Detecting scintillation light of NaI(Tl) crystals with SiPMs at cryogenic temperature

V. Trabattoni(1)(2), A. Andreani(1)(2), R. Brambilla(1), A. Castoldi(2)(3), D. D'Angelo(1)(2), G. Di Carlo(4), L. Frontini(2), M. Galli(1), N. Gallice(5) C. Guazzoni(2)(3), V. Liberali(1)(2), E. Martinenghi(2), A. Stabile(1)(2), V. Toso(1)(2), A. Zani(2)

(1) *Dipartimento di Fisica, Università degli Studi di Milano - Milano, Italy*
(2) *INFN, Sezione di Milano - Milano, Italy*
(3) *Politecnico di Milano - Milano, Italy*
(4) *Laboratori Nazionali del Gran Sasso - Assergi (AQ), Italy*
(5) *Brookhaven National Laboratory - Upton NY, USA*

Summary. — The direct search for dark matter interaction is a main open issue in astroparticle physics, and a promising technique is based on scintillation light detection with NaI(Tl) crystals to validate of refute the DAMA/LIBRA claim. The signal is observed in the (1 to 6) keV energy interval, where the main source of background is due to noise from the Photomultiplier Tubes used by all current generation experiments. This paper presents the ASTAROTH Project, whose goal is to achieve a significantly higher signal-to-noise ratio at the energies of interest and a lower threshold, by reading out the light from of NaI(Tl) crystals using arrays of cryogenic SiPMs. We present the characterisation of a first SiPM array with laser light in liquid nitrogen and the results of a cool-down of ASTAROTH's custom cryostat where a NaI(Tl) crystal is coupled to the array.

1. – Introduction

The nature of Dark Matter (DM) is one of the most important open problems in modern physics. Several astronomical phenomena can be explained by introducing dark matter [1], which can be thought as a particle with the following characteristics: it should be a particle beyond the Standard Model, interacting only through gravity and weak force; it is expected to be non-relativistic (cold), massive, and stable, or with a long lifetime (in order of 10^{17} s), since it was present in the early stages of the Universe [2].

Locally DM is supposedly distributed in a halo concentric with our galaxy. Direct search experiments aim to observe DM scattering in Earth-bound detectors due to the motion of the solar system through the halo. Including the Earth's motion around the

Sun the interaction rate is expected to show an annual modulation [4] of a few percent. Said annual modulation, where a maximum must be observed in June, is one of the most important signatures of DM interaction. It poses a challenge for modern detector technology because of the very low energy of the recoils [5]. At such low energy effective noise discrimination is mandatory and determines the energy threshold. To date, the only experiment reporting a positive observation of annual modulation is DAMA/LIBRA, at Laboratori Nazionali del Gran Sasso (LNGS) [6]. The detector is composed by 25 highly radiopure NaI(Tl) crystals and it performs detection of scintillation light with *Photomultiplier Tubes* (PMTs). DAMA/LIBRA claims to have observed an annual modulation of the signal in the (1 to 6) keV energy interval; however, the main source of background noise in this energy interval is due to PMTs-related noise, which exceeds the rate of scintillation light by about two orders of magnitude and makes it very hard to set a threshold lower than 1 keV. A few experiments are attempting to validate or refuse DAMA, although with the same limitations tied to the use of PMTs [7, 8, 9].

In this paper, ASTAROTH is presented with its innovative approach from detector design to signal processing, along with the first characterisation of a SiPM array with laser and scintillation light.

