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Cryogenic SiPMs for the DUNE experiment

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DUNE is the most ambitious long-baseline experiment under construction in the US for the study of neutrino oscillation and astroparticle physics. The DUNE far detector will employ the Liquid Argon TPC technology, enhanced by a powerful Photon Detection System that records the 128 nm scintillation light emitted by argon. The basic devices of this system are custom SIPMs. A dedicated development program has been performed over the last three years by the DUNE PDS Consortium together with Hamamatsu Photonics (HPK) and Fondazione Bruno Kessler (FBK). The tests were performed in several labs in Europe and in the US and investigated both performance and cryo-reliability. The results include the complete characterization of the sensors (gain, Dark Count Rate, correlated noise, etc.) and the most relevant phenomena that drive the detector behaviour at cryogenic temperature (thermal behaviour, signal bandwidth evolution, scaling of DCR, etc.).

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1. Introduction

Ultra-violet photon detection in liquefied noble gases plays a prominent role in several neutrino and dark matter experiments, whose needs have fostered the development of cryogenic Silicon Photomultipliers (SiPMs). Among the experiments that employ a Photon Detection System (PDS) for the scintillation light of liquid argon, DUNE [1] poses major challenges in terms of scalability to large volumes and long-term reliability. DUNE (Deep Underground Neutrino Experiment) is a next-generation dual-site experiment for neutrino oscillation studies [1]. The DUNE Far Detector (FD) will consist of four liquid argon detectors with a total mass of nearly 70 kt (fiducial mass of at least 40 kt). The first module, will be a Liquid Argon Time Projection Chamber (LAr TPC) with Horizontal Drift configuration (FD1-HD), while the second will have a Vertical Drift one (FD2-VD). Two different strategies of charge collection have been chosen: by means of wire planes in the HD and with perforated PCB anodes in the VD. The same technology, with different geometry, is foreseen for the PDS. It will detect the Vacuum Ultra Violet (VUV) scintillation light produced by ionizing tracks in LAr, operating at cryogenic temperature. The light collector modules, the so-called X-ARAPUCAs [2], proposed for DUNE Far Detector, are based on the concept of photon trapping inside a highly reflective box and wavelength shifting (WLS) bars, so that photons can be detected with SiPM arrays. The X-ARAPUCAs of the HD module are arranged in the so-called X-ARAPUCA SuperCells. A Supercell is composed by six 10×10 cm^2 pTP-coated dichroic filters, a 60 cm WLS bar and 48 SiPMs ganged in 8 group of six at the input of a cold amplifier (see Fig. 1). Four of these SuperCells are used to assemble a full optical module, with 2 m x 12 cm approximate dimensions, that is eventually embedded in the anode planes. In the full FD1-HD 1500 optical module will be installed, for a total of 288k SiPMs.

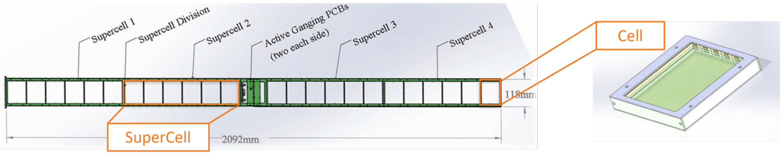

Figure 1: Schematis of X-Arapuca set-up for FD1-HD.

In the Vertical Drift Module 672 (320 on the cathode and 352 on the TPC field cage) square geometry Megacells (65×65 cm^2) will be used. A Megacell uses single large WLS light guide plane and its is read by 160 SiPM mounted on flexible strips (see Fig. 2). They form 4 groups of 20 SiPM passively-ganged in two stages with two output channels. A total of 107.5k SiPMs will be used in FD2-VD. In the paper the procedure of SiPM test and selection will be presented, together with the performances of the down selected model.

2. SiPMs requirements and tests

For SiPM selection, two photosensor vendors are being investigated, Hamamatsu Photonics (HPK) and Fondazione Bruno Kessler (FBK). They provided 6 types (splits) of 6×6 mm^2 SiPMs developed specifically for DUNE: 4 from HPK (S13360LQ LQR/HQR 50/75 µm pitch) and 2 from FBK (NUV HD CRYO single/triple trench).

