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Characterization of an AI-enhanced ToF-PET detector module with monolithic BGO crystals

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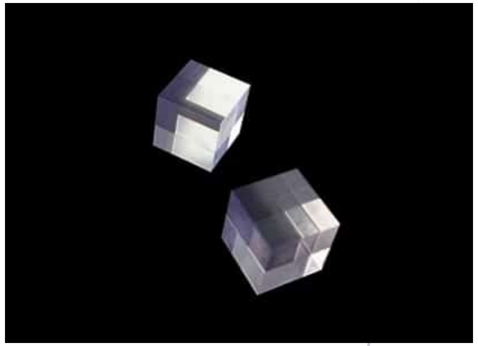
UTOFPET

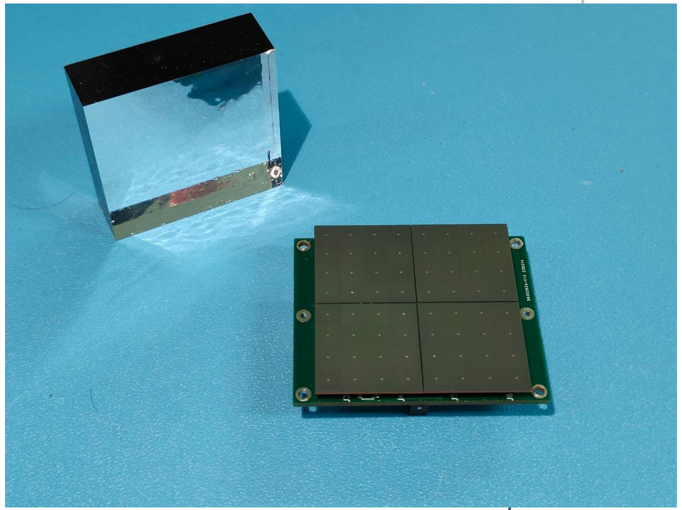
Introduction

- Large FOV PET scanners require a large number of detectors, increasing costs and placing a high burden on data acquisition systems



- Over 1,000 5 cm x 5 cm detectors may be required

- We can reduce costs by employing different materials
  - Monolithic, low-cost scintillators (BGO)
  - Large area SiPMs

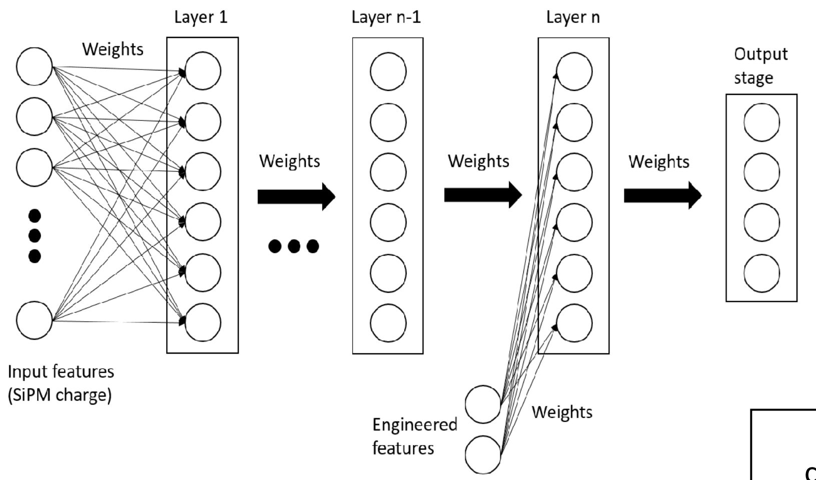


- How does performance scale with thicker and larger crystals?

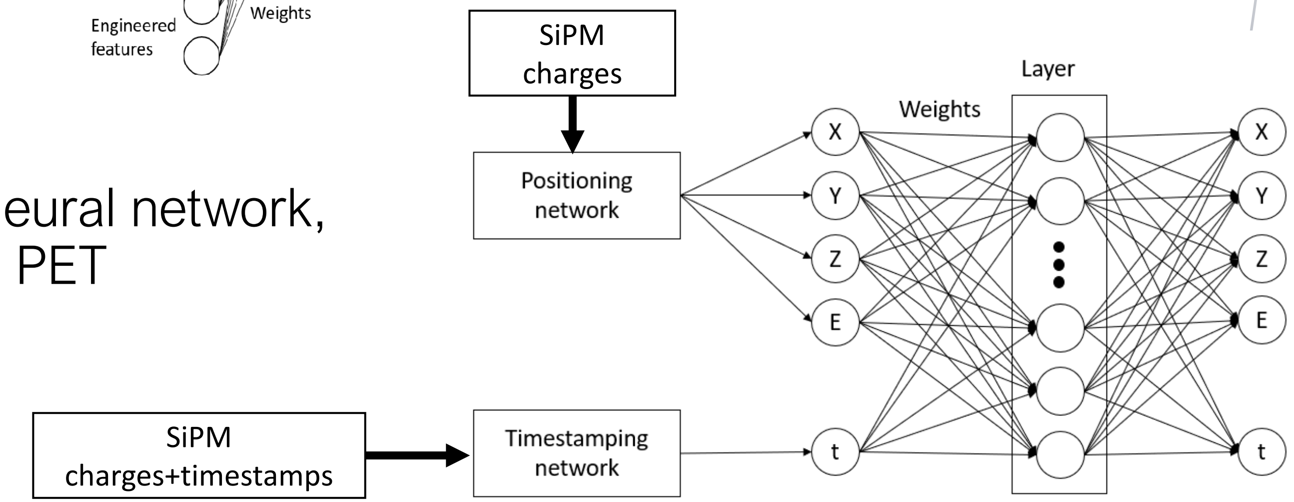
AI-enhanced PET detectors

- We have shown that we can use AI algorithms to improve detector performance in terms of:
  - 2-D Spatial resolution
  - DOI resolution
  - CTR
  - Energy resolution

Relevant for BGO and TB-PET, because of poor BGO energy resolution and large amount of scatter in TB-PET

