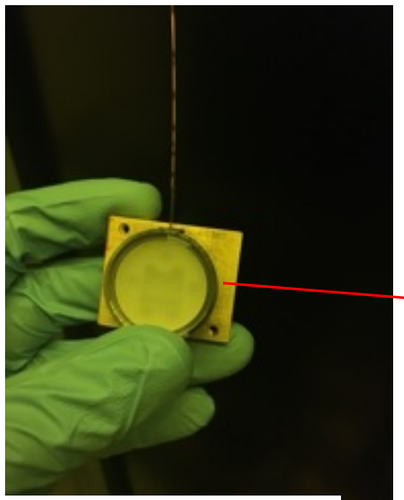
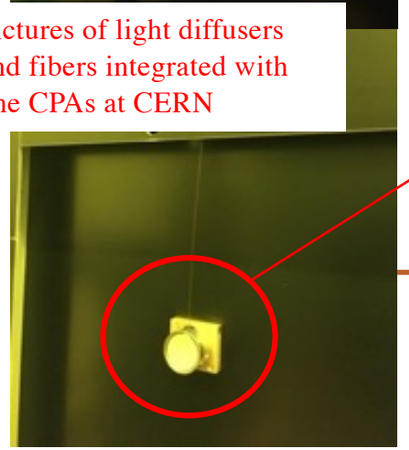
Q3: Can you show us results from ProtoDUNE-I in-situ calibrations?

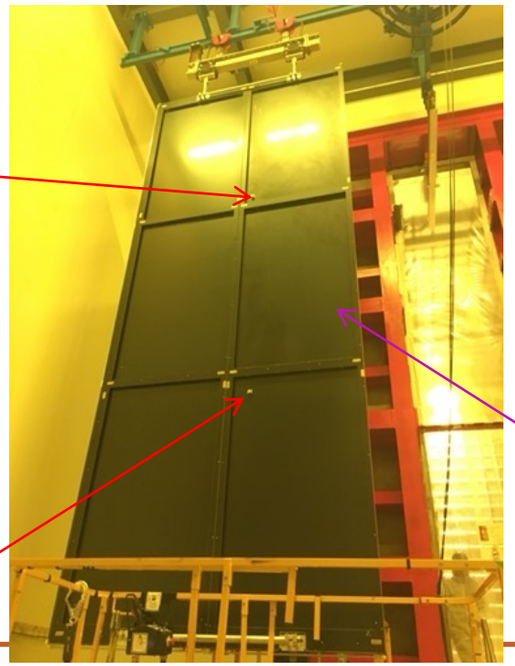
ProtoDUNE-I Calibration System: single slide to summarize the design

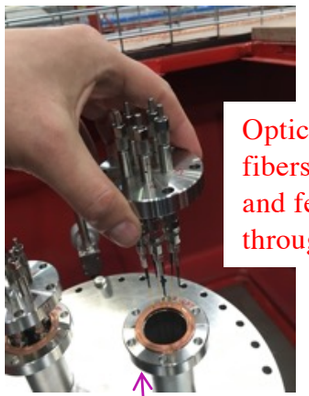
- Prototype of the system completed (designed, fabricated, installed) in ProtoDUNE-I
  - ProtoDUNE system components illustrated here in the single page
- All system components worked (see next slides)





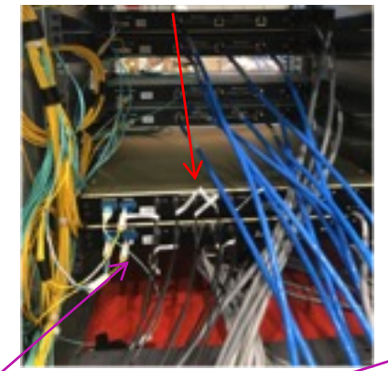
Pictures of light diffusers and fibers integrated with one CPAs at CERN

