Undergraduate Research Fellowship Proposal: Using Cherenkov Radiation for Cost-Effective Total Body PET

Firas Abouzahr with Supervisor Karol Lang

Abstract

Total body PET scanners have great potential to surpass the sensitivity capabilities of today's smaller-scale scanners. In order to make total body PET physically realizable for clinical use in the future, it is essential to develop cost-effective scanners. We are researching novel, BGO-based scanner geometries to develop financially attainable total body PET scanners. While BGO's scintillation properties are less favorable than other commonly used PET scintillators, it is much more cost-effective and has the unique ability to act as a dual Cherenkov-scintillation radiator. Geant4 Monte Carlo simulations have demonstrated that when using BGO as a dual radiator, we can reduce the coincidence time resolutions of our total body scanners by more than 500 ps when compared to only using scintillation light. I propose to experimentally study BGO scintillators to validate and optimize these simulation results. This will aid in confirming the performance of our total body scanners and the feasibility of using Cherenkov radiation for PET.

1 Introduction

Positron Emission Tomography (PET) is a medical imaging technique based on detecting radiation from positron-emitting radiopharmaceuticals injected into patients [1]. These radiopharmaceuticals accumulate in areas of high metabolic function, such as tumors [2]. The positrons emitted from the radiopharmaceuticals annihilate with electrons in the surrounding tissue to produce two back-to-back 511 keV gamma rays. The gamma rays from each event are then detected in coincidence by a PET scanner surrounding the patient. PET scanners encompass two primary components: scintillators and coupled photosensors called silicon photomultipliers (SiPMs). The coincident gamma rays (that successfully make it to the scanner) absorb within a PET scanner's scintillators and re-emit as visible-light photons which can then be detected by corresponding SiPMs.

In clinical use today, PET imaging is overwhelmingly conducted using organ-specific or generally small-scale PET scanners that only cover about 10% of a patient's body [3]. Since the annihilation gammas are isotropically produced, many gamma rays escape the patients' bodies at undetectable trajectories, making these scanners' sensitivities significantly lower. For this reason, the development of total body PET scanners has become of great interest to researchers and medical-professionals alike. Total body scanners completely encase a patient's body allowing for a significant increase in gamma ray detection. However, total body PET scanners are, in many ways, financially unviable. The technology and materials required for PET (e.g., SiPMs, scintillators, & read-out electronics) are quite costly, leading to an optimistic cost estimation of around 8 million dollars per total body scanner. Consequently, only a few total body scanners have ever been developed worldwide [3]. We propose a low-cost approach to total body PET scanners utilizing novel geometries and materials without significantly sacrificing performance.

2 Background and Research Objectives

2.1 PET Imaging

PET images are produced by localizing the position of the positron-electron annihilation events along lines-of-response (LORs). A LOR is the path that connects two SiPM channels in a PET scanner that detected coincident gamma rays [1]. A critical parameter in reconstructing high-resolution images is coincidence time resolution (CTR). CTR is a scanner's ability to determine the difference in detection time (time-of-flight) between two back-to-back annihilation gammas, which can be used to significantly improve the localization of annihilation positions along the LORs. This parameter largely depends on the properties of a PET scanner's scintillators; hence, the choice of scintillator is crucial.

2.2 Current Studies

Our group is designing and testing exploratory total body PET scanners with cost-effective geometries and inexpensive scintillators via Geant4 Monte Carlo simulations. The two geometries we are currently exploring are displayed below in Figures 1 and 2. Each of these scanners comprises multiple modules, an 8×8 scintillator array coupled to a corresponding 8×8 SiPM array. Each crystal in the 8×8 scintillator arrays is $3\times3\times12$ mm^3. The simulated scanner in Figure 1 utilizes the sparsification of modules in a checkerboard fashion, minimizing the required materials while still encompassing the increased solid-angle coverage of a cylindrical scanner. Figure 2 displays a scanner composed of two large parallel planes of modules. Highlighted in green is an example of simulated back-to-back gammas from an off-center point source striking coincident pixels. While this design loses solid angle coverage, it allows for a complete encasing of a patient's body with fewer modules than any cylindrical design.

