A Novel Concept for PET Scanners Design using Polaroid-based Detectors for Filtering Reflected Optical Photons

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***Abstract*– The aim of this work is to propose and assess a new detector module for an animal PET scanner, called Polaroid-PET. Polaroid-PET's detector modules consist of monolithic crystals on which a layer of Polaroid sheet is stick on one side to filter unpolarized optical photons. The polaroid sheet filter reflects optical photons and thus enhances the spatial resolution in the detector module based on monolithic scintillator crystals. In the initial step, the GEANT4 Monte Carlo toolkit is used to simulate a detector block consisting of a lutecium-based monolithic crystal (LYSO) with a crystal thickness of 10 mm and semiconductor-based Silicon Photomultipliers. A Polaroid sheet was placed between the crystal and the SiPMs to block unpolarized photons come from the crystal. In the next step, two preclinical PET scanners with and without Polaroid based on 10 detector modules were simulated. The performance of the two detector modules and preclinical PET scanners were assessed by calculating the spatial resolution, and depth of interaction (DOI). The Polaroid-equipped detector module resulted in a better spatial resolution with ~1.05 mm full-width at half maximum (FWHM) compared with the regular detector (~1.3 mm FHWM) for a point source placed in front of the center of the detector's entrance face. Our Polaroid-based PET scanner led to better axial spatial resolution in comparison with the regular small-animal PET scanner for a point source placed at the center of the field-of-view (0.83 mm vs. 1.01 mm FWHM). By filtering reflected unpolarized optical photons, Polaroid-PET was able to achieve improved spatial resolution and sensitivity compared to the original design.**

I. Introduction

In an ideal PET scanner, one of the most challenging problems is the undeniable trade-off between the spatial resolution and system sensitivity. Detectors with high crystal thickness and large pixel size (in pixelated detectors) result in high sensitivity and poor spatial resolution as a result of parallax error and inaccurate positioning. Thanks to the ability to the depth of interacting (DOI) extracting [1] and better energy/timing resolution in monolithic crystals, they have been taken attention by many groups for achieving high spatial resolution. Monolithic crystal-based detectors, require a complex and time-consuming calibration process and based on the application, there is a need to choose an optimized thickness to preserve sensitivity and spatial resolution simultaneously [2]-[3].

This work was supported by the Swiss National Science foundation under grant SNFN 320030_176052 and the Private Foundation of Geneva University Hospitals under Grant RC-06-01.

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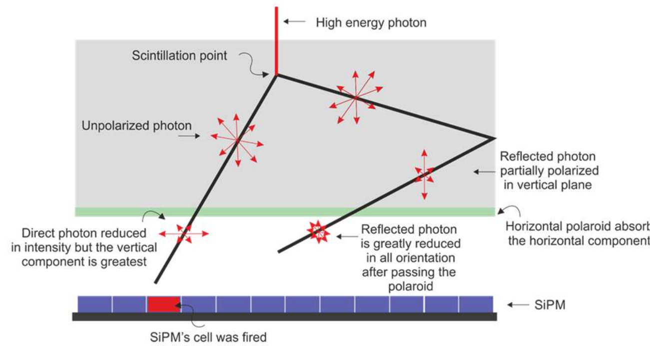

Fig. 1. A schematic diagram of a polaroid-equipped detector showing the trajectory of two imaginary optical photons and their statues after reflection and passing through the polaroid prior to reaching the SiPM.

The generated scintillation photons in the crystal are electromagnetic waves. The optical photon propagation vector and the electric and magnetic field vector can have different orientations related to each other. The type of polarization has a direct relation to the orientation of the electric field. Polaroids are of various types, including synthetic glass or plastic sheets that can be employed as a polarizer to transmit light with a special state of polarization and eliminate others. (Fig. 1).

Throughout this study, the Polaroid-PET concept is presented and its implementation on a small-animal PET scanner mounted with detectors equipped with silicon-based photomultipliers (SiPMs) and the Polaroid sheet instead of light guides located between the scintillator and SiPMs discussed [4]. Our idea is simple to use and cost-effective to implement to regular scanners, just by inserting a thin Polaroid sheet between the SiPMs and the scintillator. It is easy to expand our approach to clinical PET scanners, where even better results can be expected than in small-animal PET scanners.

II. Material and Method

Monte Carlo simulations enabled to evaluate the efficiency of the detector blocks with/without Polaroid for a small-animal PET scanner to assess the potential of the proposed concept. A detector module includes a continuous LYSO crystal with an entrance area of 50.2 × 50.2 mm^2 and crystal thickness of 10

2020 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC) | 978-1-7281-7693-2/20/$31.00 ©2020 IEEE | DOI: 10.1109/NSS/MIC42677.2020.9508069

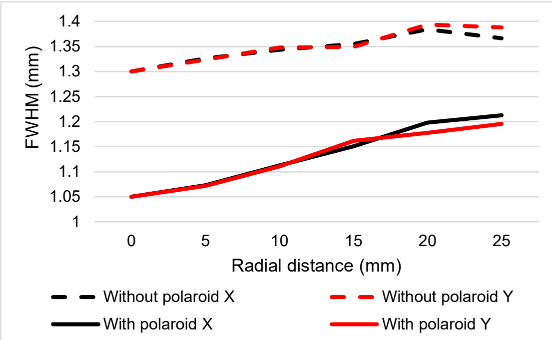

Fig. 2. Comparison of the spatial resolution between a single detector block equipped with (solid line) and without (dash line) Polaroid in X and Y directions.