2. – The ASTAROTH Project

The ASTAROTH (*All SensiTive ARray with lOw THreshold*) Project aims to investigate the interaction between dark matter particles and highly radiopure NaI(Tl) scintillating crystals [5]. To overcome the sensitivity limitations introduced by the us of traditional PMTs, ASTAROTH is choosing *Silicon PhotoMultipliers* (SiPMs) which consist in a matrix of thousand of microcells, each one made of a Single Photon Avanche Diodes (SPADs). The new approach focuses on breaking below the 1 keV energy threshold, where theories predict stronger modulation [4]. In order to validate or refute DAMA's results, the ASTAROTH detector is required to be based on the same target material. For this reason, the experiment proposes the use of cubic NaI(Tl) crystals of $5 \times 5 \times 5$ cm^3 size. Since NaI(Tl) crystals are composed of a hygroscopic material, ASTAROTH crystals are enclosed using an epoxy resin [10]. The SiPMs arrays are directly coupled to all the faces of the cubic case, not requiring the presence of reflectors for increasing light collection. However, SiPMs introduce the necessity of a cryogenic set-up to reduce the intrinsic dark count rate [11]. A cryostat was designed and realised able to keep the temperature stable at a tunable value in the $\sim$80-150 K range where the optimal working point for both the scintillating properties of NaI(Tl) and the performance of SiPMs is to be found (shown in Figure 1). The cryogenic set-up includes a dual-walled and vacuum-insulated chamber made of OFHC (*Oxygen-Free High Conductivity*) copper submersed in cryogenic liquid, with a stainless steel chimney. A heater is used to raise and regulate the temperature above the one of the cryogenic bath. In case liquid argon (boiling point 87 K) is chosen, the outer volume can be instrumented with additional SiPMs and act as veto for key internal backgrounds that feature a gamma in coincidence (^{22}Na and ^{40}K).

In March 2024, the first scintillation light read-out has been performed inside the cryostat at the Laboratorio Acceleratori e Superconduttività Applicata (LASA), in Milan.

3. – Cold array characterisation with laser

ASTAROTH has purchased few 5×5 cm^2 SiPM arrays from FBK and Hamamatsu producers; as well, few front-end electronics solutions are being investigated, either in-

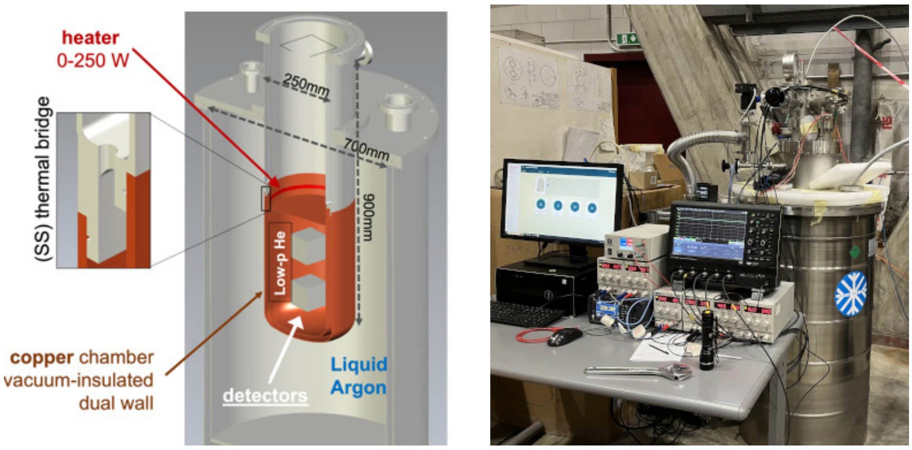

Fig. 1. – Cryostat CAD model (left); picture of the cryostat set-up at the LASA in Milan (right).

tegrated or with discrete components. Here we report on the characterisation of a FBK array, directly coupled to a custom-design discrete front-end electronics board. The array was firstly characterised in a laboratory set-up, along with the front-end board (shown in Figure 2). The array is made by 24 devices, each 8×12 mm^2, made of the NUV-HD-Cryo technology [11] organised in four channels, each corresponding to a quadrant of six devices. The front-end is coplanar and plugs into the back of the array. Each channel is served by a LMH6629 [12] transimpedence amplifier.

For the first cold characterisation, the array and the front-end were directly submerged in liquid nitrogen (boiling point 77 K). A light pulse from a laser was used to illuminate the array and provides the trigger signal for data readout. Its power has been chosen low enough to distinguish single-photon peaks during the data taking. To uniformly illuminate the SiPMs, a rail structure was constructed (in Figure 2), on which both the optical fiber support and the array support could be moved to achieve different fiber-to-array distances [14].

The nominal value of breakdown voltage [13] for this device is 27 V at 77 K. During the characterisation, however, different values of bias voltage were applied to the array to study its performance as a function of the over voltage, i.e., the difference between bias voltage and the breakdown voltage.