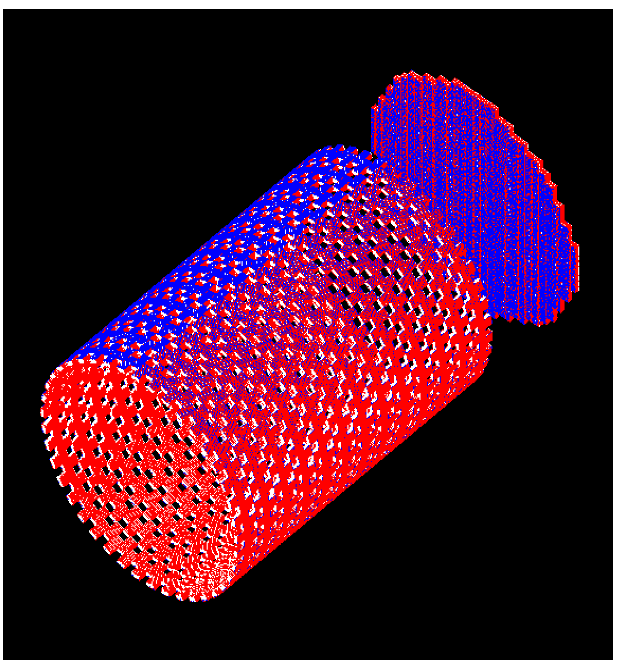

Figure 1: The sparsified cylindrical total body PET scanner.

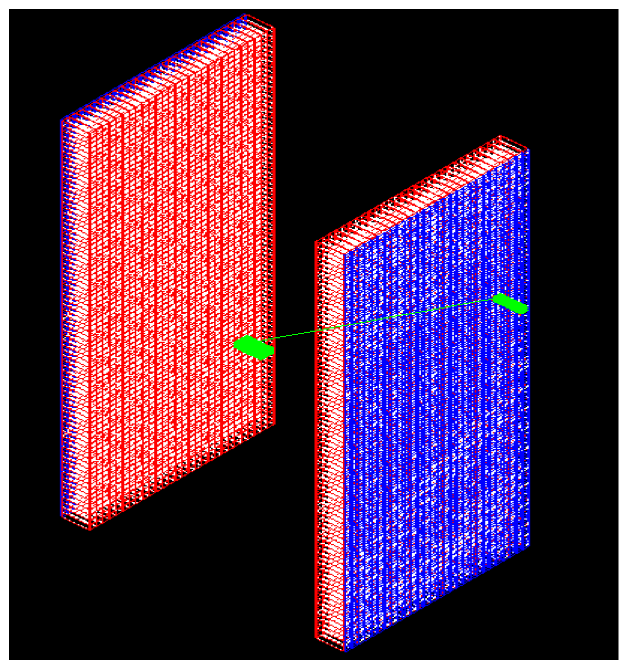

Figure 2: The parallel plane total body PET scanner.

In the current stage of simulations, we are in the process of testing the application of the inexpensive scintillator BGO ($Bi_4Ge_3O_{12}$) in our total body scanners. BGO has a low-light yield of 8-10 photons per keV, a primary decay constant of 300 ns, and a secondary decay constant of about 60 ns, which comprises only 10% of the total scintillation light [4]. The long primary decay of BGO results in large CTR values ranging from 1 to 4 ns, making it unfavorable for time-of-flight PET [5,6]. However, in recent years, researchers have been studying BGO as a dual Cherenkov-scintillation radiator [4,6]. Cherenkov radiation is the electromagnetic radiation emitted when a charged particle moves faster than light in a given medium. BGO's high refractive index of 2.15 allows electrons struck by annihilation gammas to emit Cherenkov photons along with the usual scintillation light. Cherenkov light is emitted quasi-instantaneously, which can produce significantly fast CTRs in BGO [4,6,7]. This makes BGO an excellent candidate for high-performance, cost-effective PET scanners. Geant4 simulations indicate that our BGO-based scanner modules can detect up to 40.3% of the total produced Cherenkov photons. With this Cherenkov detection efficiency, we have reduced our CTRs by over 500 ps compared to when only using scintillation light, giving our scanners a significant performance boost. Figures 3 and 4 illustrate characteristic timing differences from our scanner modules with and without the ability to detect Cherenkov photons. Further improvement can be achieved by optimizing the electronic threshold of detected Cherenkov photons.

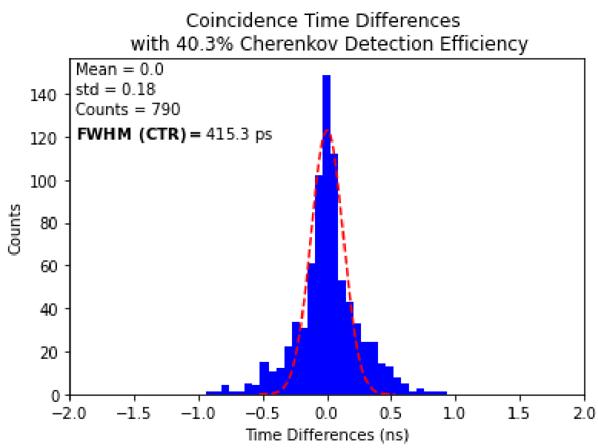

Figure 3: Simulated coincidence time difference distribution with 40.3% Cherenkov detection.

