A SiPM based cryogenic Photo Detector Module for dark matter searches

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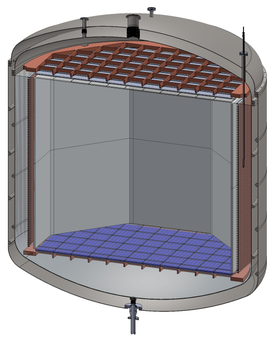
The Darkside-20k experiment will use Silicon PhotoMultipliers as sensitive detectors. After a long and successful R&D, excellent results have been obtained, fully matching the specifications required by a background-free 20t liquid argon experiment for direct WIMP search. Darkside-20k foresees to use more than 125,000 SiPMs, grouped in 5210, 25 cm² tiles. A clever cold electronics has been developed to read out this large SiPM area to reduce the number of channels while keeping the SNR above the minimum required. The Photo Detector Module (PDM) is the Darkside basic unit. It is made of a SiPM tile, a Front End Board (FEB) and an acrylic mechanical structure. Preliminary results on the first produced PDM indicate a sensitivity to the single photoelectron and an outstanding performance in terms of Signal-to-Noise ratio (SNR).

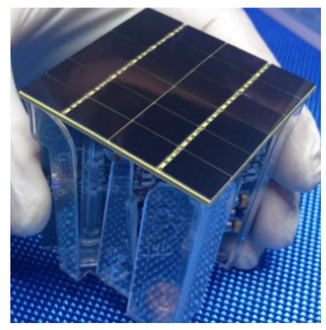
DarkSide-20k



DarkSide-20k is a Liquid Argon Time Projection Chamber aiming at the discovery of WIMP dark matter. The scintillation light produced by interactions in the active volume will be detected by 5210 25 cm² PDMs on the top and bottom planes of the detector, covering a total area of 14 m². The PDMs are sensitive at the level of single photon, they work at LAr temperature and have an area of 25 cm².

The PhotoDetector Module

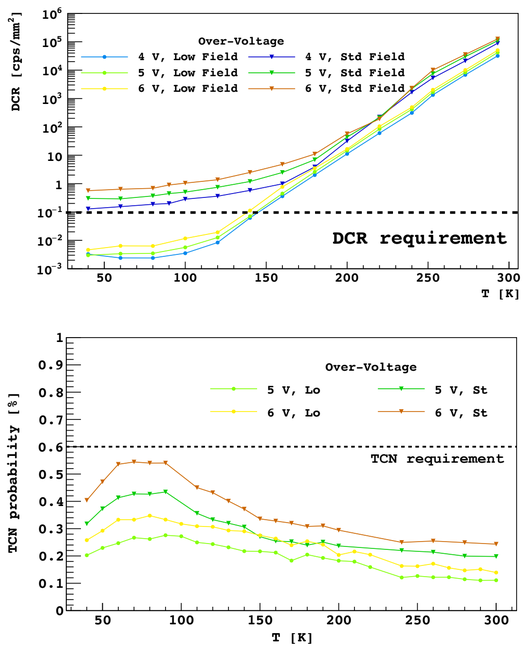
The PDM is the silicon-based equivalent of the PMT. In each PDM, 24 SiPMs (a *tile*) of size 1 cm² are read out as a single analog channel. The PDM integrates the tile and a specifically developed cryogenic electronics into a plastic cage. To be used in DarkSide-20k, the PDM must satisfy a stringent set of requirements, according to the experiment goals, for which an intense R&D has been carried out by the collaboration.



PDM Requirements

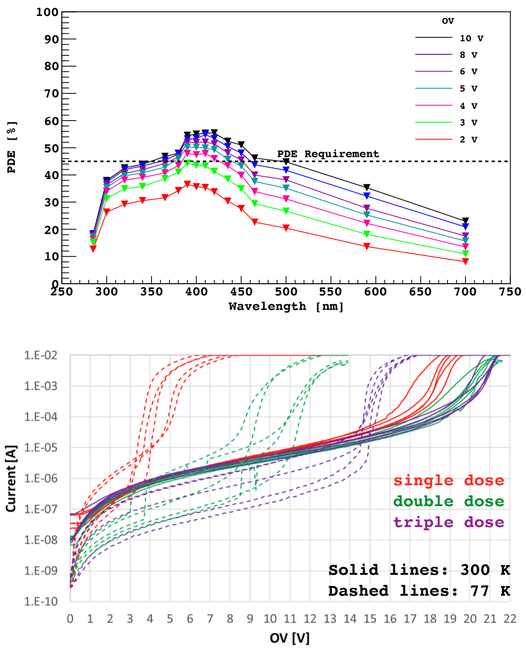
- Dark Count Rate (DCR) < 0.1 Hz/mm² to keep Pulse Shape Discrimination (PSD) effective.
- Total Correlated Noise Probability (TCNP) < 60% for energy reconstruction of S2 signals.
- Photon Detection Efficiency (PDE) of a PDM > 40%. Considering a dead space between SiPMs of 0.5 mm, the PDE of a SiPM is required to be > 45%.
- SNR > 7 to maintain high detection efficiency and avoid fake triggers.
- Timing resolution of O(10 ns) to keep PSD effective.
- Dynamic range > 50 PE for energy reconstruction of S2 signals.
- Power consumption < 250 mW to avoid LAr bubbling.
- Radiopurity at fraction of mBq (^{238}U + ^{232}Th) level.

