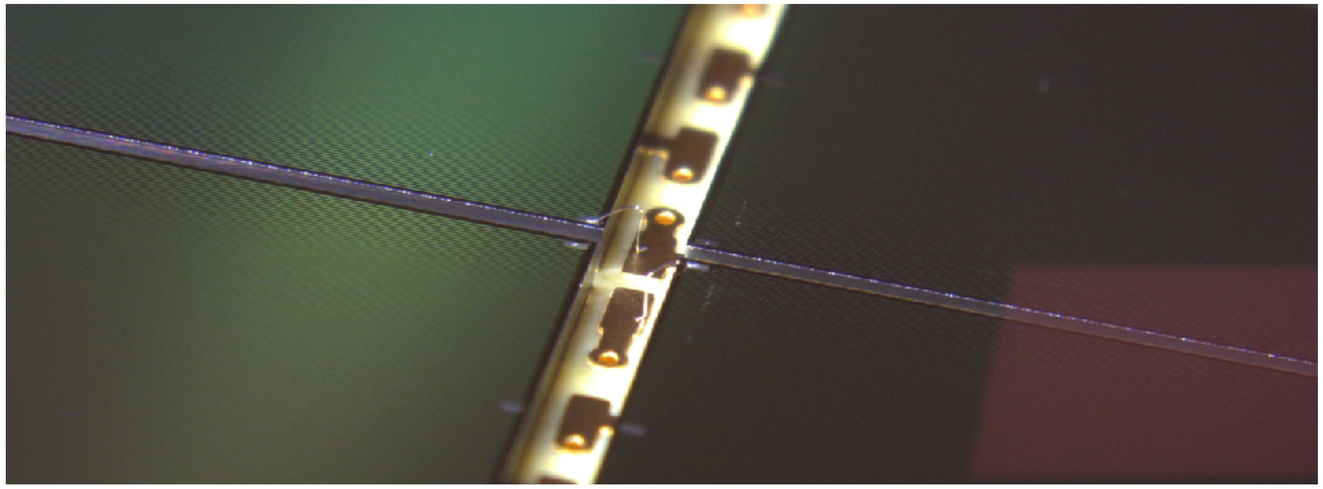
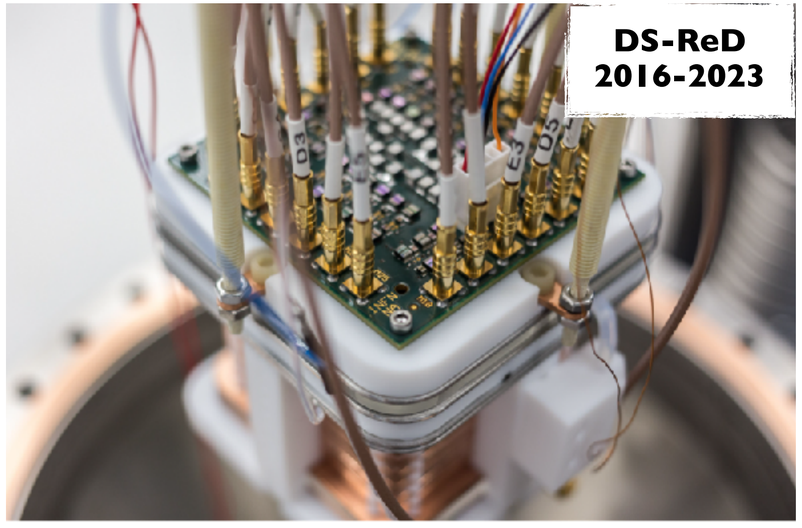
Silicon-based cryogenic Photon Detection Units testing



for DarkSide-20k experiment

Yury Suvorov
on behalf of the DarkSide collaboration,
XII ICNFP July 19th, 2023

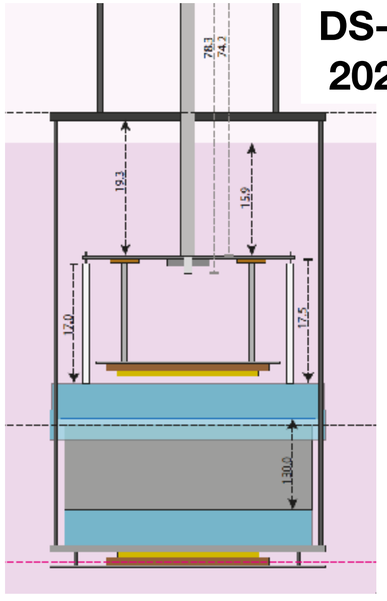
DarkSide project. 2010-2023 and beyond



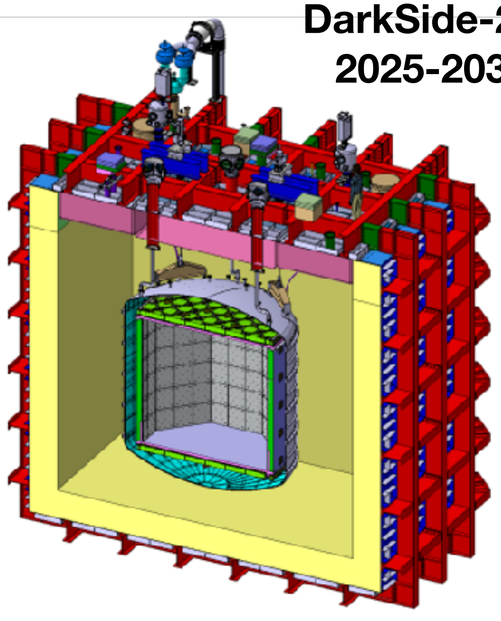
2017 - Global Argon Dark Matter Collaboration (GADMC) >400 scientists, >100 institutions distributed across 13 countries

