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DarkSide-20k Veto photon-detector units: construction and characterization

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Abstract: DarkSide-20k is a global direct dark matter search experiment situated underground at LNGS (Italy), designed to reach a total exposure of 200 tonne-years nearly free from instrumental backgrounds. The core of the detector is a dual-phase Time Projection Chamber (TPC) filled with 50 tonne of low-radioactivity liquid argon. The entire TPC wall is surrounded by a gadolinium-loaded polymethylmethacrylate (Gd-PMMA), which acts as a neutron veto, immersed in a second low-radioactivity liquid argon bath enclosed in a stainless steel vessel. The neutron veto is equipped with large-area Silicon PhotoMultiplier (SiPM) array detectors, placed on the outside of the TPC wall. SiPMs are arranged in a compact design meant to minimize the material used for PCBs, cables and connectors: the so-called Veto Photon-Detector Units (vPDUs).

A vPDU comprises 16 vTiles, each containing 24 SIPMs, together with front-end electronics, and a motherboard, which distributes voltage and control signals, sums vTiles channels, and drives the electrical signal transmission. The neutron veto will be equipped with 120 vPDUs. The paper will focus on the production of the first vPDUs, describing the assembly chain in the UK institutes, in order to underline the rigorous QA/QC procedures, up to the final characterization of the first completed prototypes. Tests will be extensively performed in liquid nitrogen baths either for the single vTiles and for the assembled vPDUs, with the purpose of assigning a "quality passport" to each component.

Keywords: Dark Matter detectors; Photon detectors for UV, visible and IR photons (solid-state); Detector design and construction technologies and materials

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1 DarkSide-20k

Dark matter (DM) remains one of the most enigmatic and elusive entities in the cosmos, suggested and early measured a century ago, still defying our understanding of the universe [1]. Unlike ordinary matter, it neither emits nor absorbs light, rendering it invisible to telescopes. Its presence is inferred solely through its gravitational effects. Despite comprising 85% of the universe's mass content, its fundamental nature eludes detection and constitutes the pivotal question of contemporary astrophysics and cosmology [2]. The most extensively studied candidate for dark matter is the Weakly Interacting Massive Particle (WIMP) which can have a mass ranging from MeV/c^2 to hundreds of TeV/c^2 [3], and has been broadly investigated but yet undetected [4].

The DarkSide-20k experiment [5], currently being constructed at INFN, Laboratori Nazionali del Gran Sasso (LNGS), Italy, is designed for the direct detection of WIMP candidates. DarkSide-20k aims to detect WIMPs by measuring their scattering with liquid argon nuclei [6] in a dual-phase Time Projection Chamber (TPC) with a 20-tonne fiducial volume, relying on the detection of the scintillation signals in specialized cryogenic photodetectors.

The experiment aims to achieve a WIMP interactions with nucleons cross section exclusion sensitivity of 7.4×10^{-48} cm^2 for a 90% confidence level, for WIMP candidates with a mass of 1 TeV/c^2 over a 200-tonne-year exposure [7]. The goal for the background is meant to be of 0.1 events for the entire duration of the experiment. The WIMP signal is characterized by a single nuclear recoil with argon nuclei with a recoil energy between few tens of keV to about 200 keV, while the principal source of background is given by radiogenic neutrons and neutron produced in (α, n) reactions in the detector material, mimicking the WIMP signal.

DarkSide-20k (figure 1) is constituted of three main volumes: a TPC, a neutron veto and a cryostat. The neutron veto (a gadolinium-loaded polymethylmethacrylate, Gd-loaded PMMA, shell) surrounds the entire TPC and is immersed in a low-radioactivity liquid argon [8] bath enclosed in a stainless steel vessel. This paper focuses on the neutron veto readout system, formed by a large array of Silicon PhotoMultipliers (SiPMs), arranged in compact Veto Photon-Detector Units (vPDUs).

