Real-time Position Reconstruction for the KamLAND-Zen Experiment using Hardware-AI Co-design

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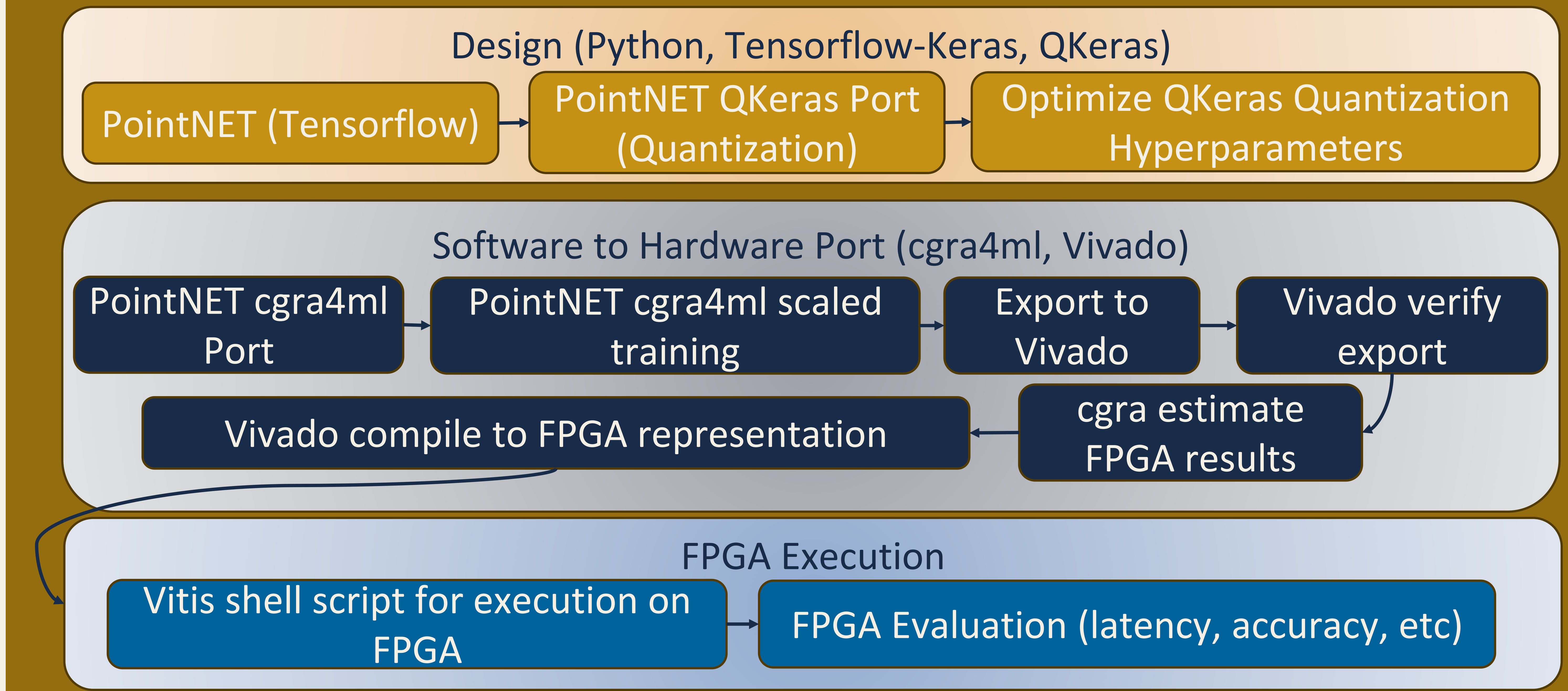
Introduction

