131.ND.02.07 Calibration: Overview

Jelena Maricic and Kendall Mahn - Calibration subsystem managers

ND-LAr Preliminary Design Review

28 June 2022

Introduction

LBNF/DUNE

- Jelena Maricic is faculty at University of Hawaii since 2012 and has been a member of DUNE/LBNE/DUSEL since 2008 with most recent previous involvement in cryogenic instrumentation and FD ionization laser positioning system.
- Previous and other projects:

  DarkSide experiment calibration manager (2012 – 2022), PROSPECT experiment source calibration (2018 – 2022), Double Chooz experiment calibration (2006 – 2016), KamLAND experiment installation, veto calibration and analysis

- Kendall Mahn is faculty at Michigan State University since 2014 and has been a member of DUNE/LBNE since 2014.
- Previous and other projects:

  DUNE FD Calibration Consortium Technical lead (2018-2019), DUNE calibration task force co-leader (2017-2019). T2K TPC system expert for shift, detector commissioning. T2K ND alignment coordinator (2009-2011). Recent analysis roles include T2K analysis coordinator (2017-2021).

Outline

LBNF/DUNE

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

131.ND.02.07 Calibration system overview

- Must facilitate ND LAr to fulfill its physics goals by providing calibration function that will correct the reconstructed charge and vertex throughout the LAr TPC volume and module-to-module variation

- PE (photoelectron) laser calibration achieves its goal by a combination of photoelectric targets on the cathode that emit charge clouds when illuminated by fiber-guided laser light inside TPC.
  - Complementary to in situ sources, including copious rock muons produced during beam spills and cosmic rays
  - PE provides rapid and precise measurements pre and post detector motion

- PE laser system motivated by T2K PE laser system used in gaseous TPC and experience from high power ionization laser in MicroBooBE and ProtoDUNE-SP.
  - novel elements: very high photoelectron yield in LAr required
  - efficient transmission in high power laser beam-to-fiber interface

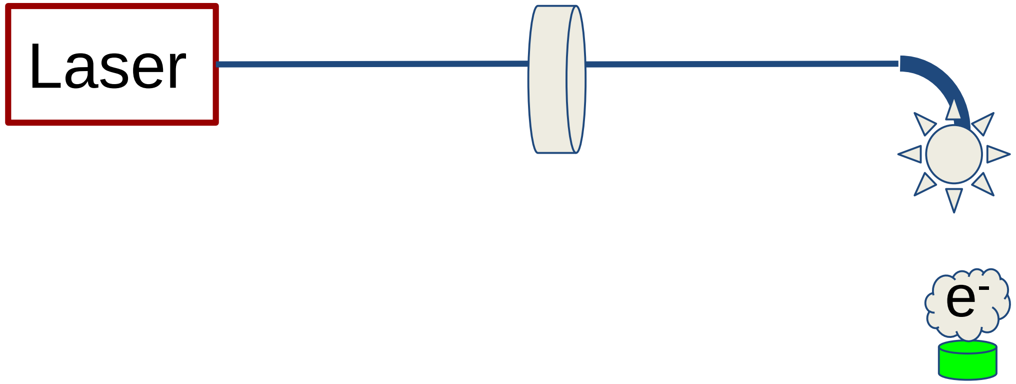
131.ND.02.07 Calibration system overview: status

- Started later - not included in 2x2 prototype
- Current status between conceptual design and PDR readiness

- PDR validation tests carried out at the lab setup at UH and MSU and SLAC Single Cube prototype.
- Final validation in FSD → acceptable plan considering relatively modest size and relatively straightforward deployment.

- Design and prototyping plan to be on US funding, but not production because of cost pressure
- Anticipated production cost about half a million USD allocated from other sources

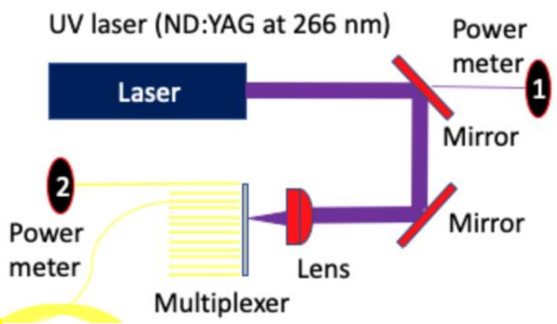
131.ND.02.07 Calibration system overview: technical maturation plan



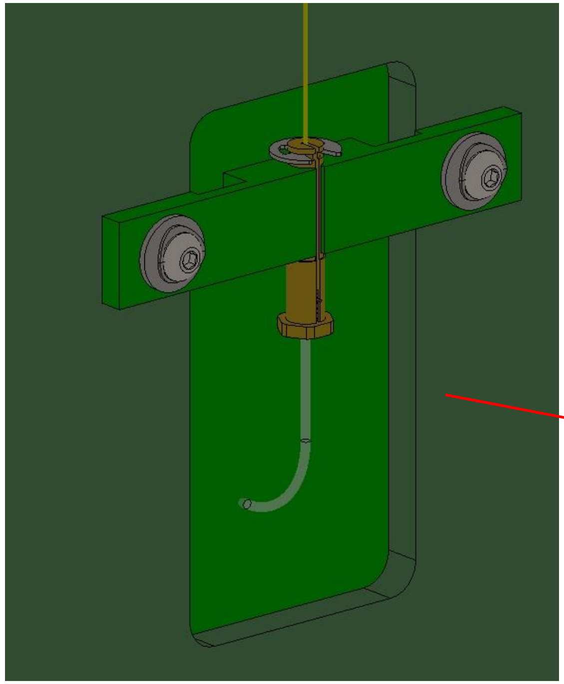
- Lab tests:
  - measure light losses at different stages of light injection (UH)
  - verify PE yield in vacuum from oxidized targets (UH)
  - produce targets, verify attachment and production (MSU)
- SLAC Single Cube test ((UH + MSU):
  - verify PE yield from targets in LAr
  - exercise the entire PE laser calibration chain
  - validate simulations with actual cosmic ray data
  - test alternative calibration sources (deploy radioactive targets)
- FSD - final validation of the PE system

