FD1 SiPMs
Downselection and Integration Tests

Antonio Verdugo (CIEMAT)

DUNE PRR

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Remainder of the strategy

The SiPMs for FD1-HD are custom products by two vendors identified in the preparatory phase and able to produce such an amount of cryogenic SiPMs:

Hamamatsu Photonics (HPK)
A Japanese company with satellite distribution companies in US and EU

Fondazione Bruno Kessler (FBK)
An Italian company serving particle and astroparticle experiments (CTA, CMS, DarkSide, LHCb, etc.)

DUNE is pursuing a «two vendor scheme» for the procurement of the SiPMs for FD1-HD (288,000+spares) because of:

- Risk mitigation (retirement/disappearance of a vendor, as it happened with SensL a few years ago)
- Cost reduction (multiple bids)

High level Requirements

From the DUNE Physics Requirements are summarized as follows:

- The **SiPM PDE** in the wavelength emitted by wavelength-shifters should be at least as good as commercial devices (>35% at 430 nm)
- SiPM dimensions compatible with the mechanical design of the PD module.
- The signal from a single SiPMs should allow **single photo-electron identification** for detection of low-energy neutrinos interacting far from the photon detectors.
- They must be able to survive multiple, room-temperature to LAr **temperature cycles** with no significant impact on their electrical or mechanical characteristics.
- Dynamic range for 48 SiPM (one electronic channel) > 2000 p.e.
- Dark count rate contribution negligible compared with background of ^{39}Ar
- The SiPMs should meet the previous requirements and function within specifications for **at least 10 years** in a LAr environment.

Low Level Requirements

Technical characteristics of SiPMs that meet the high level requirements.

They were updated with respect to the 2019 tentative proposal accounting for:

- The outcome of the 2019-2020 R&D
- The completion of the cold electronics design
- The final DUNE PDS trigger configuration for FD1-HD (1.5 p.e. in at least 1 supercell for any APA)
- The completion of the warm electronics design (DAPHNE), whose maximum throughput is compatible with a cross-talk probability <35 % at nominal overvoltage

Low Level Requirements

Parameter	value	note
SiPM dimension and packaging	6x6mm², SMT	Compatible with the PDS module final design
Cell pitch	50-100µm	As large as possible in the range allowed
PDE at nominal voltage (Vop)	>35 % at 430nm	Room temperature measurement
DCR	<200 mHz/mm²	
Cross talk probability	<35% at Vop	
After-pulsing probability	<5% at Vop	
Gain	2 to $8 \cdot 10^6$	Not critical
Fall time constant	200-1000 ns	Optimal for cold electronics
Breakdown voltage spread	< 200 mV (max-min)	Per group of 240 SiPMs (one PDS module)
Maximum Vbd voltage	< 2V (max-min)	Global
Thermal cycles	>20	Tested at 77 by the Consortium

Downselection Proccess

Started with the detailled characterization of 6 types of 6x6 mm^2 SiPMs developed **specifically for DUNE,** 4 from Hamamatsu (HPK) and 2 from Fondazione Bruno Kessler (FBK) with following characteristics:

Manufacturer & Model	Characteristics	Notes
FBK NUV-HD-CRYO	Single trench with SiO2. 25 µm cell-pitch	Conservative solution: Darkside SiPM + epoxy package
FBK NUV-HD-CRYO Triple Trench (FBK-TT)	Three trenches with SiO2 to increase optical insulation among cells. 50 µm cell-pitch	Low cross-talk, high Fill Factor compatible with technology transfer at LFoundry
HPK S13360-9932	Cell-pitch 50µm, low quenching resistance (280 kΩ) at 77K	Standard quenching and cell-pitch
HPK S13360-9933	Cell-pitch 50µm, high quenching resistance (660 kΩ) at 77K	High-R quenching and standard cell-pitch to reduce Dark Count Rate
HPK S13360-9934	Cell-pitch 75µm, low quenching resistance (280 kΩ) at 77K	Standard quenching and large cell pitch to increase Fill Factor
HPK S13360-9935 (i.e. S16517)	Cell-pitch 75µm, high quenching resistance (660 kΩ) at 77K	High-R quenching and large cell pitch to reduce Dark Count Rate

