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

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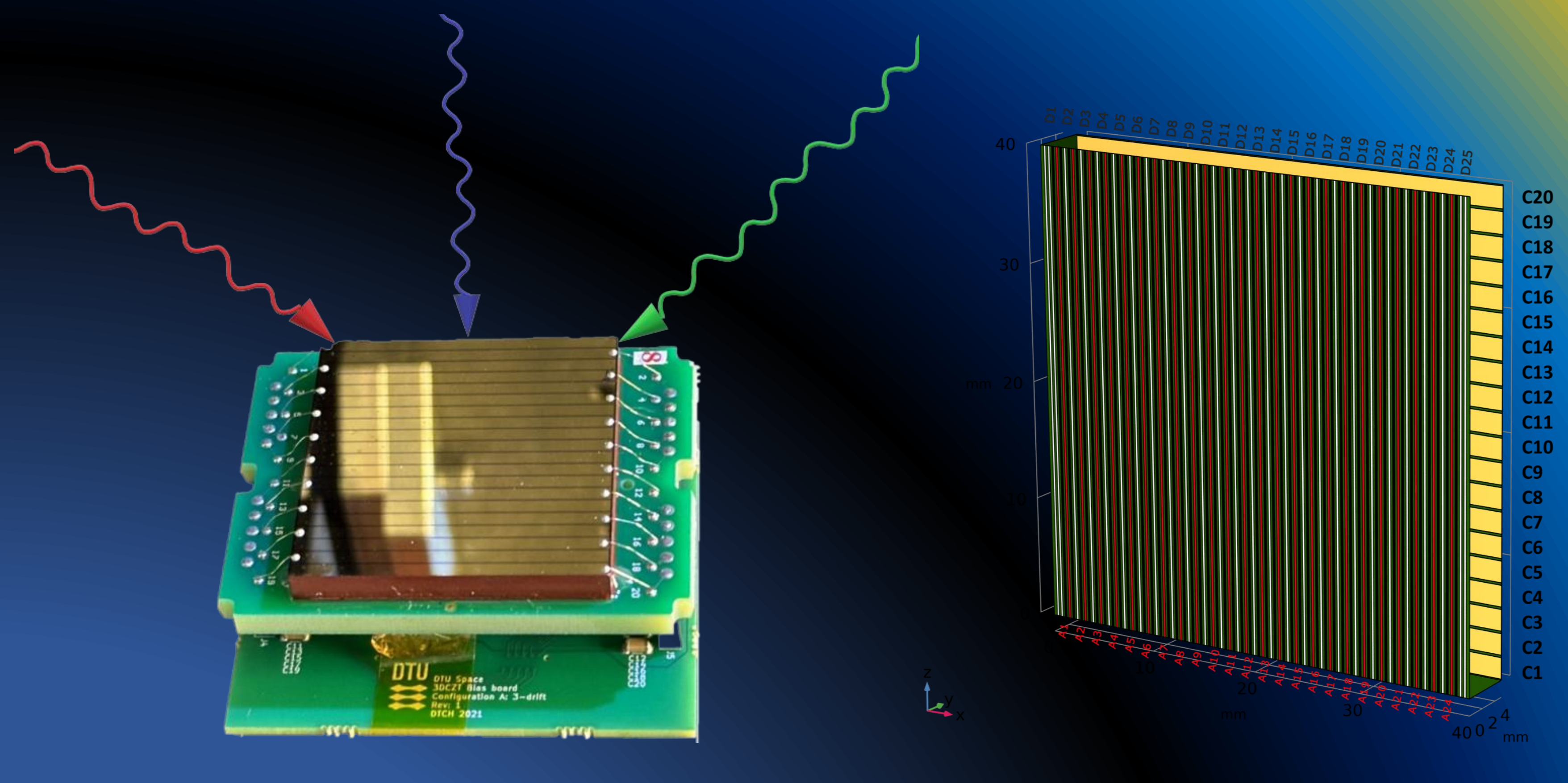
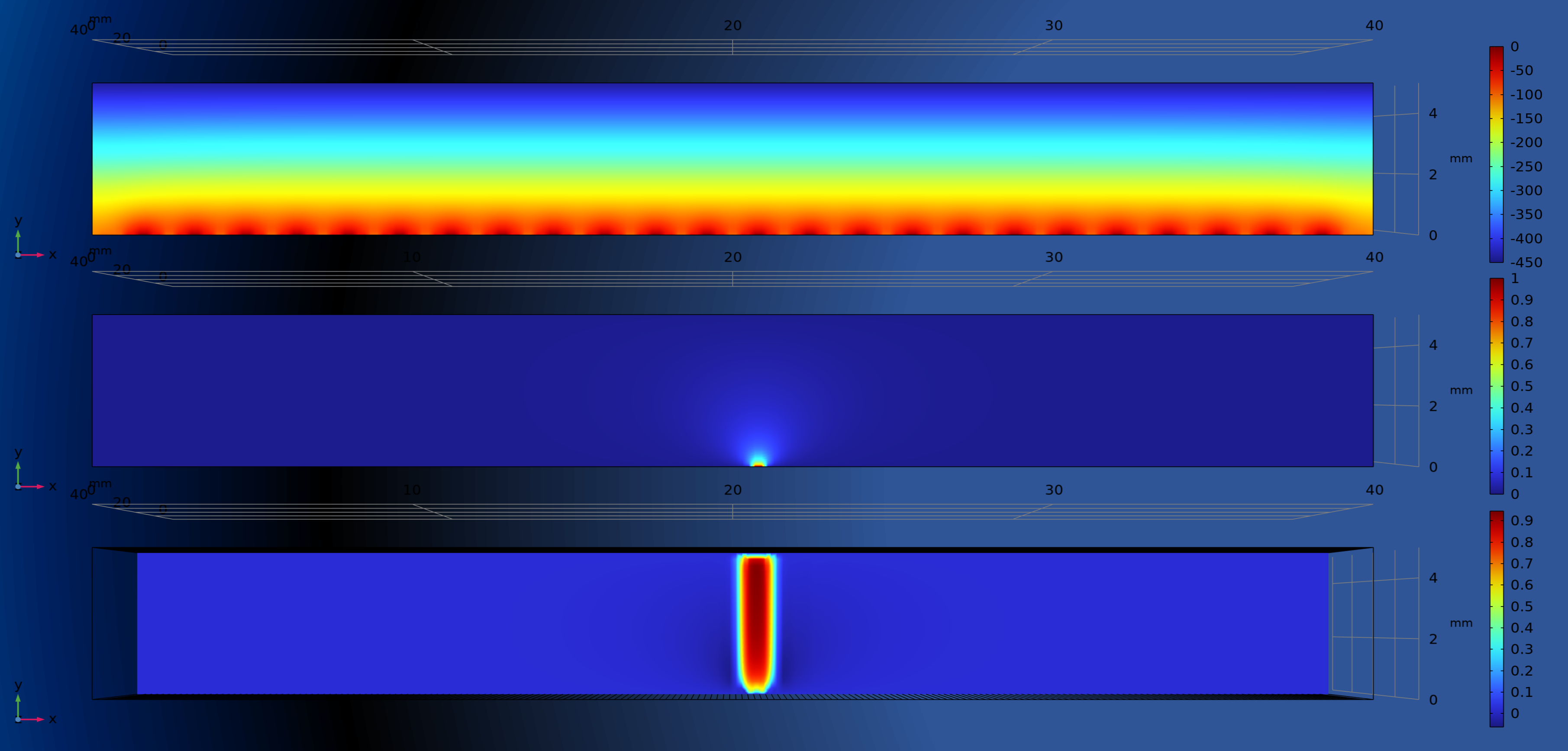
The recent surge in R&D for model prediction, AI and synthetic data analysis presents a unique opportunity for advancements in radiation imaging technologies. A challenge now rises in producing realistic models and accurate data, that describe the complex physical processes behind photon-matter interaction, 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. Synthetic data hold great potential for neural network training and could provide new insights on electrode configuration optimization and on the fly photon-by-photon measurement of radiation interactions.



