Characterisation of a new generation of VUV low-light sensors

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Abstract. Silicon Photo-Multipliers (SiPMs) have emerged as a compelling photo-sensor solution over the course of the last decade. In contrast to the widely used Photomultiplier Tubes (PMTs), SiPMs are low-voltage powered, optimal for operation at cryogenic temperatures, and have low radioactivity levels with high gain stability over the time in operational conditions. For these reasons, large-scale low-background cryogenic experiments, such as the next-generation Enriched Xenon Observatory experiment (nEXO), are migrating to a SiPM-based light detection system. In this paper we report on the characterization of the Hamamatsu VUV4 (S/N: S13370-6152) Vacuum Ultra-Violet (VUV) sensitive Multi-Pixel Photon Counters (MPPC)s as part of the development of a solution for the detection of liquid xenon scintillation light for the nEXO experiment.

1 Introduction

Thanks to the rapid evolution of signal processing and light source technologies, the field of light detection has enjoyed spectacular advancements over the last 10 years [1]. Silicon PhotoMultipliers (SiPMs) are an emerging and very promising technology that address the challenge of sensing, timing and quantifying low-light signals down to the single-photon level [2–5]. For these reasons, large-scale low-background cryogenic experiments, such as the next-generation Enriched Xenon Observatory experiment (nEXO) [6], are migrating to a SiPM-based light detection system [7–9]. nEXO aims to probe the boundaries of the standard model of particle physics by searching for neutrino-less double beta decay ($0\nu\beta\beta$) of ^{136}Xe [10]. This lepton number violating process would imply that neutrinos are Majorana fermions. The photo-sensor portion of the nEXO experiment must meet the following requirements [6]: (i) Photon Detection Efficiency (PDE) greater than 15% for light at 174.8 ± 10.2 nm (scintillation light in liquid xenon [11]), (ii) number of correlated avalanches per pulse (within a time window of 1 μs after the trigger pulse) below 0.2, (iii) dark-noise rate lower than 50 Hz/mm^2, (iv) electronic noise smaller than 0.1 Photo-electron Equivalent (PE) r.m.s.. Accordingly to recent simulations the first three constraints are in fact sufficient to achieve an energy resolution of 1% for the ($0\nu\beta\beta$) decay of ^{136}Xe [10]. In [7], it was shown that these requirements could be met with SiPMs developed by Fondazione Bruno Kessler (FBK, Trento, Italy). The aim of this paper is to assess the performance of Hamamatsu VUV4 Multi-Pixel Photon Counters (MPPC)s (S/N: S13370-6152) developed for application in liquid xenon as a possible alternative solution to FBK SiPMs. The devices tested have a micro-cell pitch of 50 μm and an effective photosensitive area of 6×6 mm^2.

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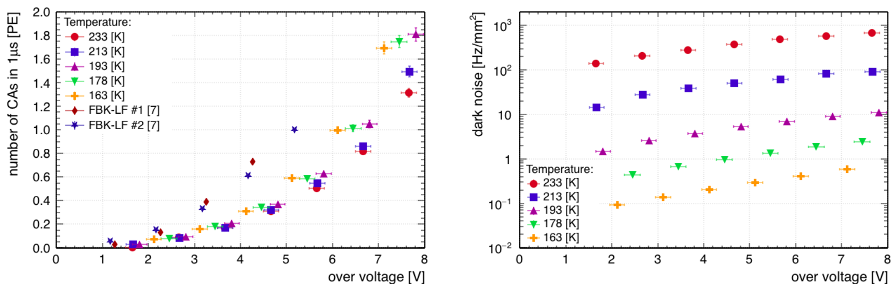
2 Noise Analysis

Dark and correlated avalanche noise are among the crucial parameters that characterize SiPMs. Dark Noise pulses (DN) are charge signals generated by the formation of electron-hole pairs due to thermionic or field enhanced processes [12]. Correlated Avalanche (CA) noise is due to at least two processes: the production of secondary photons during the avalanche in the gain amplification stage detected in nearby cells, and the trapping and subsequent release of charge carriers produced in avalanches. The latter process is usually referred to as afterpulsing, while the former is usually called crosstalk. Unlike DN events, CAs are correlated with a primary signal. DN and CAs events can be distinguished by studying the time distribution of events relative to the primary pulse using a method described in [13].



(a) (b)

Figure 1: a) Number of Correlated Avalanches (CAs) per primary pulse within a time window of 1 µs after the trigger pulse. b) Dark Noise (DN) rate normalized by the SiPM photon sensitive area.

The average number of CAs per primary pulse (N_{CA}) within a time window of 1 µs after the trigger pulse, for different SiPM temperatures and Over Voltages (OV) is reported in Fig. 1a)[1]. In order to meet the nEXO requirements (Sec. 1), the Hamamatsu VUV4 can be operated at T=163 K up to 4 V of over voltage keeping N_{CA} smaller than 0.2. For reference, at T=163 K and at 3.1 ± 0.2 V of over voltage we measure N_{CA} = 0.161 ± 0.005 for the Hamamatsu VUV4[2]. The measured DN rates, for different SiPM temperatures, are shown in Fig. 1b) always as a function of the over voltage. For the same temperature and over voltage setting used for the CA number (163 K, 3.1 ± 0.2 V of OV), the DN rate is measured to be 0.137 ± 0.002 Hz/mm^2, which satisfies nEXO requirements.