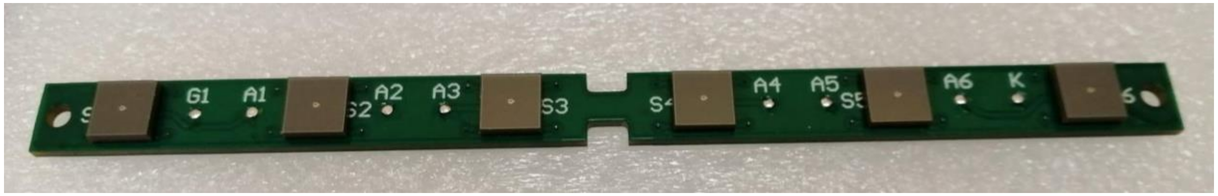
Downselection Proccess

The six prototypes were tested by the PDS Photosensor WG in 2021 and the down-selection was completed in the fall of 2021.

The tests were carried out, first, with a small-size production lot (25 SiPMs per lot) to measure the performance.

A complete characterization was performed with 250 SiPM lots to validate the thermal performance for a statistically significant set of SiPMs.

The 250 SiPM lots were mounted on PCBs allowing the testing of 48 ganged at the cold-amplified input



Testing protocol

A testing protocol was defined and shared among the different laboratories working on the SiPMs characterization.

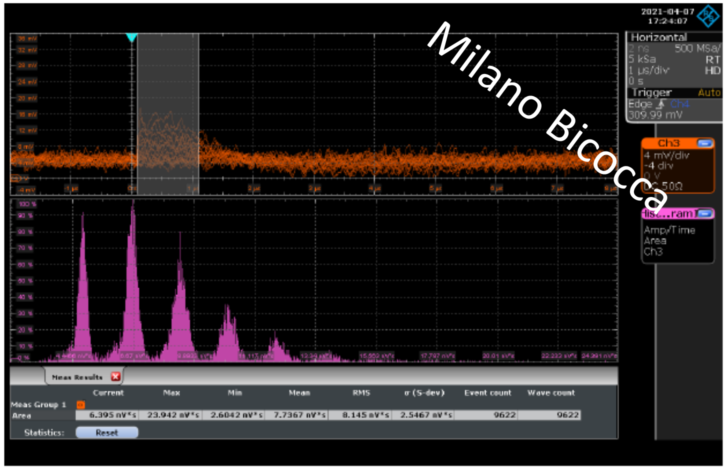
Summary of the protocol:

- ✓ I-V at room temperature
- ✓ I-V on first LN2 immersion
- ✓ Full characterization in LN2 at three OV corresponding to PDE of 40%, 45% and 50%: Gain, S/N, dark noise, correlated noise.
- ✓ 16 thermal cycles RT – LN2
- ✓ Repeat IV in LN2 and full characterization on the last thermal cycles (20 in total).

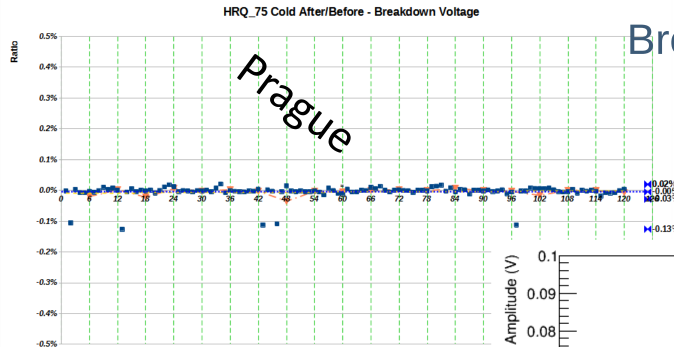
To avoid damages on the SiPM due a to fast and high temperature change, before immersing the SiPMs it was keep it in gas close to the liquid for slower thermalization. Each thermal cycle took around 30 minutes in total.