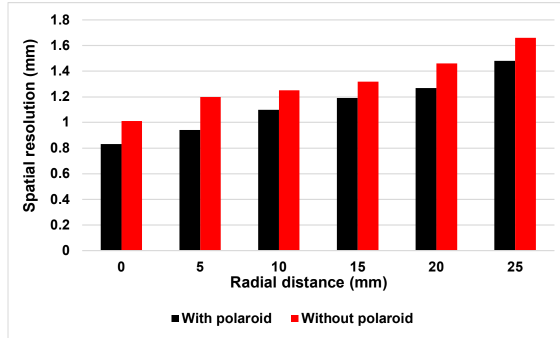

Fig. 3. The spatial resolution in the radial direction for the preclinical PET scanner comprising ten detectors' modules equipped with and without Polaroid.

mm, fixed to a SiPM array with 12 × 12 rows and columns and 4.2 mm pixel pitch, was simulated as regular configuration. For the crystal reflector, a thin layer of barium sulfate ($BaSO_4$) with 0.1 mm thickness was warped to surround the crystal. A thickness of 0.05 mm of glue was used for the optical coupling of the SiPM, crystal, and polaroid. The only modification between the regular detector module and the detector with Polaroid is the presence of a 0.5 mm thick Polaroid sheet between SiPM and the crystal and the extra layer of glue.

Two preclinical PET configurations equipped with and without the Polaroid were simulated to estimate and evaluate the potential of the Polaroid-based detector module in small-animal PET scanners.

III. Results

The validation of our simulation showed that the simulated and measured spatial resolution are in close agreement (within 5%) at the center of the field-of-view (CFOV), while the absolute sensitivity bias was close to 8% [1]. For a single detector module equipped with and without the Polaroid sheet, the estimated spatial resolution along the X and Y axes is depicted in Fig. 2.

The spatial resolution in the Z direction (DOI) was measured for various depths (depths of 2, 4, 6, and 8 mm) in a monolithic crystal for a single detector with and without Polaroid (Table 1). At comparatively far distances from SiPMs' surface, the effect of optical photon filtering by Polaroid is more evident than close distances.

The NEMA NU4 standard was considered for spatial resolution evaluation of the preclinical PET scanner with and without the Polaroid as shown in Fig. 3.

TABLE I
The DOI Resolution for a Single PET Detector Module with and without the Polaroid.

Depth (mm)	Without polaroid (mm)	With polaroid (mm)
2	0.58	0.49
4	0.73	0.56
6	0.94	0.78
8	1.09	0.91
10	1.32	1.06

IV. Discussion

The detector with Polaroid achieved a spatial resolution of 1.07 mm FWHM at the center and increased gradually to 1.19 mm FWHM at the detector corner. Conversely, the spatial resolution ranges between 1.3 mm and 1.39 mm for a regular detector module without a Polaroid. The high number of reflections and the weak performance of the positioning algorithms at the corners of the crystal provide plausible explanation on why the spatial resolution gets worse at these locations.

Our findings showed that the existence of a Polaroid sheet between crystal and SiPM in the PET scanner detector blocks enhances the spatial resolution by about 18%, although the absolute sensitivity remains almost constant. The sensitivity is a function of annihilated photons and the polaroid just filters the optical photon, therefore using polaroid does not have any influence on sensitivity.

To simultaneously enhance the spatial resolution and system sensitivity and tone down the trade-off between them, Polaroid-PET, a new small-animal PET scanner, was introduced. The proposed PE scanner comprises detectors with monolithic crystals to increase the sensitivity and a layer of Polaroid between the crystal and SiPMs to improve the spatial resolution. Considering a Polaroid sheet as an optical photon filter between the scintillator and SiPMs was the main novelty of this work. The intrinsically higher sensitivity of the monolithic crystal will maintain/enhance the scanner's detection performance, while the Polaroid sheet, helps the detectors to eliminate multi-reflected optical photons, resulting in better spatial resolution. The optimum trade-off between sensitivity and spatial resolution was achieved through this novel design, resulting in a 0.83 mm spatial resolution and a sensitivity of 4.4% at the CFOV for an animal PET scanner.

The major limitation of the current study is the absence of experimental validation of the Polaroid-PET. This validation needs a well-designed plan and access to required instruments. Another limitation is the lack of energy resolution assessment for the proposed scanner where we expect because of filtration of optical photon it influences of the energy resolution of the scanner.

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