Qualification of Photo Detector Units for the DarkSide-20k experiment in the Napoli Test Facility

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DARKSIDE

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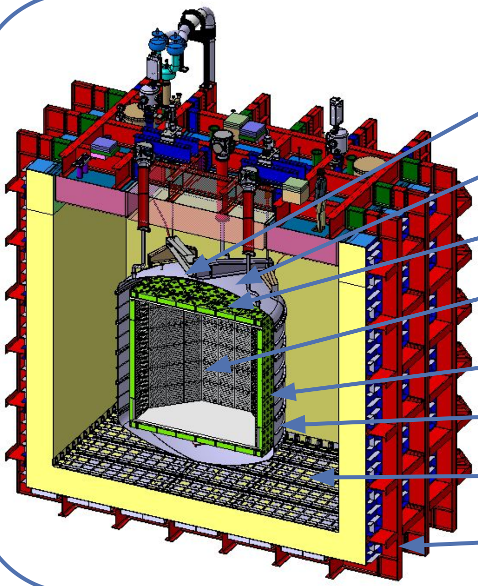
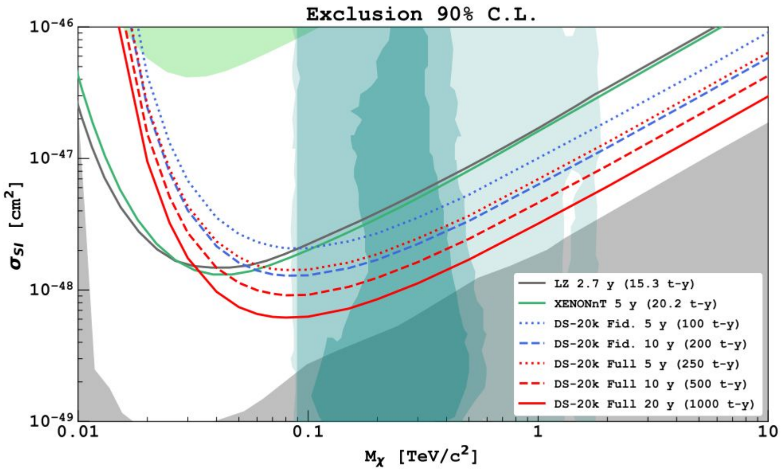
The DarkSide-20k experiment

- Dark matter direct detection experiment hosted at LNGS, Italy
- Dual-phase TPC containing 50t low-radioactivity underground Argon (UAr)
- 21 m^2 instrumented with custom designed SiPM-based light detectors
- Aims for 0.1 background event in 200 t yr exposure → world leading sensitivity





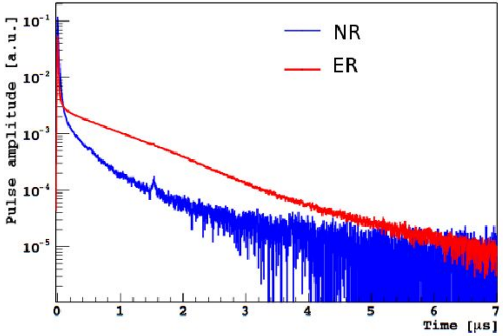
Dark matter interactions in DarkSide-20k

Particles interacting in a dual phase TPC produce two light pulses:

- **S1:** light produced in the liquid argon due to excitation and ionisation.
- **S2:** light produced in the gaseous argon pocket due to recombination of ionisation electrons drifted by an E field.

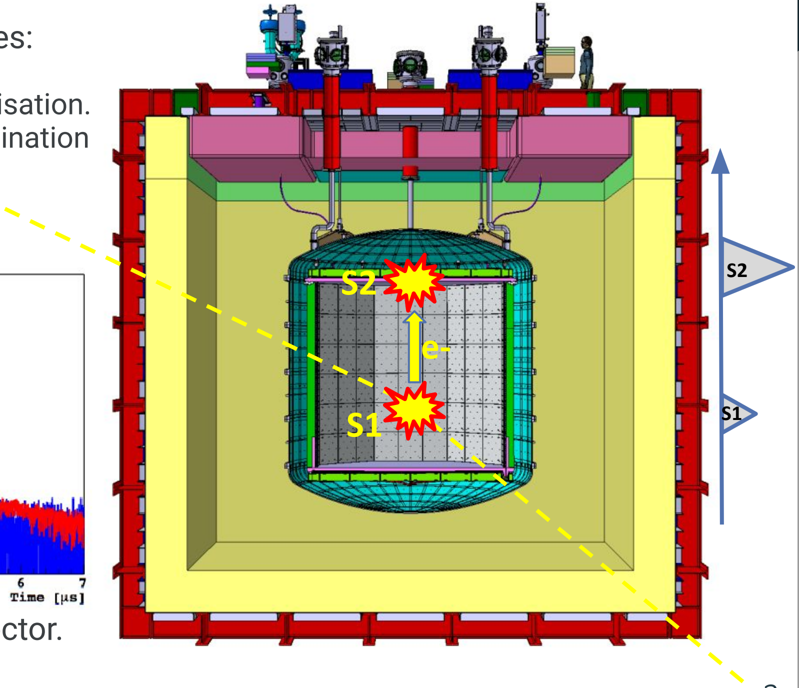
2 excited Ar_2^* states with different lifetimes:

