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Light Readout in DarkSide-20k with Cryogenic SiPMs

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Abstract. Silicon photomultipliers (SiPMs) are a compelling alternative to photomultipliers in cryogenic ultra-low background applications, such as in dark matter direct search experiments. Working on the next generation of dark matter direct search experiments, the Global Argon Dark Matter Collaboration has committed to this technology, starting from their next programmed experiment: DarkSide-20k. The development of a cryogenic SiPM-based photon detector has been a challenging task due to the strict radiopurity requirements and cryogenic conditions imposed by the expected signature for dark matter signals. The R&D culminated with the design of the Photon Detector Unit (PDU), a modular photon detector of 20x20 cm^2 with 4 readout channels, based on a SiPM technology developed by Fondazione Bruno Kessler and cryogenic front-end electronics; more than 500 PDUs will be used to construct the two $\sim$10.5 m^2 optical planes of the massive two-phase argon time projection chamber (TPC) of DarkSide-20k and as photosensors for its veto systems.

1 The DarkSide-20k Experiment

The nature of dark matter (DM) is one of the biggest puzzles left unsolved in modern physics. Numerous experiments have probed different hypotheses for the dark sector, but a definitive answer seems far from sight. One field which has witnessed global efforts into solving this riddle is that of direct detection i.e. the detection of the ultra-rare scattering of dark matter particles on ordinary matter. All direct detection experiments face the challenge of mitigating the background, a task that becomes increasingly difficult as smaller interaction cross-sections are investigated. Among the most widespread technologies, liquid argon detectors have proven to be particularly effective thanks to the extremely powerful pulse-shape discrimination techniques exploiting the peculiar scintillation properties of argon. The Global Argon Dark Matter Collaboration (GADMC) has the goal of pushing the sensitivity of direct detection experiments down to the neutrino floor, a statistical boundary caused by the neutrino background, unavoidable with current detection technologies.

The next experiment run by the GADMC is DarkSide-20k (DS-20k), a massive argon detector currently in construction at Hall C of LNGS underground laboratories (Fig. 1), with maximum sensitivity in the DM mass range of $1\,\mathrm{GeV/c^2}$ to $10\,\mathrm{TeV/c^2}$. The core of DS-20k is a two-phase argon time projection chamber (TPC) with a fiducial argon mass of 20 t, allowing for an exposure of a few hundred $\mathrm{t \cdot yr}$ with a target instrumental background of < 0.1 events in the DM region of interest.

The structure of DS-20k follows that of the DarkSide-50 (DS-50) detector [1], with a nested detector structure formed by two anti-coincidence (veto) systems enveloping the central two-phase TPC. The inner veto is specifically designed to efficiently tag neutrons, which would otherwise constitute a disruptive background by producing DM-like interactions in the TPC. Inside the TPC, the expected interaction from a DM particle is a coherent elastic scattering on an argon nucleus, which can be detected via a combined measurement of scintillation light (S1 signal) and ionization electrons (S2 signal) produced in liquid argon (LAr) by the recoiling argon nucleus. Three key innovations lay the groundwork for the design of this ultra-low background detector:

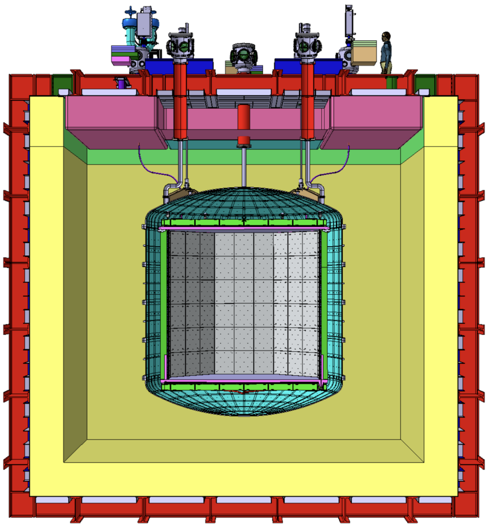

Figure 1: Section view of the DarkSide-20k detector. The membrane cryostat (red and yellow) houses the inner detector, composed of the TPC and the inner veto system in a stainless steel vessel (cyan). Liquefied atmospheric argon fills the main cryostat, while the TPC and inner veto are submerged in ultrapure underground argon.

- the use of radiopure underground-extracted argon for both the neutron veto and the TPC;
- the technology of gadolinium doped acrylic for the TPC walls, integrating the neutron veto together with the TPC and reducing total encumbrance;
- an optical readout based on large-area radiopure cryogenic SiPMs photon counters for both the TPC and veto systems.