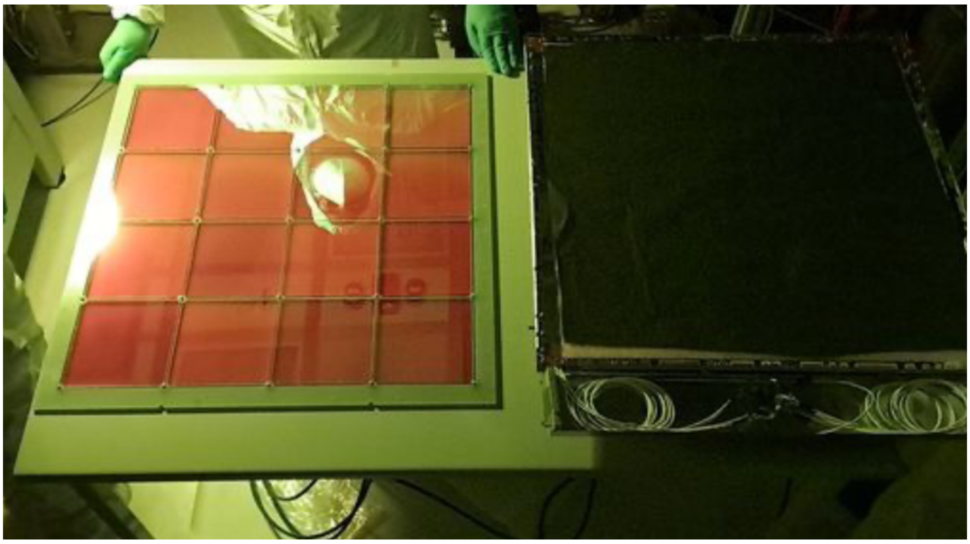

Figure 2: A Megacell to be assembled for tests.

Low level Specs	Value
Max nominal operating V	50 V at cold
Dark count rate (DCR)	<100 mHz/mm^2
Correlated noise	<35%
Time resolution	<1 μs
Thermal cycles	>20
Recovery time	a few μs
PDE at 87 K	>35% at nominal OV
High level Specs	**Value**
Dynamic range	1 - 2000 p.e.
S/N>4	per supercell (48 SiPMs)
Trigger	1.5 p.e.

Table 1: Specific requirements for the SiPMs of the DUNE Photon Detection System [3].

The SiPMs general requirements directly came from the DUNE Physics Requirements [3] and are summarized in Tab. 1.

Tests were done in dedicated test-benches arranged at seven different institutes of the PDS Consortium: *CIEMAT, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas*, in Madrid; *Istituto Nazionale di Fisica Nucleare* and *Università di Bologna*, in Bologna; *Istituto Nazionale di Fisica Nucleare* and *Università di Ferrara* in Ferrara; *Istituto Nazionale di Fisica Nucleare* and *Università di Milano-Bicocca* in Milano; *Institute of Physics, Czech Academy of Sciences* in Prague; *Instituto de Física Corpuscular*, in Valencia and the *Northern Illinois University, Department of Physics* in DeKalb.

The first delivery of customized SiPMs for DUNE consisted of 25 SiPMs of each type (6 batches). They were fully characterized trough:

- IV curve measurements at room and at 77 K temperature;
- gain, S/N and DCR measured in nitrogen bath at the overvoltages to obtain 40%, 45%, and 50% of PDE;
- 20 thermal cycles with controlled cooling down and warming up;
- all measurements repeated after the thermal stress.

All splits fulfilled the DUNE specifications. For the final selection procedure, the vendors provided 250 SiPMs per split to test compliance with the specifications in a larger sample. We employed here a faster procedure; it mimics the quality tests that will be carried on during mass production and comprises IV measurements for all SiPMs at room and 77 K temperature and 20 thermal cycles with controlled cool down and warm up. The IV measurements were repeated for all SiPMs. We performed then a complete characterization of a photosensor subsample (5% of the SiPMs per split). We also performed tests with 48 SiPM in active ganging at different overvoltages (OV) per each split, with measurements of S/N and signal shape. After all those tests, the HPK HQR 75 µm and FBK Triple Trench splits were selected.

3. Downselected SiPMs

The technology employed by Hamamatsu for the HPK HQR 75 µm uses low terminal capacitance and a new type of metallic resistance with a tunable thermal coefficient. It provides an high quenching resistance system to suppress large amplitude afterpulses and allows for careful tuning of the signal shape and fast recovery time at 87 K [4]. The FBK downselected SiPM employs a well-established technology i.e. the NUV-HD-CRYO [5] one. It is characterised by :

- a low electric field inside the junction to reduce the tunneling generation rate and so the DCR;
- internal modification of the doping profiles for reduced afterpulsing probability;
- modified polysilicon quenching resistor with reduced temperature coefficient.

