博士論文公聴会の公示(物理学専攻)

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論文題目： Study of side-readout slab-based monolithic scintillation crys- tals for total body PET application

全身PETのための、サイド読み取りモノリシックシンチレーション結晶平板の研究

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Abstract:

Positron emission tomography (PET) is a medical imaging method, using positron radiotracers to visualize the functionality of body organs or tissues. Clinical PET systems, with a typical 20 cm axial length, demand high radioactive doses for sufficient sensitivity. To address this, a current approach, named total body PET (TB-PET), extends the system length significantly (e.g. first TB-PET system, the uExplorer is approx. 2 m), boosting sensitivity by 30–40 times [1] compared to typical systems. However, this approach also increases costs by 7–8 times [1], mainly due to the amount of scintillation crystals and photosensors.

To reduce costs in TB-PET systems, alternative designs with fewer crystal elements and sensors could be considered. One of them is the side-readout slab-based monolithic crystals. This design offers two key benefits. Firstly, it reduces crystal fabrication costs by using large slabs rather than small crystal pixels in current TB-PET and most PET systems. Secondly, it offers depth of interaction (DOI) information, obtained by finding which slab has interactions in the slab stack. DOI is an important criteria but currently absent in TB-PET and most clinical PET systems. No DOI information introduces parallax errors that degrade spatial resolution. Previous studies have shown promising results, supporting the clinical application of this design. Based on a previous study's configuration, we found the potential to reduce crystal elements by a substantial factor of 60 compared to the uExplorer. The sensor amount, however, increases by a factor of 11. Despite offering DOI, this configuration still demands too many sensors.

This study aims to find the slab-based configurations that can reduce sensors (thus, electronics), and identify associated trade-offs. Using Geant4/GATE simulation toolkit, we study three parameters: (1) crystal side width, (2) sensor granularity, and (3) sensor spacing. We evaluated how these parameters affect energy, spatial, and timing resolutions.

We tested our simulation model using a prototype detector consisting a $26 \times 26 \times 3\,\mathrm{mm}^3$ LYSO crystal layer and 16 SiPM sensors on 4 sides. We scanned the detector surface along the center vertical line, using collimated

source. We then evaluated the change in photons detected by each SiPM. In simulation, SiPM photo-active surfaces ($3 \times 3\,\mathrm{mm}^2$) are directly coupled with crystal sides. Optical photons hitting the inactive borders (approx. 1.5 mm wide on each side, surrounding active surface) are absorbed without detection. The simulation model predicts correctly the trend of detected photons across SiPM channels when changing the scan position. It estimates correctly the photon change intensity half of the total SiPMs channels, mainly on the crystal's left and right sides. However, the model tends to overestimate the changes for 2 SiPMs on the top side closest to the scan position while underestimates them for 4 SiPMs at the bottom and 1 each at upper left and right. These discrepancies may arise from assumptions about direct coupling of photo-active surface and photon absorption at inactive SiPM borders.

In configuration parameter studies, we used the same simulation model but reduced the inactive SiPM borders to 0.2 mm wide, much smaller than the photo-active surfaces, aligning with SiPM array designs commmonly found in PET systems. In study (1), we found that spatial resolution scales with crystal width, i.e. resolution is defined based on the selected crystal width. In study (2), we found that sensor granularity has minimal impact on spatial resolution, enabling the use of larger, low-granularity sensor arrays to reduce sensor amount. Lastly, study (3) suggested the possibility to have gaps (covered with reflectors) between sensors without significantly degrading spatial resolution.

From the above findings, we found a configuration that could reduce crystal elements by 120 times, and provide DOI with a 1.4 times up in sensor amount, compared to the uExplorer. Energy and spatial resolutions could be as the same range with the uExplorer but timing resolution may degrade due to photon sharing by more sensors of each crystal slab, which thus, needs further studies.

[1] S. Vandenberghe, P. Moskal, and J. S. Karp, "State of the art in total body PET," *EJNMMI physics*, vol. 7, pp. 1–33, 2020.