- singlet (~6 ns)
- triplet (~1.6 μs)

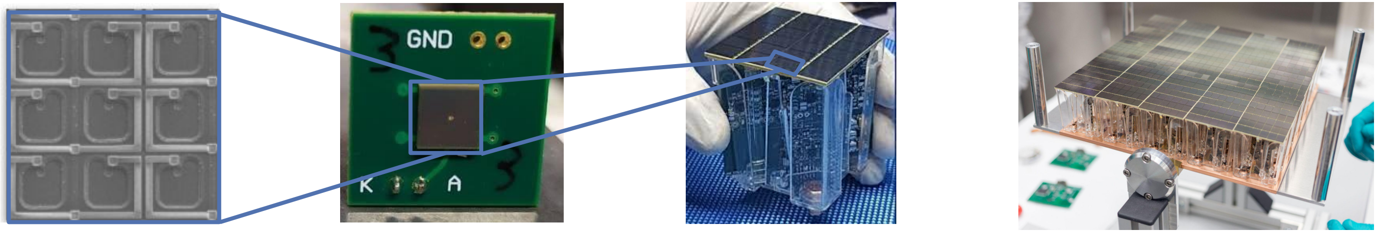


ER/NR events have different ionisation densities → different fractions of singlet/triplet decays.

DS-20k plans to group ~249,000 SiPMs into ~650 photo detector units (PDUs) to detect light from particle interactions in the detector.



SPADs → SiPMs → PDMs → PDUs



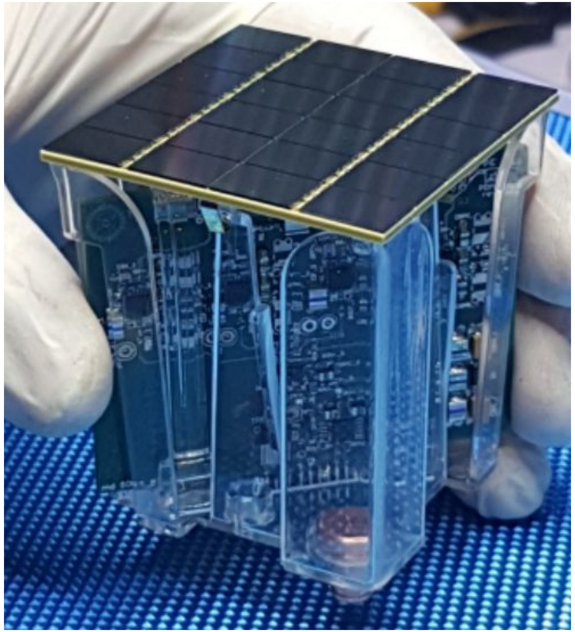
SPADs - Single Photon Avalanche Diodes: semiconductor devices based on a p-n junction reverse biased well above breakdown voltage (operating in Gieger mode).

SiPMs - Silicon Photomultipliers: A single SiPM consists of ~94,900 SPADs. 24 SiPMs are grouped into tile (with an area of 25 cm^2).

PDM tile- Photo Detector Module: The SiPM tile is combined with the front end board electronics to make a PDM. The signals from all SiPMs on the PDM are summed and read out as a single channel.

PDU - Photo Detector Unit: 25 (or 16) PDMs are grouped into a single PDU [arXiv:2201.04615].

Why use PDMs?



The 25 cm^2 PDMs will replace typical 3” PMTs in DS-20k, but:

- can be operated at a higher gain relative to PMTs
- have a high radio-purity (typically dominated by electronics)
- have a high photo detection efficiency (~45%)
- have a low noise rate at LAr temperature

These factors make PDMs ideal for use in LAr direct detection dark matter experiments such as DarkSide-20k.

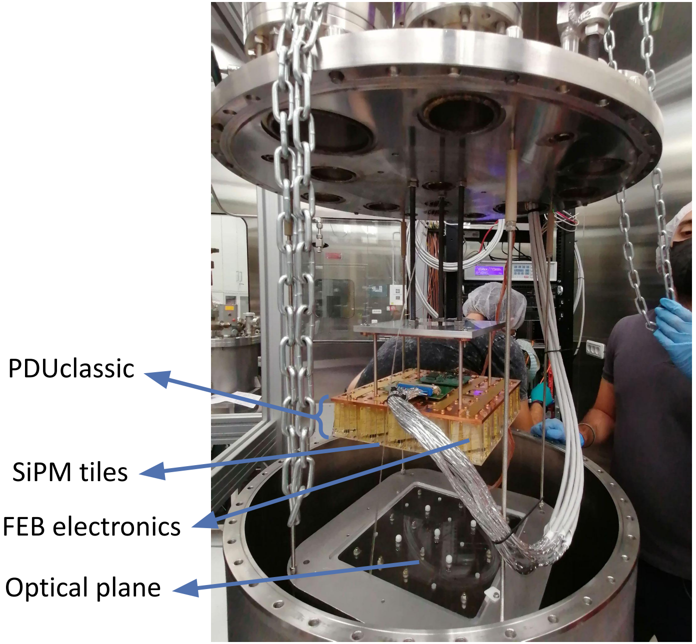
PDU qualification in the Napoli Test Facility

The Napoli Test Facility is an ISO class 6 cleanroom which contains the PDU test facility. This facility was designed specifically for the cryogenic testing (in liquid nitrogen) of the DarkSide-20k PDUs.