see talk from Simone Sanfilippo

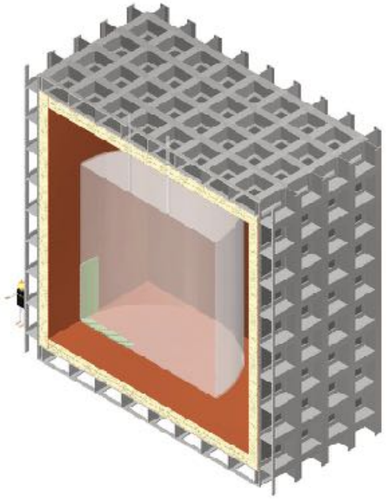
DS-Proto-0
2023-2024



DarkSide-20k
2025-2035

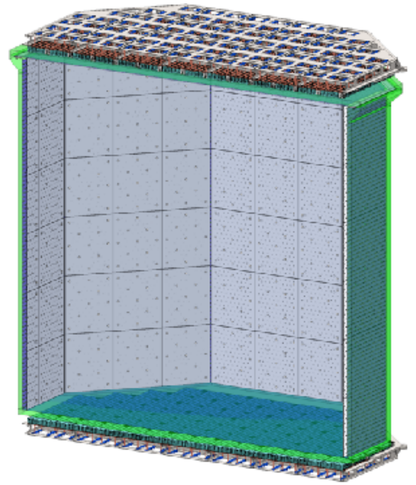


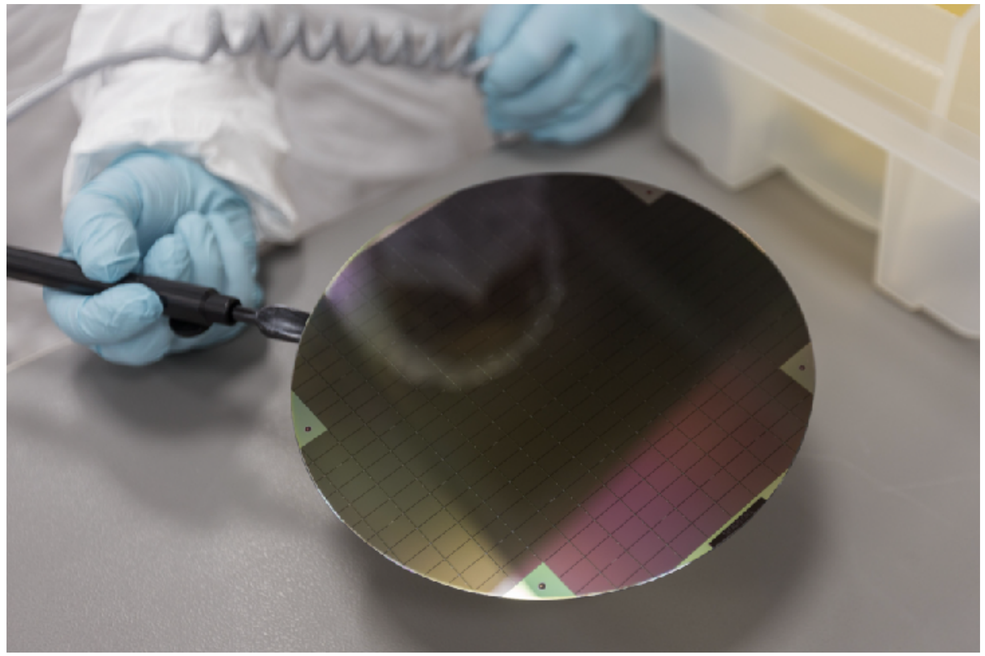
ARGO
From 2030s -



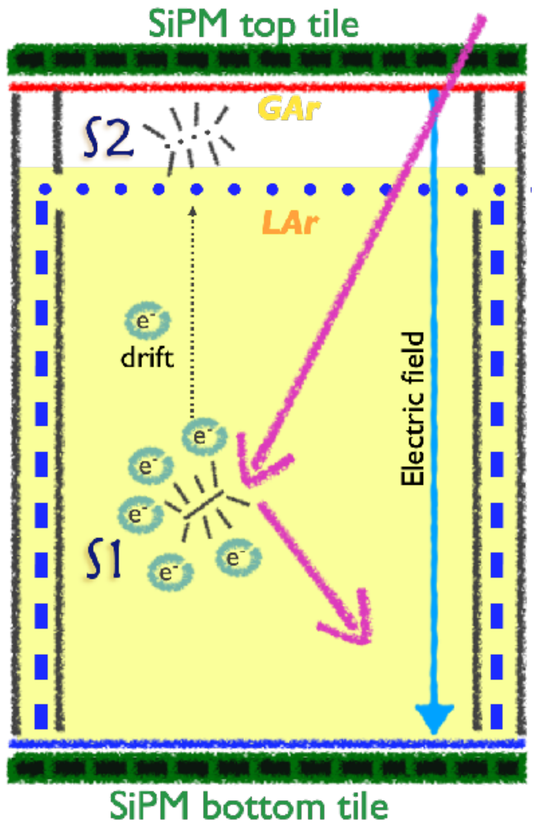
DarkSide dark matter direct search

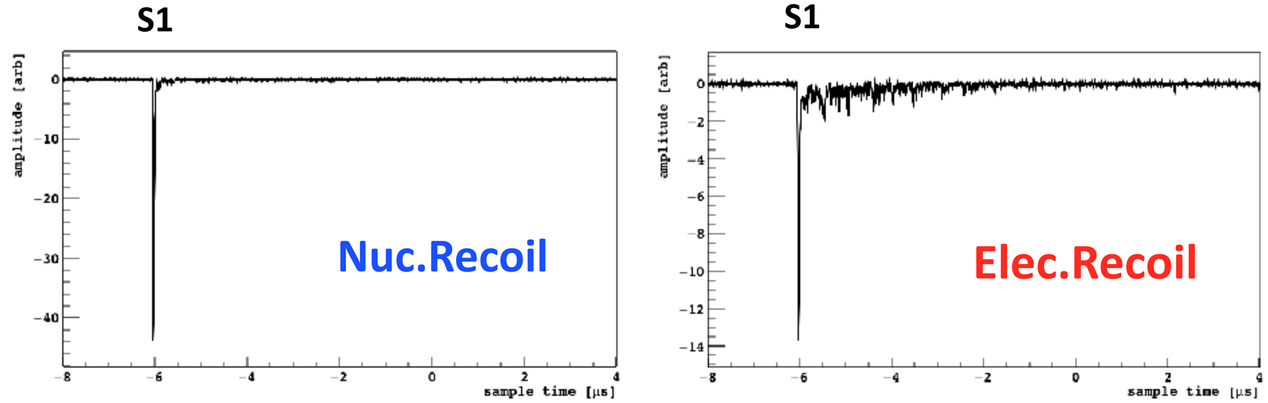
- **Deep Underground Location ▹ INFN-LNGS (3800 m.w.e.) Italy**.
- **TPC** ▹ Two phase Time Projection Chamber (scintillation S1 + ionization S2).
- **PDU** ▹ SiPM array 20x20 cm^2 coupled with TPB coated PMMA panels.
- **Active n-veto** ▹ LAr (UAr) + Gd loaded acrylic + 128 PDUs.
- **Active μ-veto** ▹ LAr (AAr) + 32 PDUs.
- **UAr** ▹ Argon from underground sources, depleted in ^{39}Ar.



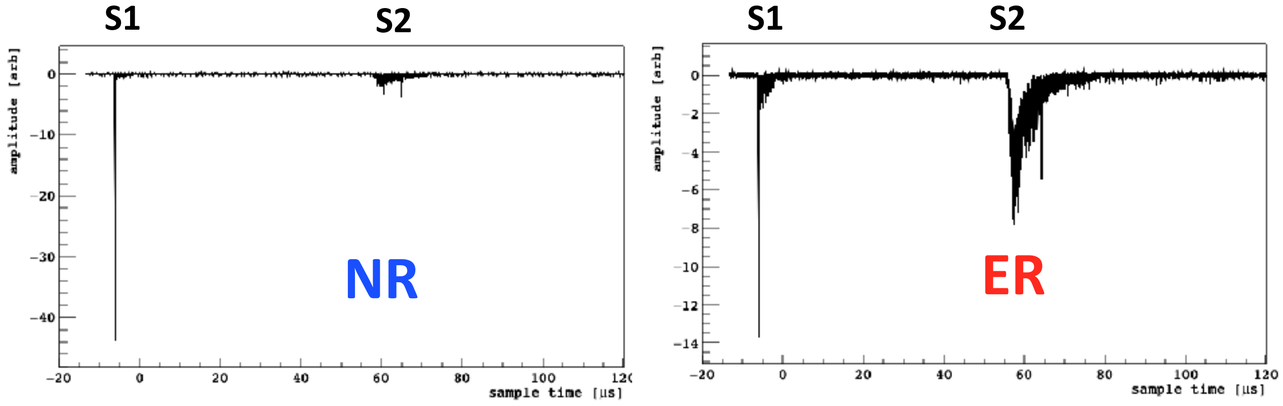


Detection Principle: Two phase TPC

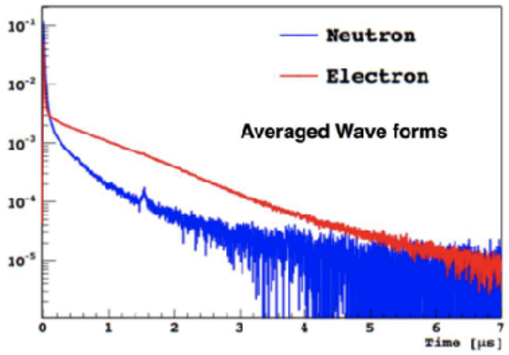




- X-Y position is determined by the top PMTs (*SiPM*) array with S2.



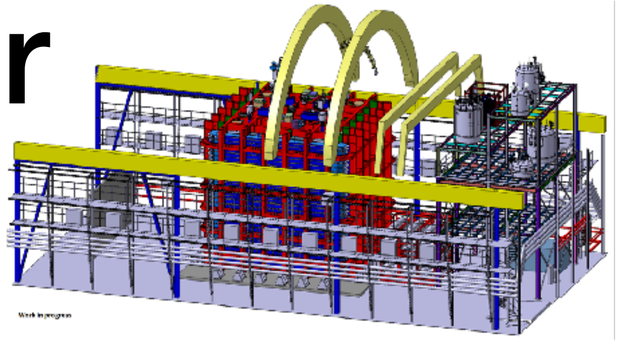
- Z position from drift time.



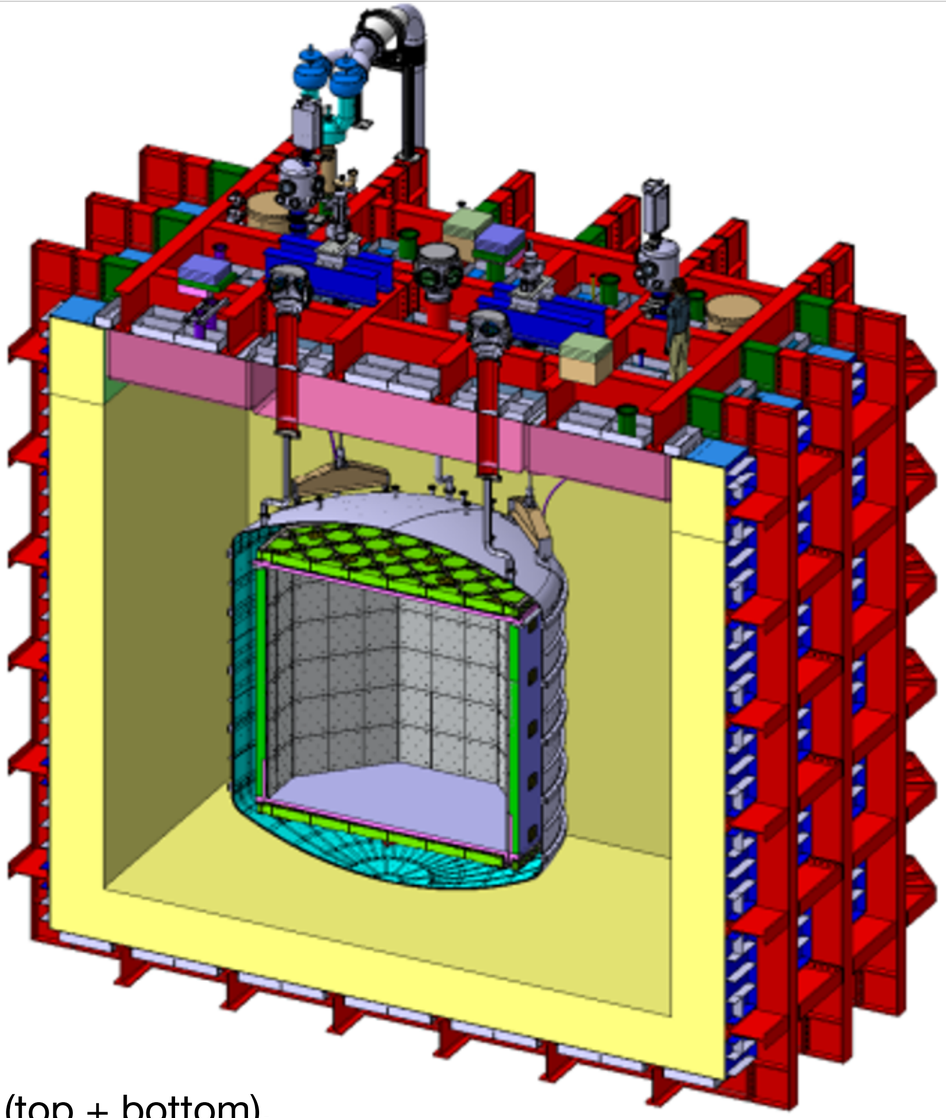
Pulse Shape Discrimination in LAr

Two time constants: 7 ns singlet & 1600 ns triplet. Temporal pulse shape of S1 (first 90 ns - f_{90}) provides powerful discrimination between NR & ER.

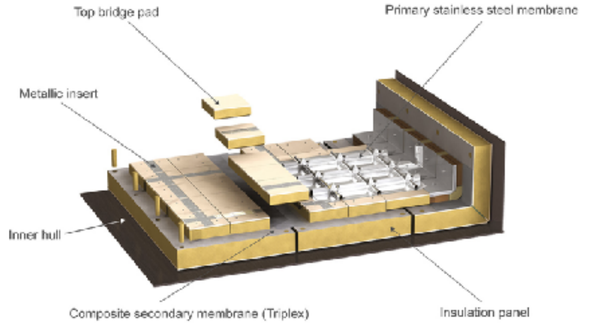
DarkSide-20k detector



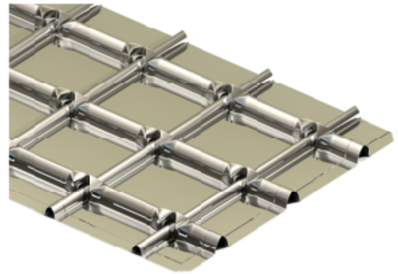
- *Onion*-type architecture



External cryostat: 8.5 x 8.5 x 8 m^3 vessel
Multilayer assembly (proto Dune like membrane)
Filled with **700** t of liquid AAr.
Active muon veto detector, equipped with SiPMs.



Stainless steel vessel: H:5.8 m & ID:4.7 m
Filled with **99** t of depleted in ^{39}Ar Argon (UAr)
Divided in two volumes:
- **Neutron Veto** (outside TPC).
- **TPC** inner volume.



Neutron veto detector:
Gd-loaded PMMA panels,
Equipped with **5 m²** of SiPMs (vPDU).
Filled with **44** t of depleted in ^{39}Ar Argon (UAr).

TPC: 3 x 3 x 3 m octagonal vessel
Filled with **55.4** t of depleted in ^{39}Ar Argon (UAr)
Two optical planes, total SiPM coverage of **21 m²** (top + bottom).