Summary of tests

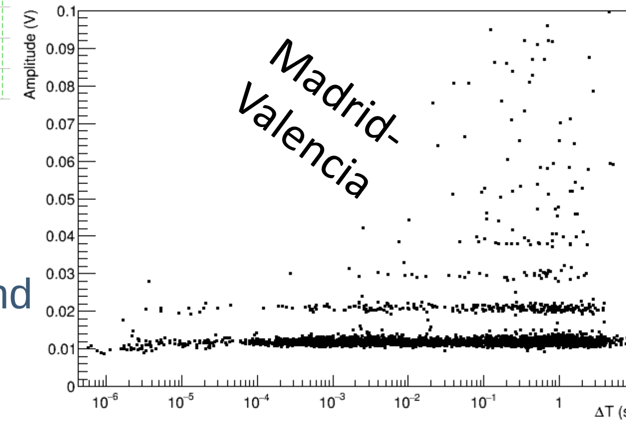
Test	Precision	Labs	Notes
Thermal tests		All: Bologna, Ferrara, CIEMAT, Prague, Milano Bicocca, Valencia	All tests were performed before and after 20 thermal cycles for both the 25 and 250 SiPM lots
Gain	10%	All	Precision limited by the calibration of the cold amplifier
Dark Count Rate	10-50%	Valencia, CIEMAT, Milano-Bicocca	Precision limited by the light tightness of the test-stand
Cross talk (%)	0.5 % (absolute value)	All	
After pulse (%)	<0.5 % (absolute value)	All	Precision limited by the peak resolution in the waveform (sampling: 10 ns)
Non accelerated aging	2 months for down-selected only	Milano Bicocca	2 months in Liquid Argon + accelerated aging in LN from thermal tests. No effects were reported.
Accelerated aging		All	Equivalent to thermal tests
Ganging tests (S/N)		CIEMAT, Milano Bicocca	Limited by environmental noise



Gain measurement



Breakdown V and change after thermal cycles



Cross talk and afterpulse

LABS INVOLVED	Model	PDE (%)	Gain Mean	Gain Std Dev	DCR+B (mHz/mm²) Mean	DCR+B (mHz/mm²) Std Dev	DCR-B (mHz/mm²) Mean	DCR-B (mHz/mm²) Std Dev	Xtalk (%) Mean	Xtalk (%) Std Dev	Afterpulses(%) Mean	Afterpulses(%) Std Dev
Valencia, Prague, Madrid, Ferrara, Bicocca, Bologna	50_LQR	40	2,38E+06	6,60E+03	54,08	0,96	12,79	0,67	9,96	0,47	2,15	0,15
		45	3,10E+06	8,97E+03	60,29	1,06	13,70	0,70	11,23	0,39	2,62	0,17
		50	3,84E+06	8,57E+03	71,92	1,01	16,62	0,85	13,38	0,37	5,13	0,21
Valencia, Madrid, Bicocca	50_HQR	40	2,25E+06	6,65E+03	38,74	0,98	7,36	0,83	7,15	0,34	2,06	0,16
		45	2,99E+06	6,79E+03	81,57	1,68	8,73	0,68	8,71	0,34	3,50	0,19
		50	3,78E+06	8,04E+03	53,25	0,92	9,65	0,46	10,92	0,36	3,95	0,21
Ferrara, Valencia, Bologna, Madrid	75_LQR	40	3,49E+06	6,72E+03	42,14	0,65	6,10	0,32	9,47	0,32	1,41	0,15
		45	4,33E+06	6,26E+03	50,70	0,75	6,58	0,34	10,18	0,35	1,83	0,16
		50	5,16E+06	7,61E+03	50,88	0,68	9,07	0,41	11,84	0,34	2,96	0,18
Bicocca, Prague, NIU	75_HQR	40	3,94E+06	2,02E+05	26,40	2,12	4,60	0,24	6,16	0,05	1,63	0,44
		45	5,43E+06	2,34E+05	31,32	0,65	5,57	0,17	7,03	0,30	2,35	0,66
		50	5,81E+06	2,73E+05	32,53	4,68	6,46	0,73	9,85	0,14	2,78	0,23

