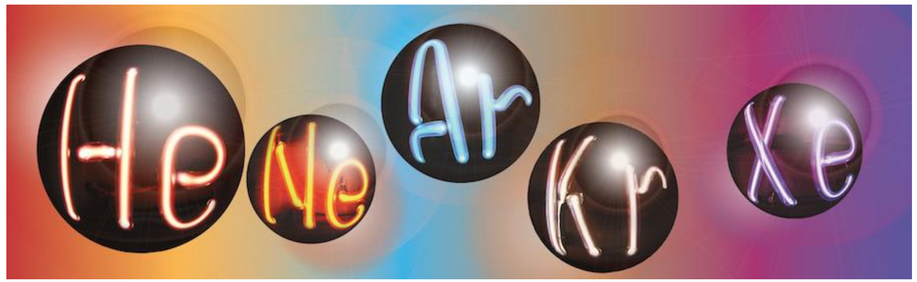
Characterization, mass tests and first results of the FBK SiPMs for the Photon detection system of DUNE Far Detector HD

Marco Guarise on behalf of the DUNE Collaboration

LIDINE conference 2025, *Hong Kong*

October 22th, 2025



Università degli Studi di Ferrara

INFN Istituto Nazionale di Fisica Nucleare

Contents

- Overview of the DUNE experiment
- DUNE FAR Horizontal Drift detector:
  - SiPMs in the Photon Detection System
- FBK SiPMs
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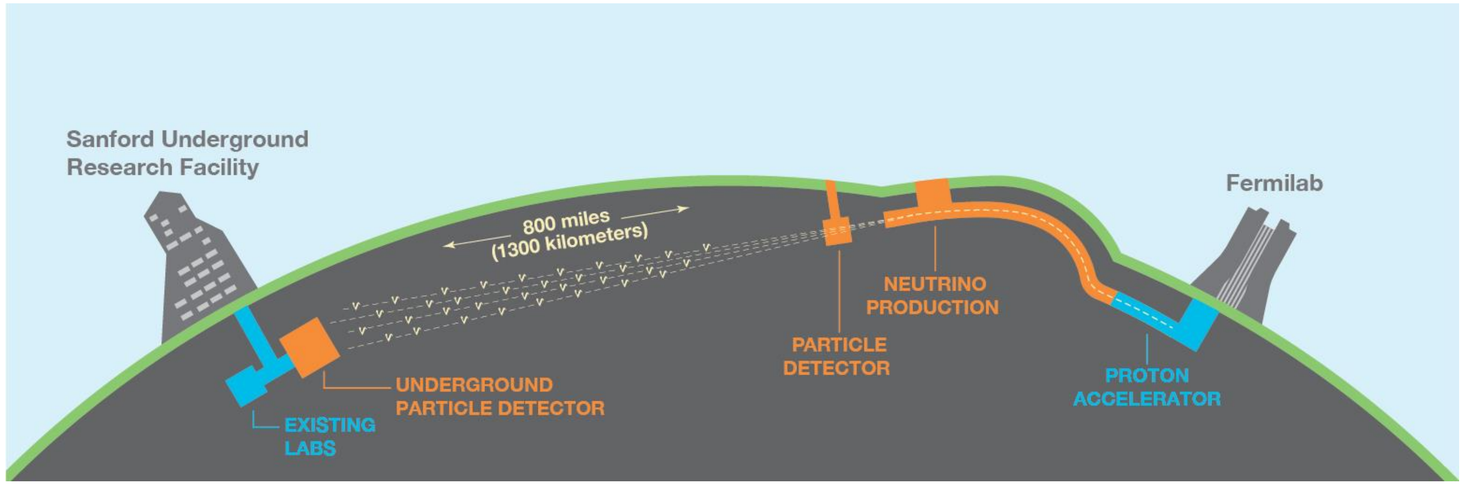
  - Procedure
  - Tests
- Characterization Results of the FBK spanish production lot
- Conclusions

Deep Underground Neutrino Experiment (DUNE)

DUNE, main physics goals:

- Precise measurement of neutrino oscillation parameters (mass ordering and δ_{CP}); *EPJC 80 (2020) 978*
- Study supernova low energy neutrino; *EPJC 81 (2021) 322*
- Physics beyond SM; *EPJC 801(2021) 423*

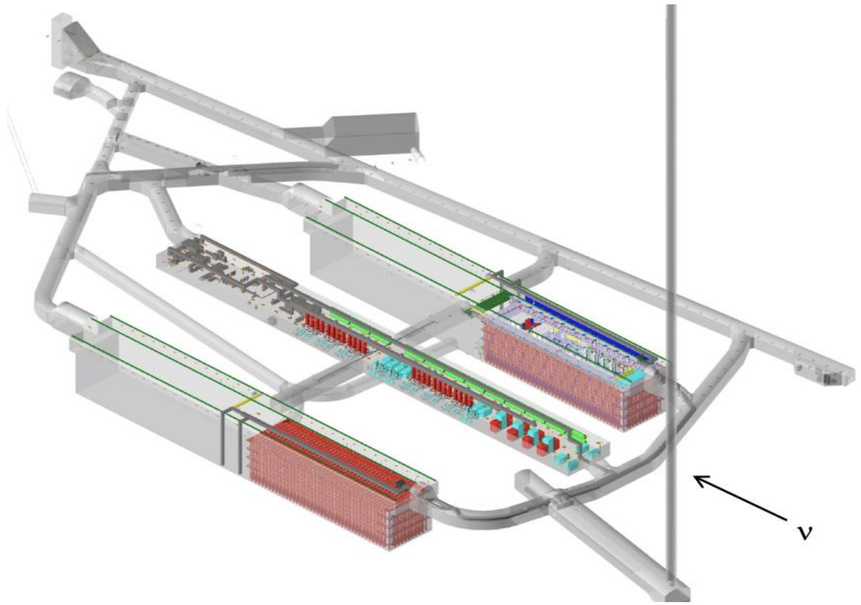


- New neutrino **beam facility** @ FNAL (LBNF)
- **Near detectors** @ FNAL→ measure unoscillated neutrino spectrum & flux constraints *JINST 15 (2020) T08008*
- **Far detectors** @SURF→oscillated neutrino studies *JINST 15 (2020) T08010*

See C. Cattadori talk "Using Argon for neutrino Physics: the Deep Underground Neutrino Experiment"

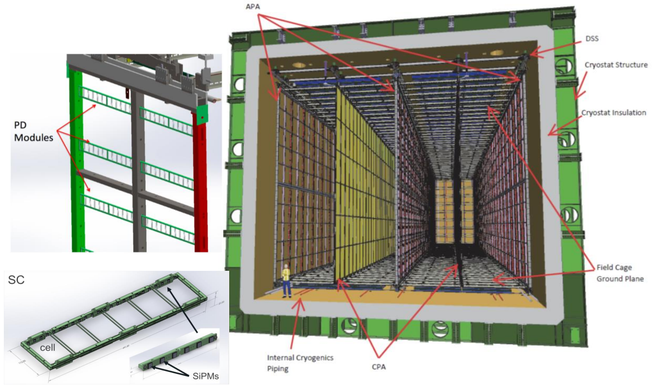
DUNE Far Detector

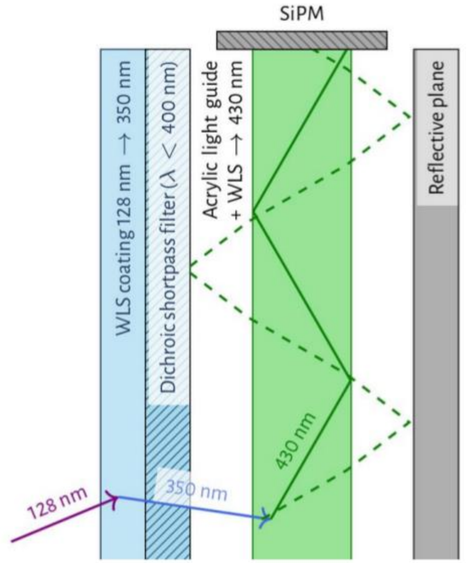
- Located ~1300km from the production site ~1.48 km underground @ Sanford Underground Research Facility in Lead, South Dakota (USA)
- Four 17-kt LAr TPC modules
- Phase I:
  - **FD-HD horizontal drift**
  - FD-VD vertical drift



FD HD

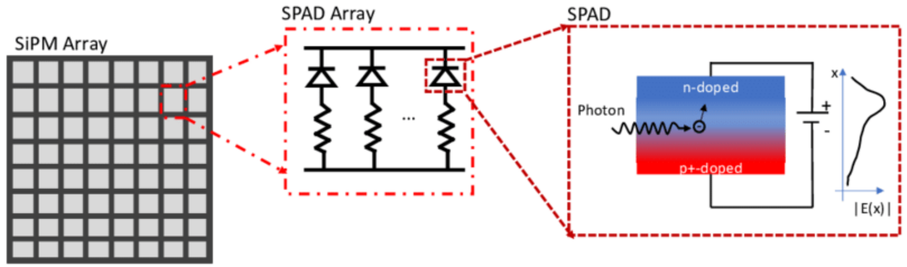
- 4 drift volumes. Anode-cathode drift distance 3.5 m with E = 500 V/cm.
- 150 Anode Plane Assemblies (APAs).
  Each APA consists of three wire planes for charge collection and
  10 Photon Detection modules.
- 10 (2m x 12cm) PD modules per APA
  each composed by 4 X-ARAPUCA supercells.
- A X-Arapuca supercell consists of six 10×10 cm^2 pTP-coated dichroic filters, a 60 cm WLS bar and 48 SiPMs.
- ~300k SiPMs in total.





The DUNE photosensors

- **SiPMs**
  - A matrix of single-photon avalanche photodiodes operating in reverse bias above breakdown voltage V_{bd};
  - Robust, high sensitivity and dynamic range, immune to B field, reduced cost/size;



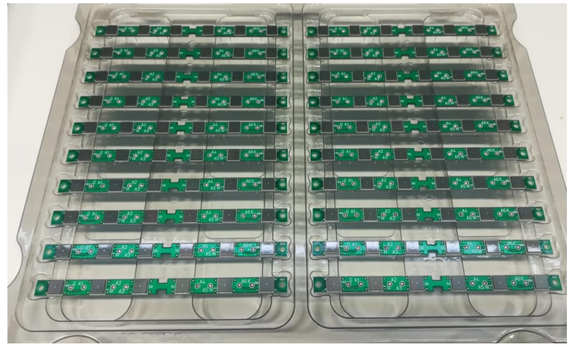
- **Specifications for DUNE**:
  - Quantum efficiency > 35% for 430 nm light @ 87 K;
  - Dimensions compatible w/ ARAPUCA design;
  - SiPM + FEE w/ dynamic range 1-2000 photons, even for events far from the ARAPUCA;
  - Dark count Rate (DCR) subdominant wrt noise from ^{39}Ar;
  - Cross-talk (CT) and after-pulse (AP) < 15%;
  - Durability (> 10 y) and cryoreliability (resistant to multiple cool-downs);
  - Few μs recovery time.

