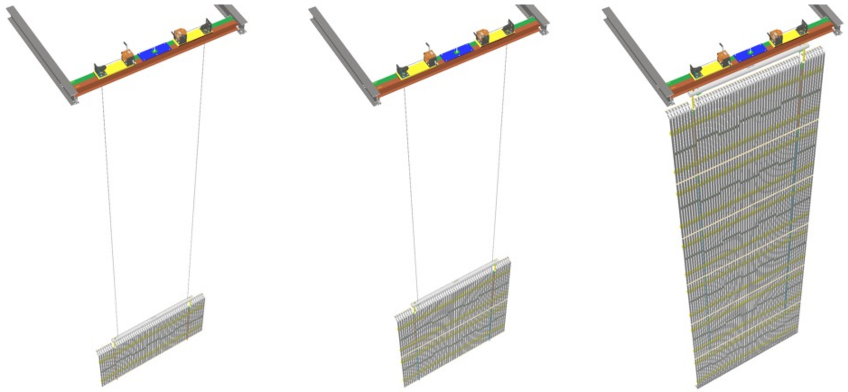
Underground Assembly and Installation

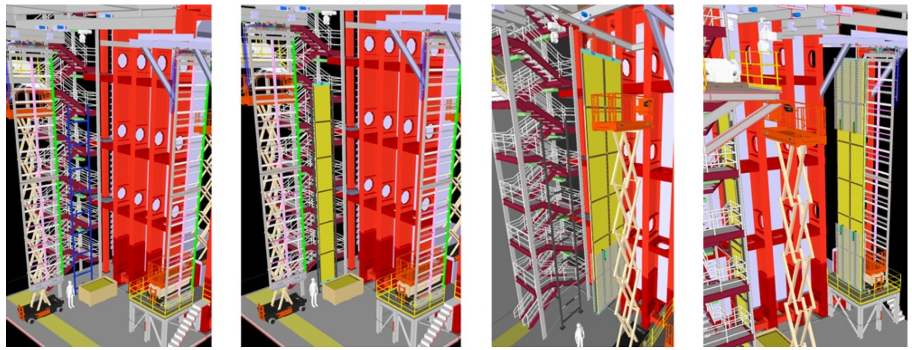
- The start of the FD1 installation is currently projected to be in the summer of 2026, when the inside of the cryostat and the adjacent cleanroom are completed.

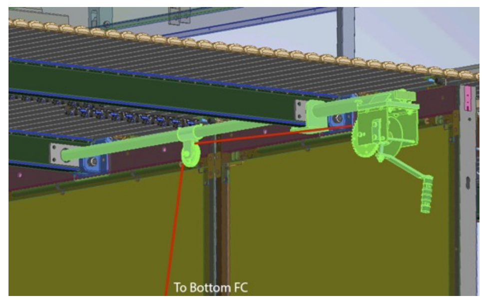


Underground Assembly and Installation

- The first major TPC component to be installed is the east EW FC modules (~1 month).
- The CPAs and T/B FC modules are integrated and installed into the cryostat at a rate about 1 week per row, with the FC modules folded against the CPAs.
- In parallel, the APAs are being installed at a rate about 1.5 week per row. Only after all the CPA and T/B FC are installed, the FC modules are deployed at a rate about 2 rows per week. This gives extra time to access the APAs and electronics if needed.
- The west end wall FC modules are installed before row 25 FC modules are deployed when floor access is still available. The deployment of row 25 is done from outside of the TPC through a temporary gap over the top of the EW FC modules. The EW FC is moved to final position after the row 25 T/B FCs are deployed.
- A low voltage test of the entire HV system will be performed in air to verify all connections.