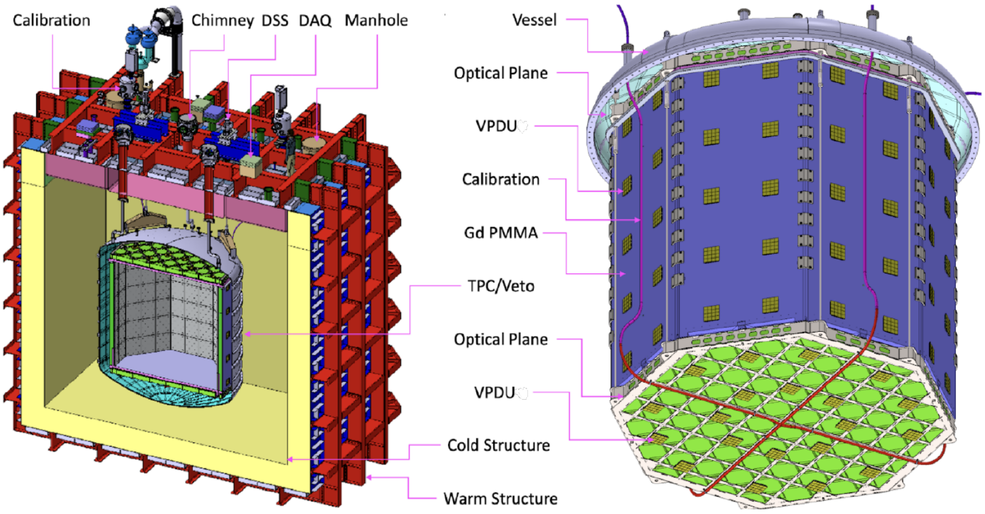

Figure 1. Schematics of the whole DarkSide-20k experimental setup, showing the inner detector inside the cryostat vessel (left). The inner detector closeup, including the bottom TPC optical planes, the calibration pipes and the veto Photo Detection Units (vPDUs) (right).

2 DarkSide-20k Neutron Veto

The neutron veto is a key component of the detector. Neutrons slowed down and captured in Gd-loaded PMMA, result in a cascade of gamma rays; the argon scintillation produced by the gamma-rays is wavelength shifted by PolyEthylene Naphthalate foils and finally detected by the 120 vPDUs facing the liquid argon volume (figure 1).

The collaboration has adopted the SiPM technology [9], which has many advantages in comparison with the well established photomultiplier tube technology [10, 11]: cryogenic temperature stability, better single photon resolution, high photo-detection efficiency, low voltage operation, greater radiopurity and lower cost per area. This permits to ask for stringent requirements [5] such as: breakdown voltage of 28 V, signal to noise ratio higher than 8, dark current rate lower than 0.001 Hz/mm^2, cross-talk probability lower than 33% and after-pulsing probability lower than 10% (at the operating voltage).

3 Veto Photon-Detector Units

A single vPDU consists of 16 vTiles integrated on a motherboard; each vPDU has 4 readout channel, corresponding to the sum of 4 vTiles. Each vTile consists of an array of 24 SiPMs assembled on a PCB hosting the front-end readout ASIC developed by the DarkSide-20k collaboration, also performing the summing of the SiPMs response. Each SiPMs is an array of 94,900 Single Photon Avalanche Diodes (SPADs) operating in Geiger mode, for a total area of 8×12 mm^2. A schematic of the light-sensitive components with their nomenclature is shown in figure 2.

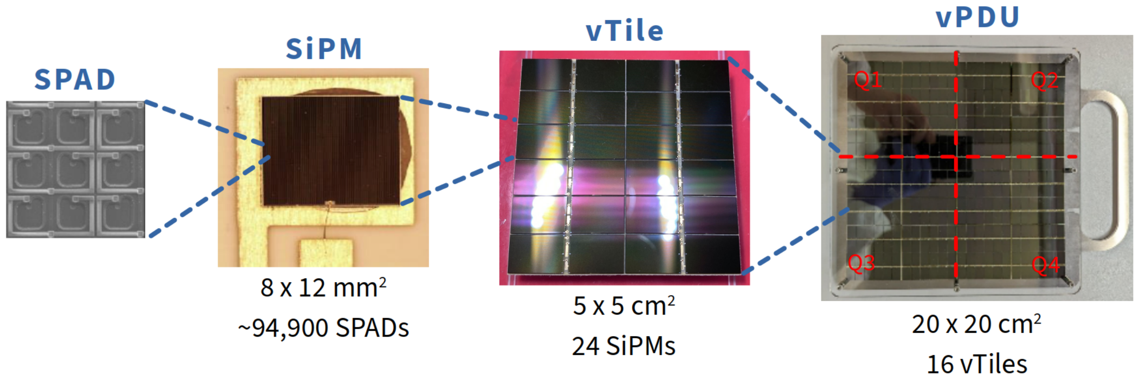

Figure 2. Components for the assembly of a Veto Photon-Detector Units (vPDUs), showing the different light-sensitive elements and their nomenclature (not in relative scale). The final object is formed by 16 vTiles, each of which is made out of 24 SiPMs sensors. On the back side of the vTile is present the front-end electronics also summing the SiPMs; on the back side of the vPDU is present the 4-vTiles channel summing electronics.