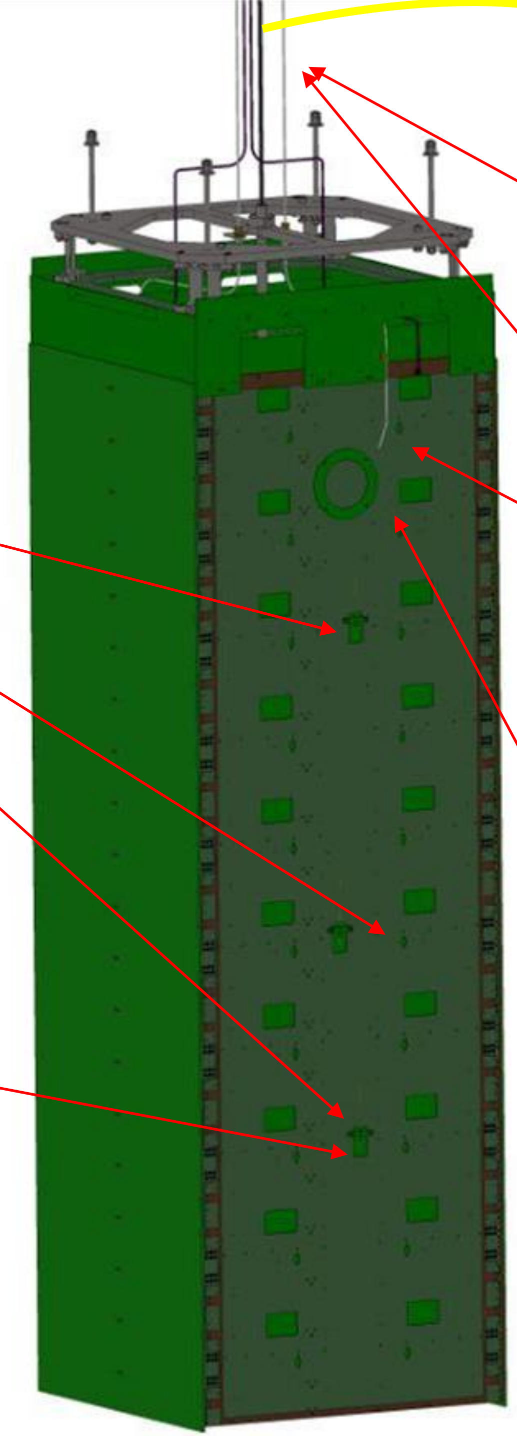
ND LAr TPC Calibration Subsystem Design

CFR200 Quantel Compact Nd:YAG 266 nm, pulsed

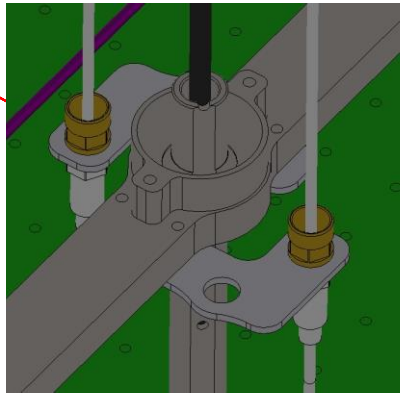


Calibration insertion points on backplate

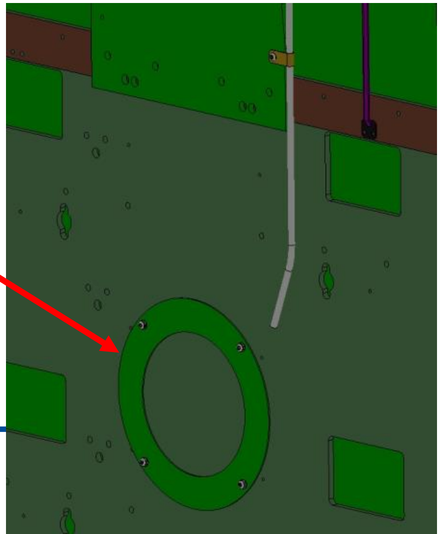




Laser fiber guidetubes



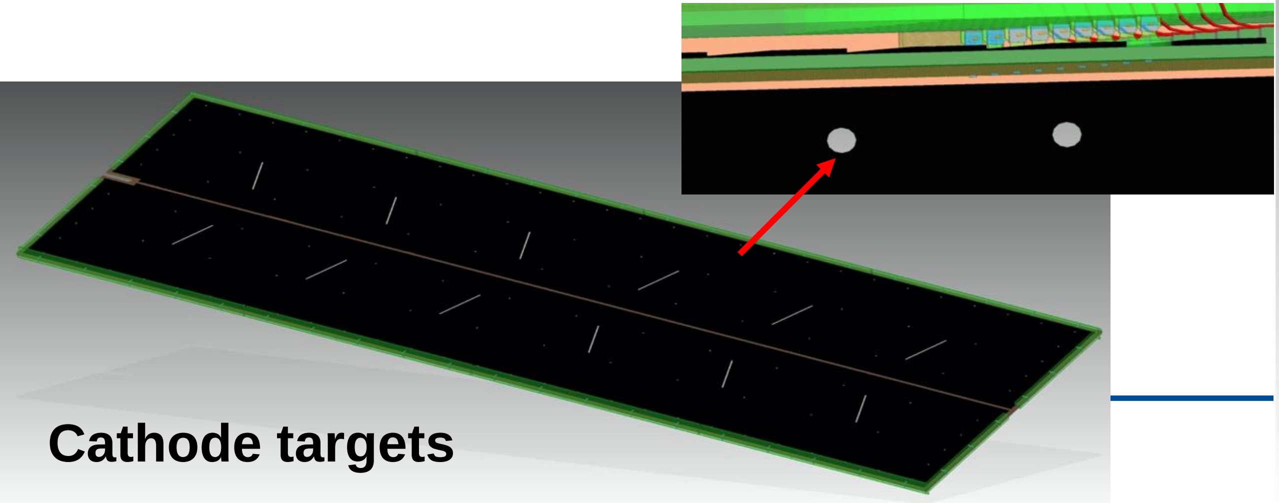
Loop to hold optical fiber slack



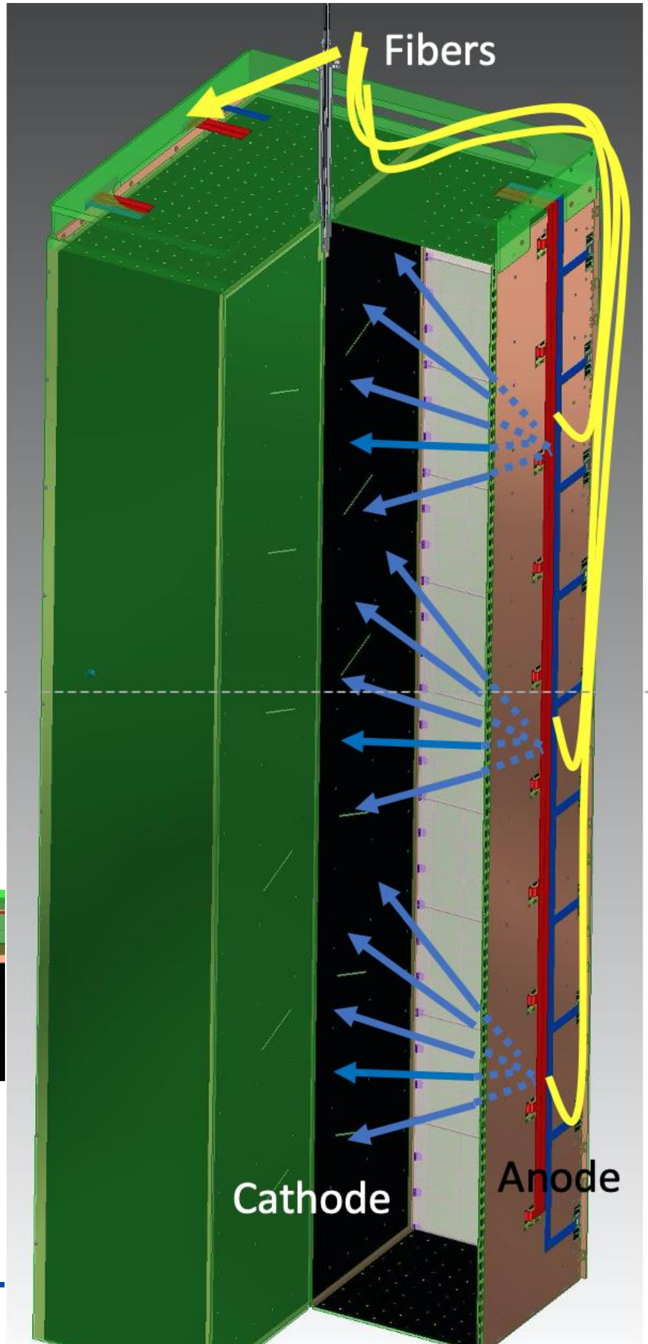
ND LAr TPC Calibration Subsystem Design

ND-LAr Calibration SubSystem Institutional Responsibilities

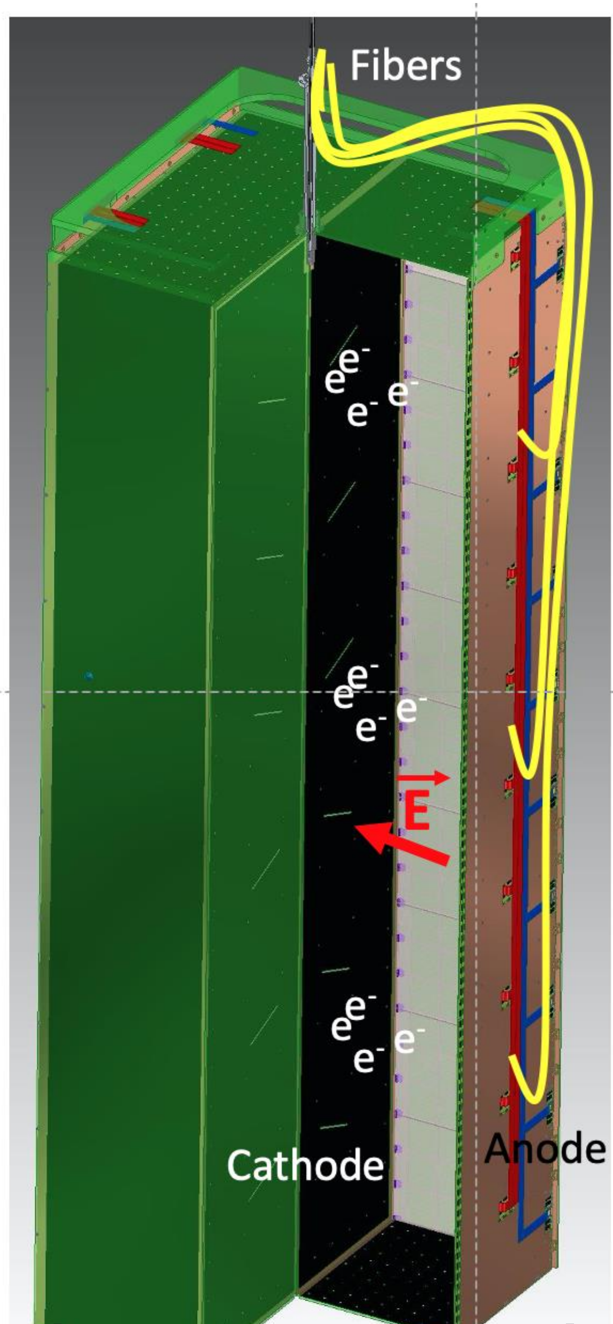
Task	Institutions
PE laser light delivery	UHawaii
Cathode photoelectric target production	MSU



Cathode targets



Cathode illumination



Photoelectron clouds

131.ND.02.07 Calibration: Scope

https://edms.cern.ch/document/2619611/1

Detailed subsystem scope per WBS dictionary:

- Calibration scope boundaries are clearly defined and encompass charge (energy) and vertex calibration

Includes:

- Deliverables, quantities, responsible institutions, and funding source during design and prototyping phases
- Production and installation phases funding TBD (options under investigation)

Informed by Single Cube module and Full Scale Demonstrator prototypes and ND-LAr CAD model.

