Timepix3 Compton Camera: Design & First Results

Petr Mánek, Martin Pichotka, Benedikt Bergmann, Petr Burian

Institute of Experimental and Applied Physics,
Czech Technical University

petr.manek@utef.cvut.cz

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  - Computed Reconstruction
- Simulations
  - Unbiased Approach
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- Conclusion & Further Work

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Compton Camera

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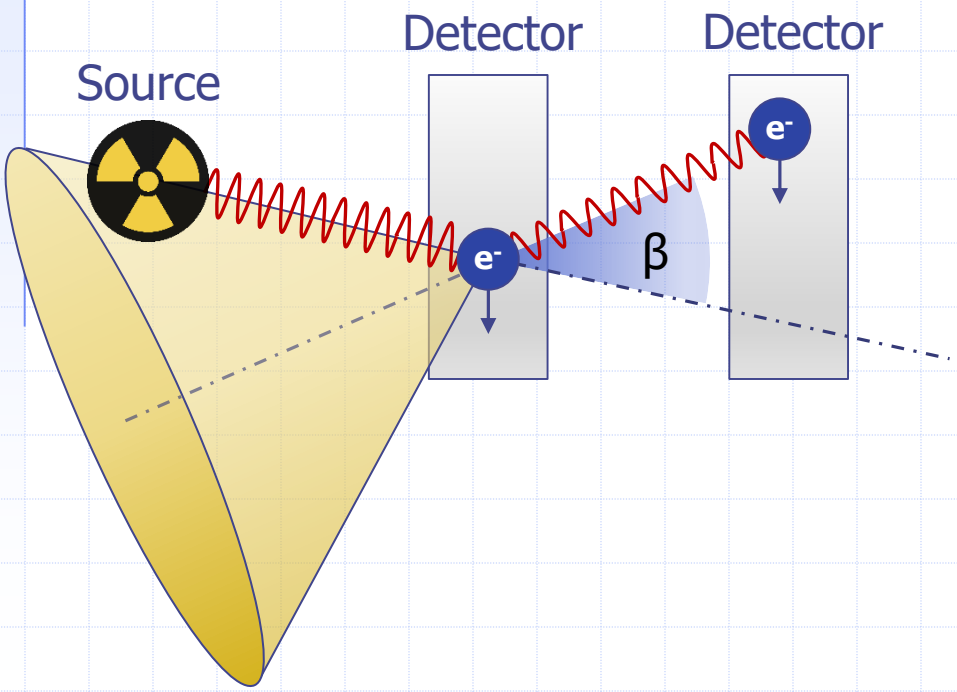
- γ-imaging device based on Compton scattering.



Method:

1. Measure energy of a photon before and after scattering.
2. From (1), the scattering angle β is estimated.
3. Scattered trajectory + angle β define a 3D cone, which intersects source.
4. Camera image is obtained by computed reconstruction using multiple cones.

$$\cos\beta = 1 - m_e c^2 \left(\frac{1}{E'_\gamma} - \frac{1}{E_\gamma} \right) \qquad (1)$$

Motivation for Timepix3

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- Improved image quality
  - Compared to Timepix, Timepix3 offers increased energy resolution.
  - From (1), energy uncertainty ~ angular uncertainty
- Improved efficiency
  - Timepix3 eliminates* dead time.
  - Fast VCOs offer time resolution up to 1.56 ns.
- Data-driven acquisition mode
  - Lower probability of cluster overlaps in high flux environments.
  - Not necessary to adjust acquisition time.
  - Live display during acquisition.
- Mechanical collimation of γ-rays not required!
  - Increased field of view → even larger efficiency
  - Lack of collimator (W, Pb) → smaller, lighter, more portable probe

Camera Design

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Scattering Detector

- Timepix3, Si, 300 μm
- Scatters photons emitted by γ-ray sources.
- Measures the energy lost by scattering (range: 1s-10s keV).

Absorbing Detector

- Timepix3, CdTe, 2 mm
- Absorbs scattered photons.
- Measures the absorbed energy (range: 10s-100s keV).

Katherine Readout

- Controls acquisition of both detectors.
- Performs time synchronization.
- Supplies bias voltage.

Control Computer

- Connected to the readout by 1 Gbit Ethernet.
- Reads raw data and reconstructs camera image.

Camera Design

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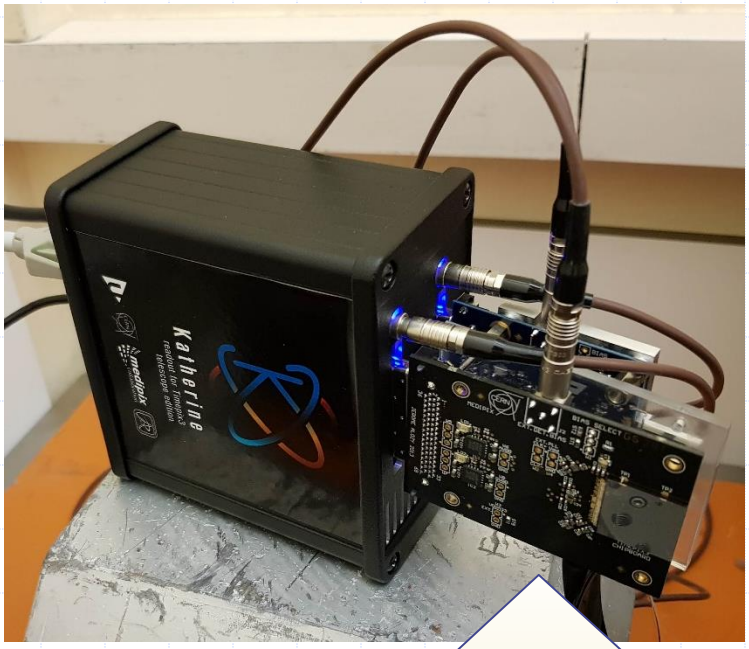
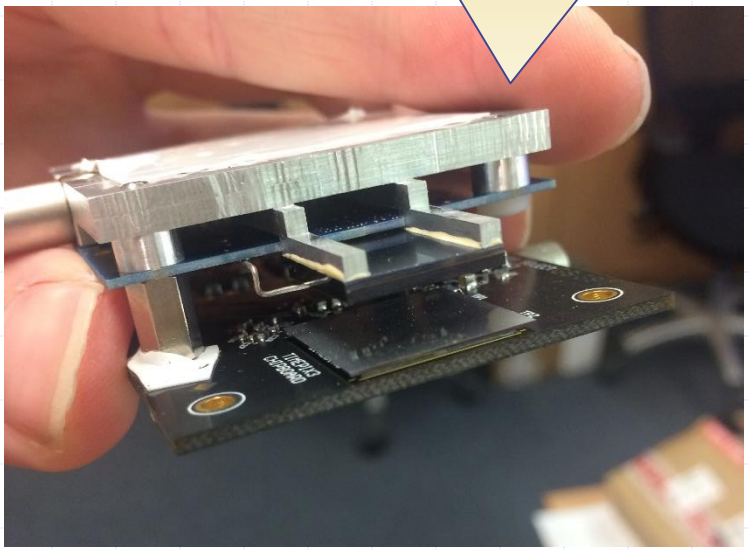