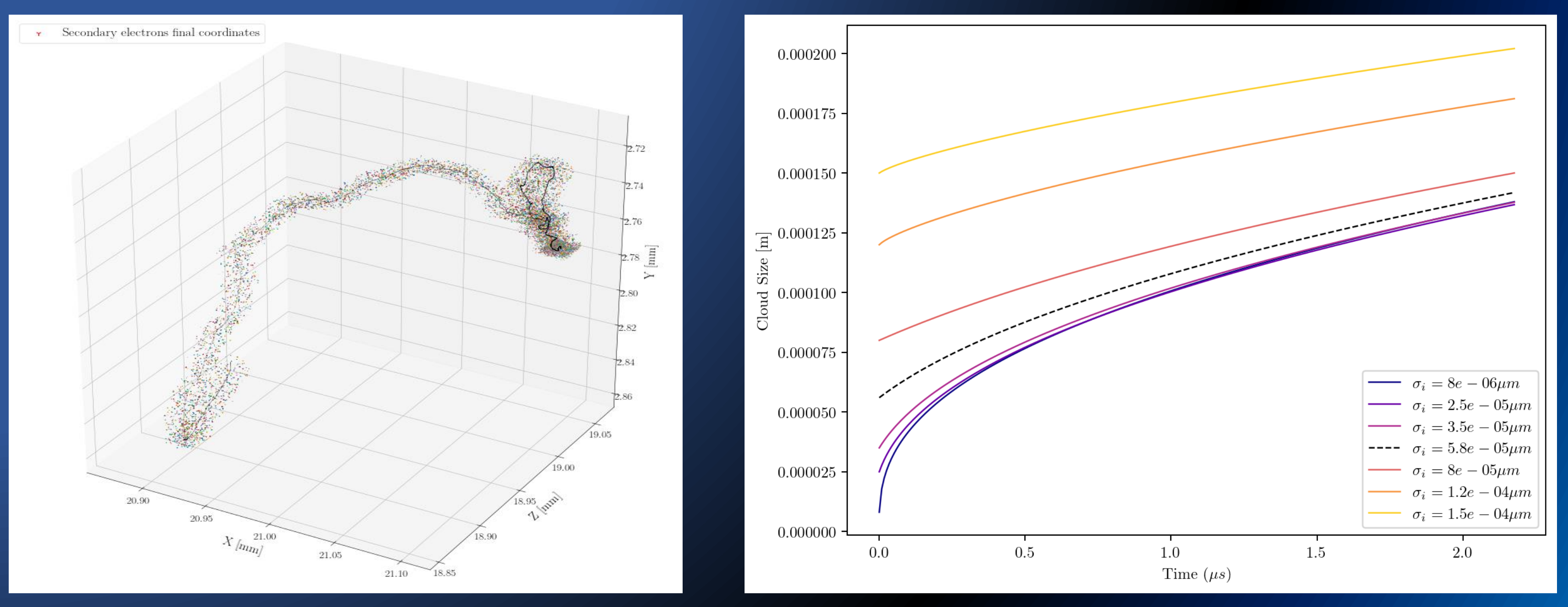
(Left): The 3D CZT drift strip detector developed by DTU Space, in its current configuration at the DTU Space detector lab, **(Right):** 3D model of the detector geometry in COMSOL Multiphysics.