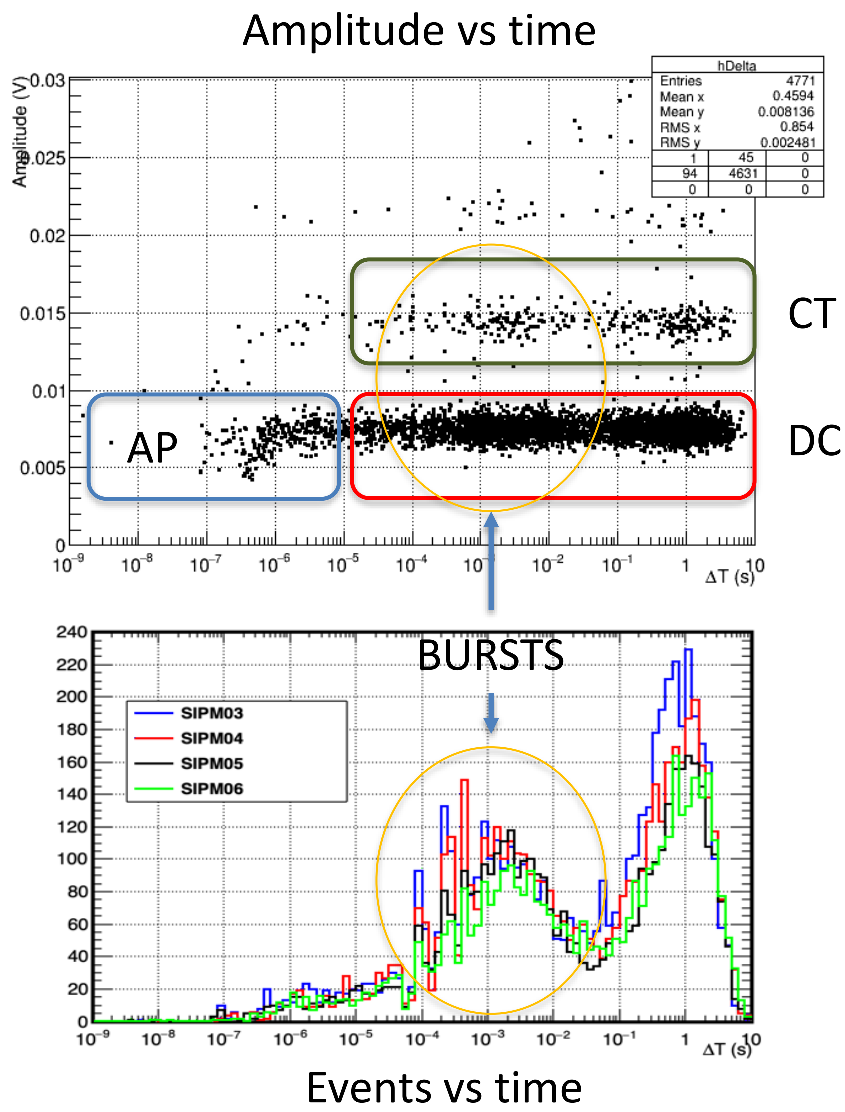
Unexpected DCR: Bursts

In the course of the tests, we discovered the appearance of bursts of correlated events that increases the DCR.

We demonstrated that the origin of the bursts is related to ionizing particles entering the bulk of the SiPMs (e.g. cosmic rays and radioactive contamination) and we validated this hypothesis by performing measurements at the INFN Gran Sasso laboratories to suppress cosmic ray events by six orders of magnitude, as in SURF.