Aligned with BOEs and resource-loaded schedule for design and prototyping phase.

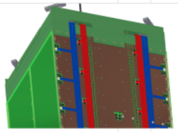
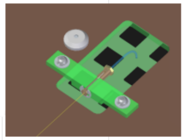
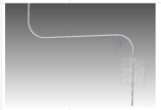
- BOE also prepared for production/installation once funding model fixed

131.ND.02.07: Calibration

WBS Dictionary (Concise):

Design and production of the calibration system for the ND LArTPC modules
Includes:
- Light, charge, field calibration system
- Cabling and feedthroughs
- Control and configuration software/firmware
- 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

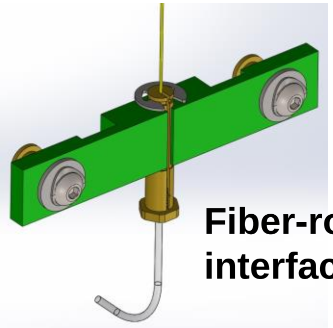
Reference CAD Image(s):

Task/Item	Qty	Spares	Institutions	Funding Source	Funding Status	Detailed description
Design and prototyping						
Laser for design stage	1	0	University of Hawaii	DUNE-US Project	Allocated	1 laser is allocated for design stage
Laser safety enclosure box for design stage	1	0	University of Hawaii	DUNE-US Project	Allocated	Custom made box to enclose the beam
Powermeter for design stage	1	0	University of Hawaii	DUNE-US Project	Allocated	Commercial device used to monitor the pulse-to-pulse variation between laser pusles and overall power stability
Multiplexer for design stage	1	0	University of Hawaii	DUNE-US Project	Allocated	Multiplexer provides an interface between the laser/fiber and multple optical fibers leading to TPC modules in sequential order. Available from a vendor.
Flanges for design stage	1	0	University of Hawaii	DUNE-US Project	Allocated	One flange with 3 optical feedthroughs for each side of each TPC module.
Quartz fibers (600 um core) for design stage	20	0	University of Hawaii	DUNE-US Project	Allocated	Quartz fiber 600 um (8 m long); 3 fibers per volume; 6 per module $47/m
Fiber holder for design stage	2	0	University of Hawaii	DUNE-US Project	Allocated	Custom-made holders to attach fibers inside TPC
Lenses and other optical elements for design stage	5	0	University of Hawaii	DUNE-US Project	Allocated	Focusing elements for laser beam - fiber interface
Photoelectric targets for design stage	30	0	MSU	DUNE-US Project	Allocated	Photoelectric target design, production and assembly
Fiber routing between flange and TPC for design stage			MSU	DUNE-US Project	Allocated	Assembly
Assembly for design stage			University of Hawaii/MSU	DUNE-US Project	Allocated	Assembly
Packaging and Shipping for design stage			University of Hawaii/MSU	DUNE-US Project	Allocated	
Production						
Laser	7	1	University of Hawaii	DUNE-US Project	Allocated	1 laser is allocated from design funds, but additional funds will be required for procurement of a spare laser
Laser safety enclosure box	7	0	University of Hawaii		Not-allocated	Custom made box to enclose the beam
Powermeter	7	1	University of Hawaii		Not-allocated	Commercial device used to monitor the pulse-to-pulse variation between laser pusles and overall power stability
Multiplexer	7	1	University of Hawaii		Not-allocated	Multiplexer provides an interface between the laser/fiber and multple optical fibers leading to TPC modules in sequential order. Available from a vendor.
Flanges	70	1	University of Hawaii		Not-allocated	One flange with 3 optical feedthroughs for each side of each TPC module.
Quartz fibers (600 um core)	210	10	University of Hawaii		Not-allocated	Quartz fiber 600 um (8 m long); 3 fibers per volume; 6 per module $47/m
Fiber holder	210	10	University of Hawaii		Not-allocated	Custom-made holders to attach fibers inside TPC
Lenses and other optical elements	210	10	University of Hawaii		Not-allocated	Focusing elements for laser beam - fiber interface
Photoelectric targets	10500	100	MSU		Not-allocated	Photoelectric target design, production and assembly
Fiber routing between flange and TPC			MSU		Not-allocated	Assembly
Wheel for fiber routing on TPC backplate	70	5	University of Hawaii/MSU		Not-allocated	Desgin, fabrication and assembly
Assembly			University of Hawaii/MSU		Not-allocated	Assembly
Packaging and Shipping			University of Hawaii/MSU		Not-allocated	
Support during ND A&T			University of Hawaii/MSU		Not-allocated	Technical/scientific support during TPC Module assembly and test program at the MATF, including travel.
Support during ND I&I			University of Hawaii/MSU		Not-allocated	Technical/scientific support during TPC Module installation and integration at the DUNE Near Detector Site, including travel.
QA/QC and characterization						
UV laser power and stability			University of Hawaii	In-kind, US base grants labor	Allocated	Lab tests at University of Hawaii
Laser fiber connectors and attenuation			University of Hawaii	In-kind, US base grants labor	Allocated	Lab tests at University of Hawaii
Optical feedthroughs on flanges throughput			University of Hawaii	In-kind, US base grants labor	Allocated	Lab tests at University of Hawaii
Quartz rod light throughput, spread and illumination uniformity			University of Hawaii	In-kind, US base grants labor	Allocated	Lab tests at University of Hawaii
Photoelectric target yield and uniformity			University of Hawaii/MSU	In-kind, US base grants labor	Allocated	Lab tests at University of Hawaii and MSU
Attachment of targets on the cathode			MSU	In-kind, US base grants labor	Allocated	Lab tests at MSU
Survey of the exact positions of the photoelectric targets on the cathodes prior to module assembly			MSU	In-kind, US base grants labor	Allocated	Pre-assembly survey by MSU
Prototypes for 2x2						
None						
Prototypes for FSD						
Laser	1	0	University of Hawaii	DUNE-US Project	Allocated	1 laser is allocated from R&D funds
Laser safety enclosure box	1	0	University of Hawaii	DUNE-US Project	Allocated	Custom made box to enclose the beam

131.ND.02.07 Calibration: Scope

https://edms.cern.ch/document/2619611/1



Fiber-rod interface

Task/Item	Qty	Spares	Institutions
Design and prototyping			
Laser for design stage	1	0	University of Hawaii
Laser safety enclosure box for design stage	1	0	University of Hawaii
Powermeter for design stage	1	0	University of Hawaii
Multiplexer for design stage	1	0	University of Hawaii
Flanges for design stage	1	0	University of Hawaii
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Fiber holder for design stage	2	0	University of Hawaii
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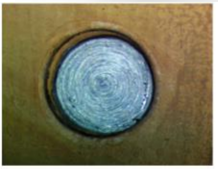
Photoelectric targets for design stage	30	0	MSU
Fiber routing between flange and TPC for design stage			MSU
Assembly for design stage			University of Hawaii/MSU
Packaging and Shipping for design stage			University of Hawaii/MSU

Fiber holder Single Cube

Flange for Single Cube

Design and Prototyping phase deliverables



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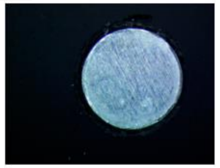
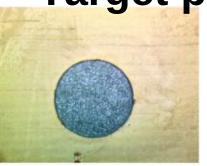


laminated 3M dot on XC cathode

Target prototypes



powder (2:3; sanded) on Cu

mixed airport beads on copper

Laser table

Laser

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131.ND.02.07 Calibration: Requirements

https://edms.cern.ch/document/2589287/1

- Low level requirements such as QE of targets in LAr and exercise of the full calibration chain can be validated in SLAC Single Cube test