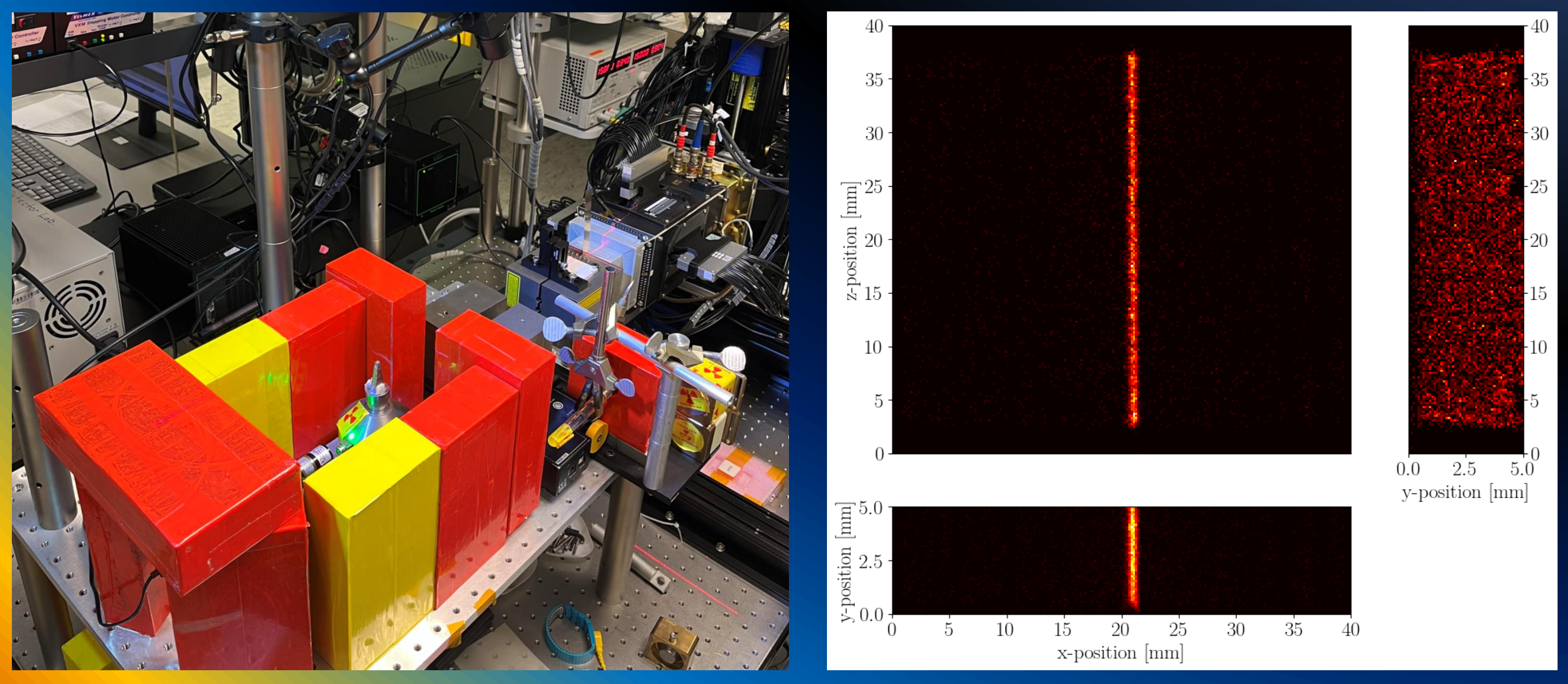
Examples of the simulated electric field (top), the weighting potential (middle), and the Charge induction Efficiency (CIE) (bottom), of an Anode, from the 3D CZT drift strip detector.

