Mass test setup for the DUNE FD1 SiPMs characterization and first results

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Università degli Studi di Ferrara

INFN Istituto Nazionale di Fisica Nucleare

DUNE

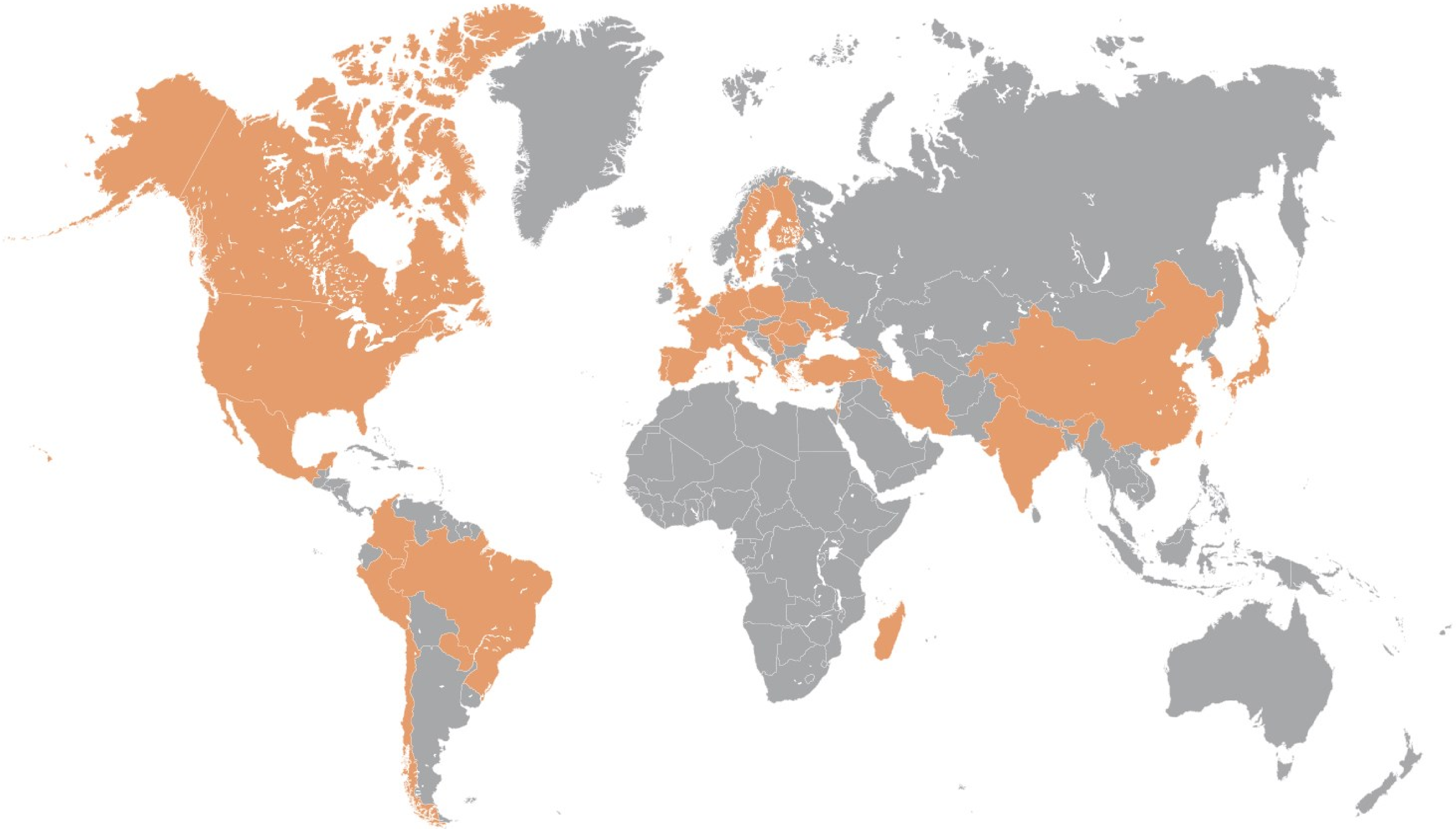
Contents

- Overview of the DUNE experiment
- ProtoDUNE & DUNE FAR detector:
  - SiPMs in the Photon Detection System
- CACTUS: the quality assurance test setup
  - Features
  - Procedure
  - Tests
- Characterization Results of the first production lot
- Conclusions

The DUNE Collaboration

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

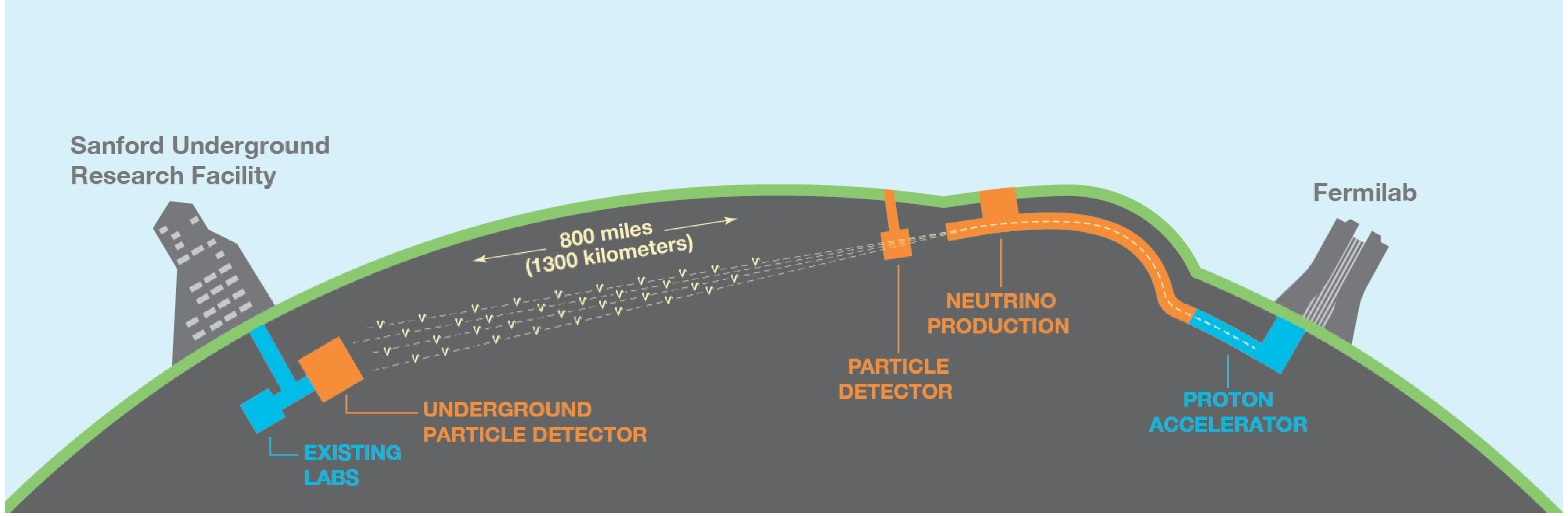
DUNE Collaboration meeting
FNAL May 2023



Deep Underground Neutrino Experiment (DUNE)

DUNE, main physics goals:

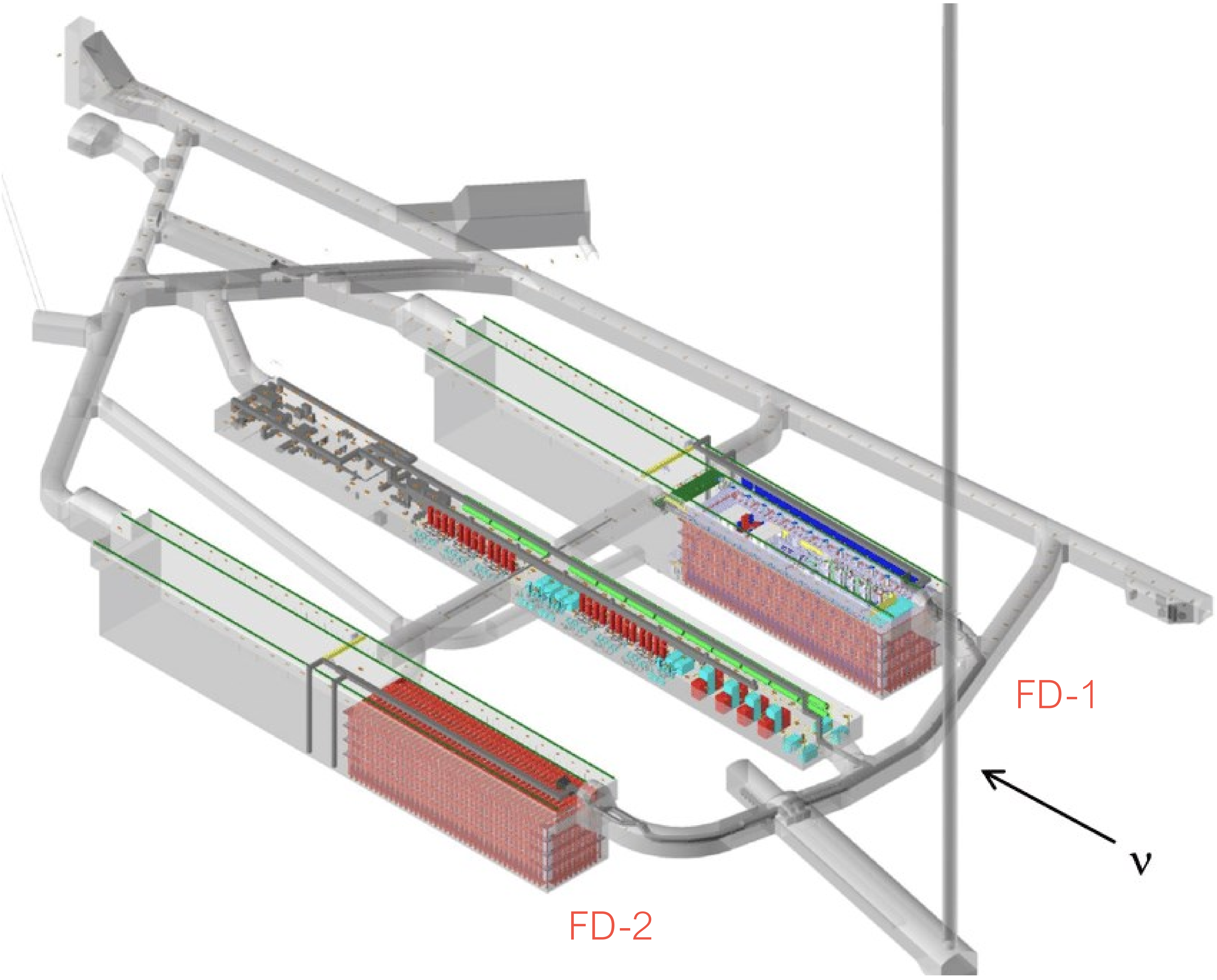
- Precise measurement of neutrino oscillation parameters (mass ordering and δ_{CP}); *EPJC 80 (2020) 978*
- Study supernova low energy neutrino; *EPJC 81 (2021) 322*
- Physics beyond SM; *EPJC 801(2021) 423*



- 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*

DUNE Far Detector

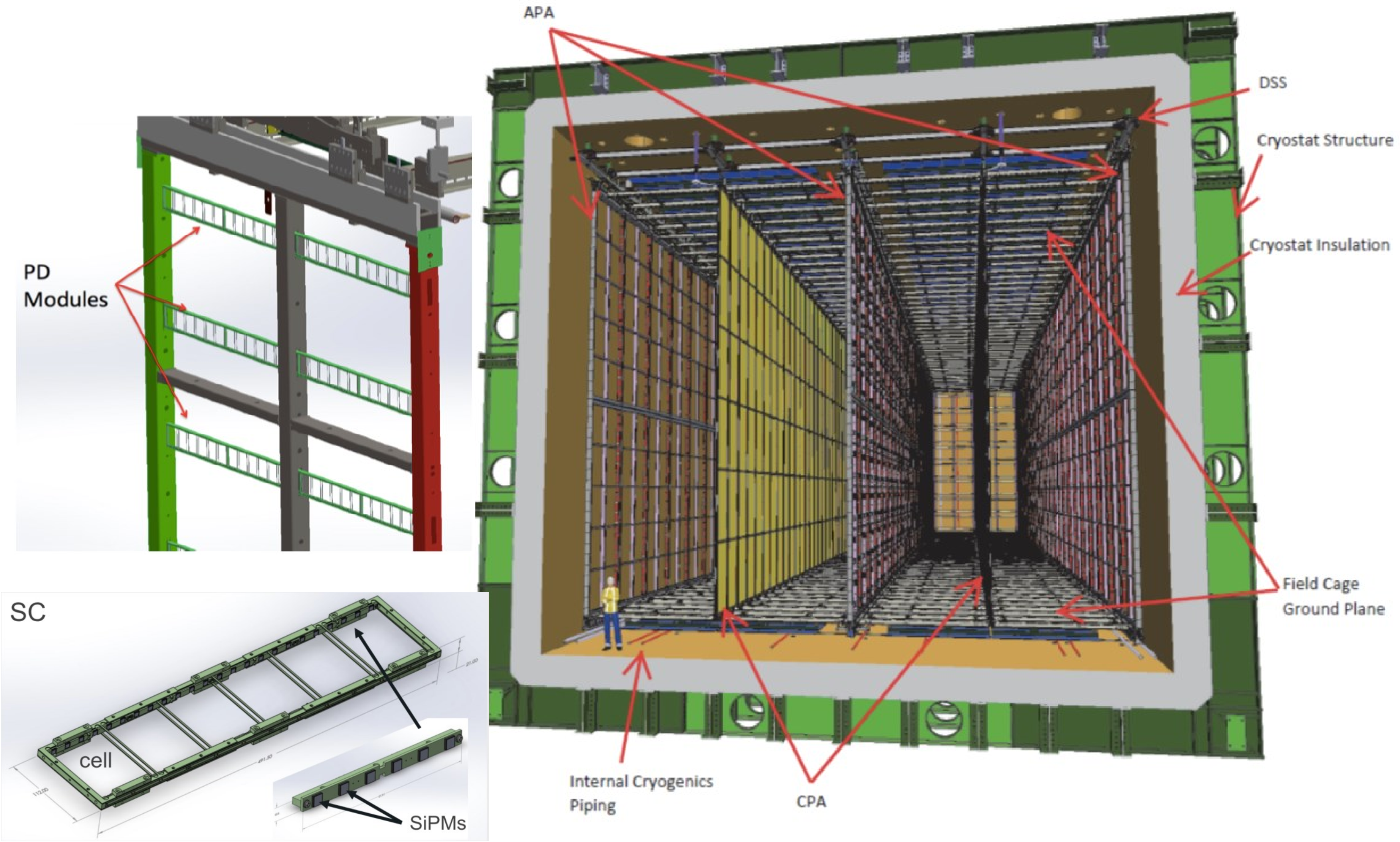
- Located ~1300km from the production site ~1.48 km underground @ Sanford Underground Research Facility in Lead, South Dakota (USA)
- Four 17-kt LAr TPC modules
- Phase I:
  - **FD-1 horizontal drift (HD)**
  - FD-2 vertical drift (VD)
- ProtoDUNEs
  - Construction and operation of 1 kton-scale prototypes at CERN, critical to demonstrate viability of technology