During the characterisation, 10000 waveforms are acquired by the oscilloscope in a time window of 10 µs for each bias voltage value, i.e., 29 V, 30 V, 31 V, 32 V, and 33 V. For each value of over voltage, a histogram of the signal amplitudes is produced. As an example, data for 5 V over voltage at liquid nitrogen temperature are shown in Figure 3. As each photon is collected by a single cell of the device, and the output signal represents the sum of the firing cells, the resulting amplitude distribution is characterised by a series of peaks corresponding to a discrete number of photons.

The first peak of the histogram, the pedestal, is due to SiPM electronic noise (i.e., no light collected); the second peak corresponds to 1 photon detected, and the following peaks respectively to 2, 3, 4, etc. photons detected. As it can be seen, the peaks are well spaced for each channel. *Signal-to-Noise Ratio* (SNR), here defined by the ratio of the mean value of the first photoelectron peak to the standard deviation of the pedestal peak, increases with the over voltage. The average value of SNR for each channel in this

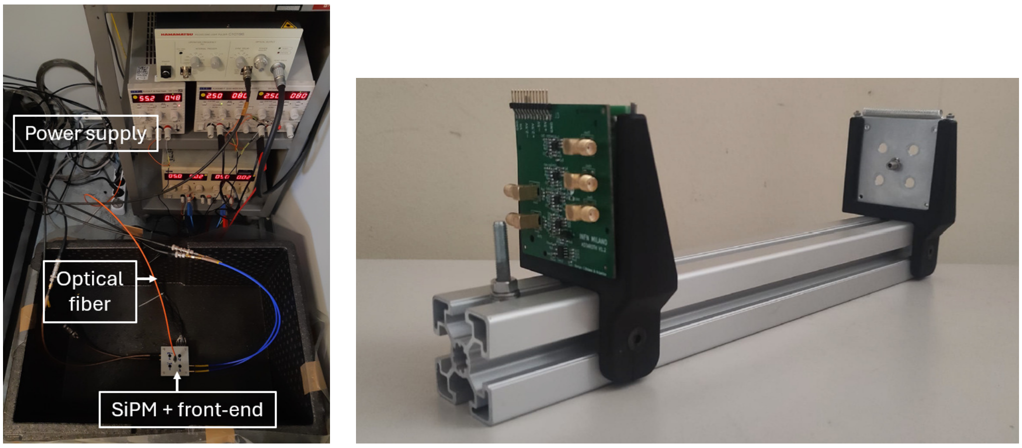

Fig. 2. – Experimental apparatus for measurements in the laboratory (left); picture of the set-up with array and its front-end spaced from the optical fiber support (right).

configuration is about 20.

4. – Cryostat set-up and preliminary results

After the preliminary characterisation performed by direct submersion in liquid nitrogen, the system was coupled with a scintillator crystal to start the measurements inside the ASTAROTH cryostat. The cryostat is now in operation at LASA in Milan, and it was tested for the first time in 2023.

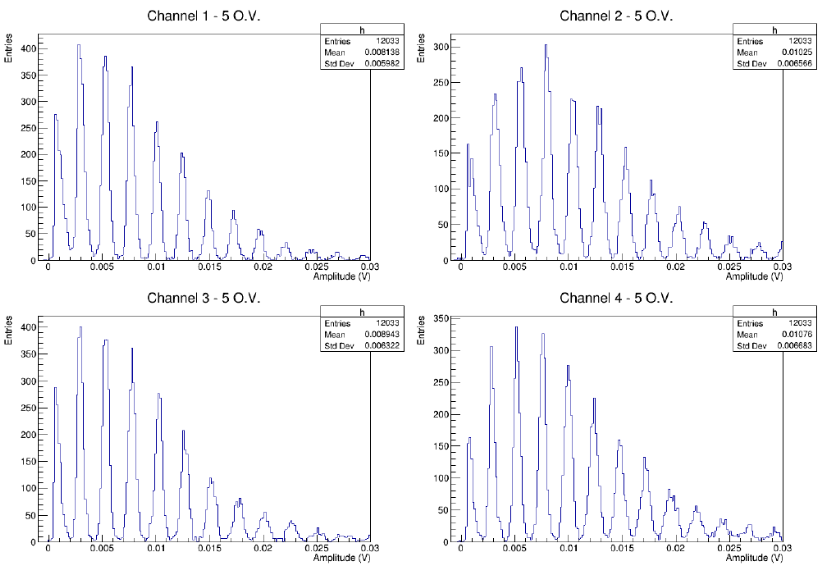

Fig. 3. – Distribution of signals amplitude at 5 V over voltage for all four channels.