Static Probe (Katherine + Timepix3)

- Compact (no VHDCI cables)
- Detector configuration is fixed.
- Not recommended for harsh radiation conditions.

Portable Probe (Timepix3 only)

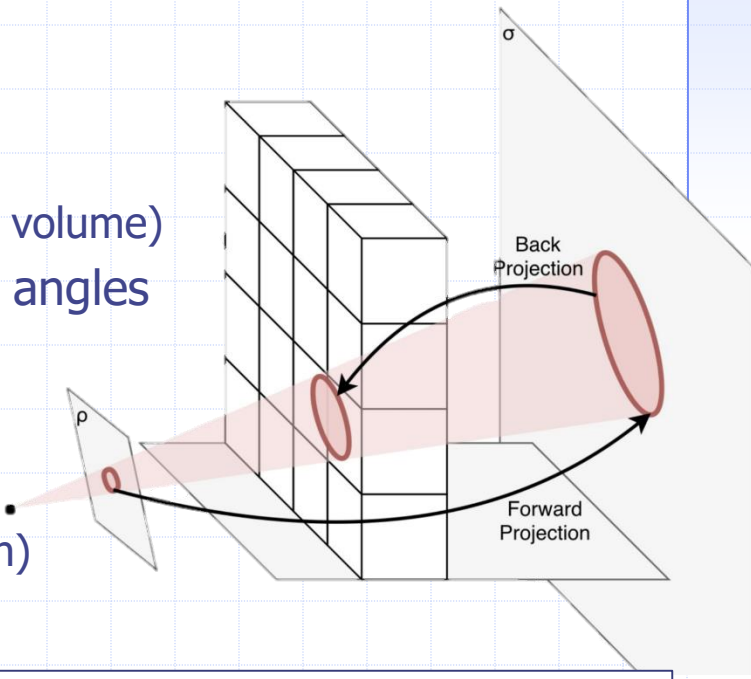
- Small, light, suitable for actuated and handheld mounts.
- Connected to the readout via VHDCI + LEMO (< 100 m).

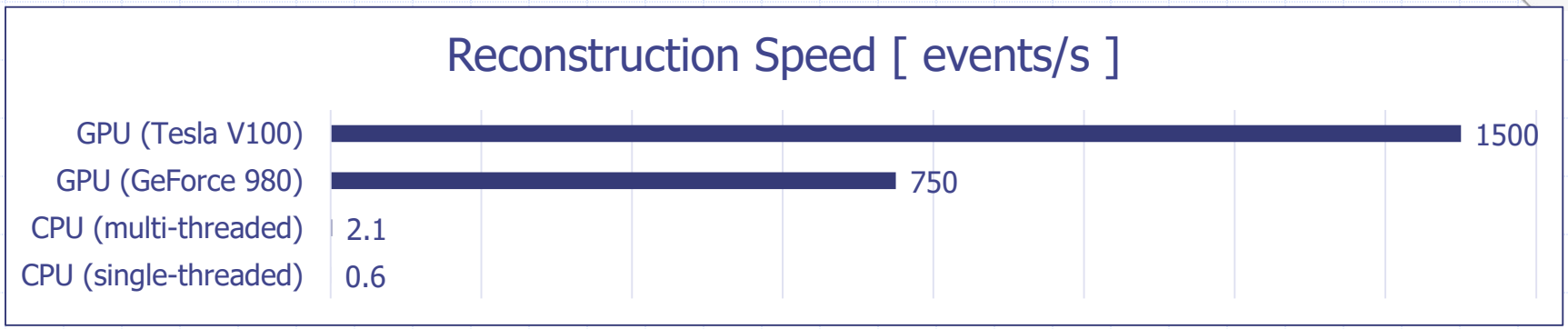


Computed Reconstruction

- Performed by back projection algorithm
- Supported reconstruction modes:
  - Planar – output is a conventional 2D image
  - Volumetric – output is a 3D image (discretized volume)
- Additive / multiplicative blending for multiple angles

- Goal: optimize speed → online display
  - Exploitation of orthogonality → 2-stage alg.
  - Conventional optimizations (LUTs, interpolation)
  - Massive parallelization (OpenMP, GPUs)

