# Cryogenic SiPMs for the DUNE experiment

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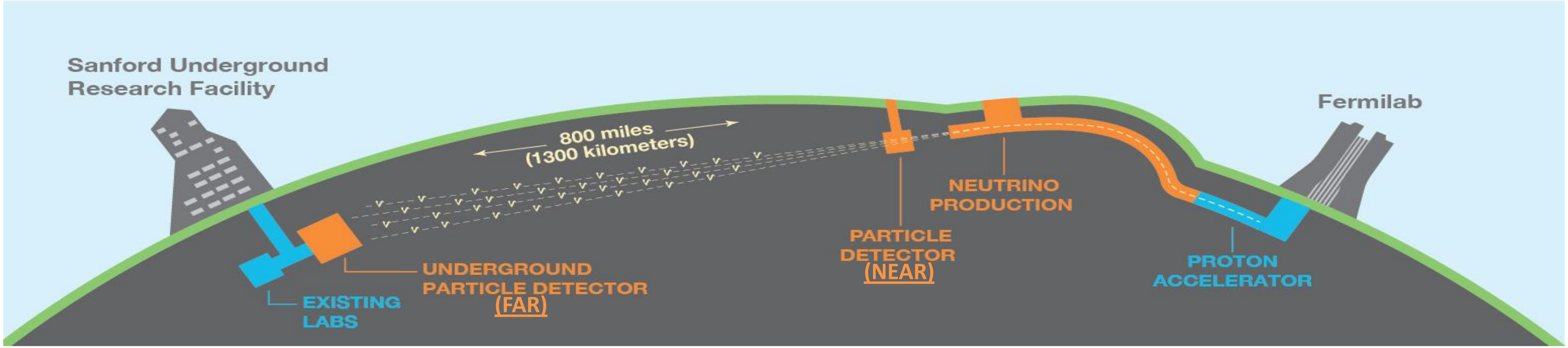
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

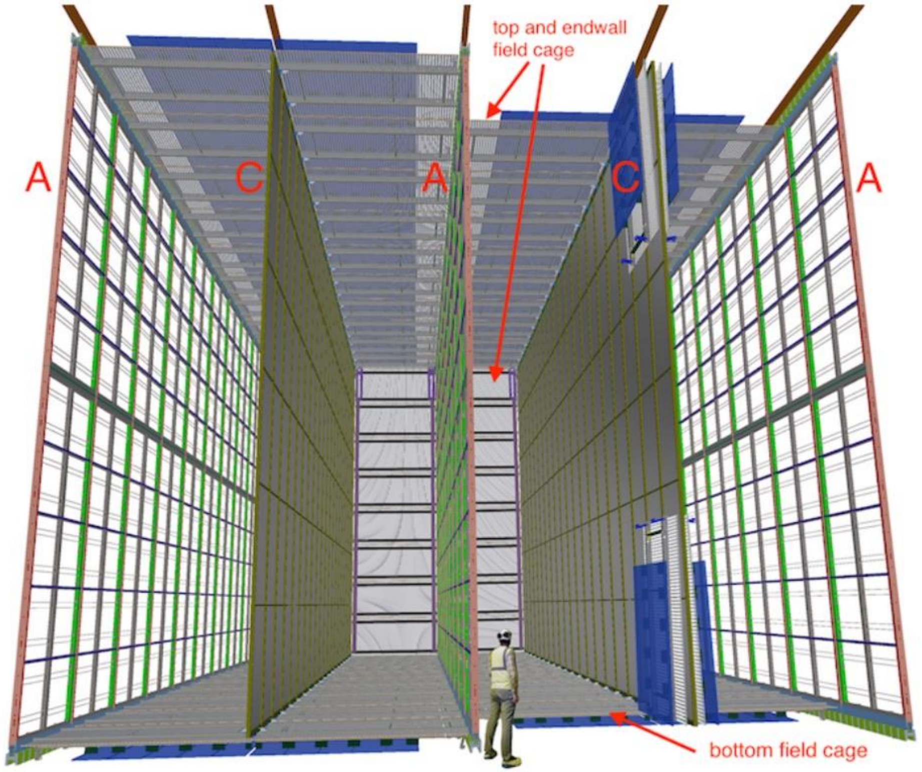
# Deep Underground Neutrino Experiment

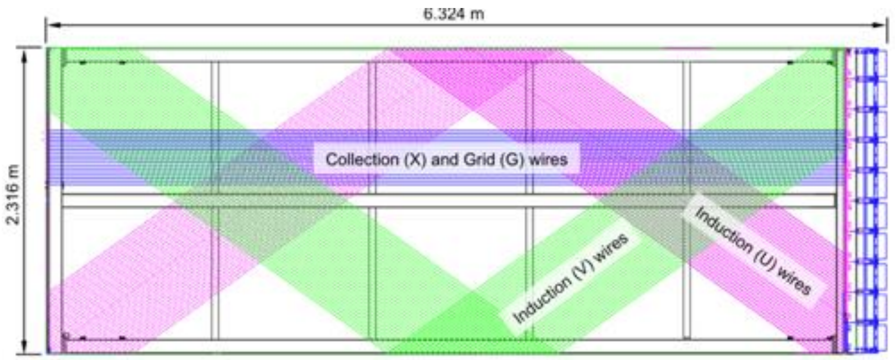
- ❑ **Long-baseline** (LB - 1300 km) experiment:
  - ✓ **Neutrino** and **antineutrino** beams.
- ❑ ~ 70 kton volume far detector, 1.5 km underground, divided in 4 modules.
- ❑ Multi-technology Near Detector, focused on beam characterization and physics.
- ❑ > 20 years foreseen life span.

- ❑ **Primary physics goals**:
  - ✓ 3-neutrino oscillations parameters: $\nu_\mu/\overline{\nu_\mu}$ disappearance, $\nu_e/\overline{\nu_e}$ appearance;
  - ✓ $\delta_{CP}$ ; mass hierarchy.
- ❑ Super Nova burst neutrinos.
- ❑ Beyond-Standard-Model physics: baryon number violation, sterile neutrinos, non-standard interactions, etc.