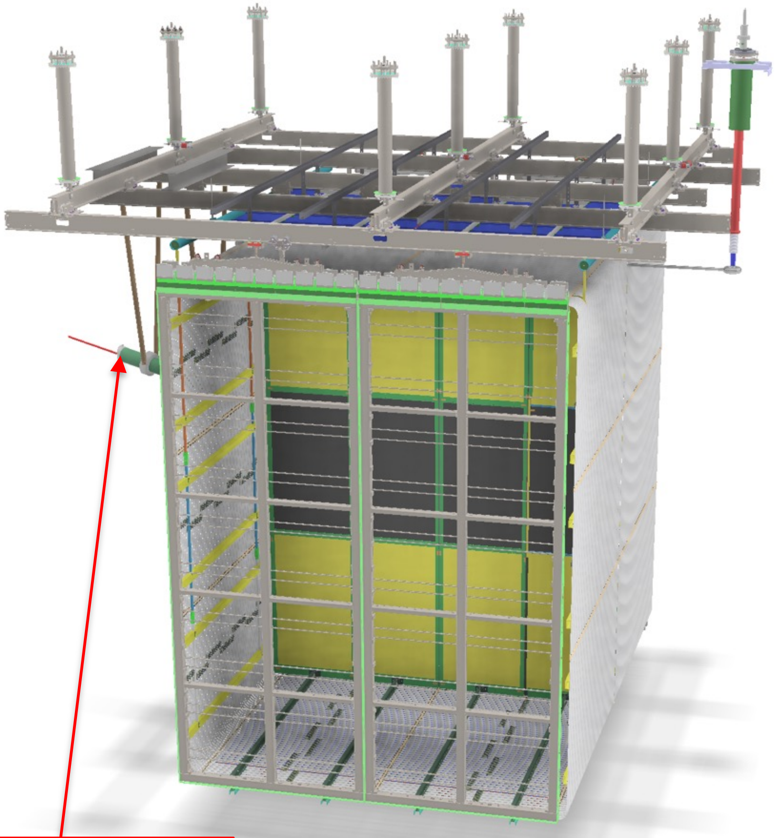




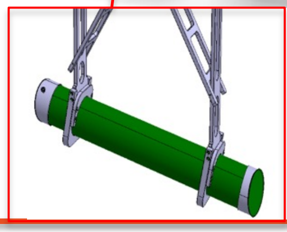


HV system for ProtoDUNE II (module-0)

- TPC in ProtoDUNE-II: 2/3 of the volume of the first run, 2 of 4 APAs in inverted orientation. TPC centered in the beam direction with larger clearance outside of End Walls (similarly to FD-SP-HD)
- **Purpose for HVS:** Validation of FD1-HD design, installation, performance of new field cage modules, new ground plane configuration, HV delivery
- HVS components
  - The CPAs has been reused with minor modifications to reflect current design changes: new frames, anti rotation bars, double HV bus,…)
  - The HV distribution (HVPS - cable - filters - HV feedthrough) is being upgraded with the common HD-VD layout. Fall back to old NP04 HVFT still possible in case the new HVFT is not fully tested when installation in NP04 is required.
  - Top/bottom and End Wall field cage modules with new FD design assembled and mounted
  - Most of the resistive divider boards reused after upgrade with 5 GOhm resistors and full QAQC'd in LSU and CERN
  - Parts for the FC modules prepared at production sites (LSU, SBU, UTA) and shipped to CERN to be assembled on site similarly to what is planned for the FD.
  - Mechanical connections to APAs and DSS will represent the FD design as much as possible.



- Few key differences wrt FD1 with impact on HVS:
  - Special support structure required to tie the bottom of the upright APA to bottom FC and top of the inverted APA to the top FC.
  - Different top/bottom clearance (GP's also at the bottom)
  - Beam plug (out of HVS scope)