DarkSide-20k SiPM

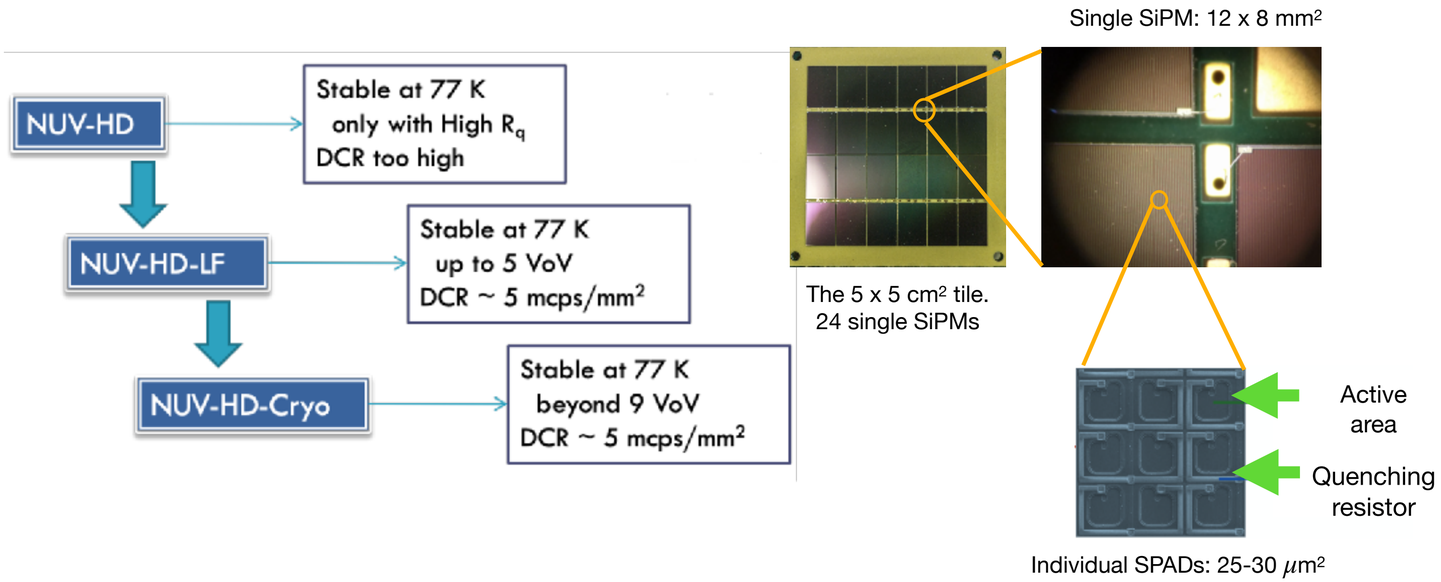
Development of new SiPMs, suitable for production of large area SiPM working in LAr temperature, in collaboration with Foundation Bruno Kessler (FBK) starts in **2014**.

Specs for SiPM & Electronics: Single SiPM size ~cm^2. PDE (420 nm) >40%. Dark Count Rate (77K) 0.1 Hz/mm^2. S/N (87K) >8. Time resolution <30ns. Gain >10^6. Dynamic Range >50. Compact & radioactively pure.

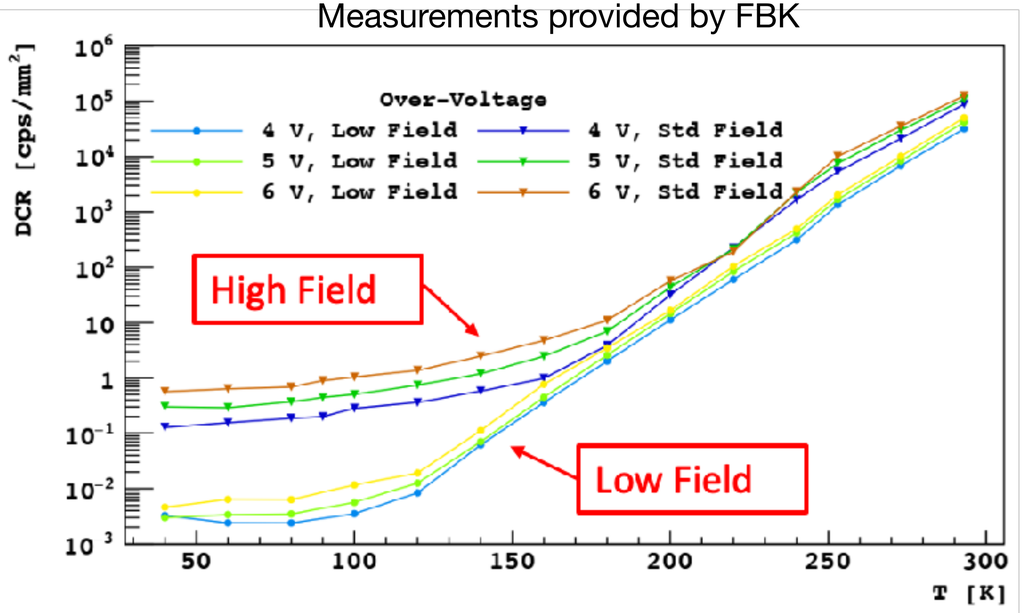
Three technological steps based on different doping profiles.
Near UltraViolet High Density SPADs SiPMs: NUV-HD, NUV-HD-LF and NUV-HD-Cryo.
Selected technology: NUV-HD-Cryo, most suitable for DarkSide needs.

Dark Side TDR specs:

Parameter	7 V of OV	9 V of OV
Internal Cross Talk probability at 77 K	< 33 %	< 50 %
Dark noise rate at 77 K	< 0.01 Hz/mm^2	< 0.1 Hz/mm^2
Afterpulse probability at 77 K [within 5μs]	-	< 10 %
PDE at 420 nm at 77 K	-	>40 %
Breakdown Voltage at 77 K (SPE charge)	26.8 ± 0.2 V	
Breakdown Voltage at 77 K (SPE amplitude)	27.5 ± 0.2 V	
Single Cell Capacitance (from SPE charge)	62.5 ± 2.5 fF	



Measurements provided by FBK



DS-20k SiPM: *PDE, DCR, CT, AP*

The SiPM Photon Detection Efficiency (PDE) goal of >40% (DS TDR) was successfully achieved. Dedicated measurements of PDE on the single SiPMs (12x8 mm²) as a function of the OverVoltage (OV) and wavelength were performed by colleagues from FBK, TRIUMF & Pisa, at room temperature (290K) and at 100K.

Dark Side TDR specs:

Parameter	7 V of OV	9 V of OV
Internal Cross Talk probability at 77 K	$< 33\ \%$	$< 50\ \%$
Dark noise rate at 77 K	< 0.01 Hz/mm^2	< 0.1 Hz/mm^2
Afterpulse probability at 77 K [within 5μs]	-	$< 10\ \%$
PDE at 420 nm at 77 K	-	>40 %
Breakdown Voltage at 77 K (SPE charge)	26.8 ± 0.2 V	
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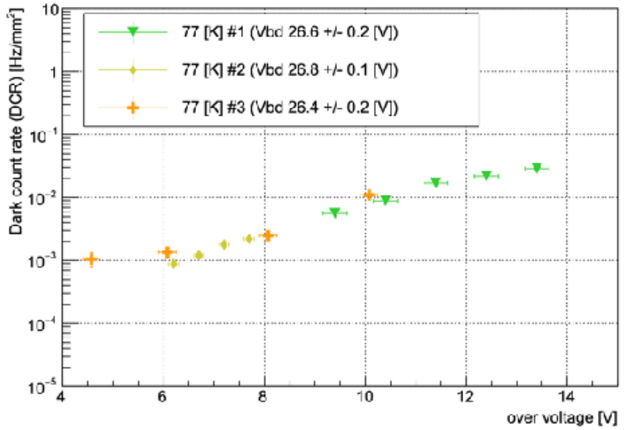
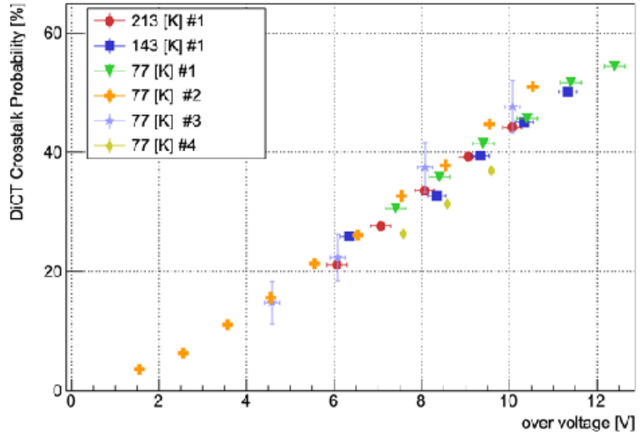
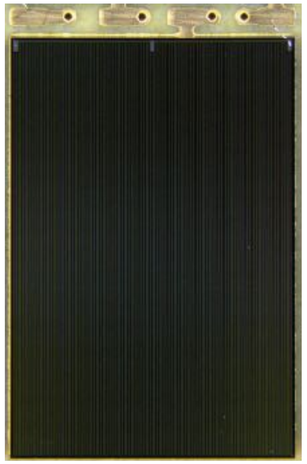
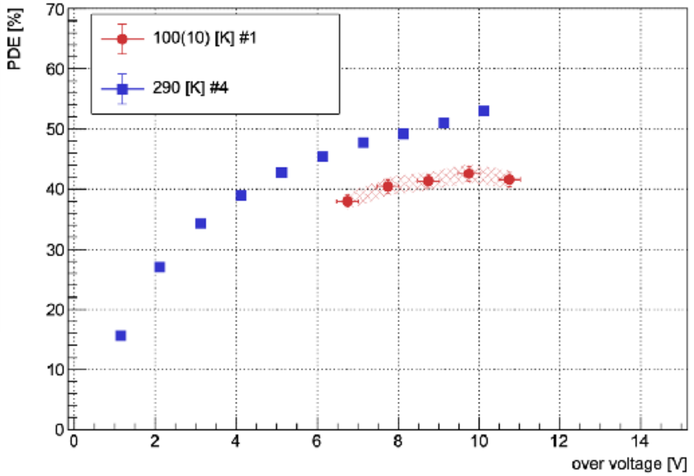
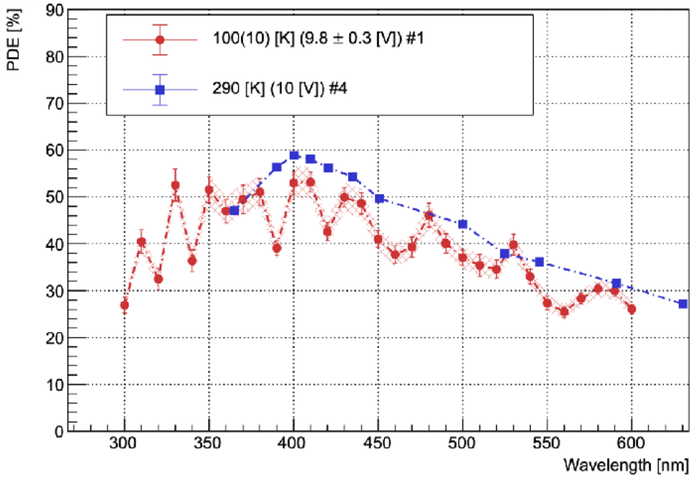