The DUNE photosensors

- **SiPMs:**
  - Several models tested from two vendors: HPK, FBK; ~50% of FD-HD SIPMs each;
  - Chosen models HPK S16517 & FBK NUV-HD-Cryo 3T;
  - Mounted in arrays with 6 SiPMs each in common cathode configuration w/ independent anode;

- ~100 SiPMs during selection process;
- ~8k SiPM for ProtoDUNE-HD tested in 2022;
- ~300k SiPM for DUNE FD-HD under test (2023 – …).

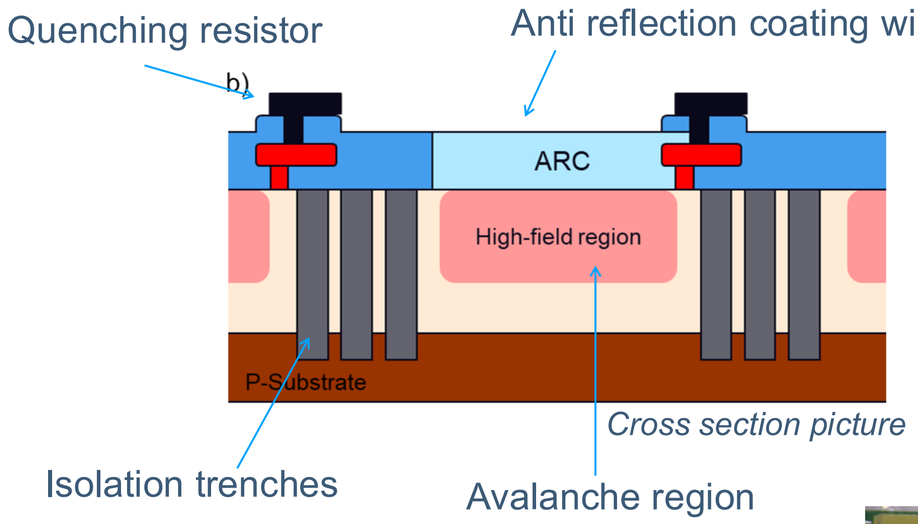
- **Measurements to be performed:**
  - IV curves in FWD and REV bias @ room temperature and LN2 temperature;
  - Thermal stresses resilience;
  - DCR @ LN2 temperature.

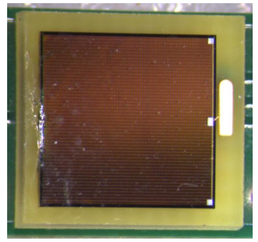


HPK tray example

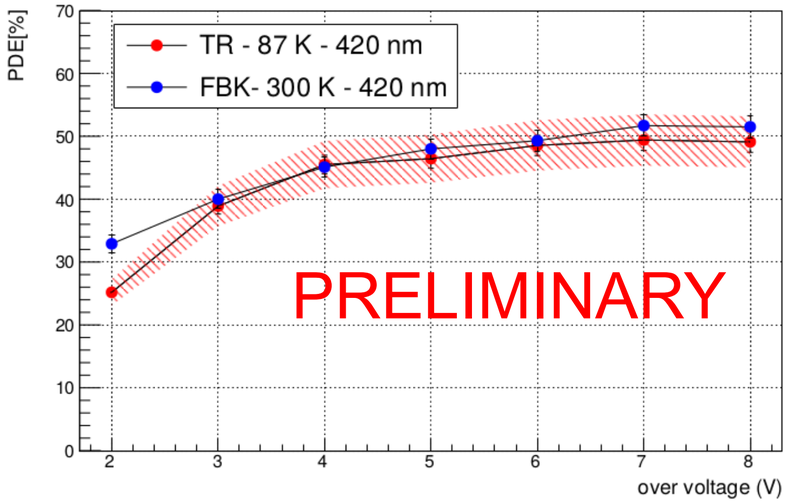
FBK SiPMs

- FBK **NUV-HD-Cryo 3T**:
  - Customization for DUNE experiment;
  - Based on the NUV-HD Cryo technology;
  - 54um cell pitch and 6x6mm^2 area;
  - 3 isolating trenches between cells to decrease cross talk probability;
  - Cryo reliability.





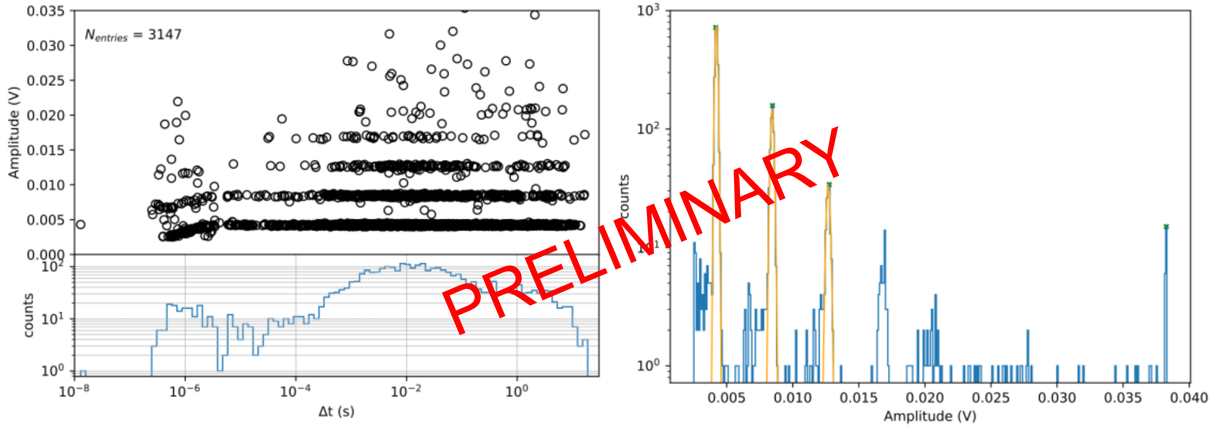
Microscope picture

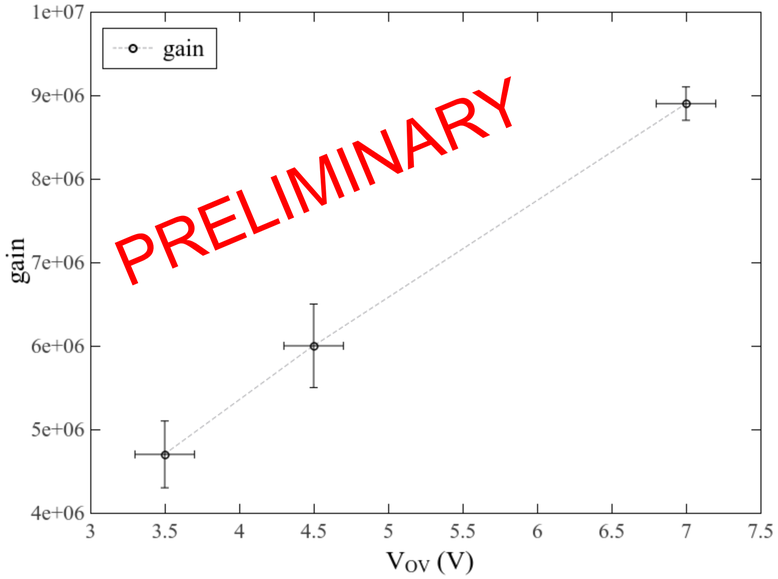


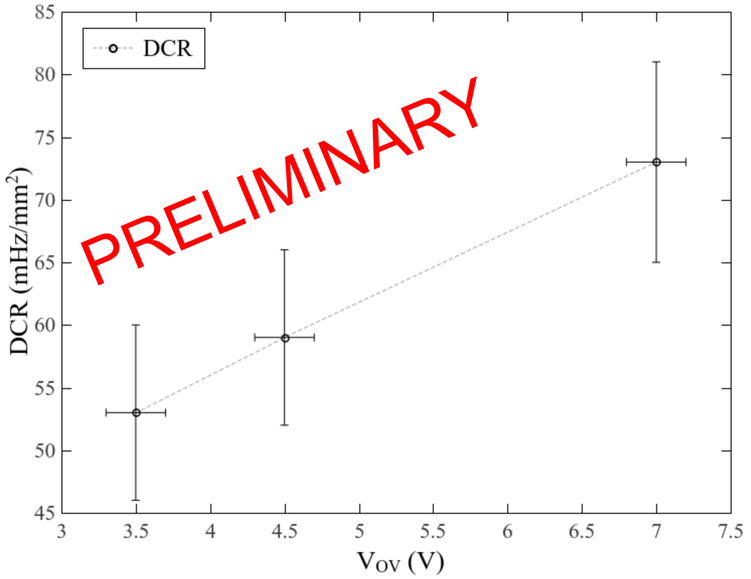
- PDE was measured also at LAr temperature;
- Measurements at TRIUMF (F. Di Capua & F: Gallina) with a dedicated custom setup based on LN2 cooling and monochromator (VERA setup) ;
- No large variations in PDE wrt the one measured at room temperature by FBK

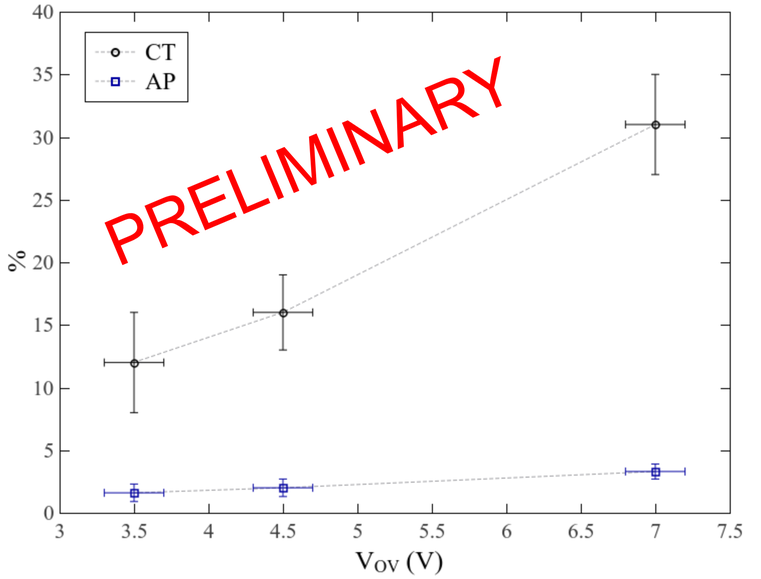
FBK SiPMs

- Preliminary characterization for a batch of 250 sample;
- Measurements at the single sensor level with commercial instrumentation:
  - IV curves Source Meter Unit 10pA precision
  - Custom amplifier for signal acquisition + oscilloscope (min requirements 1GHz band, 5GS/s and 8bit res) half p.e.