Anyway, the occurrence of bursts keeps the SiPM DCR well below the specs for DCR even assuming no overburden (i.e. assuming DUNE to be run on surface). The contribution of bursts in DUNE assuming nominal overburden is negligible.

Additional information is available in M. Guarise et al., JINST 16 (2021) T10006



FBK SiPMs Tests Results

The tests were performed for all SiPMs belonging to the 25 SiPM lot (6 lots). No thermal failures were reported and all prototypes fulfilled the low-level specs. We thus gave green light to the production of the 250 SiPM lots for all types of prototypes and we performed the tests for all SiPMs (250*6=1500 SiPMs).

The results are summarized below. All data were taken before and after 20 thermal cycles and no difference was observed within the measurement experimental uncertainty. The table reports the average values for the 250 SiPMs lot after the thermal cycles at 77 K (liquid nitrogen).

FBK prototypes	PDE (%)	Gain (10^6)	DCR+B	DCR-B	Xtalk (%)	Afterpulse (%)
NUV-HD-CRYO	40	2.0	79	18	18.0	1.6
	45	2.4	83	20	22.9	2.0
	50	2.9	88	23	35.4	3.0
NUV-HD-CRYO-TT	40	4.7	49	21	13.7	
	45	6.0	59	26	17.4	
	50	8.1	84	27	40.4	

