PROCEEDINGS OF SCIENCE

The DarkSide-20k experiment for WIMPs direct detection and its Photon Detection System

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Representing approximately 85% of the Universe's total mass, dark matter remains one of the greatest mysteries in physics. Even though evidence supporting its existence accumulate, its true nature is still unknown. A leading group of dark matter candidates is Weakly Interacting Massive Particles (WIMPs). The search for WIMPs has been an ongoing experimental challenge for over a decade, continually pushing the boundaries of detection limits. The DarkSide program is part of this direct detection effort and will advance with its next-generation experiment, DarkSide-20k.

The DarkSide-20k detector will feature a dual-phase liquid argon time projection chamber (LArTPC) enclosed within two veto systems, all housed inside an 8×8×8 m^3 cryostat. Located in the Gran Sasso underground laboratory, the experiment benefits from natural shielding against cosmic rays. The detector is designed to minimize background noise and achieve a nearly background-free operation by employing strategies to suppress unwanted signals such as neutrons, beta particles, and gamma rays. This is made possible by liquid argon's exceptional background rejection capability, particularly through pulse shape discrimination (PSD).

A key component of the detector is the Photon Detection Units (PDUs) system, which is currently in production. The project will utilize cryogenic and low-background silicon photomultipliers (SiPMs), which will undergo rigorous testing before being assembled into PDUs at the Nuova Officina Assergi (NOA) cleanroom, located in the external facility near the underground site. These advancements will enable DarkSide-20k to achieve unprecedented sensitivity to the WIMP-nucleon cross-section, probing previously unexplored regions of parameter space.

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1. The DarkSide program

Part of the Global Argon Dark Matter Collaboration (GADMC), DarkSide aims at direct detection of dark matter using a dual-phase liquid argon time projection chamber (LArTPC). Interactions in liquid argon produce nuclear or electron recoils that either excite or ionise the medium. An electric field drifts the ionisation electrons toward the anode; in a dual-phase detector the electrons are extracted into a gaseous region where they generate electroluminescence (the S2 signal). Scintillation light (S1) at 128 nm is emitted promptly with two decay components: a fast singlet (~7 ns) and a slower triplet (~1.5 μs). The singlet-to-triplet ratio differs for nuclear recoils (NR) versus electron recoils (ER), enabling pulse-shape discrimination (PSD) [1]. DarkSide also uses low-radioactivity argon extracted from underground wells, depleted in ^{39}Ar, dramatically reducing the intrinsic background rate.

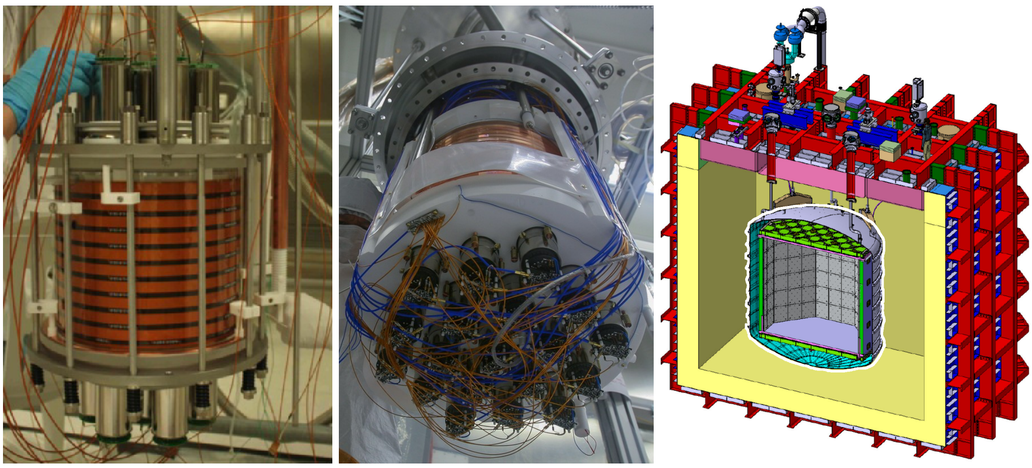

Figure 1: From left to right: DarkSide-10 TPC, DarkSide-50 TPC and DarkSide-20k detector model.

The program began with DarkSide-10, a 10 kg active-mass prototype, followed by the DarkSide-50 experiment, which operated with 50 kg of atmospheric argon from 2013 to 2015 and with 50 kg of underground argon from 2015 to 2018. DarkSide-50 achieved the current world-leading exclusion limits in the 1–3 GeV/c^2 WIMP mass range using an S2-only analysis [2].