The developed framework utilizes COMSOL Multiphysics FEM software to model the geometry, material properties, electric field, and individual electrode weighting potentials for the new large area 3D CZT drift strip detector modules [1]. These quantities form the input to the simulation of charge transport, 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 extract accurate 3D continuous mapping of the induced charge, at any time and any interaction point for each electrode, obtained with a single transient computation. Monte Carlo simulation software is employed for the generation of realistic charge cloud distributions.

The CASINO software is utilized to generate realistic electron ionization tracks in CdZnTe. Then, assuming only photoelectric absorption events, the simulated photoelectron's energy, penetration and collision profiles are studied. Based on the energy loss and average pair creation energy in CdZnTe, a corresponding number of secondary electrons is once again simulated. The results are exctracted and read from a Python script where all secondary electron trajectories are combined to form a realistic charge cloud shape and distribution with known coordinates. Charge cloud dynamics are also considered in the ATDM in the form of diffusion and electrostatic repulsion [3].



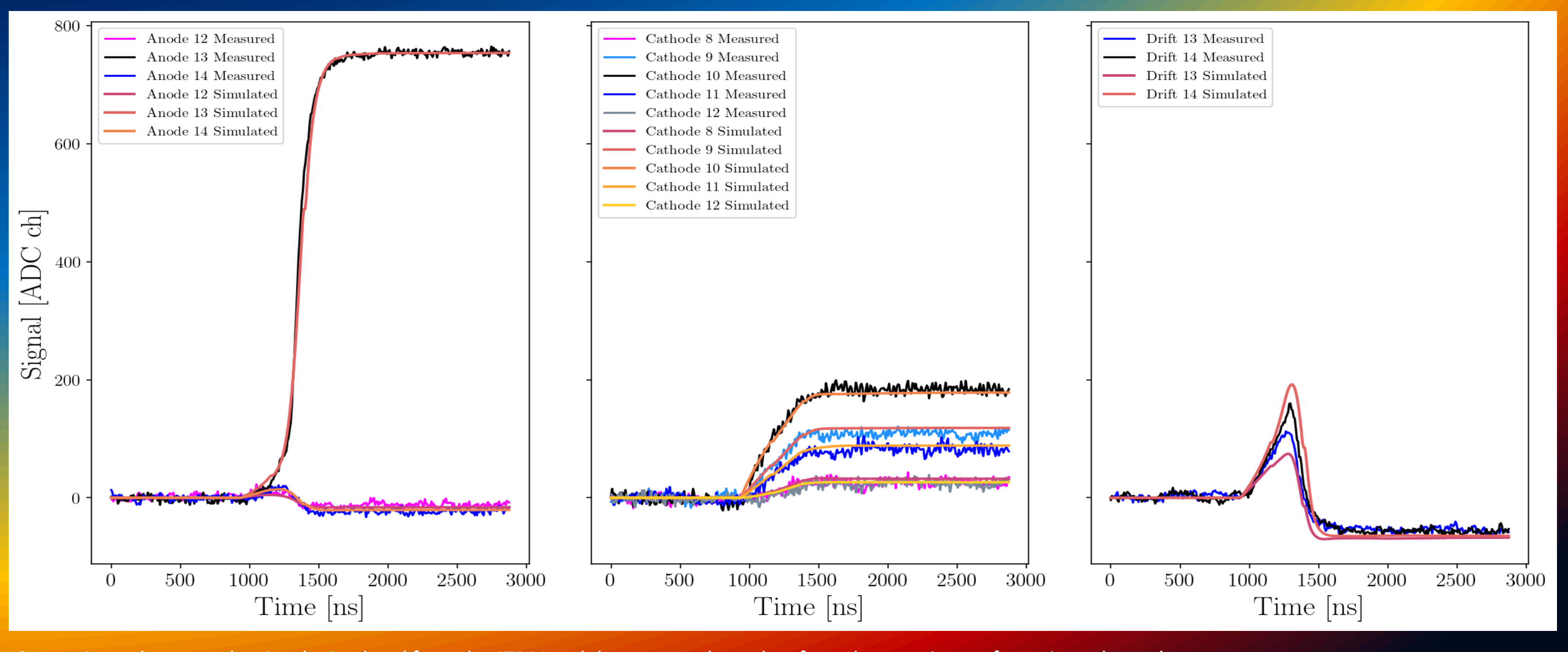
(Left): Example of simulating charge cloud distributions, resulting from the initial interaction between the high energy photon and the detector material.
(Right): Charge cloud evolution modelling results for different initial cloud sizes.



(Left): Experimental setup, showcasing the allignment lasers, Cs-137 source, collimator and 3D CZT drift strip detector . **(Right):** 2D histogram of photoelectric absorption events from the slit-beam measurements.

Verification of the ATDM is performed 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. 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.

A comparative study was performed where simulated pulse shapes are compared to real measured data. Results show very good agreement, highlighting the potential of the developed ATDM. The calculated mean value of the RMS error between simulated data and experimental measured data was found to be as low as: 10.15, 11.25 and 11.29 (ADC channel units) for the anodes, cathodes and drifts strips respectively, across different interaction positions in the detector. The model can easily be adjusted to accommodate different detector geometries, materials and configurations.



Comparisons, between the signals simulated from the ATDM and the measured raw data from the experiment, for various electrodes.

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[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.