# Far Detector – Horizontal Drift

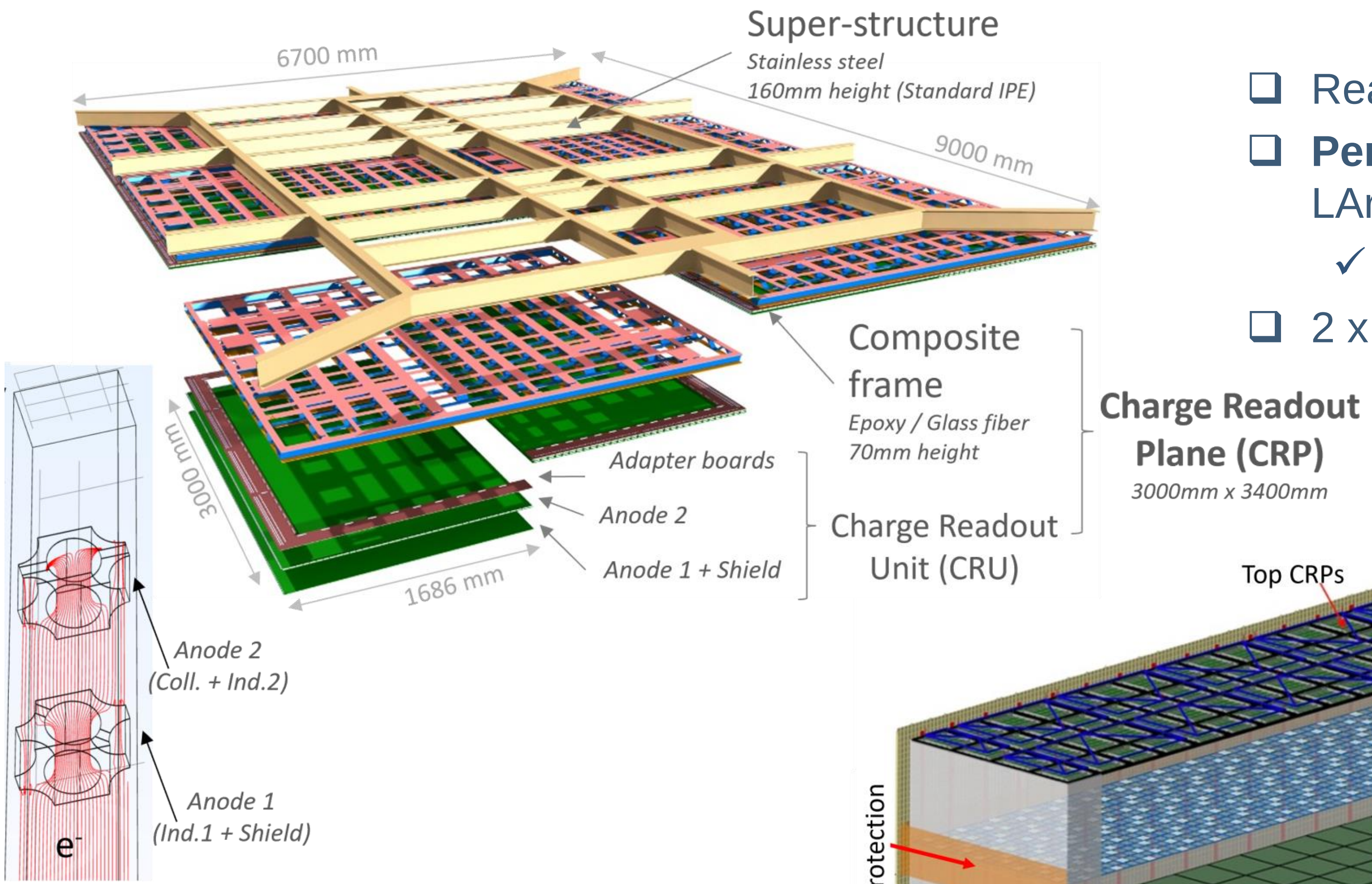


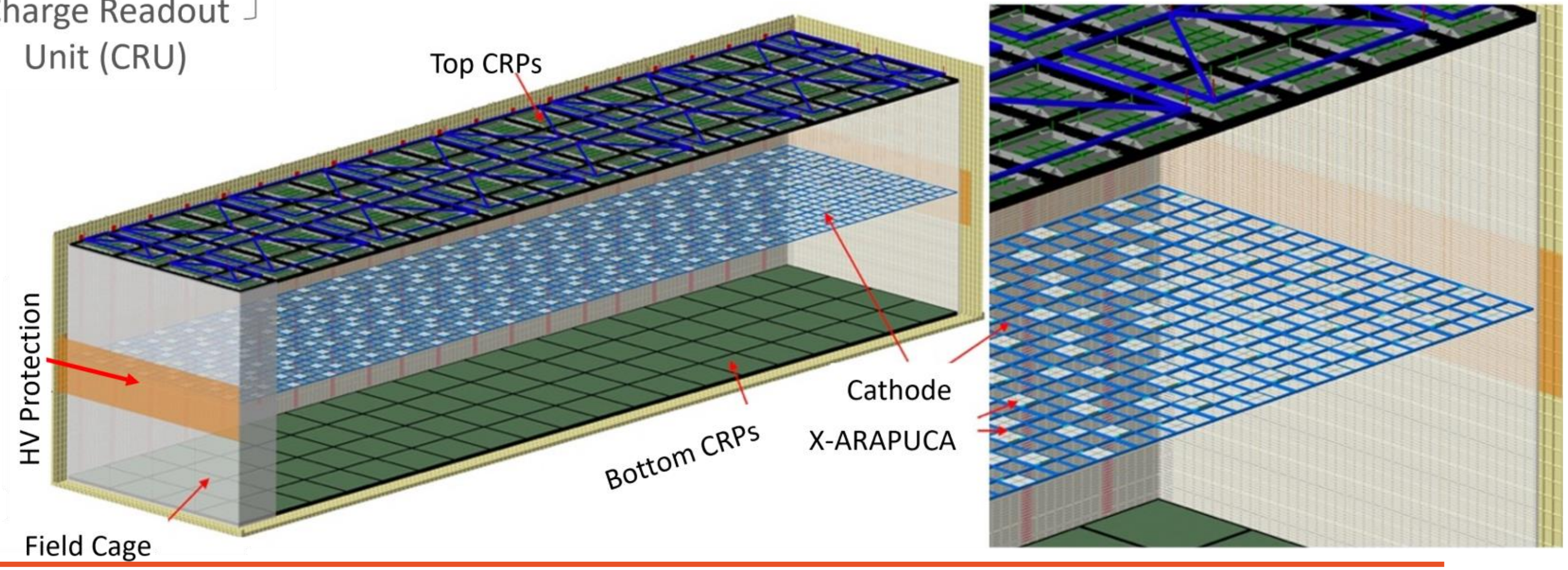




- Structure wholly suspended on roof.
- **Alternating Anode and Cathode Plane Assemblies** (APA – CPA):
  - ✓ 4 drift volumes, 3.6 m drift;
  - ✓ electric field = 500 V/cm (HV = -180 kV);
  - ✓ **high-resistivity CPA** for fast discharge prevention.
- Anode: 150 APAs, each with 4 wire planes (Grid, 2 x Induction, Collection):
  - ✓ **wrapped induction wires**;
  - ✓ 2560 wires/unit;
  - ✓ inter-plane distance = 4.75 mm.