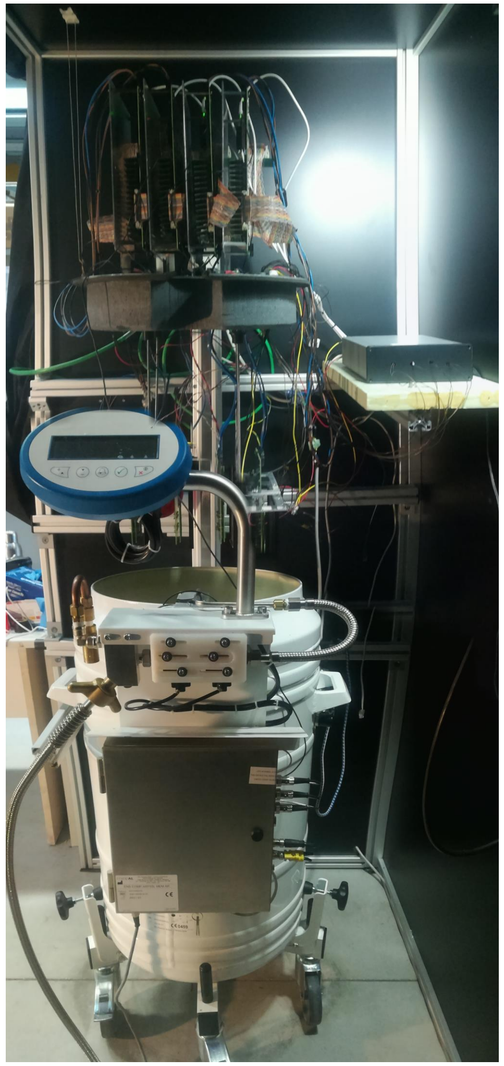








The Quality Assurance Test Setup



- Custom setup developed by INFN and Universities of Ferrara and Bologna;
- **Massive tests on the entire FD-1 SiPMs production** to assess:
  - SiPM identity;
  - Failure/mortality rate;
  - Quality assurance;
- Capability: test of 120 SiPMs (20 arrays) in a single session of complete characterization (lasting < 6 h);
- 5 different test sites: Bologna, Ferrara, Granada, Milano Bicocca and Prague;
  - Test rate ≥ 2400 SiPMs/month @ each site

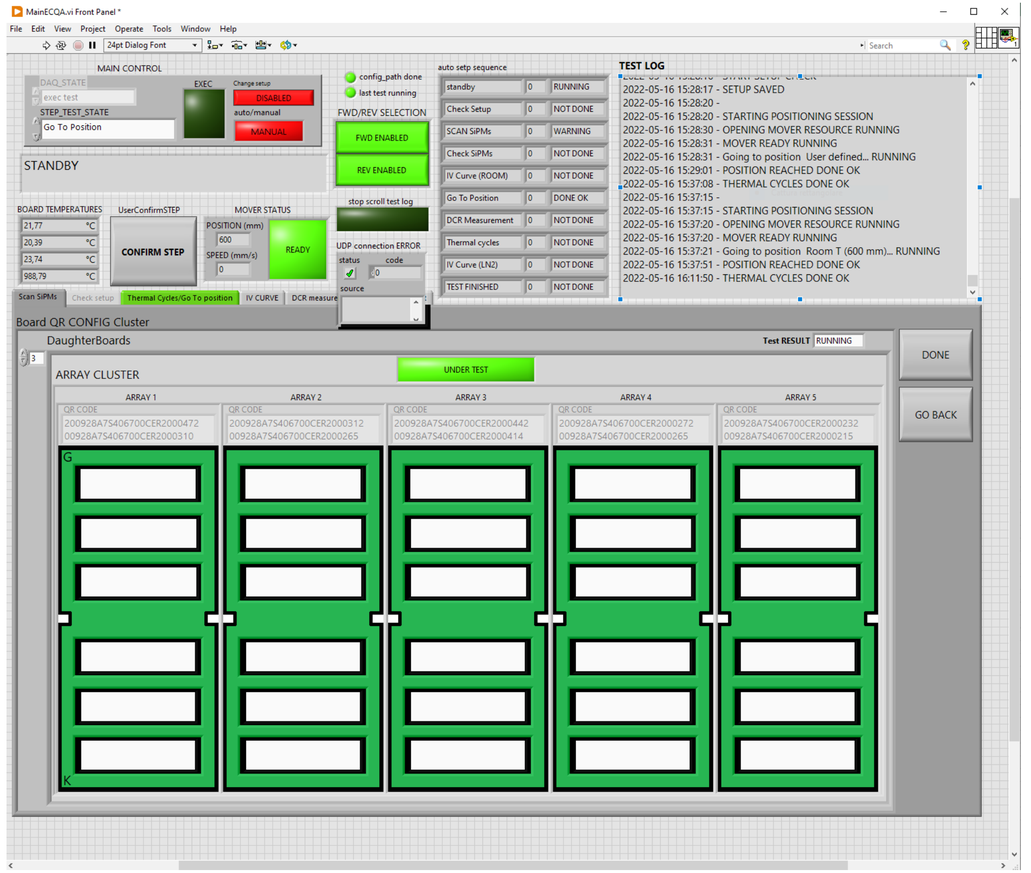
Features:

- 55 liters liquid Nitrogen auto refilling system;
- 120 parallel channels;
- Voltage range [-210;210]V;
- Voltage precision 10mV;
- DC acquisition mode;
- Measured current in range 10nA-3mA;
- AC acquisition mode;
- Programmable threshold DCR from 30ke to 16Me;
- 60cm long translator stage.

Quality assurance procedure

Unique Labview interface → perform each step of the QA tests

A panel shows the final report and if the SiPMs are in specs



Labview interface

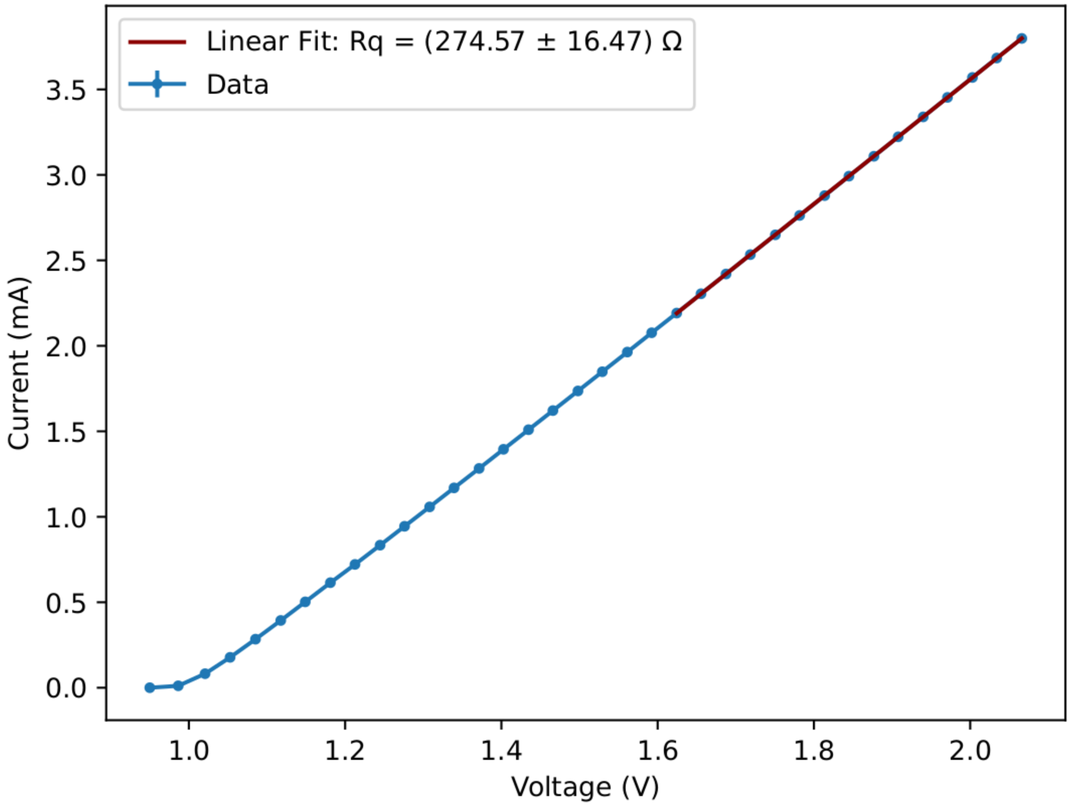
Steps & parameters:

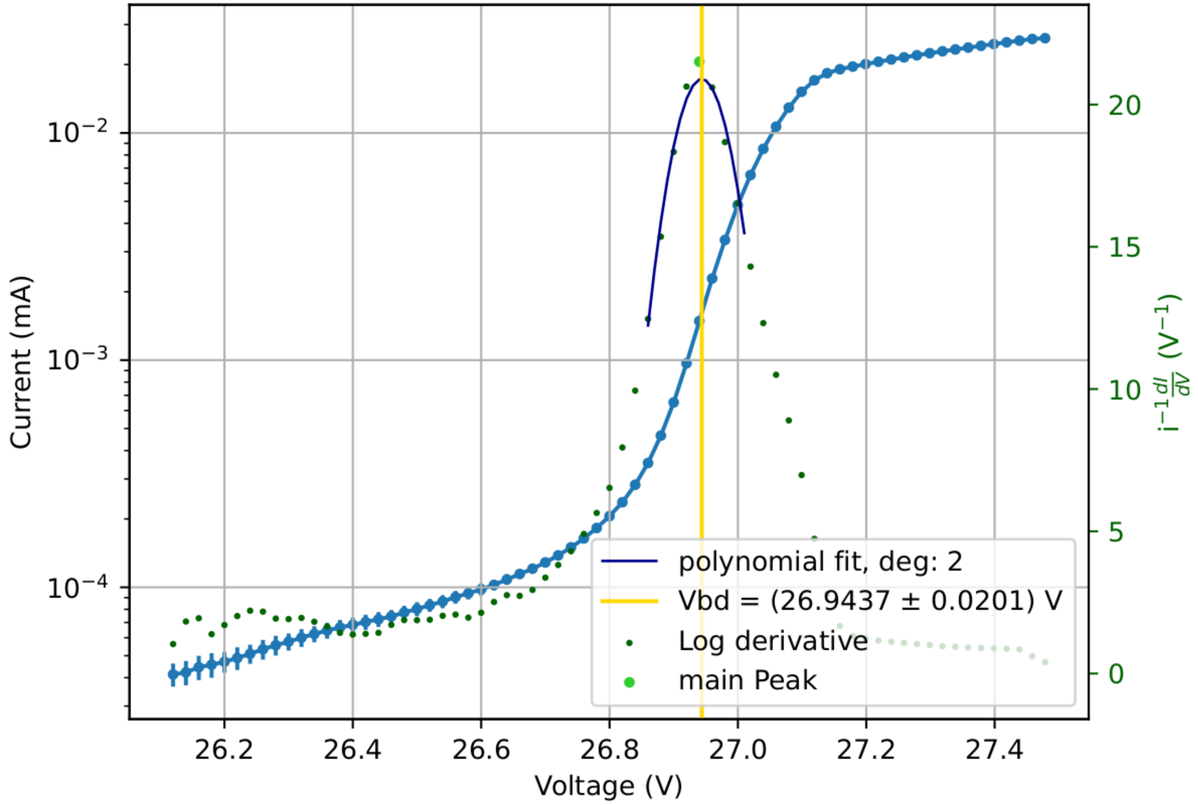
- IV@roomT (10min)→(FW) R_q^{RT} + (REV) V_{bd}^{RT};
- First LN2 immersion (20min);
- IV@LN2T (10min)→(FW) $R_q^{LN2T\_pre}$ + (REV) $V_{bd}^{LN2T\_pre}$;
- 2 thermal cycles (1.5h);
- IV@LN2T (10min)→(FW) $R_q^{LN2T\_post}$ +(REV) $V_{bd}^{LN2T\_post}$;
- Extended IV@LN2T (10min)→ dark current
- DCR@LN2 T (5min)→global-DCR total dark signals, AP, CT + bursts;