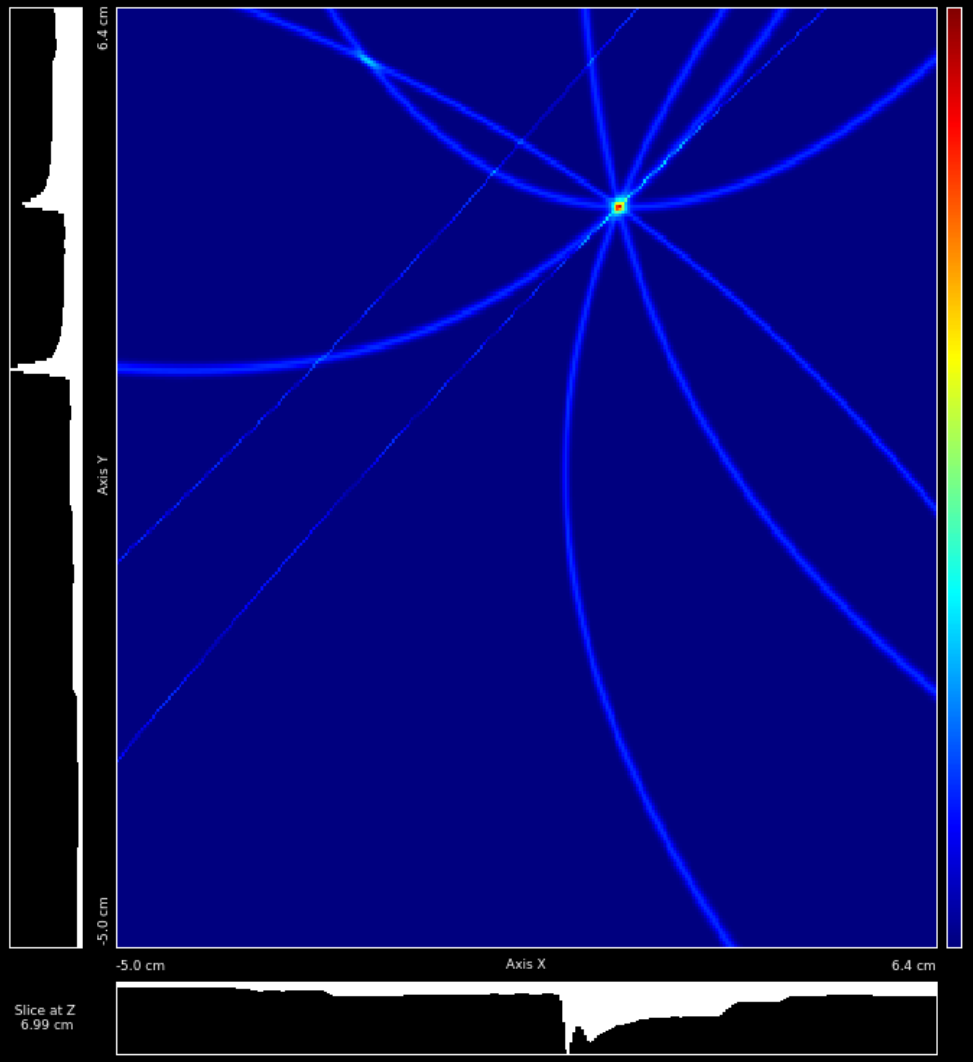




Computed Reconstruction

- Example: Point source
- Front view (XY slice)

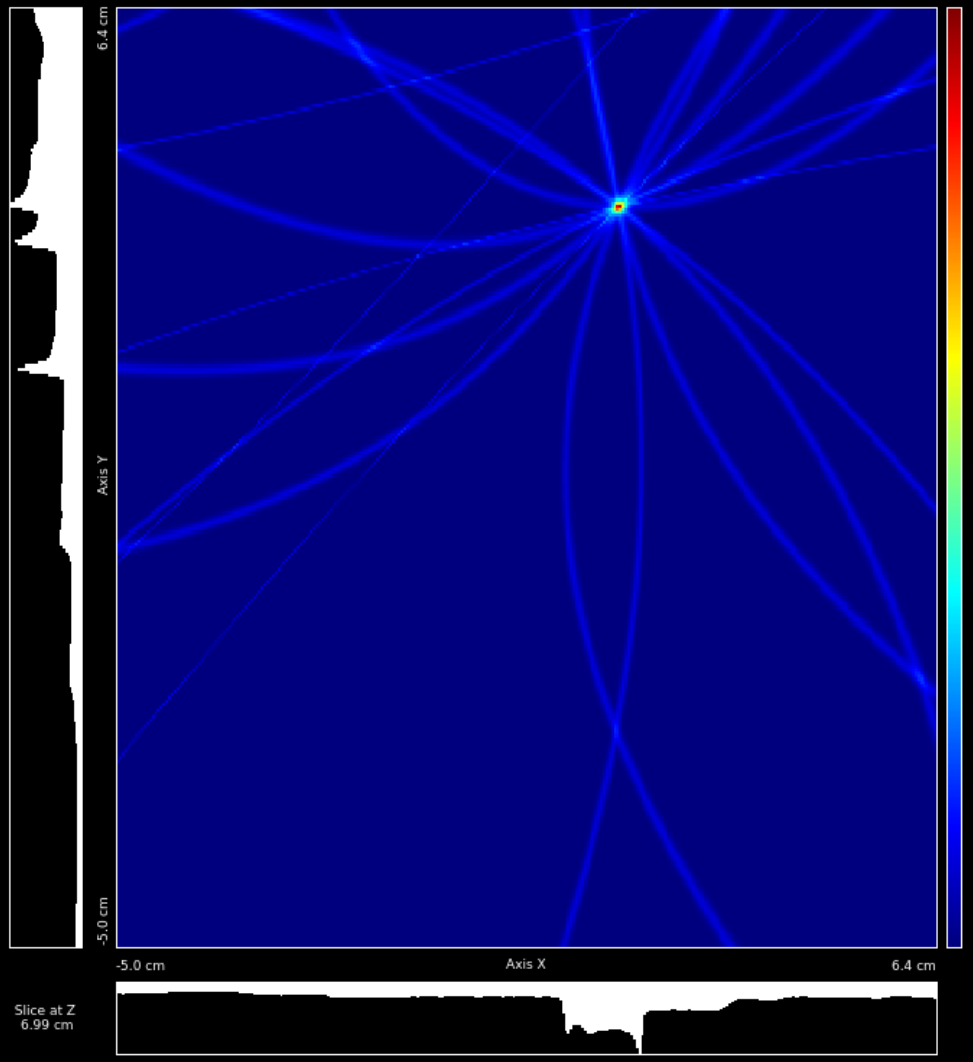
- N = 5 cones



Computed Reconstruction

- Example: Point source
- Front view (XY slice)

