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SiPMs validation for the DUNE Far Detector Photon Detection System

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Summary. — The collection of scintillation light produced by charged particles inside a Liquid Argon Time Projection Chamber requires the use of an optimized dedicated system. In the case of the Far Detector of the Deep Underground Neutrino Experiment (DUNE), a Photon Detection System based on light collectors coupled to Silicon Photomultipliers (SiPMs), will be used in a cryogenic environment.
Its design, thanks to the SiPMs reduced dimensions, allows to detect scintillation light over a large area into a compact space, minimizing the impact of the system on the Liquid Argon active volume.
This work is focused on the validation and test activities of the SiPMs for the experiment. The results obtained during a first down-selection envising a full characterization of the devices both at room and cryogenic temperatures (77 K), are reported. A campaign of validation of all the SiPMs (∼300000) produced basing on these results, is currently ongoing. A description of the semi-automated system used to validate the sensors is given along with the results obtained so far.

1. – The DUNE experiment

The Deep Underground Neutrino Experiment (DUNE) is a next generation long-baseline neutrino experiment in preparation in the US. Its main scientific goals are the measurement of neutrino parameters such as the CP-violating phase, determine the neutrino mass ordering, and precisely measure the oscillation angles θ_{23} and θ_{13}. DUNE will foresees a Near Detector complex (ND) located at Fermilab and a Far Detector (FD) situated in South Dakota, at a distance of ∼1300 km and exposed to the most intense neutrino beam in the world. The ND will consist of three different detectors that mainly serve as a beam monitor and reduce the systematic uncertainties for the neutrino oscillation measurements at the FD. The FD will consist of four multi-kiloton modules of Liquid Argon Time Projection Chambers (LAr TPCs), placed about 1.5 km underground.

2. – The Photon Detection System

The first module of the DUNE Far Detector will be a single phase LAr TPC with Horizontal Drift [1]. The detector will be instrumented with a Photon Detection System,

TABLE I. – *Specific Requirements for the SiPMs of the FD1-HD Photon Detection System.*

Model	Characteristics
HPK	Cell pitch **50** μm, **low** quenching resistance
HPK	Cell pitch **50** μm, **high** quenching resistance
HPK	Cell pitch **75** μm, **low** quenching resistance
HPK	Cell pitch **75** μm, **high** quenching resistance
FBK	Cell pitch **30** μm, **Single** Trench
FBK	Cell pitch **50** μm, **Triple** Trench

to collect and measure the Vacuum Ultra Violet scintillation light produced by ionizing particles inside the active volume. The system will be embedded in the anode planes structure of the detector, in order to reduce its impact on the LAr active volume. The PDS modules are so confined into slots of reduced size, detecting scintillation light over a large volume into a compact space. Due to the specific anode planes design, the detection of scintillation light through the use of traditional large area photomultiplier tubes (PMT) is not feasible. The Photon Detection System is based on light collector, which act as light trap capturing photons inside boxes with highly reflective internal surfaces, coupled to Silicon Photomultipliers (SiPMs) [2]. The system is designed to ensure uniform light collection across the detector, which is crucial for accurate event reconstruction and energy measurements. The total number of SiPMs which will be used for the PD system of the first Far Detector module, will be of the order of ∼300000. Given this large number of sensors working at cryogenic temperature, an accurate selection and characterization of the SiPMs is envisaged.

3. – SiPMs selection

The SiPMs for DUNE are custom products by two vendors: Fondazione Bruno Kessler (FBK) and Hamamatsu Photonics K.K. (HPK), optimized for being used in DUNE cryogenic conditions. Several prototypes addressing DUNE technical requirements have been produced and accounted in the selection campaign undertaken. The vendors proposed two different technology to be tested in the pre-production phase are:

- Hole Wire Bond (HWB) technology of HPK with a Silicon package;
- NUV-HD-Cryo (Near Ultra Violet-High Density-Cryo) technology of FBK implemented in SMD epoxy resin package.

Different types of these technologies have been produced with area of 6×6 mm^2, differing mainly in number of cells per SiPM and technology used (table I). A selection campaign aimed to identify the models which best fulfills the experiment requirements (table II) was then conducted.

The characterization of the samples has followed a precise protocol. Some preliminary tests at room temperature were performed before a first cool down in LN2 to validate the information provided by the vendors. The I-V characteristics in forward and reverse bias were measured at room temperature for all the sensors, extracting the SiPM breakdown voltage and quenching resistance and compare them to the data given by the vendors. Then, a first submersion in Liquid Nitrogen was executed. Since the characteristics of

TABLE II. – *Specific Requirements for the SiPMs of the FD1-HD Photon Detection System.*

recovery time (τ_{rec})	200-1000 ns
maximum V_{bd} global spread	<2 V
Dark Count Rate (DCR)	200 mHz/mm^2
Crosstalk probability (CT)	<35%
Afterpulsing probability (AP)	<5%
thermal cycles	>20

the SiPMs change at 77 K, measurements of the main sensors features were performed again. To complete the characterization, a study of the primary Dark Count Rate (DCR) at 77 K and of the correlated noise (Crosstalk and Afterpulsing) was conducted (fig. 1). The sensors cryogenic reliability to thermal stress was verified in Liquid Nitrogen (LN)