Note: DCR+B (with Bursts), DCR-B (without Bursts) in mHz/mm^2

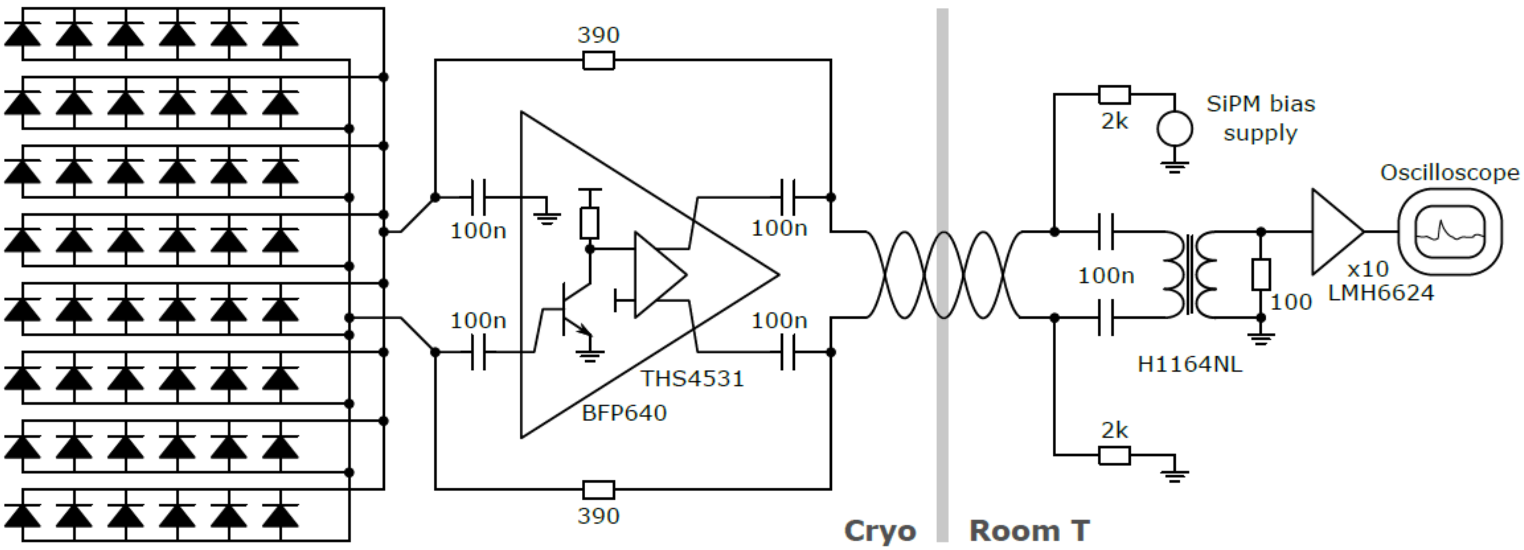
Single SiPMs Tests Results

HPK prototypes	PDE (%)	Gain (10^6)	DCR+B	DCR-B	Xtalk (%)	Afterpulse (%)
HPK S13360-9932	40	2.5	54	22	12.4	2.2
(50µm, Low R)	45	3.3	53	19	12.9	2.8
	50	4.0	58	21	15.1	4.2
HPK S13360-9933	40	2.5	84	19	8.1	1.5
(50µm, High R)	45	3.0	92	28	10.3	2.3
	50	4.0	117	50	11.2	2.5
HPK S13360-9934	40	3.8	86	25	11.0	0.7
(75µm, Low R)	45	4.7	86	32	11.0	0.5
	50	5.6	94	32	12.9	1.1
HPK S13360-9935	40	3.8	71	48	8.2	0.9
(75µm, High R)	45	4.8	79	52	10.9	1.4
	50	5.7	73	59	13.7	1.5

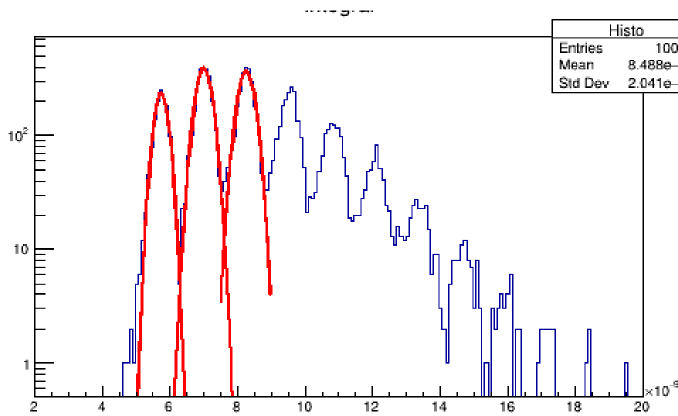
The PDE defines the overvoltage (OV) for each manufacturer and model

