Modeling the Effects of Scintillation-Induced Spatial Response on Dual-Layer Charged Particle Imaging for Radiopharmaceuticals

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Conventional charged particle tracking detectors for radiopharmaceuticals, which is called digital autoradiography (DAR), provides activity maps of thin-slices ($10 - 12\ um$) of *ex-vivo* samples. However, this technology lacks depth information, limiting its ability to localize short-lived radiopharmaceutical uptake and small-scale dosimetric activity maps in three dimensions. To alleviate these limitations, dual-layer charged particle tracking [1,2] is suggested for 3D DAR, in which particle trajectories are estimated from two spatially separated interaction points at each layer of detector. These trajectories define the line-of-responses that are used to reconstruct volumetric activity distributions.

In case of ultra-thin pixelated silicon sensors, spatial resolution degradation can be attributed to pixel quantization and inter-layer particle deflection. On the other hand, in scintillator-based dual layer tracker implementations, spatial uncertainty is inherently introduced by scintillation light spread and interaction depth, which can dominate trajectory uncertainty and subsequent 3D image blurring. However, the quantitative impact of scintillation-induced spatial response on trajectory-based reconstruction has not yet been explicitly characterized. Here, we investigate how layer spatial response propagates into trajectory uncertainty in a dual-layer charged particle imaging.

Using Geant based Monte Carlo simulation tool (Allpix-squared), a dual-layer geometry consisting of two $500\ um$ plastic scintillator (EJ-232) layers separated by $4\ mm$ and coupled to SiPM readout was modeled. Interaction positions in each layer were represented by Gaussian response kernels, where the centroid was used as the hit position and the variance encoded spatial uncertainty arising from scintillation light spread and interaction depth. An isotropically emitting 1 MeV beta particle emitting isotropic point source was placed at a depth of $50\ um$ to maximize the detection efficiency.

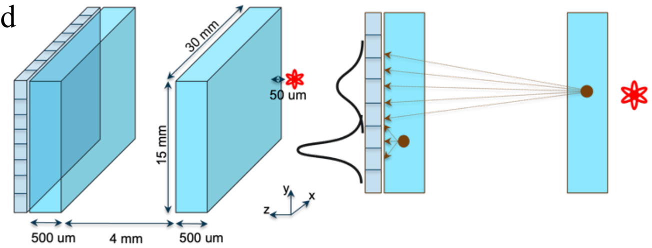

Fig. 1. Configuration of scintillator based dual layer tracker and double gaussian distribution from sensor used for position estimation

The results demonstrate that increasing layer-response variance leads to systematic broadening of reconstructed angular distribution and depth-dependent point spread kernels. These results show the necessity of incorporating scintillation-induced spatial response into trajectory-based reconstruction models for radiopharmaceutical imaging. This study provides the modeling framework for interpreting scintillation based measurements within trajectory driven 3D DAR.

1. Ding, Yijun, et al. "Charged-particle emission tomography." *Medical physics* 44.6 (2017).
2. Chu, Hyeyeun, et al. "Silicon-based 3D beta ray radiopharmaceutical trackers: a Monte Carlo computational study." *Physics in Medicine & Biology* 70.20 (2025)

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