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Optimization of the SiPM Pixel Size for a Monolithic PET Detector

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Abstract

Molecular imaging of small animals with PET requires high detection efficiency (DE). PET detectors consisting of monolithic scintillator coupled to position sensitive photo-detectors can yield high DE by reducing detection-inactive space. Silicon photo-multipliers (SiPMs) are compact photo-detectors with high gain, high photon detection efficiency (PDE) and fast response. There is a substantial interest in employing SiPMs for developing monolithic scintillator-based PET detectors. In this work, we investigate the optimization of the pixel size of an SiPM array to read out a monolithic scintillator. The pixel size of the SiPM affects the spatial resolution of the resulting detector in two ways. First, in general smaller pixels can measure more accurately the distribution of the scintillation lights at the exit surface of the scintillator to attain higher spatial resolution. On the other hand, a smaller pixel detects fewer light photons and yields higher pixel noise. As a result, the spatial resolution and energy resolution may be degraded. Consequently, the optimal pixel size of the SiPM array to use for achieving the best spatial resolution must be determined by considering the trade-off between these two factors. We conducted Monte-Carlo simulation to analyze the relationship between the SiPM pixel size in a monolithic-scintillator PET detector and the resulting spatial resolution. In our simulation, the scintillator was 10 mm thick, the gamma rays were assumed to interact at the center of the scintillator and the PDE of the SiPM was set to 20%. A range of scintillator light output was considered, including 30,000 photons per MeV that is typical of LYSO. The 3-d position of the interaction point of the gamma ray was estimated from the light distribution pattern measured by the SiPM array by employing the Nonlinear Least Squares Position Estimation method developed by Li et al. The results show that, for achieving the best resolution at the center of the detector the optimal pixel size of the SiPM array is between 5.4×5.4 mm^2 and 6.3×6.3 mm^2. Also, for achieving the best overall sptial resolution for the detector, the optimal pixel size was between 5×5 mm^2 and 8×8 mm^2.

Keywords:
SiPM PET detector Optimal pixel size Spatial resolution Monolithic scintillator

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1. Introduction

Silicon photo-multiplier (SiPM) is a novel photo-sensor with high gain at low operating voltage, fast timing response, and high quantum efficiency (QE). These properties, and its low-cost prospect when mass produced, make the SiPM an attractive candidate for replacing the photo-multiplier tubes (PMTs) in building positron emission tomography (PET) detectors [1, 2, 3]. A PET detector that consists of a monolithic scintillator readout by an SiPM array could provide a high spatial resolution and high detection efficiency, together with the advatnages of a compact structure and insensitivity to magnetic fields [4, 5]. The performance of such a detector is affected by the parameter settings of the SiPM array [6, 7]. Specifically, an SiPM array containing smaller pixels can measure the light distribution at the exit surface of the monolithic array more accurately to lead to a better spatial resolution. On the other hand, smaller pixels also mean fewer detected light photons and higher pixel noise, which can worse the detector's energy resolution and spatial resolution. Therefore, there should exist an optimal pixel size for the SiPM array. In this work, we characterize the relationship between the pixel size in an SiPM array and the spatial resolution of the monolithic PET detector by conducting Monte-Carlo (MC) simulation.

2. Methods and Results

2.1. Monolithic scintillator detector

The structure of a PET detector consisting of a monolithic scintillator and an SiPM array to be considered in this paper is shown in figure 1. The bottom surface of a 10 mm thick monolithic scintillator is optically coupled to a 3×3 SiPM array and the other five surfaces are polished and painted black. All scintillation lights that reach the black surfaces are completely absorbed. There are no gaps between the SiPM pixels.

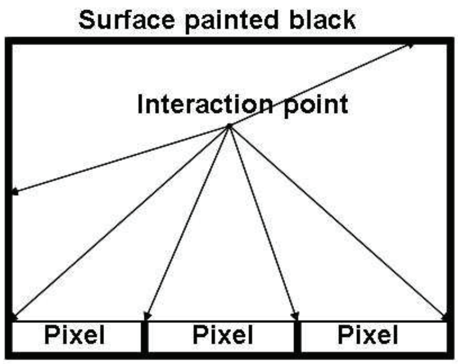

Figure 1. A SiPM PET detector

2.2. Pixel size optimization for achieving the best resolution at the center of the detector

As already mentioned above, the pixel size of an SiPM array affects both the accuracy and precision of the measurements of the scintillation light distribution on the exit surface of the scintillator. The accuracy and precision both affect the performance of the estimation of the gamma photon interaction position, and hence affect the spatial resolution of the detector. In this section, we study the relationship between the noise and spatial resolution by fixing the pixel size, and also the relationship between the pixel size and spatial resolution by fixing the noise level.