3.1 Production and assembly

The vPDUs production and testing activities are distributed across the UK and include also AstroCeNT (Warsaw, Poland). Single vTile PCBs are received at the University of Birmingham from an UK manufacturer, where the PCBs are populated with the front-end electronics, including the ASIC amplifier. The die attach of the 24 SiPMs on a single PCB and the wire bonding are done at the University of Liverpool and at STFC-Interconnect (Rutherford Appleton Laboratory, UK). The final integration of 16 vTiles on a the motherboard (procured from an Italian manufacturer) is done at the University of Manchester.

In order to ensure the low background required by DarkSide-20k, several remedies are in place. All the assembly and testing procedures are done in ISO5–ISO7 clean rooms to limit the possible contamination, ensuring a radon level lower than 5 Bq/m^3. Moreover, each component of a vPDU and the fully assembled vPDU have been radio-assayed at LNGS, Boubly and Canfranc Underground Laboratories (table 1) showing a negligible contamination during the manufacturing process. Overall, the whole Veto photodetectors constitute less than 4% of the total DarkSide-20k radioactive budget.

Table 1. Comparison of the radioactive budget between summing the assays done on the single components constituting a vPDU, and the whole vPDU assay. The contamination coming from the assembly process is negligible.

Isotope	Summing components [Bq]	Full vTile assay [Bq]
^{40}K	14	13
^{232}Th	1.3	1.1
^{235}U	0.16	0.11
^{238}U	9.2	12.0

3.2 Testing and QA/QC

The Veto photodetectors undergo tests at various stages throughout the production process, from the single SiPM, up to the final assembled vPDU; Quality Assurance and Quality Control (QA/QC) criteria are defined for each step of the production (an extensive paper describing the whole QA/QC is under preparation).

Diced wafers are received at the University of Liverpool and at STFC-Interconnect from INFN-NOA (LNGS, Italy) where they have been cryoprobed at liquid nitrogen temperatures, flagging all the single SiPMs that have not passed the quality controls on the breakdown voltage, quenching resistance and leakage current before breakdown.

Charge injection tests (with a 100 mV, 4 μs, 1 kHz input pulses) are performed at the University of Birmingham, on the single ASICs and on the PCBs populated with the ASICs (prior to the dies attachment), in order to find outliers in the maximum amplitude and in the current draw distributions.

After the full integration of vTiles with SiPMs, each vTile undergoes an initial capacitance and resistance (CR) testing at the production sites mentioned above. In addition to that, warm noise analysis and breakdown voltage from reverse current-voltage (I-V) measurement are performed. This data is used to reject vTiles before passing to the further tests, in order to exclude outliers, exclude vTiles presenting double breakdown or manifesting an anomalous noise spectrum.

A full characterization of each vTile is done at liquid nitrogen temperatures using triggered laser light both at the University of Oxford (formerly at Royal Holloway University of London) and at STFC-Interconnect, assessing breakdown voltage from reverse I-V measurement, signal-to-noise ratio for a single photoelectron (PE) detection (SNR, defined here as single PE amplitude divided by the RMS of the baseline) (figure 3), dark count rate, correlated delayed avalanche, cross talk and mean number of additional prompt avalanche [12] and performing a noise spectrum shape analysis and pulse shape analysis for single PE waveforms.

The finally assembled vPDUs are going to be tested at ambient temperature at the Universities of Manchester and Warwick, and at liquid nitrogen temperatures in one of the distributed testing sites at the University of Manchester, Liverpool, Edinburgh, Lancaster and at AstroCeNT. Preliminary tests have been performed on the first assembled vPDUs, showing an average higher SNR with respect to the single vTiles, due to the better filtering performed by the vPDU motherboard (example in figure 4).

All the production steps and tests are tracked in a centralized production database. The unique identifier is a QR code which permits to keep the whole production history from the single probed SiPMs up to the final tests on the fully assembled units. The full characterization of each vPDU is assigned to the object as a "passport" that will follow the component until the final detector integration.

The collaboration has currently produced and tested the first 160 vTiles, including early-stage prototypes, resulting in 6 vPDU completed and undergoing the first tests to characterize and commission the test facilities and test procedures. A preliminary version of the QA/QC acceptance criteria (based on the warm and cold tests) has been defined and will be refined along with the production process. For the first batch of vTiles produced with cryoprobed SiPMs, around 90% have passed the acceptance criteria, largely exceeding the required 80%.