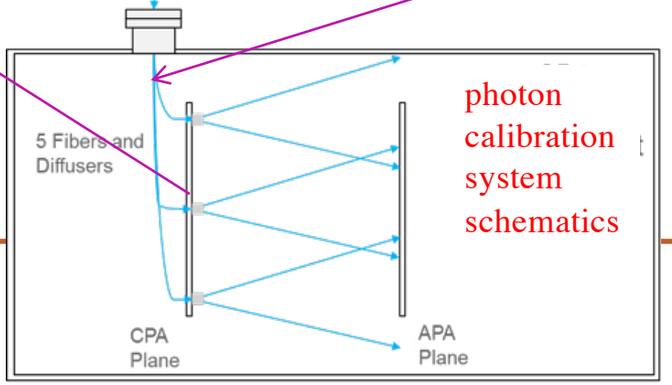




Optical fibers and feed-through

Two electronics Calibration Modules with 275nm light sources





photon calibration system schematics

ProtoDUNE Design Components

Argonne NATIONAL LABORATORY

DUNE

ProtoDUNE-I Calibration System: Motivation and Validation

Motivation

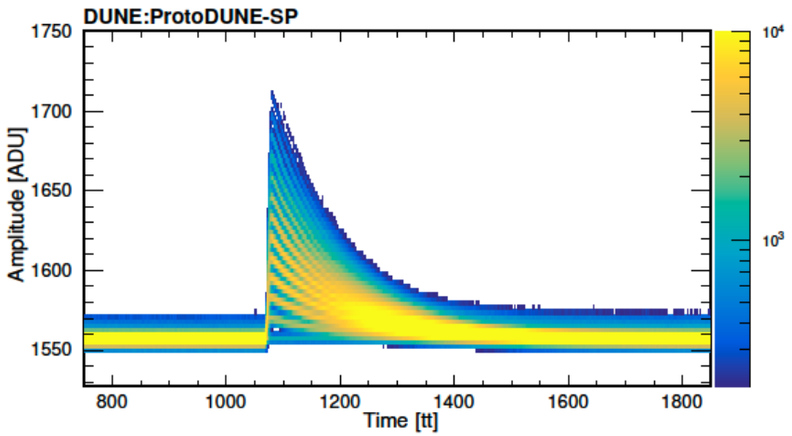
- Use the UV calibration/monitoring system as the detector verification tool: before closing the cryostat, in the cool-down phase, and when filled with LAr- to test the photon detectors ("is the detector alive?")
- Measure the photon detector gain, linearity, and timing resolution
- Monitor stability and response over time
- Use in special study cases
- Make use of it for quick reliable test of PDS when a change is made

  => Don't wait for cosmic muon coverage of entire detector.

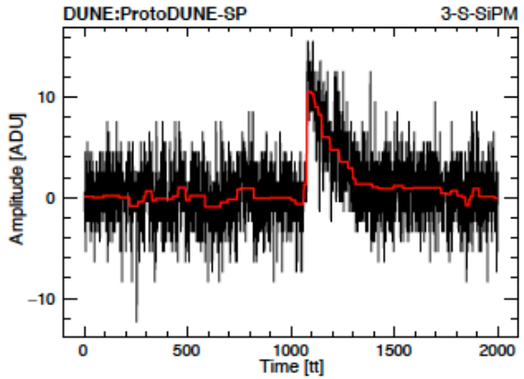
- **The full prototype of the UV-light calibration and monitoring system was designed for the FD1-HD PDS and validated in ProtoDUNE-SP operation** [B. Abi *et al* 2020 *JINST* **15** P12004, arXiv:2007.06722].

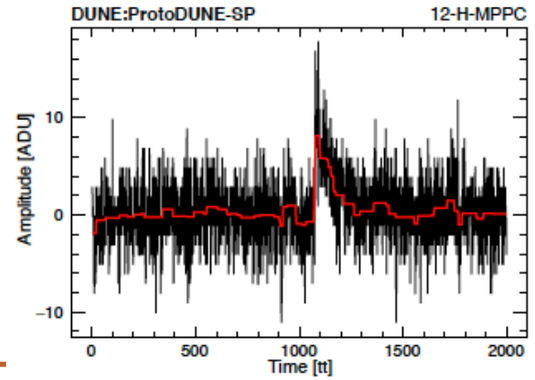
ProtoDUNE-I Calibration System: Selected Results

- Gain Calibration



➢ PDS Waveforms collected by the SSP digitizer in a calibration system run displayed in persistence trace mode shows recorded single and multi-photon signals. Each time tick (tt) represents 6.67 ns.

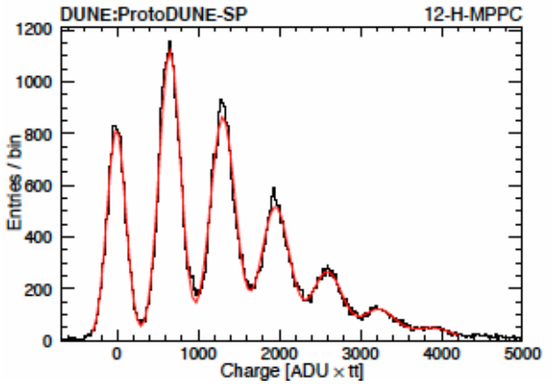


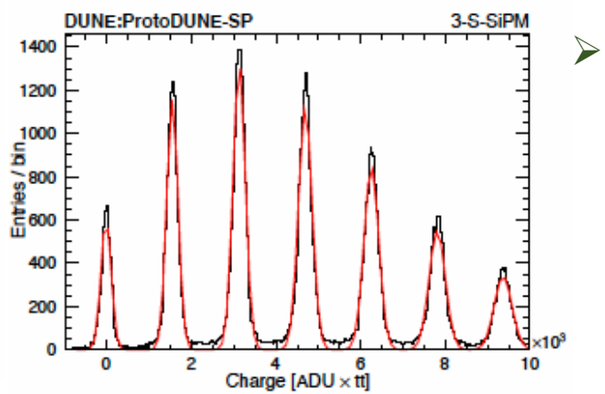


➢ Sample waveforms of single photon signal from the calibration system runs: 3-S-SiPM channel (left) and 12-H-MPPC channel (right), corresponding to three and twelve sensors passively ganged in parallel, respectively.