Total # PDUs to be produced: ~650

Napoli test facility target testing rate: 12 PDUs / week

Hardware and DAQ



The DarkSide collaboration has worked with FBK to develop custom SiPM technology optimised for LAr temperatures . Different tile manufacturing processes were considered, and industrial production with LFoundry has begun.

In the NTF, we conducted a 10 week cold test of a single PDU (containing SiPMs with three different backside metallisations). We configure the DAQ as desired, by defining:

- the acquisition window (typically use a 20 µs window)
- the trigger threshold (typically use 0.7 PE)
- the type of run (laser or self-trigger)
- the laser intensity/frequency (typically use 100 Hz)

PDU qualification - what do we consider?

Quantity	Requirement
Breakdown voltage	26.8 +/- 0.2 V
SiPM response - recharge time	300 - 600 ns
Single Photoelectron (SPE) spectra	distinct PE
Gain	stable gain
Signal to noise ratio (SNR)	> 8
Dark count rate (DCR)	< 0.01 Hz/mm^2 (7 Vov) < 0.1 Hz/mm^2 (9 Vov)
Internal cross talk (CT) probability	< 33 % (7 Vov) < 50 % (9 Vov)
Afterpulsing (AP) probability	< 10 %

multiple SiPMs readout in a single channel (PDM)

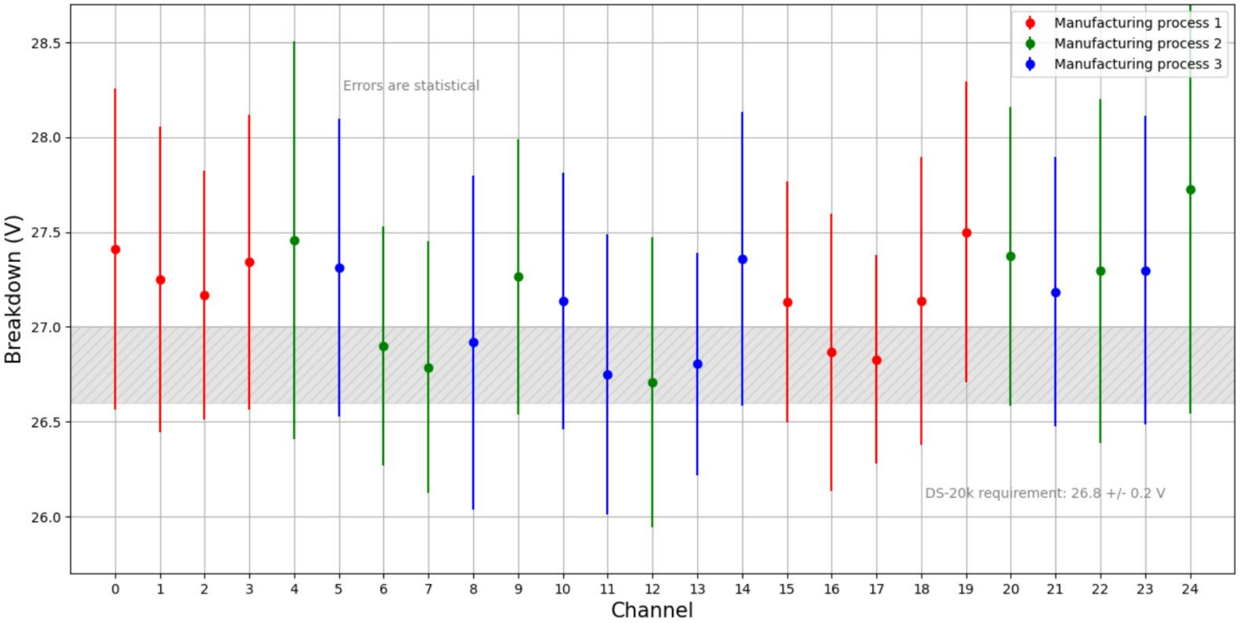
correctly model SiPM response for high-level analysis

inspect spectra for irregularities (non uniform gain, anomalous CT, etc.)

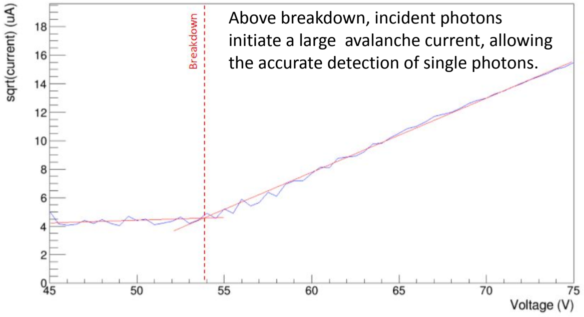
correctly understand the charge each incident PE creates

aim to minimise noise sources (and maximise signal) to increase PSD power and detection potential

IV curves - extracting breakdown voltage (V_{bd})



DS-20k acceptance criteria highlighted: **all PDMs** across all tile manufacturing processes **meet the requirement within errors.**



Data reconstruction

Baseline: find the average waveform over X samples (150 sample pretrigger window).