For a given interaction point and SiPM pixel size, we assumed complete deposition of the 511 keV energy of the gamma ray at the interaction point and from there a certain number of light photons were isotropically generated in accordance with the assumed light output of the scintillator. We then employed the DETECT2000 software to track the transport of the light photons until they reach the exit surface of the scintillator and calculated the number of light photons that each SiPM pixel would detect in accordance with its position and size, by assuming a 20% PDE [10]. We repeated such simulation and calculation 10,000 times and from them we obtained the mean, s_{ij}, and standard deviation, σ_{ij}, of the number of light photons that each SiPM pixel would detect, where ij index the row and column number of the pixel. The SNR of the measurement was calculated by SNR = $\sum_{ij} s_{ij}^2 / \sum_{ij} \sigma_{ij}^2$. For each simulated data set, we also applied the 3D Nonlinear Least Squares Position Estimation (NLSPE) method proposed by Li *et al* [8, 9] to estimate the interaction point from the numbers of the photons detected by the SiPM pixels. Conceptually, this estimation method is based on the observation that, because the top and side surfaces are painted black and fully light-absorbing, the number of the light photons collected by each pixel in the SiPM array will be proportional to the solid angle subtended by the pixel with respect to the interaction point of the gamma ray. Thus, the interaction position could be estimated as the space point that minimizes, in the least-squares sense, the difference between the actual numbers of photons detected by the SiPM pixels and the estimated numbers of photons these pixels shall detect basing on their solid angles to the space point. The spatial resolution was then defined as the full-width-at-the-half-maximum (FHWM) of the histogram of the resulting 10,000 position estimates from the 10,000 repeated simulations.

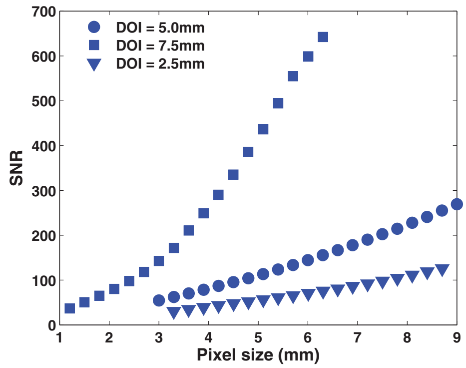

Figure 2. The SNR of the detector as a function of the SiPM pixel size.

We first considered a scintillator light output of 30,000 photons per MeV, which corresponds to that of LYSO. The interaction position was fixed at the center of the detector but at various depths of interaction (DOIs), including 2.5 mm, 5.0 mm, and 7.5 mm. Figure 2 shows the resulting SNR of the light distribution as a function of the pixel size. As shown, better SNR is obtained by an SiPM array having larger pixels because a larger pixel has a larger solid angle to light photons generated at the interaction point. Due to Poisson statistics of photon detection, more lights collected means higher SNR. Also observed in figure 2 is that, when the interaction point is deeper (closer to the SiPM array), the solid angle of the SiPM pixel becomes larger and more lights, and hence higher SNR, are obtained.

Next, we examined the relationship between the noise and spatial resolution by fixing the pixel size at $8 \times 8\,\mathrm{mm}^2$ and the interaction position at the center of the scintillator with DOI=5 mm DOI. First, we varied the light output of the scintillator in the simulation and figure 3.a shows the linear increase of the SNR with the light output, as anticipated from the Poisson statistics. Figure 3.b shows the variation of the spatial resolution with the SNR, indicating that a better SNR leads to higher spatial resolution. Note that in this case, the accuracy in the light distribution measurement is fixed because the SiPM pixel size is fixed. However, when the light yield increases the precision (and SNR) of the light distribution measurement improves, leading to less statistical variations in the position estimate generated by the NLSPE method and hence better spatial resolution.