# Far Detector – Vertical Drift

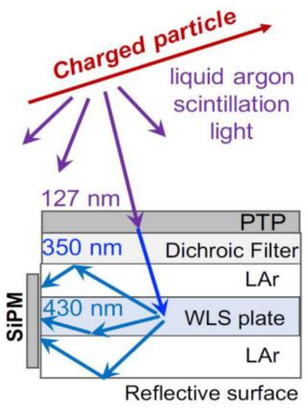
- Read-out on cryostat top and bottom;
- **Perforated PCB anode**, fully immersed in LAr:
  - ✓ 3-view design plus shield (2 anodes);
- 2 x 6 m drift ⇔ **300 kV HV on cathode**.



# X-Arapuca

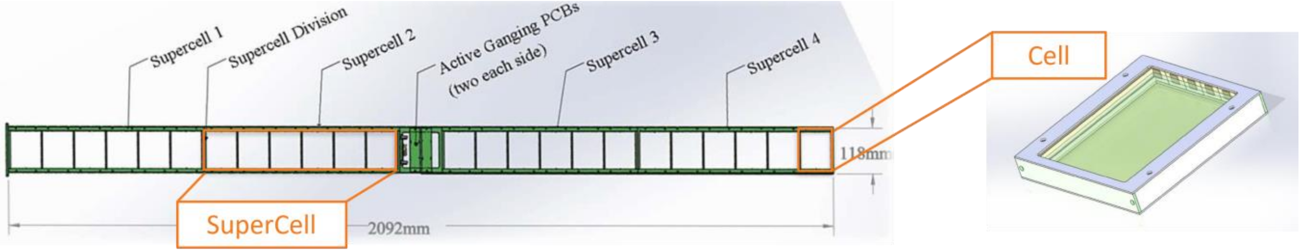
- ❑ **X-ARAPUCA**: internal reflection and highly reflective boxes:
- ✓ efficient conversion of VUV photons;
- ✓ high fraction of captured photons;
- ✓ efficient photosensors.




See Francesco di Capua talk (06/09)!

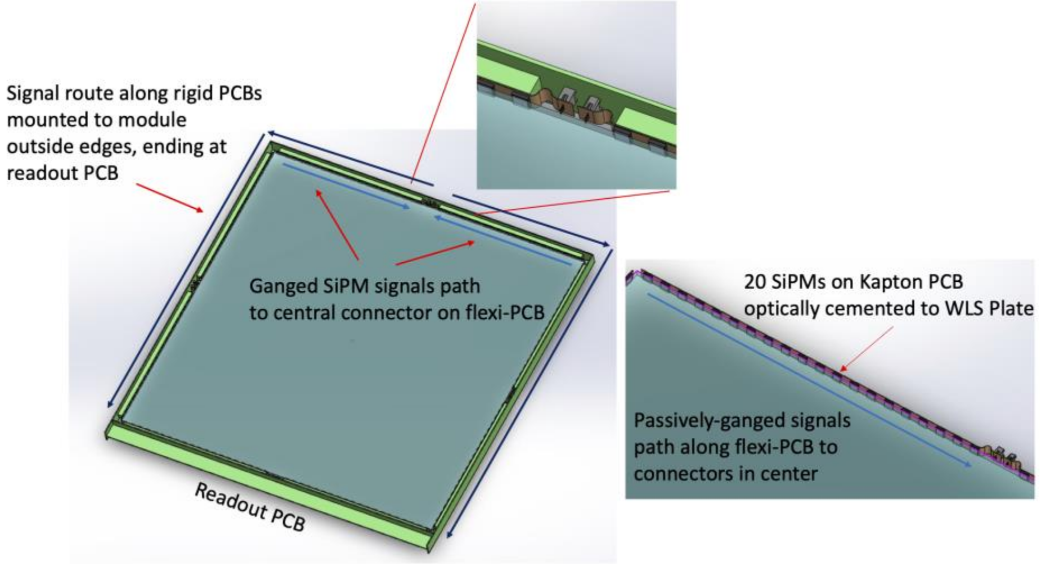
**Horizontal Drift**

- ❑ SuperCell: 6 cells 488 × 100 × 8 mm$^3$.
- ❑ Module: 4 SC 2092 × 118 × 23 mm$^3$ (bars configuration).
- ❑ 10 modules / APA.




**Vertical Drift**

- ❑ "4π" reference design.
- ❑ 320 X-ARAPUCA 60 x 60 cm$^2$ on cathode, and 320 + 32 on cryostat membrane (~3 m from cathode), analog readout.



# SiPMs

- ❑ **Horizontal Drift**:
- ✓ 48 SiPMs per SuperCell;
- ✓ 1 readout channel per SC (passive+active ganging);
- ✓ 288,000 SiPMs in total.

- ❑ **Vertical Drift**:
- ✓ 160 SiPMs per Plate;
- ✓ 1 readout channel per Plate (passive+active ganging);
- ✓ 107,502 SiPMs in total.