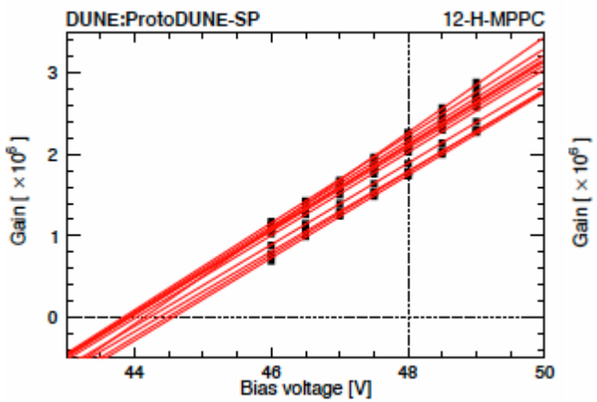
ProtoDUNE-I Calibration System: Selected Results

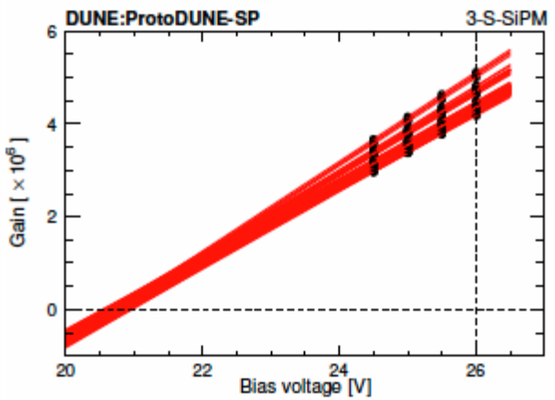
- Gain Calibration





➢ Charge distribution for typical 12-H-MPPC channel (VB = 48V) (left) and 3-S-SiPM channel (VB = 26 V) (right) under low amplitude pulsed LED illumination.

