

# High Voltage Distribution: Design Overview

Saba Parsa, L3 HV Subsystem Lead  
ND-LAr Preliminary Design Review  
28 June 2022



Schweizerische Eidgenossenschaft  
Confédération suisse  
Confederazione Svizzera  
Confederaziun svizra



U.S. DEPARTMENT OF  
**ENERGY**

Office of  
Science

## Who am I (or We with subsystem lead and engineer)

- Saba Parsa
  - Postdoc at University of Bern since April 2021

# Outline

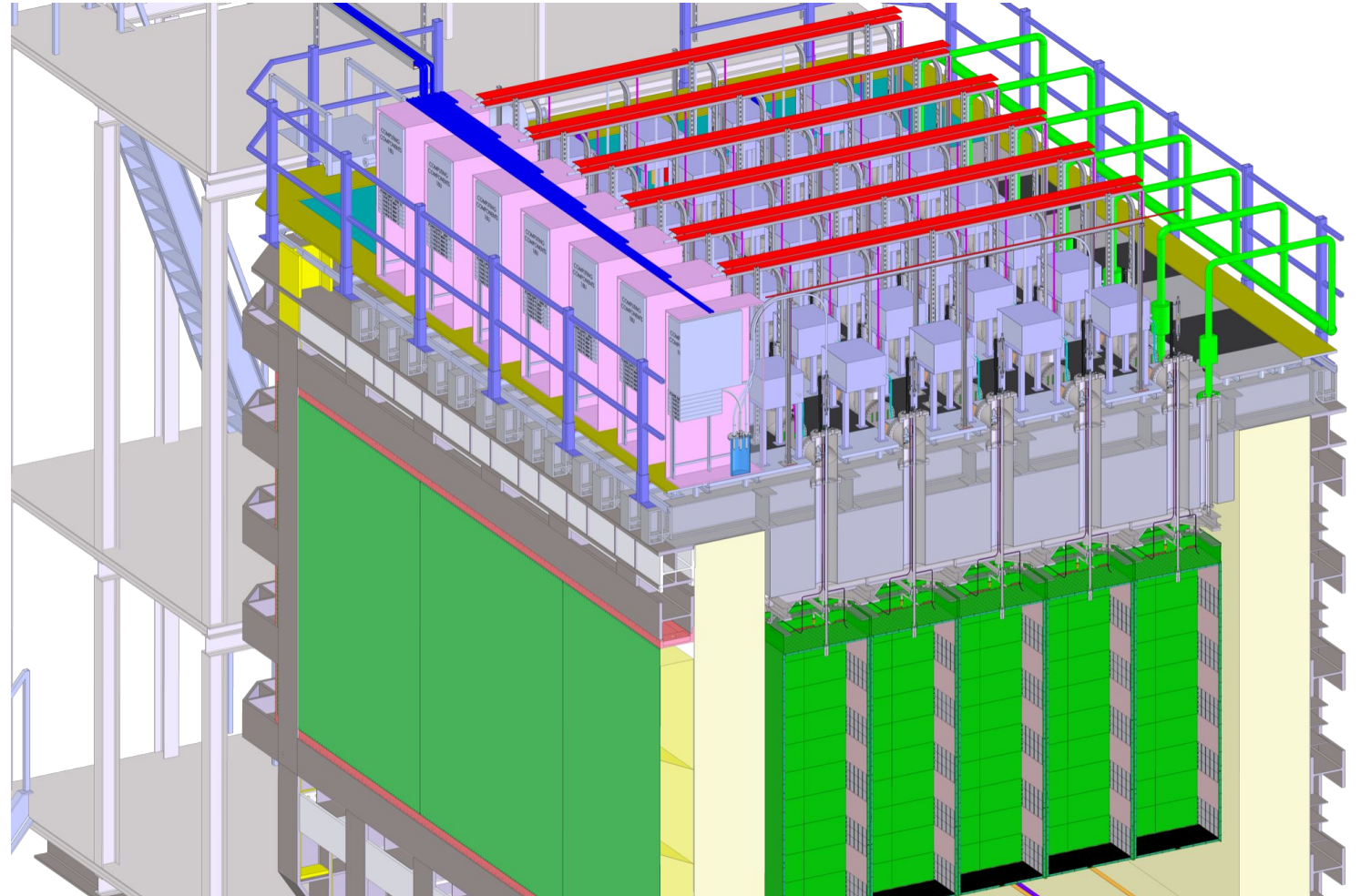
- Scope
- Requirements
- Interfaces
- Procurement, Manufacturing, QA/QC
- Risks and Prototyping
- Recommendations from Previous Reviews
- Cost and Schedule
- Summary

# Subsystem Overview

ND-LAr TPCs will operate with a nominal E field of 0.5 kV/cm, similar to DUNE far detectors

Modular design results in Drift distance of 50 cm in each TPC, Nominal Cathode potential is 25 kV

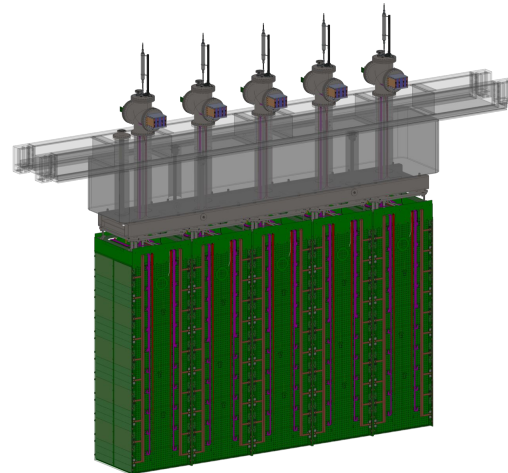
**The HV distribution system** has the role to provide stable 25 kV DC potential with very low noise to the module's Cathode planes