The next stage, DarkSide-20k, is currently under construction at the Laboratori Nazionali del Gran Sasso (LNGS). Figure 1 illustrates the successive detectors in the DarkSide program.

The DarkSide-20k dual-phase LArTPC will be housed within two veto systems, an outer veto, the largest volume, filled with 650 tons of atmospheric argon, and an inner veto, 32 tons of underground argon, located between the TPC and the inner detector vessel.

The TPC itself will be an octagonal prism, 3.5 m in height and 3.9 m wide, with acrylic walls and two optical planes instrumented with silicon photomultipliers (SiPMs). The fiducial volume, containing 20 tonnes of underground liquid argon (51 tonnes for the active volume), will provide sensitivity to WIMP masses ranging from 1 GeV/c^2 to 10 TeV/c^2, approaching the so-called neutrino fog limit.

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2. Sillicon PhotoMultipliers (SiPMs)

From DarkSide-50 to DarkSide-20k, the change of scale (50kg to 51 tonnes) is not the only big challenge to face, but also the change of type of photodetectors technology. While DarkSide-50 was using 19 3-inch photomultiplier tubes (PMTs) Hamamatsu R11065, DarkSide-20k will be equipped with cryogenics SiPMs.

This technology is based on arrays of reverse-biased pn-junction diode operated in Geiger mode and with the correct applied voltage above the breakdown voltage, also called Over voltage, an absorption of photons triggers an avalanche of electrons. The use of SiPMs over PMTs present several advantages and challenges. In DarkSide-50, PMTs were a major source of background due to the presence of radioactive elements. Photodetectors with SiPMs present the advantage of a better radiopurity per unit of sensitive area. They can reach a better photon detection efficiency (PDE higher than 40%), critical for the pulse shape discrimination, and a better single photon resolution. Moreover, intrinsic noises like Dark Count Rate (DCR) in SiPM are at their lowest at cryogenic temperature. And their specific design in collaboration with Fondazione Bruno Kessler (FBK) achieved an additional DCR reduction by a factor 10^3 at low temperature (Figure 2) [3].

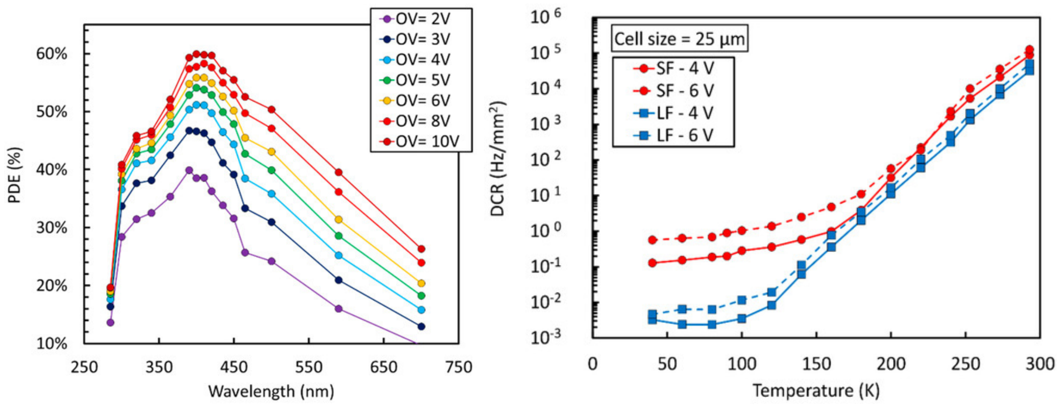

Figure 2: Left: Photodetection efficiency as a function of the wavelength for different over voltages from 2V to 10V. Right: Dark Count Rate as a function of the temperature for Standard Fields in red and for Low Field in blue. [3]

3. Production of DarkSide-20k's photodetectors

The 11.7×7.9 mm^2 SiPMs were designed in collaboration with FBK and manufactured on a large scale by LFoundry. A dedicated ISO6 clean, Nuova Officina Assergi (NOA), of 400m^2, was built at LNGS for the next steps of the production. SiPMs undergo cryoprobe testing, tile assembly (24 SiPMs per 5×5 cm^2 tile) and subsequent integration into Photon Detection Units (PDUs). To instrument the two optical planes (2×10.5 m^2) the experiment requires 528 TPC PDUs and 152 veto PDUs (~ 260k SiPMs).