Single measurements examples

- LN2 temperature IV:

	Voltage range (V)	Current range	Step (mV)	Fit
Forward curve	0-2	[0.1-3.5]mA	20	Linear
Reverse curve	26-28	[10-500]nA	15	parabolic



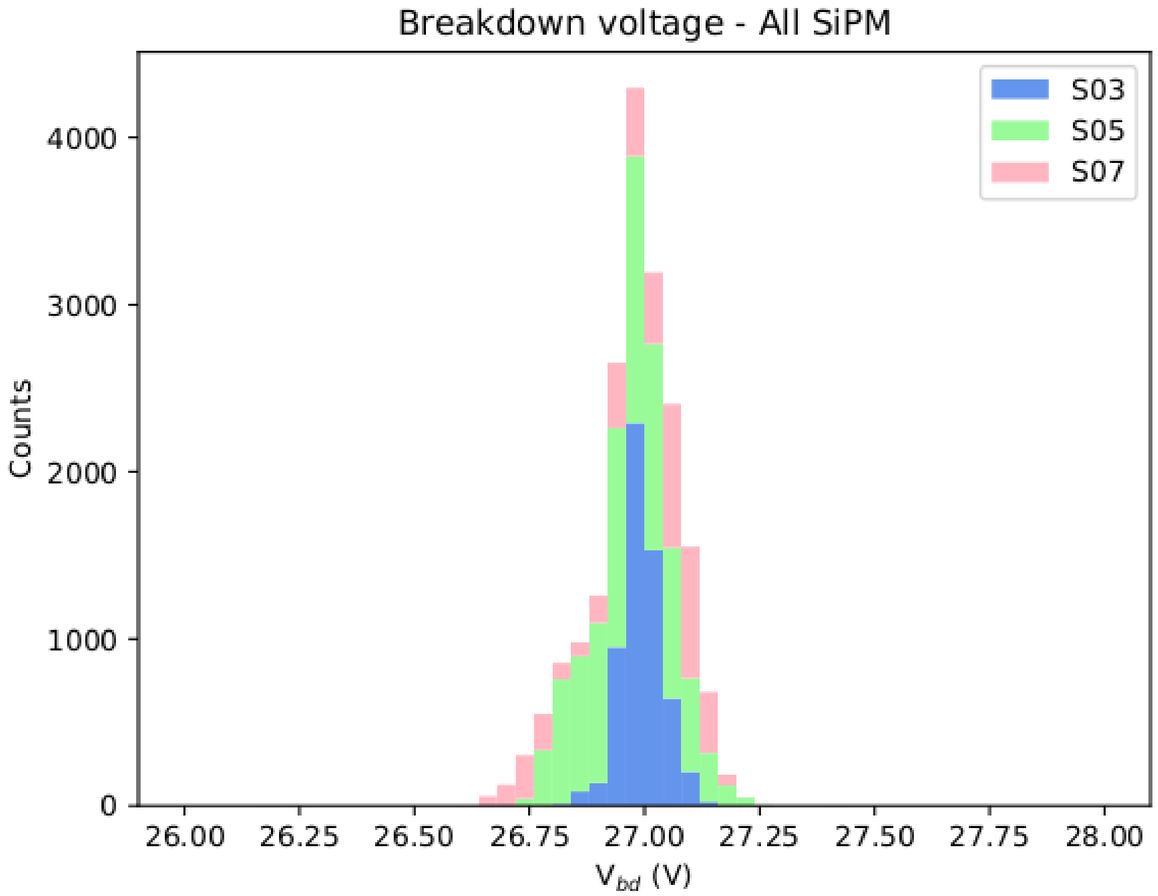


FBK production lot

FBK tray

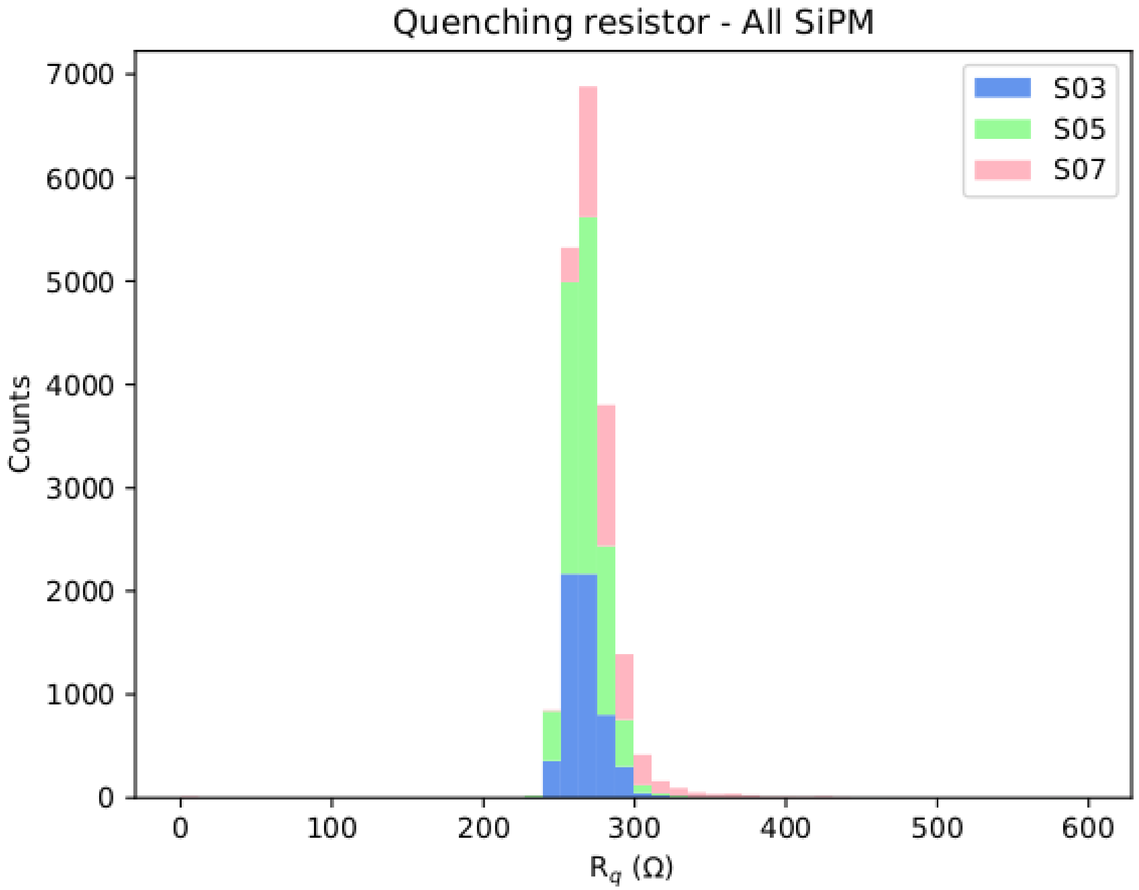
- FBK **Spanish lot** 10500 arrays of 6 SiPM each: 63000 sensors;
- To now 9 deliveries: in total 19 boxes have been produced (8200 boards) and are under test (78% of Spanish lot);
- Mechanical tests;
- Batches shared among CACTUS test sites for electrical characterization;
- **Deliveries 3, 5 and 7 completely tested** (3500 boards= 21000SiPMs) results are in this presentation (33% of Spanish lot).

Results: LN2 V_{bd}



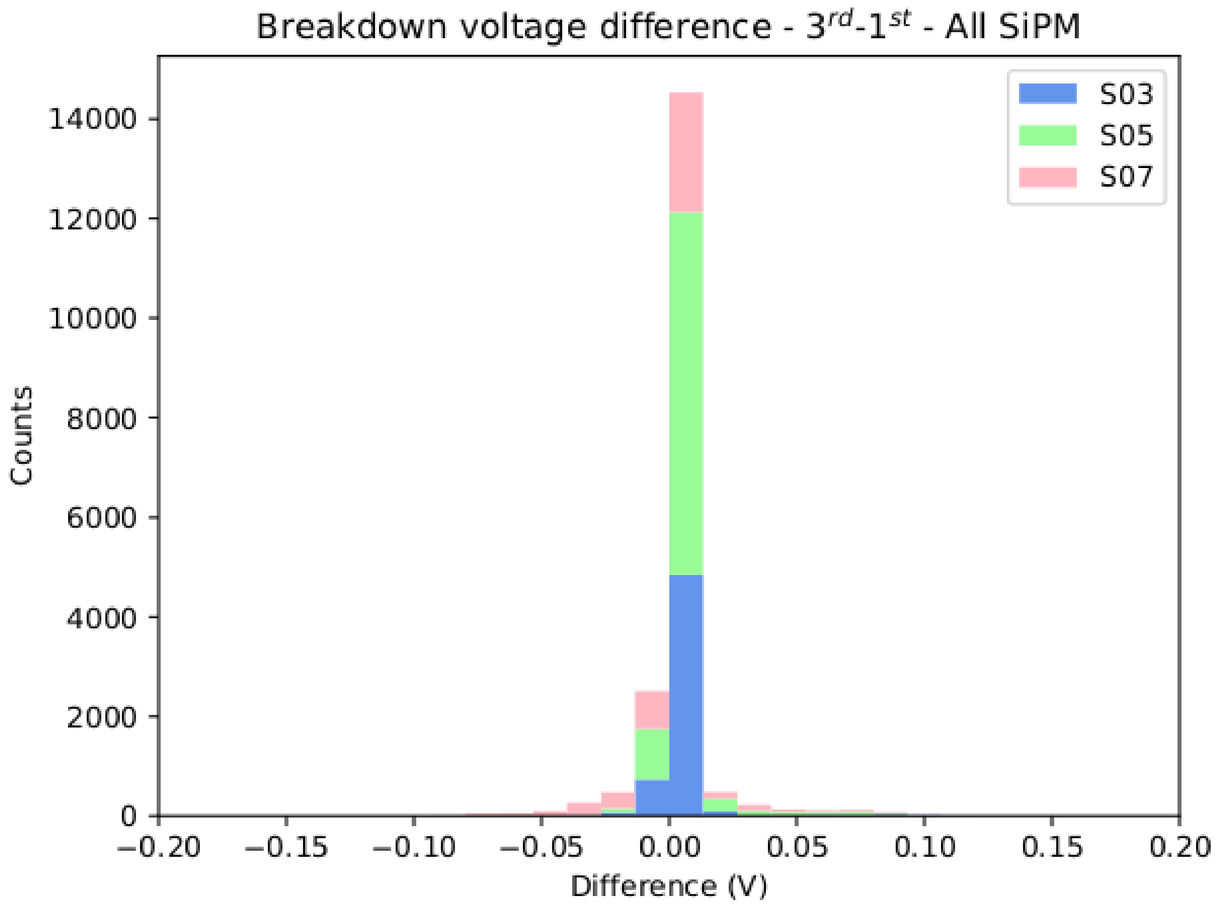
- **Breakdown voltage** distribution at LN2 3rd thermal cycle;
- 600mV total width;
- Behaviour as from vendor;
- SiPMs are in specs;
- Accordance with thermal coefficient (~ 26mV/K).