3 Photon Detection Efficiency

To meet nEXO requirements, the SiPM PDE must be ≥ 15% [7] for liquid xenon scintillation wavelengths (174.8 ± 10.2 nm [11]). In this paper, the PDE was measured using a filtered pulsed Hamamatsu L11035 xenon flash lamp enabling measurements free from correlated avalanches [2]. The mean wavelength after filtering is 189 ± 7 nm. The measurements

[1] The over voltage is defined as the difference between the reverse bias voltage and the breakdown voltage. The breakdown voltage is defined as the bias voltage at which the SiPM single PE gain (or charge) is zero.

[2] 3.1 ± 0.2 V is the closest measured points for which the requirement on N_{CA} is satisfied. At this over voltage and temperature the electronics noise was measured to be 0.064 PE.

were performed at 233 K to prevent dark noise overwhelming the light signal. The absolute light flux was calibrated using a reference PMT (R9875P Hamamatsu PMT). The Quantum Efficiency (QE) and the Collection Efficiency (CE) ([14]) reported by Hamamatsu for this phototube are 16.5 ± 2.1% and 71%, respectively. The CE of this phototube was reported by Hamamatsu without any estimate of the uncertainty. Conservatively, in agreement with [7], we assume a 10% error for the CE of this PMT (i.e. 71 ± 10%) to account for the non-uniformity of the photon collection efficiency at the photo-cathode.

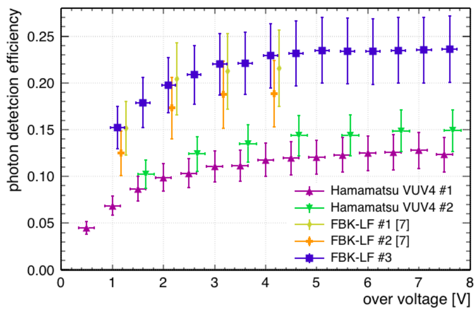


Figure 2: Photon Detection Efficiency (PDE) as a function of the over voltage for two Hamamatsu VUV4 MPPCs and three FBK-LF SiPMs. The error, on each point, for all the five devices accounts for the presence both to the statistical and the systematic uncertainty.

The measured PDE as a function of the over voltage is shown in Fig. 2 for two different VUV4 devices labelled VUV4 #1 and VUV4 #2. VUV4 #2 is the device for which DN and CAs are reported in the previous section of this paper. The measured saturation PDE for VUV4 #2 and VUV4 #1 are 14.8 ± 2.8% and 12.2 ± 2.3%, respectively. For comparison, we measured the PDE of one FBK LF (FBK LF # 3 in Fig. 2), for which the saturation PDE was measured to be 22.8 ± 4.3%, in agreement with [7] (FBK-LF #1 and #2 in Fig. 2). It is important to mention that different sources of systematic uncertainty were considered and investigated for this measurement. The PMT gain stability was found to be a negligible source of uncertainty. The stability of the light flux, monitored with a photo-diode (Newport 918D-UV-OD3), was also found to have a negligible effect, with fluctuations within 1 %. The dominant source of systematic uncertainty is therefore the uncertainty on the PMT CE.

4 Conclusion

This paper describes measurements performed at TRIUMF to characterize the properties of VUV sensitive SiPMs at cryogenic temperatures. For a device temperature of 163 K, the VUV4 dark noise rate is 0.137 ± 0.002 Hz/mm^2 at 3.1 ± 0.2 V of over voltage, a level comfortably lower than what required for nEXO (<50 Hz/mm^2). At the same over voltage setting and temperature, we measure a number of correlated avalanches per pulse in the 1 µs following the trigger pulse equal to 0.161 ± 0.005, also consistent with nEXO requirements. Finally, the PDE of the Hamamatsu VUV4 was measured for two different devices (labelled as VUV4 #2 and VUV4 #1) at T = 233 K. At 3.6 ± 0.2 V and 3.5 ± 0.2 V of over voltage we measure, for a mean wavelength of 189 ± 7 nm, a PDE of 13.4 ± 2.6 % and 11 ± 2% for the two devices, corresponding to a saturation PDE of 14.8 ± 2.8 % and 12.2 ± 2.3 %, respectively. Both values are well below the 24 % saturation PDE advertised by Hamamatsu [15]. More generally, the VUV4 #1 at 3.5 V of over voltage is below the nEXO PDE requirement. The VUV4 #2 instead yields a PDE that is marginally close to meeting the nEXO specifications. This suggests that with modest improvements the Hamamatsu VUV4 MPPCs could be considered as an alternative to the FBK-LF SiPMs for the design of the nEXO detector.

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