- ❑ Two photosensor vendors are being investigated: **Hamamatsu Photonics (HPK)** and **Fondazione Bruno Kessler (FBK);**
- ✓ 6 types (splits) of 6x6 $mm^2$ SiPMs developed specifically for DUNE: 4 from HPK (S13360 – LQR/HQR – 50/75 µm pitch) and 2 from FBK (NUV-HD-CRYO single/triple trench);

| Low level specs | Value |
|---|---|
| Max nominal operating V | [50 V at cold] |
| Dark count rate (DCR) | <100 $mHz/mm^2$ |
| Correlated noise | <35% |
| Time resolution | <1 $\mu s$ |
| Thermal cycles | >20 |
| Recovery time | $\tau \sim$ a few $\mu s$ |
| PDE at 87 K | >35% at nominal OV |
| **High level specs** | **Value** |
| Dynamic range | 1-2000 p.e. |
| S/N>4 | Per supercell (48 SiPMs) |
| Trigger | 1.5 p.e. |

# SiPMs : selection procedure

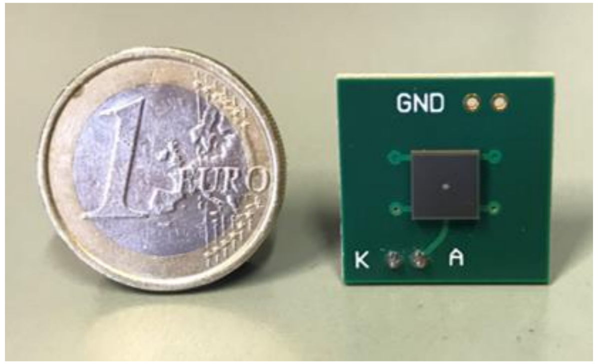
- **25 SiPMs of each type** fully characterized at single SiPM level:

✓ IV curve measurements at room T and at 77 K;

✓ gain, S/N and DCR measured (77K) at OV to obtain 40%-45%-50% of PDE;

✓ 20 thermal cycles with controlled cooling down and warming up;

✓ all measurements repeated after the thermal stresses.



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- ❑ **250 SiPMs per type** tested at single SiPM level:
- ✓ IV measurements for all SiPMs at room T and at 77K;
- ✓ 20 thermal cycles with controlled cooling down and warming up;
- ✓ IV measurements repeated for all SiPMs and complete characterization for 5% sample per split.
- ❑ Test with 48 SiPM in active ganging at different OV per each split: test of S/N and signal shape.

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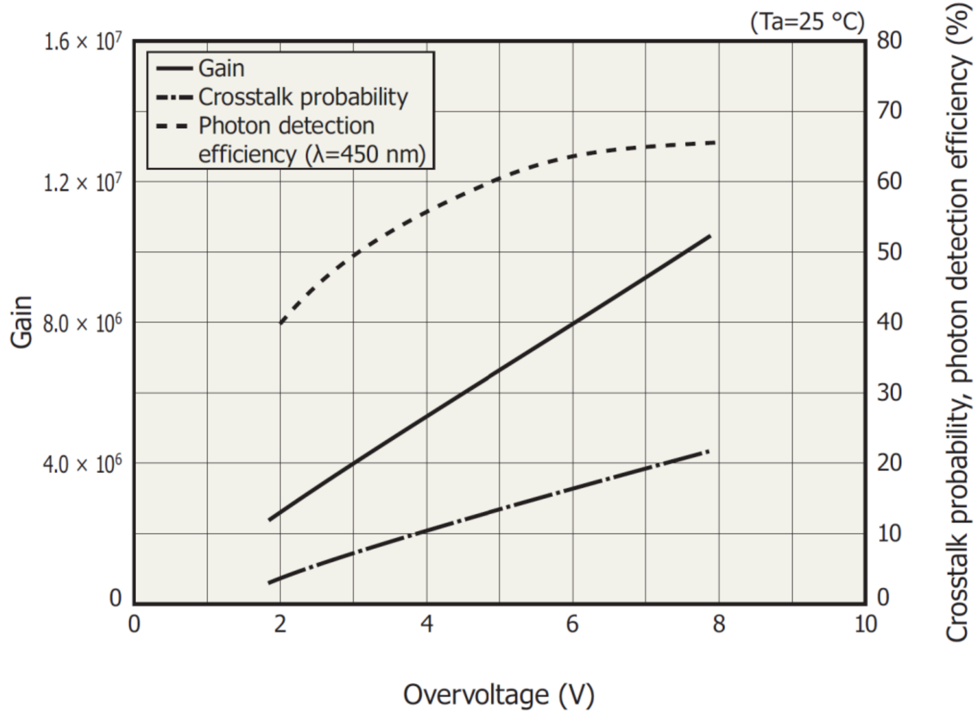
**HPK HQR 75 µm and FBK Triple Trench down selected**

# HPK HQR 75 μm

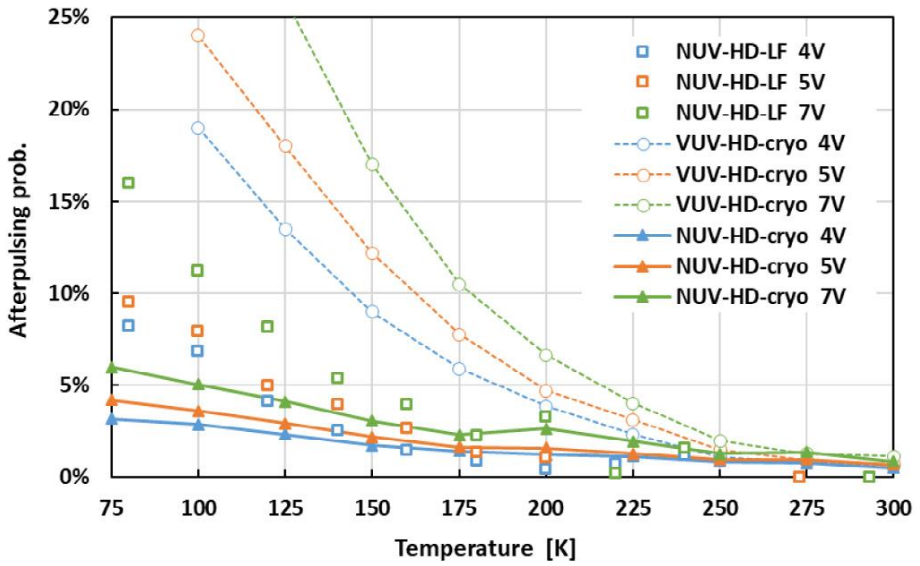
- ❑ The technology employed by Hamamatsu[1]:
- ✓ low terminal capacitance;
- ✓ a new type of metallic resistance with a tunable thermal coefficient;
- ✓ high quenching resistance system to suppress large-amplitude afterpulses;
- ✓ allows for careful tuning of the signal shape and fast recovery time at 87 K.