FD-1 HD

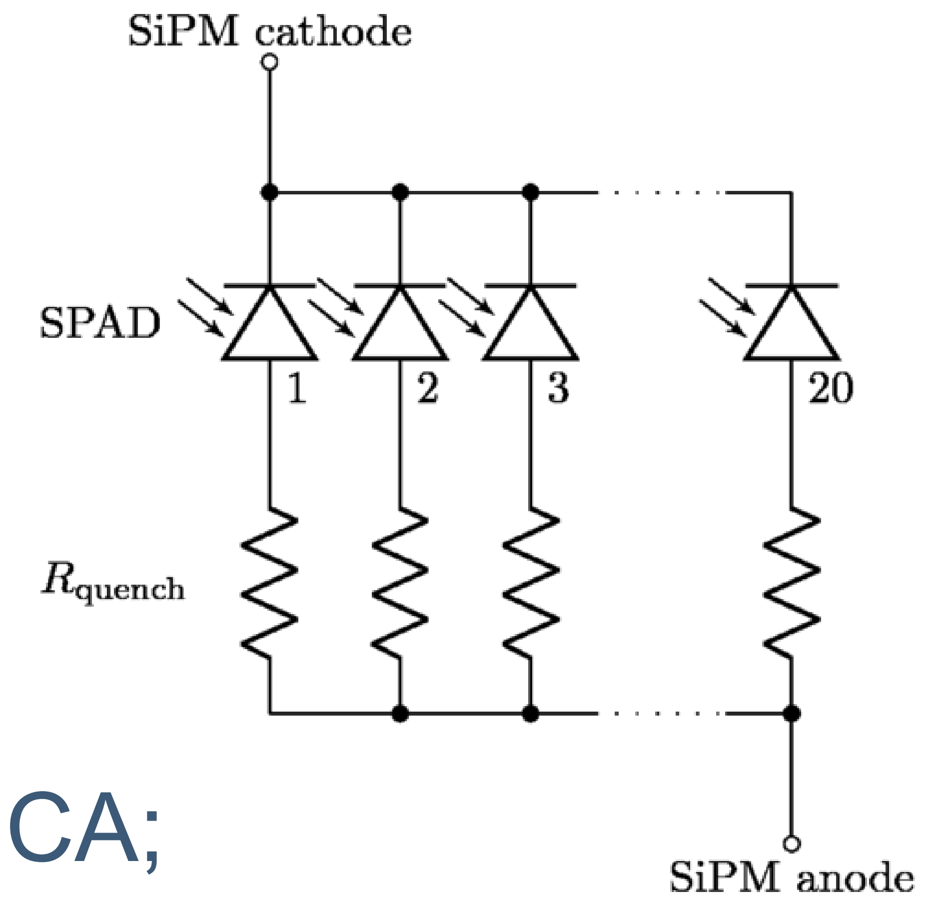
- 4 drift volumes. Anode-cathode drift distance 3.5 m with E = 500 V/cm.
- 150 Anode Plane Assemblies (APAs).
  Each APA consists of three wire planes for charge collection and
  10 Photon Detection modules.
- 10 (2m x 12cm) PD modules/APA
  each composed by 4 X-ARAPUCA supercells.
- A supercell consists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

see "DUNE Photon Detection System" presentation by Gabriel Botogoske!

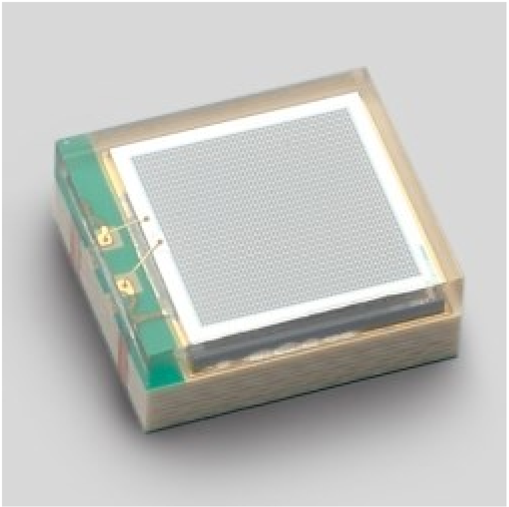


The DUNE photosensors

- 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;



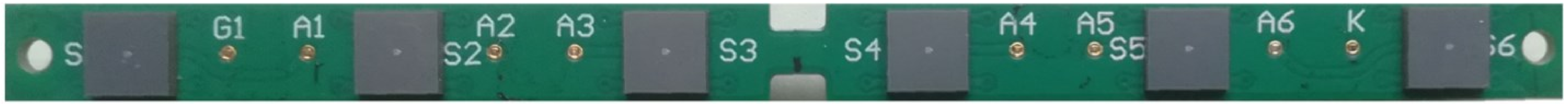
- Specifications for DUNE:
  - Quantum efficiency > 35% for 430 nm light @ 87 K;
  - Dimensions compatible w/ ARAPUCA design;
  - SiPM + FEE w/ dynamic range 1-2000 photons, even for events far from the ARAPUCA;
  - Dark count Rate (DCR) subdominant wrt noise from ^{39}Ar (<200mHz/mm^2);
  - Cross-talk (CT) < 35%and after-pulse (AP) < 5%;
  - Durability (> 10 y) and cryoreliability (resistant to multiple cool-downs);
  - 200-100ns recovery time.



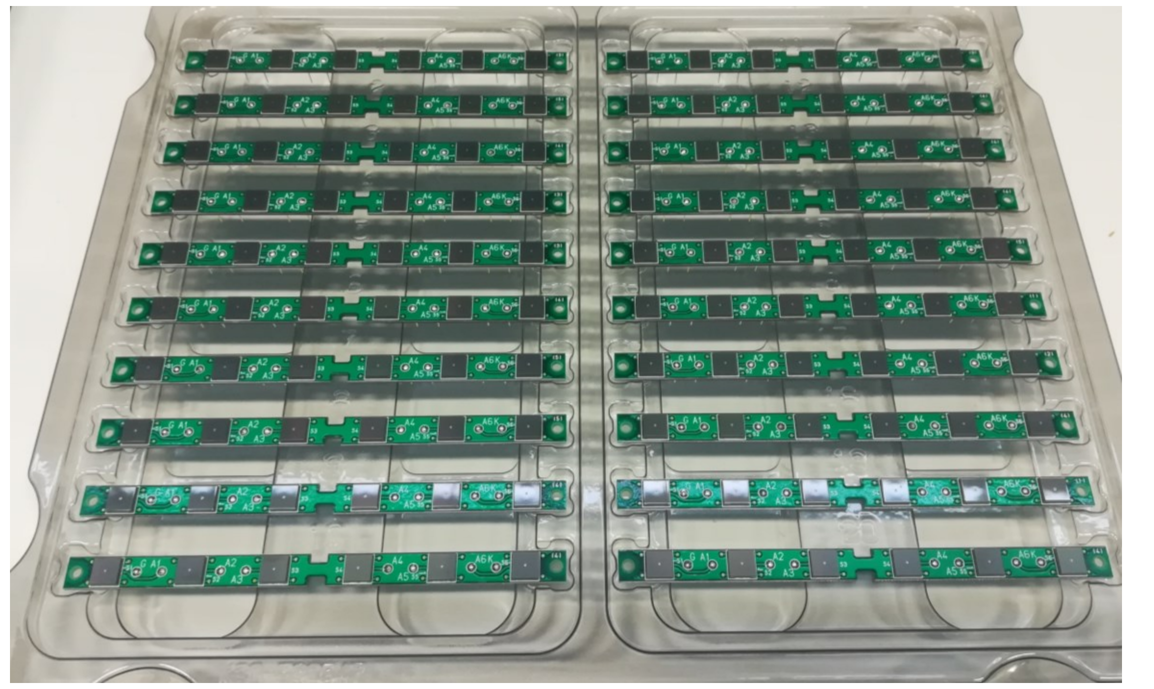
JINSTRUM 19.01 (2024): T01007

The DUNE photosensors

- **SiPMs:**
  - Several models tested from two vendors: HPK, FBK; ~50% of FD-1 SIPMs each;
  - Chosen models **HPK** S16517 (6x6mm^2, 75um pitch) & **FBK** NUV-HD-CryoTT (6x6mm^2, 33um pitch);
  - 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-1** under test (2023 – …).