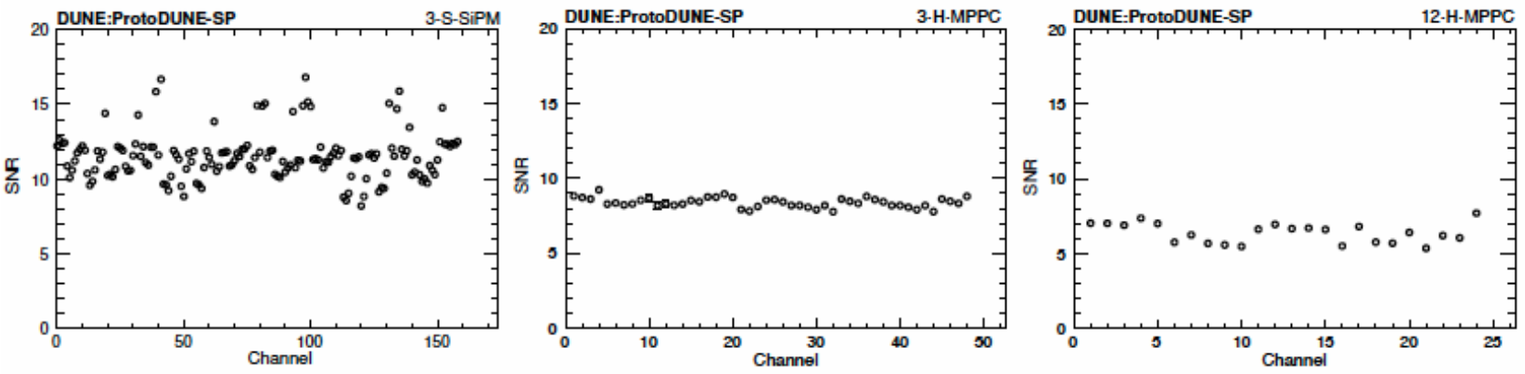




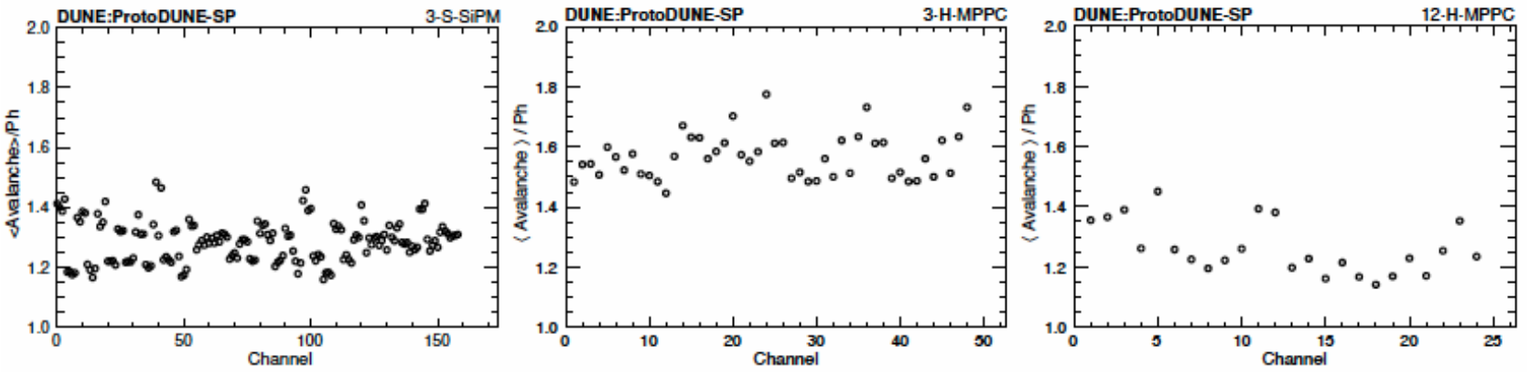
➢ Gain as a function of applied bias voltage for 12-H-MPPC channels (left), and for 3-S-SiPM channels (right). Linearity of individual channel response is shown by the linear fit (red line) across the points at different bias voltage setting.

ProtoDUNE-I Calibration System: Selected Results

- PDS/SiPM Characterization



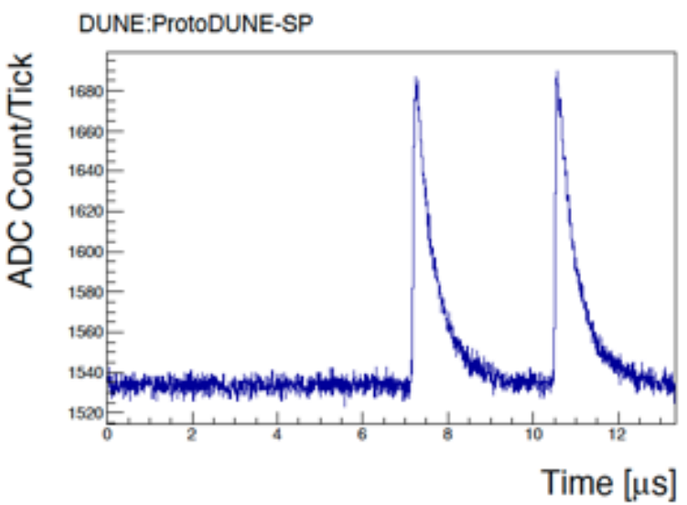
- Signal-to-Noise Ratio (SNR) for the 3-S-SiPM channels (left), for the 3-H-MPPC channels (center), and for the 12-H-MPPC channels (right).

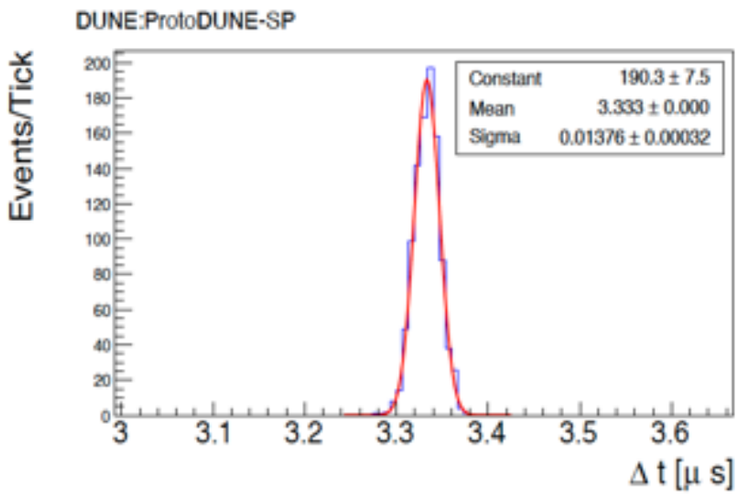


- Afterpulse and crosstalk contribution to the photosensor signal expressed by the average number of avalanches generated per detected photon for the 3-S-SiPM channels (left), for the 3-HMPPC channels (center), and for the 12-H-MPPC channels (right).

