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Abstract of Thesis

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Title	Study of side-readout slab-based monolithic scintillation crystals 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)

Abstract of Thesis

Positron emission tomography (PET) is a medical imaging method that uses positron tracers to visualize the functionality of body organs and tissues. Clinical PET systems, typically 20 cm long, require high radioactive doses injected into patients for sufficient count rates. To reduce doses, one approach is total body PET (TB-PET), which extends the system length significantly. The first TB-PET system, the uExplorer, nearly 2 m long, increases system detection sensitivity up to 40 times in whole-body scans compared to 20 cm systems. However, this increases the system cost nearly 8 times, mainly due to additional scintillation crystals and photosensors.

To reduce costs, alternative designs with fewer crystal elements and sensors could be considered. One option is the side-readout slab-based monolithic crystals. This design offers two key benefits: (a) reducing crystal costs by using large crystal slabs (vs. small pixels) and (b) offering depth of interaction (DOI) information (an important criterion but currently absent in TB-PET and most clinical PET systems) when stacking multiple crystal slabs. Previous studies have shown promising results, supporting clinical applications of this design. However, estimations using a configuration from these studies indicate a requirement of much more photosensors, compared to the uExplorer.

This study aims to find an optimal side-readout slab-based configuration for TB-PET.
Specifically, we aim to reduce crystal and photosensor counts; and identify associated trade-offs. Using simulation, we studied three parameters: (1) crystal width, (2) sensor granularity, and (3) sensor spacing. We evaluated how these parameters affect energy, spatial, and time resolutions.

We evaluated our simulation model using measurements results from a prototype detector consisting of one crystal slab and 16 SiPM sensors on 4 sides. We scanned the crystal surface with a collimated source from the center to toward the top edge (assuming 4 crystal sides face top, bottom, left, and right). We evaluated the change in the number of photons detected by each SiPM. In our model, we simulated a direct coupling between SiPM photo-active surfaces and crystal sides. Optical photons hitting SiPM inactive borders were simulated to be absorbed without detection. Our simulation model can predict how the number of photons detected by each SiPM changes with varying scan position. It correctly estimates photon changes for SiPMs on left and right sides relative to the scan positions. It overestimates the changes for SiPMs on the near side (top) and underestimates them for SiPMs on the far side (bottom). These discrepancies may arise from the assumptions about direct coupling of photo-active surface and photon absorption at SiPM inactive borders. In measurements, photons can reflect at the optical coupling interfaces between crystal and SiPMs.

In reconstructed positions, measurements showed position distortion for interactions near the inactive gaps in between sensors. This was also observed in our simulations. We found that our simulation model is a good estimator for the center region. Different from simulations, measurements also showed position shrinking, likely due to reflections at the crystal-coupling material interfaces. The effect of these reflections needs further study. Our measurements show biases in reconstructed positions due to lack of calibration. A simple linear correction for the crystal center's offset suggests position accuracy is approx. 0.2 mm. A previous side-readout slab-based study demonstrated a position calibration method that could correct both shrinking and biases. We expect that distortion can also be corrected with proper calibration.

Using the above simulation model, we studied the effect of configuration parameters on PET performance. Important findings for spatial resolution are: (1) Spatial resolution scales with crystal width, i.e., select the crystal width will define the resolution. (2) Sensor granularity has a minor impact on spatial resolution, allowing the use of larger sensor arrays to reduce sensor count. (3) It is possible to have gaps (covered with reflectors) in between sensors without significantly degrading spatial resolution.

Using the above findings, we proposed 2 side-readout slab-based configurations for TB-PET. Compared to a configuration from previous studies, our configurations can further reduce the crystal amount 2 times. The 2^{nd} configuration, with 50% sensor coverage, can reduce sensor count by a factor of 8. This results in a 1.4-fold increase in sensor count compared to the uExplorer but provides DOI information. This 50% coverage configuration is expected to reduce the system total cost. Achieving DOI in pixelated crystals (as in the uExplorer) typically increases either sensor or crystal costs. Energy and spatial resolutions of the proposed configurations could be in the same range with previous configurations and the uExplorer. Time resolution may degrade and requires further study.

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論文審査の結果の要旨及び担当者

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論文審査の結果の要旨

医療診断における PET の役割は大きい。その一つの開発方向として、全身のスキャンを効率的に行う Total Body PET が注目を浴びている。しかし、これまでの PET を単に大きくしただけでは必ずしも最適化されたものとはいえない。このため、さまざまな開発が行われている。本論文は Total Body PET を効率的に実現するために、モノリシックシンチレーション結晶平板の側面読み取りを応用した場合の最適化について議論したものである。

モノリシックシンチレーション結晶平板の側面読み取りは別の用途での研究は行われていたが、Total Body PET への応用に関しては本論文が先駆的なものとなる。本論文ではさまざまな設定条件に関する性能評価をシミュレーションで行っている。同時に、プロトタイプの検出器を製作し、それによる測定とシミュレーションの結果を比較した。本論文では、測定結果とシミュレーションの結果を比較するだけでなく、それをもたらす物理現象を、シミュレーションを用いて理解している。このため、シミュレーションを、測定条件を超えて、より広い範囲に応用することができる。

本論文では、さまざまな条件に関してシミュレーションを行い、性能を決めるパラメーターを見出し、Total Body PET の最適化に関し、寄与する結果を得た。

プロトタイプの検出器の開発・測定、シミュレーションによる結果の導出は申請者を主体とするものであり、研究内容は当論文に明瞭に記載されている。得られた結果は PET の開発に寄与するもので、ガンマ線計測においても重要な成果であり、学術的価値は高い。

よって、本論文は博士(理学)の学位論文として十分価値あるものと認める。