A Novel Theoretical Model Framework with Experimental Verification for the 3D CdZnTe Drift Strip Detector

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The recent surge in research and development for data analysis and model prediction presents a unique opportunity for advancements in the field of radiation imaging technologies, ushering a new era for the development of detector characterization techniques and real time signal analysis. A challenge now rises in producing realistic models and accurate data, that describe the complex physical processes behind photon-matter interaction, detection, signal formation and measurement, to lay down the foundations for design optimization and provide true knowledge of the detector physics and response. The principal objective of this study is to develop an Advanced Theoretical Detector Model (ATDM) framework, which incorporates the complex physical effects of charge diffusion, repulsion, and trapping, enabling the generation of detector specific data through model prediction. The ATDM utilizes powerful physics simulation tools to model the geometry, material properties, electric field, and individual electrode weighting potentials for the DTU Space new large area 3D CZT drift strip detectors [1]. The simulations are based on the adjoint equations method, which when applied to the charge continuity equation allows deriving the description of the underlying Charge Induction Efficiency in the model [2]. Hence, we obtain accurate 3D continuous mapping of the induced charge, at any time and any interaction point for each electrode, obtained with a single transient computation. Then, a Monte-Carlo simulation tool is utilized to generate realistic photo-electron trajectories in CZT, resulting from the initial interaction between a 661.6 keV photon and the CZT material. The photo-electron energy, collision and penetration profile are analyzed, and secondary electron trajectories are once again simulated. The resulting trajectories are combined to form a realistic charge cloud shape with known coordinates. By extracting charge cloud specific electron-hole pair positions from the 3D map of the induced charge, the need for large amounts of exported data is effectively reduced, while increasing the accuracy of the generated pulse shape. Charge cloud dynamics are employed in cloud evolution modeling, based on analytical models [3],[4]. The mobility-lifetime product of the 3D CZT drift strip detector is characterized at the DTU Space detector lab, and is incorporated into the ATDM[5].

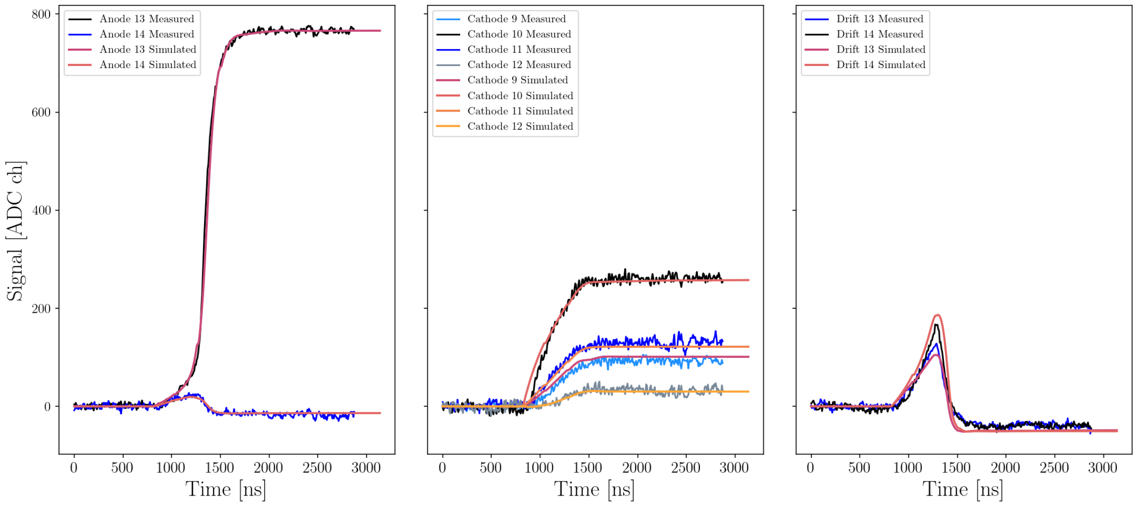

Figure 1: Raw measured signal versus simulated signal for adjacent electrodes - single 661.6 keV photoelectric absorption event

Finally, the validity of the ATDM is confirmed through experimental measurements conducted at the DTU Space detector laboratory, through means of a Cs-137 source slit-beam illumination. The experimental program employed Nuclear Instrumentation Module (NIM) standard charge sensitive pre-amplifiers and high-speed digitizers to measure induced pulse shapes in the 3D CZT drift strip detectors[6]. The large detector modules measure 40 x 40 x 5 mm^3, comprising a total of 119 electrodes, with 20 cathode strips, and 24 drift cells configured from 99 electrodes (these drift cell configurations contain 3-strip electrodes between 24 anodes). The developed model framework is applicable for a wide range of detector types and electrode configurations. Results exhibit excellent agreement with real measurement data and provide insights in pulse shape formation and timing, as well as probing on intrinsic detector parameters that can pave the way for electrode configuration optimization and on the fly photon-by-photon measurement of radiation interactions. We will present the current status of the ATDM framework, highlighting its implications on future development.

References

[1] S. R. H. Owe. “Development of 3D Imaging Detectors for High Energy Astronomy Instrumentation”. PhD thesis. Technical University of Denmark, 2023. URL: https://orbit.dtu.dk/en/publications/development-of-3d-imaging-detectors-for-high-energy-astronomy-ins.

[2] T. H. Prettyman. “Theoretical framework for mapping pulse shapes in semiconductor radiation detectors”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 428.1 (1999), pp. 72–80. ISSN: 0168-9002. DOI: 10.1016/S0168-9002(98)01582-4. URL: https://doi.org/10.1016/S0168-9002(98)01582-4.

[3] Emilio Gatti et al. “Dynamics of electrons in drift detectors”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 253.3 (1987), pp. 393–399. ISSN: 0168-9002. DOI: 10.1016/0168-9002(87)90522-5. URL: https://doi.org/10.1016/0168-9002(87)90522-5.

[4] Mathieu Benoit and L. A. Hamel. “Simulation of charge collection processes in semiconductor CdZnTe γ-ray detectors”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 606.3 (2009), pp. 508–516. ISSN: 0168-9002. DOI: 10.1016/j.nima.2009.04.019. URL: https://doi.org/10.1016/j.nima.2009.04.019.

[5] Selina Owe, Irfan Kuvvetli, and Carl Budtz-Jørgensen. “Carrier Lifetime and Mobility Characterization using the DTU 3D CZT Drift Strip Detector”. In: *IEEE Transactions on Nuclear Science* PP (Mar. 2021), pp. 1–1. DOI: 10.1109/TNS.2021.3068001.

[6] C. Budtz-Jørgensen and I. Kuwetli. “New position algorithms for the 3D CZT drift detector”. In: *2016 IEEE Nuclear Science Symposium, Medical Imaging Conference and Room-Temperature Semiconductor Detector Workshop (NSS/MIC/RTSD)*. 2016, pp. 1–7. DOI: 10.1109/NSSMIC.2016.8069957.