To enable the experiment physics reach, the PDUs have to meet specific requirements when operated at 7 VoV:

- Signal-to-noise-ratio single photon electron (PE) > 7

- Timing resolution < 10 ns (TPC)
- DCR < 1E-2 Hz / mm^2
- PDE > 40%

The production started at NOA with the cryoprobe of SiPM wafer received from LFoundry and reached a 93% yield [4]. The good labelled SiPMs from the cryoprobe are selected to be assembled on a PCB and bonded to form a tile with 24 SiPMs of $5 \times 5\text{cm}^2$. The tiles are then used to form PDUs by grouping them by 16 on a motherboard. Currently about 10% of TPC PDUs has been produced. The tiles and the PDUs, when produced, undergo rigorous testing phase to validate them. The Figure 3 shows pictures of a SiPM wafer, a complete tile and a PDU being assembled.

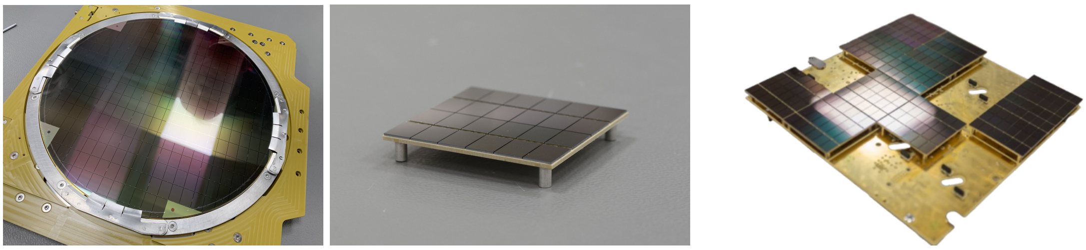

Figure 3: From left to right: Wafer with individual SiPM die, Tile and PDU partially assembled.

4. Validation of the photodetectors

4.1 Tile tests

Once a tile is completed, it undergoes two tests, one at warm temperature (~295K), the other at cold temperature (77K), in a nitrogen bath. The setup can be seen in Figure 4, with an oscilloscope, dewars and the tray with 4 tile slots, a control board and optical fibers to transport light from an external laser source (Hamamatsu PLP-10). The tests are measuring the tiles I/V curve, noise spectrum, single photon resolution and perform a pulse count rate analysis. These values need to respect specific quality assurance and quality control (QA/QC) criteria in order to be selected to be mounted on PDU [5]. I/V curves allow one to measure the breakdown voltage and divider resistance (related to the gain of the SiPMs) both for the warm and cold test. Examples of figures from a cold tile test can be seen in Figure 5. The tile tests yield (tiles passing both warm and cold tests) on production tiles reached 88%. When a tile has passed the tests respecting the QA/QC criteria, it can be mounted on a PDU.

4.2 PDU tests

After a TPC PDU is completed with 16 tiles, it is first tested at warm temperature at NOA and then sent to a dedicated facility for PDU testing, Photosensor Test Facility (PTF) in the clean room located at INFN Naples. Figure 6 shows the PDU test setup at PTF, where 16 PDUs can be loaded on the tray. Tests are also performed at warm and cold temperature and a ps-pulsed laser is used to expose PDUs to light during the tests. QA/QC acceptance criteria are currently being set for the TPC PDU tests.

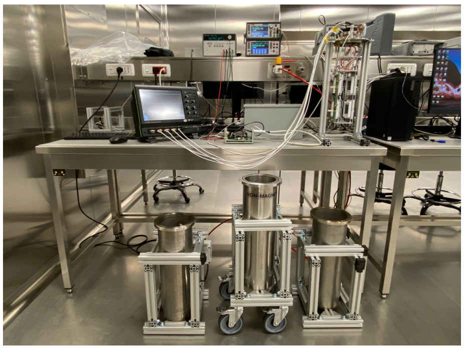

Figure 4: Tile test setup in NOA.

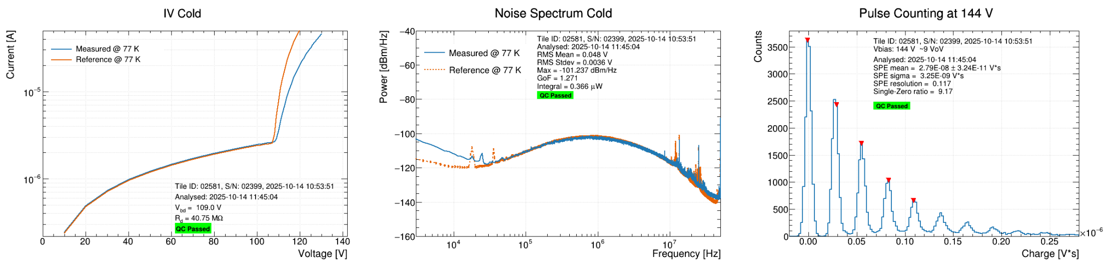

Figure 5: From left to right: Example of an I/V curve, a noise spectrum and the charge distribution from light pulses, all from a test at cold temperature.