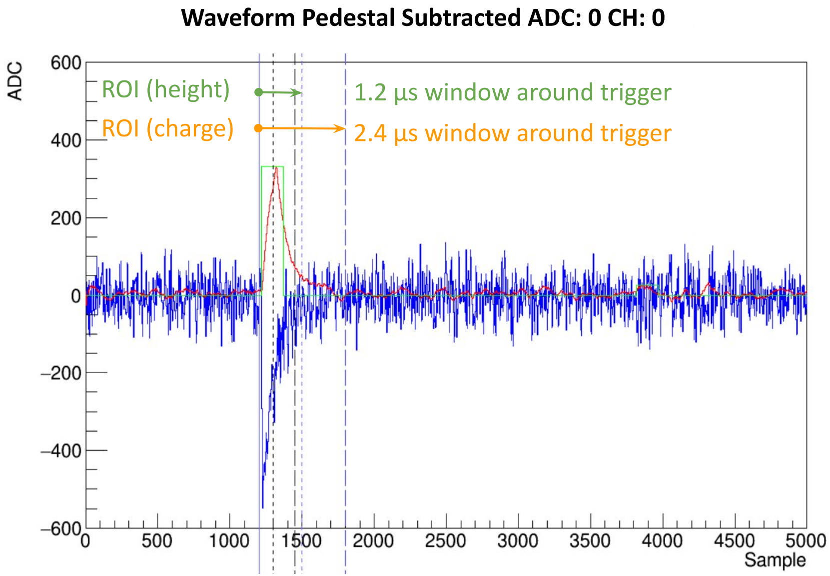
Baseline subtraction: subtract the baseline from the entire waveform, resulting in a zero centered waveform (seen in blue).

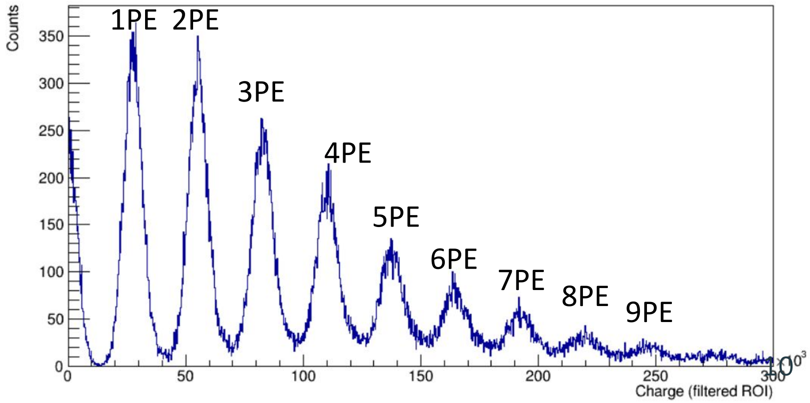
Waveform filtering: use an Auto Recursive Moving Average (ARMA) filter (100 sample window) to filter and invert the waveform (seen in red).

Two key reconstruction parameters are:

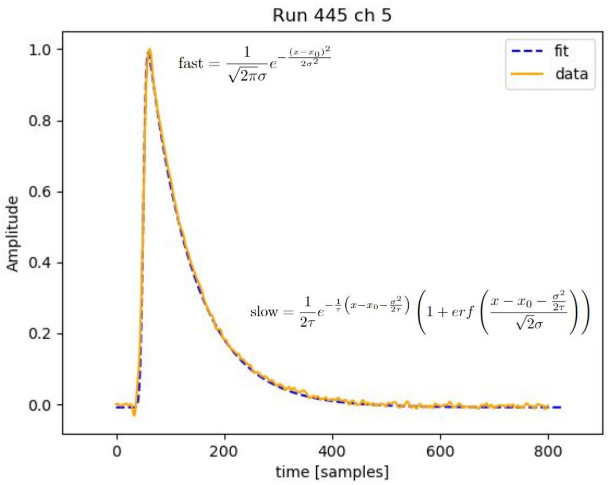
- **Height:** maximum amplitude of filtered waveform in given region.
- **Charge:** integral of pulse in filtered waveform in given region.

For both quantities, we consider only the region of interest (ROI) shown. Single photoelectron (SPE) spectrum demonstrates resolution obtained by SiPMs.