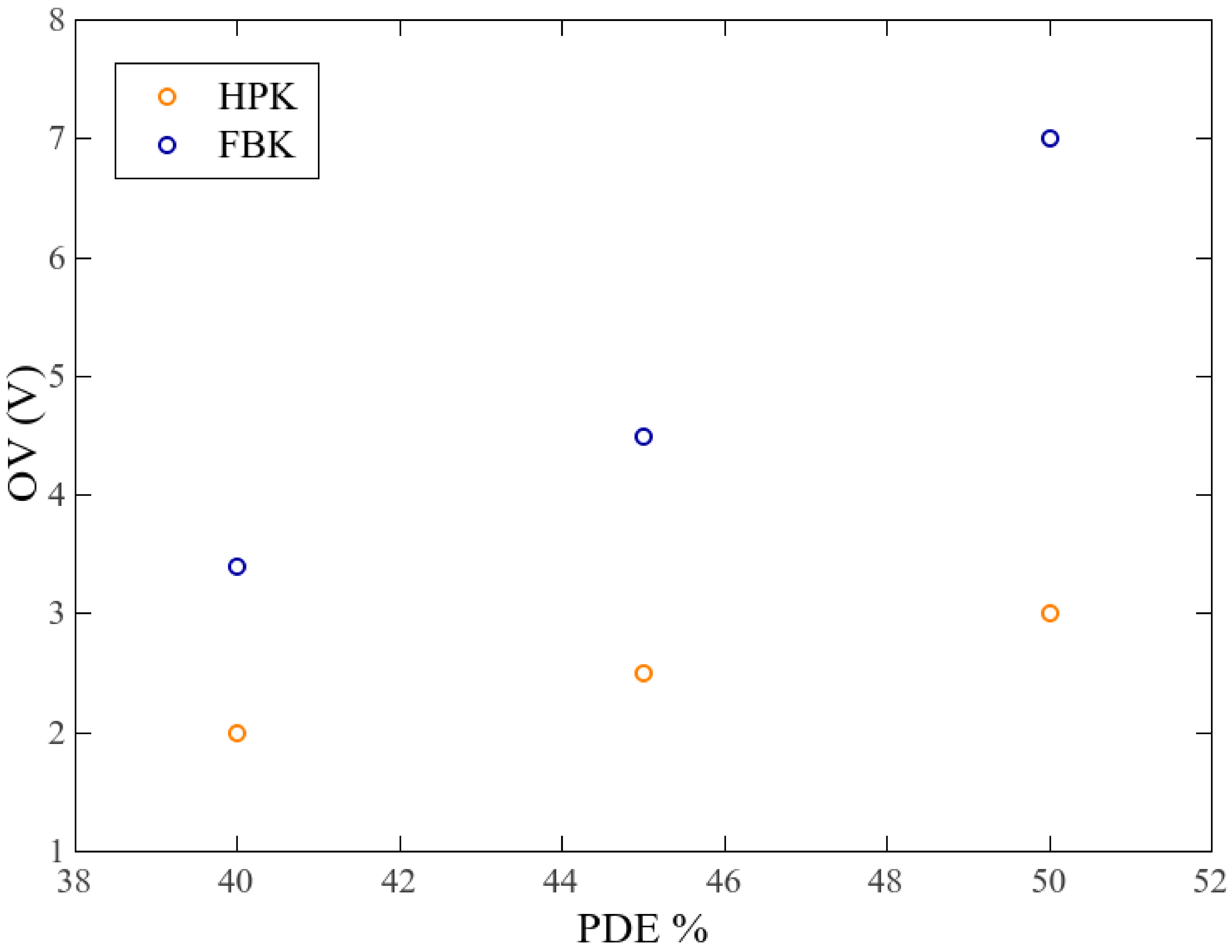


HPK tray example

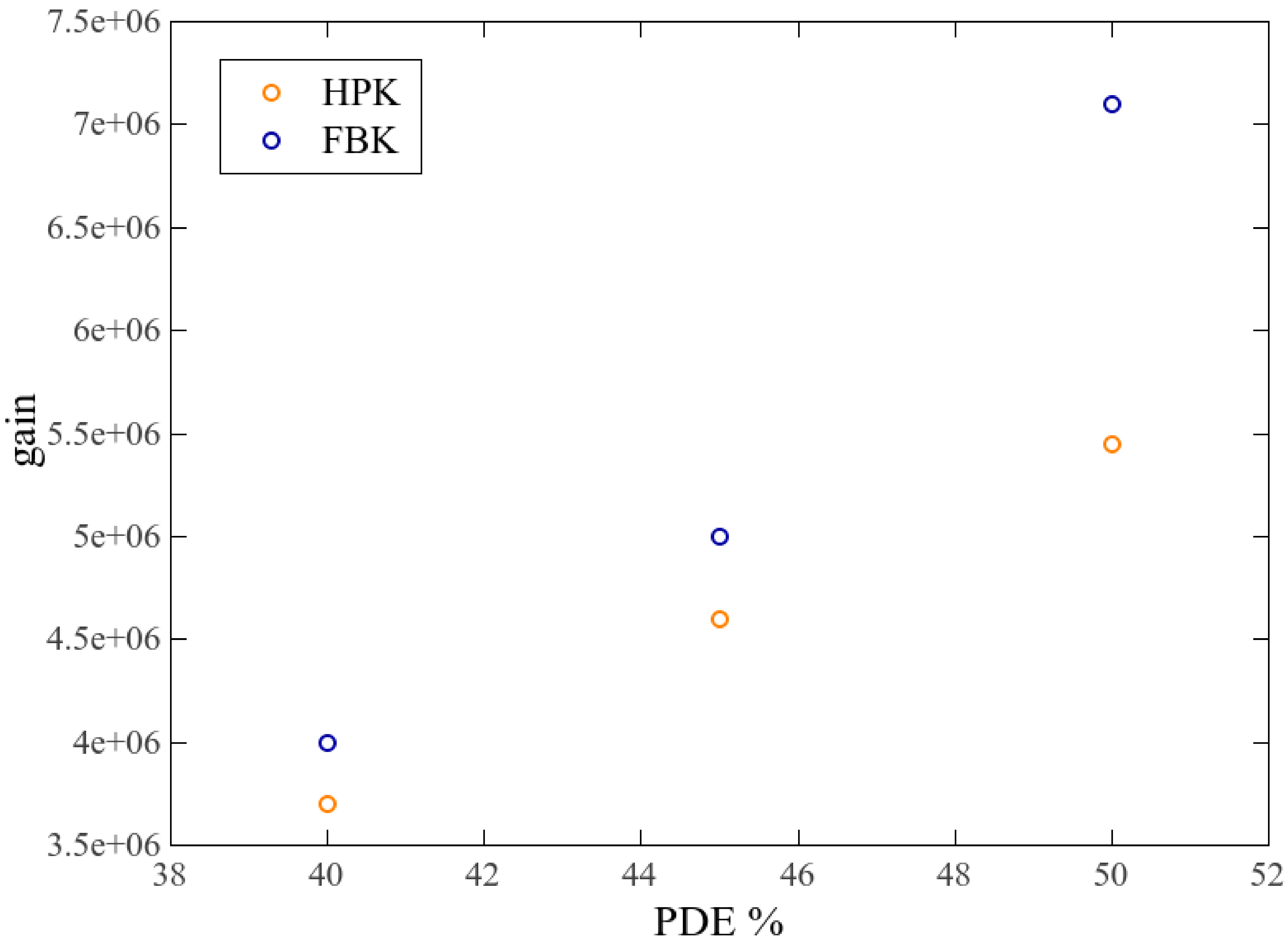
- **Measurements to be performed:**
  - IV curves in FWD and REV bias @ room temperature and LN2 temperature;
  - Thermal stresses resilience;
  - DCR @ LN2 temperature.

The DUNE photosensors

- Operating voltage VS PDE



- Gain VS PDE

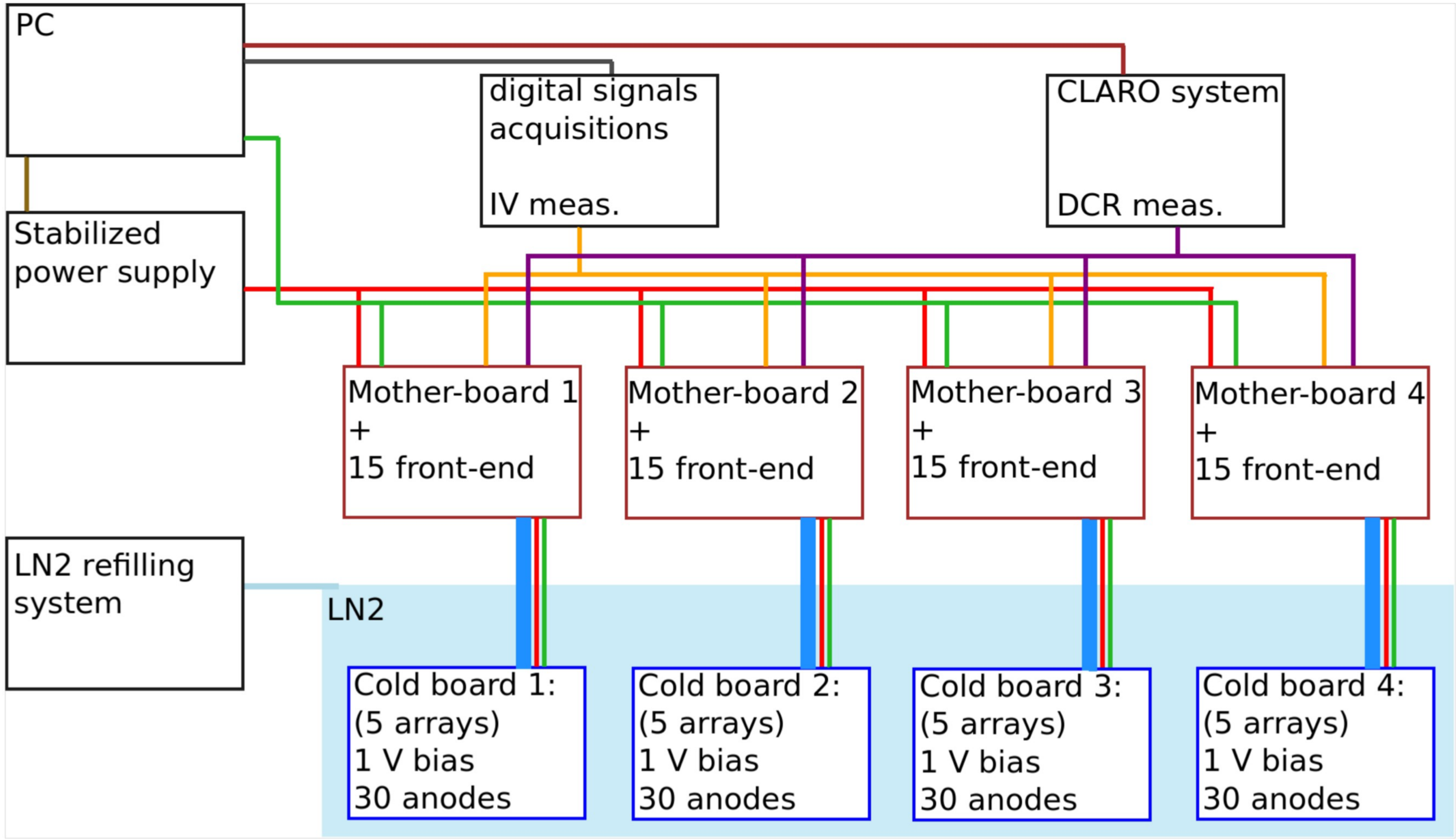


The Quality Assurance Test Setup

- 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 SiPM (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 SiPM/month @ each site

The Quality Assurance Test Setup

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

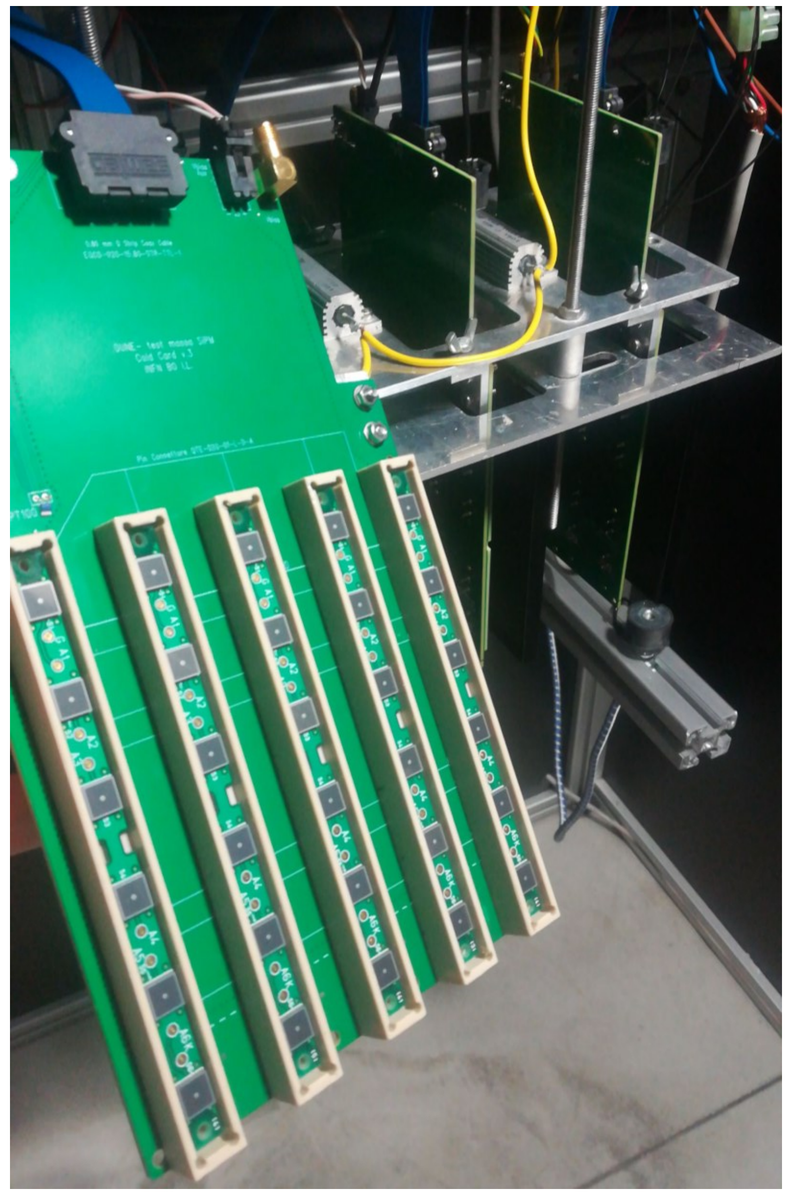


Features:

- 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.