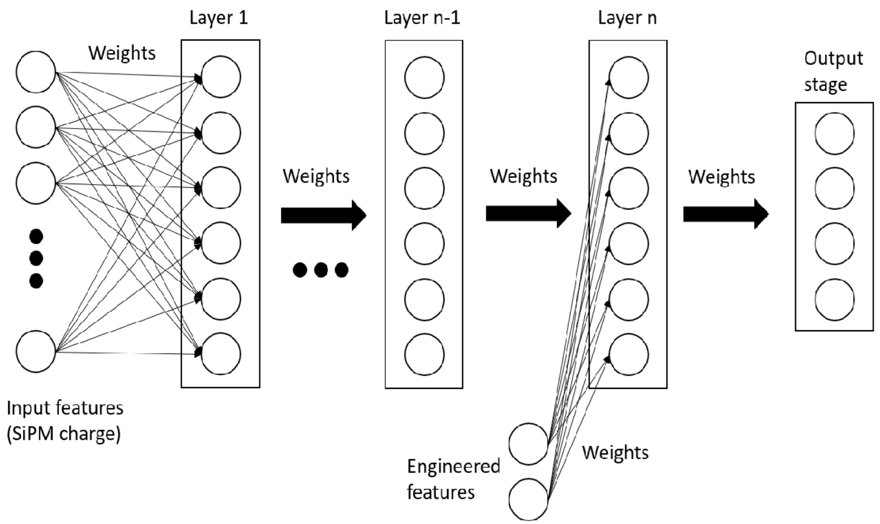


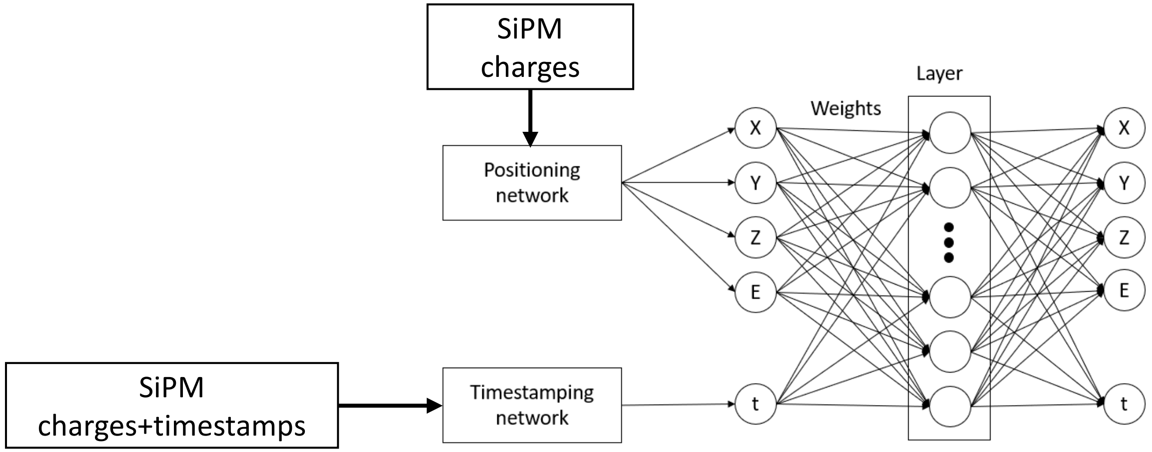
- The algorithm is based on a lightweight neural network, that can be implemented in real-time in a PET detector hardware



Neural network architecture

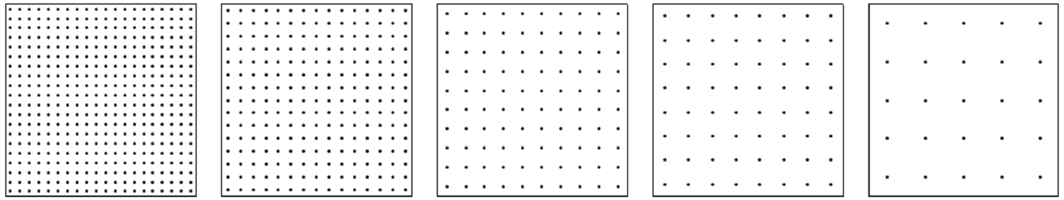
- We use two separate networks for position-energy and timing
- The inputs of the position-energy network are the charge measured by each SiPM
- Engineered features are
  - Number of pixels with a signal above a certain threshold %
  - Light spot width
- The network outputs (x,y,z,E)
- A similar network is used for timing
- The two networks are then fused by a fully-connected layer