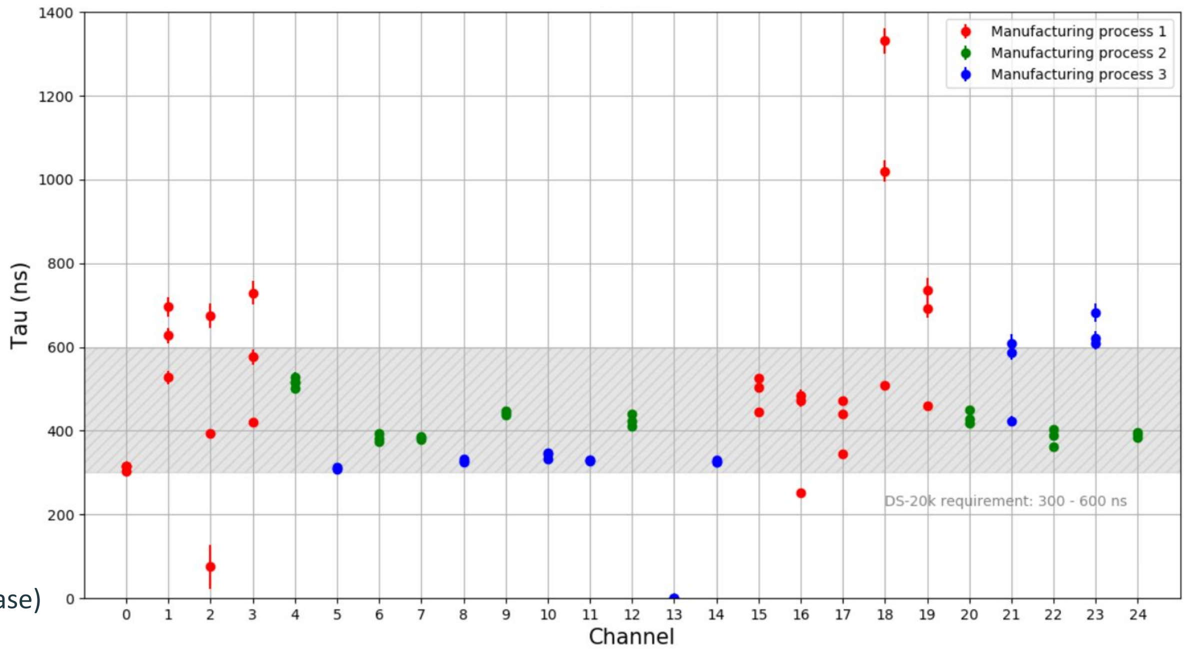


SiPM response - signal shape



Typical SiPM response contains:

- a prompt component (SiPM discharge phase)
- a slow component (SiPM recharge phase)



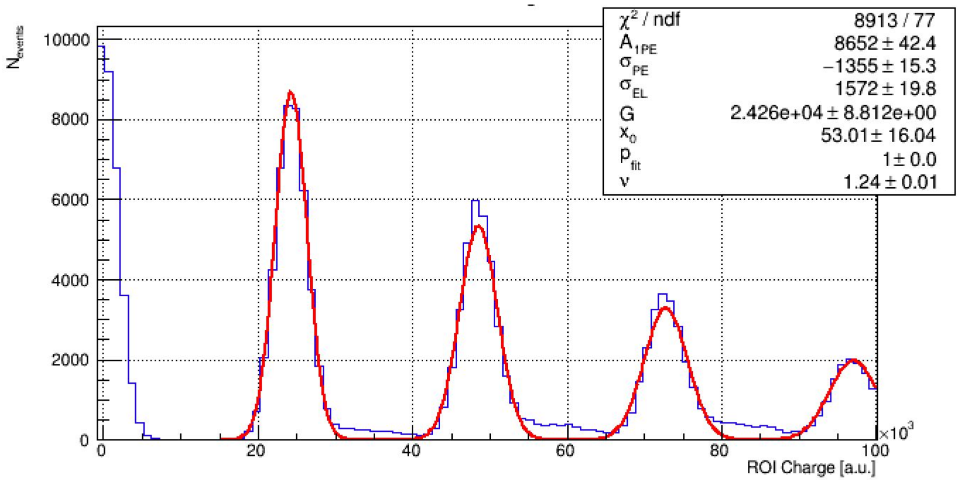
Stability of signal shape was key criteria used to select final SiPM technology

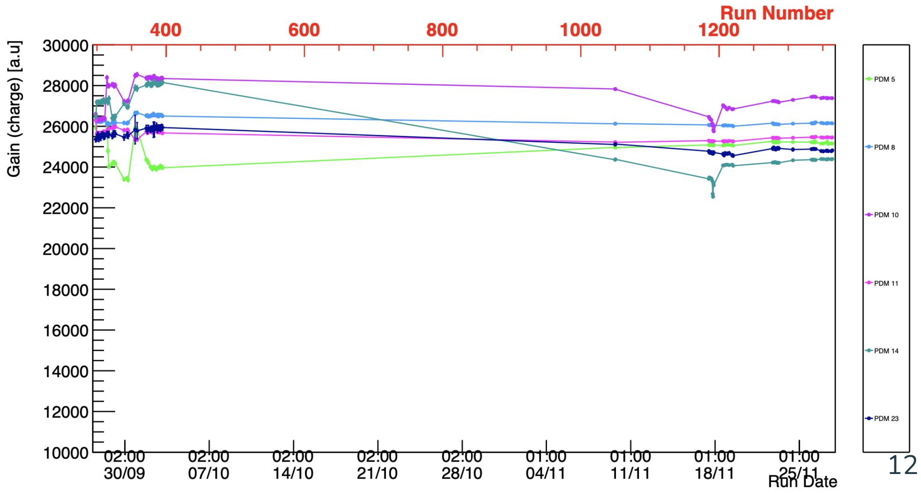
Gain

SiPM gain: charge released by a SPAD after absorbing a photon. We calculate the gain by:

- fitting SPE spectra with Vinogradov model [arXiv:1109.2014]
- extracting the average charge of each PE peak
- plotting the average charge value of each PE peak against the corresponding number of PE.
- fitting this distribution with a linear function in order to extract the gain.

We monitor the stability of the gain over 8 weeks, shown for PDMs containing one type of SiPM backside metallisation.