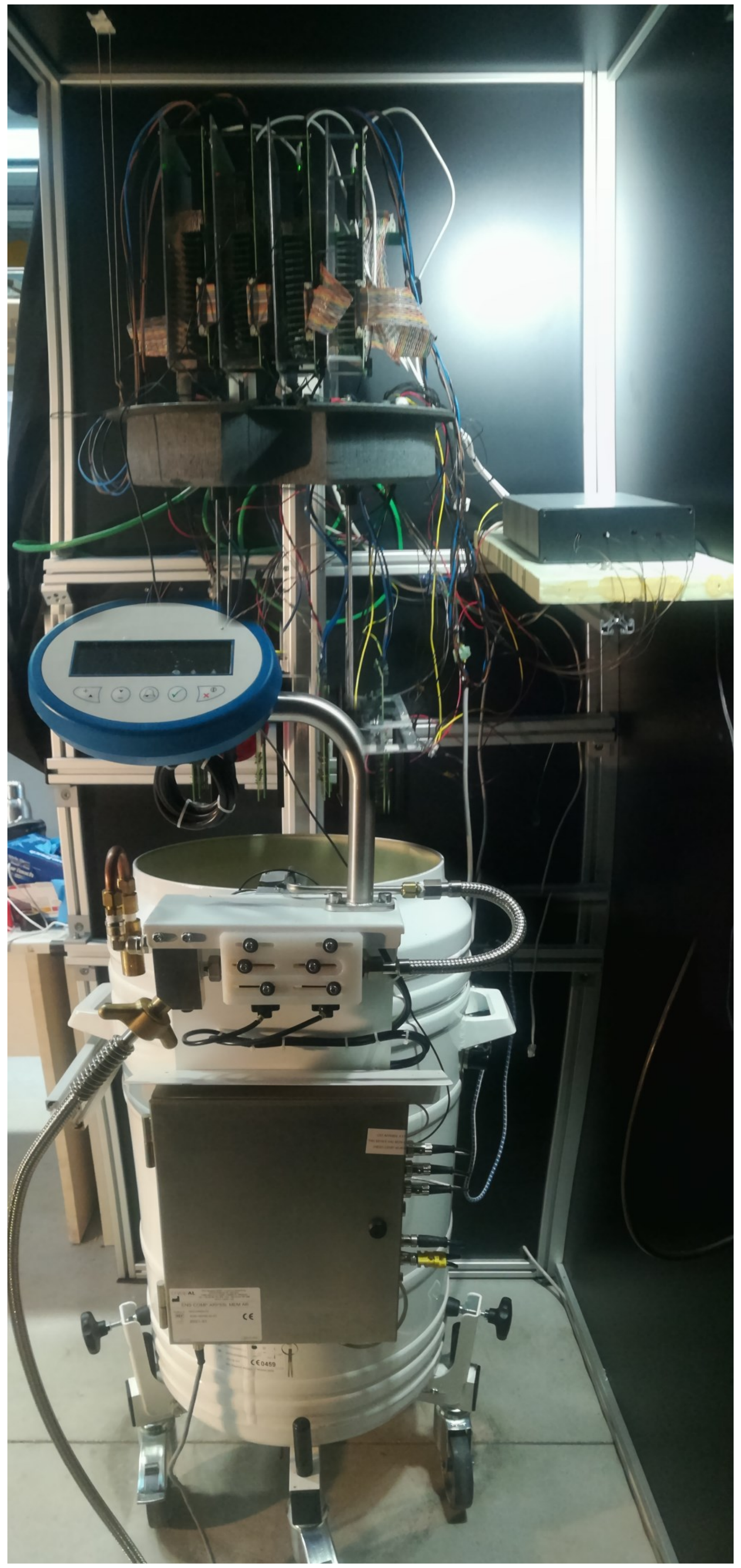
The Quality Assurance Test Setup

- **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.



Cold boards

Motherboards + front-end



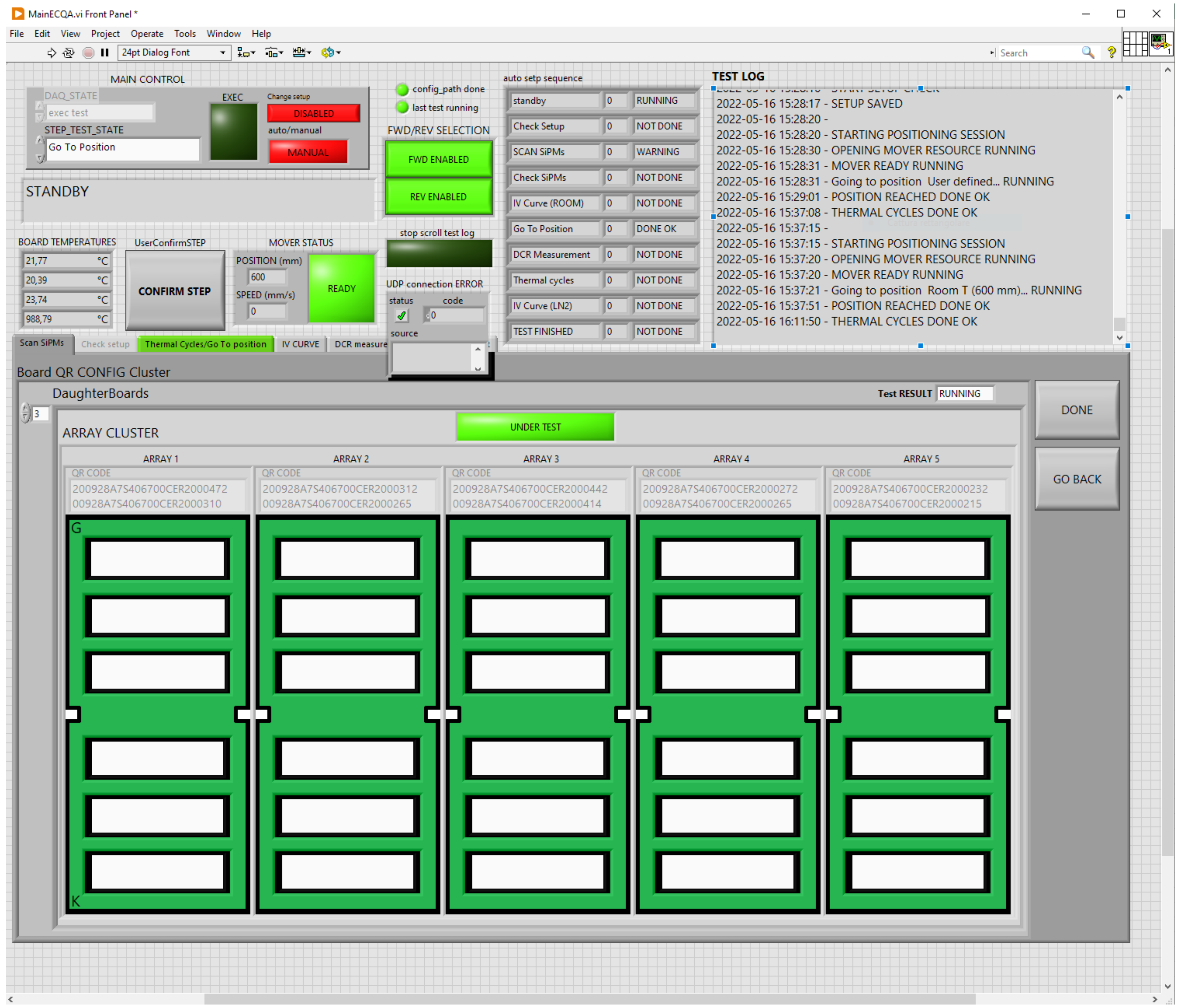
Ferrara system

- **Python software** for run-time acquisition and analysis

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

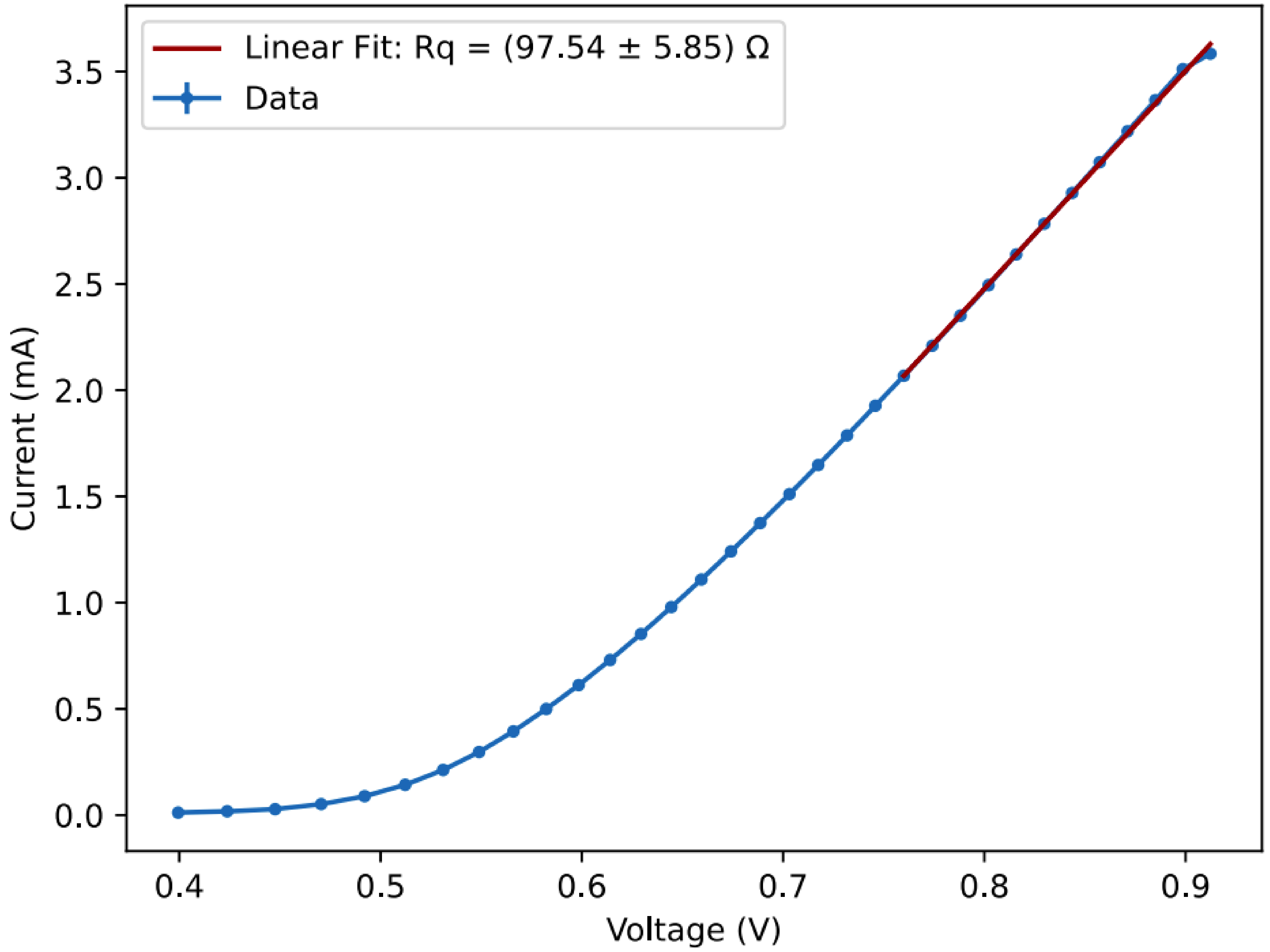
Steps protocol & parameters:

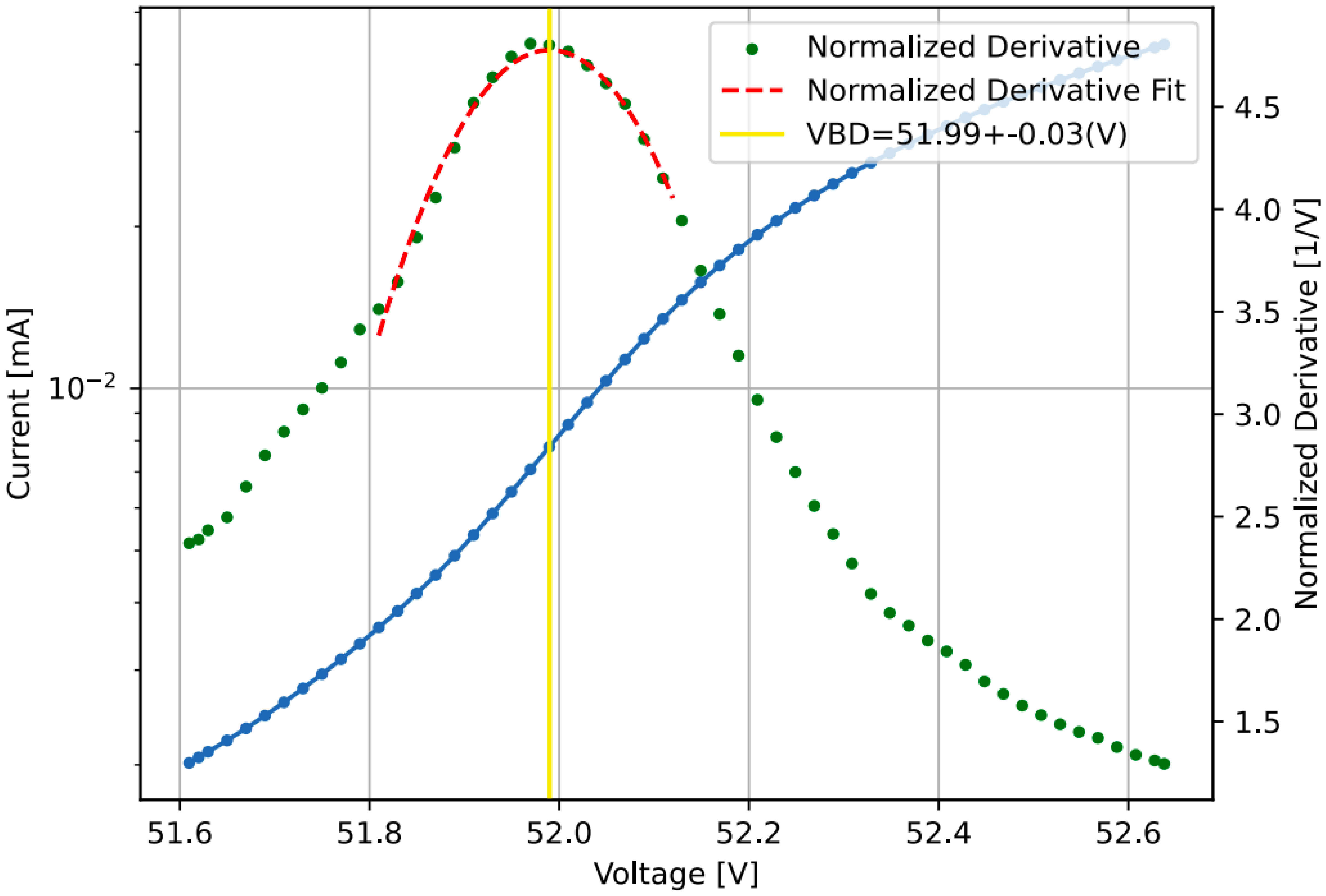
- IV@roomT (10min)→(FW) $\mathbf{R_q^{RT}}$ + (REV) $\mathbf{V_{bd}^{RT}}$;
- First LN2 immersion (20min);
- IV@LN2T (10min)→(FW) $\mathbf{R_q^{LN2T\_pre}}$ + (REV) $\mathbf{V_{bd}^{LN2T\_pre}}$;
- 2 thermal cycles (1.5h);
- IV@LN2T (10min)→(FW) $\mathbf{R_q^{LN2T\_post}}$ +(REV) $\mathbf{V_{bd}^{LN2T\_post}}$;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