Results: LN2 R_q



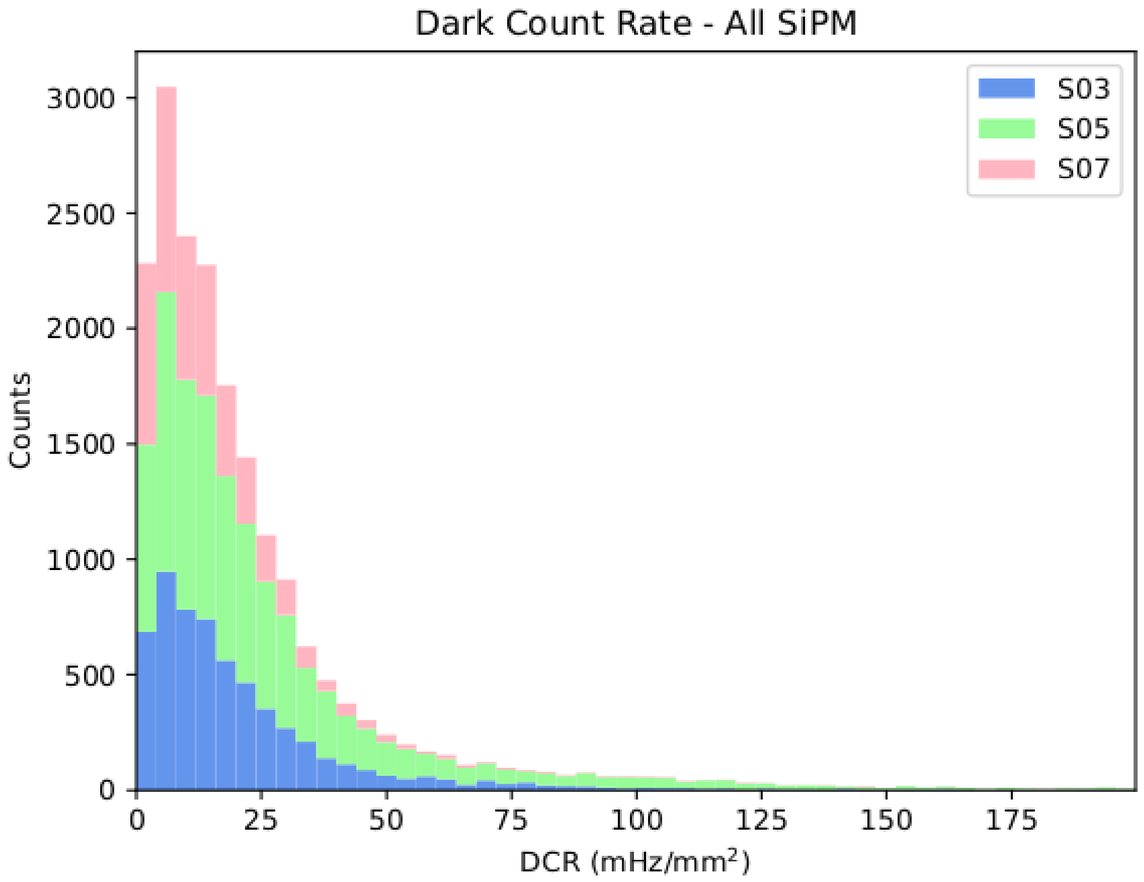
- **Quenching resistor** distribution at LN2 3rd cycle ;
- Behavior as expected from vendor;
- SiPMs in specs;
- Mean value @LN2 ~ 267Ω;
- Accordance with thermal coefficient (~1Ω/K);
- STD deviation of distribution @LN2<50Ω.

Results: thermal cycles



- **Resilience to thermal stresses** has been checked looking at data at the 1st and at the 3rd thermal cycle;
- Distribution of the discrepancies between the breakdown voltage measured at 3rd and at 1st thermal cycle center at 0V;
- V_{bd} Data within errors (50mV)

Results: DCR



- Distribution of the **DCR measured at LN2** in a time window of 120s in a complete dark environment;
- Considering all dark signals (primary, cross talk, afterpulses, bursts);
- Few dark counts are dominant;
- Almost all SiPMs below 200mHz/mm^2
- 61 failed sensors with a very high DCR (>1kHz/mm^2), rejected.

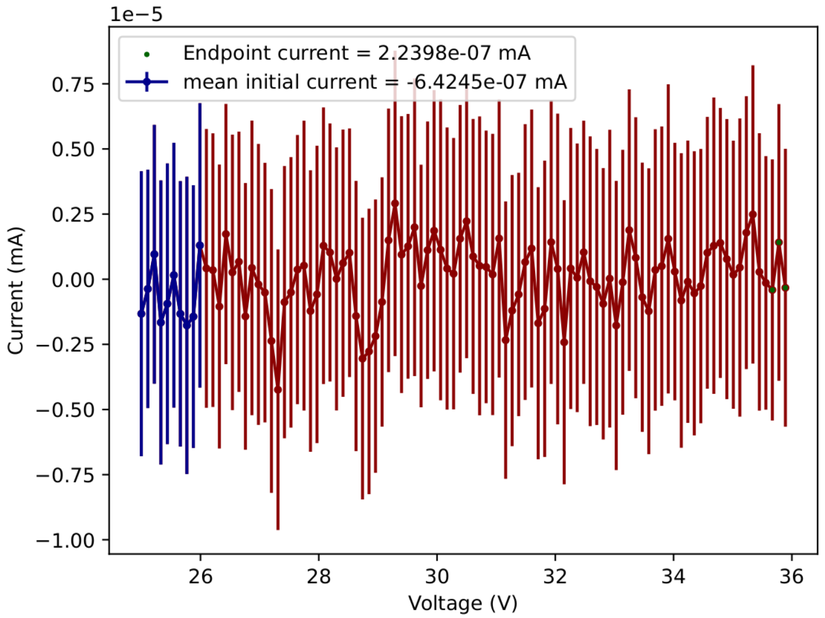
Bursts: JINST 16 (2021) T10006

Results: DCR

- Sensors with high DCR has been double checked looking at the current in reverse mode at LN2: extended IV curve
- In case of high DCR also the current (integral of the signals) will increase

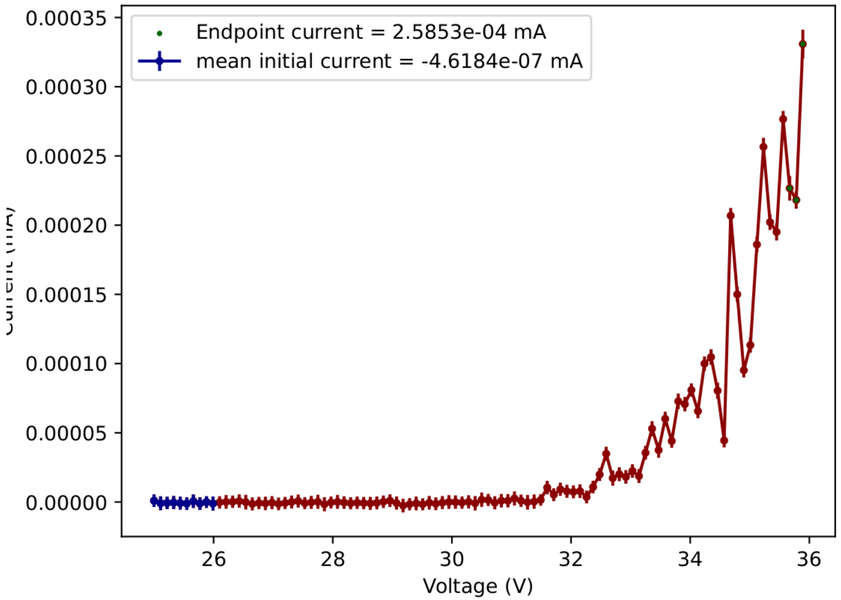
Normal SiPM: mHz DCR

Current below CACTUS electric noise (20nA)



Anomalous SiPM: KHz DCR

Count ~ 32kHz -> Current ~ uA



Conclusions

- Dune SiPMs 300k sensors FD Horizontal Drift;
- FBK NUV-HD-Cryo 3T SiPMs: 150000 sensors to be produced and tested
- CACTUS setup: quality assurance and massive tests (Ferrara, Bologna, Granada, Milano Bicocca, Prague);
  - Tests:
    - IV forward + reverse @ Room Temp;
    - IV forward + reverse @ LN2 Temp before and after thermal stresses;
    - Global DCR;
- Tested so far 21000 sensors (33% of Spanish production);
- FBK sensor failure rate due to high DCR 0.2%;
- We plan to end tests during 2026.

Thanks to all involved in CACTUS measurements!