# Subsystem Overview

HV distribution system consists of 7 independent units, each serving a row of 5 ND-LAr Modules:

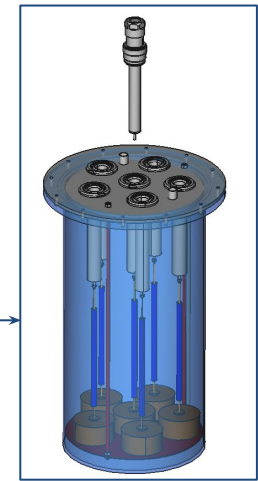
- **HV power supply (Spellman)** to supply 5 modules
- A **low-pass filter-distributor (PFD-5)**, situated between the PS and the modules
- **HV resistive cables**



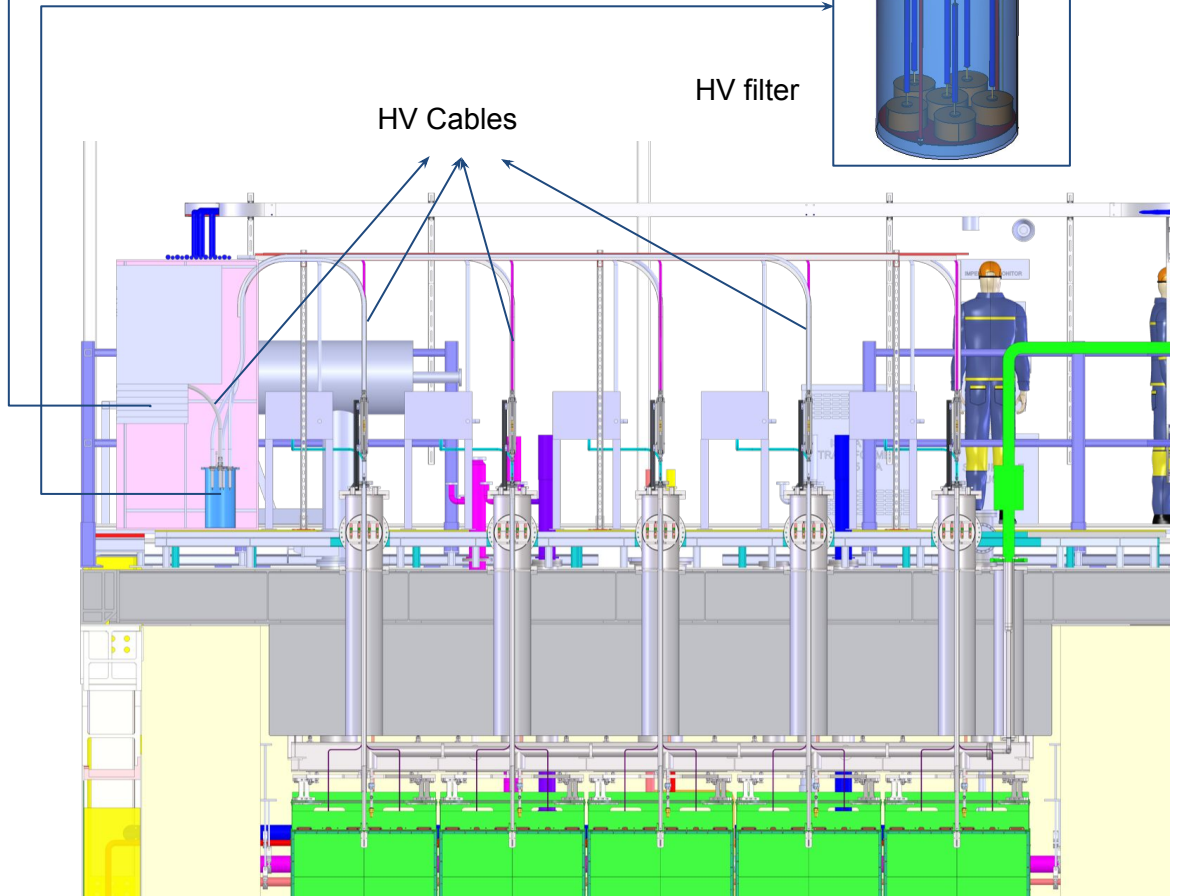
HV delivery to a row of 5 modules  
(In Field Structure Scope)