Single measurements examples

- Room temperature IV:

	Voltage range (V)	Current range	Step (mV)	Fit
Forward curve	0-1	[0.1-3.5]mA	20	Linear
Reverse curve	51-53	[10-500]nA	15	parabolic

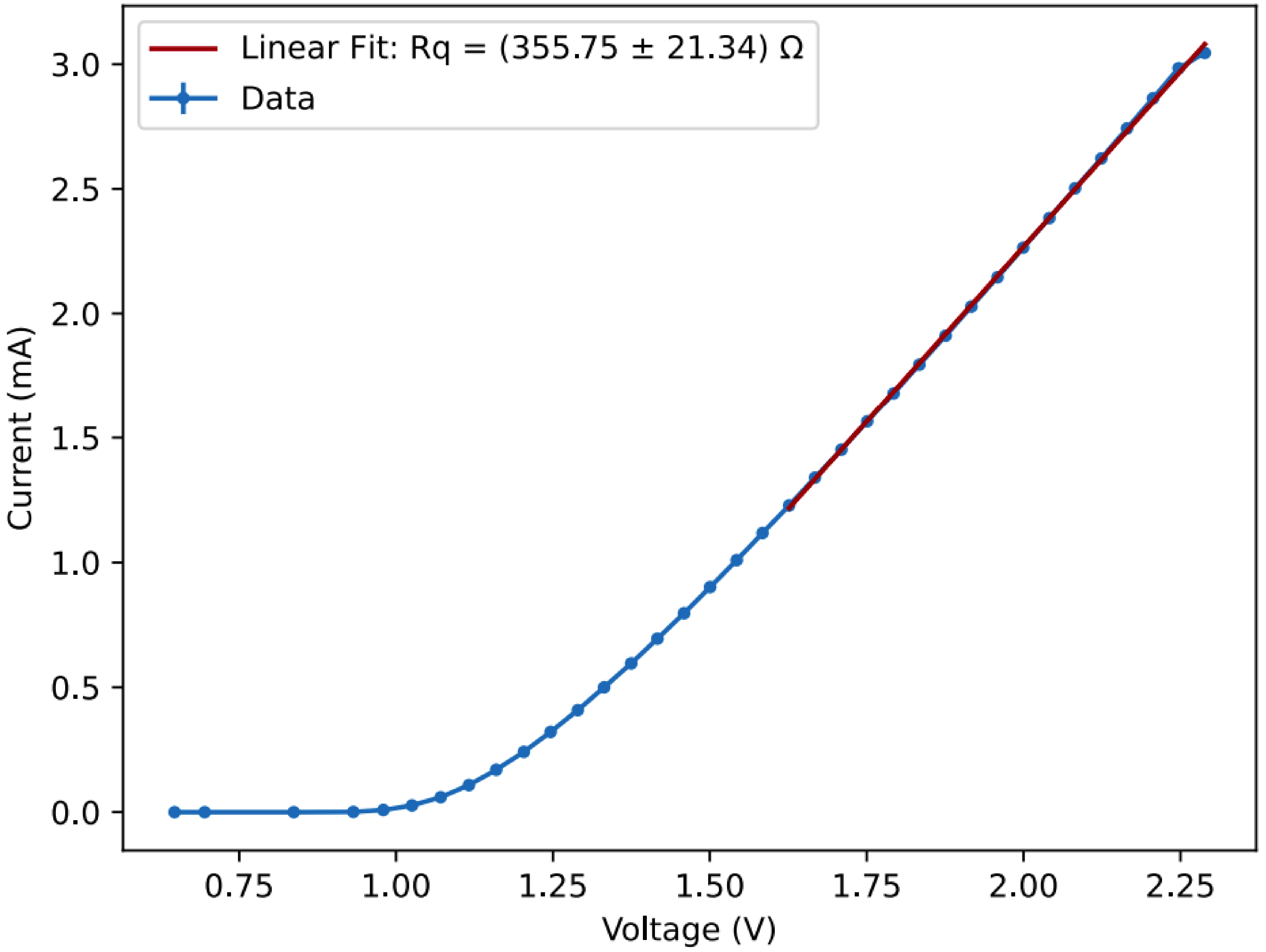


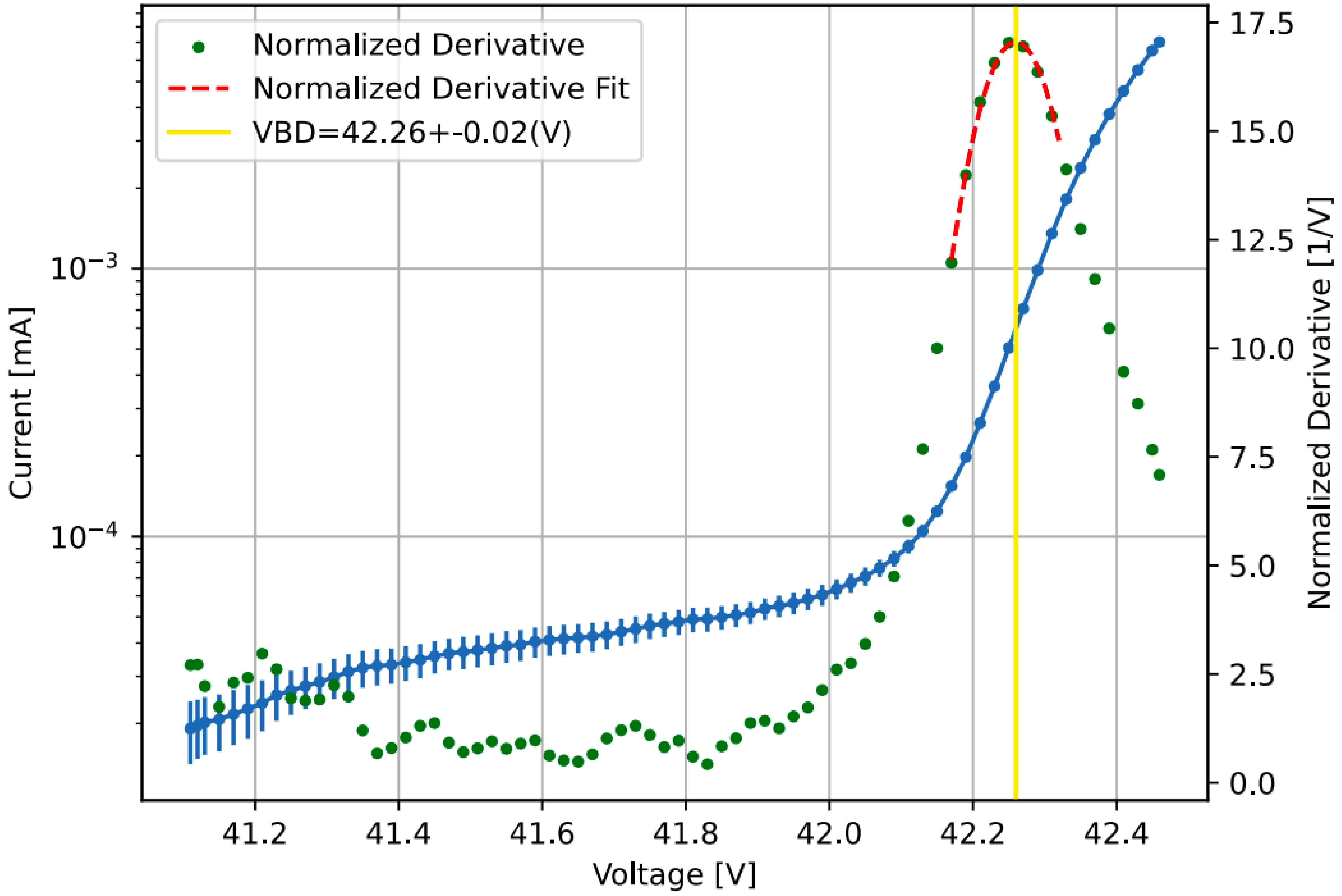


Single measurements examples

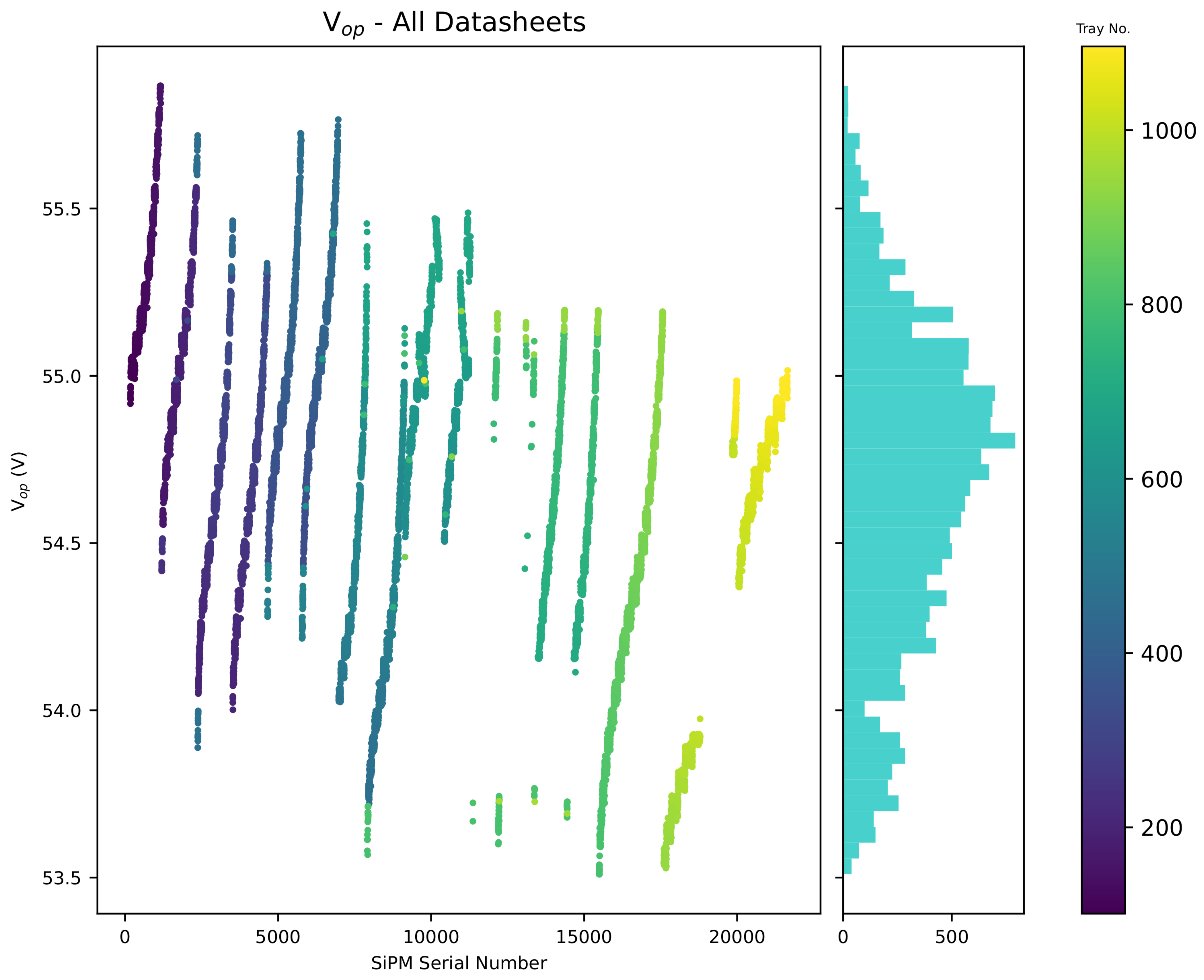
- LN2 temperature IV:

	Voltage range (V)	Current range	Step (mV)	Fit
Forward curve	0-2,3	[0.1-3.5]mA	20	Linear
Reverse curve	41-43	[10-500]nA	15	parabolic