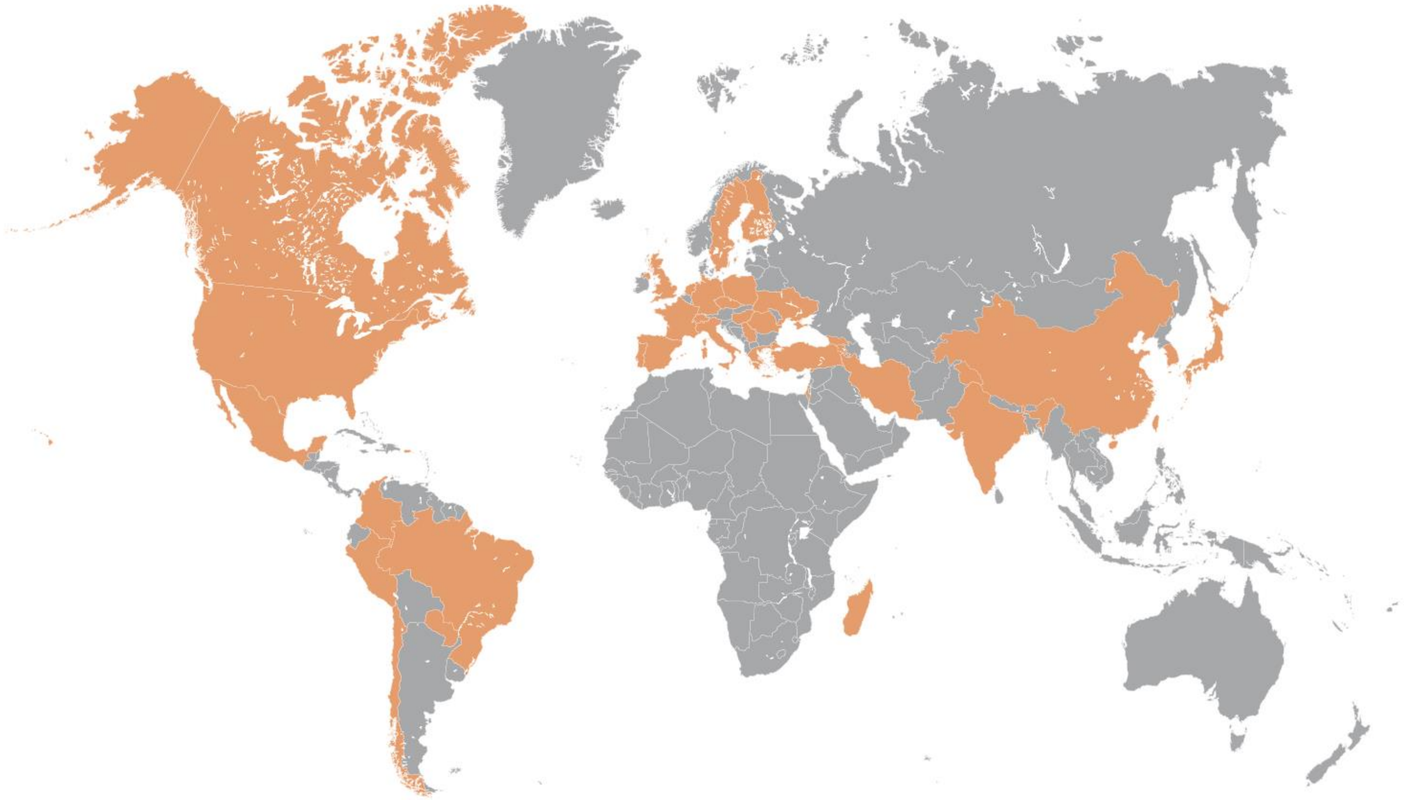
Thank You

Backup slides

The DUNE Collaboration

- More than 1440 collaborators;
- 37 countries;
- 208 institutions including CERN.

DUNE Collaboration meeting
FNAL May 2023



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- A supercell consists of
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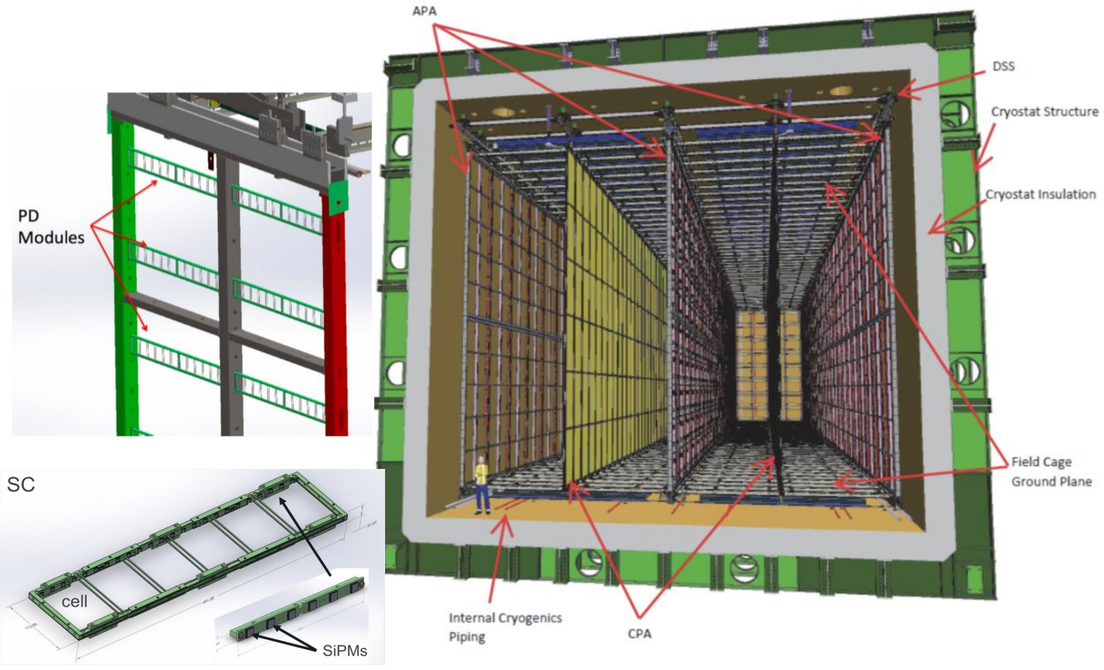
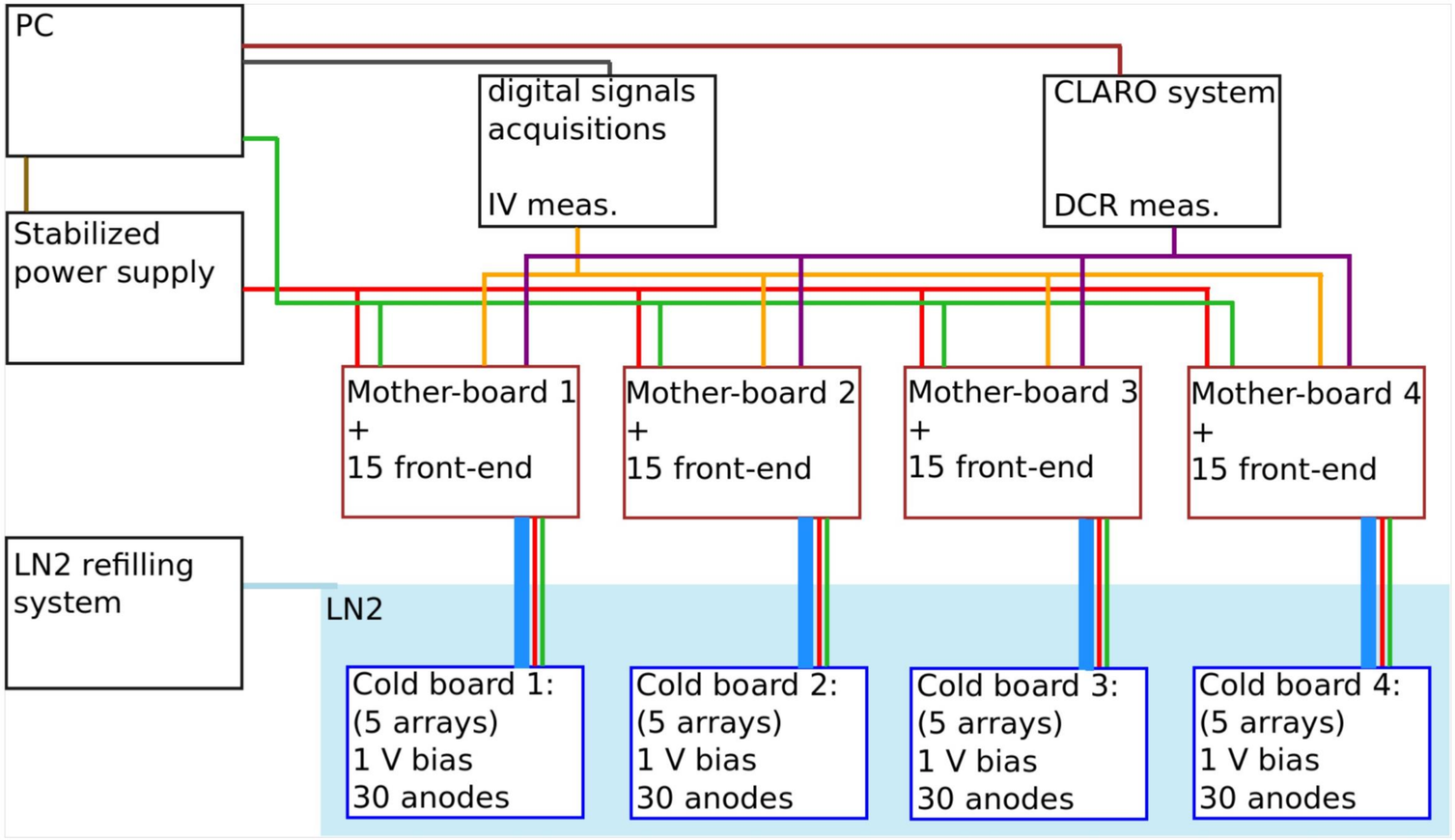
- ~300k SiPMs in total.

See X-ARAPUCA module



The Quality Assurance Test Setup

Scheme of the setup, featuring modularity, automation, easy replication

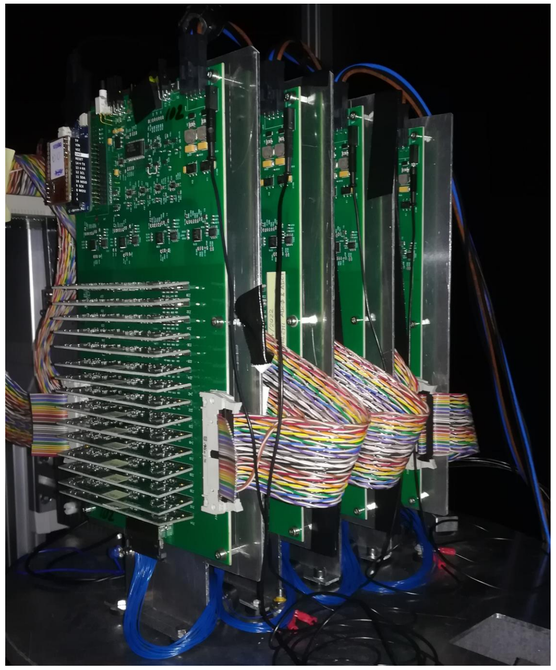


Features:

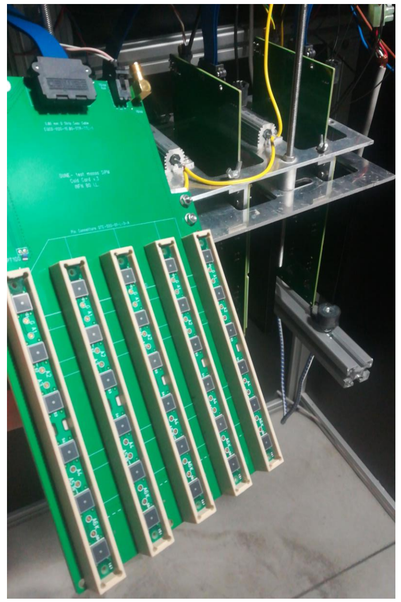
- 55 liters liquid Nitrogen auto refilling system;
- 120 parallel channels;
- Voltage range [-210;210]V;
- Voltage precision 10mV;
- DC acquisition mode;
- Measured current in range 10nA-3mA;
- AC acquisition mode;
- Programmable threshold DCR from 30ke to 16Me;
- 60cm long translator stage.