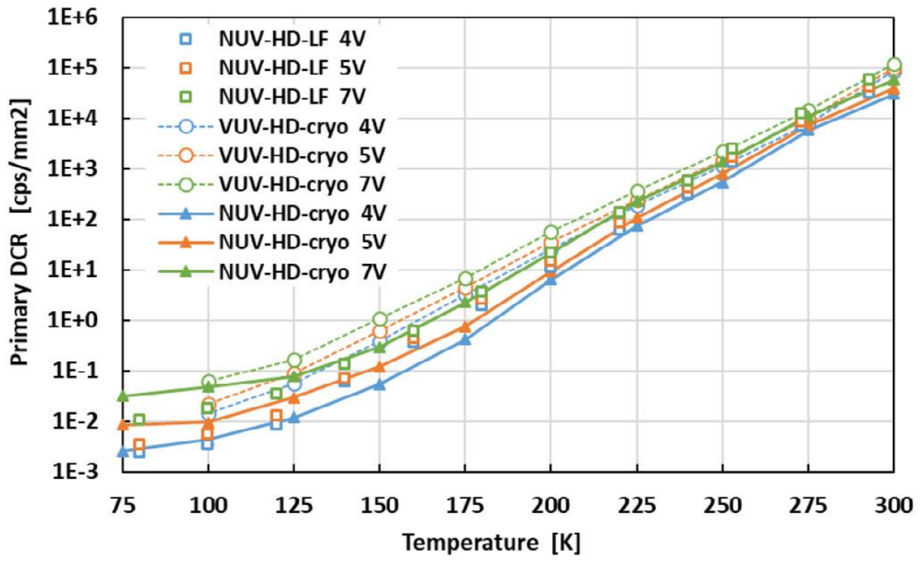



[1] https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/s13360_series_kapd1052e.pdf

# FBK NUV-HD-CRYO Triple Trech

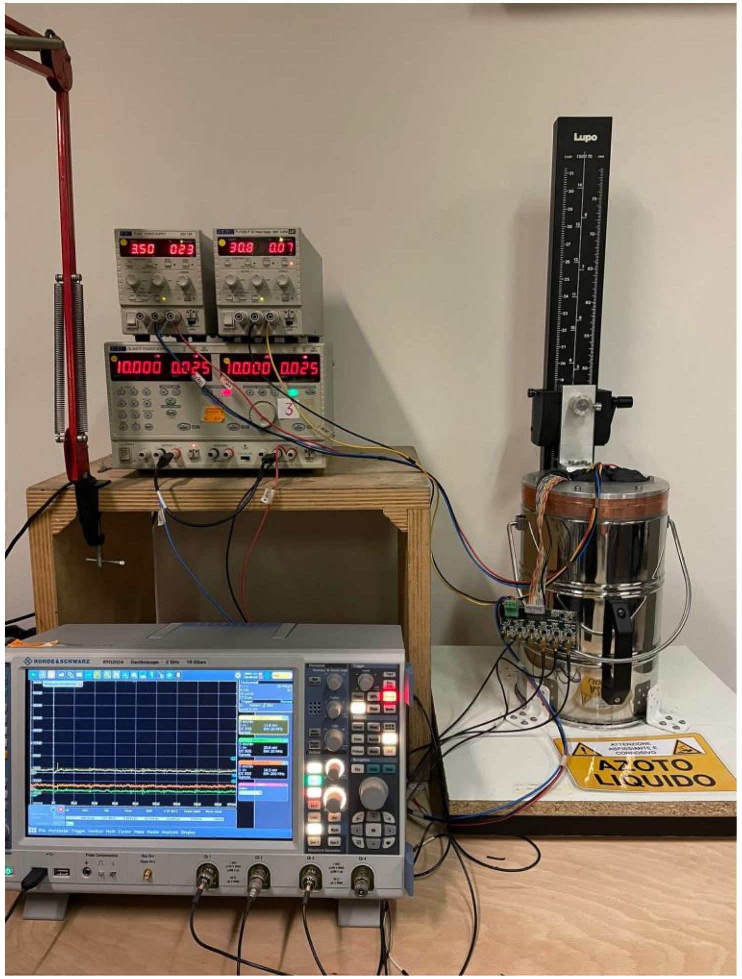
- ❑ FBK employed a well-established technology i.e. NUV-HD-CRYO[2]:
- ✓ low electric field inside the junction to reduce the tunneling generation rate and so the DCR;
- ✓ internal modification of the doping profiles for reduced afterpulsing probability;
- ✓ modified polysilicon quenching resistor with reduced temperature coefficient.
- ❑ Enlarged tranches to reduce cross talk.