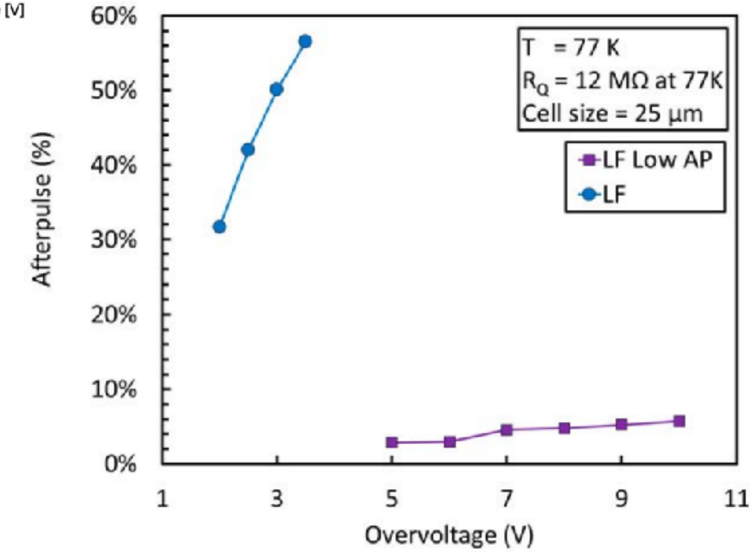


SiPMs (12x8 mm²)







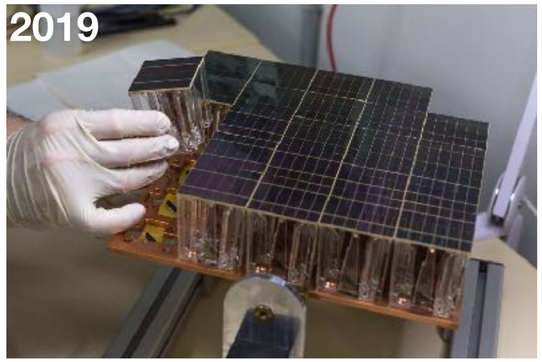


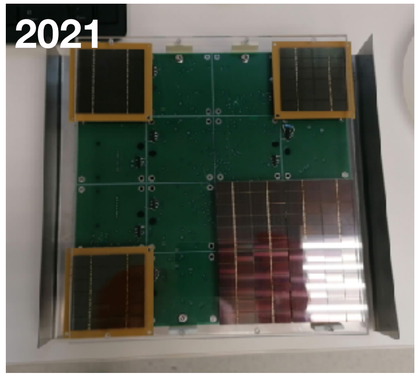
The 24 rectangular SiPMs (12x8 mm²) assembled in one 5x5 cm² tile. Coupled with Front End Board give (Photo Detecting Module).

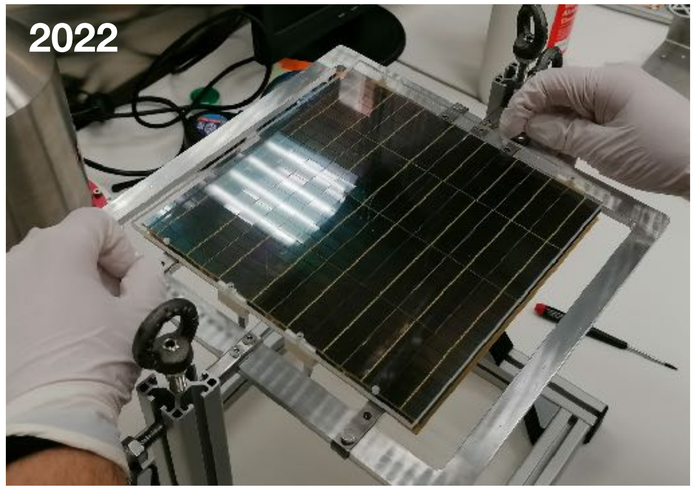
DS-20k SiPM, PDU

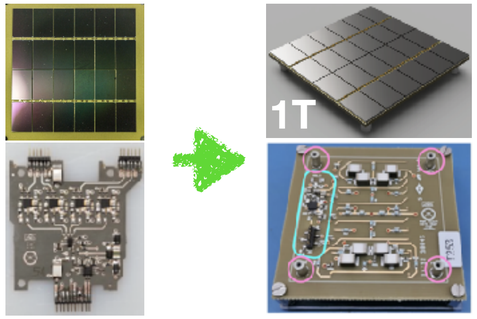
2021-2022 Optimised version of PDM and PDU was designed, fabricated and tested.

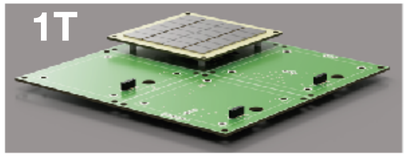
- Reduced PDMs number 25 → 20. Smaller size 20x20 cm^2 instead of 25x25 cm^2.
- No single PDM readout. Four tiles are summed in one channel (100 cm^2). New PDU has 4 channels (not 16).
- Great reduction of overall weight: from 5 kg to ~ 0.4 kg.
- Simplified assembly: tile + Mother Board (no plastic cage).
- Reduced hight: 1.5 cm.
- Acrylic protection for the SiPMs surface and wire bondings + metal support plate for secure transportation.

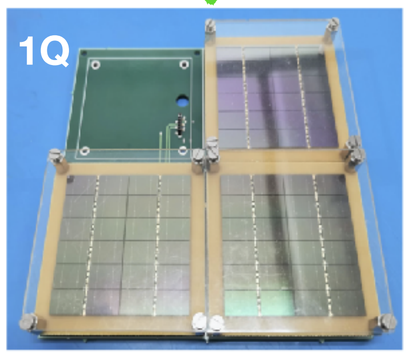




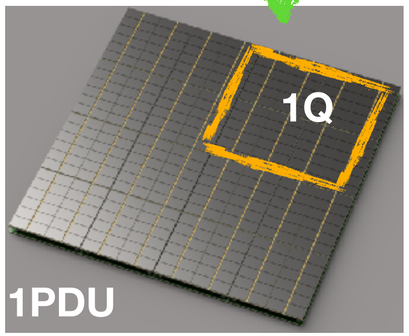








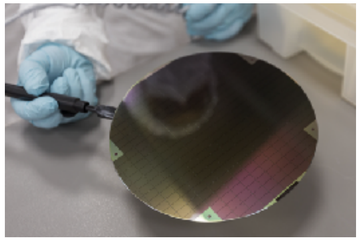
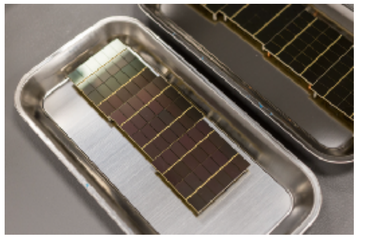
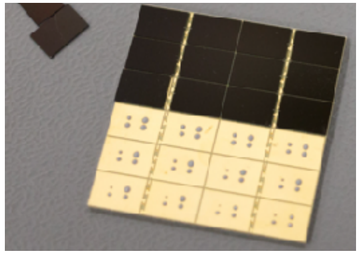
4 tiles = 1 channel



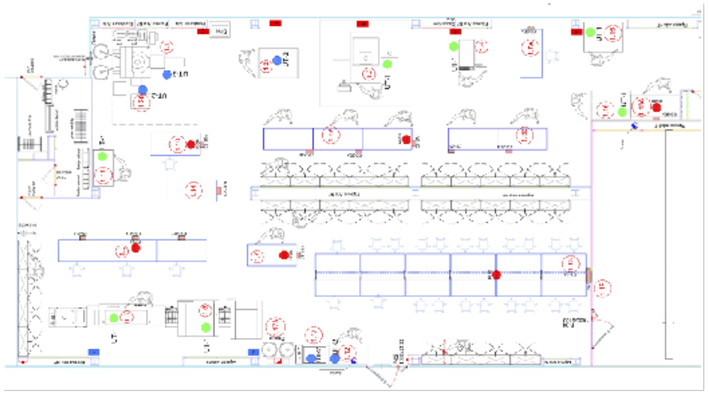
Tests in Naples facility are ongoing since fall of 2021

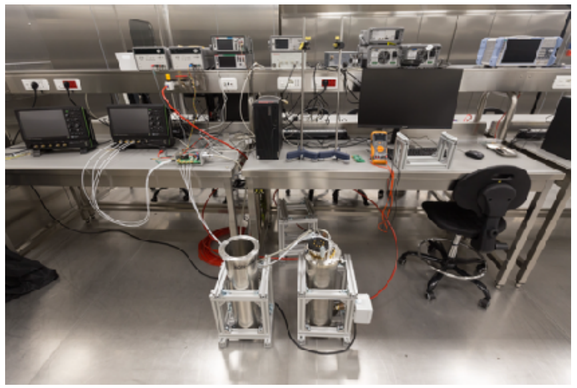
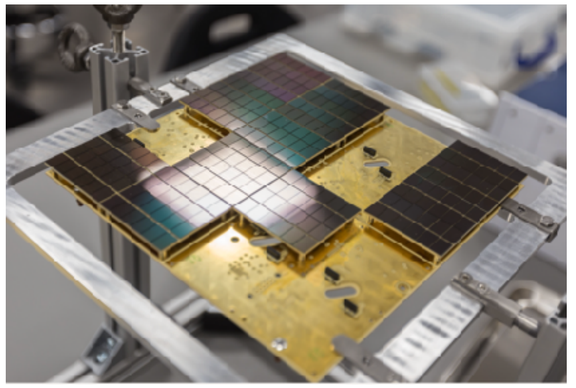
DarkSide-20k. NOA

Nuova Officina Assergi (NOA) dedicate ISO6 Clean Room (420 m^2) at Laboratori Nazionali del Gran Sasso (LNGS), Italy.


- 1400 raw wafer, produced by LFoundry. Tests in cryo-prob machine are ongoing. 15% done, to be completed in Q3 of 2024.
- Dicing of the wafer to cut the it in 268 single SiPMs (12x8 mm^2).
- Fully Automated Flip-chip bonder to assemble the 5x5 cm PCB with 24 individual SiPMs.
- Wire-bonder to make an electrical connection of individual SiPMs.
- Test measurements of IV and SPE (@LN) for all tiles in two identical dedicated setups (8 tiles a batch).
- Assembly of the 528 PDUs (from Feb 2024, ~60-70 weeks) and shipping to Naples PDU test Facility for full integration test in LN.