The Quality Assurance Test Setup

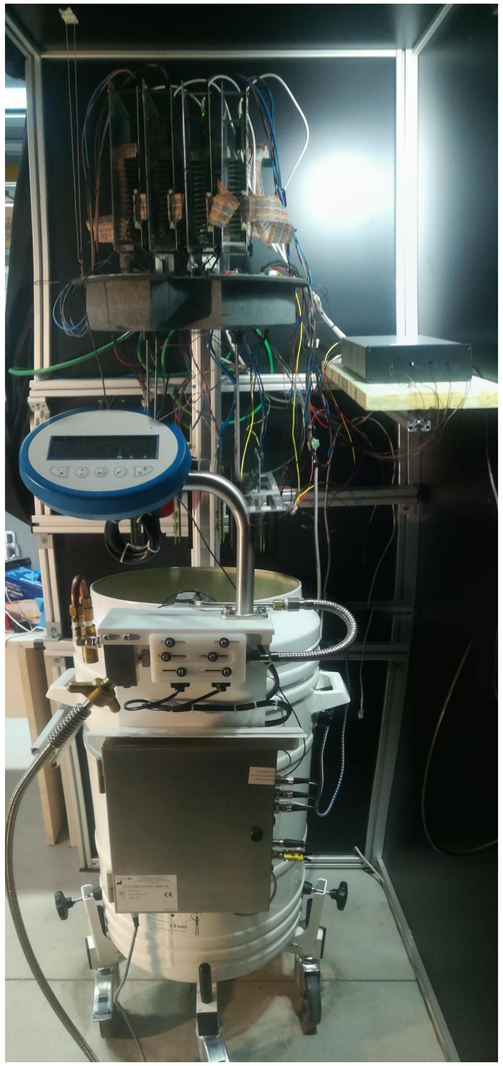
- **Motherboards + front-end cards (@ warm):**
  - 4 motherboards/system;
  - 15 front-end cards/motherboard;
  - 120 independent channels;
  - Current measure/digitalization;
  - Signals acquisition.
- **Cold boards (@LN2):**
  - 4 boards;
  - 5 arrays/board;
  - 120 SiPM;
  - Temperature monitor;
  - Bias voltage.
- **Python software** for run-time acquisition and analysis



Motherboards + front-end



Cold boards

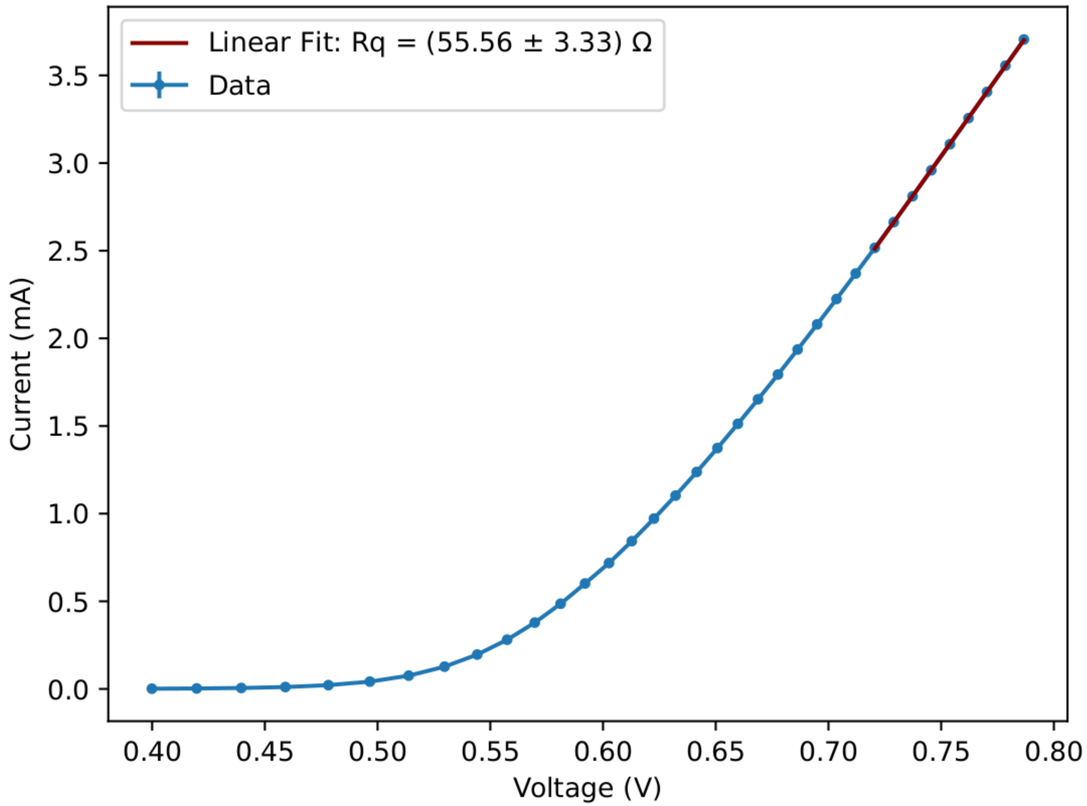


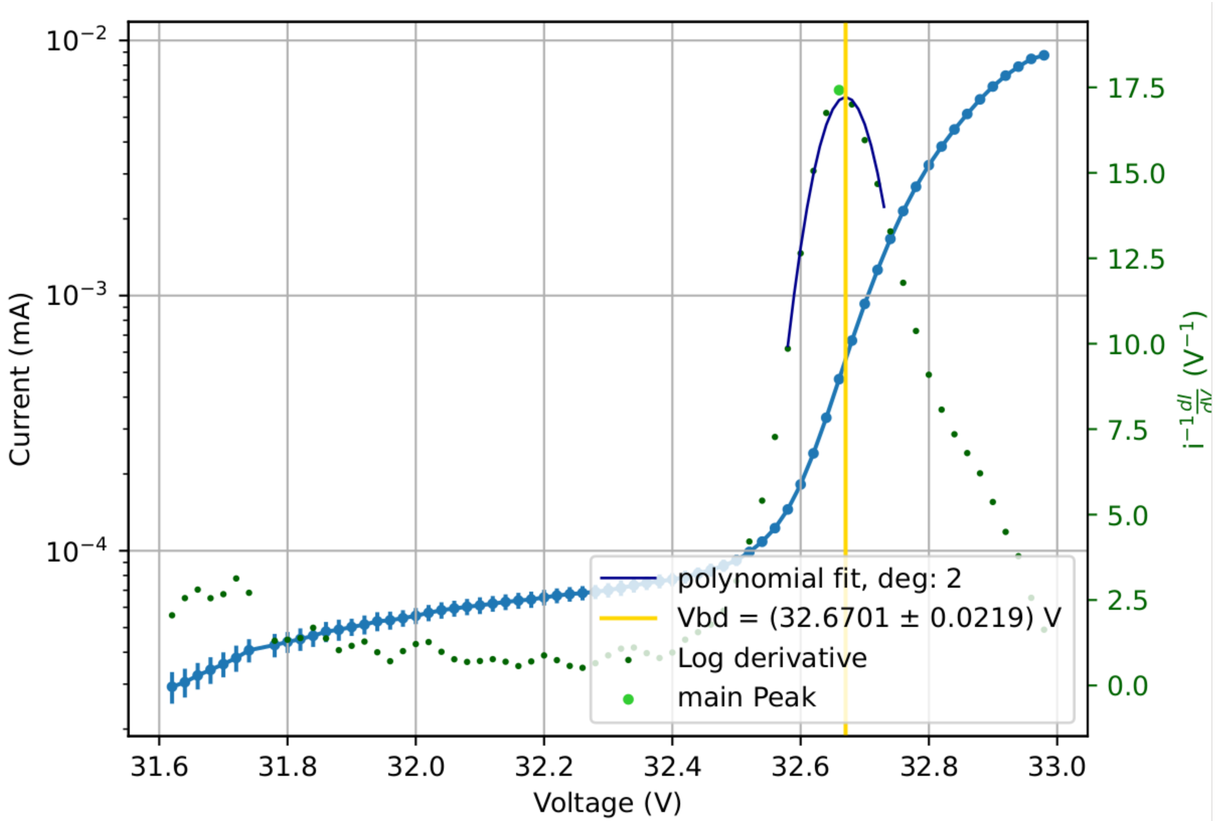
Ferrara system

Single measurements examples

- Room temperature IV:

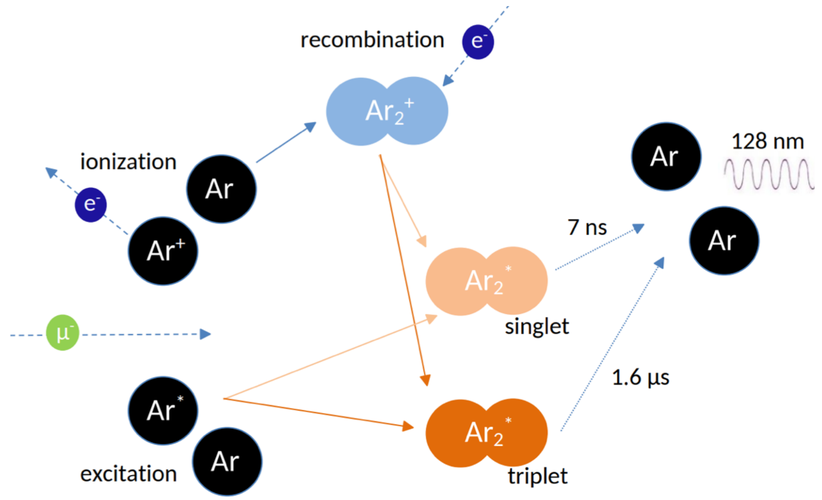
	Voltage range (V)	Current range	Step (mV)	Fit
Forward curve	0-1	[0.1-3.5]mA	20	Linear
Reverse curve	31.5-33.5	[10-500]nA	15	parabolic





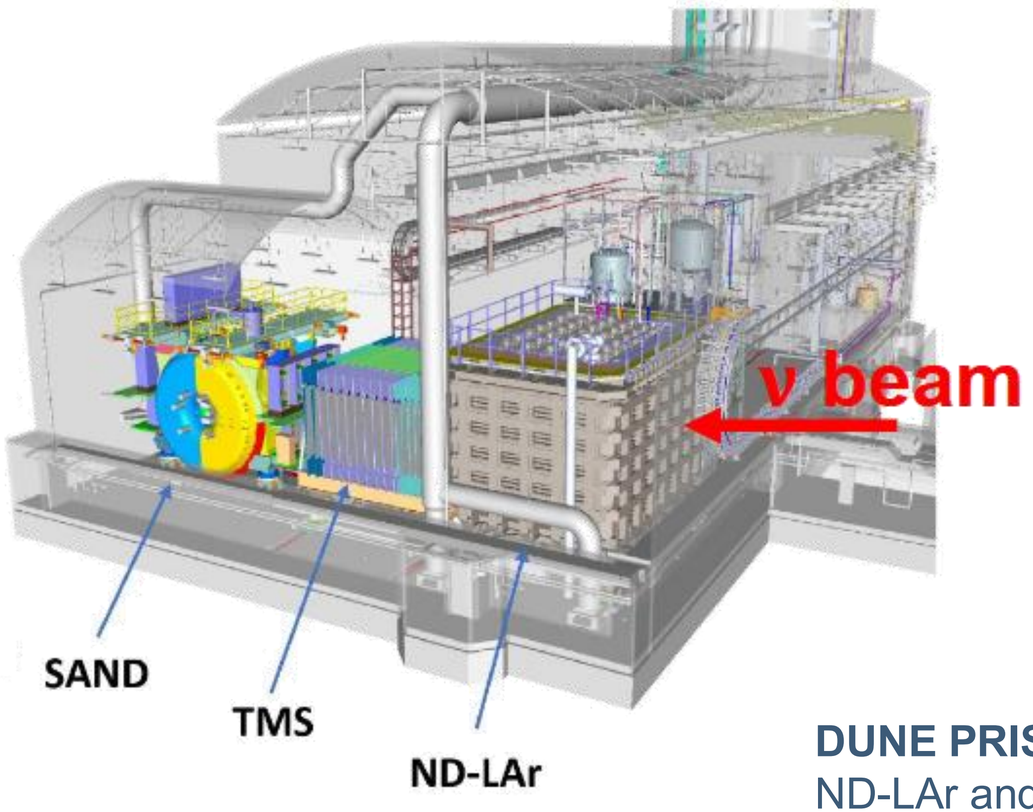
LAr VUV Light Detection

- Excited argon interacts creating excited molecules in singlet and triplet states
- LAr VUV scintillation light (λ = 128 nm) is
  - Abundant (25k photons/MeV @ 500 V/cm)
    → enhance calorimetry, especially at low E
  - Fast (fast component has τ = 7ns)
    → provides event t_0, crucial for triggering non-beam events
  - Topological
    → Slow/Fast component relative contribution has PID and backg