[2] https://doi.org/10.1016/j.nima.2022.167683

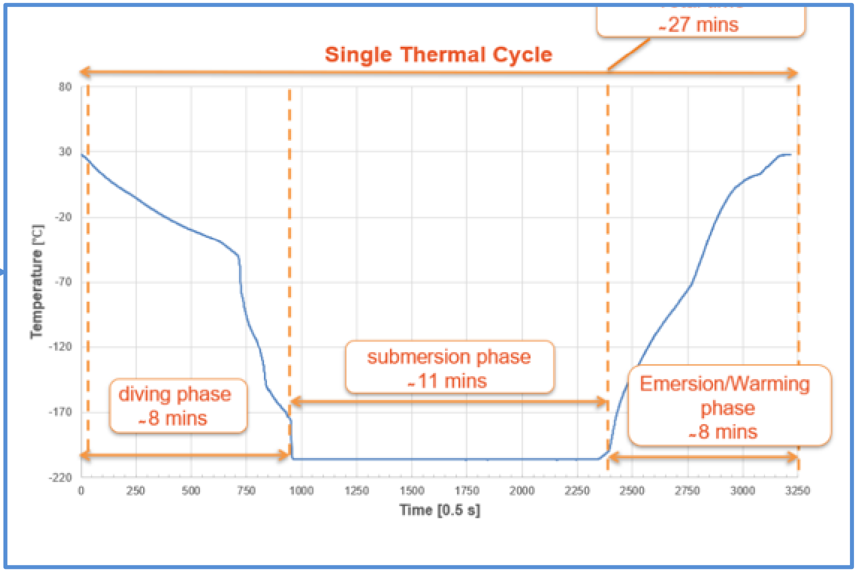
# Test stands



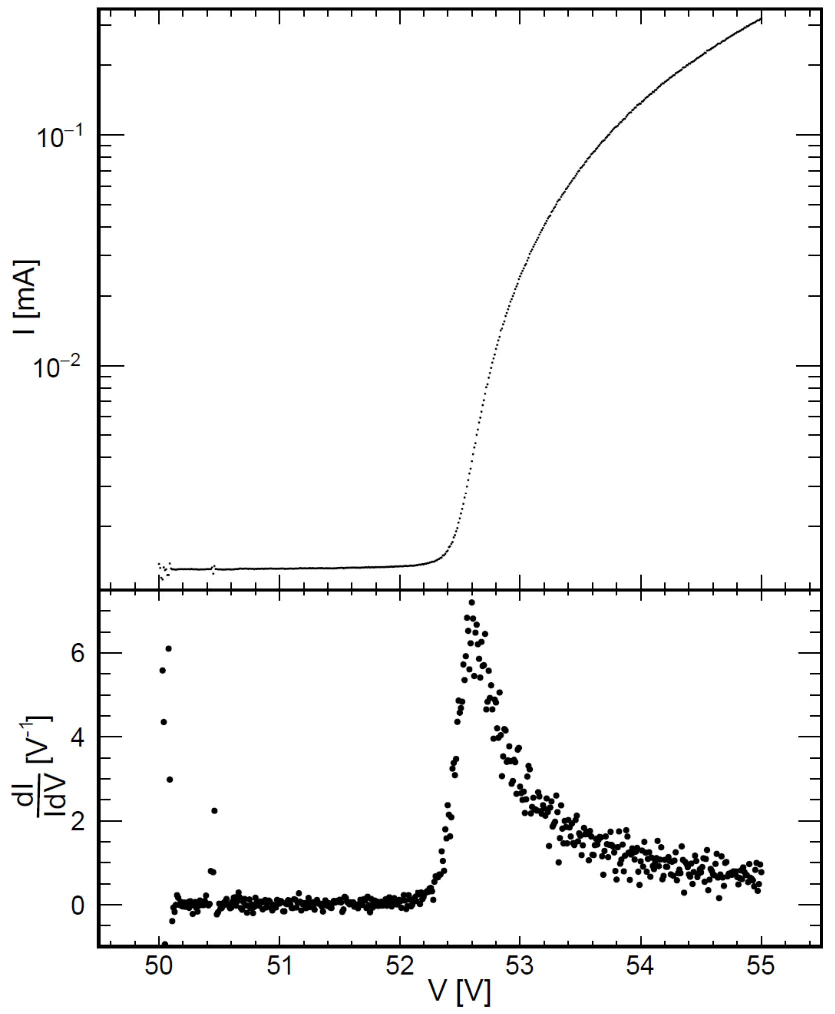

- CIEMAT, Madrid
- INFN and Università of Bologna;
- INFN and Università of Ferrara;
- INFN and Università of Milano-Bicocca;
- Institute of Physics, Czech Academy of Sciences, Prague;
- Instituto de Física Corpuscular, Valencia
- Northern Illinois University, Department of Physics