DS-20k requirement: SNR > 8

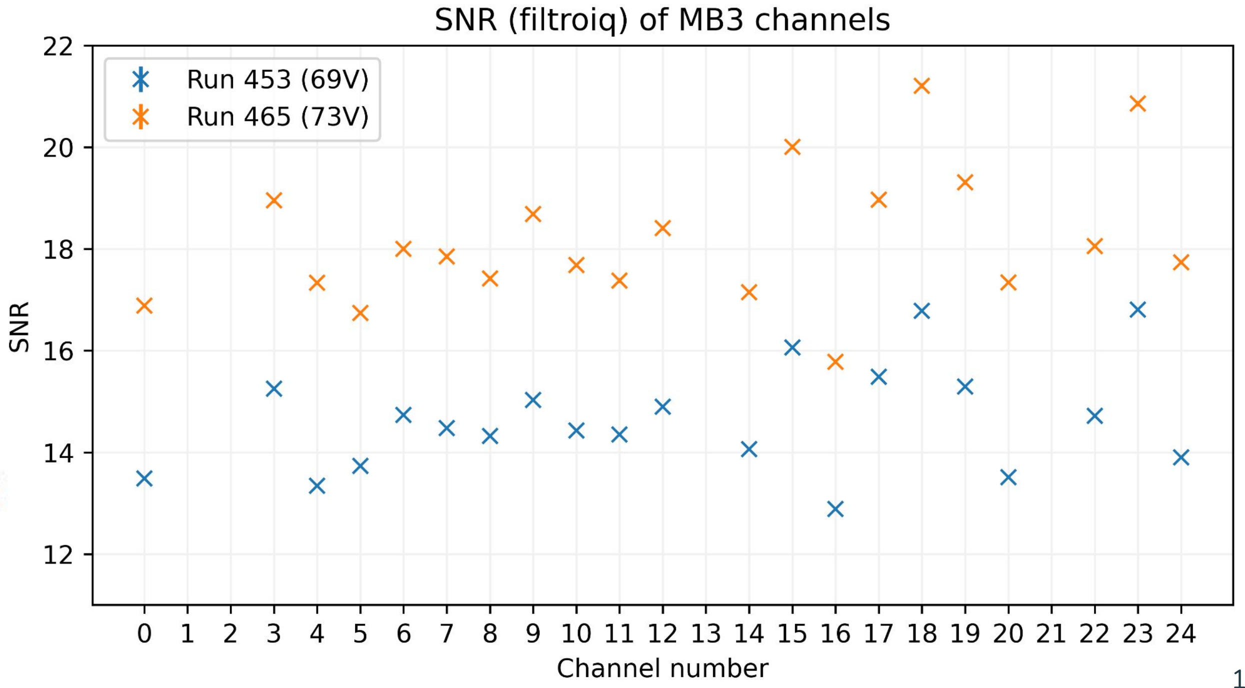
Signal to Noise ratio - SNR

Measure of the size of a single PE response compared to the size of the background noise.

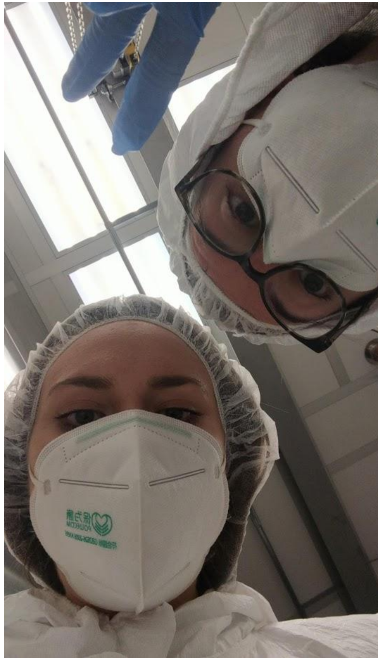
We define noise as the RMS of the baseline (calculated in X sample pre-trigger window).

$$\mathrm{SNR} = \frac{\text{mean of 1PE peak}}{\text{mean of the baseline RMS}}$$

All PDMs meet requirement.