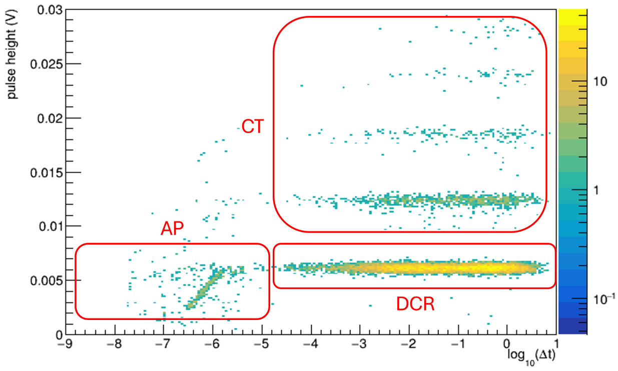

Fig. 1. – SiPMs pulse amplitude and relative frequency as a function of the time difference between consecutive events. Different population of events are visible correspondent to Dark Count Rate, Crosstalk and Afterpulsing.

over 20 thermal cycles. The response of the SiPMs was tested at 77 K before and after the cycles and the results eventually compared to ensure no significant change in the characteristics. The results obtained for the tested models reported in table III and IV show agreement with the experiment requirements (table II).

The results obtained from the campaign led to the selection of the models for the final production of the DUNE Far Detector: the 75 μm High Quenching Resistance (HQR) model produced by Hamamatsu Photonics K.K. (HPK) [3] and the NUV-HD-cryo Triple Trench technology from Fondazione Bruno Kessler (FBK).

TABLE III. – *Results obtained at cryogenic temperature during the selection campaign of the HPK SiPMs.*

vendor	cell (μm)	R_q (Ω)	V_{bd}(max-min) (V)	DCR(mHz/mm^2)	AP (%)	CT (%)
HPK	50	98.5±0.7	0.2±0.4	34±0.7	4.3±0.2	7.2±0.3
	75	93.9±0.4	0.4±0.4	38±0.4	4.6±0.1	14.3±0.2

TABLE IV. – *Results obtained at cryogenic temperature during the selection campaign of the FBK SiPMs.*

vendor	cell(μm)	$R_q(\Omega)$	V_{bd}(max-min)(V)	DCR(mHz/mm^2)	AP(%)	CT(%)
FBK	30	112±0.7	0.1±0.4	40.8±0.7	2.8±0.1	16.9±1.1
	50	334.6±0.4	0.1±0.4	53.4±0.4	4.1±0.1	14.2±0.2

4. – System for SiPMs cryogenic validation

Basing on the results obtained from the downselection campaign the production of the SiPMs for the Photon Detection System (PDS) of the first module of DUNE Far Detector (FD1) has started. A characterization of all these sensors in order to verify their performances according to the experiment requirements was demanded. Considering the amount of samples to be tested, ~300000, the development of a semi-automated validation facility was mandatory.

The developed system is composed of a black box hosting the mechanics and the front-end electronics. Some LEDs are mounted on the upper structure of the black box and used to provide a controlled light source during measurements at cryogenic temperature. For the tests at 77 K a 55 lt dewar filled with Liquid Nitrogen is used, equipped with an automated refill system and level monitoring. An aluminum flange is attached to a vertical movable semi-automated mechanical stage and used as a lid to the dewar. On the top of the flange the warm front-end electronics is mounted while on the bottom, it is attached the supporting structure where the samples under test are located (fig. 2). The apparatus is capable of testing up to 120 SiPMs in parallel, providing values for the breakdown voltage, quenching resistance and DCR of each sensor.

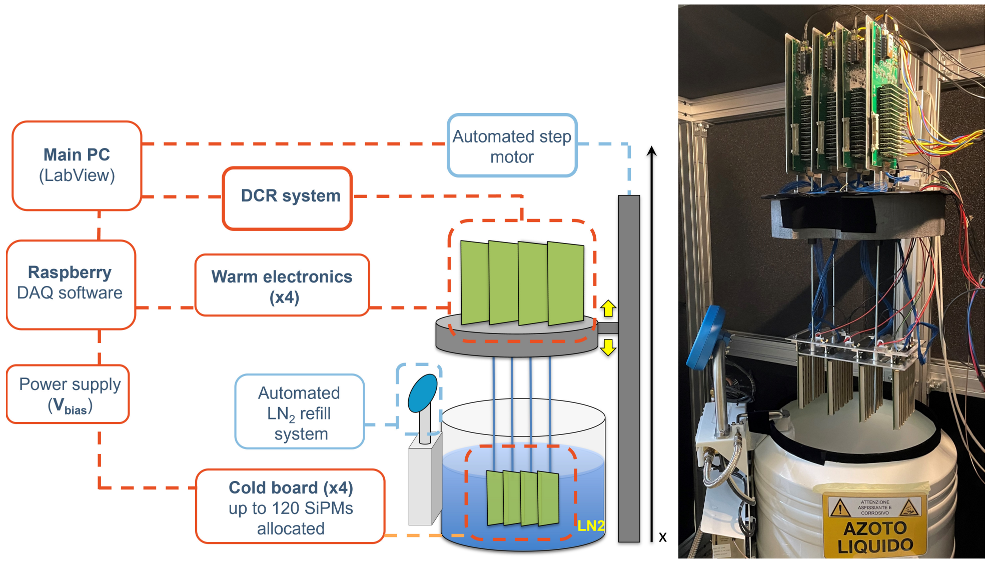

Fig. 2. – Description of the semi-automated system used for the validation tests.