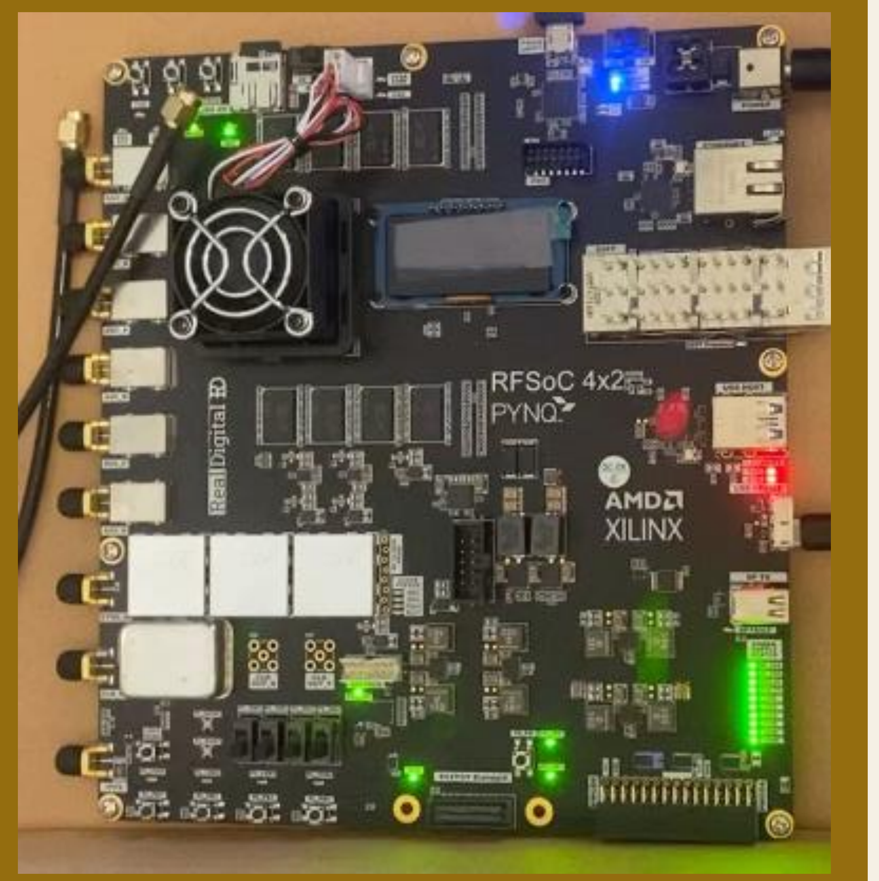
Monolithic liquid scintillator detector technology is the workhorse for detecting neutrinos and exploring new physics. The KamLAND-Zen experiment exemplifies this detector technology and has yielded top results in the quest for neutrinoless double-beta decay. To understand the physical events that occur in the detector, experimenters must reconstruct each event's position and energy from the raw data produced. Traditionally, this information has been obtained through a time-consuming offline process, meaning that event position and energy would only be available days after data collection. This work introduces a new pipeline to acquire this information quickly by implementing a machine learning model, PointNet, onto a Field Programmable Gate Array (FPGA). This work outlines a successful demonstration of the entire pipeline, showing that event position and energy information can be reliably and quickly obtained as physics events occur in the detector. This marks one of the first instances of applying hardware-AI co-design in the context of neutrinoless-double-beta decay experiments.

KamLAND-Zen Experiment schematic (Photo: LBL)

[1] A. Migala, E. Ku, Z. Li, and A. Li. https://arxiv.org/abs/2410.02991
[2] A. Li, "The Tao and Zen of neutrinos: neutrinoless double beta decay in KamLAND-Zen 800," PhD Thesis, Boston U., 2020.
[3] G. Abarajithan *et al.*, "CGRA4ML." https://arxiv.org/abs/2408.15561
[4] Data and support from The KLZ Collaboration

Methods: We developed a pipeline for deploying a complex model onto an AMD RFSoC4x2 heterogeneous system