HV power supply



HV filter

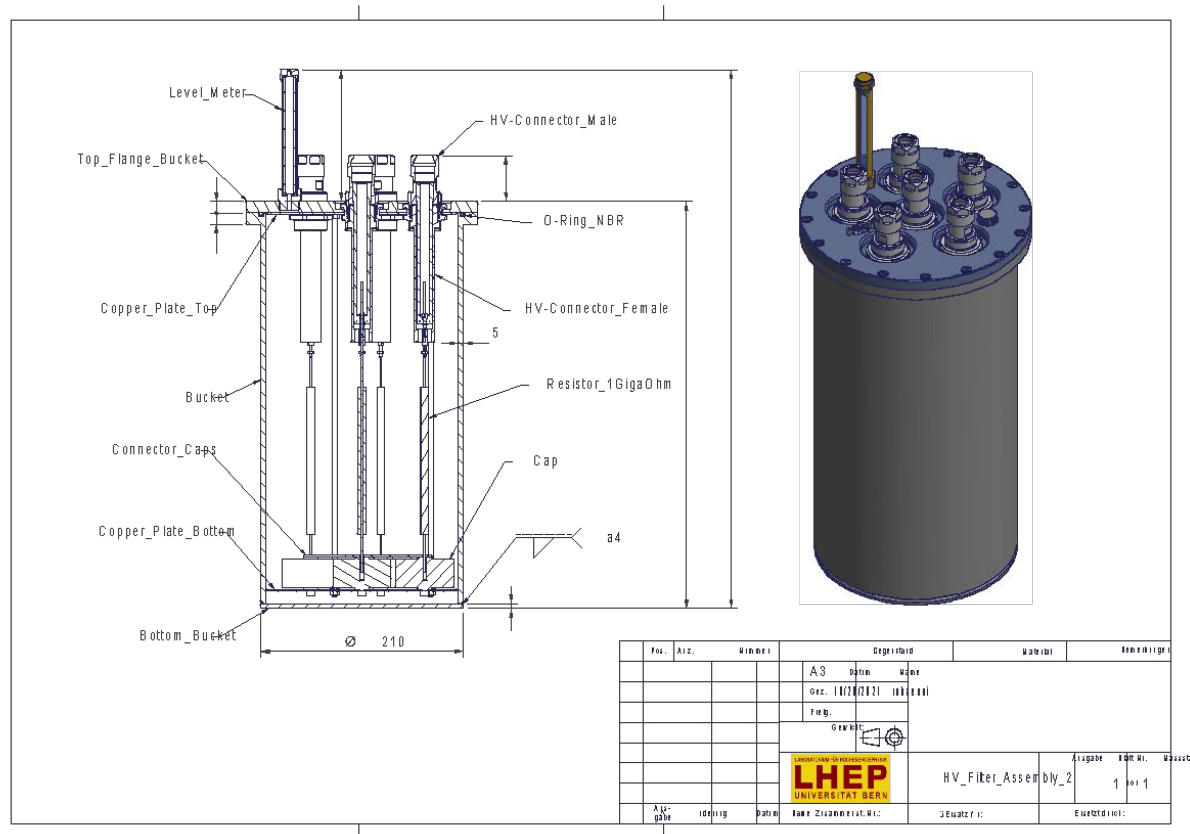


<https://edms.cern.ch/document/2746041/1>

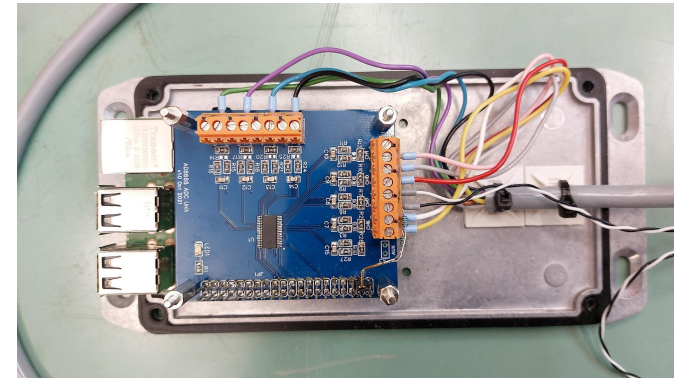


# Subsystem Overview

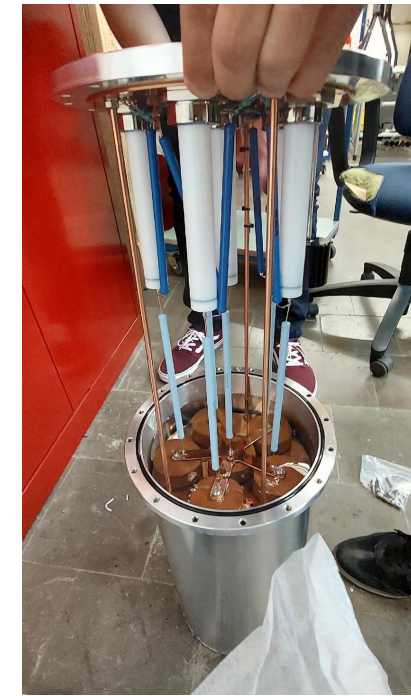
- HV filter, PFD-5 (Potted Filter-Distributor with 5 channels)
  - One PFD-5 unit with the final design is constructed and tested



PFD-5 CAD drawing



HV Monitoring unit



PFD-5 outer and inner view

# Scope

Detailed subsystem scope is defined

- Describes deliverables, quantities, responsible institutions, and funding source during design, prototyping, production and installation phases
- Informed by HV Filter prototypes constructed and tested during 2x2 Single module runs

131.ND.02.03: High Voltage

WBS Dictionary (Concise):

Design and production of the HV supply and distribution for the ND LArTPC modules

Includes:

- HV supplies and cables
- HV filters
- Control and monitoring instrumentation and readout
- Component testing/QC/QA, and associated tooling
- Prototypes for 2x2, Full-scale Demonstrator
- Packaging and shipping
- Support personnel for prototyping, A&T, and I&I, and their travel

Reference CAD Image(s):

HV power supply	PFD-5	HV cables	HV monitor
			

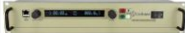
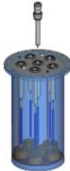
Task/Item	Qty	Spares	Institutions	Funding Source	Funding Status	Detailed description
HV power supply	7	1	Unibe	Switzerland		Specification and Procurement
PFD-5 (Potted Filter Distributer)	7	3	Unibe	Switzerland		Design, production, assembly and testing
HV Cables PS to PFD-5	7	4	Unibe	Switzerland		Specification and Procurement
HV cable PFD to TPC	35		SLAC			
HV Monitor and control unit	7	1	Unibe	Switzerland		Design, production, assembly and testing
Packaging and shipment			Unibe	Switzerland		packaging and shipment
Assembly procedures			Unibe	Switzerland		subsystem procedures for use during A&T and I&I
Support during ND A&T			Unibe	Switzerland		Technical/scientific support during TPC Module assembly and testing pr
Support during ND I&I			Unibe	Switzerland		Technical/scientific support during TPC Module installation and integrat