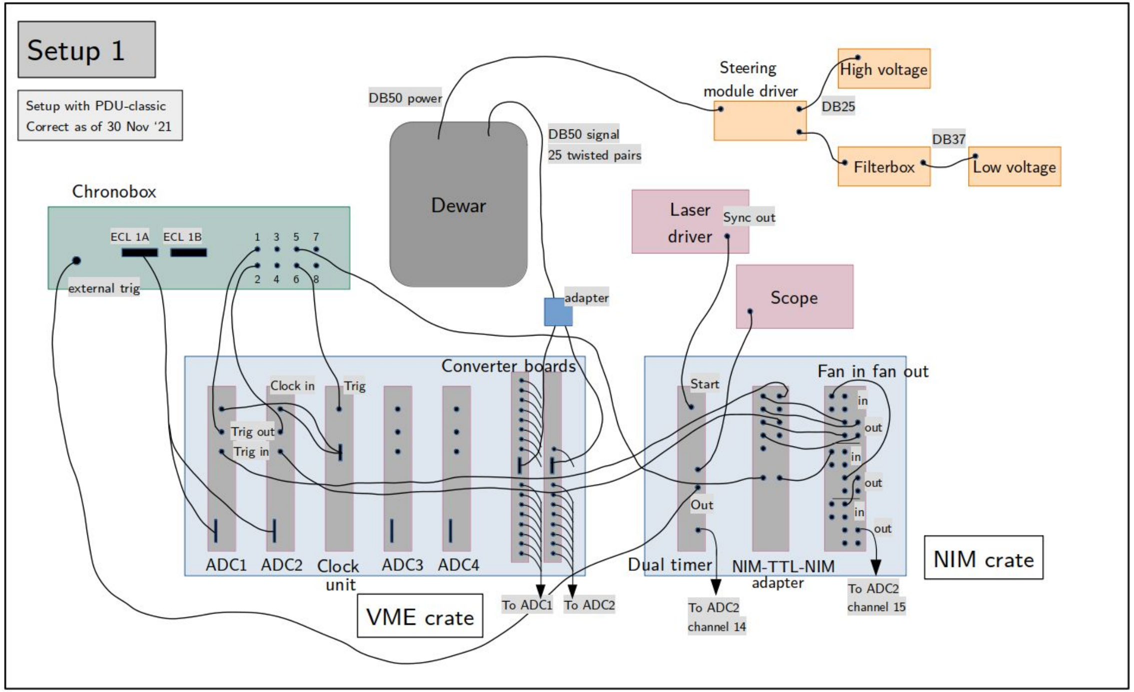
Conclusions



- The Napoli Test Facility's cryogenic and DAQ systems are now successfully commissioned, and we are providing the DarkSide collaboration with the environment to perform the longest cold tests to date.
- Quantities monitored demonstrate that the PDUs meet production criteria, and industrial production has begun.
- SiPM stability has been monitored, showing a promising future for dark matter experiments using SiPM technology.
- Veto PDU production is beginning in the UK, with plans to test the PDUs in the NTF this summer, before ramping up to full production-scale testing.

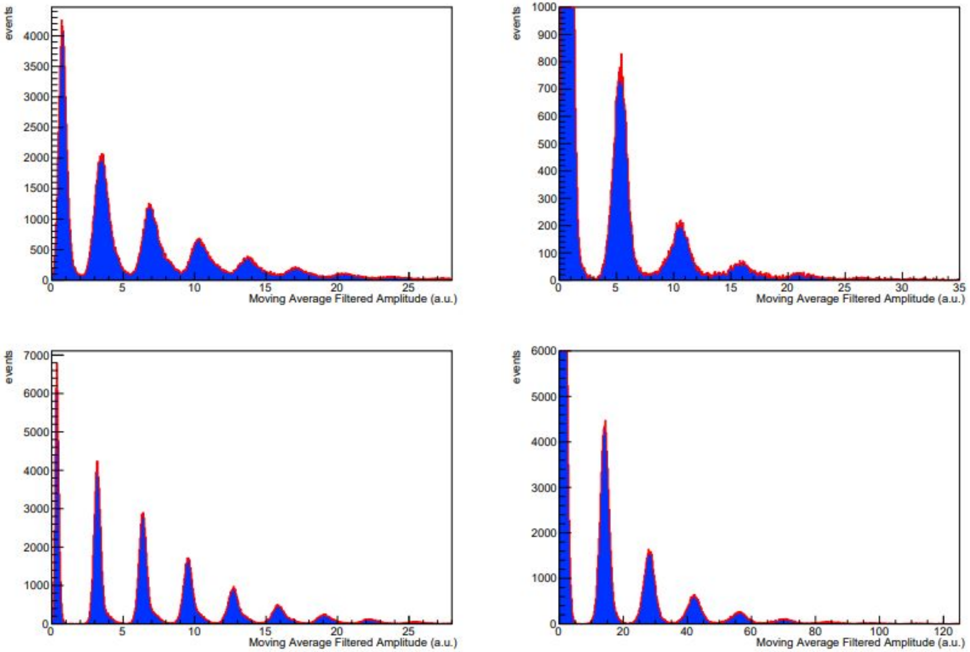
Back up

Hardware

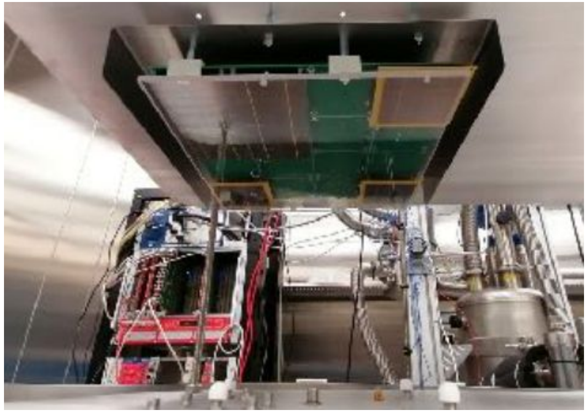


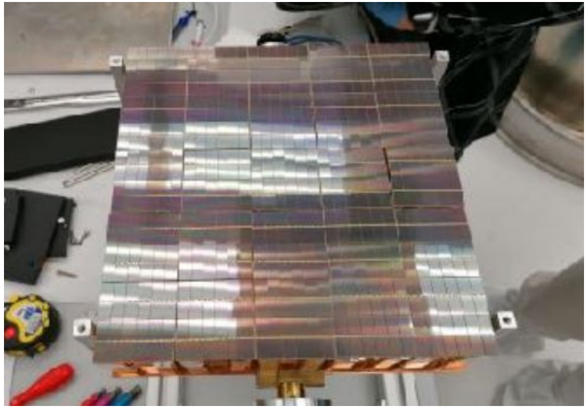
Setup 1
Setup with PDU-classic
Correct as of 30 Nov '21
Chronobox
ECL 1A
ECL 1B
1 3 5 7
2 4 6 8
external trig
DB50 power
Dewar
DB50 signal
25 twisted pairs
adapter
Steering
module driver
DB25
High voltage
DB37
Filterbox
Low voltage
Laser
driver
Sync out
Scope
Converter boards
Clock in
Trig
Trig out
Trig in
ADC1
ADC2
Clock
unit
ADC3
ADC4
VME crate
To ADC1
To ADC2
Fan in fan out
Start
in
out
Out
Dual timer
NIM-TTL-NIM
adapter
NIM crate
To ADC2
channel 14
To ADC2
channel 15