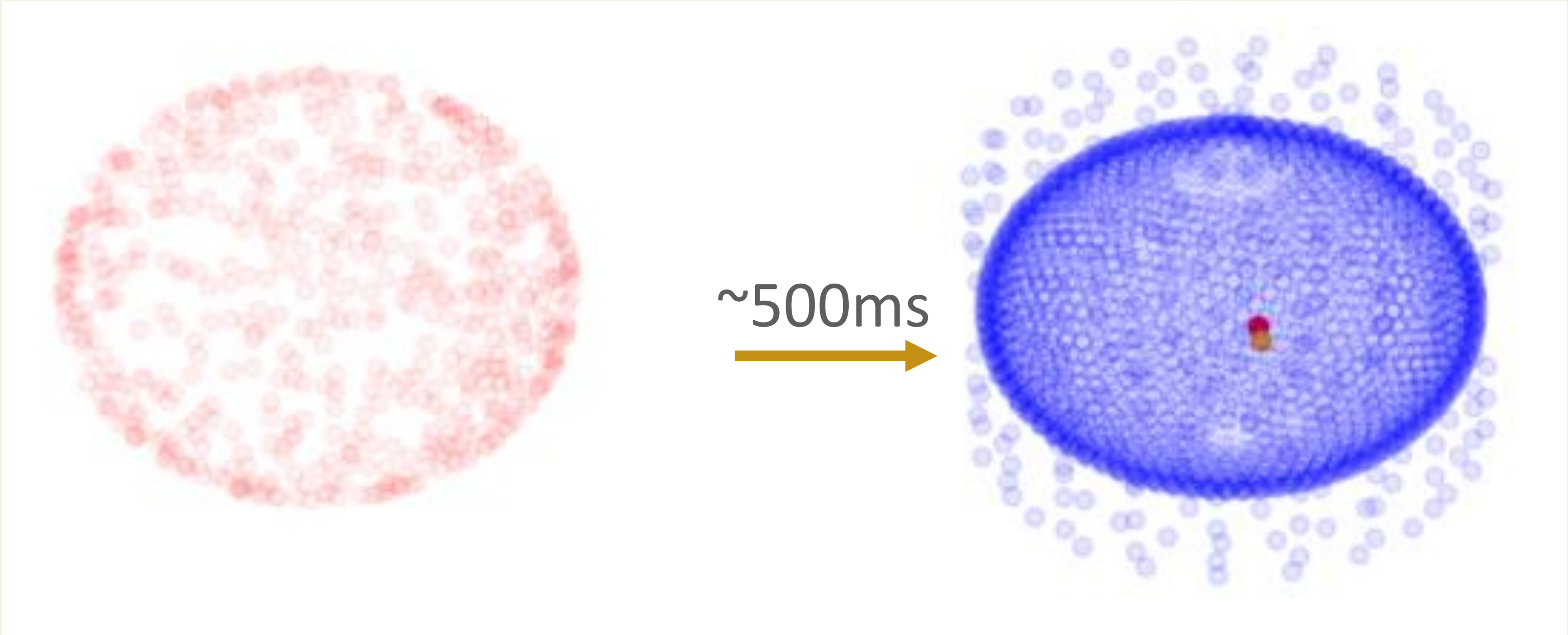




AMD RFSoC4x2 Development Board

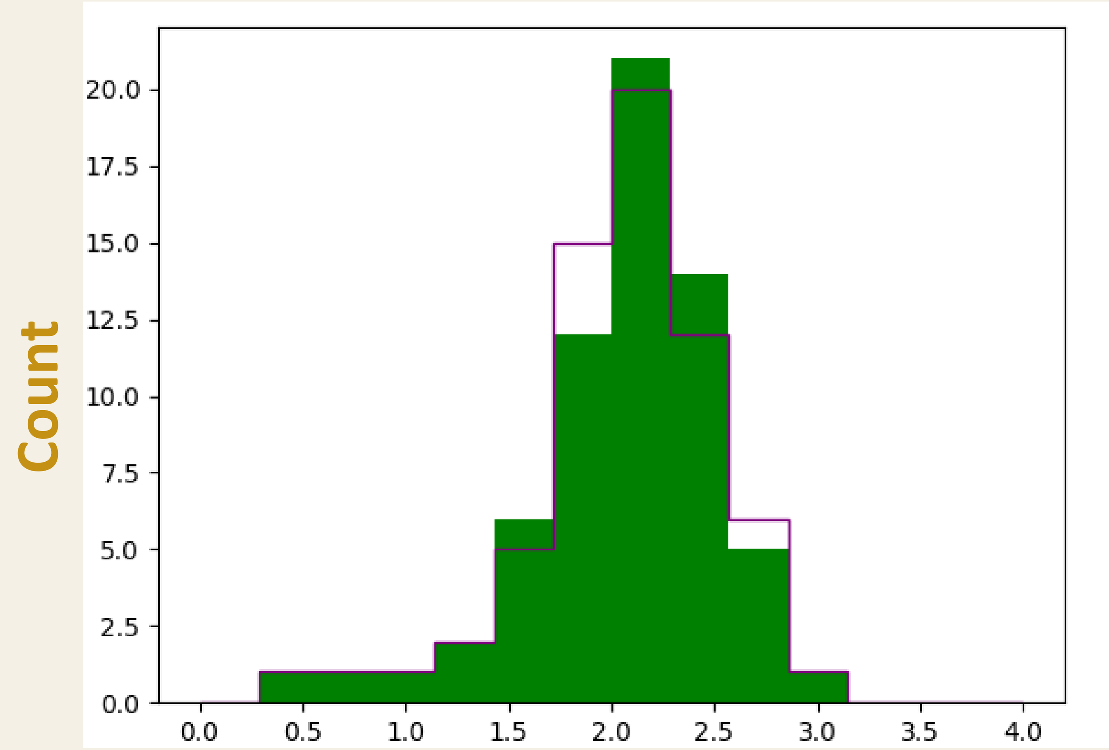
Results: ~500ms for Position and Energy Reconstruction