SiPMs



Strong collaboration with FBK allowed many SiPM variants to be tested **[1,2]**. NUV-HD Low Field technology shows a DCR < 10 mHz/mm² at LAr temperature and TCNP well within the required limits. PDE is peaked at 420 nm and is above 50% at 5 V of over-voltage.

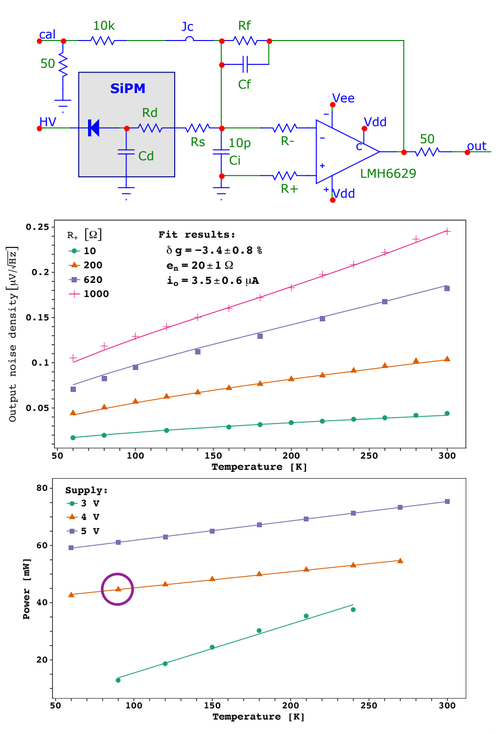
FBK also developed a NUV-HD variant with increased doping levels that shows reduced afterpulse and allows operation at up to 14 V of over-voltage at 80 K, resulting in extended gain. The DCR is compatible to NUV-HD Standard Field devices.



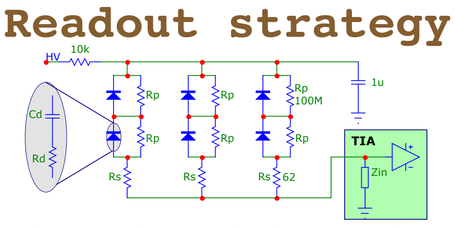
Low Field and triple dose technologies were combined in a new R&D run of NUV-HD SiPMs. Characterization of these devices at cryogenic temperature is currently ongoing.

Transimpedance Amplifier

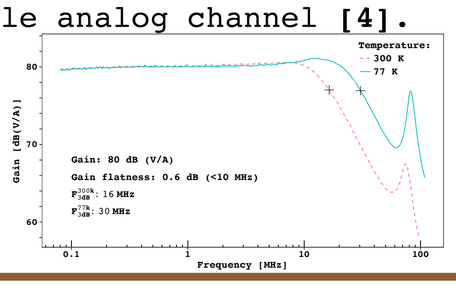
Readout electronics is based on an operational amplifier, model LMH6629 from Texas Instruments, configured to work as a transimpedance amplifier (TIA) with low noise and high speed. The TIA has been fully characterized at cryogenic temperature **[3]**. The chosen configuration guarantees a high bandwidth (in excess of 60 MHz at 80 K with a 10x10 mm² SiPM), necessary to maintain the fast peak of the SiPM pulses. The power consumption at 80 K and supply voltage of 4 V is ~40 mW.