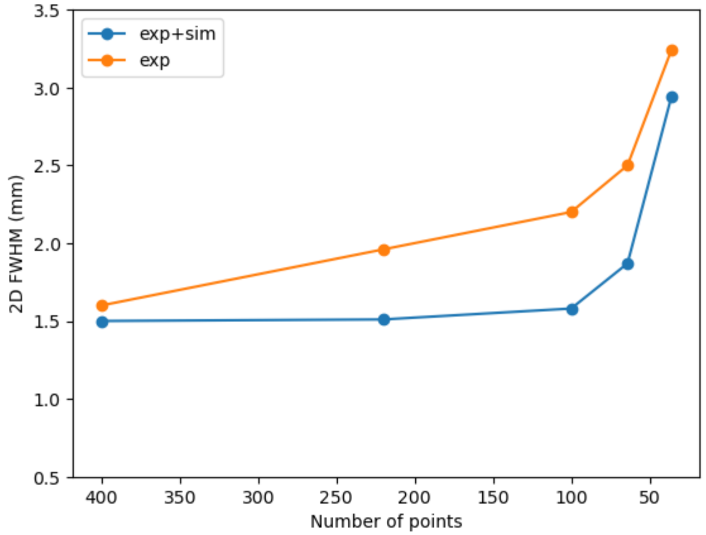


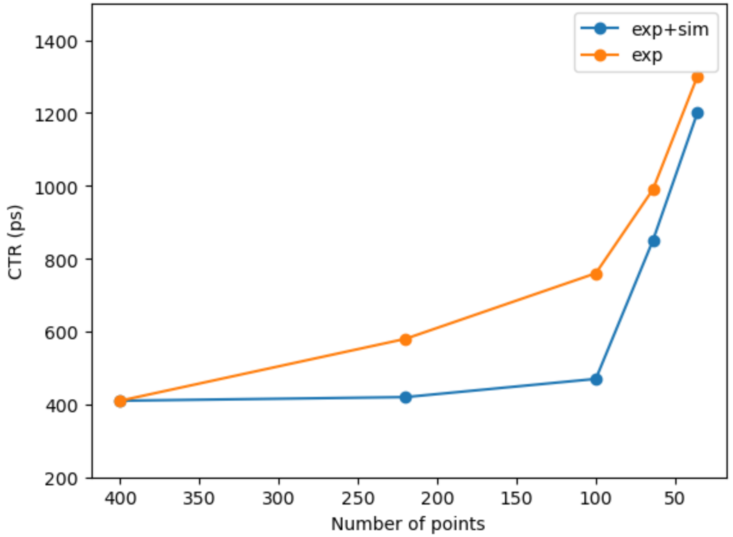
Data generation/acquisition process

- Simulations:
  - Geant for optical simulations
  - Custom framework, based on Julia, for SiPM simulation
  - Simulations made on a grid for spatial resolution assessment



  - Training of the neural network. Evaluation in terms of:
    - Bias
    - 2-D FWHM
    - DOI
    - CTR
    - Energy resolution
- Experimental data
  - Grid acquisition for spatial resolution assessment
  - Flood irradiation for CTR and energy resolution





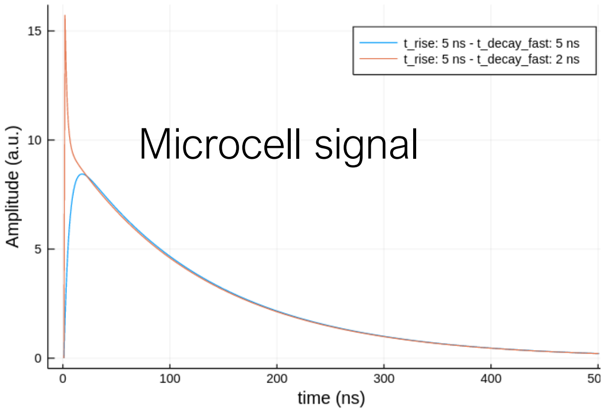
Simulations

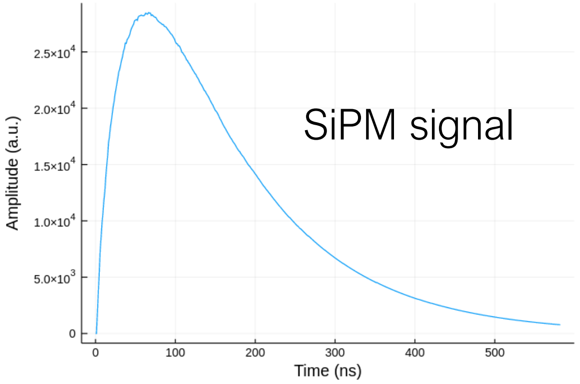
SCINTILLATOR SIMULATION

- The optical simulation is based on Geant4
- We model 511 keV photons hitting the scintillator perpendicularly
- The simulation models BGO lateral sides as black, and top side reflective. All sides are polished
- The simulation outputs the point and time of entrance of the photons into the SiPM array

SiPM SiMULATION

- SiPM simulation superposes single-microcell signals
- The microcell signal is represented by a tri-exponential function
  - Rise time, fast decay time, slow decay time
- Dark counts, crosstalks and afterpulses
- Inhomogeneities in microcell amplitude