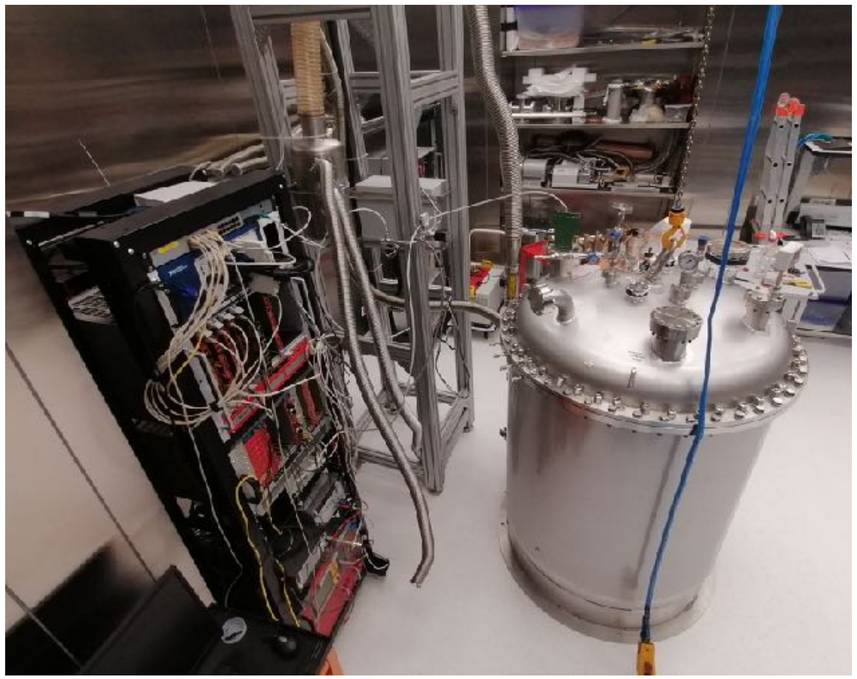
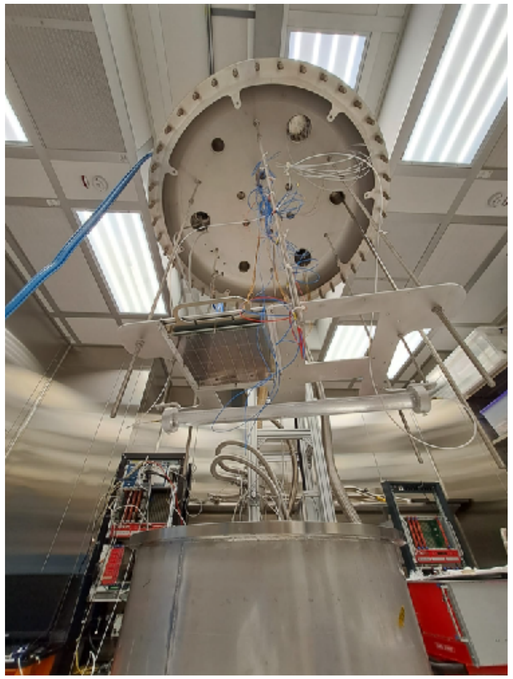


All 528 assembled in NOA PDUs will then arrive to the Naples Facility for the LN characterisation

Naples PDU Test Facility

The Naples PDU Test facility (PTF) is composed of ~800L double wall cryostat with domed top flange, coupled with custom cryogenic system. Vacuum insulated inlet and outlet lines for LN and cold vent. Custom Cold Box. External LN storage plant with 3000L tanks.
Designed, fabricated, assembled, commissioned and is active since summer 2021.

ISO6 50m^2 clean room for PDU handling and LN characterization. Fully automated process of FILL, DRAIN and constant level maintenance over the period of testing (*evaporation rate of 0.2 cm/h*).

Mechanical structure composed of four floors to host 4 PDUs each (16 in total). Full integration with light distribution system.

Electronic rack with Caen mainframe for the Power Supplies board, VME crate for VX2740 ADCs, NIM crate with trigger logic formation unite and laser unite.

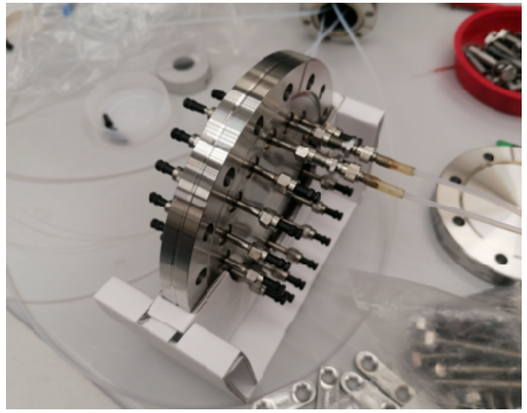
Dedicated software (online and offline tools) integrated in the MIDAS framework. DAQ system: daq server, analyses and storage server 40Tb.

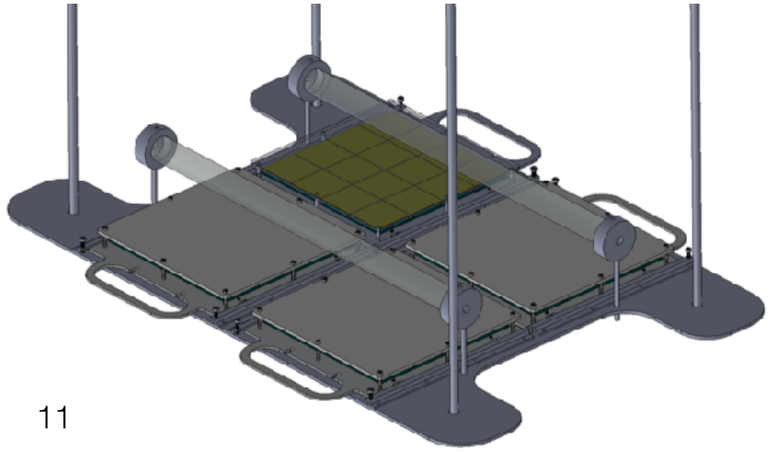
PTF Mechanics & illumination

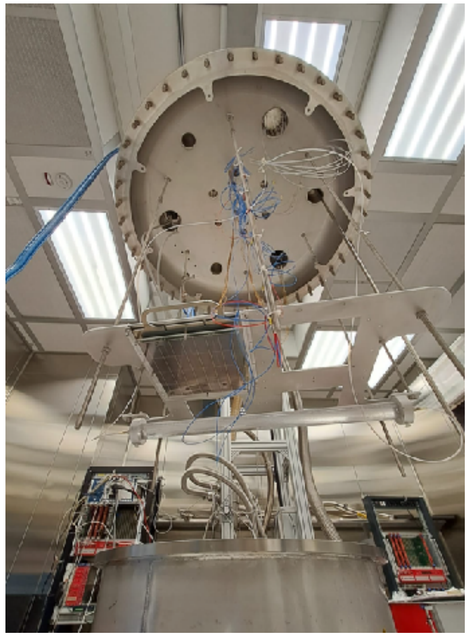
Four Stainless Steel (SS) support planes fixed on four SS tubes and locked with pins and blocking rings. Up to 16 PDUs (4 PDUs on each plane). PEEK adapters to avoid thermal connection with the top flange.

Laser illumination system integrated with mechanical structure: PMMA rod (ID 30mm) with 2 fibers (1 rod to illuminate 2 PDUs). Four floors, 4 rods, total of 16 fibers (CF100 flange with 16 single optical feedthroughs). Hamamatsu PLP10 laser 403 nm, fiber splitter 1-16.

Special shipping case for the PDUs delivery between NOA & Naples. Dedicated protocols for handling, packaging and transport.







PTF. Electronics

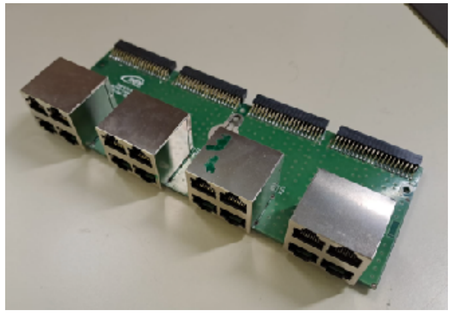
Signal readout chain

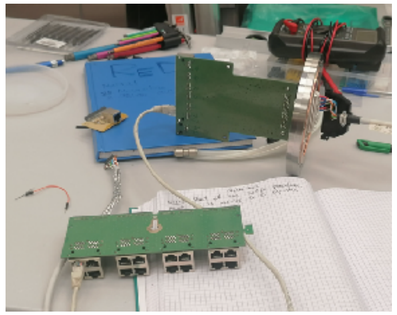
Warm side:

Two custom adapters & CAT6 ethernet cable with RJ45 connectors. One adapter is mounted on the Caen VX2740 ADC board, second is on the DB50 feedthrough (top flange). One cable - one PDU. Every board has 6 RJ45 connectors.

Cold side (inside the cryostat):

SAMI cables (8 weirs: 2 x channel) 2 m long (from the PDU to the feedthrough).





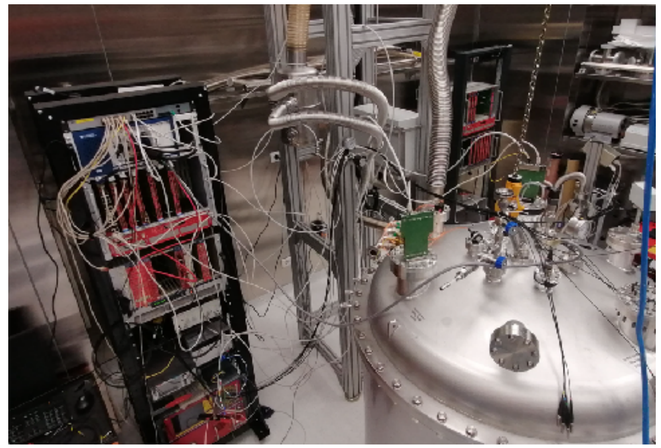

Powering scheme

Warm side:

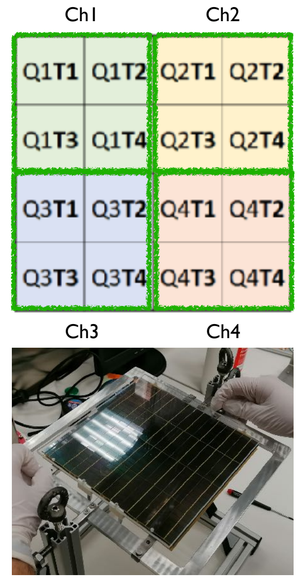
Custom Control Box to receive the LV & HV from the A2518 (7V) and A1619 (138V) Caen PS boards, filter and then deliver, through the micro-controller and standard CAT6 cable, to the adapter board mounted the DB50 feedthrough of the top flange (very similar to the signal readout adapter, identical feedthrough). One cable - one PDU, RJ45 interface between Control Box and adapter as for the signal. 1 board - 6 PDUs.

Cold side (inside the cryostat):

SAMI cables (8 weirs: LV, HV, Control, identification) 2 m long from the PDU to the feedthrough.