ProtoDUNE-I Calibration System: Selected Results

- Time resolution study

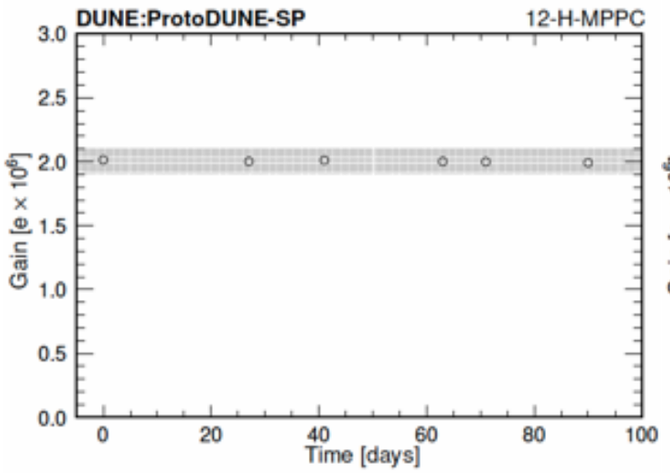


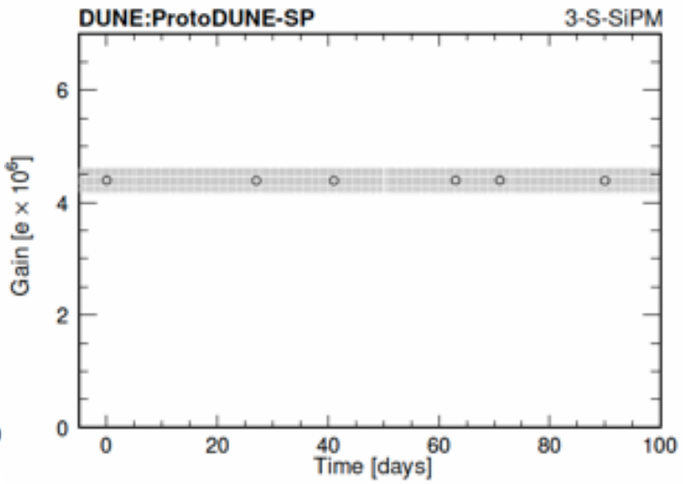


- PDS timing measurements with LED calibration system: Double pulse light signal using the photon detector calibration system (left); Resolution in the time difference measurement between correlated light signals (right).

ProtoDUNE-I Calibration System: Selected Results

- Stability Monitoring



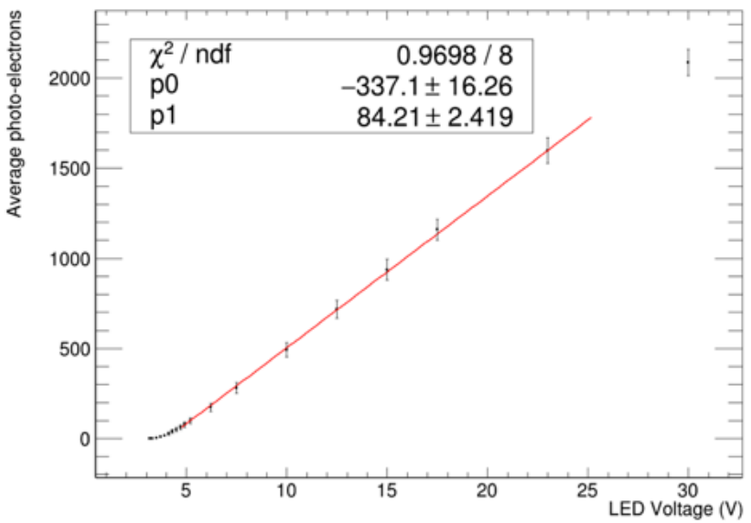


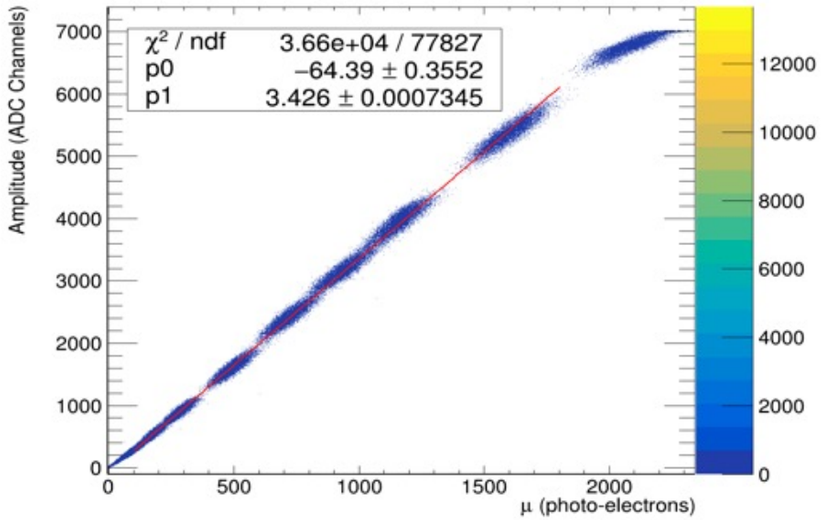
➢ Stability of the photo-sensor response over time: gain stability (charge signal per avalanche) for typical 12-H-MPPC channel (left) and 3-S-SiPM channel (right), from calibration runs performed over 100 days of operation. The shaded band corresponds to a 5% gain interval. Gain variations over time are contained well within the band. Statistical error bars are small, not visible inside the symbol.