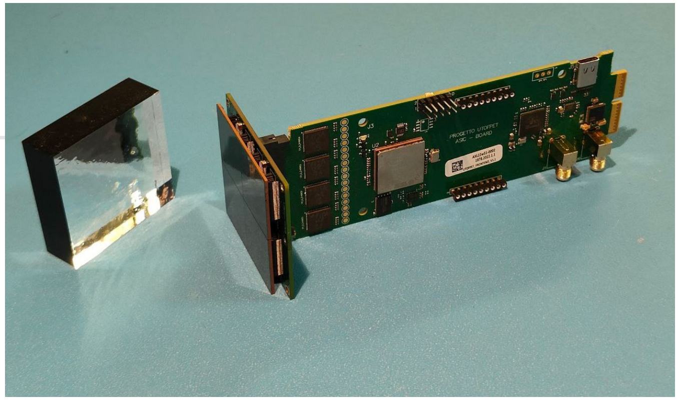


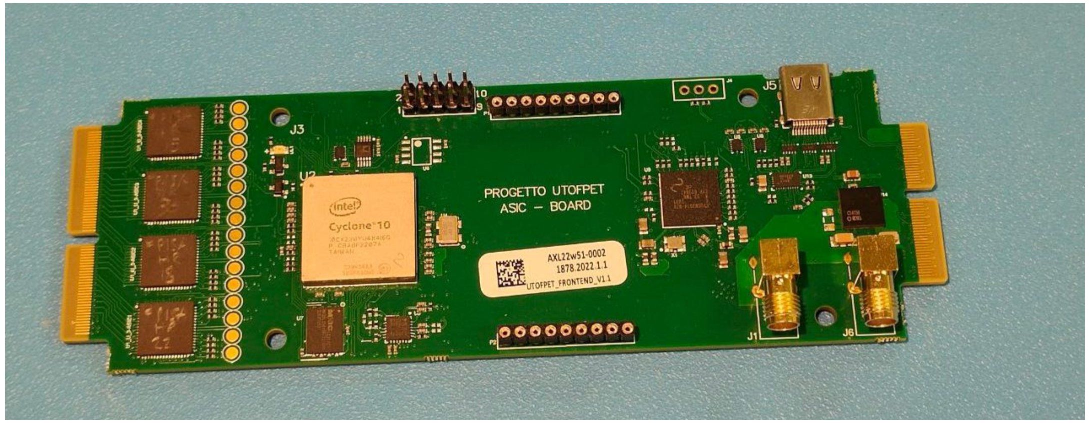


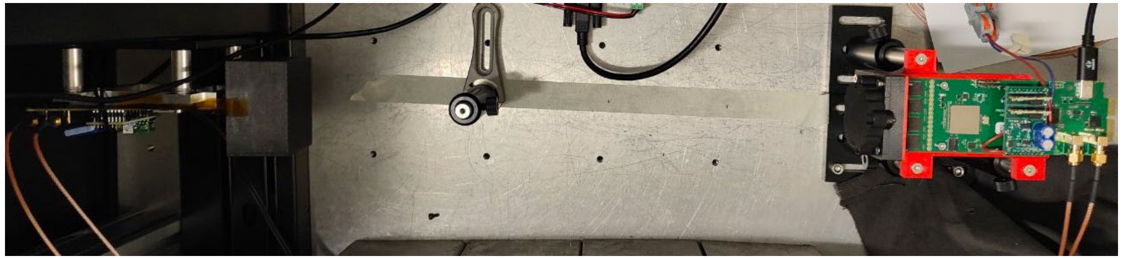
Experimental setup

We use a subset of the UTOFPET detector

- 4x HRFlexToT ASICs
- 64 channels
- 8x8 array of S14160-6050 Hamamatsu MPPCs (6.2 mm pitch)
- 50 mm x 50 mm x 16 mm BGO crystal
- We use a reference detector with a resolution of 130 ps for generating CTR training data





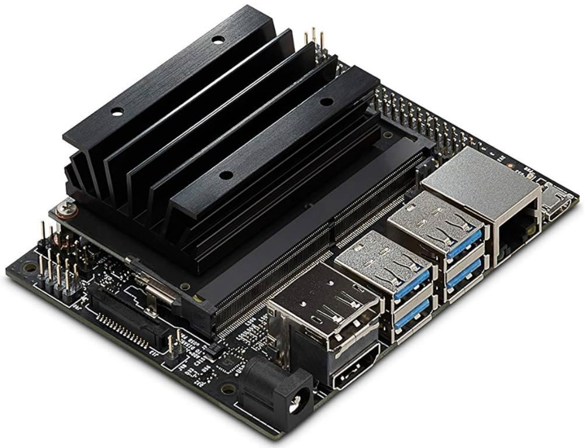


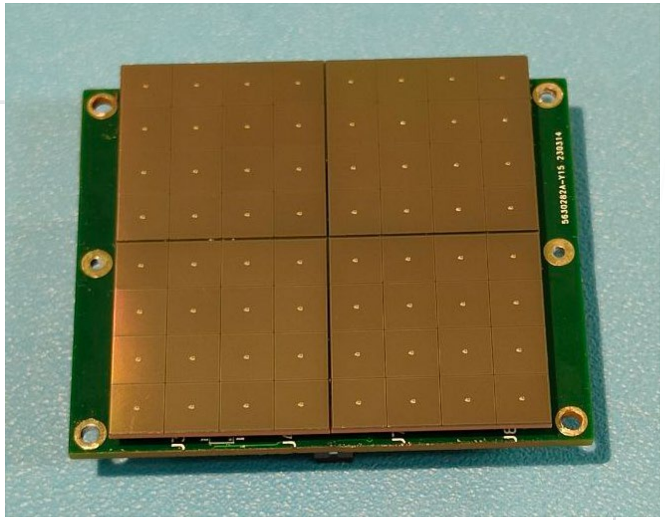
DAQ

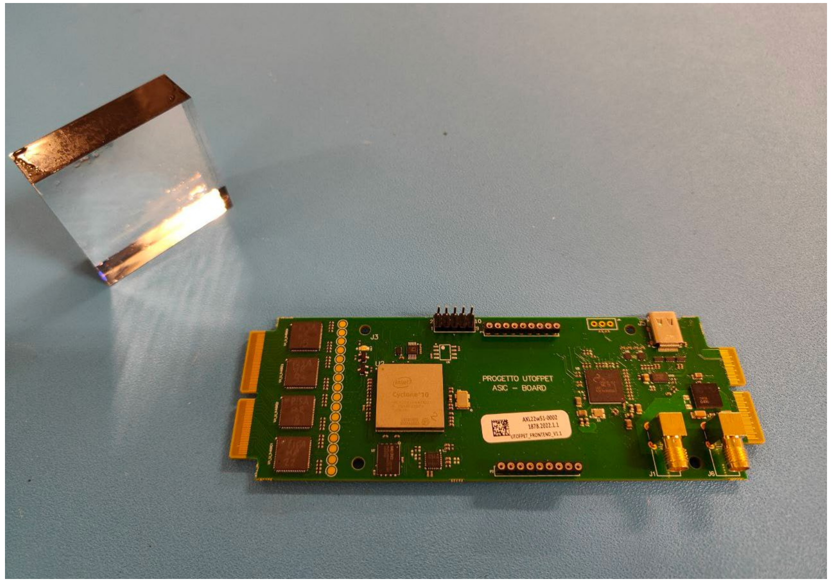
- One Cyclone 10 FPGA with on-board TDCs for ASIC read-out and event clustering

- An NVIDIA Jetson board for running the neural network algorithm.

- One NVIDIA board can handle up to three ASIC boards with three different neural networks at an event rate of 1.3 Mcps each.