An enlarged tranches to reduce cross talk was then developed to fulfill DUNE requirements.

From the IV curves we obtained the V_{bd} for the SiPMs: at 77 K they resulted 27.09±0.04 V for the FBK Triple Trench and 41.97±0.32 V for the HPK HQR. The spread of V_{bd} is minor for FBK, but the HPK one is less than 0.5 V as required for DUNE. Vendors provides us the overvoltages for 40%, 45% and 50% of Photon Dection Efficiency (PDE): the values are 2-2.5-3 V and 3.5-4.5-7 V for HPK and FBK respectively. SiPM charachteristics were mesured in LN bathat these OV; results are reported in Tab. 2 and Tab. 3.

For the tests with 48 SiPM in ganging, a dedicated cold electronics board developed in Milano Bicocca was used [6]. It is based on a two-stage amplifier, composed by a SiGe bipolar transistor and a fully differential op-amp. It provides a fast response, with lower than 100 ns rise time, dynamic range greater than 2000 p.e. and a S/N of 5-10 depending on SiPM type and overvoltage (at 45% PDE, S/N=5.96 for the HPK HQR 75 μm and 7.16 for the FBK Triple Trench), allowing a clear separation of photoelectron peaks when the 48 SiPMs are read out in parallel (see Fig. 3).

PDE	Gain (10^6)	DCR (mHz/mm^2)	Crosstalks (%)	Afterpulses (%)
40	3.73	57.54	6.62	0.86
45	4.59	64.97	8.97	1.10
50	5.44	66.32	10.96	1.30

Table 2: Results of measurements for the HPK HQR 75 μm photosensors.

PDE	Gain (10^6)	DCR (mHz/mm^2)	Crosstalks (%)	Afterpulses (%)
40	4.73	80.79	13.76	2.85
45	6.01	86.33	15.67	3.25
50	8.21	93.35	40.50	4.05

Table 3: Results of measurements for the FBK Triple Trench photosensors.

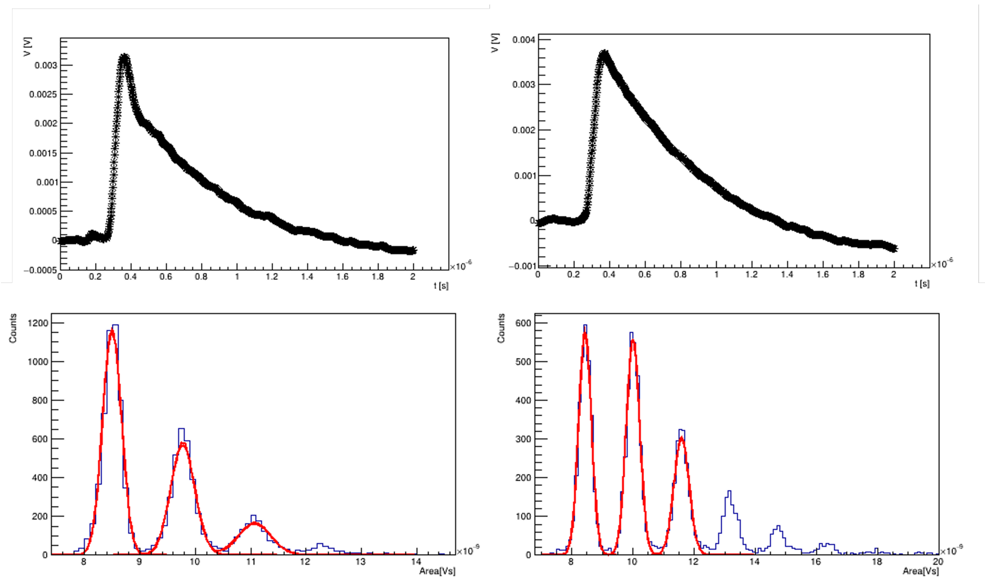

Figure 3: (Top) Mean 1 p.e. waveform and (bottom) and signal area histogram for HP HQR 75 *mu*m (left) and FBK Triple Trench (right) respectively [7].

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