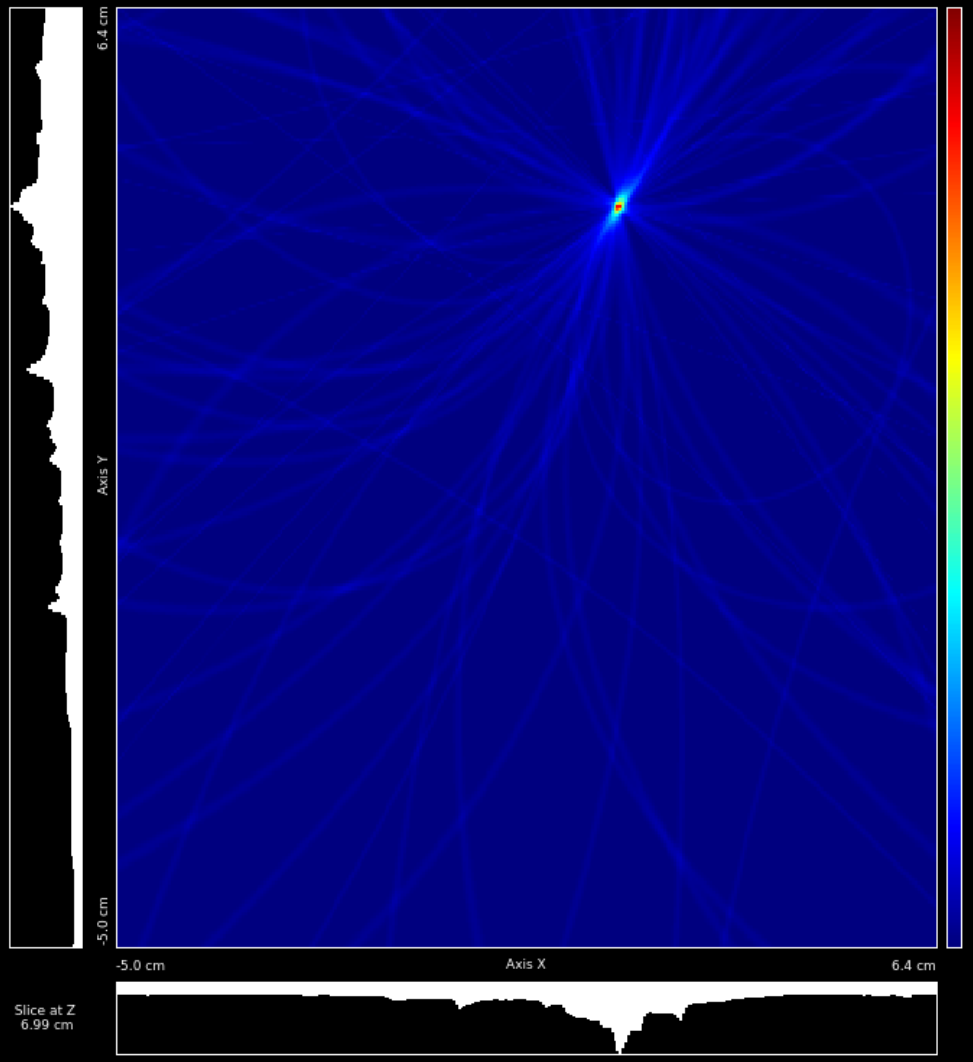
- N = 10 cones



Computed Reconstruction

- Example: Point source
- Front view (XY slice)

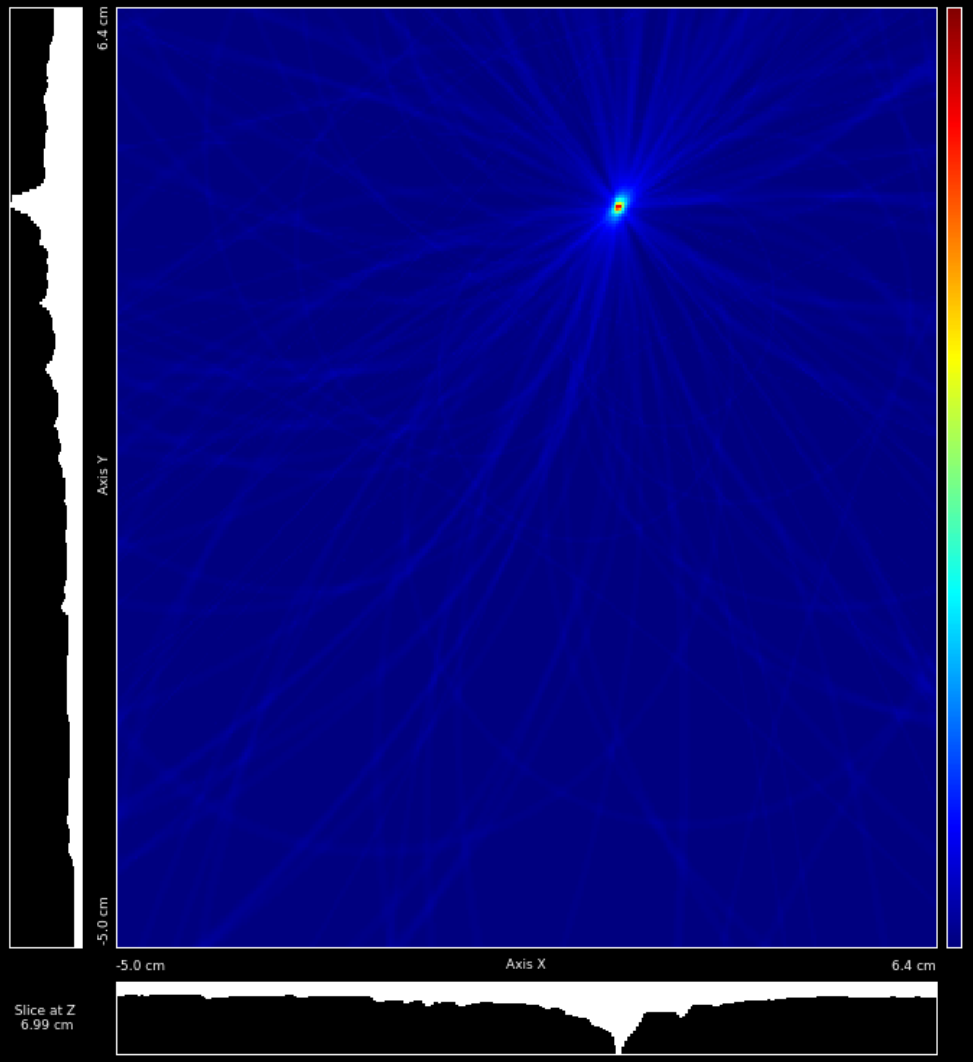
- N = 50 cones



Computed Reconstruction

- Example: Point source
- Front view (XY slice)

- N = 100 cones



Simulation: Unbiased

- Goal: Evaluate reconstruction algorithm correctness
- Method: Simulate 3D cones directly (no noise or biased angular dist.)