Post ProtoDUNE-I Tests

- **Additional prototyping/testing:** The system components have also been verified at dedicated test stands.
  -Single-channel pulser boards have been extracted from the 12-channel Calibration Module design.
  -Several of single-channel boards are now used for QA/QC at ANL, CERN and Fermilab in cold box tests.

CERN cold box: calibration module pulser has been verified in CERN cold box when to observe ARAPUCA response to 275 nm light





Next Steps: ProtoDUNE-II Tests

- The FD1-HD Module 0 PDS calibration system consists of ten calibration channels with two types of optical fibers connected to CPA diffusers, and the calibration module with light source of 275 nm and 367 nm wavelength.

- Optical fiber and diffuser installation was completed in the cryostat.
  -Along with the 275 nm deep-UV light source with light transported through Polymicro Technologies™ quartz fibers (already validated in the ProtoDUNE-SP run), a 367 nm light source paired with a Tefzel™ fiber will be evaluated.

- The electronics calibration board (Calibration Module) is built with 12 optical output channels and integrated with the ProtoDUNE DAQ and timing systems at CERN to enable operation and triggering in FD1-HD Module 0 run

- Calibration and Monitoring plan PDS operation in ProtoDUNE HD includes the following :
  -Collect data runs with two type of fibers (Polymide, Tefzel) and with two type of LEDs (275nm, 367 nm)
  -Take data runs with multiple diffusers and with individual (a single) diffuser to verify the calibration light coverage
  -Analyze data to calibrated PDS gain and monitor stability.
  -Use results to inform and validate DUNE FD systems.

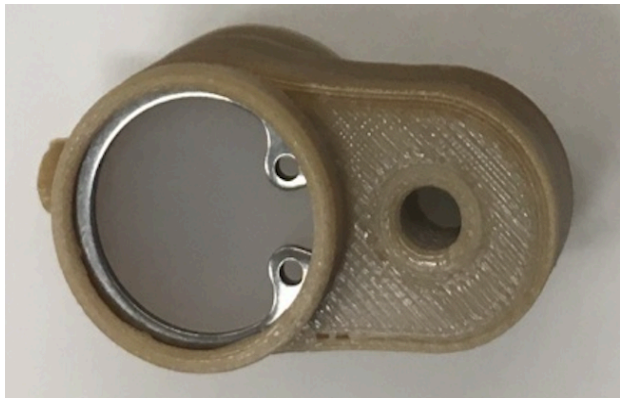
- Upon final FD1-HD Module-0 validation, the system will be fabricated for FD1-HD.

Q10. (S) For the LED calibration system:
(i) Please give more specifics on QA/QC LED calibration system plan pre- and post-installation
(ii) the diffuser mounts are 3D printed, what aging tests have been done?
(iii) There is a discrepancy between the slides presented and the interface control document at EDMS 2088721. Is the distribution of the diffusers completely settled or are more studies needed? Regardless, the ICD should be updated to communicate the agreed upon layout.