QA/QC and characterization			Institutions	Funding Source	Funding Status	Detailed description
Prototyping PFD-4 and PFD-5			unibe	Switzerland	allocated	Design, production, and assembly
Test of PFD-4 during Module-0 run			unibe	Switzerland	allocated	Full Operation test in LAr
Test of PFD-5 during Module1-3 runs			unibe	Switzerland	allocated	Full Operation test in LAr
Test of the ND PFD-5s			unibe	Switzerland		Bench qualification tests
Test of all HV connectors			unibe	Switzerland		Bench qualification tests
Test of all HV cables			unibe	Switzerland		Bench qualification tests
Test of the monitoring and control unit			unibe	Switzerland		Bench qualification tests

Prototypes for 2x2			Institutions	Funding Source	Funding Status	Detailed description
HV power supply	1	0	unibe	Switzerland	allocated	Specification and Procurement
PFD-5 (Potted Filter Distributer)	1	0	unibe	Switzerland	allocated	Design, production, assembly and testing
HV Cables	5	1	unibe	Switzerland	allocated	Specification and Procurement
HV Monitor and control unit	1	0	unibe	Switzerland	allocated	Design, production, assembly and testing
Packaging and shipment			unibe	Switzerland	allocated	packaging and shipment
Assembly procedures			unibe	Switzerland	allocated	subsystem procedures for use during assembly
Support during 2x2 operation			unibe	Switzerland	allocated	Technical/scientific support during 2x2 operation, including travel.

<https://edms.cern.ch/document/2720713/1>

- [illegible]

131.ND.02.03: High Voltage				
<b>WBS Dictionary (Concise):</b> Design and production of the HV supply and distribution for the ND LA $\pi$ TPC modules Includes: <ul style="list-style-type: none"> <li>- HV supplies and cables</li> <li>- HV filters</li> <li>- Control and monitoring instrumentation and readout</li> <li>- Component testing/QC/QA, and associated tooling</li> <li>- Prototypes for 2x2, Full-scale Demonstrator</li> <li>- Packaging and shipping</li> <li>- Support personnel for prototyping, A&amp;T, and I&amp;I, and their travel</li> </ul>				
<b>Reference CAD Image(s):</b>				
<b>HV power supply</b> 	<b>PFD-5</b> 	<b>HV cables</b> 	<b>HV monitor</b> 	

QA/QC and characterization	Institutions	Funding Source	Funding Status	Detailed description
Prototyping PFD-4 and PFD-5	unibe	Switzerland	allocated	Design, production, and assembly
Test of PFD-4 during Module-0 run	unibe	Switzerland	allocated	Full Operation test in LAr
Test of PFD-5 during Module1-3 runs	unibe	Switzerland	allocated	Full Operation test in LAr
Test of the ND PFD-5s	unibe	Switzerland		Bench qualification tests
Test of all HV connectors	unibe	Switzerland		Bench qualification tests
Test of all HV cables	unibe	Switzerland		Bench qualification tests
Test of the monitoring and control unit	unibe	Switzerland		Bench qualification tests

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PFD-5 (Potted Filter Distributer)	1 0 unibe	Switzerland	allocated	Design, production, assembly and testing
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HV Monitor and control unit	1 0 unibe	Switzerland	allocated	Design, production, assembly and testing
Packaging and shipment	unibe	Switzerland	allocated	packaging and shipment
Assembly procedures	unibe	Switzerland	allocated	subsystem procedures for use during assembly
Support during 2x2 operation	unibe	Switzerland	allocated	Technical/scientific support during 2x2 operation, including travel.



# Requirements

## Key requirements of the HV distribution system

ID	Requirement title	Description	Value	Rationale	Validation
HV-001	Range for cathode potential	HV range for cathode potential shall be between 15 to 50 kV	15 to 50 kV	Provide choice for charge R factor 0.6 to 0.7 for MIPs	Full scale Demonstrator
HV-002	HV long term stability	Variation of HV shall be 0.1% (0.5mm deviation at cathode or 0.01% in charge) at F<1 Hz	0.1% (0.5mm deviation at cathode or 0.01% in charge)	Coordinate accuracy < 1 mm Charge accuracy <0.1%	Full scale Demonstrator
HV-003	HV ripple/noise	Variation of HV shall be <4 mV (0.016fC or 100e) at 100kHz > f >1 Hz	<4 mV (0.016fC or 100e)	Noise induction to R/O	Full scale Demonstrator
HV-005	HV nominal ramp rate	Nominal ramp rate provided by HVPS shall be 300 V/s (~2pA per pixel)	300 V/s (~ 2pA per pixel)	Ramp up/down rate to limit recharging currents in the TPC to < 5 pA	Full scale Demonstrator