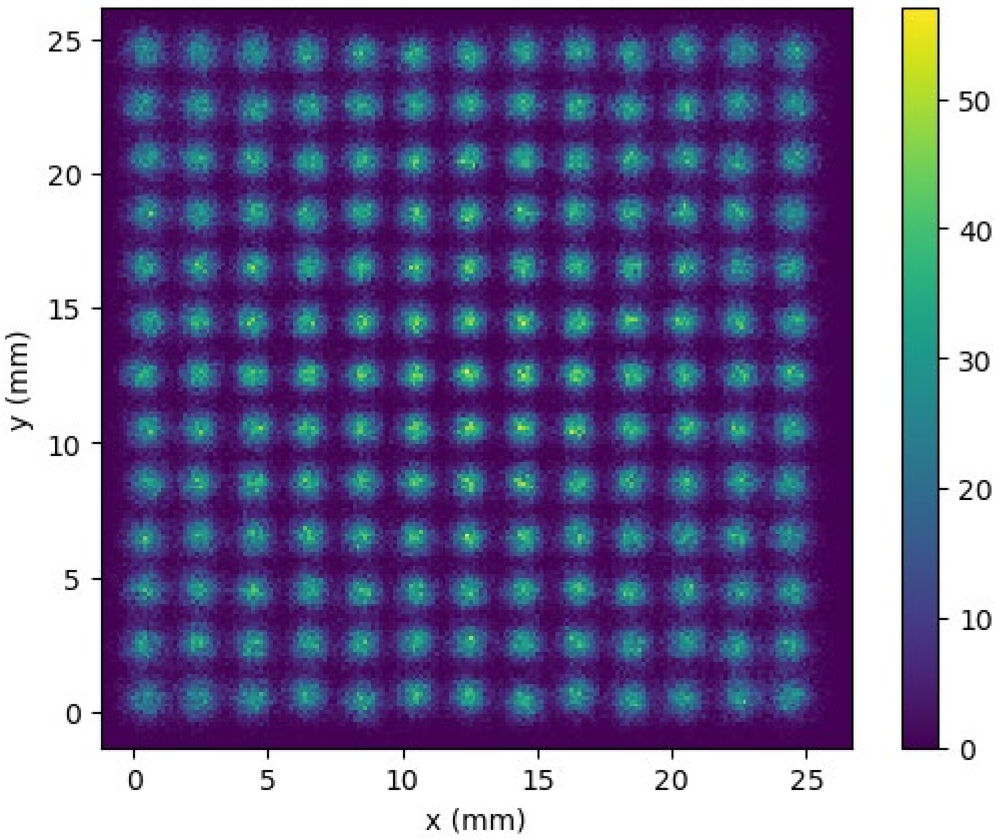






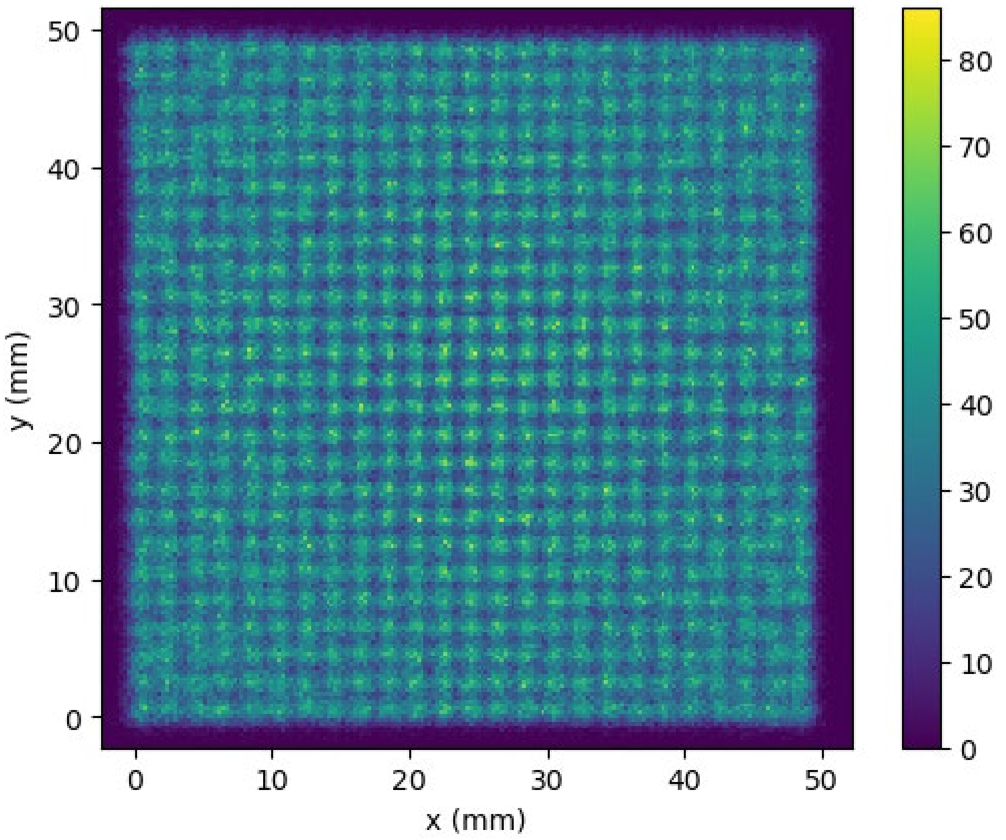
Simulation results: spatial resolution

8 mm thickness – 25 mm crystal



FWHM 0.85 mm
DOI 1.5 mm

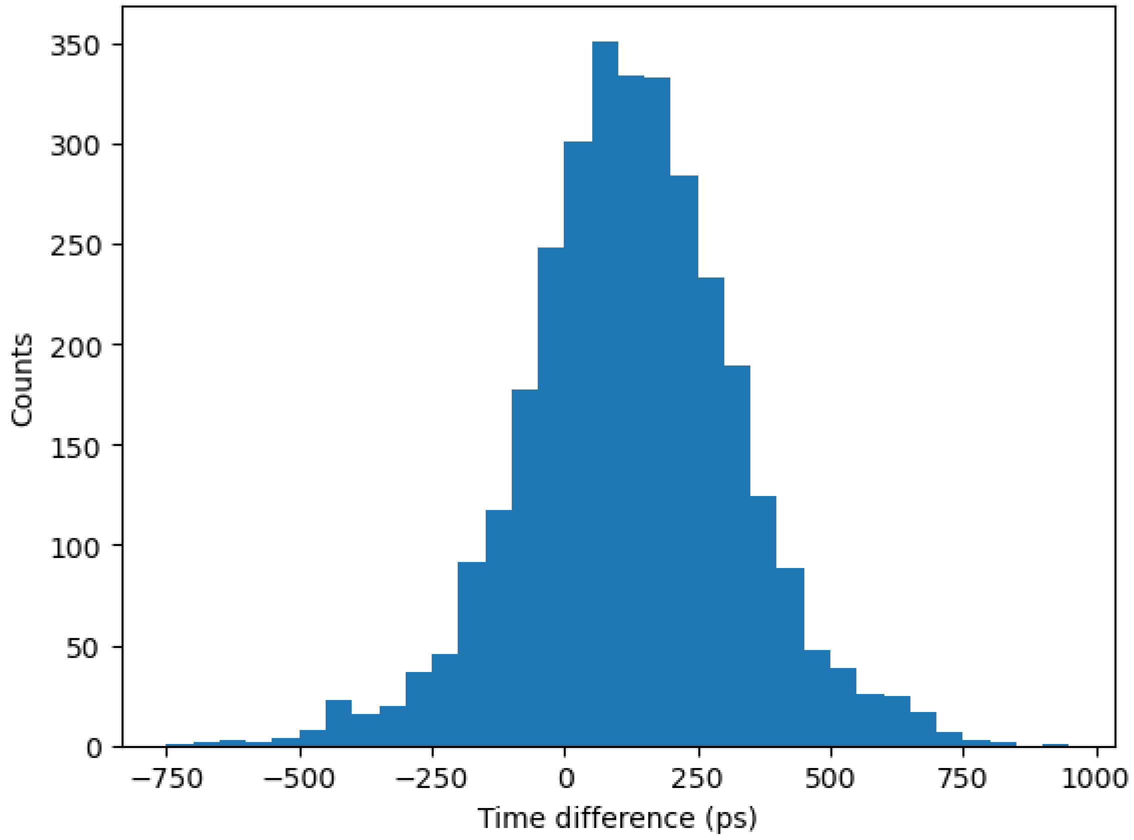
16 mm thickness – 50 mm crystal



FWHM 1.4 mm
DOI 1.8 mm

Simulation results: CTR

- CTR was calculated as the time resolution of a single detector, multiplied by $\sqrt{2}$
- There is a small deviation from a perfectly gaussian shape, probably because of how the task is set up:
  - We estimate only the last 10 bits of the time, the remaining ones are assumed to be measurable without error.
- 16 mm crystal: CTR of 345 ps
- 20 mm crystal: CTR of 367 ps



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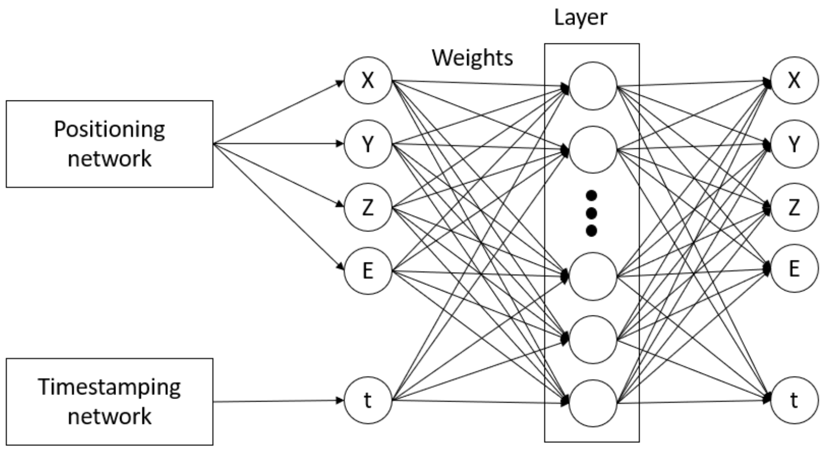
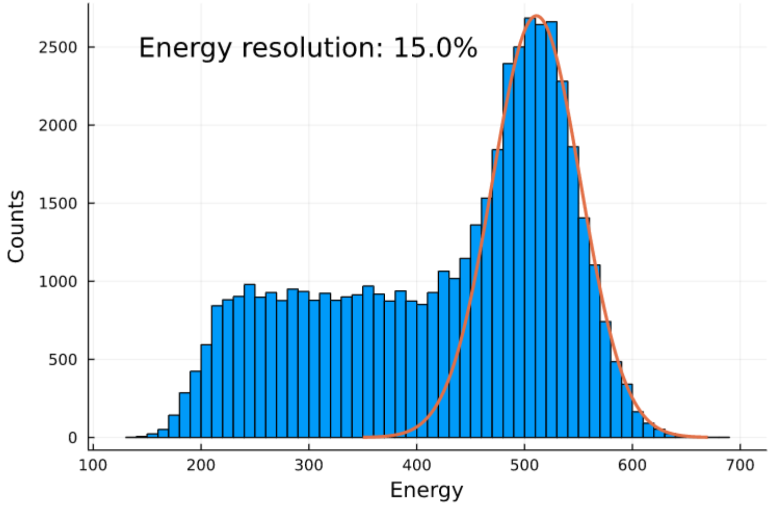
Simulation results: energy resolution

- Energy resolution is estimated with a neural network
- Lower and higher energy events were simulated to avoid overfitting