- Detection of light in DUNE LArTPC
  - VUV photons converted to longer wavelength by photofluorecent compounds (WLS)
  - Visible light is trapped inside a module and a fraction of it is conveyed to photosensors (SiPMs)

Near detectors

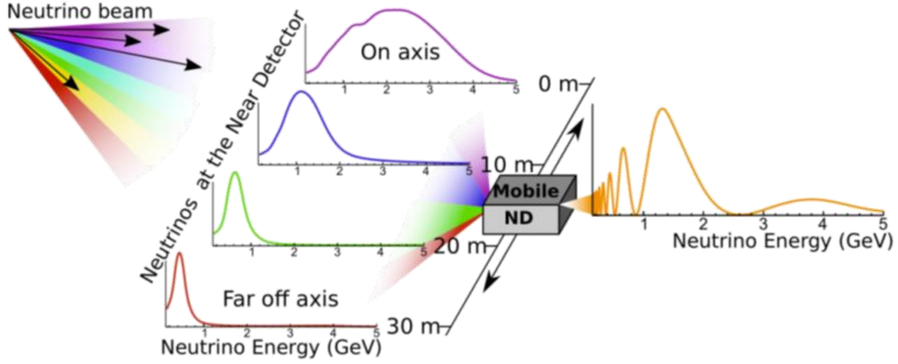


Near Detector will be located 574 m downstream (60m underground) of the neutrino beam and will include three detectors:

- **ND-Liquid Argon**: 60 tons fiducial mass liquid Argon Time projection chamber (Lar-TPC)
- **Temporary muon spectrometer (TMS)**: muon catcher for forward muons not contained in ND-Lar, 100 planes of 192 scintillator strips each + steel
- **SAND**: trackers + ECAL + magnets

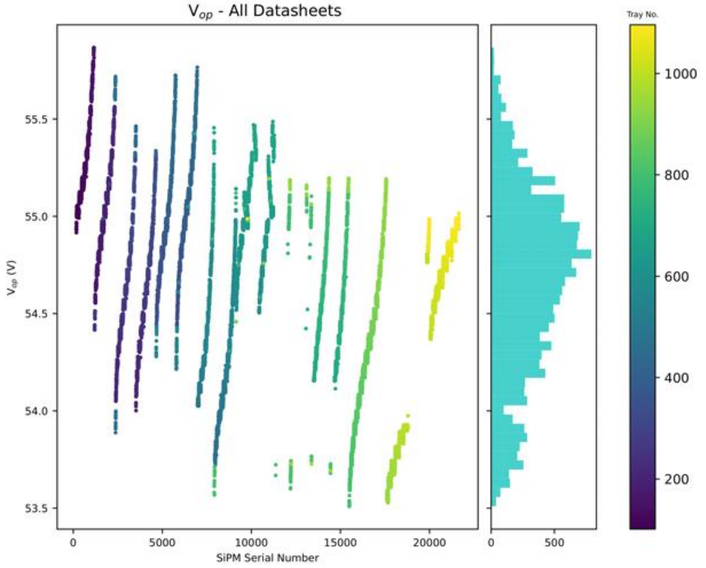
DUNE PRISM:
ND-LAr and TMS will move perpendicular to the beam axis in order to sample multiple fluxes using same detectors

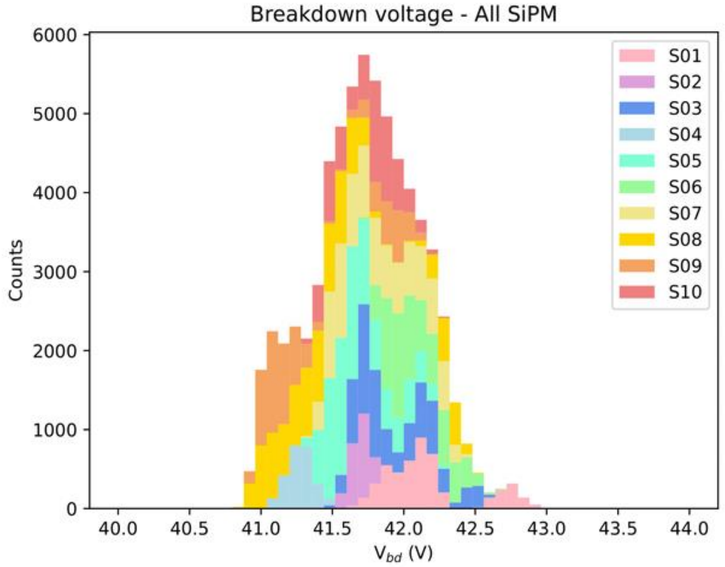
DUNE PRISM

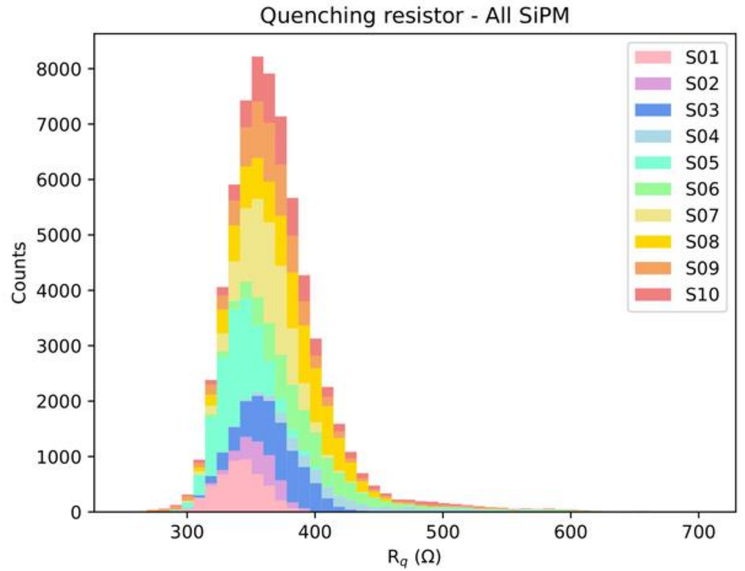


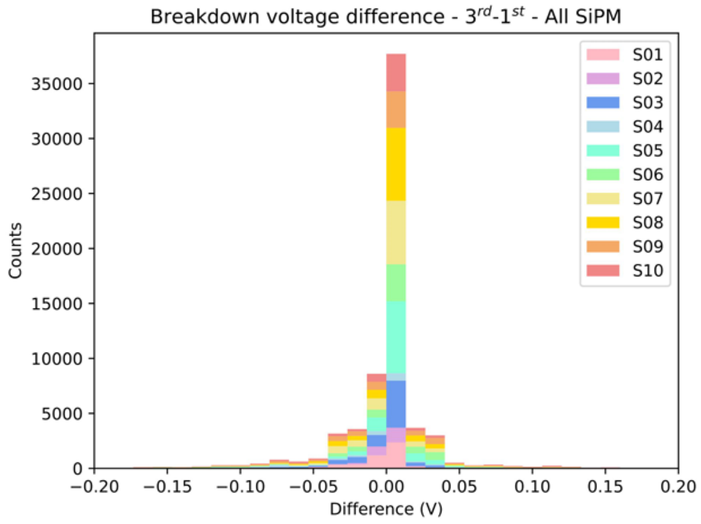
HPK sensors

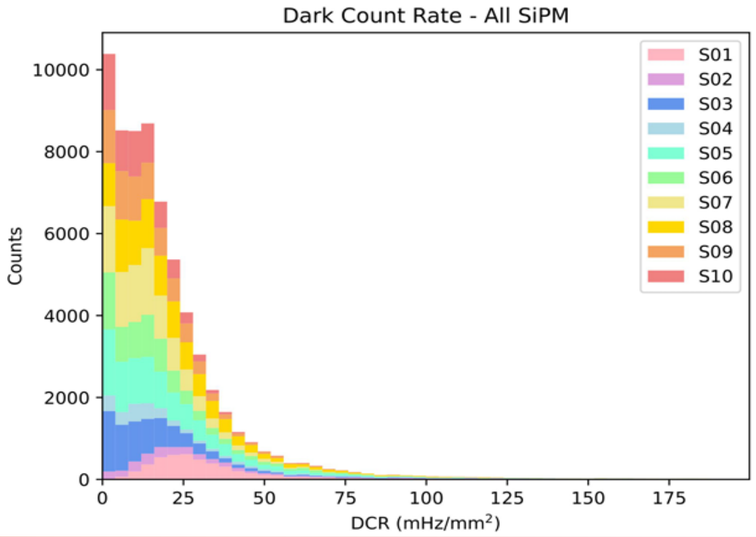
Failure rate ~0.05% at single SiPM level











DUNE status and plans

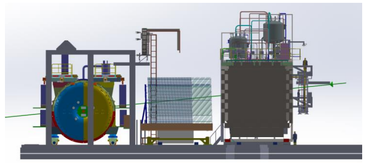
The work proceeds in all the fields:

Neutrino beam:

- RF-cavity Cryostat built and arrived at FNAL
- Warehouse-sized cooling unit in construction for PIP-II

ND at FNAL:

- Final review ongoing
- SAND: many activity at LNF for the KLOEtoSAND project
- LAr prototype for ND-Lar in operation



FD at SURF:

- Excavation completed in Dec 2024
- Cryostat 2 (FD-VD) warm structure arrived safely in the Rapid City warehouse, installation will start in 2026
- Cryostat 1 (FD-HD) also arrived at the warehouse, with two accidents (dropped load while downloading in Houston and a truck rollover on the way to Rapid City), installation will start in 2026

ProtoDune:

- Following the safety accident of the 17th of January CERN authorized restart of VD-CRP activities NP02 after completion of few recommendations
- Data analysis protoDune-HD ongoing
- ProtoDune_VD ready to start