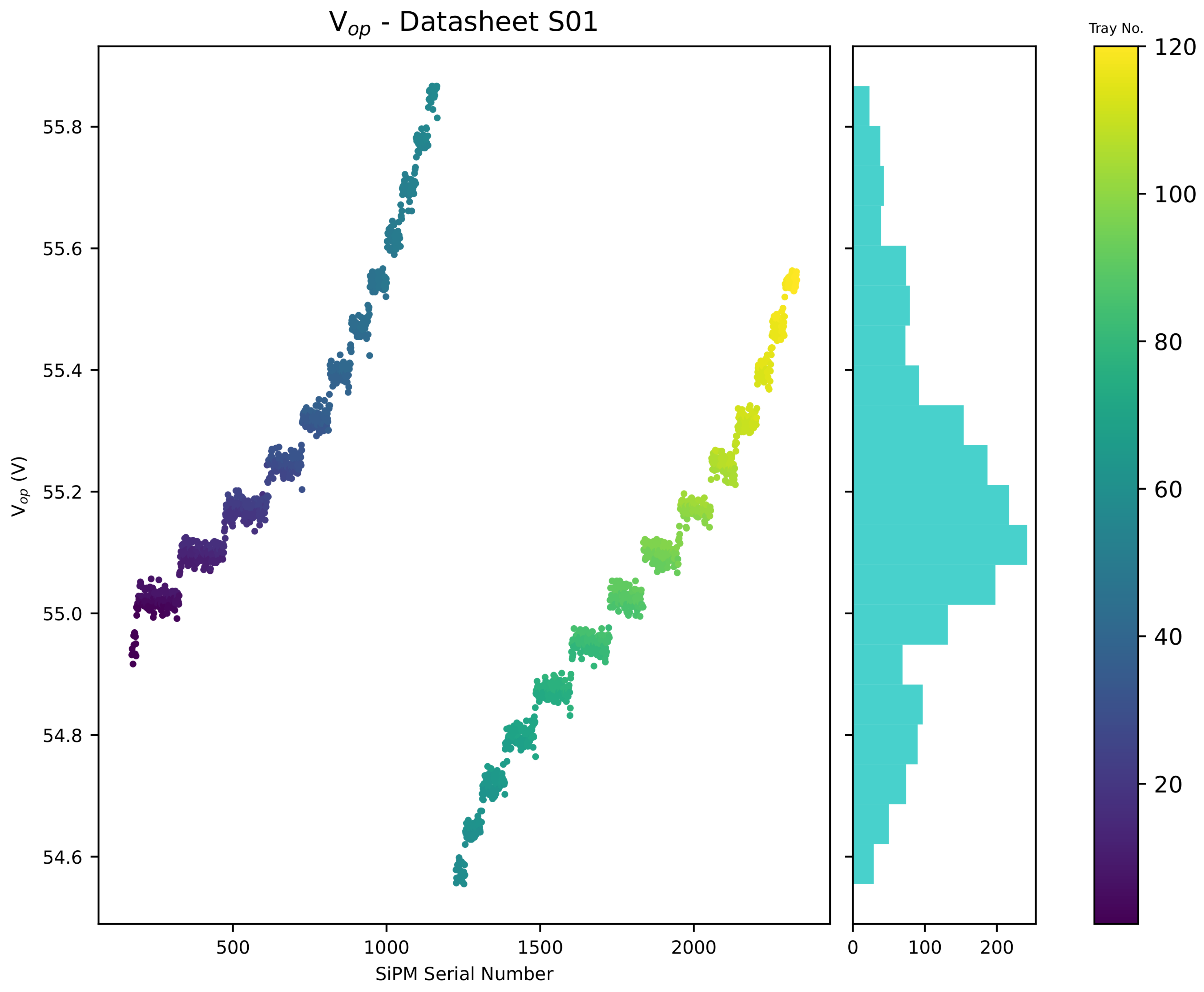


1st HPK production lot



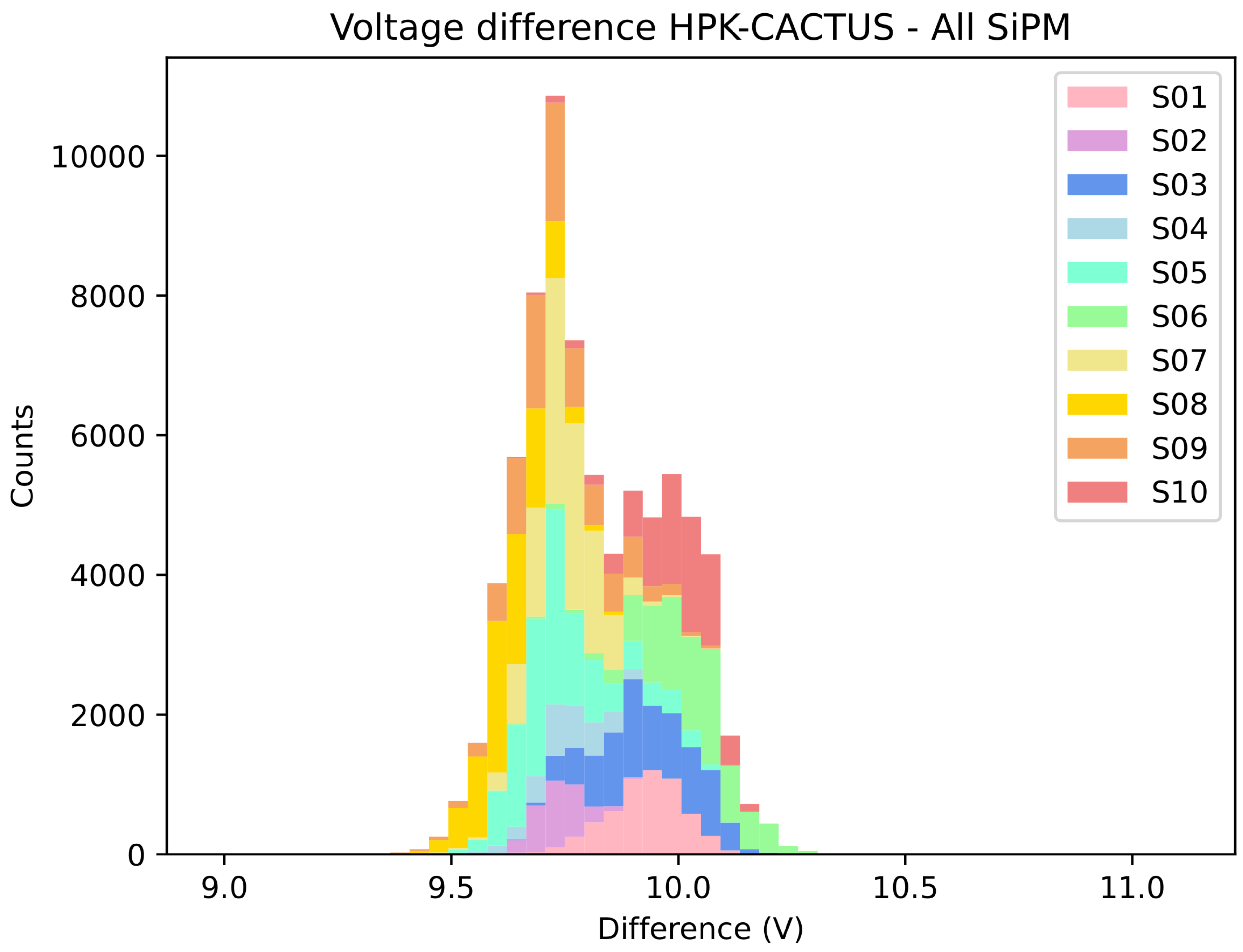
- HPK delivered the first production lot (“Spain”) in 2023-2024;
- Total of 98700 sensors (~16k arrays);
- Total sensor area covered ~ 3.6m^2;
- Splitted in 10 deliveries, divided in trays;
- HPK provided us Voltage of operation V_{op} $=V_{bd}$+3V for each sensor;
- Breakdown voltage total range ~ 2.4V;
- Batches shared among test sites;

Results: data from HPK



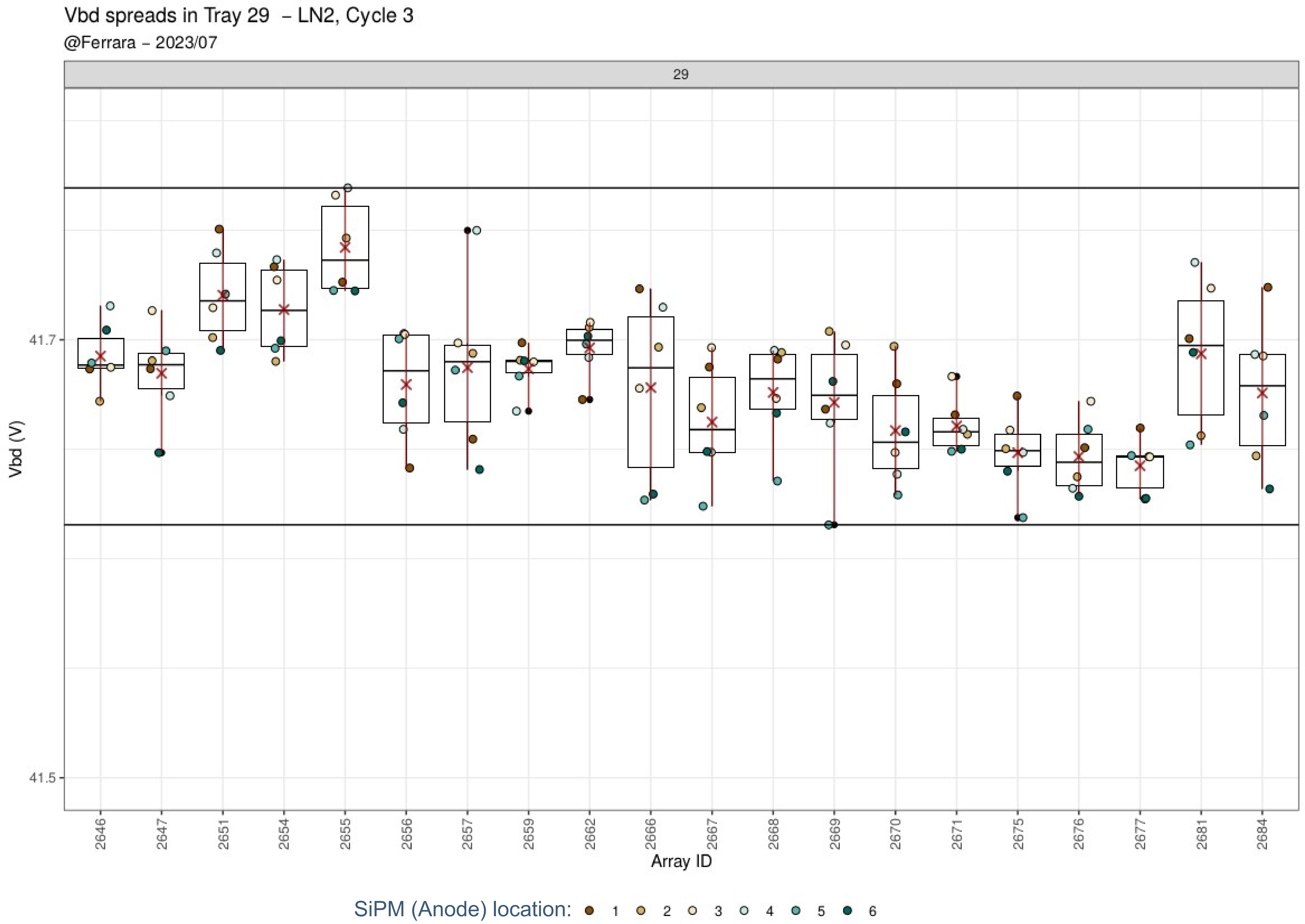
- Example of the 1st delivery;
- Behavior related to manufacturing processes;
- Trays are pre-grouped by the vendor considering similar breakdown voltage values (within 200mV);
- Not continuous serial number.

Results: SiPM check



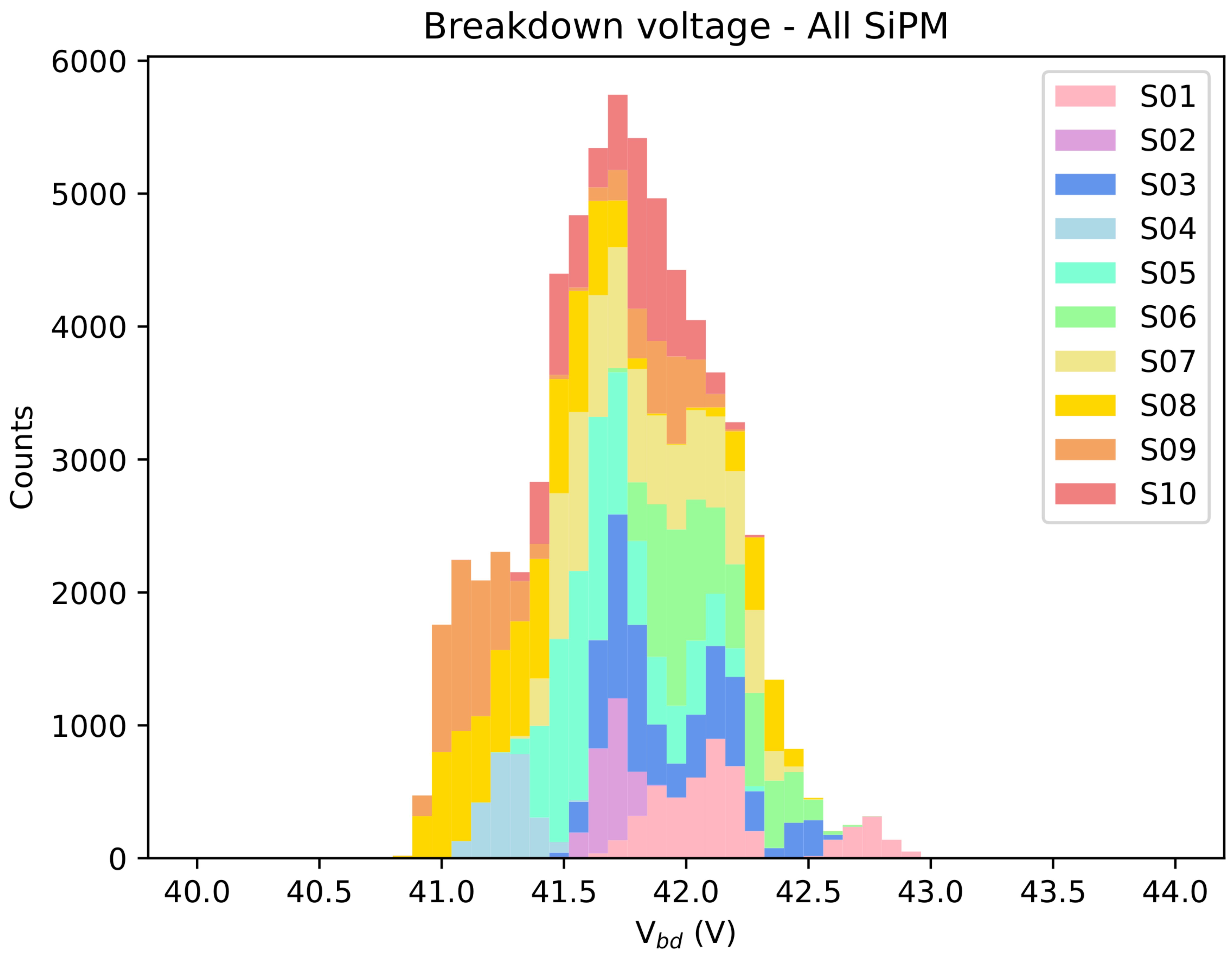
- Compatibility with vendor data at room temperature has been check using data of breakdown voltage measured at LN2 (to maintain temperature constant) by CACTUS at the 1st thermal cycle;
- Difference centered at ~ 10V because of the thermal coefficient of the breakdown voltage for these sensors ~43mV/K;
- Good results, maximum discrepancy of 0.3V.