- Other requirements can only be validated in the Full Scale Demonstrator or by design and simulations of the full ND LAr TPC

Name	Primary Text	Value	Rationale
Electric field measurement precision	Measure the electric field at a given position to better than 1%	1%	In order to reach the physics goals of DUNE, ND must deliver flux measurements for FD and not increase systematic errors associated with the measurements.
Calibrated Field Uniformity of 96% of active volume	Calibration correction matrix for the Field Uniformity of 96% of the active volume shall be accurate to 1%, for all ND LAr TPC modules drift volumes	<1%	Modeling of the as-delivered electric field needs to be better than FD.
E field measurement coverage	Develop a calibration matrix for the E-field spatial uniformity and TPC module cross-calibration for all ND LAr TPC modules drift volumes	All drift volumesin all TPC modules	Match performance of FD TPC.
E field granularity	PE target sampling density shall be 20 x 20 cm2	20 x 20 cm2	Set by maximal expected E field distortions.
E field stability over time	Run calibration tests between beam spills and monitor E field stability (spatial uniformity and cross-calibration) and update calibration matrix as needed.	Between beam spills	Calibration conducted between beam spills does not affect detector livetime, while calibrating detector regularly.
Cross-calibration of ND TPCs	Calibration system shall be able to cross-calibrate (lifetime, drift time/velocity, diffusion, vertex reconstruction, cathode tilt, Efield uniformity) TPC modules in the ND better than 1%	1%	For the entire detector to produce measurements at 1% precision, individual module measurements should be cross-calibrated at better than 1% precision.
Vertex reconstruction precision	Calibration system shall provide measurements to determine corrected vertex (interaction point) precision to better than 0.4 cm	0.4 cm	ND pixels are spaced at 0.4 cm driving the limit on the precison of vertex reconstruction. Their spacing in turn is driven by the wire spacing in the FD which is 0.43 cm.
Cathode plane tilt	Calibration system shall detect cathode plane tilt from vertical larger than 0.5 cm/m	0.5 cm/m	0.5 cm/m corresponds to 1% change in electric field strength in the drift direction.
Electron Lifetime	Calibration system shall measure the electron lifetime of self generated electron cloud with an uncertainty of 1%	1%	Measurement precision of the electron lifetime should be such to not affect the energy reconstruciton of interactions in the ND modules and this should guide the requirement for the measurement.
Electron diffusion	Calibration system shall measure electron diffusion in TPC with uncertainty of 5%	5%	Electron diffusion effects must be accurately understood to meet ND-C1.1
Linearity of charge collection efficiency	Calibration system shall measure the linearity of charge collection better than 1%	1%	Linearity of charge collection efficiency effects must be accurately understood to meet ND-C1.2
PE circular laser target size	Calibration system shall provide PE target size < 0.4 cm to ensure small electron cloud formation and required vertexing precision	0.4 cm	
PE strip target width	Calibration system shall provide PE strip width < 0.4 cm	0.4 cm	
PE target photoelectron yield uncertainty	Calibration system PE target yield uncertainty should be known to better than 10%	10%	
PE target yield uncertainty stability	Calibration system PE target yield uncertainty shall be stable to 1% over 10 years (timeframe)	1%	
PE laser target positioning	Calibration system Laser target positions should be surveyed after installation and their coordinates know to better than 2 mm	2 mm	PE laser toarget position effects must be accurately understood to meet ND-C1.3
Minimum PE target yield	Electron cloud should be above detector triggering threshold 5000 electrons	5000 electrons	

131.ND.02.07 Calibration: Requirements

https://edms.cern.ch/document/2589287/1

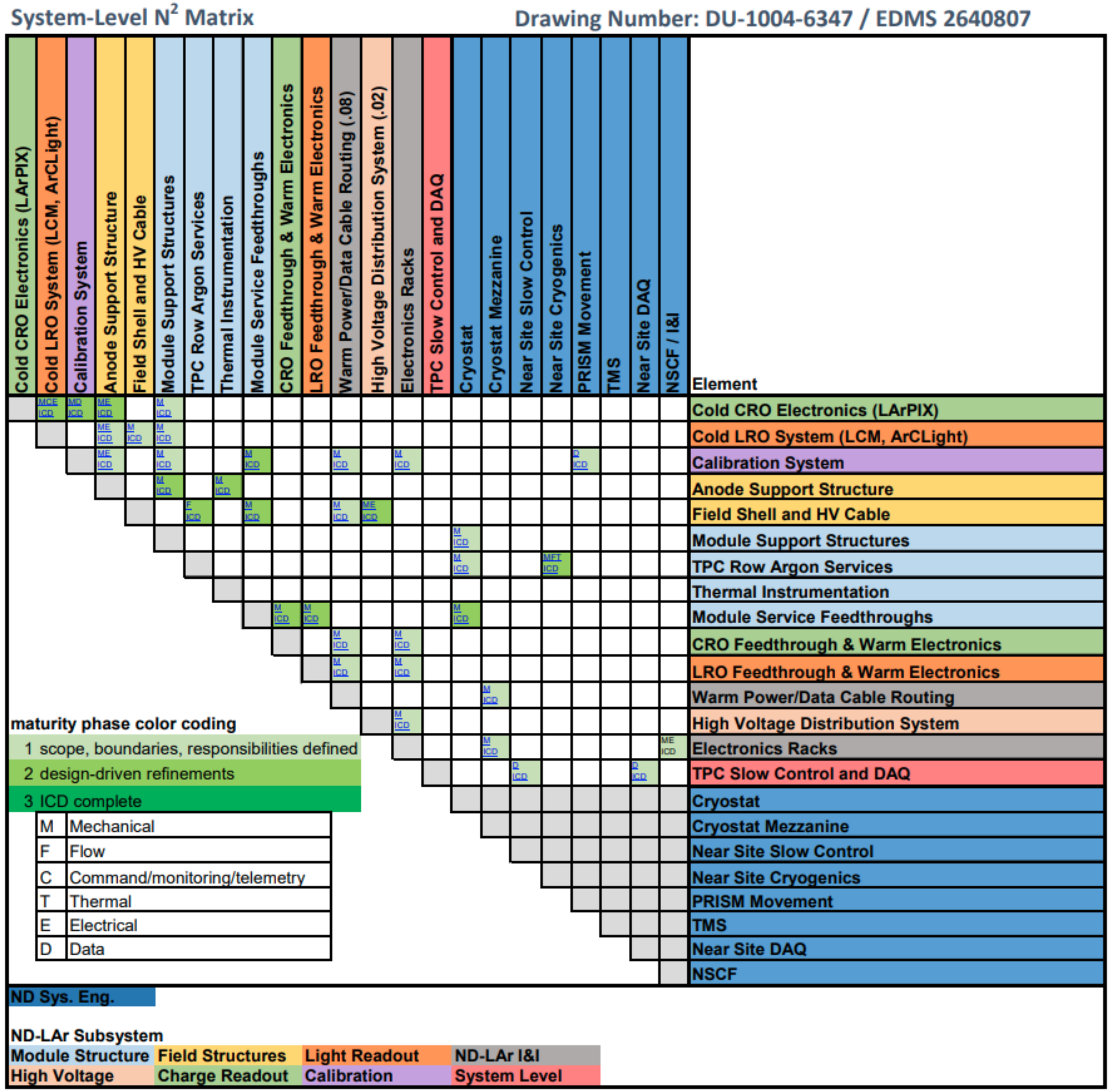
Key Calibration Requirements

ID	Name	Details	Validation
CAL-001	Electric field measurement precision	Measure electric field at given position to better than 1%	ND LAr TPC + simulations
CAL-004	Cross-calibration of ND TPCs	Calibration system shell be able to cross-calibrate TPC modules (vertex reconstruction, cathode-tilt, field uniformity in ND better than 1%	Design + ND LAr TPC
CAL-005	Vertex reconstruction precision	Calibration system shall provide measurements to determine corrected vertex (interaction point) precision to better than 0.4 cm	ND LAr TPC + simulations
CAL-009	Photoelectric target positioning	Calibration system Laser target positions should be surveyed after installation and their coordinates know to better than 2 mm	FSD
CAL-010	Stability of the calibration system during move	Calibration system performance shall be repeatable to 1% during 28 m move	Design + ND LAr TPC

131.ND.02.07 Calibration: Interfaces

- Engineering CAD model captures interfaces, https://edms.cern.ch/project/CERN-0000226247
- Interfaces realized and validated in Full Scale Demonstrator.