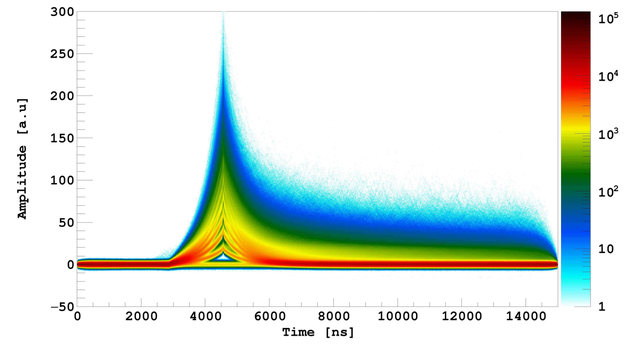
Readout strategy



The tile is divided in four quadrants of 6 cm², each with three branches of two SiPMs in series, read with a TIA. Bandwidth is 30 MHz at 77 K, enough to preserve the fast peak. Quadrants are summed with an active adder to obtain a 24 cm² single analog channel **[4]**.

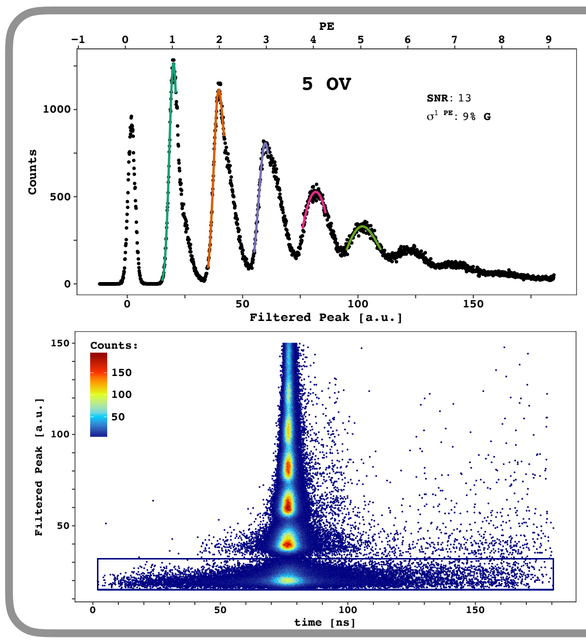


Digital filtering



A matched filter, obtained by cross-convoluting the waveforms for the signal template, is applied to the raw waveforms. The matched filter returns a symmetric waveform around the peak, giving a better identification of the timing.
An online FPGA based implementation of the matched filter was successfully tested.

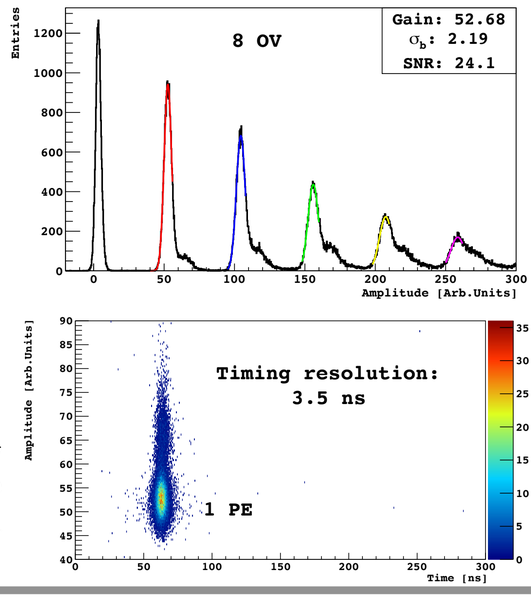
PDM performance



Best SNR is obtained on the amplitude of the filtered waveform **[4]**. At 77 K and 5 V_{OV} for NUV-HD-LF devices with standard doping levels:

- SNR = 13
- σ_{1PE} = 9% μ_{1PE}
- Timing resolution 1PE = 16 ns
- Power dissipation: ~170 mW
- Dynamic range: > 100 PE

Preliminary results at 77 K and 8 V_{OV} obtained with NUV-HD-LF + triple dose SiPMs show SNR = 24 and timing resolution of 3.5 ns.



Bibliography

[1] F. Acerbi *et al.* Cryogenic "Characterization of FBK HD Near-UV Sensitive SiPMs". IEEE Trans. Elec. Dev., 2017.
[2] C. E. Aalseth *et al.* "Cryogenic Characterization of FBK RGB-HD SiPMs". JINST, 12(09):P09030, 2017.
[3] M. D'Incecco *et al.* "Development of a Very Low-Noise Cryogenic Preamplifier for Large-Area SiPM Devices". IEEE Trans. Nucl. Sci. vol. 65, no.4, 2018.
[4] M. D'Incecco *et al.* "Development of a Novel Single-Channel, 24 cm², SiPM-Based, Cryogenic Photodetector". IEEE Trans. Nucl. Sci. vol. 65, no. 1, 2018.