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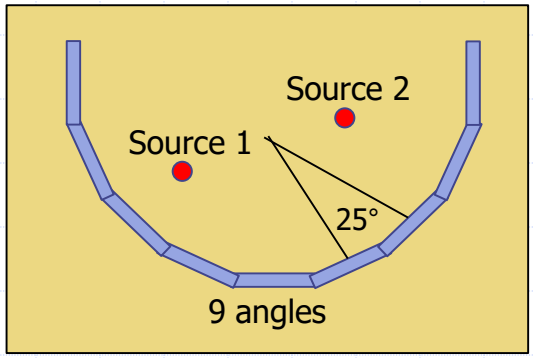
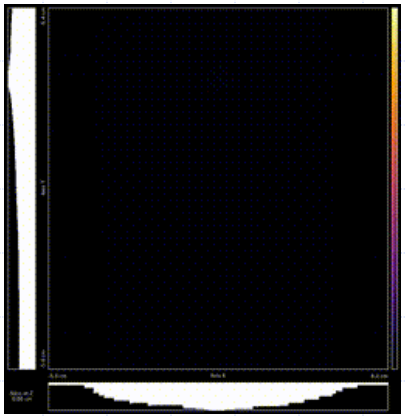
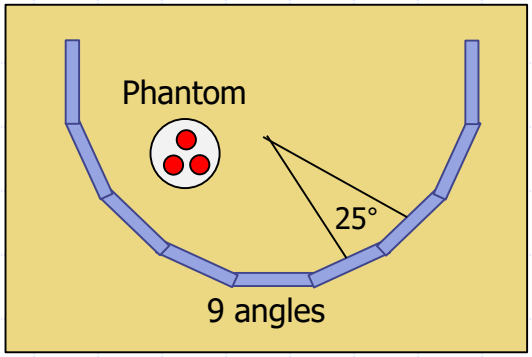
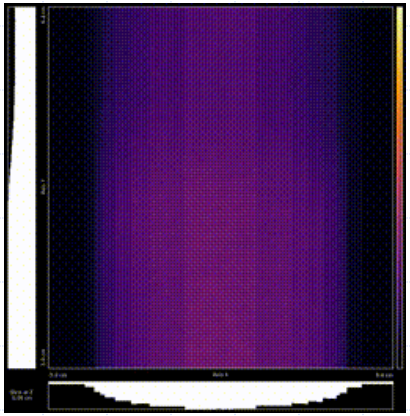
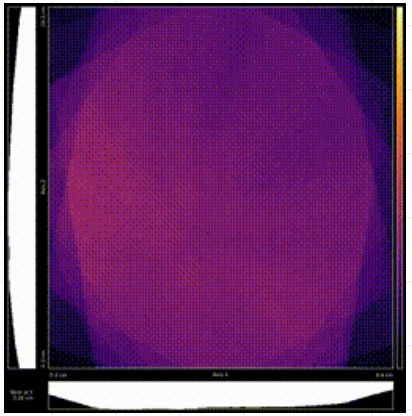
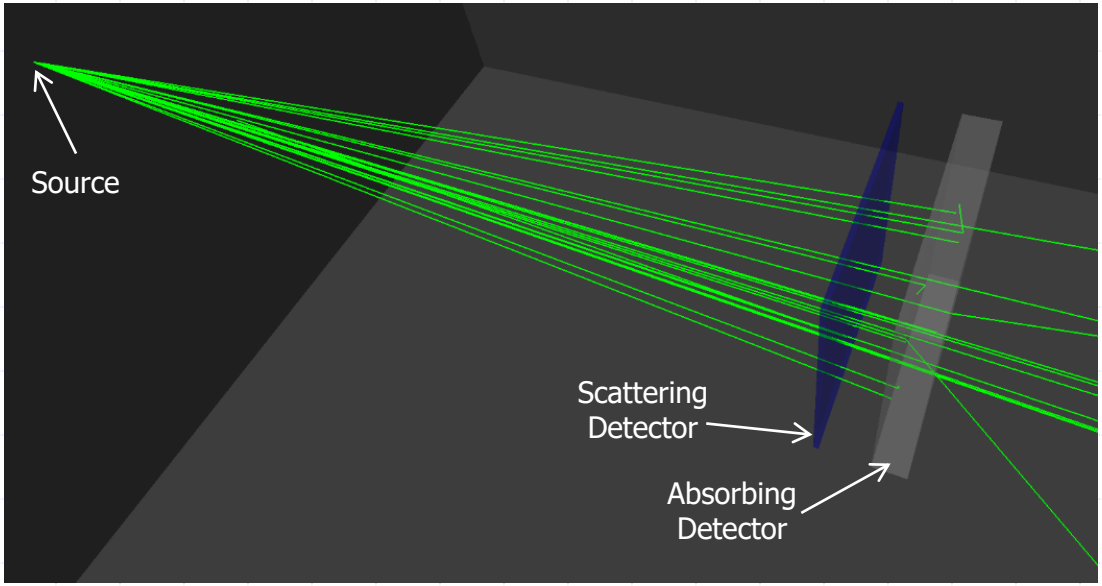
	Simulated Geometry	Front View (XY)	Top View (XZ)
Point Sources			
Shape Source			

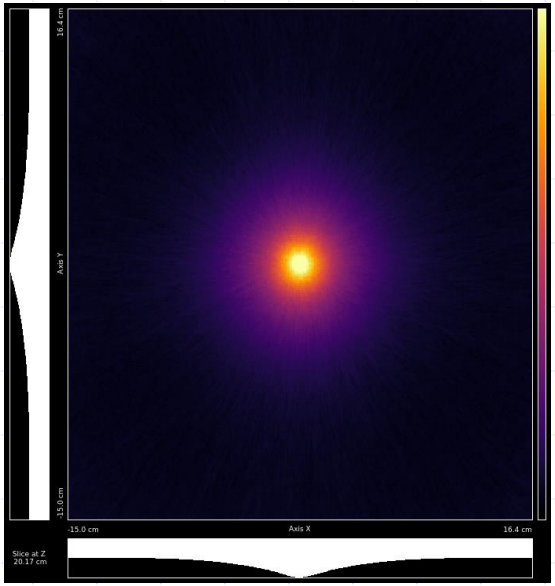
Simulation: Geant4 (1)

- Goals:
  - Simulate Timepix3 response as accurately as possible,
  - Evaluate reconstruction software as a whole.
- Conditions: vacuum, standard pressure, room temperature, no noise
- Simulated $500 \cdot 10^6$ 140 keV photons emitted from a point source.