Subsystem	Interface	Maturity
Anode support structure	Mechanical	Partially defined
Module Support Structure	Mechanical	Defined
Module Service Feedthroughs	Mechanical	Partially defined
Light readout	UV damage control	Partially defined
DAQ	Calibration data	Defined
Field Structure/HV/Cathode	Traget attachment and positioning	Partially defined



131.ND.02.07 Calibration: QA/QC, Procurement, Manufacturing

QA/QC plan: https://edms.cern.ch/document/2617454/1

Procurement plan: https://edms.cern.ch/document/2617478/1

Manufacturing plan: https://edms.cern.ch/document/2617469/1

Scientific labor, off-project, i.e. DOE university umbrella grants.

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TM

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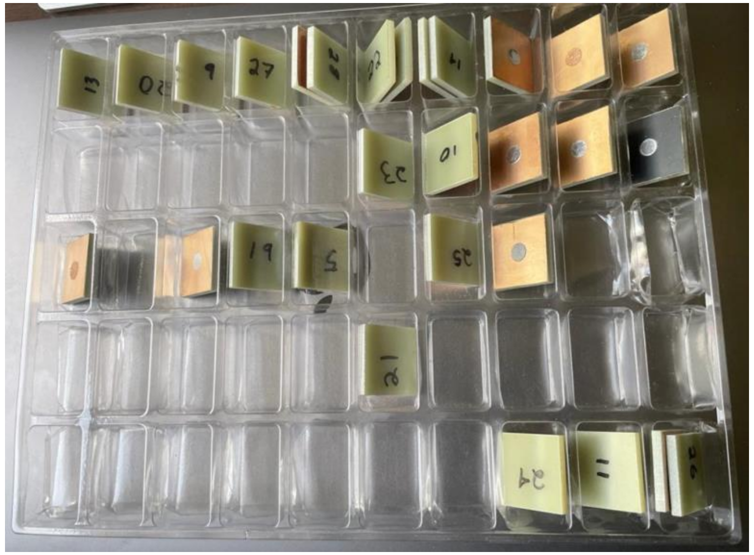
131.ND.02.07 Calibration prototyping plan for PE laser system validation

Fully functioning end-to-end system must demonstrate all major steps:

- Photoelectric targets yield
  - optimize photoelectric targets and confirm photoelectric field from oxidized metallic surface (targets routinely exposed to air)
  - sufficient photoelectric yield in LAr to collect signal on charge readout

Target samples



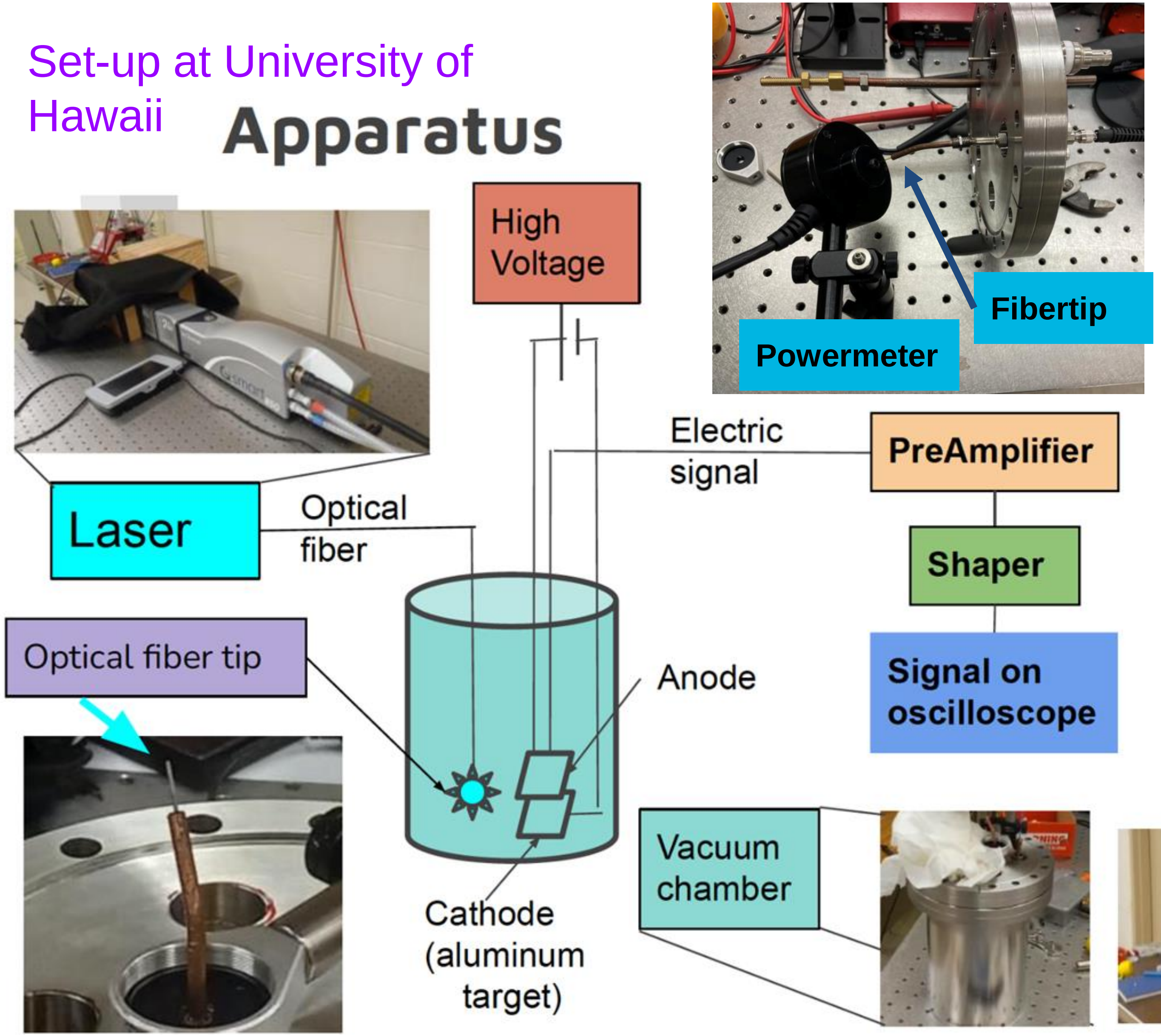
- Efficient light injection requires:
  - quantify laser beam-to-fiber interface power losses
  - quantify light loss in the flange optical feedthrough
  - verify sufficient illumination of the cathode

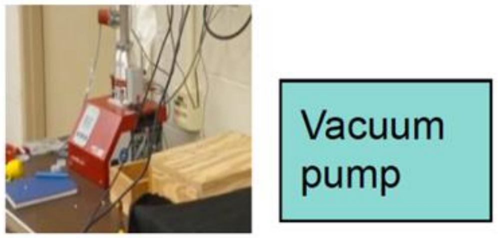
- Observe photoelectron cloud signals with charge readout.

- Combine PE laser calibration data with cosmic ray data in SLAC Single Cube prototype to produce calibration correction function.

131.ND.02.07 Calibration: Analyses and/or Performance Assessment - Demonstration of photoelectron cloud emission from targets in vacuum setup