Laboratories involved

Thermal Cycle



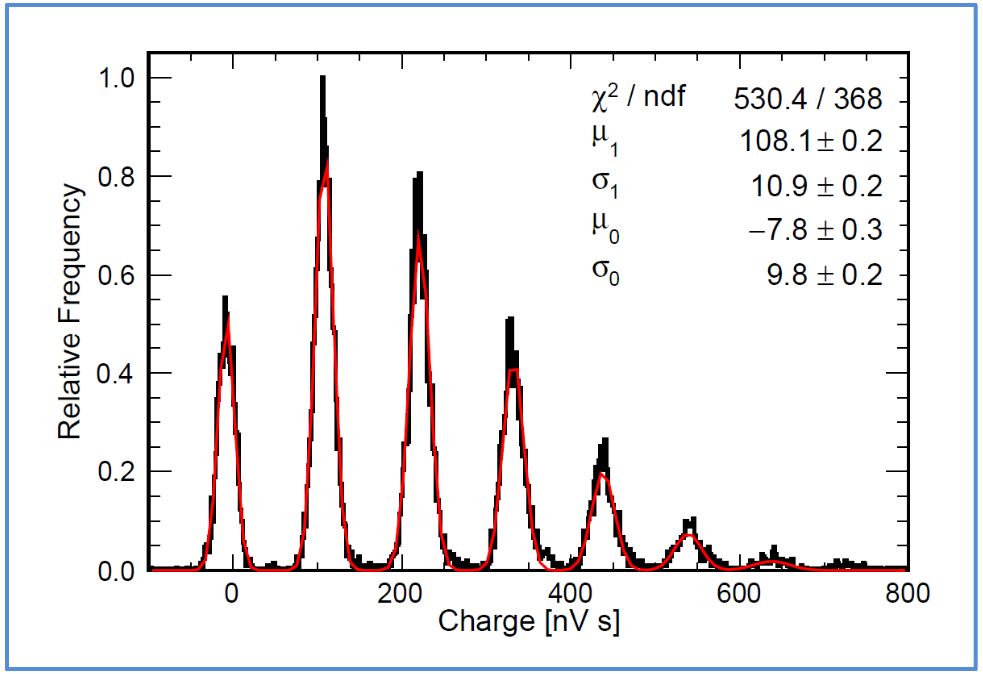
# $V_{bd}$ and OV




| $V_{bd}$ | HPK | FBK |
|---|---|---|
| 300 K | 51.86±0.33 V | 32.70±0.05 V |
| 77 K | 41.97±0.32 V | 27.09±0.04 V |

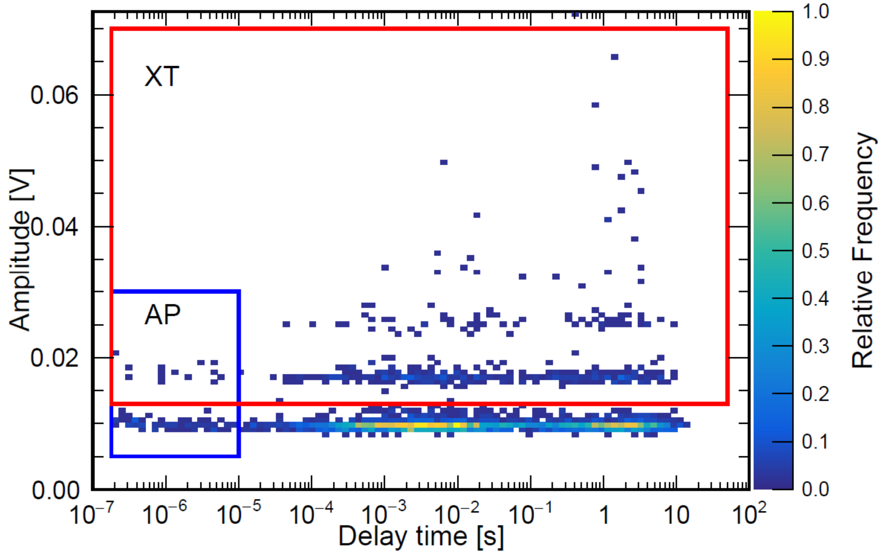
| PDE | HPK | FBK |
|---|---|---|
| 40 % | 3 V OV | 3.5 V OV |
| 45 % | 4 V OV | 4.5 V OV |
| 50 % | 5 V OV | 7 V OV |

# Gain




| PDE | HPK | FBK |
|---|---|---|
| 40 % | $3.73 \cdot 10^6$ | $4.73 \cdot 10^6$ |
| 45 % | $4.59 \cdot 10^6$ | $6.01 \cdot 10^6$ |
| 50 % | $5.44 \cdot 10^6$ | $8.21 \cdot 10^6$ |

# Dark Noise




**HPK HQR 75 µm**

| PDE | DCR (mHz/mm²) | Cross-talk | After pulse |
|---|---|---|---|
| 40 % | 57.54 | 6.62 | 0.86 |
| 45 % | 64.97 | 8.97 | 1.10 |
| 50 % | 66.32 | 10.96 | 1.30 |

**FBK Triple Trench**

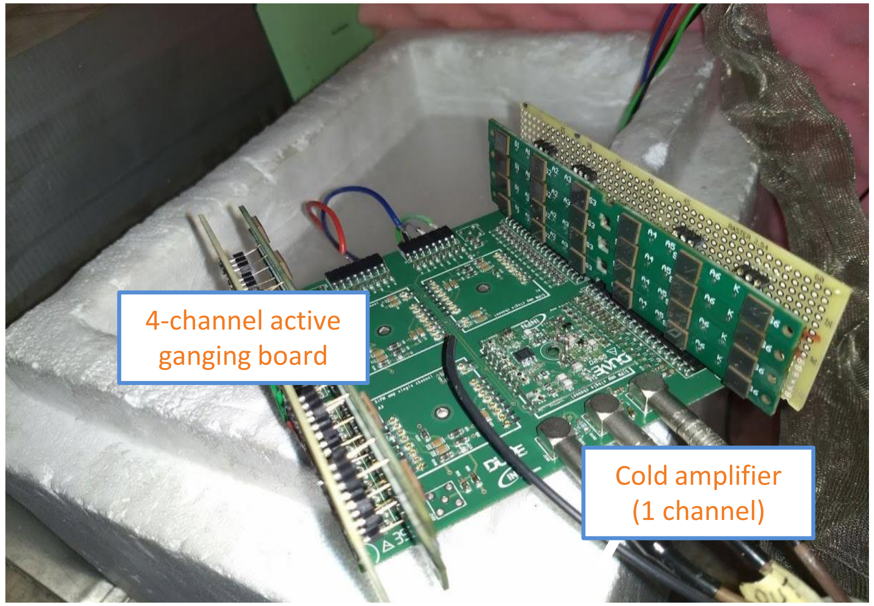
| PDE | DCR (mHz/mm²) | Cross-talk | After pulse |
|---|---|---|---|
| 40 % | 80.79 | 13.76 | 2.85 |
| 45 % | 86.33 | 15.67 | 3.25 |
| 50 % | 93.35 | 40.50 | 4.05 |

# Ganging tests

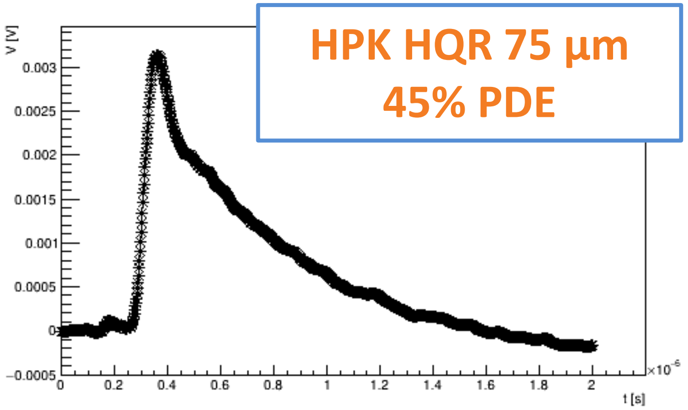
- ❑ Test with the **ganging of 48 SiPMs** of a supercell.
- ❑ **DUNE FD1 amplifier** [3]: Two-stage amplifier - SiGe bipolar transistor + fully differential op-amp:

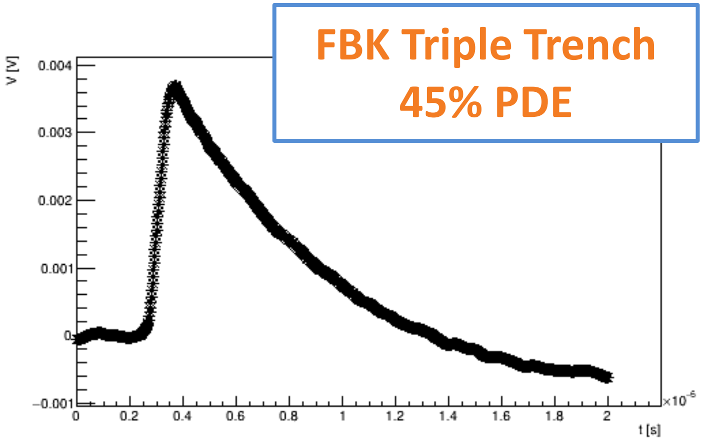
✓ fast response;

✓ dynamic range 2000 p.e. .




