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Cherenkov TOF PET with silicon photomultipliers

R. Dolenec [a,b,c,*], S. Korpar [a,b], P. Križan [c,b], R. Pestotnik [b]

[a] Faculty of Chemistry and Chemical Engineering, University of Maribor, Maribor, Slovenia
[b] Jožef Stefan Institute, Jamova cesta 39, SI-1000 Ljubljana, Slovenia
[c] Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana, Slovenia

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ABSTRACT

As previously demonstrated, an excellent timing resolution below 100 ps FWHM is possible in time-of-flight positron emission tomography (TOF PET) if the detection method is based on the principle of detecting photons of Cherenkov light, produced in a suitable material and detected by microchannel plate photomultipliers (MCP PMTs). In this work, the silicon photomultipliers (SiPMs) were tested for the first time as the photodetectors in Cherenkov TOF PET. The high photon detection efficiency (PDE) of SiPMs led to a large improvement in detection efficiency. On the other hand, the time response of currently available SiPMs is not as good as that of MCP PMTs. The SiPM dark counts introduce a new source of random coincidences in Cherenkov method, which would be overwhelming with present SiPM technology at room temperature. When the apparatus was cooled, its performance significantly improved.

1. Introduction

The time resolution in time-of-flight positron emission tomography (TOF PET) measurements can be improved by basing the detection method on the use of Cherenkov light, produced promptly in a suitable Cherenkov radiator material. In this way, the contribution from scintillation light production mechanisms can be avoided and the time resolution becomes limited predominantly by the photodetector response and the optical photon travel time spread in the radiator. This method and an experiment, demonstrating a coincidence resolving time of 87 ps FWHM, were presented in our previous work [1–4]. Such a fast detection was achieved using lead fluoride (PbF_2) crystals with a thickness of 15 mm. At such thickness, the stopping power of PbF_2 is comparable to 20 mm of LSO scintillator. In addition, the PbF_2 has a higher photofraction due to its high Z_{eff}. The crystals were coupled to microchannel plate photomultiplier (MCP PMT) photodetectors, which were selected due to their very fast time response. The prototype Hamamatsu MCP PMTs used had a single photon time response of 50 ps FWHM [2], but had a relatively low quantum efficiency (QE) with peak value of 20%. Furthermore, due to the microchannel plate collection efficiency of approximately 60%, the photon detection efficiency (PDE) was only about 12%. With super-bialkali photocathode with peak QE of 35% and MCP collection efficiency of 60% a single side gamma detection efficiency of about 10% would be possible.

In efforts to improve the efficiency, the silicon photomultiplier (SiPM) was considered as a photodetector for the Cherenkov TOF PET method. Compared to MCP PMTs, the SiPMs have significantly higher peak photon detection efficiency that can typically reach 40%. However, with SiPMs this peak is shifted to higher wavelengths and the efficiency drops more abruptly at lower wavelengths, where more Cherenkov photons per unit wavelength are produced (Fig. 1). According to simulation prediction, the net effect is still an approximately four fold increase in coincidence detection efficiency; in addition, the improvement in UV sensitivity has already been demonstrated [6] so a further improvement in gamma detection efficiency can be expected. The SiPMs also have other benefits: they are insensitive to strong magnetic fields (suitable for PET/MR scanners) and might soon become more cost effective than other photodetectors currently used in PET. However, compared to MCP PMTs the SiPMs have a worse time response – the single photon time resolution of larger area SiPMs is about 200 ps FWHM [7] – and have high dark count rates on the order of 100 kHz/mm^2 at room temperature. The dark count rate represents a challenge for the use of SiPMs in Cherenkov TOF PET: on average, only a few Cherenkov photons reach the photodetector after 511 keV gamma interactions with the radiator and the method has to rely on detection of single photons, which produce pulses indistinguishable from the pulses due to dark counts. To

* Corresponding author at: Jožef Stefan Institute, Jamova cesta 39, SI-1000 Ljubljana, Slovenia. Tel.: +386 1 477 3157; fax: +386 1 477 3166.
E-mail address: rok.dolenec@ijs.si (R. Dolenec).

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reduce the dark noise background, the presently available SiPMs have to be cooled.

In this paper, the first Cherenkov TOF PET measurements using SiPMs are presented. Hamamatsu S10931-050P $3 \times 3\ mm^2$ SiPMs were used in combination with PbF_2 Cherenkov radiators in a back-to-back set-up presented in the next section. The measurements were performed at temperatures between $-25\ °C$ and $+25\ °C$. The effects of the temperature and overvoltage on the investigated detector performance are shown and discussed in Section 3, followed by the conclusion in Section 4.

2. Experiment and methods

Two gamma detectors, consisting of a $3 \times 3\ mm^2$ active area SiPM optically coupled to a $5 \times 5 \times 15\ mm^3$ PbF_2 crystals, were positioned in a back-to-back configuration (Fig. 2). This crystals were already used in our previous measurements with MCP PMTs as photodetectors. Hamamatsu S10931-050P SiPM samples with 50 µm pixels were used due to their low dark count rates. According to producer specifications, at room temperature they have a dark count rate of 0.77 MHz per device. Their specified single photon time resolution is