Set-up at University of Hawaii



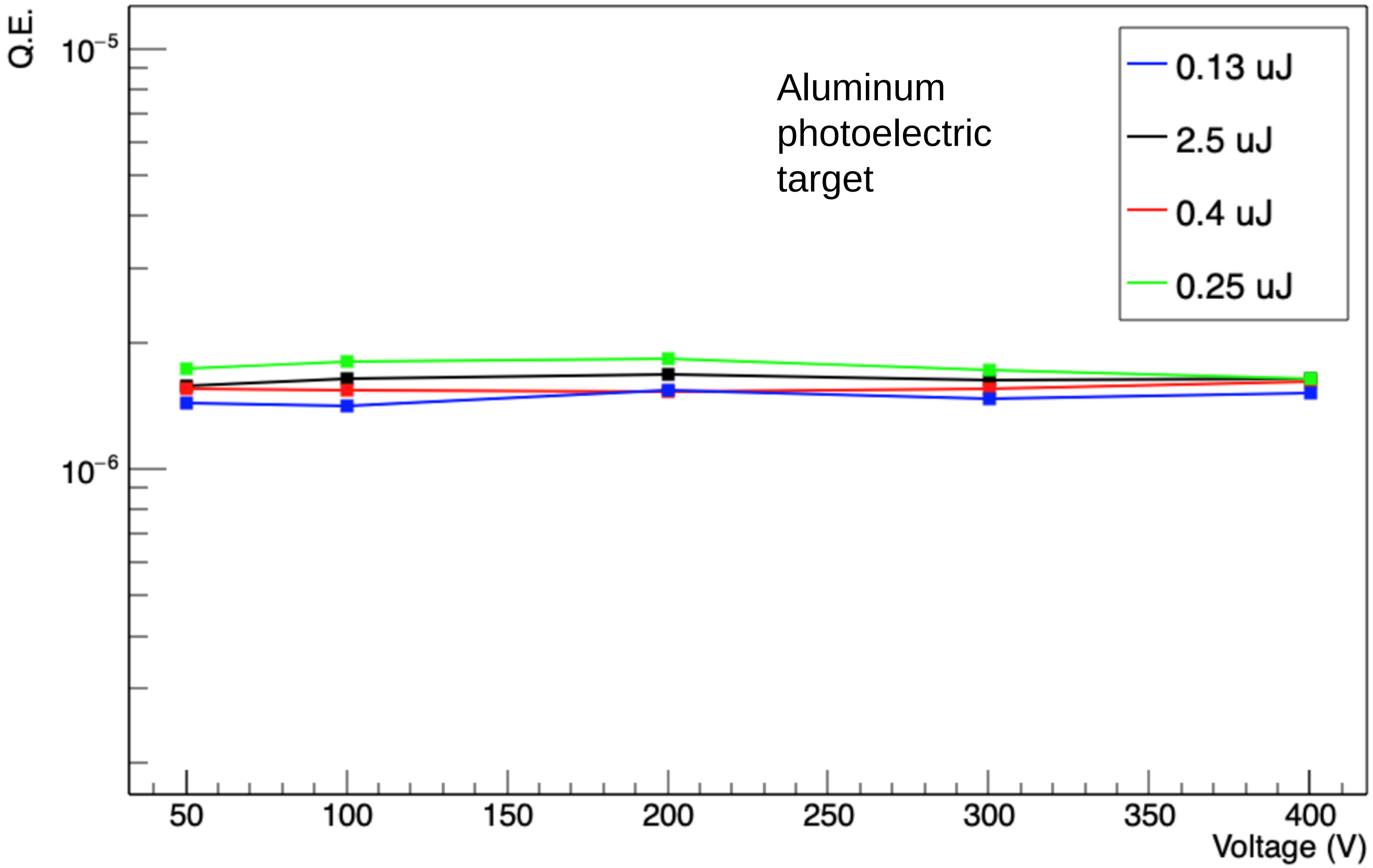


Photoelectric targets act as cathode; illumination by light coming from the laser releases photoelectrons that drift to anode in the electric field, maintained by HV.

Photoelectrons create an electric signal that is amplified, shaped and recorded on oscilloscope.

Intensity of laser light pulses is measured by the powermeter.

131.ND.02.07 Calibration: Analyses and/or Performance Assessment - Demonstration of photoelectron cloud emission from targets in vacuum



QE = $N_{electrons}/N_{photons}$

Photoelectron cloud emission in vacuum has been confirmed with samples from various materials.

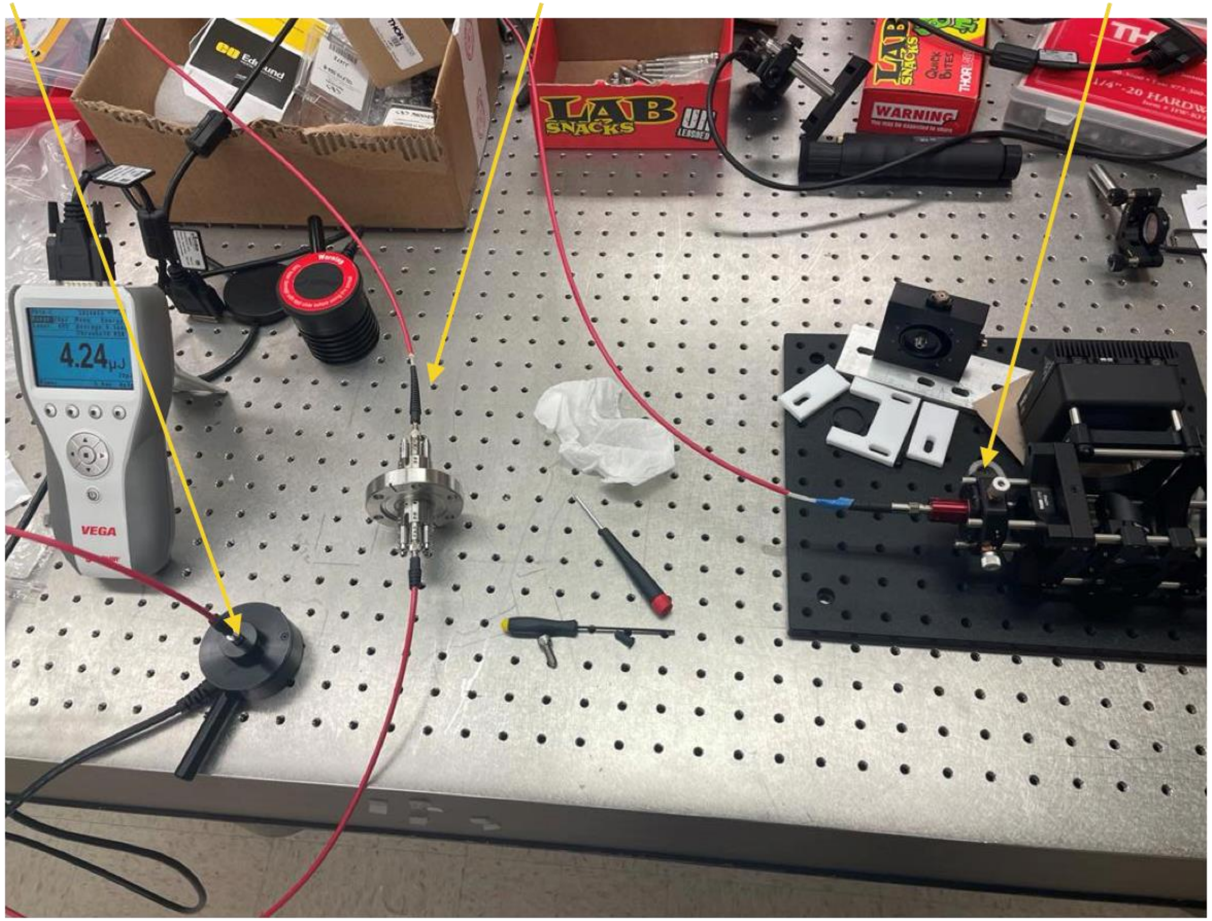
Best results obtained with aluminum.

QE in the expected range from 10^{-5} - 10^{-6}

Oxidized layer on aluminum surface does not significantly increase work function.

131.ND.02.07 Calibration: Analyses and/or Performance Assessment - Characterization of light losses through flange

4 uJ (0.3%) 19 uJ (1.46%) 1.3 mJ (100%)



Flange allows 21% of the light through

Assume fiber loss negligible

Light attenuation tracked from laser beam injection into fiber, and then through the flange.

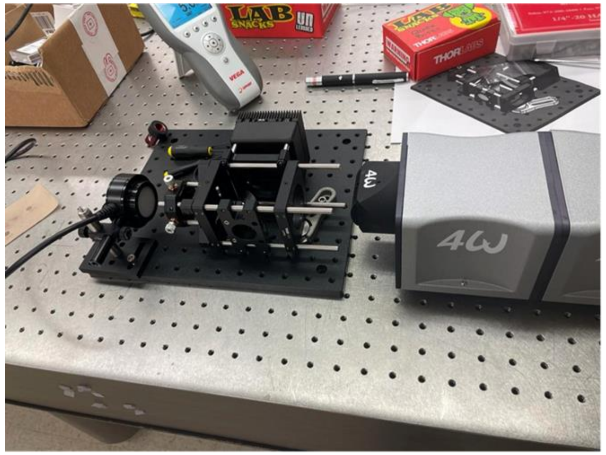
Light intensity at every step measured by a powermeter.

Light losses in a couple of meters of fiber negligible.

Light passing through flange~20% of input.

131.ND.02.07 Calibration: Analyses and/or Performance Assessment - Light injection into fiber

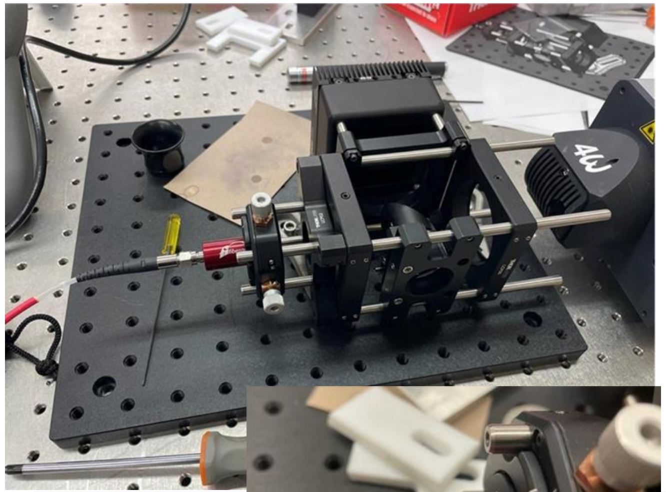
2 mJ Laser (low power setting)



Light injected in fiber - no collimation

1.2 uJ

25 uJ



Light injected in fiber - collimator from Edmund optics.