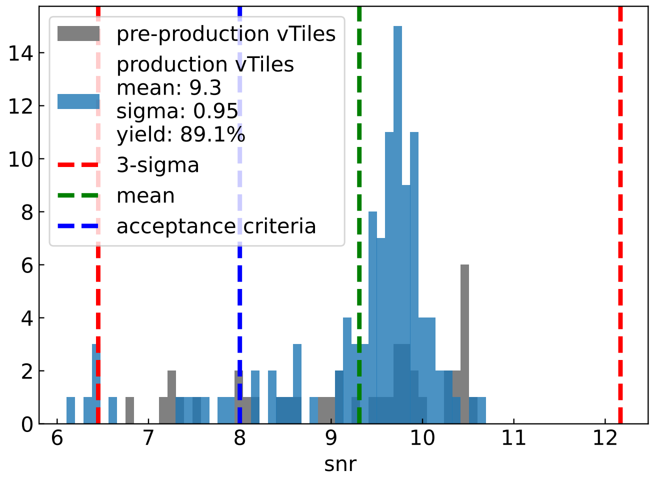

Figure 3. Example of one of the acceptance criteria for the QA/QC of the vTile production: the signal-to-noise ratio (SNR) distribution for vTiles tested in liquid nitrogen biased at 69 V. The blue (grey) distribution is for the (pre-)production vTiles assembled with (un-)probed "good" SiPMs; the red dashed lines correspond to the 3σ limits of the production vTiles; the blue dashed lines correspond to the low acceptance criterion for this quantity (SNR>8). 89.1% of the vTiles pass this acceptance criterion.

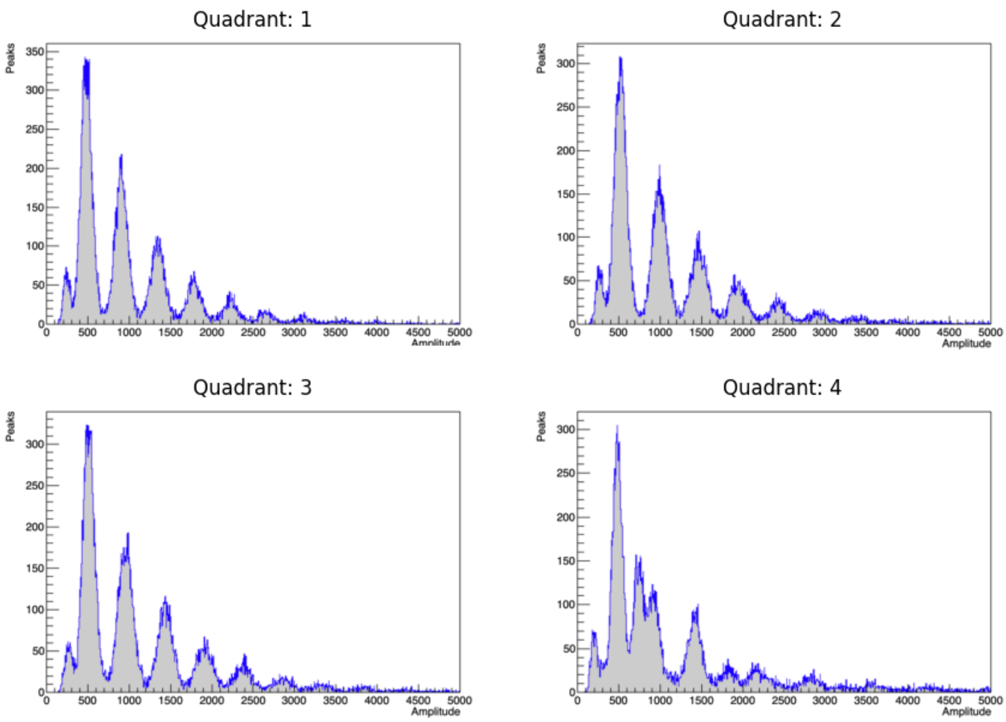

Figure 4. Example of a preliminary amplitude spectra for each quadrant (sums of 4 vTiles) of a production vPDU tested in liquid nitrogen, showing the multiple PE peaks (the quadrant 4 presents some artefacts due to the testing equipment).

4 Conclusion

The Veto detector is a key component needed to reach the low instrumental background required in DarkSide-20k. The UK and Polish production and test sites are ready for the imminent start of the full regime production, after the prototyping phase. A distributed analysis infrastructure is in place and has already been exercised over the first assembled vPDUs, whose components already met the quality requirements.

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