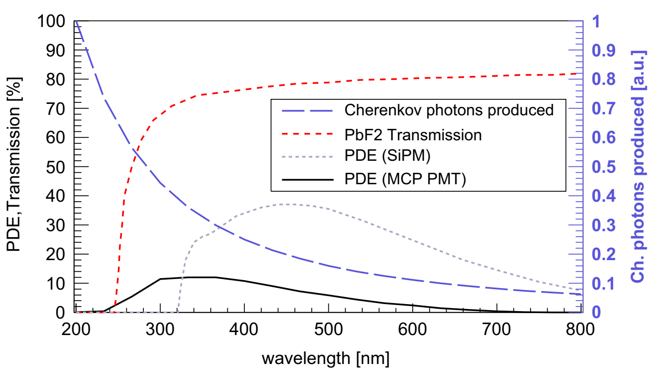

Fig. 1. The PDE of MCP PMT photodetector used in previous experiments [1–4], compared to the PDE of Hamamatsu S10931-050P SiPM. The former was calculated as quantum efficiency × collection efficiency, while the latter is the standard SiPM PDE as reported by the producer, excluding the effects of crosstalk and afterpulses. Also shown are the optical transmission of 25 mm thick PbF_2 crystal [5] and the $1/\lambda^2$ distribution, indicating the wavelength dependence of produced Cherenkov photons.

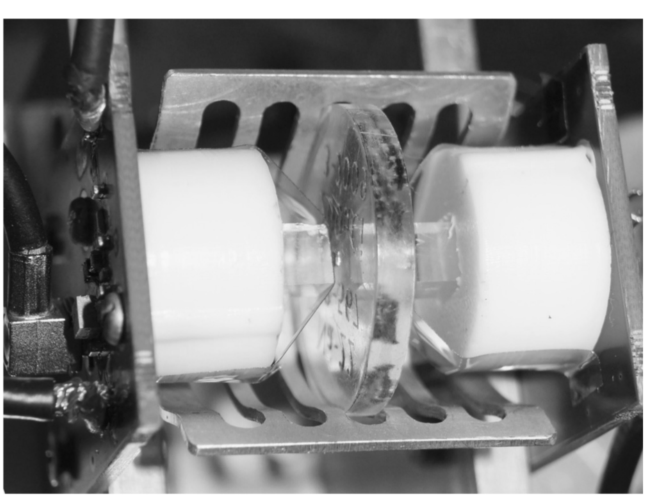

Fig. 2. The experimental set-up: two PbF_2 Cherenkov radiators coupled to SiPM photodetectors, positioned very close to a ^{22}Na point source. Optical crosstalk between the two detectors was suppressed using a thin, black plastic foil, which is not shown in this figure.

about 500 ps FWHM [8], while recent reports indicate a better resolution of about 200 ps FWHM with the same SiPM type [7]. The crystals were polished and either bare or black painted, while their exit surface was centered with SiPM active surface using mechanical supports, machined out of 10 mm thick Teflon. In case of bare PbF_2, the reflectivity of the Teflon supports also contributed to an increased number of detected Cherenkov photons.

The two detectors were positioned very close to a 1.8 MBq ^{22}Na point source, so that the distance between individual crystal entry surface and the source was approximately 5 mm. Such small distance was used so that even at room temperature the rate of true coincidences was not significantly smaller than the rate of random coincidences due to SiPM dark counts. The source and both detectors were enclosed in lead radiation shielding, which in turn was stationed in a light tight, temperature controlled freezer.

The SiPMs were soldered to custom electronic boards with a NEC uPC2710TB preamplifier. Preamplified signals were lead out of the freezer box and into a leading edge discriminator (Phillips Scientific Mod.708), after additional amplification (Ortec FTA820) and a passive signal splitter. Discriminator threshold was set to 0.5 single photoelectron signal height. Logic signals from the discriminator were used for time information (Kaizu works KC3781A TDC) and coincidence logic (Phillips Scientific Mod.752). The other outputs of the signal splitter were used for the charge information (CAEN Mod.V965 QDC), which was needed for the correction of time-walk due to the use of a leading edge discriminator. The measurement was triggered by an AND output of the coincidence logic, with a coincidence resolving time set to 10 ns. To accommodate the time needed to form the coincidence trigger, the signals led to TDC and QDC were delayed by approximately 70 ns.

The coincidence time was calculated as the difference between the time-walk corrected TDC measurements from the two detectors. The obtained distributions were fitted with a sum of a constant and two Gaussian functions and the time resolution was expressed as full width of the peak at one half between the constant noise floor and the peak maximum (e.g. FWHM of the double Gaussian component of the fit function). This value will be reported simply as FWHM throughout this paper.

To quantify the effects of SiPM dark counts in Cherenkov TOF PET, a signal-to-noise (S/N) value was defined as the ratio between the number of detected Cherenkov coincidences and the number of random coincidences due to dark counts. These were estimated from the integral of the double Gaussian and the constant components of the fit function, respectively. The ratio was calculated for the coincidence time windows (integration intervals) of ± 10 ns, ± 4 ns and ± 2 ns. The shortest 4 ns ($= \pm\ 2$ ns) wide time window corresponds to a field-of-view of 60 cm. This is more or less the smallest practical time window for full-body PET, especially considering the axially tilted lines of response.

3. Results and discussion

3.1. TOF PET measurements

Fig. 3 shows the coincidence time distributions in cases with and without the ^{22}Na source present between the two detectors. Here, bare PbF_2 crystals were used, while the SiPMs were biased at a producer recommended overvoltage of $V_{ov} =$ 1.5 V and the temperature was set to $+25\ °C$. As can be seen, the random coincidences due to SiPM dark counts result in a constant background.[1] The measurement

[1] The count ripple in both cases, with and without the source, was caused by crosstalk between the channels of the discriminator. This crosstalk has no significant effect on the measured efficiency and timing resolution.