Laser beam injection into fiber with collimator improved about 20 times with respect to no collimator.

Efficiency is still very low.

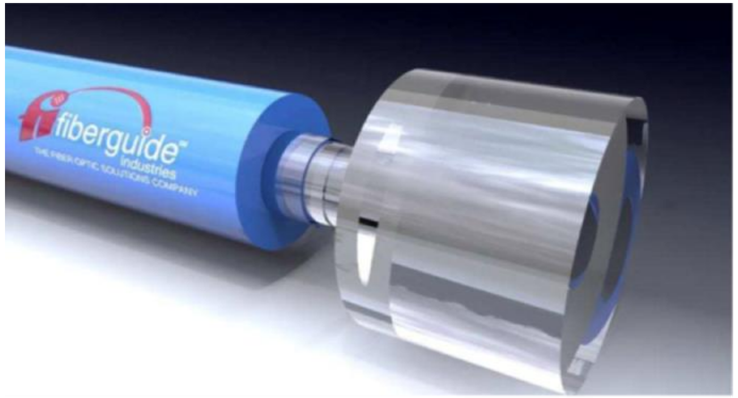
Observe damage on fiber tip after prolonged use even with recessed SMA for high power beam.

Recessed SMA

Regular SMA

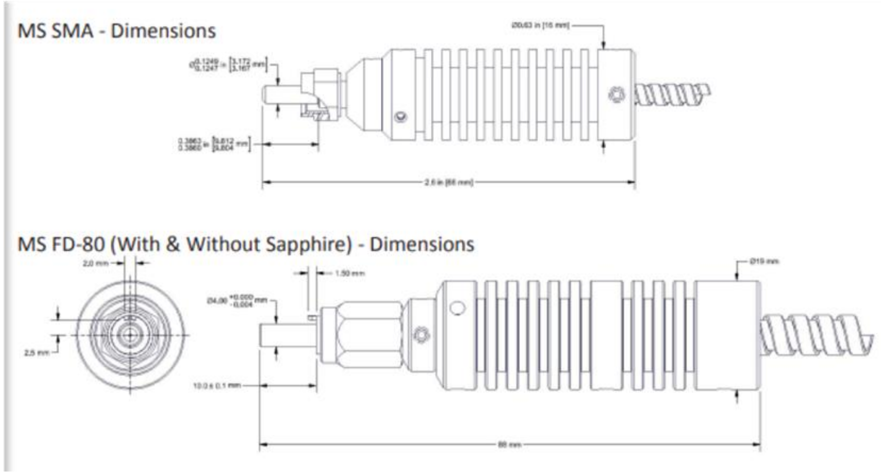
131.ND.02.07 Calibrtion: Analyses and/or Performance Assessment - Light injection into fiber

- Full laser power is 60 mJ and we observe fiber tip damage even at 2 mJ with Edmund collimator
- injection efficiency very low



Promise in specs about 80% light injectiction efficiency.

- We want to investigate an alternative way of injecting laser beam into fiber using end-capped laser-fiber interface
- Order from Fiberguide/Molex (USA) (5 months delay) - should arrive by the end of July.
- Also ordered an alternative from Fiberconnect (Germany),



131.ND.02.07 Calibration prototyping plan for PE laser system validation: current status

Fully functioning end-to-end system must demonstrate all major steps:

- Photoelectric targets yield
  - optimize photoelectric targets and confirm photoelectric field from oxidized metallic surface (targets routinely exposed to air) (UH + MSU) - **DONE**
  - measure photoelectric yield in LAr to collect signal on charge readout - **SLAC Single Cube**
- Efficient light injection requires:
  - quantify laser beam-to-fiber interface power losses - **measured, improvement ongoing**
  - quantify light loss in the flange optical feedthrough - **DONE**
  - verify sufficient illumination of the cathode - **SLAC Single Cube**

- Observe photoelectron cloud signals with charge readout - **SLAC Single Cube**
- Combine PE laser calibration data with cosmic ray data in SLAC Single Cube prototype to produce calibration correction function - **SLAC Single Cube**

All tests expected to converge in time for full system design test at FSD.

131.ND.02.07 Calibration: Risks

https://edms.cern.ch/document/2589288/1

Risks with > 1% probability.

Title	Summary	Mitigation	Probability	Schedule Impact [Months]	Cost Impact [$k]
Calibration Laser Alignment Repeatability	If laser alignment system repeatability is insufficient to control light distribution when moved then calibration results may not meet specifications.	Laser-to-optics fiber upgrade that may include additional light sources for redundancy	25%	3	580
Low photoelectric target yield	If photoelectric targets have too low yield in liquid argon	Design modifications that may include increased illumination, double cathode with transmissive target design	25%	6	180
Damage to laser tip fiber from beam	Due to high light intensity damage to fiber tip at the fiber-beam interface will take place eventually	Replacement fibers planned; and can be replaced; external to cryostat	15%	2	10
PE laser only, insufficient to calibrate for all physics goals	If the PE laser system is insufficient for the physics goals/neutron program, then additional calibration systems must be explored such as embedded beta sources and other alternatives	Ongoing simulation studies to establish full calibration potential of the PE laser required for successful execution of the LE physics/neutron program; Identify deficiencies and explore alternatives such as embedded beta sources via simulations; Develop conceptual design for alternative systems until the conclusion of the simulation studies and performance of the PE system in Single Cube	5%	3	0
Loss of key calibration personnel	If key scientific personnel or engineer has to leave, the project may be delayed	Ensure redundancy in scientific personnel and train them. Ensure design draft is regularly updated in project system	25%	6	50