We also fixed the SNR (arbitrarily at the value 218) by varying the scintillator light output and studied the variation of the spatial resolution with the SiPM pixel size. Figure 4 shows that smaller SiPM pixels lead to better spatial resolution. The increase is originally linearly until it reaches a best resolution of about 0.34 mm (possibly reflecting the limiting resolution achieved by the set SNR level). Note that in this case, the SNR (and precision) in the light distribution measurement is fixed but the accuracy is increased by the

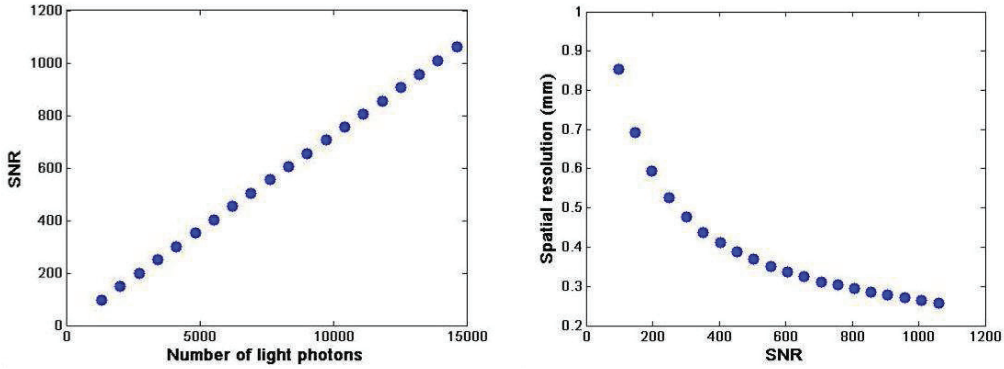

Figure 3. (a) The SNR as a function of the light output. (b) The spatial resolution at the center of the detector as a function of SNR.

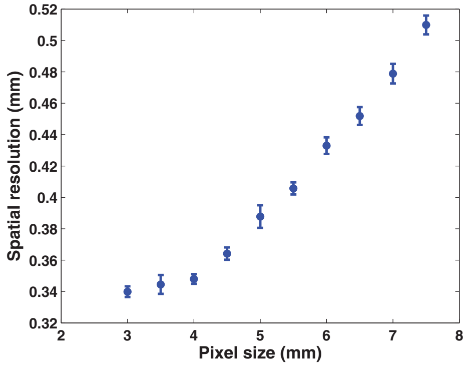

Figure 4. The spatial resolution at the center of the detector as a function of the pixel size with fixed SNR.

use of smaller SiPM pixels.

Thus, the SiPM pixel size affects the spatial resolution of the detector in two ways. One is the noise, and generally a larger pixel size is required to collect more light photons and reduce noise. The other is the accuracy, and generally a smaller pixel size is required to provide more accurate measurement of the light distribution. The trade-off between these two factors will result in an optimal pixel size for achieving the best spatial resolution. To investigate this, we considered interaction point at the center of the detector with the DOI equals to 7.5 mm, 5 mm or 2.5 mm, set the scintillator light output to 30,000 photons per MeV (corresponding to that of LYSO), and fixed the PDE at 20%. Figure 5 shows the variation of the resulting spatial resolution with SiPM pixel size. As shown, for given DOI there is an optimal pixel size for achieving the best spatial resolution, which is between 2.1×2.1 mm^2 and 3.0×3.0 mm^2 for DOI=7.5 mm to reach a best resolution of ~0.9 mm, between 5.4×5.4 mm^2 and 6.3×6.3 mm^2 for DOI=5.0 mm to reach a best resolution of ~0.6 mm, and between 6×6 mm^2 and 9.7×9.7 mm^2 for DOI=2.5 mm to reach a best resolution of ~0.3 mm. Away from this optimum, the spatial resolution worsens as the SiPM pixels becomes larger due to decreased accuracy in the light distribution measurement, and smaller due to decreased precision in the light distribution measurement. It is also observed that the best spatial resolution is higher for a deeper DOI but smaller SiPM pixels must be used to achieve it. This is because, as we have already observed above, as the interaction points go deeper the SNR of the light distribution measurement obtained by using the same pixel size increases. On the other hand, a deeper interaction point also leads to more concentrated light distribution at the exit surface that requires the use of smaller pixels to measure it accurately. Thus, the DOI=7.5 mm curve has an optimum that is narrower, reflecting its more concentrated light distribution, and deeper, reflecting its better SNR.

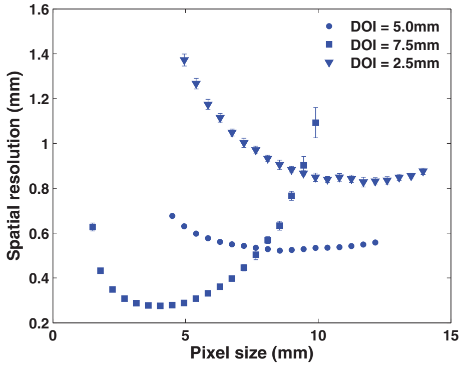

Figure 5. The spatial resolution at the center of the detector as a function of the pixel size