PDUclassic vs PDU+



operated at 7VOV. **Top left:** PDU+ with 4 Tile+ summed (SNR=8.5); **Top right:** PDUSlim with 2 Tiles summed (SNR=13); **Bottom left:** PDU+ with only 1 Tile+ (SNR=16); **Bottom right:** MB3 typical channel (SNR=19),





DS-20k requirement: DCR < 0.01 Hz/mm^2 (7 Vov)
DCR < 0.1 Hz/mm^2 (9 Vov)

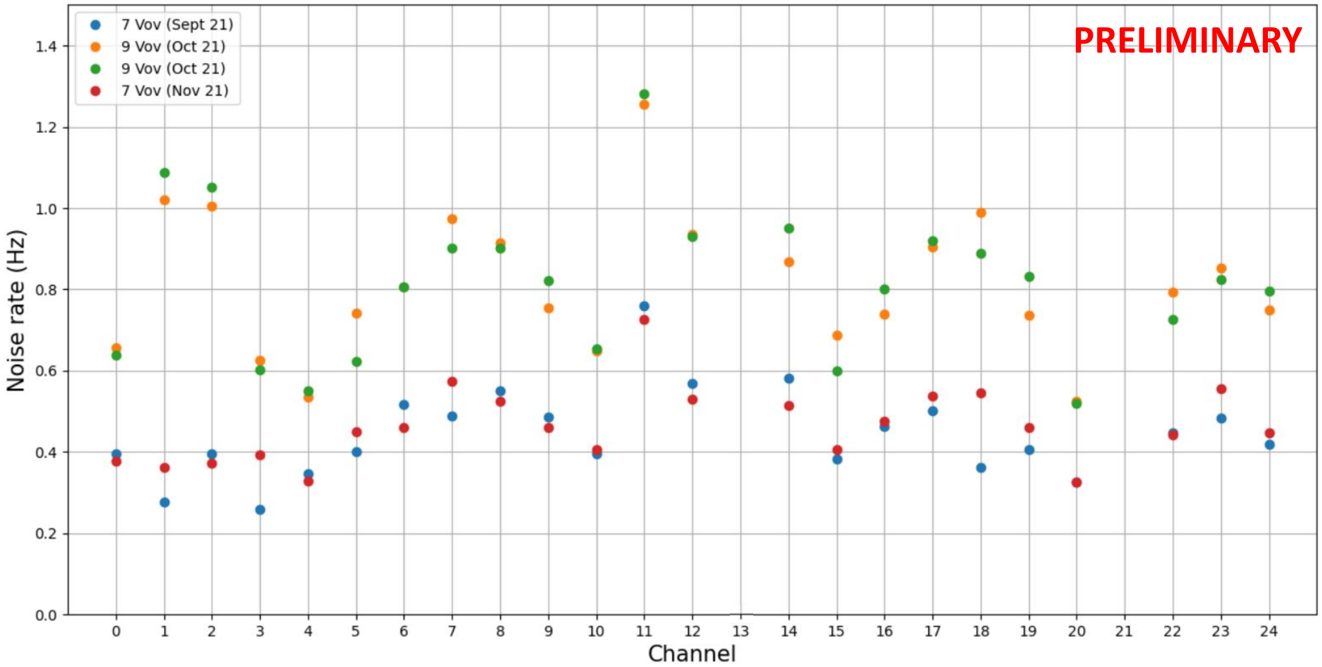
Random noise rate

DCR: an intrinsic uncorrelated SiPM noise (average number of incident photons detected with no incident light). We:

- eliminate all external light
- consider a 4 µs pre-trigger region
- require amplitude of any pulses found > 0.7 * 1PE

$$DCR = \frac{\text{Number of found pulses}}{\text{Total number of pulses} \times \text{time}}$$

Most channels show rates ~0.4 Hz/mm^2 at 7 Vov. **Note: this rate includes DCR, AP & eCT → when accounting for the other noise probabilities, DCR meets the DS-20k requirements.**



Vinogradov model

$$f_N(\mu, \lambda) = \frac{\mu(\mu + \lambda \cdot k)^{k-1} \cdot e^{(-\mu - k \cdot \lambda)}}{k!},$$

- On average, SiPM response to excitation by a primary photon corresponds to the measurement of > 1 PE (due to AP/CT).
- P(detect N PE) != strictly Poisson, so use Vinogradov model instead
- μ = mean number of primary PE
- λ = probability of primary PE to induce secondary emission

$$K_{dup} = \frac{\lambda}{1-\lambda}$$

- K_dup represents the total number of PE detected for each primary photon to induce excitation in the SiPM