The protocol followed for the validation of this mass production is similar to the one used for the selection with the only exception that in this case only 3 thermal cycles are requested and for the evaluation of the noise only a measurement of the Dark Count Rate is demanded and not a complete characterization through a detailed waveform analysis. The results obtained so far with the use of the system are reported in fig. 3 showing the overall spread in the measured quenching resistance and breakdown voltage, within the experiment requirements. Fig. 4 reports the measurements for the DCR obtained up to now. The majority of the samples presents values below 200 mHz/mm^2. For those with higher values a more detailed waveform analysis will be conducted in different laboratories.

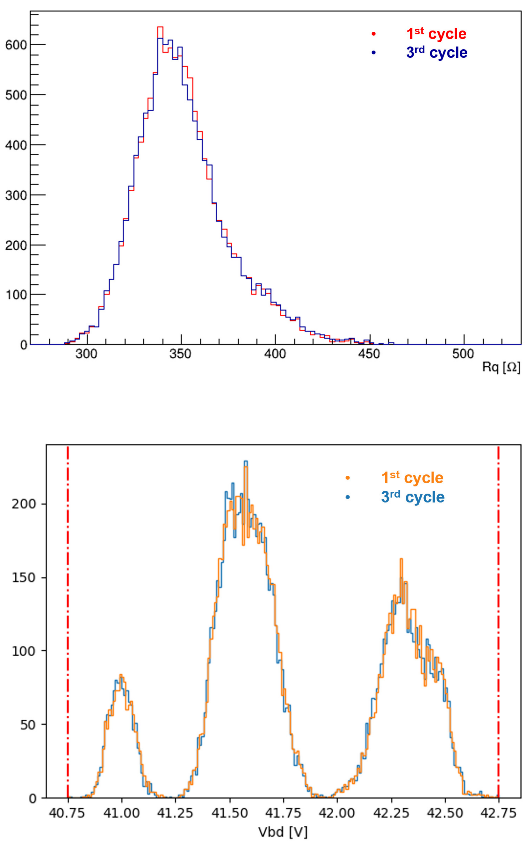

Fig. 3. – Results of the overall quenching resistance values (top) and breakdown voltage (bottom), compared for the first and last thermal cycle.

5. – Conclusions

A selection campaign for the SiPMs of the DUNE Far Detector Photon Detection System aimed to identify a device that best match the experiment requirements has been conducted. Different photosensor technologies have been proposed. Of all the evaluated samples a complete characterization was performed obtaining values for the quenching

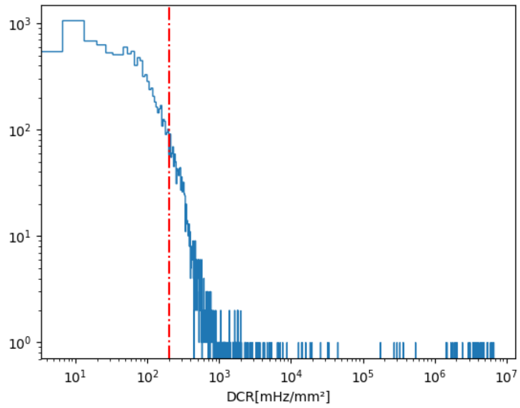

Fig. 4. – Distribution of the Dark Count Rate measured at 77 K.

resistance and breakdown voltage both at room and liquid nitrogen temperature. A detailed analysis of the SiPMs signal allowed to obtained values for the Dark Count Rate, as well as for the Crosstalk and Afterpulsing probability. The reported tests results for both the sensors parameters main sources of noise showed a good agreement with the experiment requirements.

From the validation tests the selected model were the 75 μm High Quenching Resistance (HQR) model produced by Hamamatsu Photonics K.K. (HPK) and the NUV-HD-cryo Triple Trench technology from Fondazione Bruno Kessler (FBK).

Basing on the results of the selection campaign, a large number of SiPMs was started to be produced for the first module of the DUNE Far Detector, demanding a specific validation campaign. Considering the large number of sensors to be tested (∼300000) a specific setup has been developed in order to automate the validating procedure. The results obtained so far showed no significant damages after the thermal stress tests and in the variation of the sensors properties. The spread in the values of the SiPMs quenching resistance and breakdown voltage have been analyzed and judged compliant with the requirements. Currently a mass test campaign is ongoing to validate a first production.

REFERENCES

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