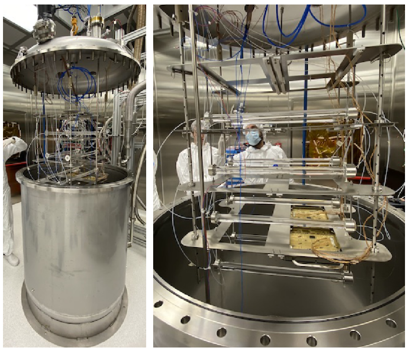

Figure 6: PDU test setup in PTF.

For Veto PDUs, produced in the UK (STFC Interconnect,Liverpool, Manchester and Warwick), different facilities are used for testing located at AstroCeNT, Edinburgh, Liverpool and Oxford. Their test setups can be seen in Figure 7.

4.3 Proto-0

Proto-0 was conceived as a compact, acrylic LArTPC whose sole aim was to validate the full DarkSide-20k photon-detection chain under realistic operating conditions. By integrating two fully-qualified DarkSide-20k PDUs into a functional TPC, the prototype allowed the collaboration to verify that the SiPM-based PDUs retain their performance (gain, PDE, dark-count rate, timing) after mechanical assembly, cabling, and immersion in liquid argon. The Chamber contains about

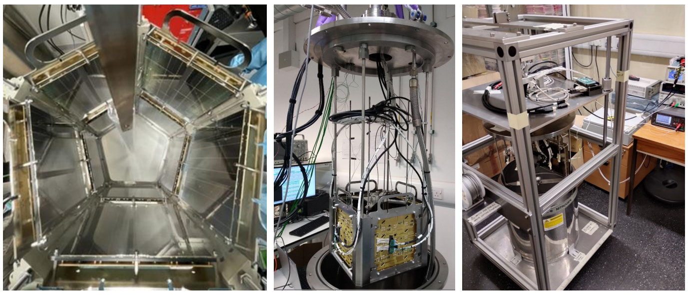

Figure 7: From left to right: Astrocent PDU test setup, Edinburgh PDU test setup and Oxford PDU test setup.

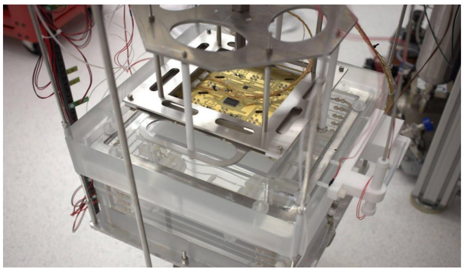

Figure 8: Photo of the Proto-0 TPC with a view of the back of the motherboard from the top PDU.

7 kg of liquid Argon with 12 cm of drift and is operated in the INFN Naples clean room. A photo of the TPC is in Figure 8. This detector has been the first successful use of the DarkSide-20k PDUs, an important step and validation in the production of the DarkSide-20k photosensors. Moreover, this prototype also allows the study of the S2 signal under different gas-pocket and grid condition.

Summary

The DarkSide-20k detector presents a significant challenge, particularly in the production of its photodetectors, and has the potential to mark a major milestone in the application of SiPM-based photosensors within the astroparticle physics domain. Their production is ongoing at the NOA facility using SiPM designed by FBK and manufactured by LFoundry. The characterization of the SiPM has been successfully done [6] as well as their quality assurance and quality control [4] with a yield of 93%. The assembly of tiles is currently ongoing at NOA, it is at an advanced stage and their test procedures and QA/QC has been published [5] reaching a yield of 88%. The next step of the production, assembling 16 tiles to form a PDU, has also started with currently about 10% of the PDU produced. The PDU produced are sent to their dedicated facilities to be tested PTF in Naples for TPC PDUs and Astrocent, Edinburgh and Oxford for Veto PDUs. A prototype of a TPC equipped with two DarkSide-20k PDUs, Proto-0, has been successfully operated at INFN Naples, representing the first use of these PDUs in a LArTPC.

References

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