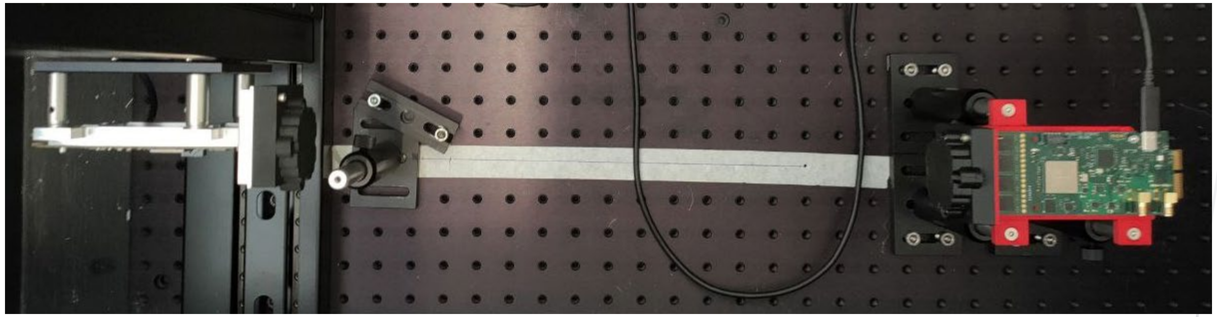


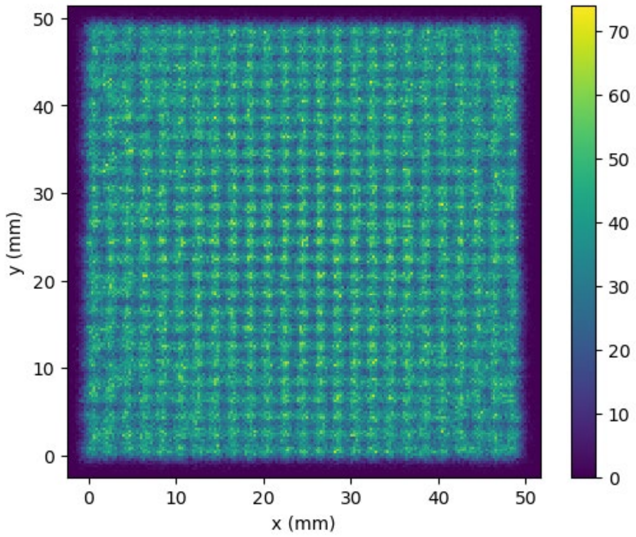


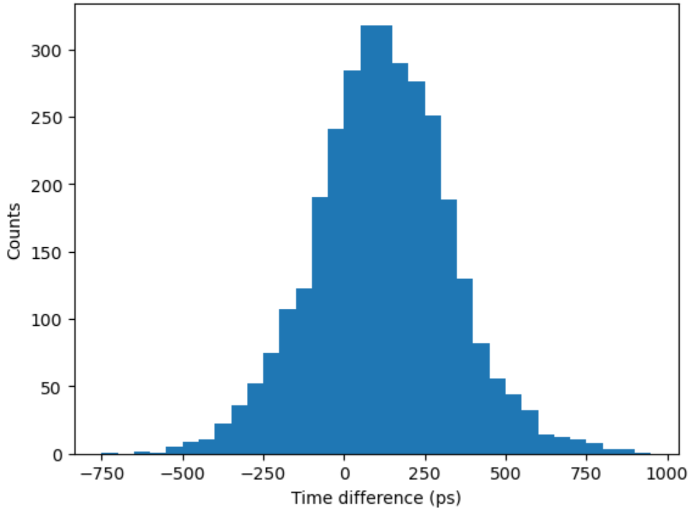
- Energy resolution obtained: 15 % @511 keV