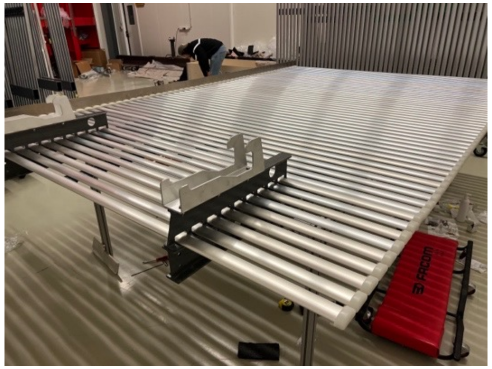


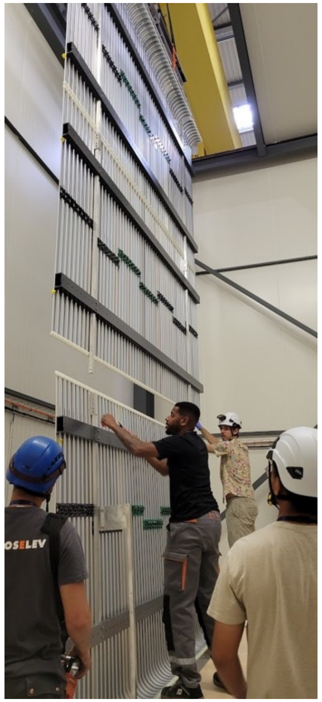
Charge Question #4

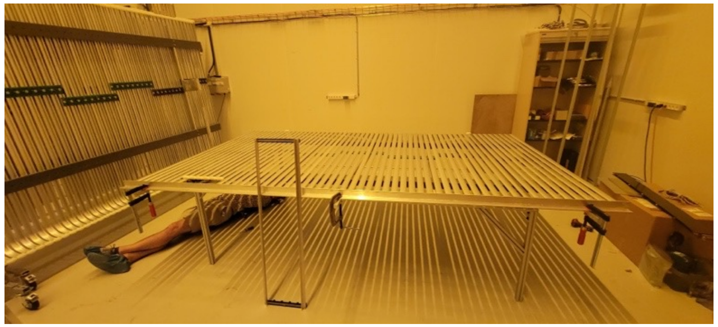
HV system installation in ProtoDUNE II

- From early 2022, teams from production sites (ANL, LSU, SBU, UTA) gathered at CERN for the assembly and installation of the HVS subsystems, in close collaboration with the CERN and Ash River Installation team.
  - Subsystem parts shipped in crates as for FD1
  - NP02 clean room used as assembly area
  - Assembly procedures carefully applied and optimized.
  - QC procedures followed by means of the online applications
  - Personnel requirements and assembly times recorded and validated
  - Lessons learned collected and discussed. FD1-HD HVS design and tools modified accordingly.
- At present, all CPA and FC elements are built and hanging inside the NP04 cryostat
  - No major issues encountered
  - FC Deployment procedures partially tested.
  - Deployment tools tested, optimized and validated
  - CPA-FC-APA and CPA-EW-APA warm alignment partially tested
- Next (Saleve side) installation steps with HVS team involvement:
  - BP installation
  - Top GP's deployments and electrical connections
  - Upstream EW positioning and electrical connections (CPA, terminations boards), QC
  - Top FC's deployment, alignment and electrical connections, QC
  - Bottom GP's deployments and electrical connections (False-floor removal)
  - Bottom FC's deployment, alignment and electrical connections, QC
  - Downstream EW positioning and electrical connections (CPA, terminations boards), QC
- Jura side and HV delivery will follow