<https://edms.cern.ch/document/2723207/1>

## HV subsystem design, tested with 2x2 program, meets all the requirement

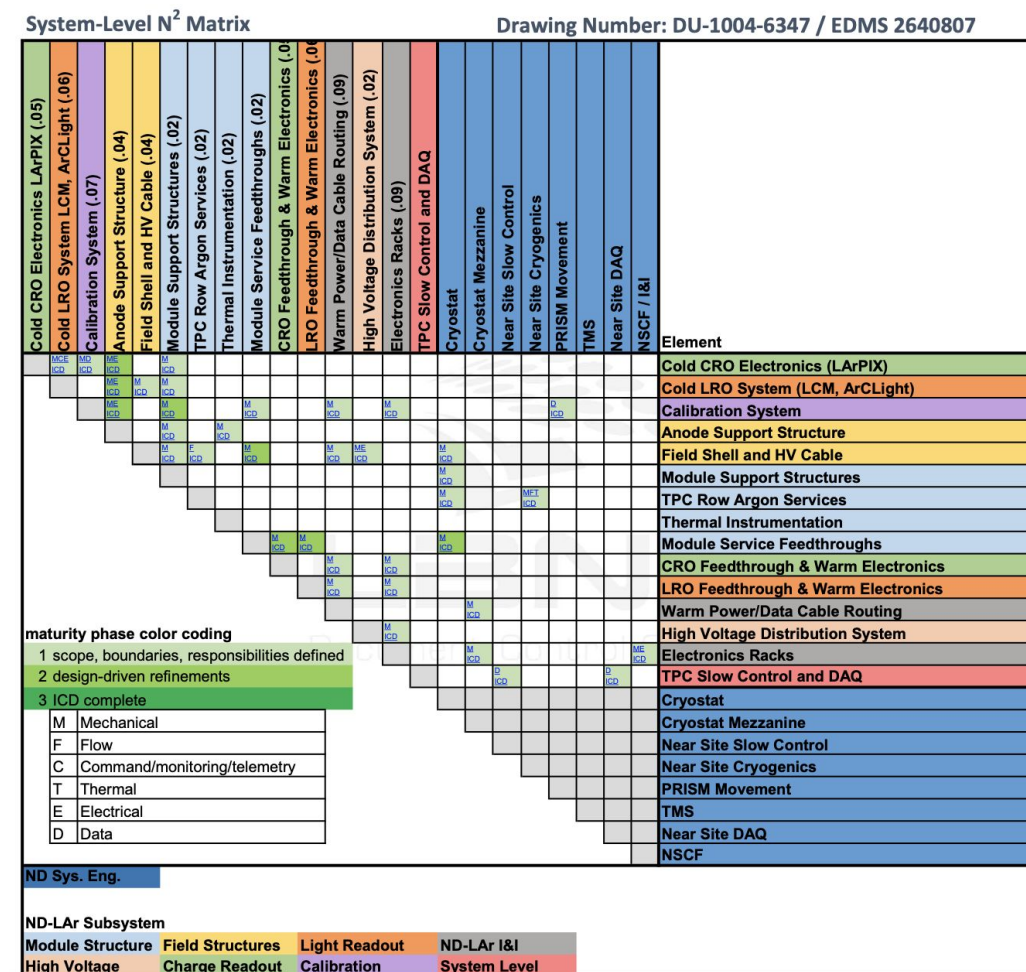
Key	Type	Component	Name	Description	Value	Rationale	Tests	Parent Req/Spec (ID)	Design Validation	Verification Method
131.82.01.01: System Level										
SYS-001	Requirement		ND LACTPC Fiducial Mask	The ND LACTPC shall provide <20 mm fiducial light upon target area	<20 mm	To deliver the required statistical precision (>2%) for the measurement of neutron-electron elastic scattering	To deliver the required statistical precision (>2%) for the measurement of neutron-electron elastic scattering	ND-C1.2.1: Fiducial mask / statistics	Design	Test/Inspection
SYS-002	Requirement		ND LACTPC Active Size	The ND LACTPC active volume shall be $\geq 5$ m in the beam direction, and $\geq 7$ m in transverse directions	$\geq 5$ m in the beam direction, and $\geq 7$ m in transverse directions	To sufficiently contain the ionization signal from beam neutron interactions as gases, except for forward going muons and energetic neutrons.  The size is driven by maintaining sensitivity to the kinematic phase space of the cross-section, and by detector efficiency. Detector efficiency as low as ~5% can be tolerated, as long as the detector is not blind to substantial (low-%) regions of the cross-section phase space.	To sufficiently contain the ionization signal from beam neutron interactions as gases, except for forward going muons and energetic neutrons.  The size is driven by maintaining sensitivity to the kinematic phase space of the cross-section, and by detector efficiency. Detector efficiency as low as ~5% can be tolerated, as long as the detector is not blind to substantial (low-%) regions of the cross-section phase space.	ND-C1.1: Classify interactions and measure outgoing particles in a LACTPC with performance comparable to or exceeding FD	Design	Test/Inspection
SYS-003	Requirement		Prompt Rejection Efficiency	The ND LACTPC shall be able to associate interaction signals to fiducial neutron interactions with a prompt, averaged over interactions, of > 97% by energy	> 97% by energy	After the rejection of prompt, the residual prompt systematic uncertainty should be sub-dominant to other uncertainties in the production of the far detector signal based on near detector data.	After the rejection of prompt, the residual prompt systematic uncertainty should be sub-dominant to other uncertainties in the production of the far detector signal based on near detector data.	ND-C1.1: Classify interactions and measure outgoing particles in a LACTPC with performance comparable to or exceeding FD	Sc-Simulations	Sc-Simulations
SYS-004	Requirement		3D Charge Imaging Accuracy	The ND LACTPC shall be able to associate interaction signals to fiducial neutron interactions with a prompt, averaged over interactions, of > 97% by energy	> 97% by energy	Accurate 3D charge signal imaging is required in order to correctly associate charge deposition to their parent neutron interactions in the high-pileup ND environment.	Accurate 3D charge signal imaging is required in order to correctly associate charge deposition to their parent neutron interactions in the high-pileup ND environment.	ND-C1.1: Classify interactions and measure outgoing particles in a LACTPC with performance comparable to or exceeding FD	Sc-Simulations	Sc-Simulations