Simulated Geometry



Reconstructed (XY)



Simulation: Geant4 (2)

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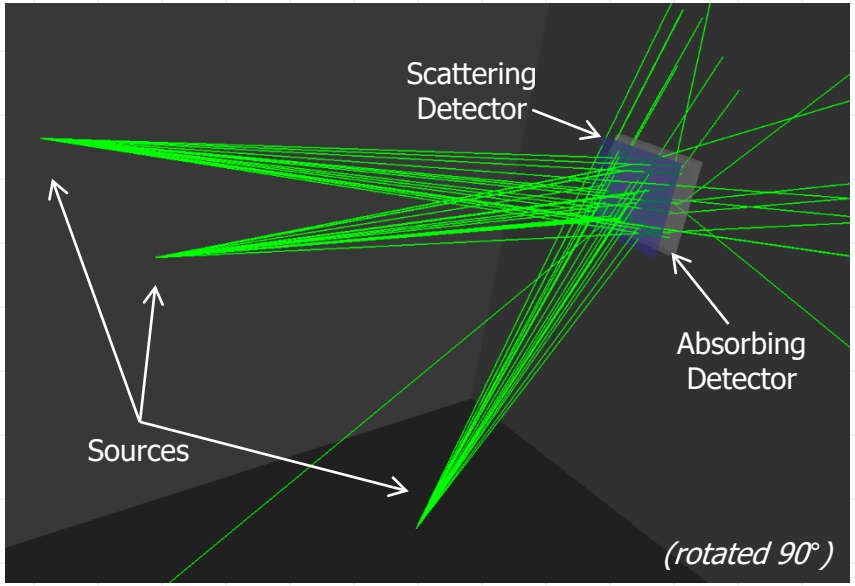
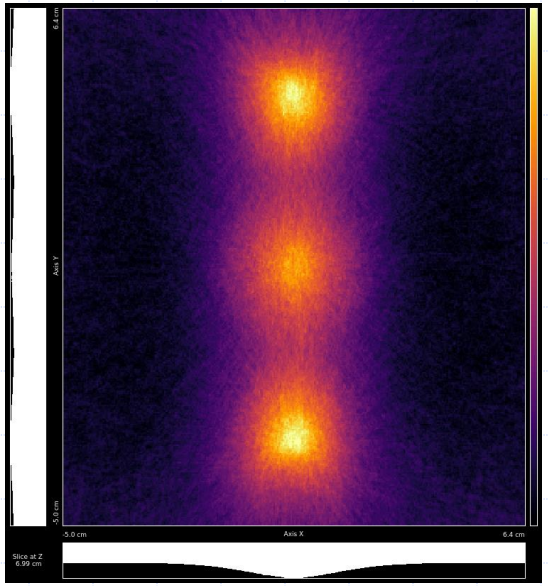
- Goals:
  - Simulate Timepix3 response as accurately as possible,
  - Evaluate reconstruction software as a whole.
- Conditions: vacuum, standard pressure, room temperature, no noise
- Simulated $500 \cdot 10^6$ 140 keV photons emitted from 3 point sources.

Simulated Geometry



Reconstructed (XY)



First Measurement: ^{241}Am

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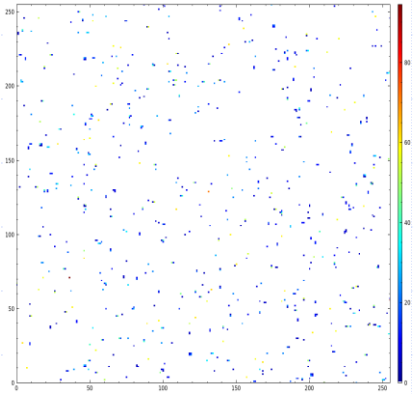
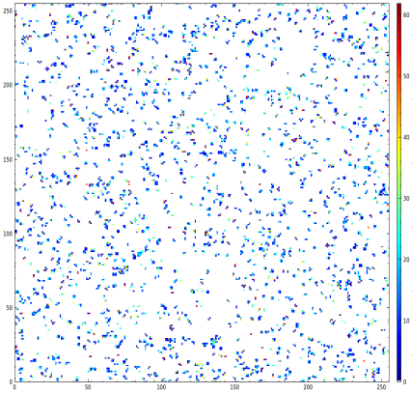
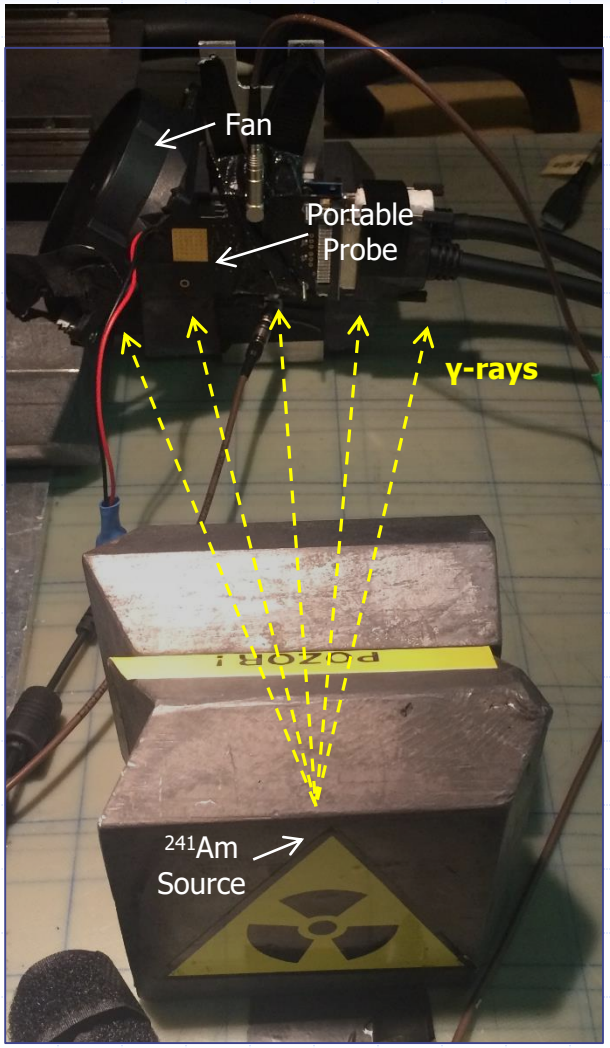
- Uncollimated ^{241}Am source
  - Activity: 3.7 GBq
  - Assumed to have point-like appearance
- Measured using portable probe.
  - Face-to-face configuration
  - Distance between chips: 5.1 mm
  - Distance from source: 14 cm