ProtoDUNE II HVS photogallery

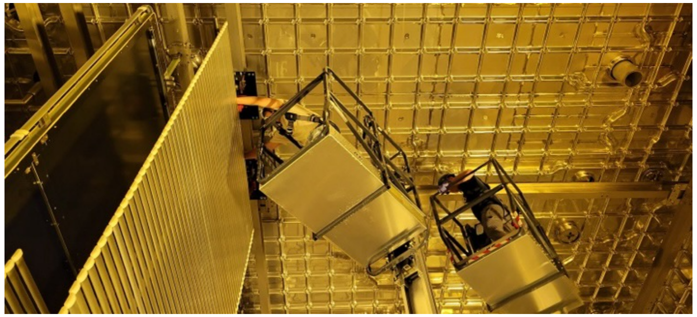


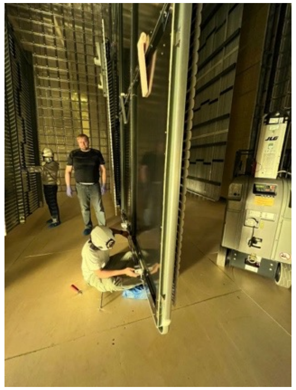


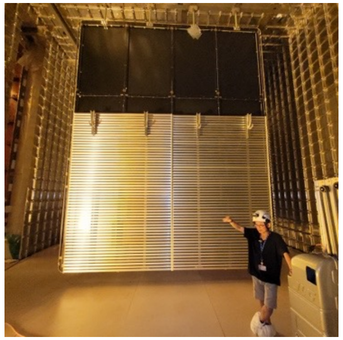


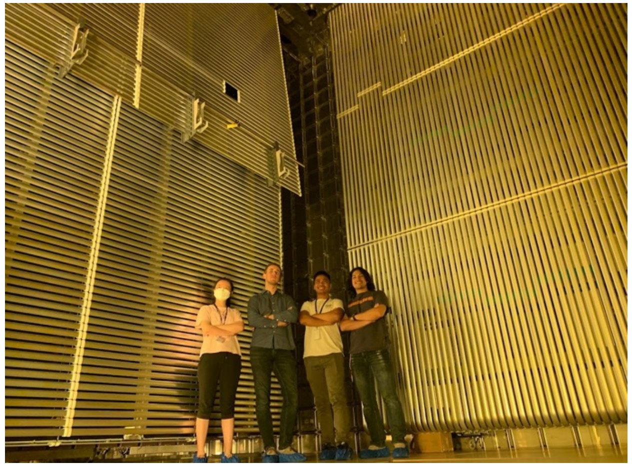
https://photos.google.com/share/AF1QipMORrWjxMKuCObJaXZjCGwk8ZAxZEympW0WEp_CjC19gfc_Br_Cjt9B5cIJ8PgEhg?key=eVBUV1owemRRbXdlMHFTR2d6UVpkTWVheDRSVWN3