1st PDU. Test results



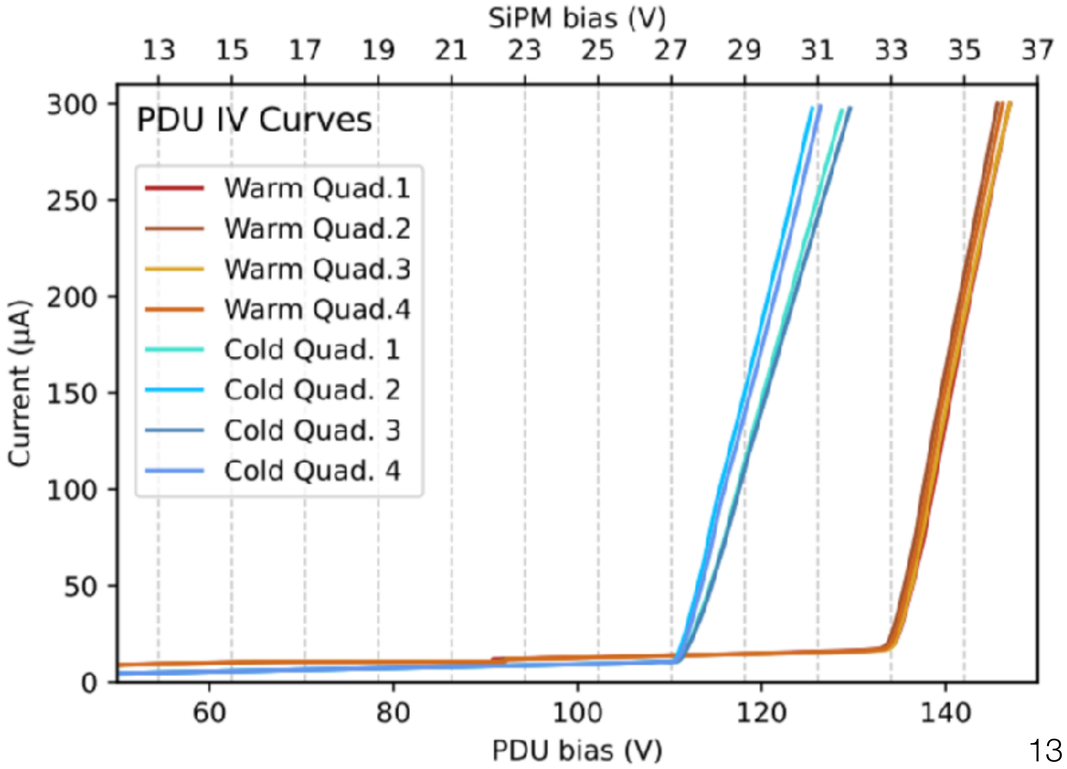
May - June of 2022: first intense LN testing campaign of fully populated PDU prototype (4 weeks).
Full characterisation in terms of: breakdown voltage, pulse shape of single photoelectron, response of single photoelectron, gain, charge, amplitude spectra and signal-to-noise ratio (on quadrant bases, 4 tiles summed). Stability of the PDU parameters in time, on a ~ month scale.

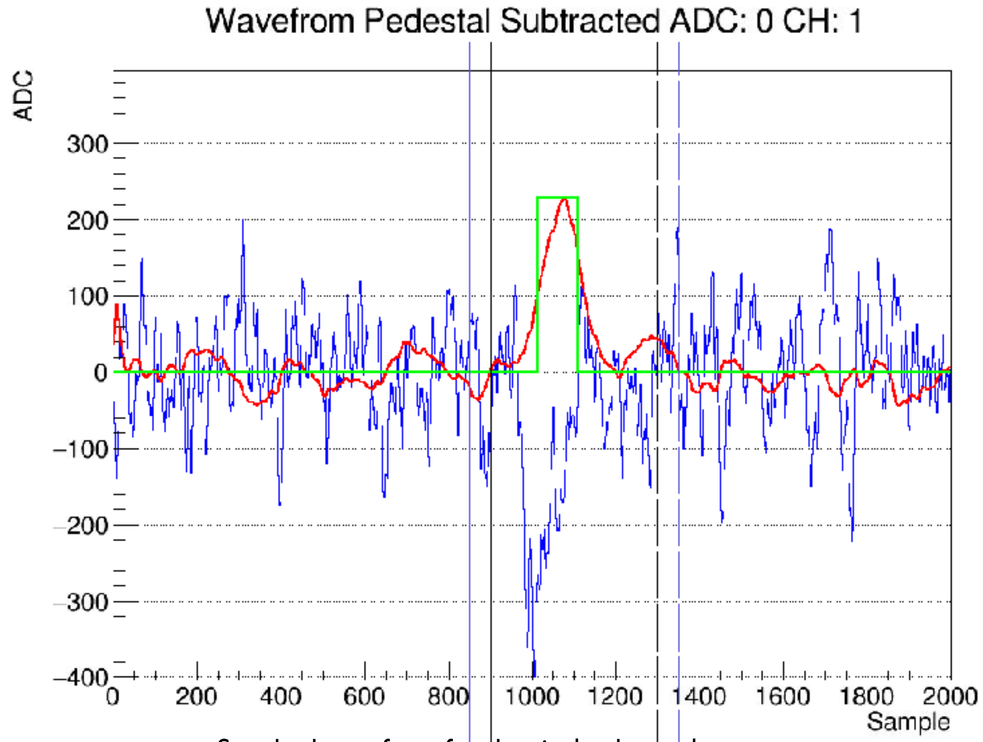
VX2740 ADC parameters: 16 bit @ 125 MS/s, 2Vpp → 1 sample = 8 ns , 1 ADC count = 0.0305 mV.

Laser calibrations runs and periodic trigger data. Acquisition window of 5 ms and 16 μs.

Operational voltages: V_{bias} 138.5V ((27V +7V)x4) & Low Voltage 7.0V.

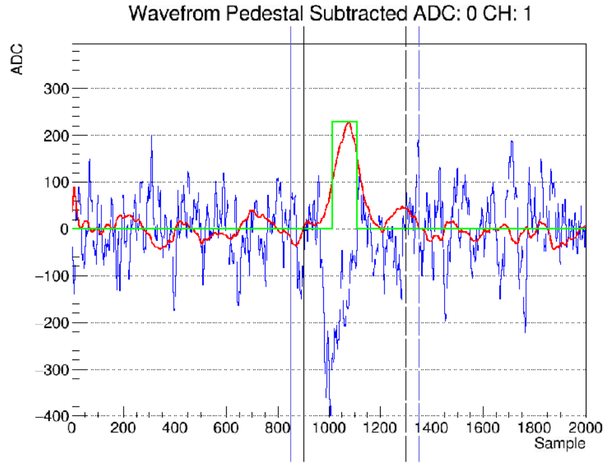
IV curves @ 290K / 77K.





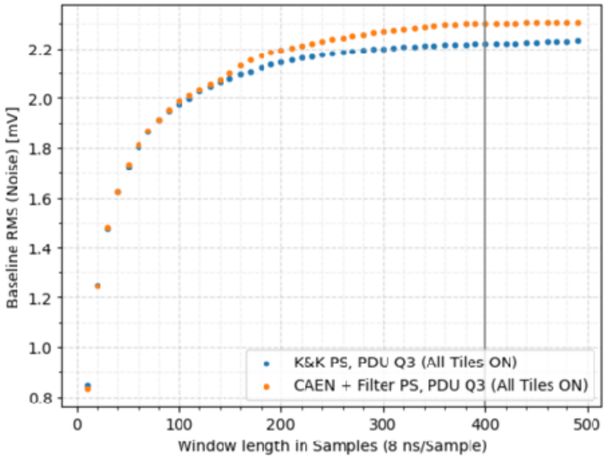
Standard waveform for the single photo electron event.
Pedestal subtracted

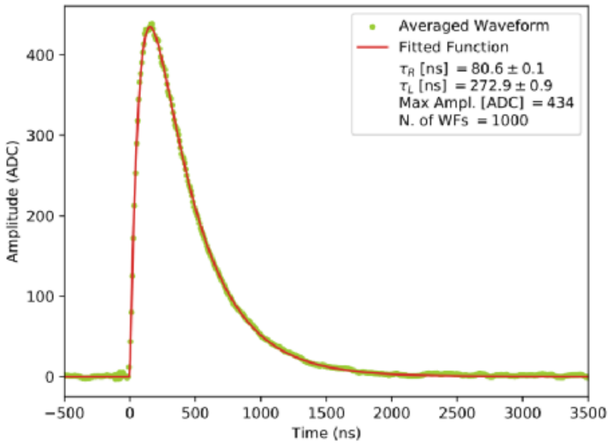
1st PDU. Test results

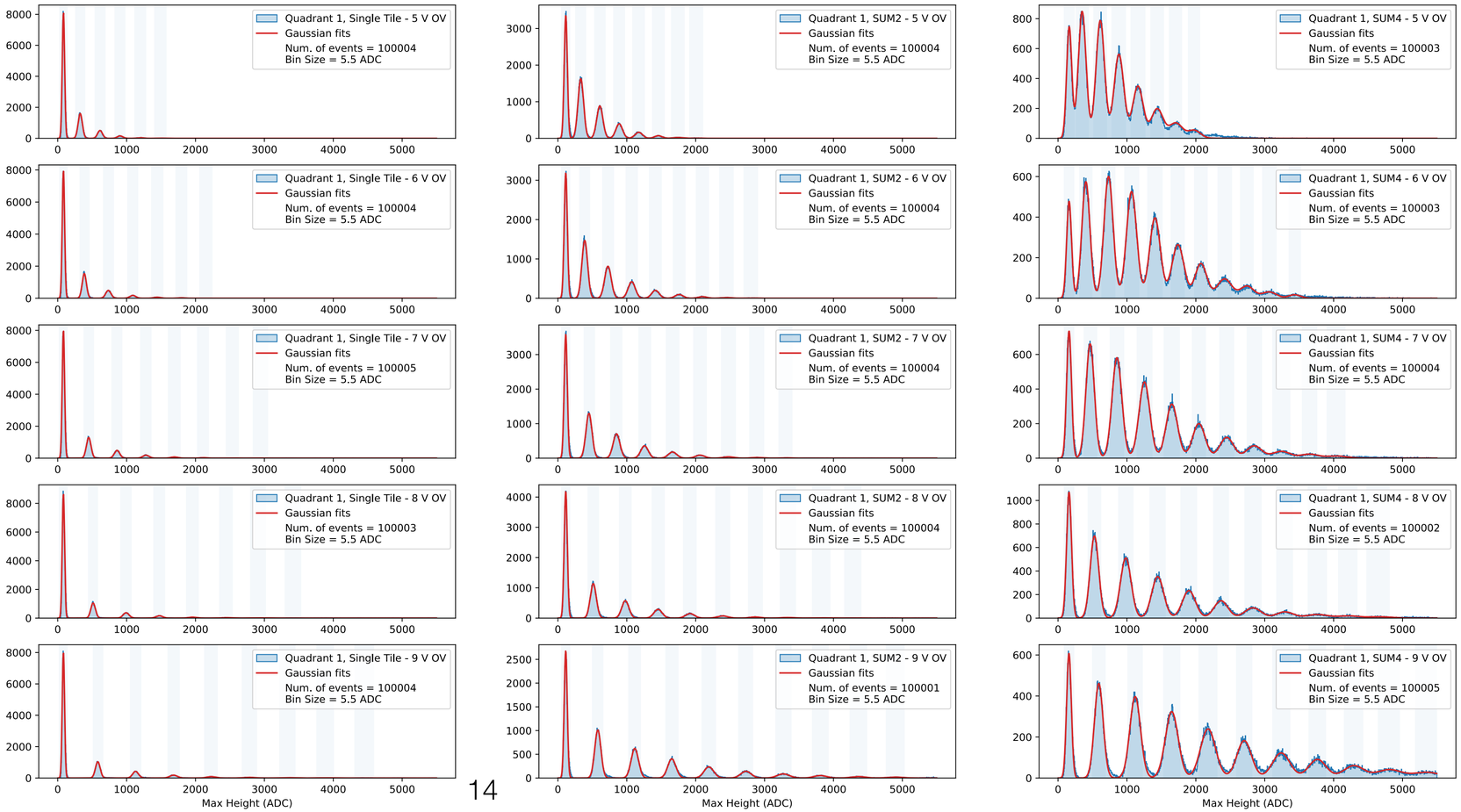


Raw data analysed with dedicated *dsanana* analysis tool. Baseline estimated over 400 samples (3.2μs of 16 μs). In Laser calibrations runs, the pulses are delivered with acrylic diffuser and acrylic bars that covers both PDUs.