The DS-20k cryostat is a ProtoDUNE-like membrane cryostat [2] with a volume of about 580 m^3 and filled with atmospheric liquefied argon (AAr). This volume of AAr is instrumented to function as an outer veto. Within the cryostat lies the inner detector, an ensemble of two conjoined systems, the inner veto and the TPC: the walls of the TPC are built out of Gd-infused PMMA, as gadolinium is an excellent neutron tagging material emitting several gammas after the absorption of a thermalized neutron, to which Gd exhibit a high cross-section. With such a compact design, the veto system can be entirely submerged in low-radioactivity underground-extracted argon (UAr) together with the TPC. Both are isolated from the AAr by a stainless steel vessel in a bath of AAr.

The necessity of radiopure argon is motived by the fact that atmospheric argon (AAr) is intrinsically radioactive due to the presence at an activity of 1 Bq/kg [3] of the radio-isotope ^{39}Ar, a β-emitter with an endpoint of 565.5 keV and a half-life of 269 yr. The low energy threshold of the TPC ($< 1\,\mathrm{keV_{ee}}$) together with its mass scale makes it impossible to realize an AAr-only detector with no less than an extreme amount of pile-up. As ^{39}Ar is activated by cosmic rays, underground extracted argon can achieve reduced radioactivity by a factor greater than one thousand, as demonstrated by DarkSide-50 [4]. The URANIA project will procure all the necessary UAr for DS-20k, extracted from a CO2 well in Cortez, CO, USA, which will be then shipped to the Aria facility in Sardinia for chemical purification [5].

The TPC of DS-20k is a regular octagonal prism with an inscribed-circle diameter and height of 350 cm, capped by two transparent acrylic windows. A thin film of the conductive material Clevios is deposited on both windows to serve as electrodes for generating an electrostatic field in the detector's volume. This field allows for the drifting of ionization electrons towards the upper region of the chamber, where a much stronger field extracts the electrons into a thin layer of gas and converts charge into light via electroluminesce. The drift field is decoupled from the extraction field with a metallic grid placed a few millimeters below the gas layer, while field disuniformities and leakage through the grid are contained by a suited field cage also made out of Clevios.

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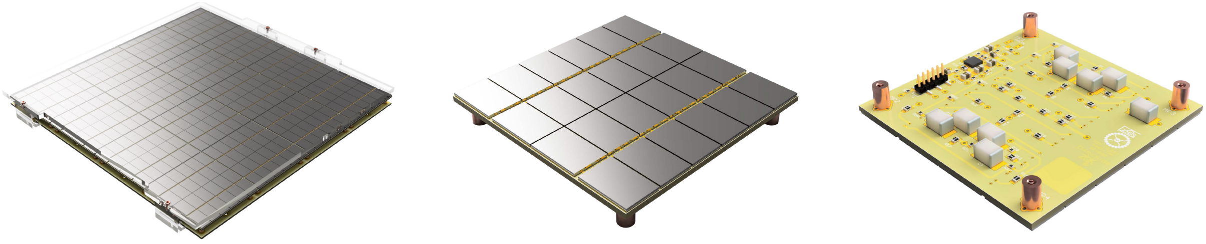


(a) (b) (c)

Figure 2: *(a)* Picture of the fully assembled PDU, with a total surface of 20×20 cm^2. The transparent cover is for protection during transport and handling. *(b)* Top view of a DarkSide-20k 5×5 cm^2 tile, with the 24 SiPMs comprising it visible. *(c)* Bottom view of the tile, showing the front-end electronics.

2 PDUs for Light Detection in DarkSide-20k

The light produced by direct argon scintillation and by charge-to-light conversion in the gas pocket lives on the VUV part of the electromagnetic spectrum with a wavelength of about 128 nm. To match the efficiency maximum of the photon collection devices in use, argon light is shifted in the optical spectrum with the use of TPB wavelength shifter evaporated on the internal surfaces of the detector. In the TPC, the converted light is finally collected by the two SiPM-based optical planes of $\sim 10.5\,\mathrm{m}^2$ each, which are placed behind the acrylic caps, facing the internal volume. The internal walls feature a layer of highly reflective material to guide the light towards the optical planes.

SiPMs are the photon detection technology of choice of DS-20k because of their intrinsic low radioactivity [6], good performance [7] and scalable production techniques. The SiPM technology employed in DS-20k has been developed in a combined effort with Fondazione Bruno Kessler (FBK) specifically for cryogenic use [8].