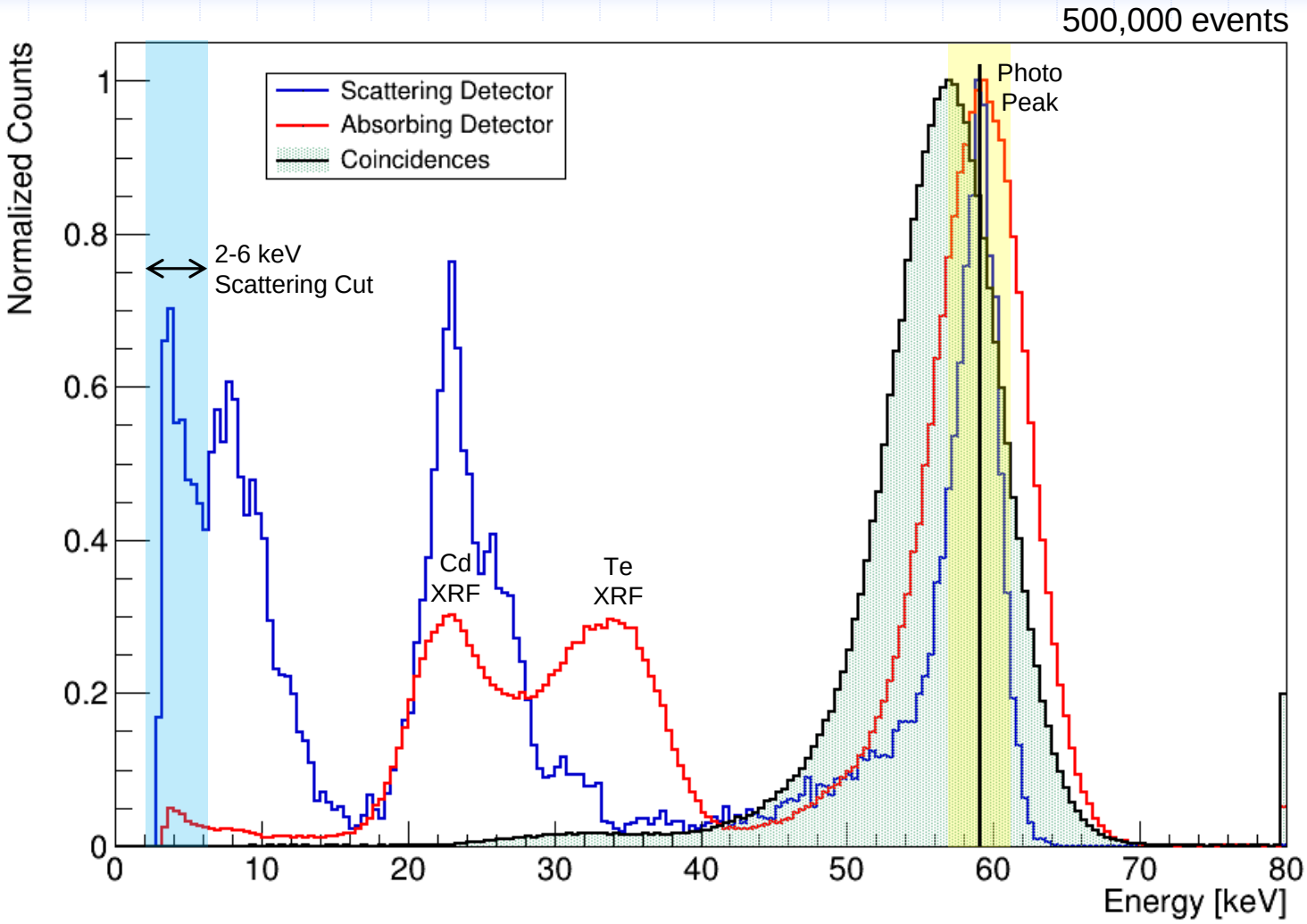
Scattering Detector Output
(integrated 100 ms)



Absorbing Detector Output
(integrated 10 ms)