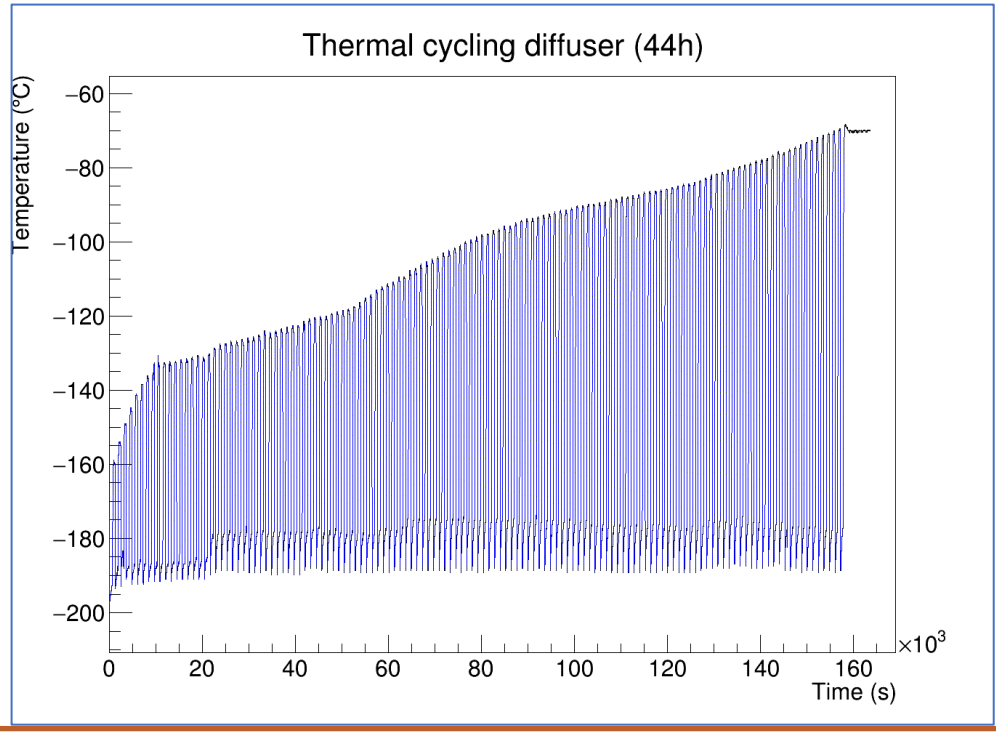
Diffuser Aging Studies

- Testing material: PEEK.
- Long time test: ~2 years (Feb. 2021) submerged in nitrogen (previous version of the design)
- In addition to the long-time test, we performed a LN2 thermal cycling test (warm up and cold down) during 44 hours
- No visible signs of damage in the 3D printed diffuser

Previous design tested during 2 years in LN2



Latest design installed in ProtoDUNE HD

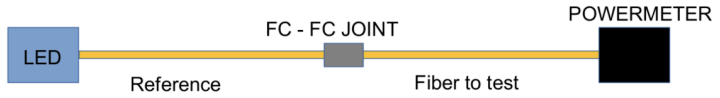


Pre-installation test

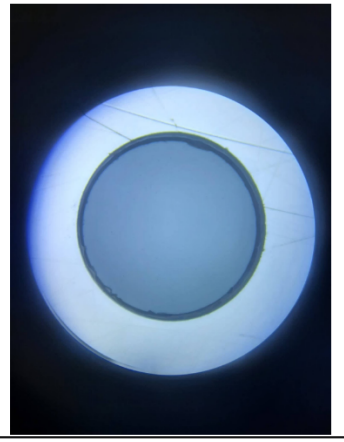
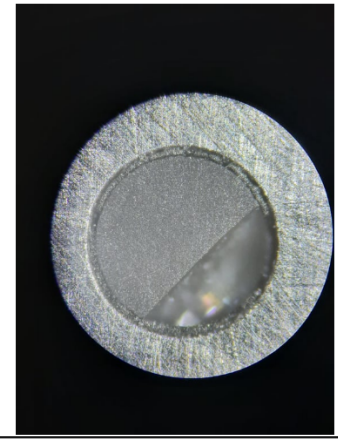
- During the assembly of the fibers, multiple check were done to guarantee the quality of them.
  - **Transparency test:** The goal is keeping at the minimum the difference between the power input and power output in the tested fiber to avoid large attenuations
  - **Visual inspection:** Both ends are inspected with fiber inspection scope. If visible scratches are present, the fiber is not used.

•**First Stage:** measure the power of the reference fiber which is the light input for the tested fibers.

•**Second Stage:** measure the power at the end of the tested fibers.