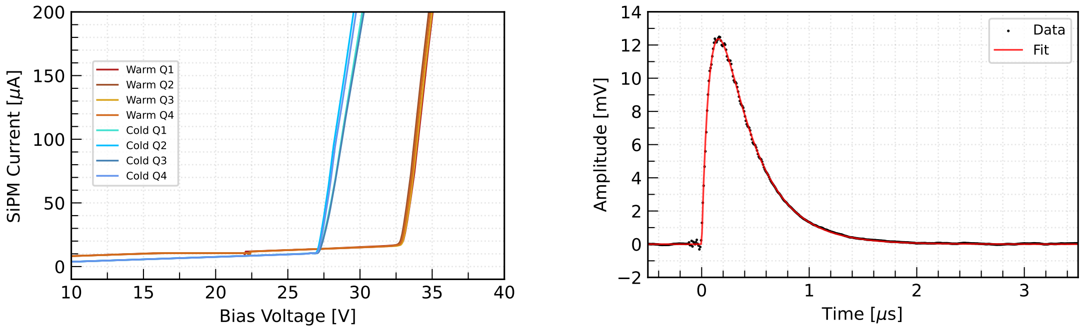
To instrument tens of square meters of DS-20k with $\mathcal{O}(1\,\mathrm{cm}^2)$ SiPMs, the Collaboration has finalized a long R&D process aimed at producing a modular and scalable design for a suited photon detector while preparing the necessary infrastructures for mass production and testing. This phase converged to a final design for a cryogenic modular photon counter of 20×20 cm^2 which is known as the Photon Detector Unit (PDU) (Fig. 2a).

A PDU has four independent analog readout channels with surface area 100 cm^2 each and it is comprised of 16 smaller units, the Photon Detection Modules (PDMs), assembled onto a motherboard. On a PDM, 24 SiPMs are die attached to a printed circuit board (Fig. 2b) and wire bonded. The SiPMs on a PDM are ganged in a hybrid parallel-series configuration to contain the total capacitance of the unit. The front-end electronics of the PDM are instead placed on the back of the PCB (Fig. 2c), where a trans impedance amplifier (or a custom ASIC, for PDUs of the veto system) receives the aggregate signal of the SiPMs ganging and outputs a voltage signal. Together with the readout electronics of the PDM, a precision voltage divider is also positioned on the back of the device to provide the bias voltage to each SiPM. On the motherboard, voltage signals from the PDMs are summed in four by four active summers, and then converted from single-handed to differential. A power management unit allows to regulate bias and power independently and remotely for each PDM. At LAr temperature, one PDU has a power consumption of about 2 W.r

DS-20k will employ PDUs in both the optical planes of the TPC, for a total of 2112 readout channels, and the veto systems, which will make use of $512 + 128$ channels (inner and outer veto, respectively) comprised of PDUs uniformly scattered on the surface of the veto chambers. Thanks to the high PDE of the SiPMs [9], the excellent optical coverage and the high reflectivity of the lateral walls, the TPC of DS-20k can achieve a photon detection efficiency of $\approx 45\,\%$.

3 Production and Testing of PDUs

PDU manufacturing is predominantly carried out within infrastructures of the Collaboration. SiPM wavers are mass-produced by FBK/LFoundry and shipped to the recently established INFN-LNGS facility Nuova Officina Assergi (NOA) [10]. NOA boasts a $420\,\mathrm{m}^2$ ISO 6 clean room and is equipped with all the necessary machinery for PDU fabrication, for single SiPM testing, PDM/PDU assembly, inspection and packaging/shipment. Several prototypes and pre-production PDUs have been manufactured in the last years to characterize their performance; only recently the pre-production moved to NOA, which was



(a) (b)

Figure 3: *(a)* The I-V characteristic of the four channels of the PDU with respect to SiPM bias voltage, at ambient temperature (labelled as *warm*) and in liquid nitrogen (labelled as *cold*). At 77 K the breakdown voltage is 27.1(1) V. *(b)* Average waveform for the signal associated with stimulation from one photon, for one channel of the PDU in LN, measured for 7 V over voltage. A convolution of exponential signals is fit to the data. The decay time of the pulse, averaged over four channels, is $\tau_L = 345(5)$ ns with a relative deviation within $2\%_{\rm rms}$.

inaugurated in 2023 and is foreseen to begin production of TPC PDUs in May 2024.

From NOA, PDUs are sent to the Photosensor Test Facility (PTF) [11] located at the Cryogenic Laboratory of INFN Naples, which is the responsible facility for the cryogenic testing of the full TPC PDU production. A comprehensive testing protocol is carried out on batches of up to 16 PDUs, at both room temperature and in liquid nitrogen (LN). To accommodate the expected production rate and the intensive testing procedure, the PTF is equipped with a massive 1000 L cryostat, which can be filled (and drained) with LN from an external 3000 L reservoir by a fully automatized cryogenic system. The PTF is equipped with a MIDAS-based DAQ system.