SYS-005	Requirement		Charge-Light Signal Matching Efficiency	The ND LACTPC shall be able to associate interaction signals to fiducial neutron interactions with an efficiency, averaged over interaction, of > 97% by energy	> 97% by energy	Efficient matching of the charge signals with the fast (~ns-scale) light signals enable accurate discrimination of the charge signals from the approximately 30 neutron counts contributing to the charge signals per ~10 ns wide beam spill.	Efficient matching of the charge signals with the fast (~ns-scale) light signals enable accurate discrimination of the charge signals from the approximately 30 neutron counts contributing to the charge signals per ~10 ns wide beam spill.	SYS-005: Prompt Rejection Efficiency SYS-006: 3D Charge Imaging Accuracy	Sc-Simulations	Sc-Simulations
SYS-006	Design Choice		Detector Optical Modularity	The ND LACTPC shall have optically isolated regions, nominally 1.5 m <sup>2</sup> , to facilitate matching between the charge and optical signals	1.5 m <sup>2</sup>	Isolation of scintillation light within LACTPC modules facilitates charge-light signal matching.	Isolation of scintillation light within LACTPC modules facilitates charge-light signal matching	SYS-005: Charge-Light Signal Matching Efficiency	Design	Test/Inspection
SYS-007	Requirement		ND LACTPC performance after PRISM detector move	The ND LACTPC shall meet operational performance requirements (electric field uniformity & stability, module alignment, noise, live-probe), within 1 hour after PRISM movement of the detector	1 hour	Start taking high quality data within an hour. This is a allocation of time to complete all activities associated with PRISM moves within an 8 hour shift, driven by operational constraints, and to achieve the required number of moves in a year with a 5% integrated downtime attributed to moving the detector (1 move/week)	Start taking high quality data within an hour. This is a allocation of time to complete all activities associated with PRISM moves within an 8 hour shift, driven by operational constraints, and to achieve the required number of moves in a year with a 5% integrated downtime attributed to moving the detector (1 move/week)	ND-C4.2: Maintain uniform detector performance across full range of movement	Eng. Analysis	Eng. Analysis
SYS-008	Specification		Electric Field Strength (V/cm)	The ND LACTPC shall be able to achieve an electric field strength >250 V/cm (peak 500 V/cm)	>250 V/cm (peak 500 V/cm)	Equivalent electric field as FD to enable operation of the near detector with equivalent levels of electron reconstruction and other field-dependent effects.	Equivalent electric field as FD to enable operation of the near detector with equivalent levels of electron reconstruction and other field-dependent effects.	ND-C1.1: Classify interactions and measure outgoing particles in a LACTPC with performance comparable to or exceeding FD	Eng. Analysis	Full Scale Demonstrator
Validation										
Equivalent electric field uniformity in FD										
The HV system shall be engineered so that it is not a significant source of background and noise.										
This specification is needed to achieve prompt detection and rejection, SYS-003, to provide the required efficiency and accuracy in charge-light signal matching, SYS-005.										
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or Modeling of the anodeless electric field needs to be better than FD										
derived from heat load from charge readout and field map. New hybrid readout - capture heat loads, required flow rate										
RAD Prototype										
ND-C1.1: Classify interactions and measure outgoing particles in a LACTPC with performance comparable to or exceeding FD										
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ND-C1.1: Classify interactions and measure outgoing particles in										