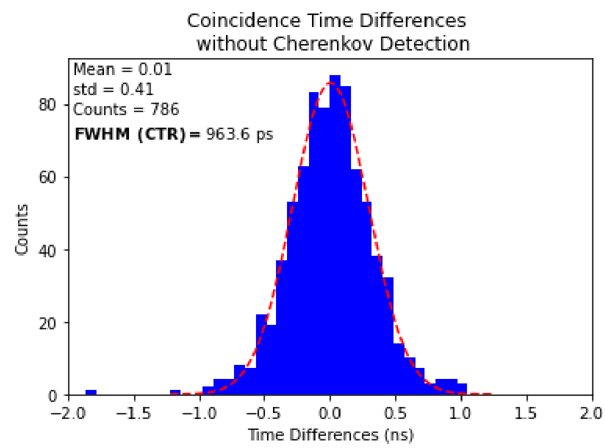

Figure 4: Simulated coincidence time difference distribution without Cherenkov detection.

3 Methods

Our group already has SiPMs, from which our simulated SiPMs are accurately modeled after, as well as the proper read-out electronics and software needed to assemble PET modules. With access to BGO, we will fully assemble two characteristic modules from our simulated scanners, put them in coincidence, and irradiate them with a positron source. We will also simultaneously simulate the experimental configuration to cross-check results. We will then measure various observables to produce canonical parameters such as CTR and energy resolution. After initial measurements, we will vary experimental parameters such as SiPM bias voltage to study how to improve the Cherenkov photodetection efficiency of our modules. This will serve as a way to fine-tune our simulations and contribute to the ongoing research regarding Cherenkov-based PET.

4 Resource Requirements

The required funds for experimental validation of our simulated modules is approximately $1500. This grant money would be used to purchase two 8x8 BGO crystal arrays with the exact crystal dimensions from our simulations. I am requesting the maximum Undergraduate Research Fellowship grant of $1000 in order to cover the majority of these expenses. My principal investigator Dr. Karol Lang has agreed to cover the additional $500.

5 Significance

The Undergraduate Research Fellowship grant would greatly benefit my personal experience as an undergraduate research assistant and help us make meaningful strides forward in making total body PET accessible in the future. This semester, Spring 2023, I have begun my senior thesis on cost-effective, BGO-based total body PET scanners. For the past two years, I have actively participated in many PET-related experiments and simulations, primarily conducted under the guidance of graduate students. While these have been excellent learning experiences, obtaining scintillators specific to my independent study would give me an excellent opportunity to act as a lead researcher, affording me valuable experience as an aspiring experimental physicist. Moreover, the data collected from these experimental studies with BGO would significantly strengthen the simulation results presented in my thesis and possibly a peer-reviewed paper.

Total body scanners have a chance to greatly help with the detection of cancer and other diseases. My simulation results are thus far yielding promising results that suggest cost-effective total body scanners are achievable without sacrificing substantial performance of more traditional PET scanners. If we can experimentally validate the technology behind these total body scanners, our studies will take many steps further in demonstrating the attainability of low-cost total body scanners and, more generally, Cherenkov-based time-of-flight PET scanners.

References

[1] Turkington, T. G. (2001). Introduction to PET instrumentation. *Journal of nuclear medicine technology*, 29(1), 4-11.

[2] Shahhosseini S. (2011). PET Radiopharmaceuticals. *Iranian journal of pharmaceutical research* : IJPR, 10(1), 1–2.

[3] Cherry, S. R., Jones, T., Karp, J. S., Qi, J., Moses, W. W., Badawi, R. D. (2018). Total-Body PET: Maximizing Sensitivity to Create New Opportunities for Clinical Research and Patient Care. *Journal of nuclear medicine*, 59(1), 3–12.

[4] Brunner, S. E., Schaart, D. R. (2017). BGO as a hybrid scintillator/Cherenkov radiator for cost-effective time-of-flight PET. *Physics in Medicine Biology*, 62(11), 4421.

[5] Szczęśniak, T., Kapusta, M., Moszyński, M., Grodzicka, M., Szawłowski, M., Wolski, D., ... Zhang, N. (2013). MPPC arrays in PET detectors with LSO and BGO scintillators. *IEEE Transactions on Nuclear Science*, 60(3), 1533-1540.

[6] Efthimiou, N., Kratochwil, N., Gundacker, S., Polesel, A., Salomoni, M., Auffray, E., Pizzichemi, M. (2020). TOF-PET image reconstruction with multiple timing kernels applied on Cherenkov radiation in BGO. *IEEE transactions on radiation and plasma medical sciences*, 5(5), 703-711.

[7] Kratochwil, N., Gundacker, S., Lecoq, P., Auffray, E. (2020). Pushing Cherenkov PET with BGO via coincidence time resolution classification and correction. *Physics in Medicine Biology*, 65(11), 115004.