| | HPK | FBK |
|---|---|---|
| Rise time | 58 ns | 64 ns |



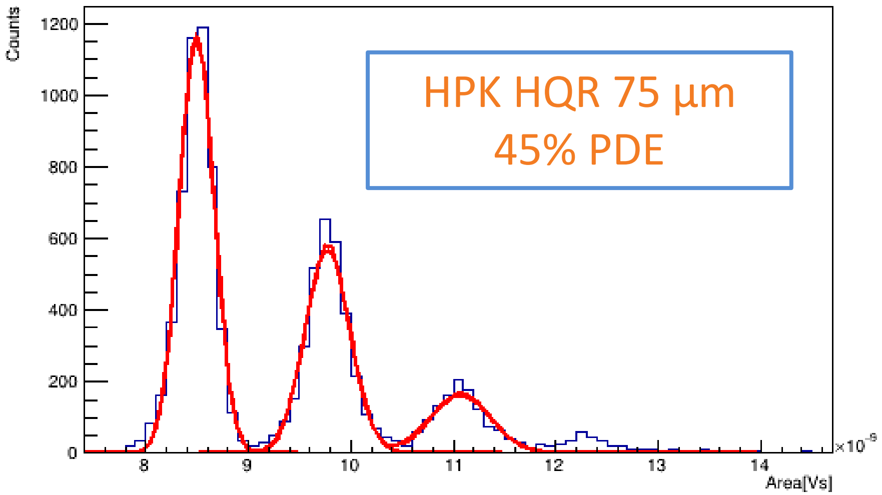



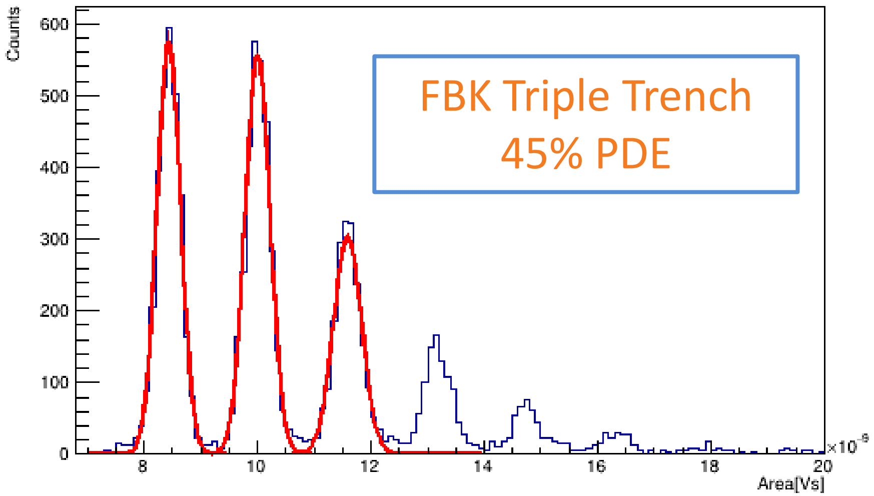

[3] JINST (2020) 15 P01008

# Ganging tests

- ❑ Good **S/N ≈ 5-10** → Allows clear separation of photoelectron peaks with 48 SiPMs in parallel.

| PDE | HPK | FBK |
|---|---|---|
| 40 % | 5.21 | 5.69 |
| 45 % | 5.96 | 7.16 |
| 50 % | 6.66 | 10.34 |

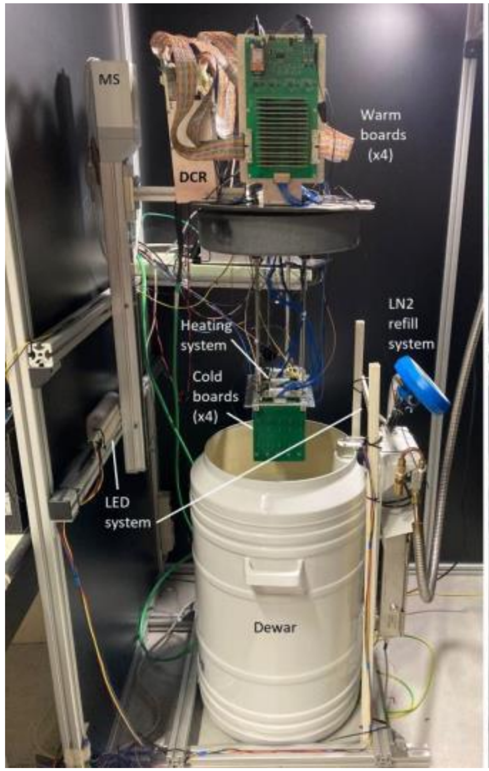


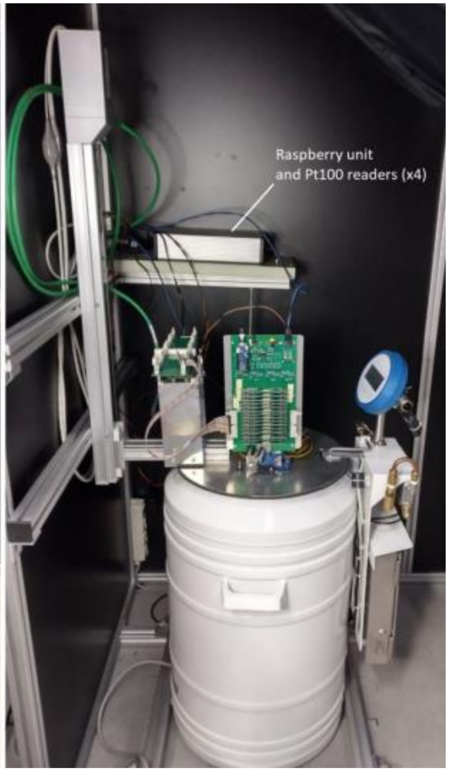



# Future tests

- ❑ **Mass test facilities in place** (5 institutes) to test all 300,000 FD-I SiPMs:
- ✓ reject faulty elements;
- ✓ I-V curves to gang SiPMs by similar $V_{bd}$;
- ✓ DCR measurement.

See Marco Guarise talk (06/09)!




- ❑ For **VD SiPMs** are connected in bunch of 20, on flexible PCB.
- ❑ Tests for Proto Dune VD Module ongoing:
- ✓ reject faulty elements;
- ✓ I-V curve in reverse mode for $V_{bd}$.

# Thanks!