# Interfaces

- Interface Control documents, <https://edms.cern.ch/project/CERN-0000223195>
- Engineering CAD model captures interfaces, <https://edms.cern.ch/project/CERN-0000226247>
- Interfaces realized and validated in 2x2 program

Corresponding system	Interface	Maturity
Field shell and HV cable	Mechanical	Defined
Electronics Rack	Mechanical	Defined
Slow control	Monitoring data	Partially defined

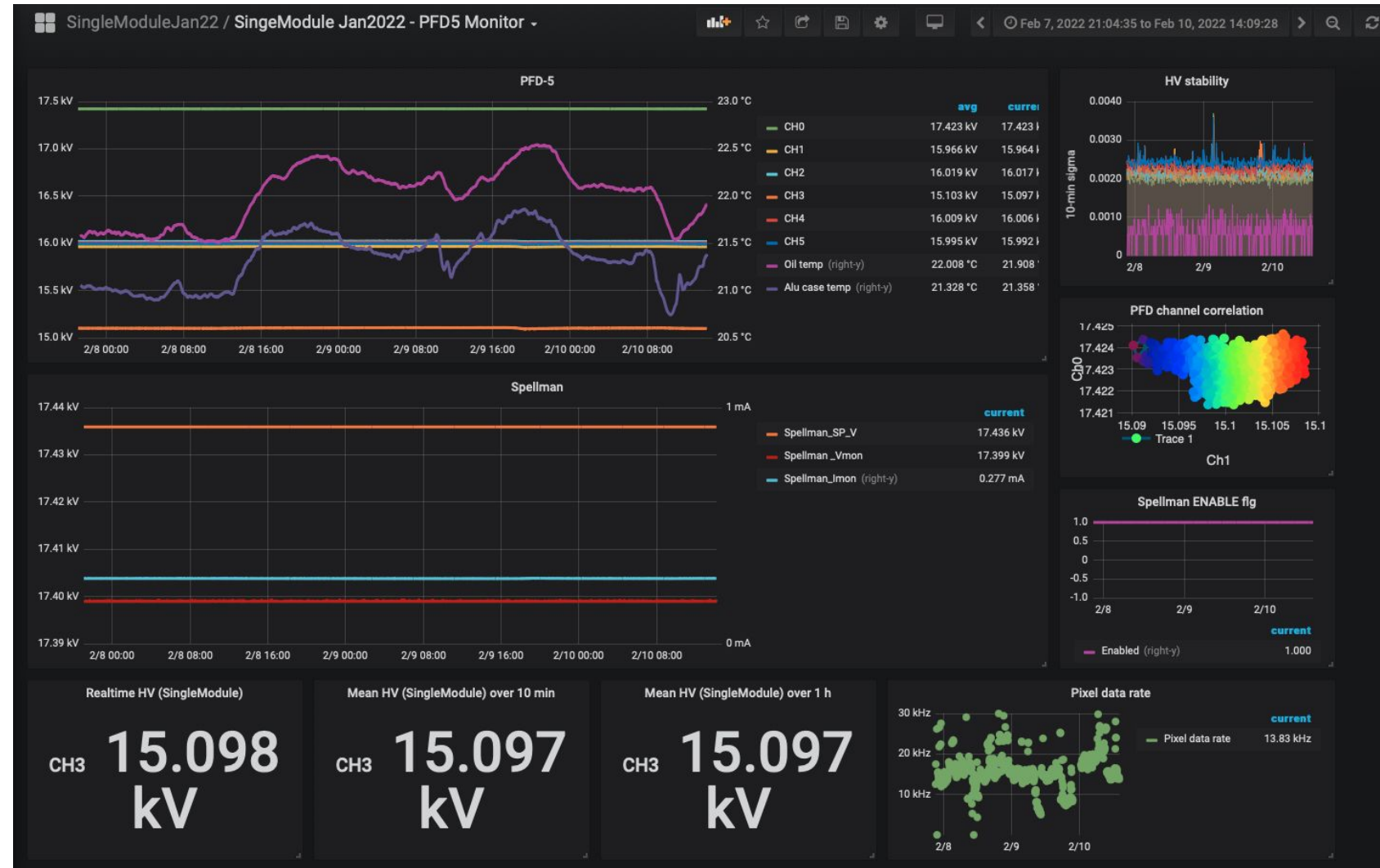
Defined = meets preliminary design maturity



# Slow control implementation at Bern

- Spellman remote control and Monitoring via Ethernet
- PFD-5 Monitoring via a Custom Unit+RPi
- Python scripts
- Data base: InfluxDB
- Visualization: Grafana

Similar dashboard to be integrated within the broader ND-LAr Slowcontrol





# Procurement, Manufacturing, QA/QC

The procurement, manufacturing and QA/QC tests of the HV subsystem will be carried out in-house at University of Bern.

Document	Link to EDMS
Procurement plan	<a href="https://edms.cern.ch/document/2611199/1">https://edms.cern.ch/document/2611199/1</a>
Manufacturing plan	<a href="https://edms.cern.ch/document/2611198/1">https://edms.cern.ch/document/2611198/1</a>
QA/QC plan	<a href="https://edms.cern.ch/document/2611197/1">https://edms.cern.ch/document/2611197/1</a>



## Procurement plan for DUNE ND-LAR HV Distribution System

S. Parsa  
Release Date:

LBNL Document Number:   
CERN EDMS Document Number: 2611199

Revision:   
Revision: v.1

Document Status: Working  
Type: PROCUREMENT PLAN  
LBNL Category Code: DU1000



## Manufacturing Plan for DUNE ND-LAR HV Distribution System

S. Parsa  
Release Date:

LBNL Document Number:   
CERN EDMS Document Number: 2611198

Revision:   
Revision: v1

Document Status: Working  
Type: MANUFACTURING PLAN  
LBNL Category Code: DU1000



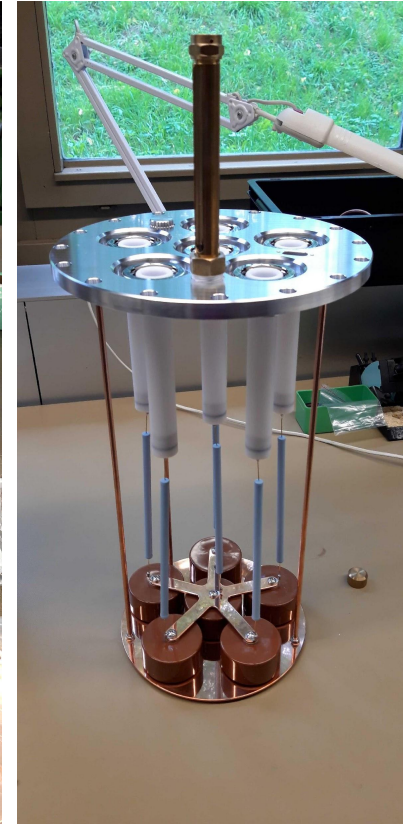
## QA/QC Plan for DUNE ND-LAR HV Distribution System

S. Parsa  
Release Date:

LBNL Document Number:   
CERN EDMS Document Number: 2611197

Revision:   
Revision: v.1

Document Status: Working  
Type: QA/QC PLAN  
LBNL Category Code: DU1000



Manufacturing stages of the HV filter, PFD-5  
Assembly of a PFD-5 takes about one week

# Risks

Risks are actively tracked through Consortium risk registry.