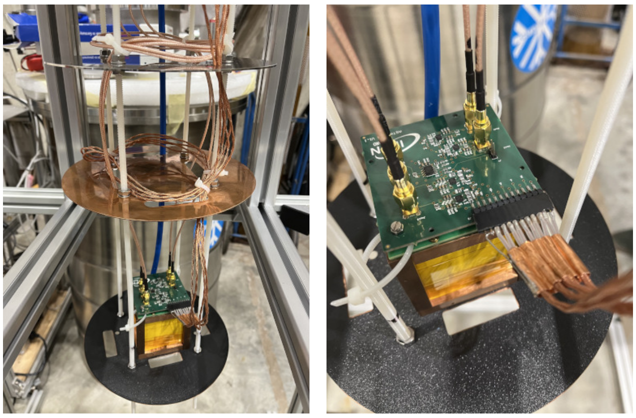

Fig. 4. – Close-up pictures of the NaI(Tl) crystal coupled with SiPM array and front-end electronics.

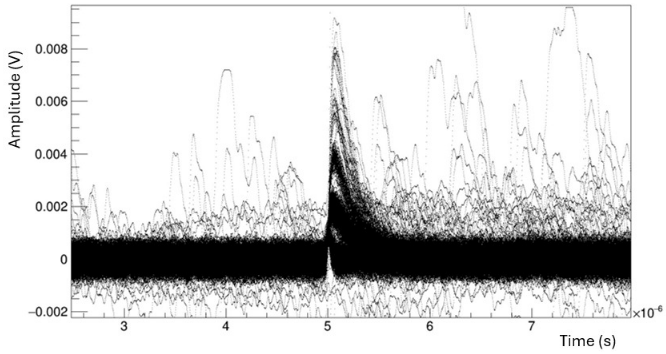

Fig. 5. – Waveforms referring to the preliminary results from NaI(Tl) scintillation read-out. The data refers to the condition of 5 V over voltage value at 200 K.

For this test we used a cylindrical crystal (5 cm diameter, 5 cm length) enclosed in a fused silica cube under neon atmosphere([1]). The crystal is supported by a copper cage of $7 \times 7 \times 7$ cm^3 size, where each open side permits the positioning of the SiPM array (shown in Figure 4). For this test, only one side of the cube was instrumented, while a full coverage is in the aim of the project. For consistency, it has been followed the same procedure as the laboratory tests for the different over voltage values and time windows for data taking. Since breakdown voltage changes with temperature, trigger thresholds had to be adjusted for every new acquisition. This characterisation will give information regarding the best configuration of temperature and biasing for future measurements.

Figure 5 shows waveforms taken with 5 V of over voltage value at 200 K and a 1.2 mV threshold. The pedestal and the first three photoelectron peaks are visible.

([1]) This sub-optimal design has been our working solution while the coating with epoxy resin is being finalised.

5. – Conclusions and future developments

The number of dark matter experiments based on highly radiopure NaI(Tl) detectors is increasing due to the scientific community interest in validating the DAMA/LIBRA claim. A crucial improvement in ASTAROTH is the introduction of *Silicon PhotoMultipliers* in substitution of traditional *Photomultiplier Tubes* for scintillation detection. SiPMs present a greater intrinsic noise at room temperature. To suppress this limitation, the detector will be immersed in liquid argon which may also function as a veto to eliminate background events by coincident measurements. The cryogenic set-up includes the use of front-end readout electronics performing at the same cryogenic temperatures. In this paper, it is presented the first characterisation of a cold SiPMs array in a laboratory set-up. Data from more recent measurements performed inside the ASTAROTH cryostat are still under analysis. However, preliminary results have shown the excellent performance of the cryostat and the potential of the ASTAROTH concept, and have given insights on how to proceed with development of the detector.

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