Concurrently, the production and testing of Veto PDUs is being carried out by several institutions: the University of Birmingham for veto PDM assembly, the University of Liverpool and STFC-Interconnect for SiPM die attach and wire-bonding, the University of Oxford for ambient temperature and cryogenic testing of PDMs, the University of Manchester for veto PDU assembly and ambient temperature testing, the University of Liverpool for cryogenic testing, with additional facilities at the University of Edinburgh, the University of Lancaster, and AstroCeNT (Poland).

4 Performance of the PDU

The results presented in this section have been obtained with a prototype PDU characterized at the Naples PTF. The PDU has been tested both at ambient temperature and LN, starting from the measurement of I-V characteristics. As SiPMs operate in Geiger mode, their performance is strongly dependent upon the excess voltage applied above their breakdown point, where the devices enter Geiger regime. This excess voltage is typically referred to as over voltage. The I-V characteristic for all channels of the PDU is reported in Figure 3a. The steep ankle visible in all curves corresponds to the breakdown voltage, measured to be 27.1(1) V in LN and 32.8(1) V at ambient temperature.

To characterize the PDU in LN, the SiPM are biased with the nominal over voltage value of 7 V o.v. and exposed to a ps-pulsed laser; a synchronous trigger is provided to a VX2740 CAEN board digitizing the differential signals from the PDU. The average waveform corresponding to the detection of a single photon is shown in Figure 3b, fitted with a convolution of two exponential signals. The measured rise time and long decay component are of 85(3) ns and 345(5) ns respectively, with a signal amplitude of ≈ 12 mV.

Signals obtained from the pulsed laser are integrated to measure the response charge, as plotted in Figure 4 for one channel. The charge spectrum exhibits the finger-shaped curve typical of SiPM devices, enabled by their exceptional charge resolution of $\mathcal{O}(1\,\%)$. Each successive peak corresponds to an increasing number of detected photons, and the spectrum is well described by a sum of multiple Gaussian distributions. The single photon resolution (defined as the σ/μ ratio for the first photon peak in the charge spectrum) is measured to be 13 % with the dominant contribution being from electronic noise.

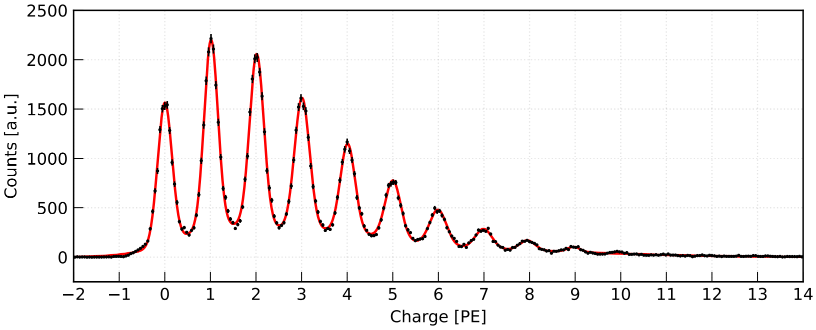


Figure 4: Charge spectrum obtained from one channel of the PDU in LN illuminated with a short-pulsed laser, at 7 V over voltage. Each peak corresponds to a given number of photons, starting from zero with the leftmost peak (pedestal). Together with data points (black) a multi-Gaussian fit is plotted (red).

From the event distribution, the average number of correlated pulses can be extracted from a compound Poissonian fit [12] and its average value is of 43(3) % (at 7 V o.v.) i.e. for each primary photon an average of 0.43 additional pulses are generated due to cross-talks and after pulses. One key performance parameter for a photon counter is the signal-to-noise ratio (SNR). For the PDU (at 7 V o.v.) the SNR evaluated on the raw data is 5.8(1), which is increased with the use of a matched filter to a value greater than 10, well within specifications.

All of the reported quantities have been measured as a function of time over the course of about 10 days in stable conditions, and a typical stability of the order of $0.5\,\%_{\mathrm{rms}}$ is observed.

5 Summary

The development and implementation of cryogenic SiPM-based photon detectors represent a significant technological achievement in the fields of noble liquids detectors and dark matter direct detection. Through extensive R&D efforts, the Global Argon Dark Matter Collaboration has successfully integrated this technology into the DS-20k experiment. The PDUs, based on SiPM technology developed in Collaboration with Fondazione Bruno Kessler, are set to be mass-produced at the Nuova Officina Assergi facility starting in 2024. With over 500 PDUs planned for integration into the DS-20k experiment, rigorous testing protocols have been established, including cryogenic testing at the Photosensor Test Facility at INFN Naples.

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