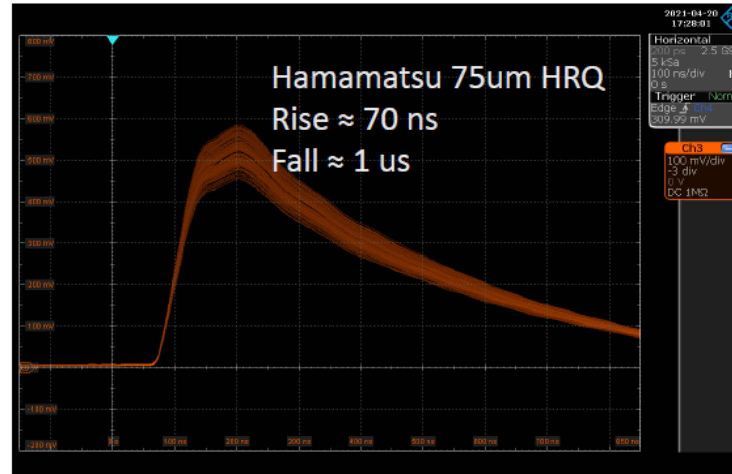
Ganging Tests

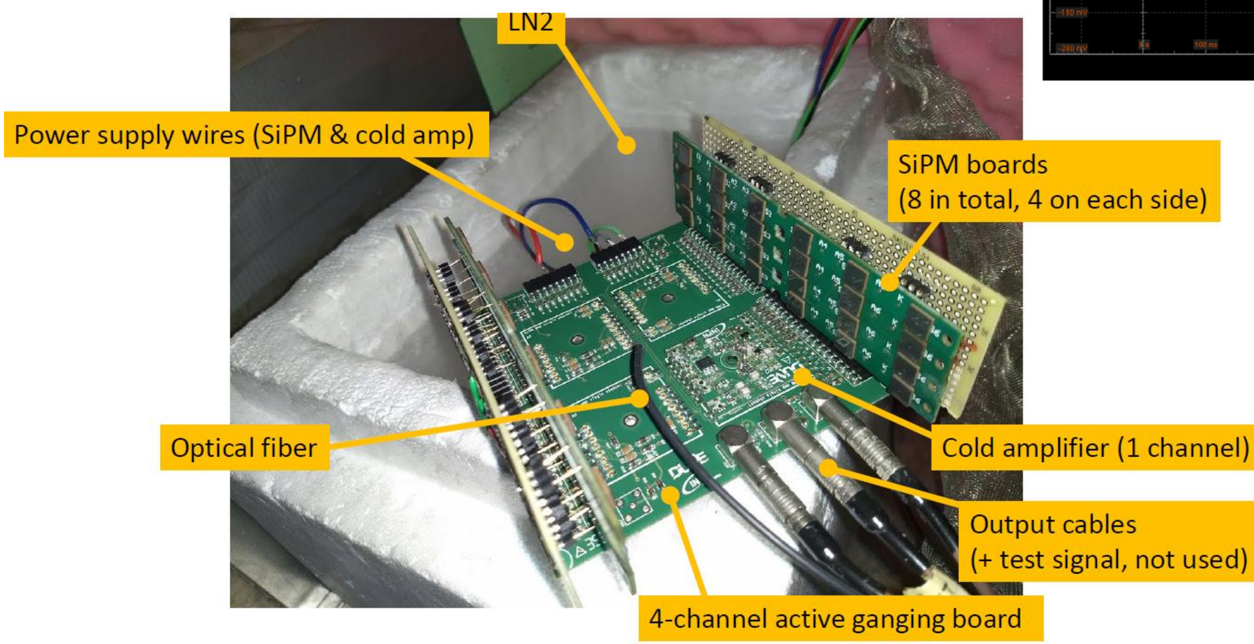
All SiPM prototypes were tested with the final DUNE cold amplifier in the same topology as the network of SiPM of a PDS supercell



Ganging Tests







CIEMAT, Milano Bicocca, Milano Statale

Ganging Tests Results

Three different S/N definitions were considered to evaluate the performance of the different prototypes together with the cold-amplifier. For any of these definitions, all SiPM prototypes fulfill the DUNE requirements at 45% PDE except for NUV-HD-Cryo.

$$SN_0 = \frac{\text{Gain}}{\sigma_0} \qquad SN_1 = \frac{\text{Gain}}{\sigma_{1st}} \qquad SN_C = \frac{\text{Gain}}{\sqrt{\sigma_0^2 + \sigma_{1st}^2}}$$

We employed the S/Nc definition because it is the most conservative estimate to check whether a SiPM prototype was within the S/N spec (S/N>4 at 45% PDE).

Manufacturer & Model	S/Nc @ 45% PDE
FBK NUV-HD-CRYO	2.6
FBK NUV-HD-CRYO TT	5.2
HPK S13360-9932 (50µm, Low R)	6.1
HPK S13360-9933 (50µm, High R)	4.1
HPK S13360-9934 (75µm, Low R)	4.5
HPK S13360-9935 (75µm, High R)	4.8

Down-selection Criteria & Results

Before the tests, the PDS Photo-sensor WG defined the criteria to down-select the prototypes to one sensor per vendor. The criteria were:

1) Fulfillment of all low-level specs. The output is binary (true/false) and prototypes not fulfilling these specs are rejected

2) Best performance in cross-talk, after pulse and DCR at 77 K. The output is a figure of merit (FoM) given by the product of correlated noise (cross-talk + after pulse) times the DCR divided by the gain. The down-selected sensor is the sensor with minimum FoM among the prototypes passing 1st condition.