ProtoDUNE II HVS photogallery

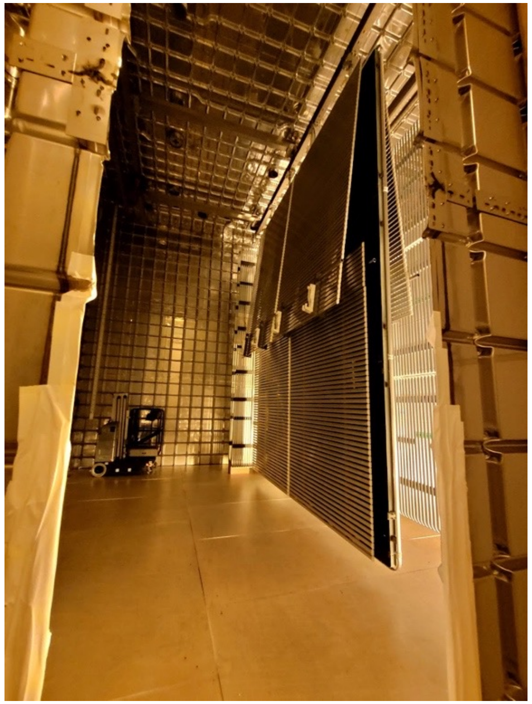


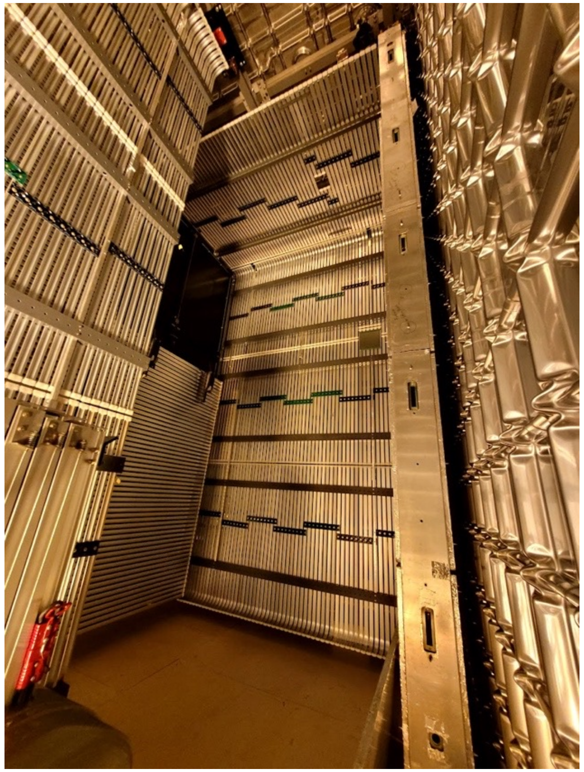
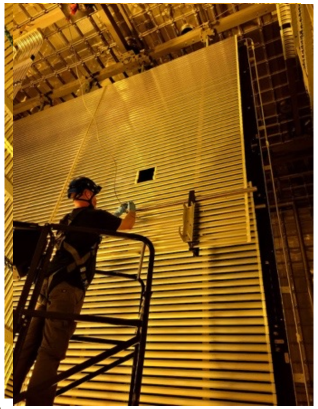


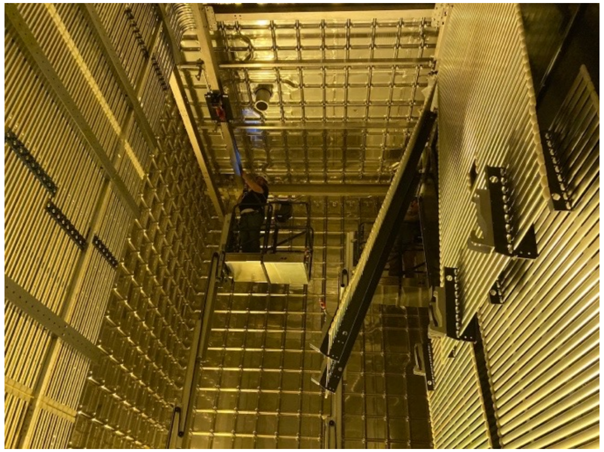




ProtoDUNE II HVS photogallery





Plan towards FD1-HD

- Key milestones:
  - FD1 HVS final design review: now ongoing
  - ProtoDUNE II installation and commissioning: now to summer 2023
  - Post PD2 HVS review: initially planned for Spring 2023, most likely to be pushed just after PD-II commissioning
    - At least few weeks of HVS operation in PD2 to determine if any changes are needed for FD1-HD production ?
    - Start of procurement of long lead time items
    - Start of production tooling fabrication, set up assembly sites
    - Produce pre-production components
  - Production Readiness Review at each production site: late Fall 2023
  - Start full production: Early 2024
  - Start shipping to SURF: 2025 (when SDWF available)
  - FD1 start of installation: Summer 2026

Summary

- The HV System in ProtoDUNE SP operated at the goal voltage of 180kV (highest in a large LArTPC) with >99% uptime during long term operation.
- At the design level, actions were taken to mitigate the occasional HV instabilities observed in ProtoDUNE by increasing the FC to ground plane distance and removing the exterior insulating FC support structures.
- As a value engineering case, a significant reduction of the estimated material and labor of the FC production and assembly has been achieved → validation in progress with ProtoDUNE-II
- Field cage assembly and testing procedures have been highly simplified and will mostly take place at the underground far detector site. → validation in progress with ProtoDUNE-II
- Structural safety analysis completed and approved by CO. Open issues related to interface with DSS to be settled before DSS FDR.
- The plan toward the PRR and FD1-HD is defined and well advanced (no major critical issues identified).