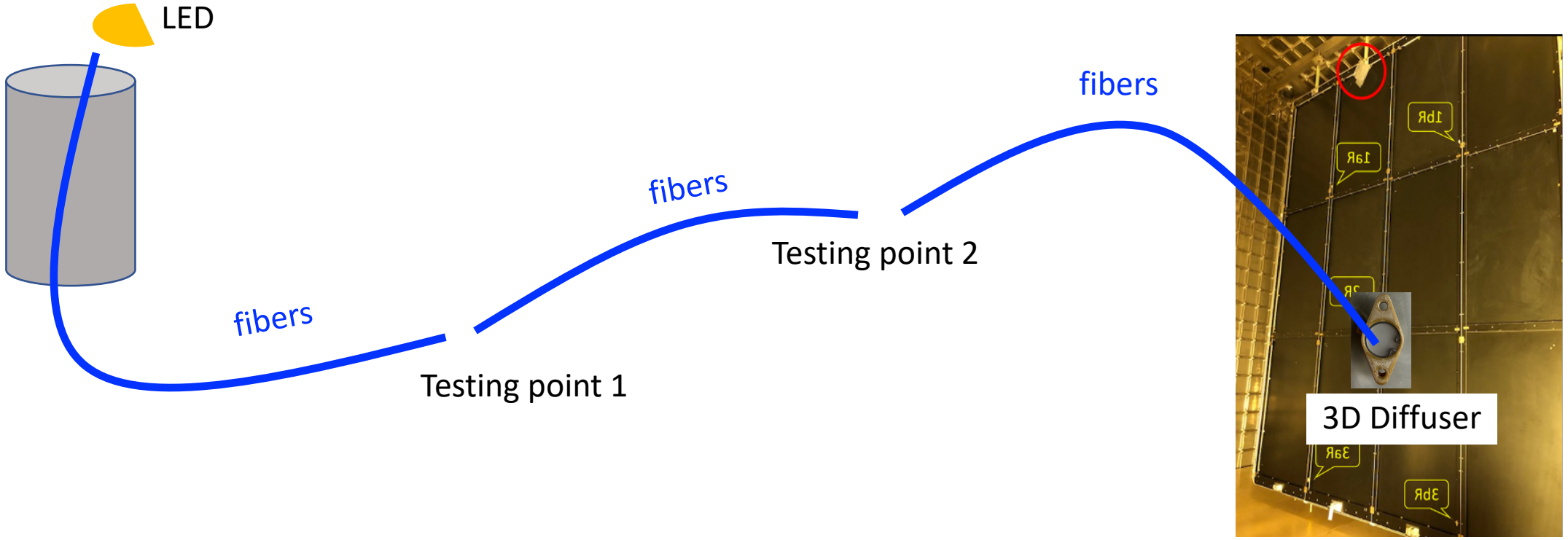


	Fiber Information							Test												
								Power supply		Reference (@ ~450nm)					Tested fiber (@ ~450nm)					
		Date Manufactured	Fiber Code	Fiber Length before SMA (in)	Fiber Length before SMA (cm + 10cm)	Fiber Length After SMA (cm)	Polishing	Date Tested	Voltage (V)	Current (mA)	file name # samples	mean (uW)	std dev (pW)	mean (dBm)	# samples file name	mean (uW)	std dev (pW)	mean (dBm)	Attenuation coefficient (dB/km)	Transparency (1m)
4		FP600URT	12/2/2021	1aR	188	488	482	PASS	12/7/2021	3.1474	2.9998	file33 - 201	13.67	--	-18.64	file34 - 202	10.63	440	-19.73	-226.367	0.949
5		POLYMICRO	12/2/2021	1aL	188	488	482	PASS	12/7/2021	3.1478	2.9997	file27 -201	13.67	430.9	-18.64	file28 - 200	11.05	399.9	-19.56	-191.062	0.957
6		FP600URT	12/2/2021	1bR	133	348	342	PASS	12/7/2021	3.1478	2.9997	file31 - 200	13.65	130.6	-18.65	file32 - 200	11.45	220.7	-19.41	-222.339	0.950
7		POLYMICRO	12/2/2021	1bL	133	348	342	PASS	12/7/2021	3.1479	2.997	file25 - 201	13.67	379	-18.64	file26 - 201	11.47	413.1	-19.41	-225.265	0.949
8		FP600URT	12/2/2021	2R	225	582	576	PASS	12/7/2021	3.1471	2.995	file39 - 201	13.6	587.9	-18.66	file40 - 200	11.24	558.2	-19.49	-144.222	0.967
9		POLYMICRO	12/2/2021	2L	229	582	576	PASS	12/7/2021	3.148	2.9998	file29 - 200	13.67	200.7	-18.64	file30 - 201	10.84	477.8	-19.65	-175.500	0.960
10		FP600URT	12/2/2021	3aR	372	955	949	PASS	12/7/2021	3.1471	2.9998	file35 - 201	13.66	--	-18.65	file36 - 203	11.61	--	-19.35	-73.771	0.983
11		POLYMICRO	12/2/2021	3aL	372	955	949	PASS	12/7/2021	3.1485	2.9996	file23 - 201	13.66	806.1	-18.64	file24 - 201	10.68	675.3	-19.71	-112.765	0.974
12		FP600URT	12/2/2021	3bR	317	815	809	PASS	12/7/2021	3.1147	2.9995	file37 - 201	13.62	--	-18.66	file38 - 201	10.46	--	-19.8	-140.883	0.968
13		POLYMICRO	12/2/2021	3bL	317	815	809	PASS	12/7/2021	3.1482	2.9995	file21 - 202	13.66	719.6	-18.65	file22 - 201	10.9	612	-19.63	-121.110	0.972
14		POLYMICRO	02/19/2022	L1 (C)	163	424	418	PASS	02/19/2022	3.5732	20.006	file93 - 201	22.09	2447	-16.56	file94 - 201	17.47	353.3	-17.55	-236.831	0.947
15	C Group - GP gap to below flange	02/19/2022	L2 (C)	163	424	418	PASS	02/19/2022	3.5732	20.006	file95 -212	23.03	2002	-16.38	file96 - 209	18.31	--	-17.37	-236.831	0.947
16		02/19/2022	L3 (C)	163	424	418	PASS	02/19/2022	3.5731	20.006	file97 - 202	22.54	1436	-16.47	file98 - 201	17.74	1449	-17.51	-248.792	0.944

GOOD polishing	BAD polishing and chipped
	

Post-Installation test

- Light continuity test was performed at the end of installation.
  - Using LED test each fiber group after install it.



FD1-HD Calibration and Monitoring System

- **Schematic of FD1-HD cathode plane** (60 m × 12 m) showing the locations of the calibration and monitoring system diffusers
  - -Calibration and monitoring system with a total of 204 diffusers: 51 on each side of the two CPA panels
  - -Each diffuser illuminates a region of 4 m × 4 m on APAs 3.6 m away
  - -The diffuser locations will be in the CPA field-shaping strip (FSS) notches.