Risk Title	Summary	Mitigation	Probability	Schedule Impact (Months)	Cost impact (\$k)	Technical Impact
HVPS delivery delay	IF the 9 HVPS are delivered with delay, THEN the detector commissioning is delayed as well	Perform Production Readiness Review well in advance and place the order for HVPS	10%	6	-	0 Negligible
Delays with PFD production	IF COVID situation in CH gets worse, THEN manufacturing of the 9 PFD-5 (Potted Filter Distribution) units will be delayed	Perform Production Readiness Review well in advance and start manufacturing a.s.a.p.	10%	6	63	0 Negligible
Change of filter requirements on Fcut	IF requirements of filter cutoff frequency changes, THEN values of R and C in PFD-5 will change, pulling changes in mechanical design	Implement reasonable safety margin (~1 order of mag), <b>retired based on module-1 test</b>	1%	5	30	1 Somewhat Substandard
Change of filter requirements on Vmax	IF requirements of filter max voltage changes, THEN specs of R and C in PFD-5 will change, pulling changes in mechanical design	Implement reasonable safety margin (factor of 2), <b>retired based on module-1 test</b>	0%	5	30	1 Somewhat Substandard
HV Breakdown (Recoverable)	IF changes from MOD0 to ND results in HV Recoverable Breakdown, THEN operation schedule delayed	<b>FSD</b> testing of ND, lowering operating voltage	5%	1	-	1 Somewhat Substandard
HV Instabilities	IF HV instabilities occur, THEN NDLaR TPC will not meet operational data performance will be reduced	<b>FSD</b> testing of ND	10%	-	-	1 Somewhat Substandard
HV Breakdown (Non-Recoverable)	IF HV Breakdown damages equipment, THEN operation cost & schedule is delayed and/or performance degradation	<b>FSD</b> testing of ND, spares	1%	6	200	0 Negligible

Lessons learnt from 2x2 single module runs, to be added to risk registry

Variation in Field shell resistance	IF the modules have different resistances, THEN it is not possible to keep equal drift field in a row of TPCs	Being tested in <b>2x2 program</b> , QA for Field shell resistance, Splitting the filter into individual circuits, using separate power supplies for each module.	10%	4	130	1 Somewhat Substandard
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# Recommendation from previous reviews

<https://edms.cern.ch/document/2741842/1>

Reviewer/Committee: Linda Bagby (FNAL), Francesco Pietropaolo (CERN), Bo Yu (BNL)

Recommendation / Comment	Responder(s)	Comments / Answers / Actions	Status
1. Provide redundancy for the PFD oil temperature monitor.	S. Parsa, I. Kreslo	Second thermocouple added to the PFD5	Closed
2. Provide hardware stack details for external PFD connections.		Acknowledged	In progress
3. Conduct a Grounding Review with the DUNE Grounding and Shielding Committee.		Acknowledged	In progress
4. Conduct a Safety review with the Electrical Safety subcommittee.		Acknowledged	In progress
5. Upload and maintain updates of all required documentation in EDMS within the dedicated folder for all the HV system components. Provide a summary table to help reviewers.		Acknowledged	In progress
6. Cost estimates and schedule should be made available and presented at the PDR.		Acknowledged	In progress
7. Test HV breakdown effect of one module on other channels		Acknowledged	In progress

# Cost

From Mar. 2022 cost review

	Design & Prototyping				Production					
	On-Project		Off-Project		On-Project		Off-Project		On-Project	
	M&S [CY-k\$]	Labor [k-hrs]	M&S [CY-k\$]	Labor [k-hrs]	M&S [CY-k\$]	Labor [k-hrs]	M&S [CY-k\$]	Labor [k-hrs]	Total Cost [FBAY-k\$]	Avg. Uncert.
131.ND.02: ND-LAr										
01 ND LArTPC Management	\$401.5	18.3	-	43.9	\$412.5	13.8	-	72.5	\$10,114.9	10%
02 Module Structure	-	-	-	14.3	-	-	\$2,448.0	22.0	-	-
03 HV	-	-	-	10.5	-	-	\$816.0	14.0	-	-
04 Field Structure	\$159.1	9.4	-	0.6	\$3,560.1	4.9	-	6.5	\$7,642.6	60%
05 Charge Readout	\$1,331.3	17.7	-	16.6	\$3,366.0	5.5	-	20.8	\$10,741.6	35%
06 Light Readout	-	-	-	71.1	-	-	\$5,508.0	15.1	-	-
07 Calibration	\$193.7	1.3	-	33.1	-	-	-	20.3	\$414.0	50%
08 TPC Module Assembly and Testing	\$368.1	7.1	-	8.6	\$103.0	5.7	-	32.0	\$1,865.1	41%
09 TPC Integration and Installation	\$584.2	11.4	-	12.4	\$426.0	9.6	-	15.0	\$5,384.2	50%
10 Module Assembly & Test Facility	-	5.7	-	-	\$1,483.0	10.8	-	27.3	\$4,114.0	60%
11 Full-scale Demonstrator Test Facility	\$1,497.5	9.1	-	6.3					\$3,726.2	60%
12 ArgonCube Test Facility	-	-	\$1,250.0	20.9					-	-
13 2x2 NUMI Test Beam Facility	-	-	\$2,300.0	15.0					-	-
Total:	\$4,535.3	79.9	\$3,550.0	253.2	\$9,350.6	50.5	\$8,772.0	245.5	\$44,002.5	43%

## Notes:

1. Extracted EAC from working resource-loaded schedule for internal cost review (P6/Cobra ND-LAr Sandbox, 22 Mar. 2022)
2. Includes all on-project and majority of off-project resource estimates for ND-LAr Consortium.
3. Off-project resources include both international and domestic investments
4. CY-k\$: Costs in current-year direct kilo-dollars. FBAY-k\$: Costs in fully-burdened at-year (escalated) kilo-dollars.

[illegible]

# Summary

- Validation and maturity of High Voltage system design exercised through 2x2 program
  - Scope is well-defined with no gaps
  - Intra-system and inter-system interfaces are well-understood
  - System requirements evaluated with prototype operation
  - Exercised parts production, QA, and QC with already constructed PFD-5 for Module-1 test
- HV distribution system is ready to move towards final design and production of FSD