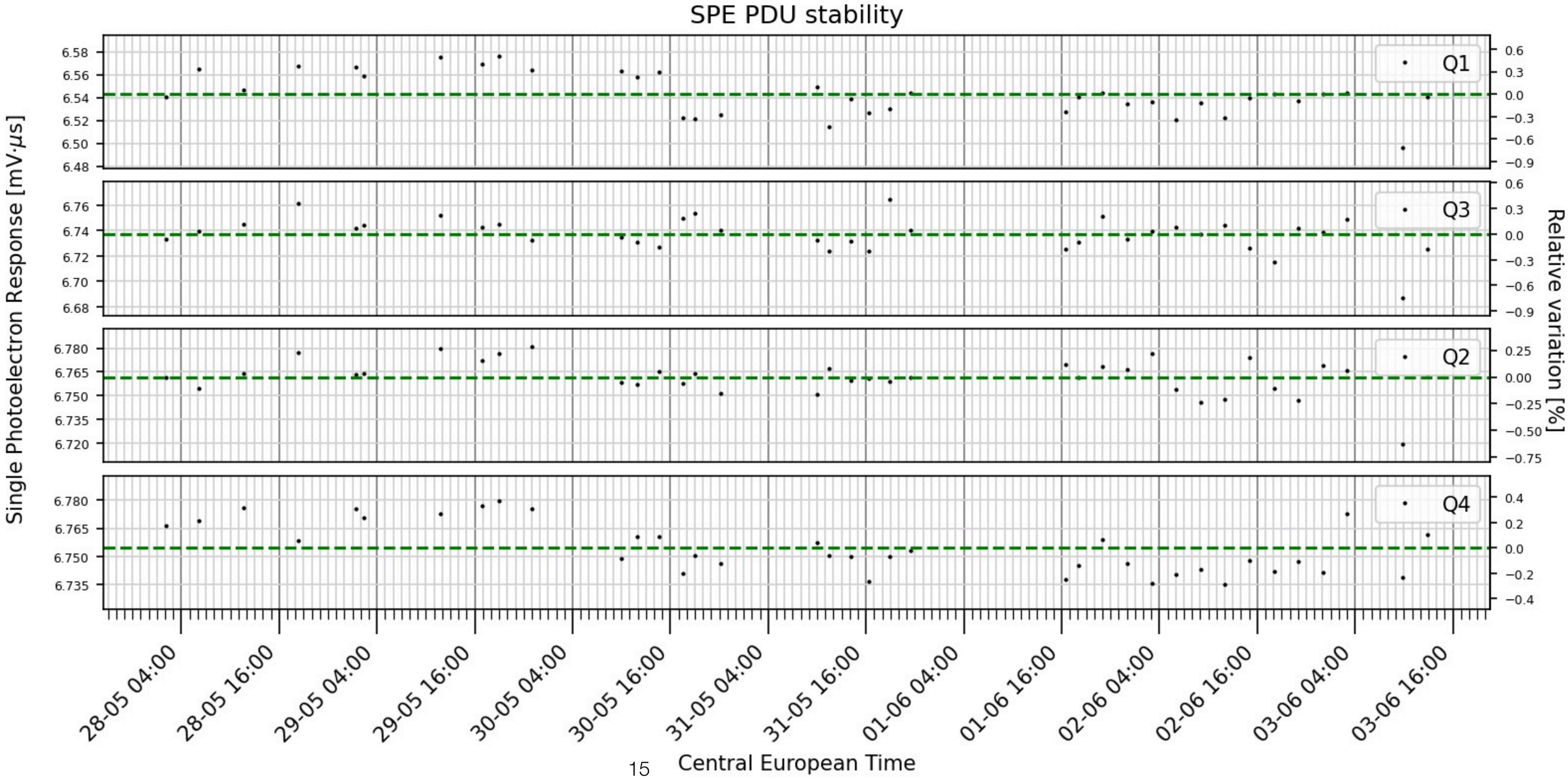
The SPE response as a function of tiles number: 1 tile, 2 tiles or 4 tiles together. Different values of OV: 5V - 9V. Nominal value is 7VOV. Resolution: σ_{1PE} / A_{1PE} : ~13 %.





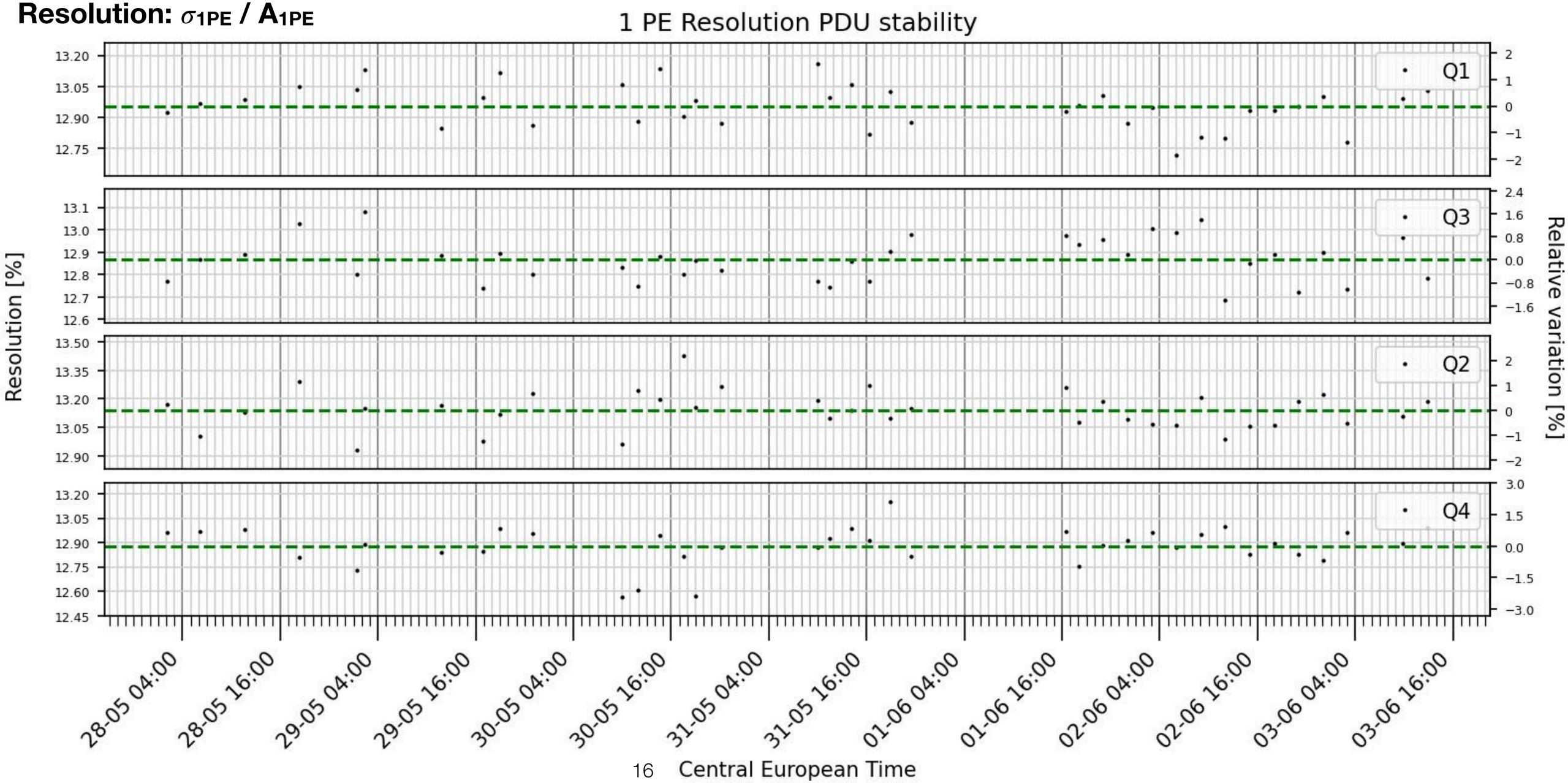


1st PDU. Test results



1st PDU. Test results

Resolution: σ_{1PE} / A_{1PE}

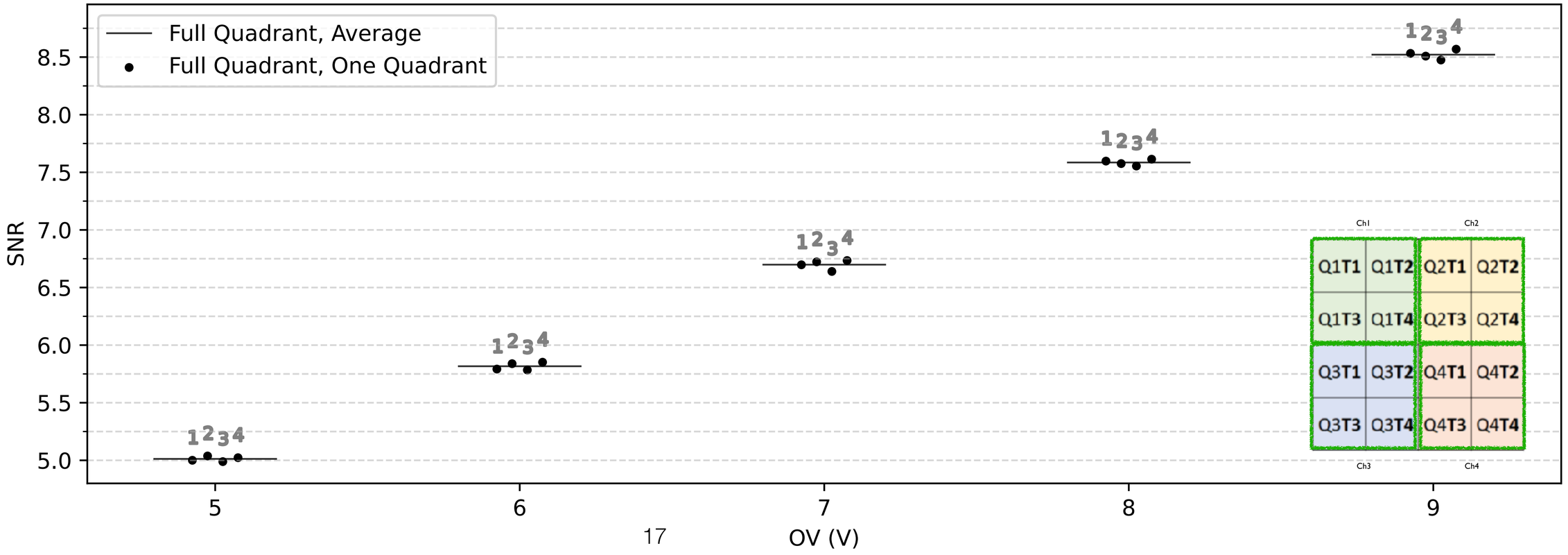


1st PDU. Test results

Raw SNR for all quadrants, in range from 5 (@5V VOV) to 8.5 (@9V VOV).