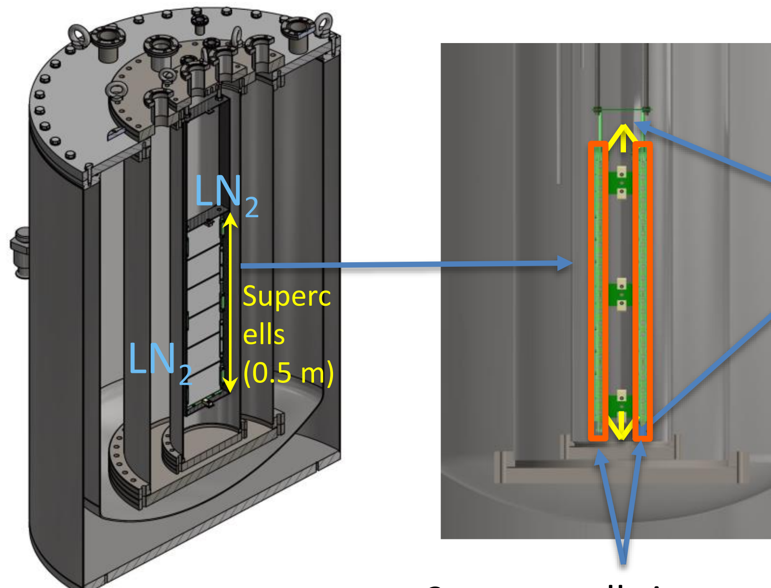
Following these criteria the selected sensors are:

- **S13360-9935 75μm High Quenching Resistance from Hamamatsu**
- **NUV-HD-CRYO 50μm with Triple Trenches from FBK**

Cross check: Validation Tests of Supercells in LN

- To check the operation in LN2 and compare the performance of super-cells equipped with different SiPMs (HPK High and Low quenching resistance and FBK).
- Tests performed at Ciemat and Milano (LASA)

LASA Setup
2 Super-cells (2 channels = half module)

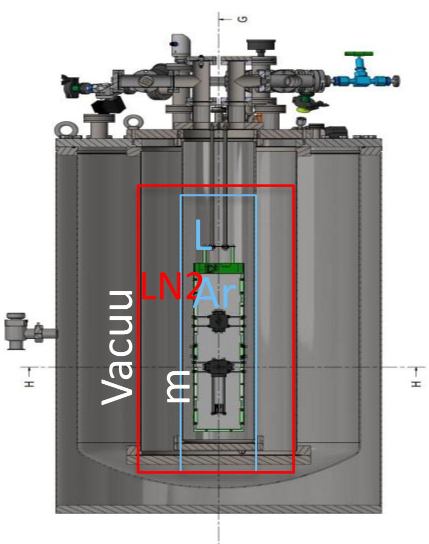


CIEMAT Setup
2 Super-cells equipped with different sensors

Super-cell Tests in LAr

Tests performed at CIEMAT and Milano-Bicocca for the estimation of the Super-cell detection efficiency with two different approaches: Alpha source and calibrated VUV sensitive reference sensors (Method A @ CIEMAT) and Alpha source and #PEs calculation by simulation (Method B @ Milano-Bicocca). Similar results obtained by both institutes.

Quantity	HPK	FBK	Notes
SN0 at 45% PDE	5.3	5.1	[a]
S/N at 45% PDE	4.7	4.1	[b]



CIEMAT Setup
One Super-cell

Met hod	PDE (FBK + EJ) %	PDE (HPK + EJ) %	PDE (HPK + G2P) %
(A)	2.12 ± 0.15	2.36 ± 0.17	3.15 ± 0.23
(B)	1.56 ± 0.12	1.72 ± 0.14	2.28 ± 0.19

Milano Bicocca Setup
SBN X-Arapuca (20cm)