Experiment	Avg. Validation MSE	X Error (cm)	Y Error (cm)	Z Error (cm)	E Energy (MeV)
Traditional Method [2]	N/A	17	17	17	0.14
QKeras	366.25	20	21	21	0.06
cgra4ml [3]	987.40	34	34	36	0.06

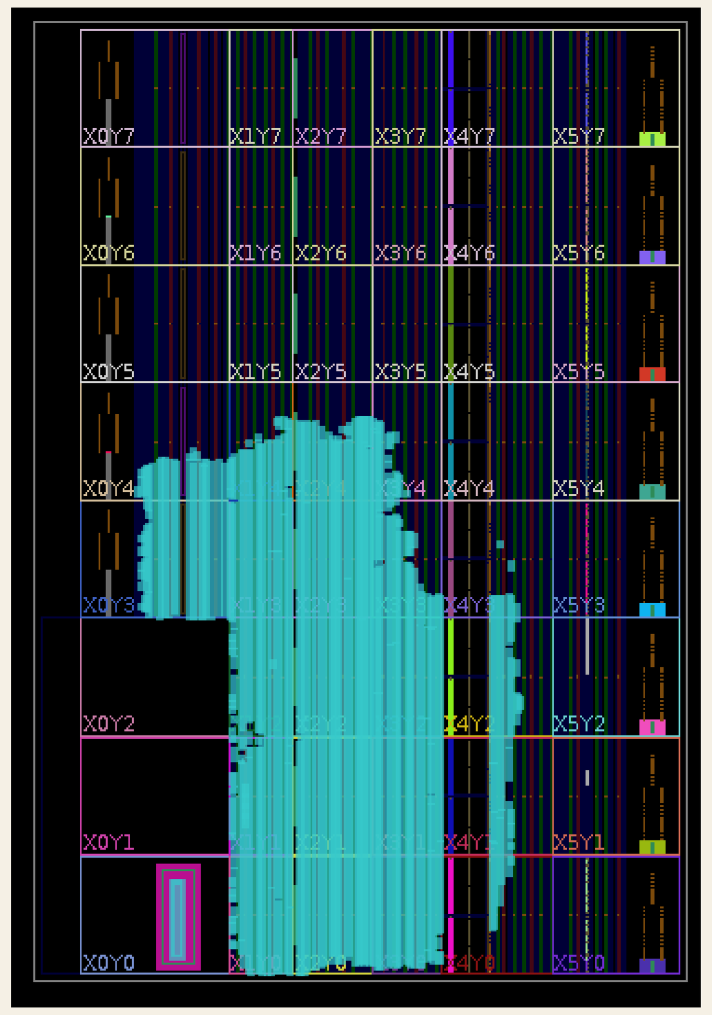


Activated Photomultiplier Tubes (detector data)

Simulation True Vertex
RFSoC FPGA Output



True Energy
FPGA Reconstructed Energy



AMD Vivado Synthesis of PointNet on an AMD RFSoC4x2