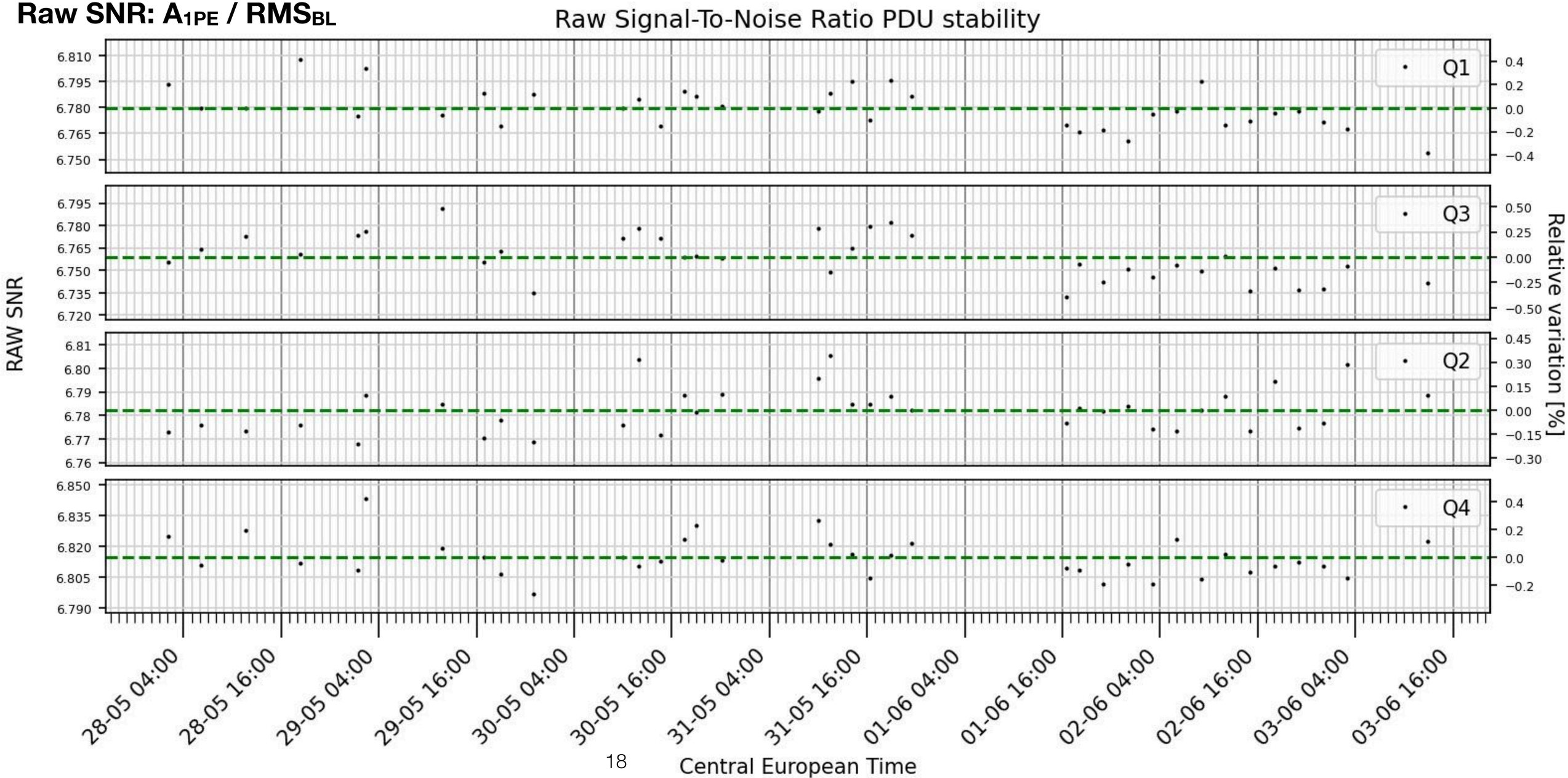
Raw SNR: A_{1PE} / RMS_{BL}: ~7.

Naples, November Data Campaign (SiPM Bias 34 V)						
	Tile			SUM x4		
	K&K	CAEN Filtered	CAEN No Filter	K&K	CAEN Filtered	CAEN No Filter
Raw SNR	13.1	12.9	12.8	6.7	6.6	6.7



1st PDU. Test results

Raw SNR: A_{1PE} / RMS_{BL}

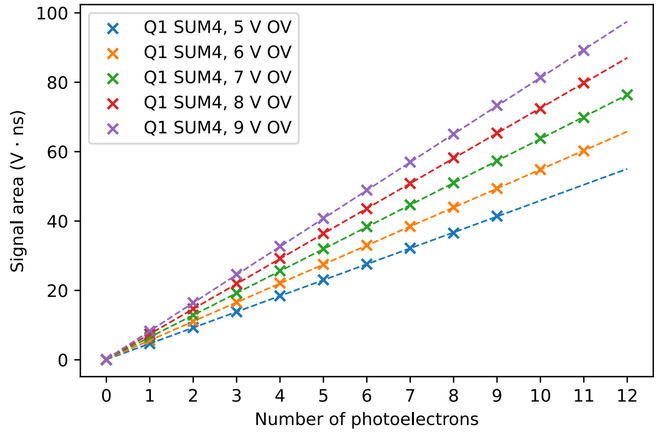


1st PDU. Test results

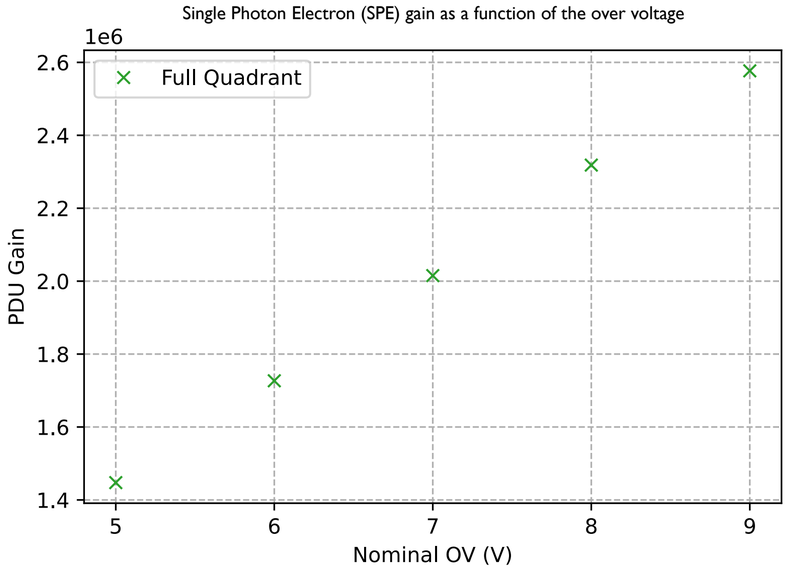
Gain evaluation based on voltage variation associated with 1PE signal (result of the conversion of the current produced by the SiPM in response to the trapped photoelectron, done by the cold TransImpedance cold Amplifier TIA); feedback resistance and the elementary charge.

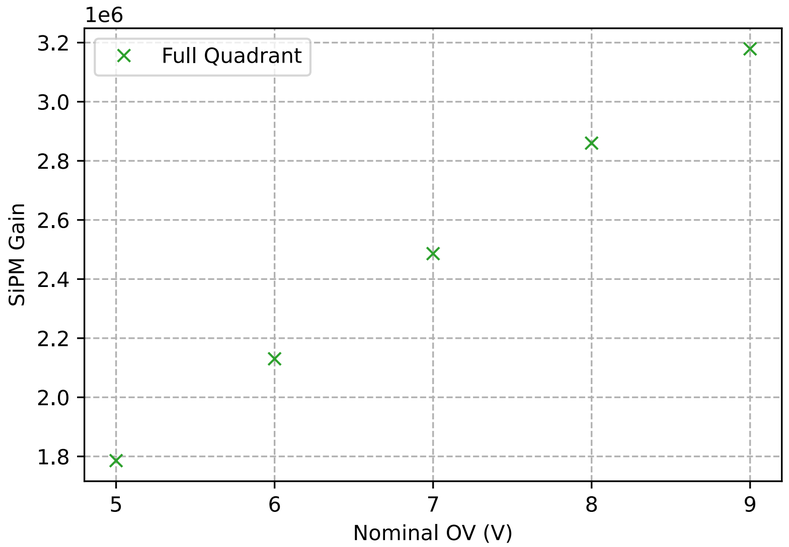
$$G_{\mathrm{PDU}} = \frac{1}{R_{\mathrm{TIA}}}\frac{1}{e}\int_{1\ \mathrm{PE}} v(t)\,dt \qquad G_{PDU} = A \cdot \frac{1}{2}\int_{1PE} i(t)dt = A \cdot G$$

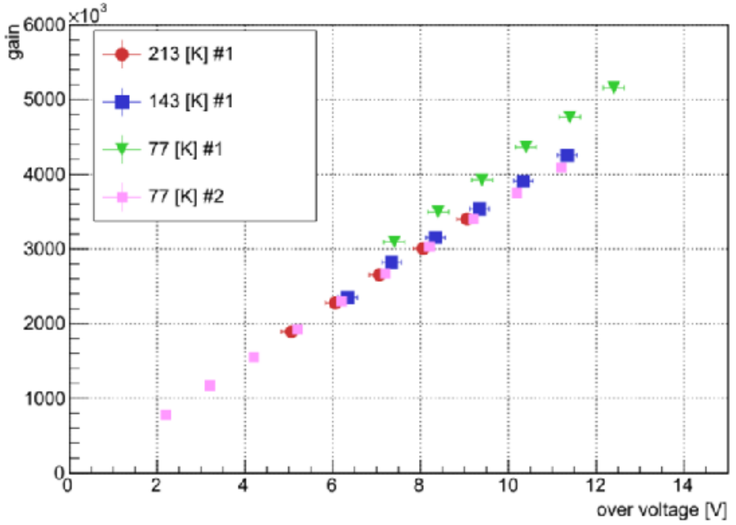
$$G_{PDU} = 2.0 \times 10^6$$
$$G = 2.6 \times 10^6$$



Estimation of the absolute gain considering value of a constant A of ~0.81. Obtained value for 7VOV is in good agreement with previous measurements performed with single SiPM by colleagues from TRIUMF and LNGS.







Thank you!