Results: V_{bd} @LN2



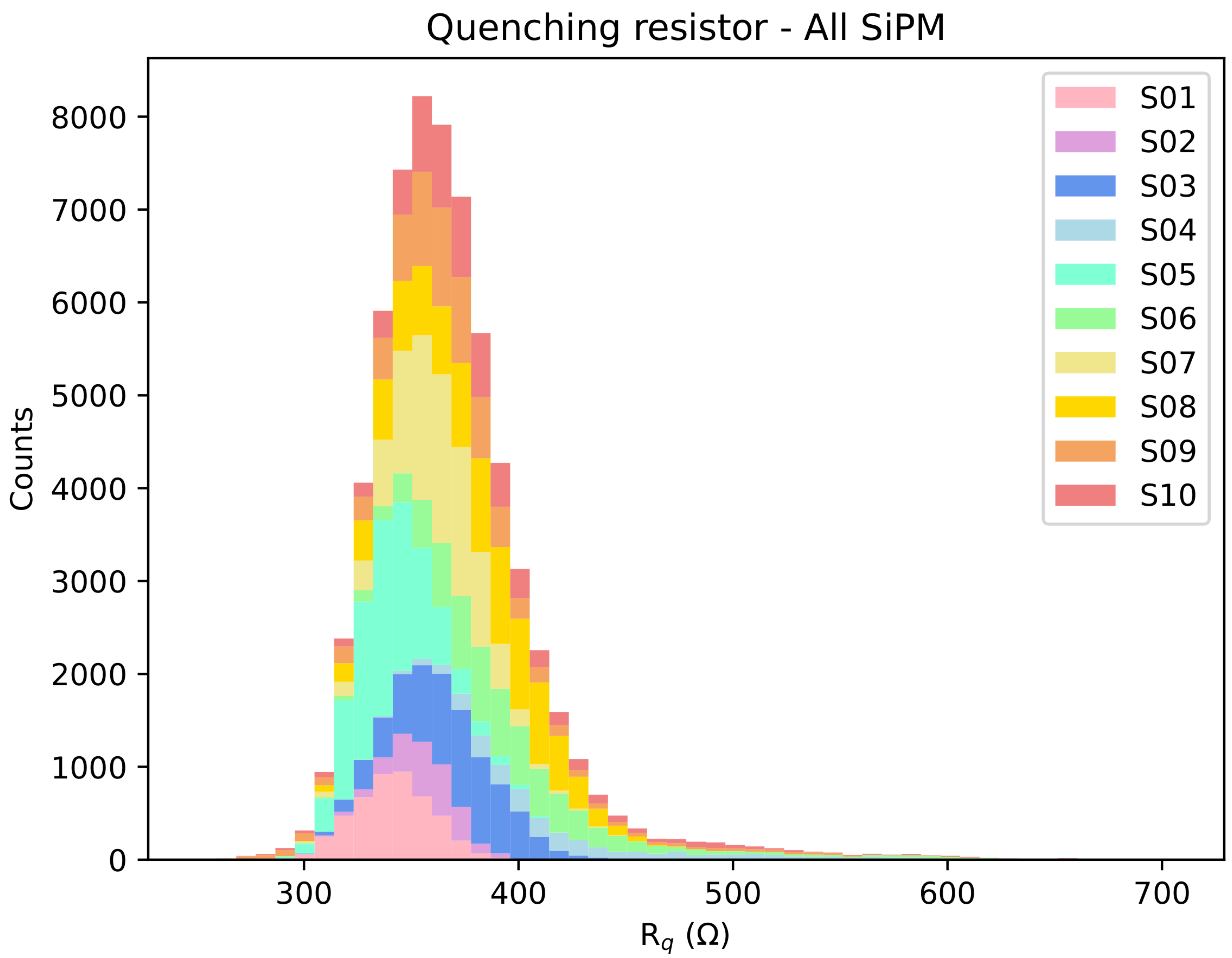
- Example of breakdown voltage measured by CACTUS for a tray (20 arrays of 6 SiPMs each) @LN2;
- Pre-grouped by HPK;
- Min-Max<200mV .

Results: V_{bd} @LN2



- Breakdown voltage distribution at LN2 3rd thermal cycle;
- 2V total width;
- Behaviour as expected looking at HPK data (~ 2V spread)
- SiPMs are in specs;
- Accordance with thermal coefficient (~ 43mV/K).

Results: R_q @LN2



- Quenching resistor distribution at LN2 3rd cycle ;
- Behavior as expected from vendor;
- SiPMs in specs;
- Mean value @LN2 ~ 358Ω (recovery time <1000ns);
- Accordance with thermal coefficient (~1Ω/K);
- STD deviation of distribution @LN2<50Ω.

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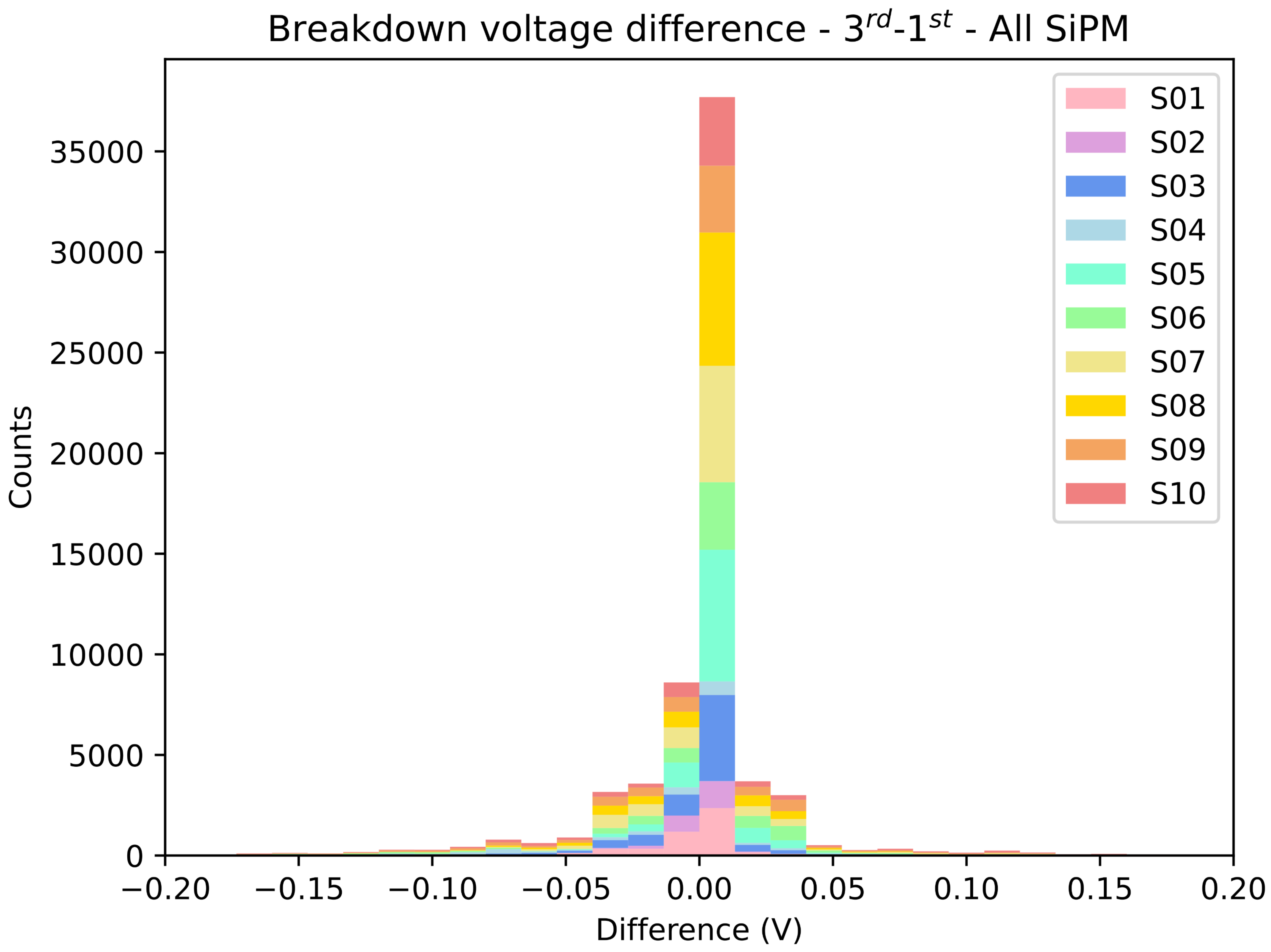
Results: thermal cycles



- 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).

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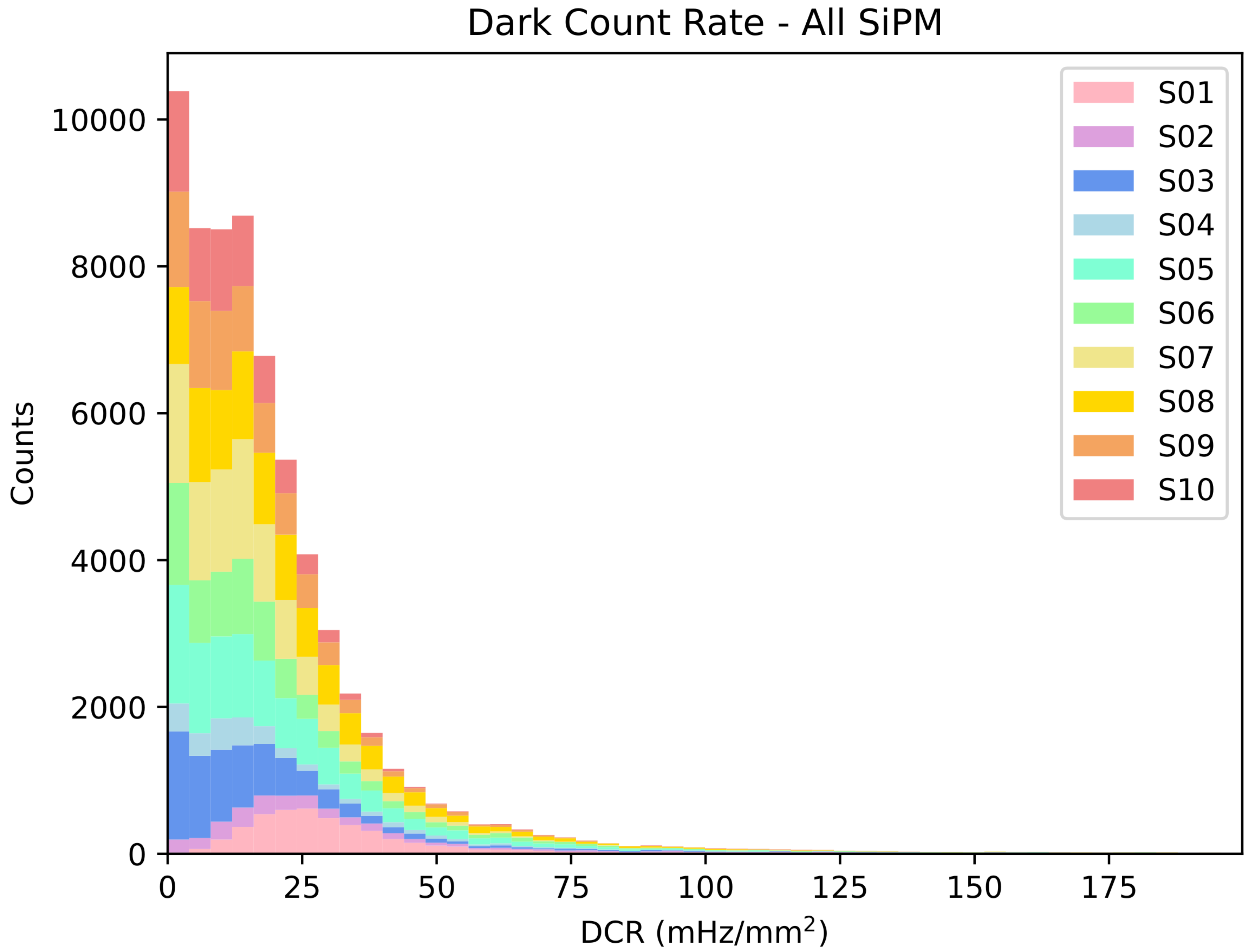
Results: DCR @LN2



- 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
- 48 failed sensors with a very high DCR (>1kHz/mm^2), rejected;
- Failed SiPM re-tested at Valencia laboratory.