Previous Review Recommendations

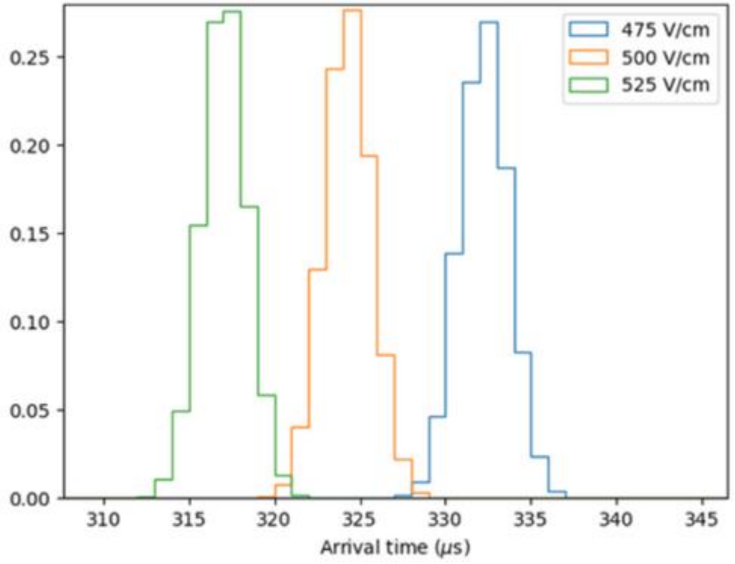
https://edms.cern.ch/document/2741842/1

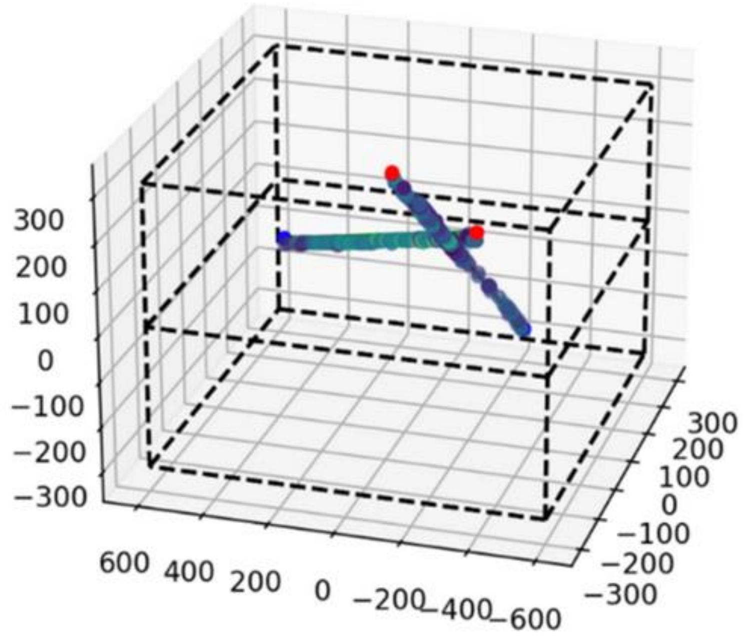
Recommendation	Status	Response
High level requirement to be “equal or better” than FD, needs to be translated into different into different reconstruction performance requirements and different parameter uncertainty requirement for different detectors.	In progress	Simulation chain of the calibration system and rock muons will inform the requirements for translation to FD in addition to articulation of the design requirements.
Investigate alternative with LEDs.	In progress	This will be addressed with Single Cube Prototype test, during the second phase when it will be assessed if sufficient illumination can be achieved with LEDs. Possible cons are also failure rates, noise issues in the vicinity of cold electronics
Misalignment of anode/cathode and tilt, specially given the PRISM movements.	Closed	No action required, based on understanding of the PRISM design, detector installation and design.
E field distortions. Further clarification is needed on the scope of the planned calibration measurements: a) a “microphysics” approach that attempts to measure E-field/drift velocity distortion maps, as well as electron diffusion and lifetime to correct those parameters in a detector model; b) an effective response mapping, in which the details of those parameters are not needed, only a dQ/dx and dE/dx response maps. Some parts of the presented material, including the requirements table suggest approach a), but the method shown in the “ND LAr calibration requirements” document, and the replies to our questions point to b).	In progress	This is correct and the requirements will be updated to reflect b) instead of a) option.
Investigate the potential of cosmic muons in addition to rock muons to measure E-field distortions	In progress	Simulation combining both expected rates of cosmic and rock muons underway.

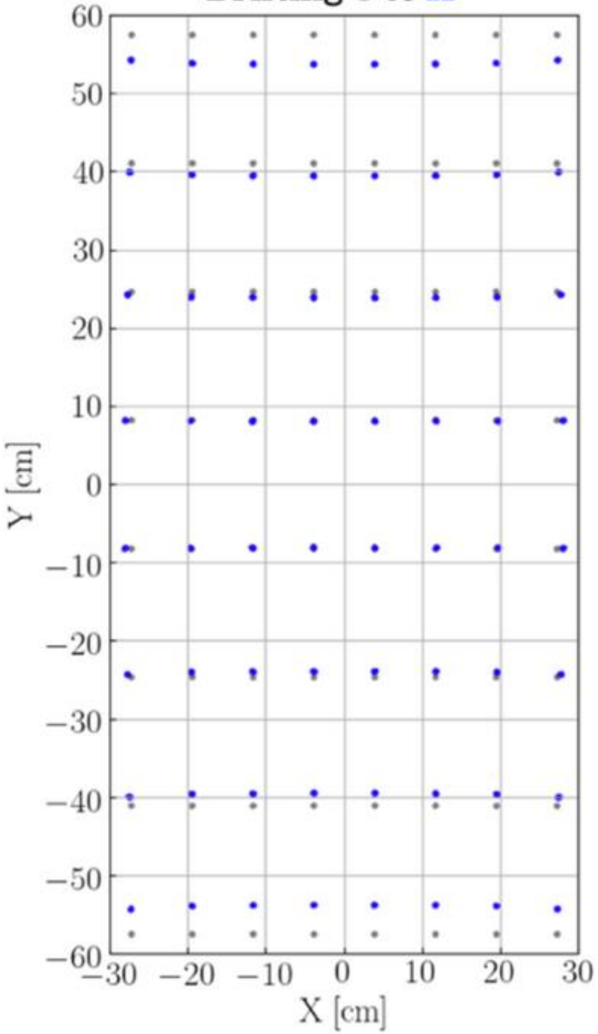
131.ND.02.07 Calibration: Simulations

Analyses and/or Performance Assessment

- PE system can observe from laser time vs. arrival time: E field distortions OR cathode displacement, tilt
- Ambiguity is resolved with a second measurement from muons
- Simulation in development for analysis of Single Cube and combined analysis with crossing muon tracks







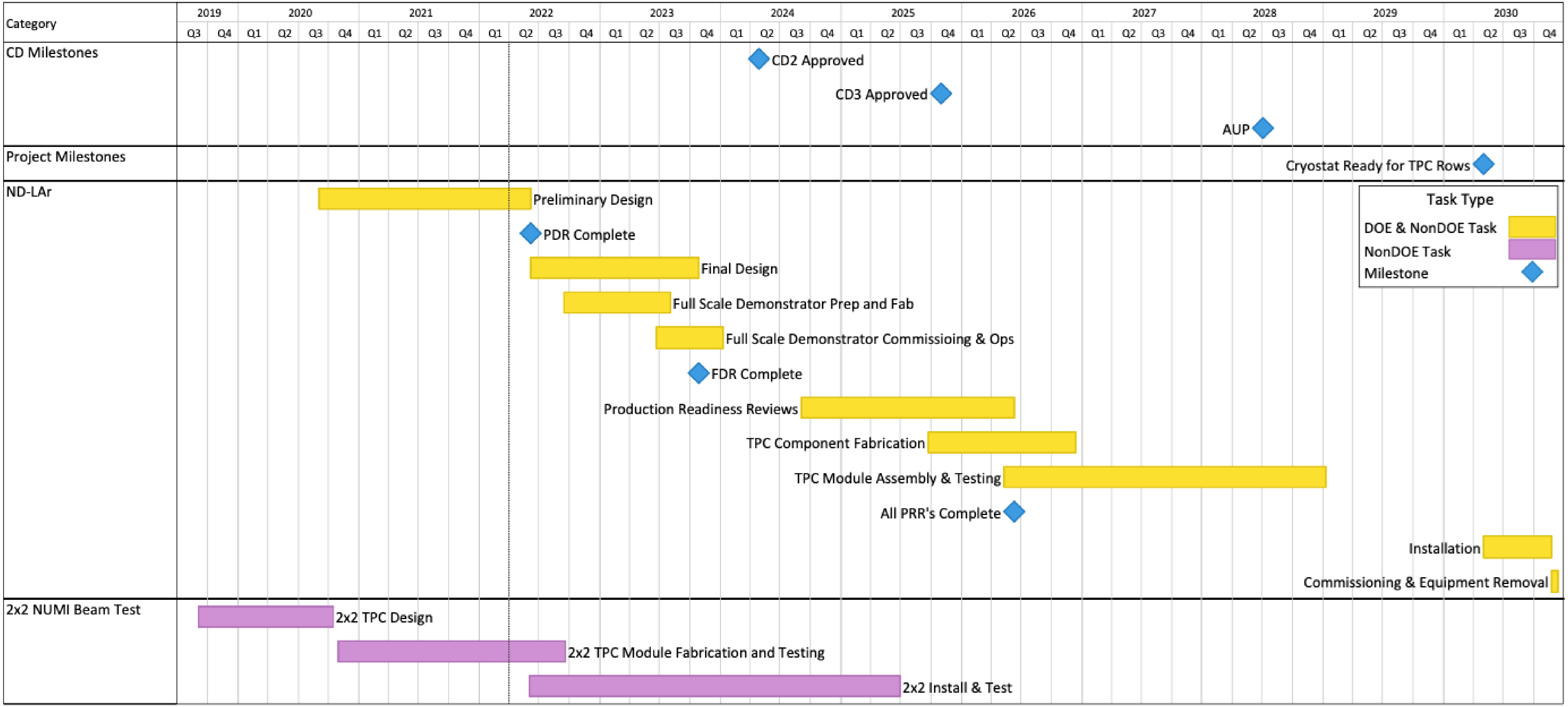
131.ND.02.07 Calibration Cost

https://edms.cern.ch/document/2742778/1

	Design & Prototyping				Production					
	On-Project		Off-Project		On-Project		Off-Project		On-Project	
131.ND.02: ND-LAr	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.*
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.

Schedule



LBNF/DUNE

131.ND.02.07 Calibration: Summary

- The calibration system is designed to meet the needs of DUNE's precision oscillation program
- Calibration system is in the preliminary design phase, with validation in SLAC single cube tests:
  - Individual design elements evaluated in U Hawaii or MSU test stands
  - Validate system integration and operation in liquid Argon
- Scope is well defined; interfaces are mostly well-understood; requirements defined and being validated; QA/QC, manufacturing, procurement under development
- Design stage and pre-production development that includes FSD deployment has been funded by US project
  - M&S cost for the production are off-project; possible in-kind contribution from foreign ND collaborators (BERN group) or faculty start-ups
  - The main cost driver for the system are M&S cost, thanks to large fraction of uncosted labor funded by the US DOE base grants
- Previous review recommendations have been closed or are in progress