2.3. SiPM pixel size optimization for the overall spatial resolution of the detector

Above, we have investigated the spatial resolution at the center of the scintillator. In this section, we will evaluate the overall spatial resolution property of the detector. For this purpose, we employed the GATE software to obtain the random interaction points of the gamma rays in the scintillator by placing a point source sufficiently away to create a flood field to the detector. Then, the procedure described above with the use of the DETECT2000 was applied (assuming a light yield of 30,000 photons/MeV and a 20% PDE for SiPM). We obtained the histogram of the difference value (D-value) between the estimated interaction position and its true position and the overall spatial resolution of the detector was defined as the FWHM of this histgoram. Figure 6.a plots the estimated x positions of the gamma rays with the actual positions obtained by an SiPM array containing $15 \times 15\,\text{mm}^2$ pixel sizes and figure 6.b shows the corresponding histogram of the D-value. Figure 7 shows the overall detector resolution thus obtained by varying the SiPM pixel size. It indicates that a best spatial resolution of ~0.85 mm when a pixel size between $5 \times 5\,\text{mm}^2$ between $8 \times 8\,\text{mm}^2$ is used.

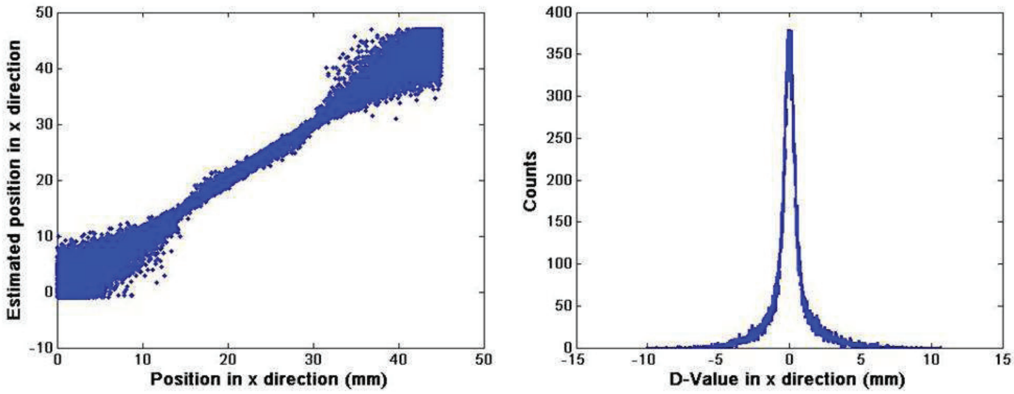

Figure 6. (a) The estimated interaction position as a function of true interaction position. (b) The histogram of the D-value.

3. Conclusions and Discussion

In this work we study the spatial resolution of a monolithic scintillator with different SiPM pixel size by using Monte Carlo simulation. The results show that in order to obtain a better spatial resolution, we should use a SiPM array consisting of small pixels in order to measure the scintillation light distribution

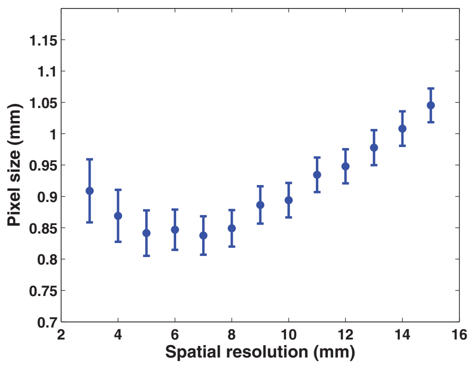

Figure 7. The spatial resolution of the detector as a function of the pixels size.

accurately. On the other hand, it is also necessary to use large pixels in order to obtain measurement of good precision and SNR. The tradeoff between the accuracy and precision determines the optimal SiPM pixel size to use for achieving the best spatial resolution. Specifically, our results indicate that the optimal pixel size for achieving the best overall spatial resolution for the detector is between $5 \times 5\,\mathrm{mm}^2$ and $8 \times 8\,\mathrm{mm}^2$ when the scintillator light output is 30,000 photons/MeV (that of LYSO) and the PDE of the SiPM is 20%. In this case, the best overall spatial resolution of the detector is ~0.85 mm. Based the results, we can stipulate that when the PDE of the SiPM is improved, the SNR of the measured light distribution will increase; as a result, smaller SiPM pixel size can be used to achieve higher spatial resolution. When the scintillator becomes thicker, the average distance between the interaction point to the SiPM array increases to result in less detected lights and less concentrated light distribution. In this case, larger SiPM pixel size shall be used to achieve the best spatial resolution, which in turn will be worse than that reported in this paper.

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