Bursts: JINST 16 (2021) T10006

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Conclusions

- DUNE SiPMs 300k sensors FD1 (+ProtoDUNE HD ~10k sensors);
- CACTUS setup: quality assurance and massive tests;
- System capability: 120 SiPM per single run;
- Tests:
  - IV forward + reverse @ Room Temp;
  - IV forward + reverse @ LN2 Temp before and after thermal stresses;
  - Global DCR;
- Sites: Ferrara, Bologna, Granada, Milano Bicocca, Prague ~2400SiPM/month;
- Tested 95% of the sensors of 1st HPK production lot (94000 SiPMs) with very good results;
- Failure rate untill now ~0.05% at single SiPM level;
- 2024-2025 complete tests on all SiPM (HPK + FBK) for FD HD1 with CACTUS.

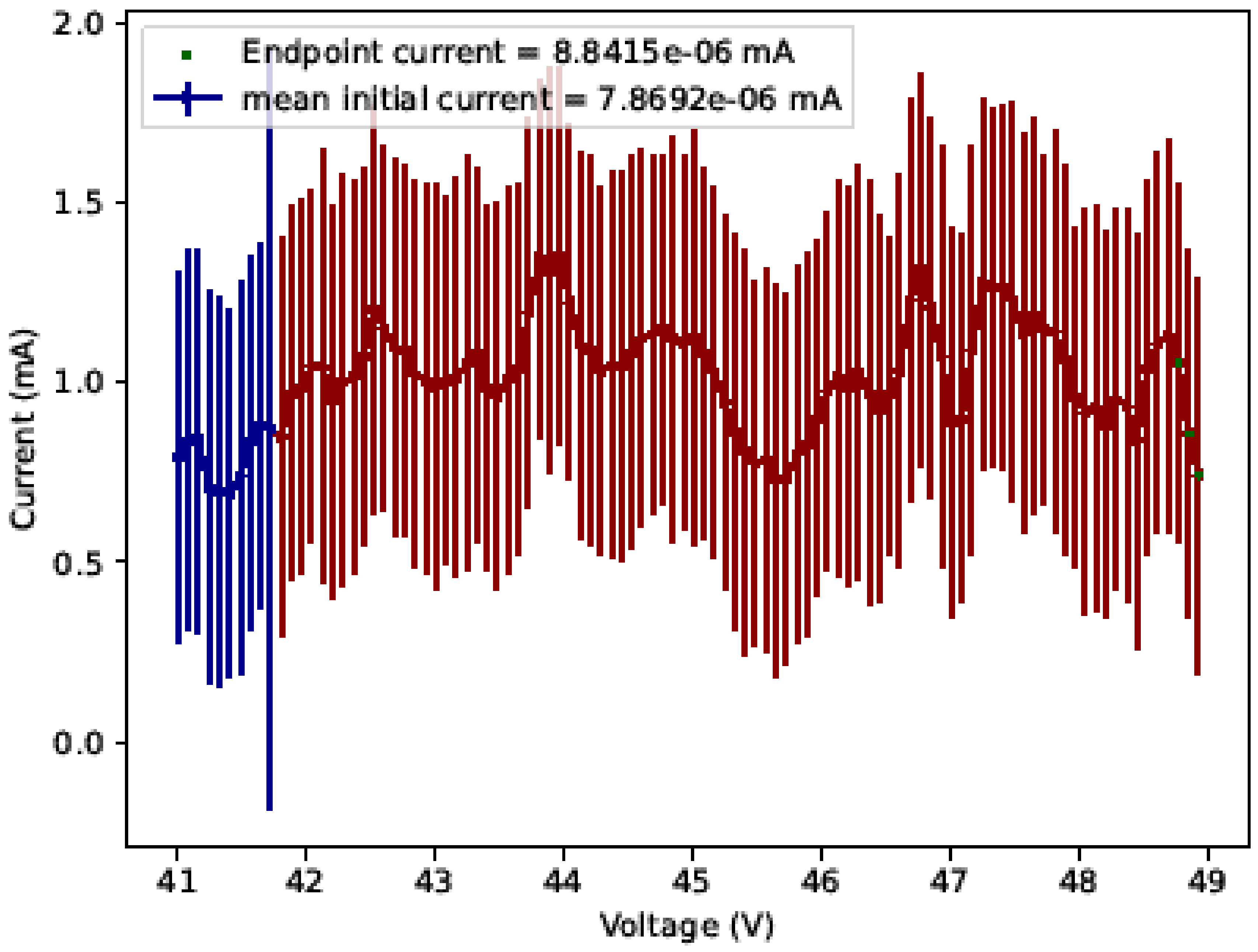
Thank You

Backup slides

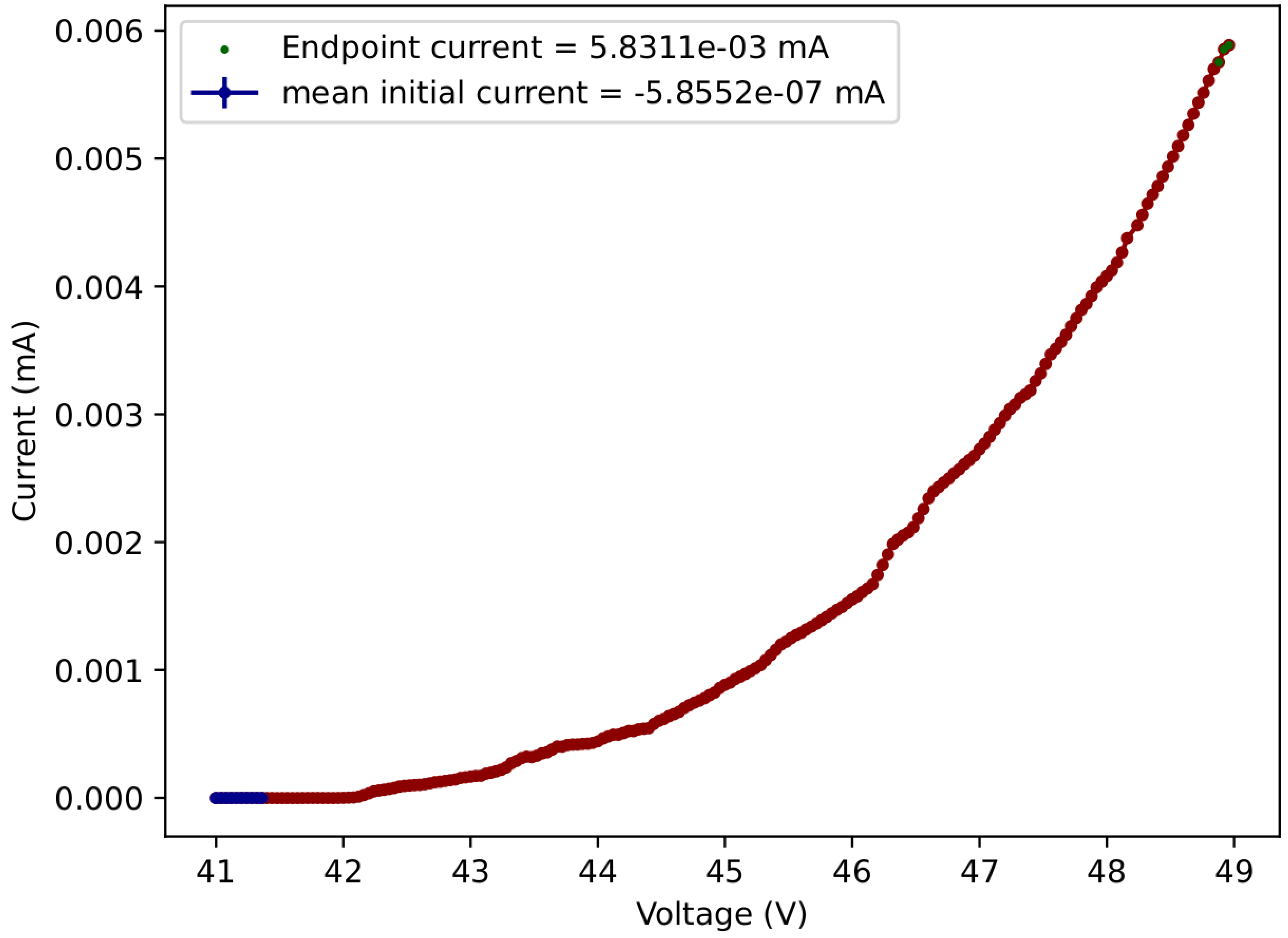
Extended IV curve

An alternative way to check for DCR is to perform a IV reverse curve in complete dark environment.
For normal SiPM (low dark counts) current is under a measurable threshold while for failed SiPM with very high DCR we can measure a DC current

- Extended IV for normal SiPM

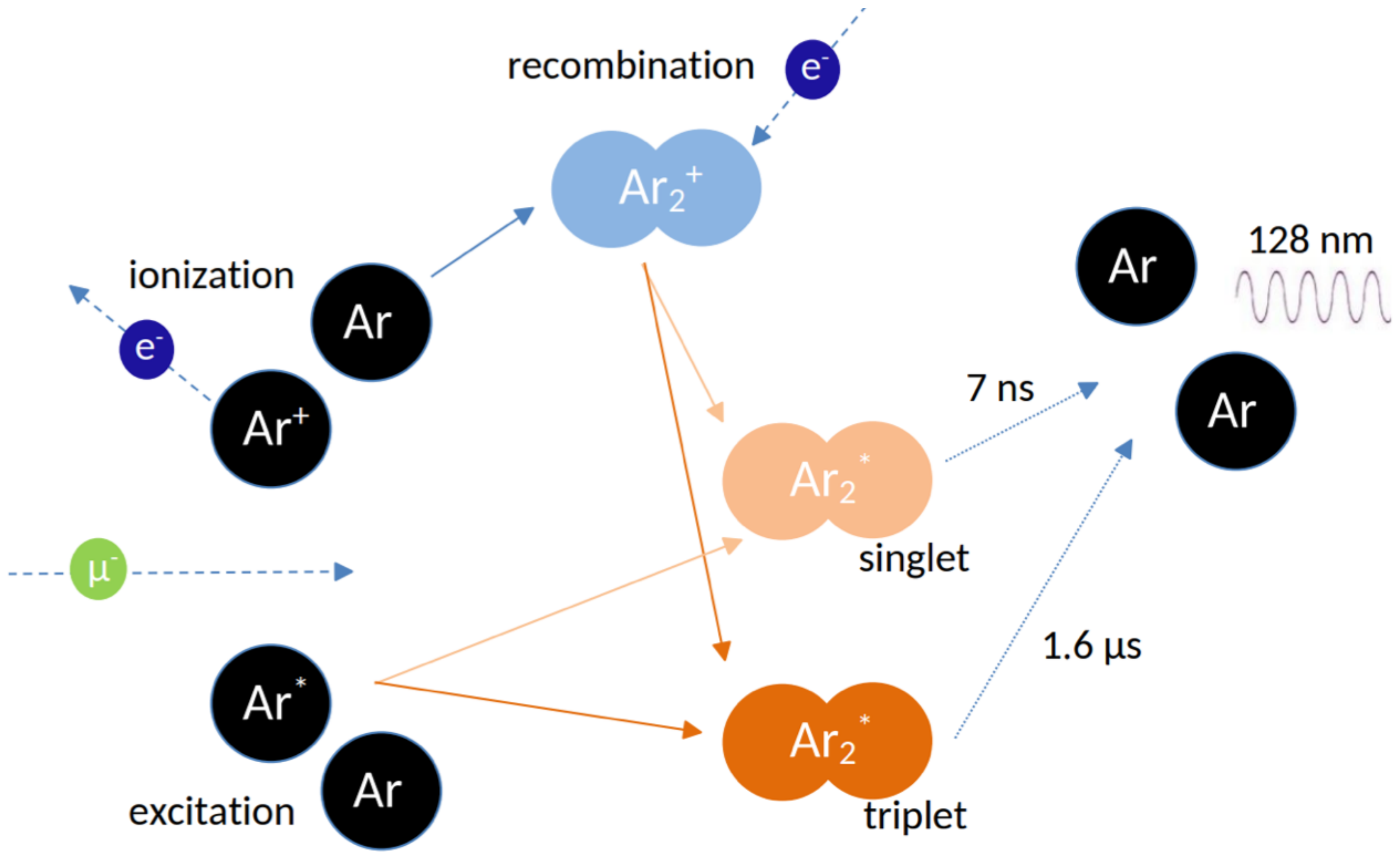


- Extended IV for SiPM with high DCR



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)