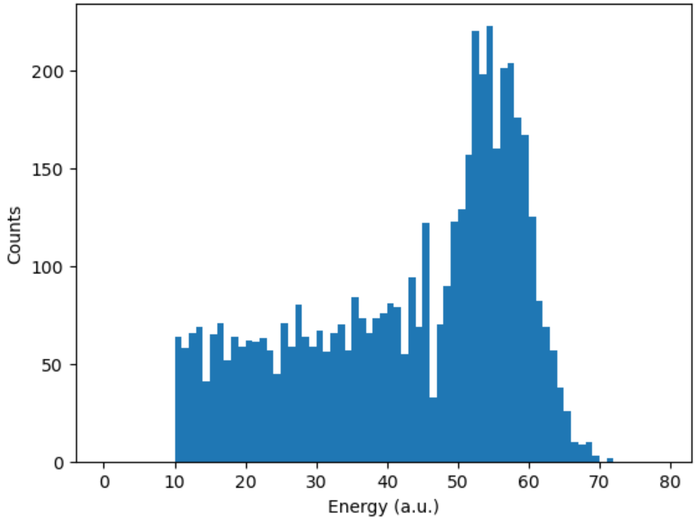
Experimental results – 16 mm

- Bias: < 0.3 mm
- FWHM: 1.55 mm
- CTR: 397 ps FWHM
- Energy resolution: 17.9 %



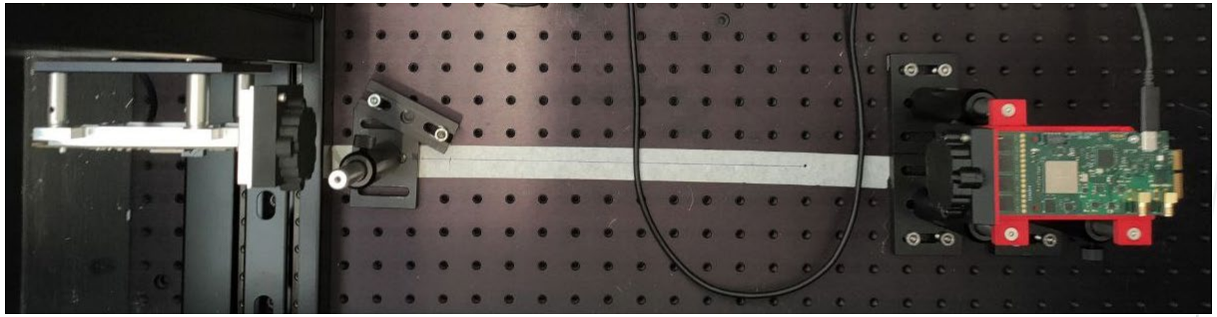


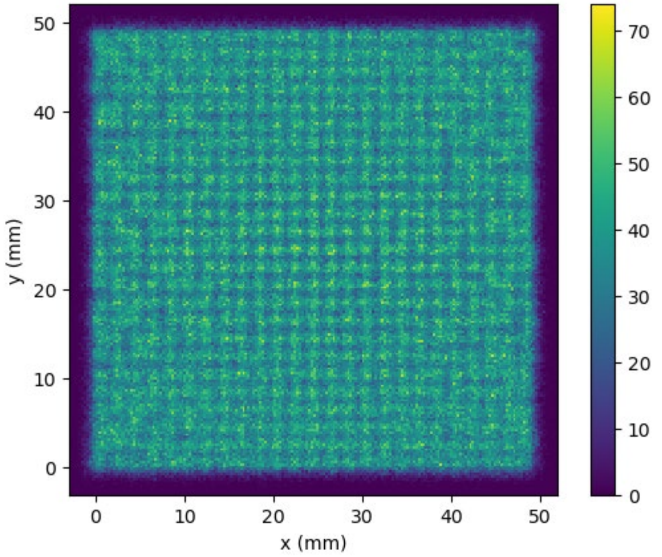


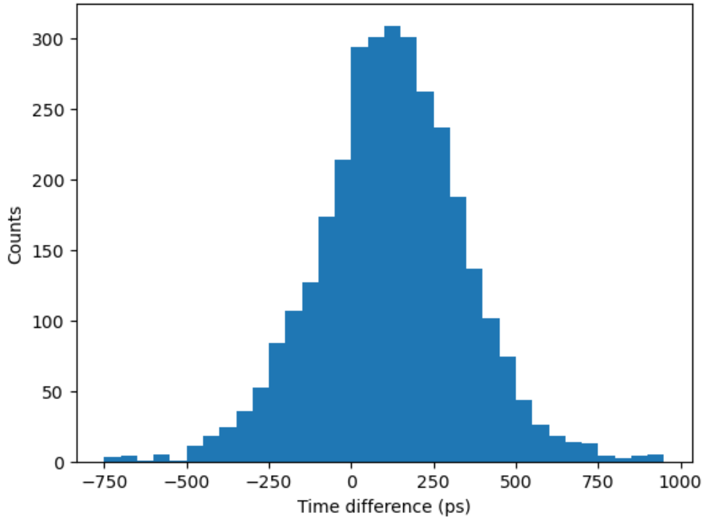


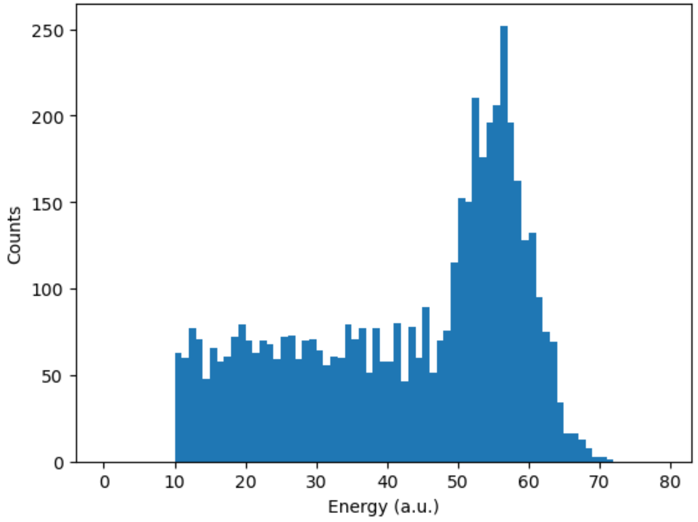
Experimental results – 20 mm

- Bias: < 0.5 mm
- FWHM: 1.68 mm
- CTR: 409 ps FWHM
- Energy resolution: 17.7 %









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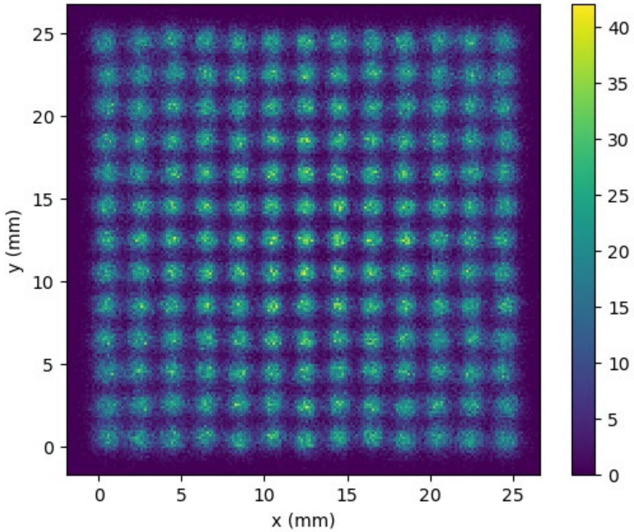
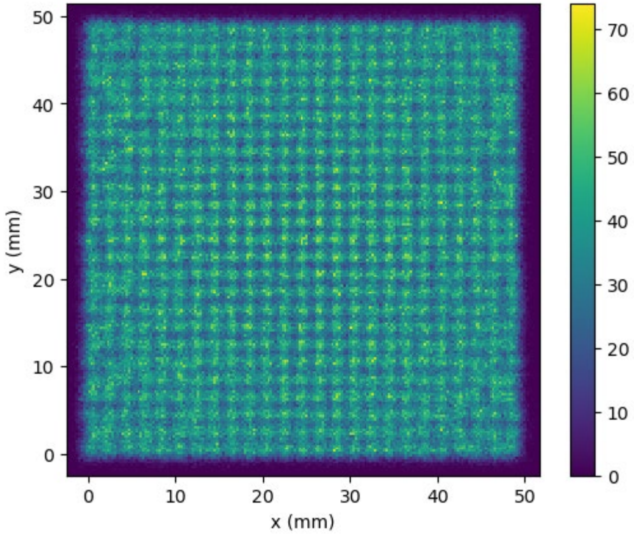
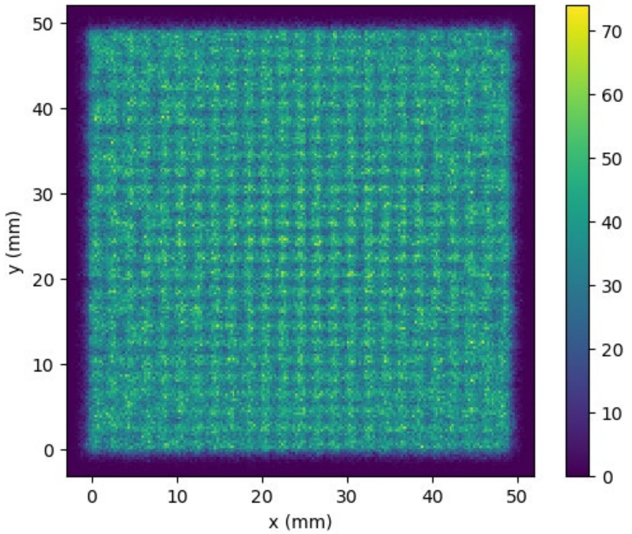
Spatial resolution: effect of crystal thickness



25 mm x 25 mm x 8 mm



50 mm x 50 mm x 16 mm



50 mm x 50 mm x 20 mm

Conclusions

- We have proved that the performance of monolithic BGO remains suitable for clinical PET scanners even when going to 16 mm and 20 mm – thick crystals
- The issue of lower energy resolution of BGO compared to LYSO can be mitigated with an AI algorithm. We have obtained an energy resolution of 17.7 %.
- The 1.55 / 1.68 mm FWHM spatial resolution of 16 mm-thick and 20 mm-thick BGO is insufficient for pre-clinical scanners