First Measurement: ^{241}Am



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First Measurement: ^{241}Am

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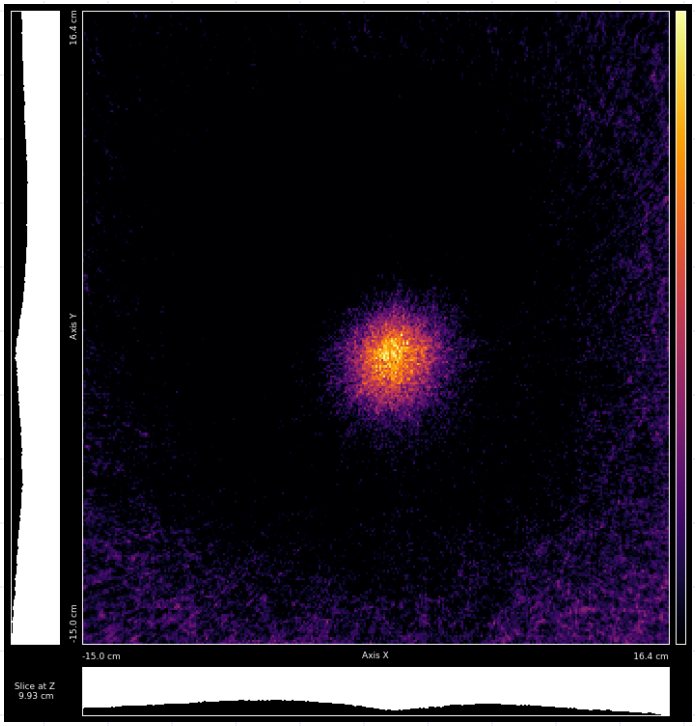
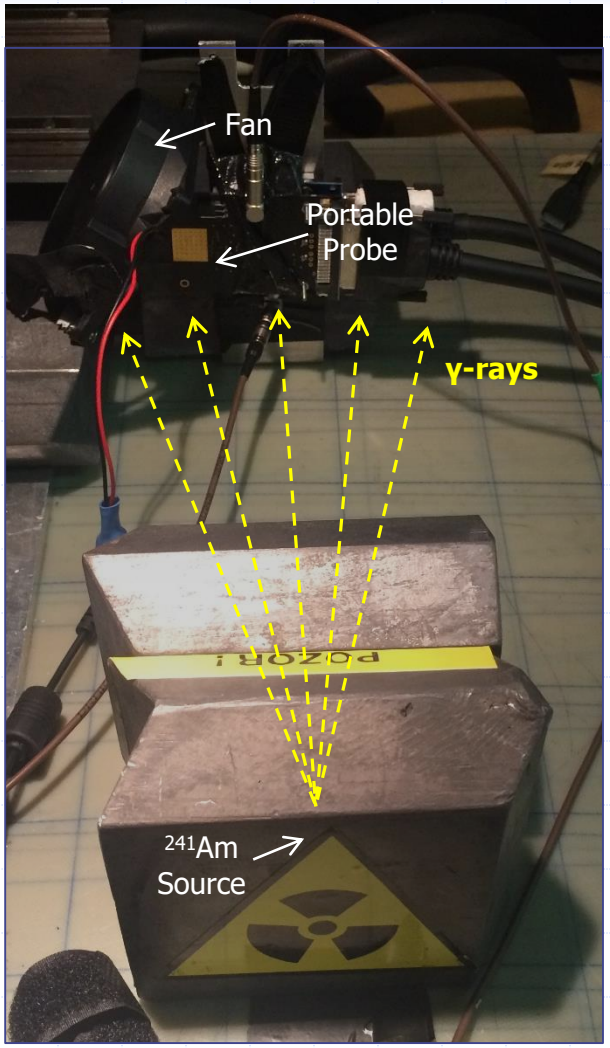
Reconstructed (XY)





Second Measurement: ^{99m}Tc

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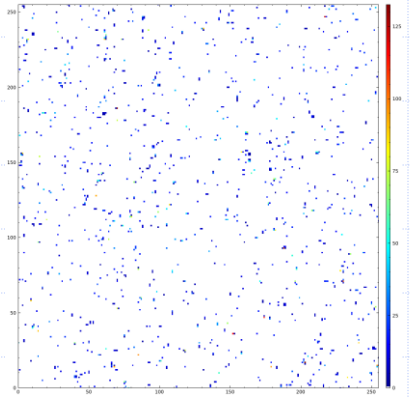
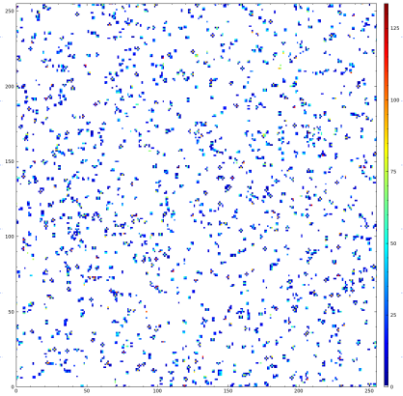
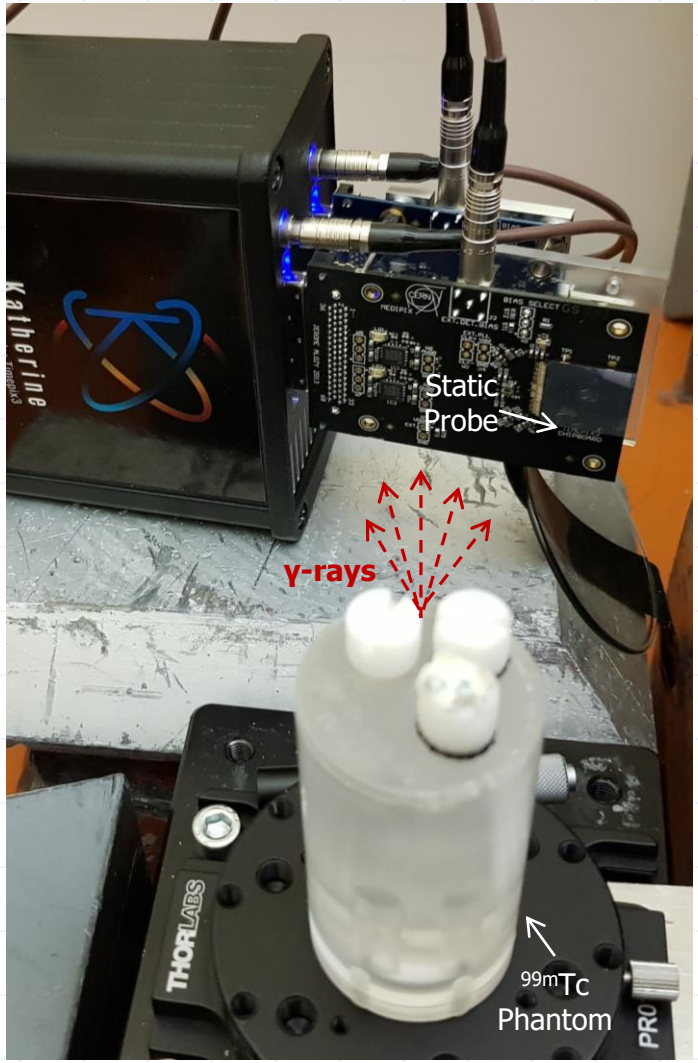
- Phantom with 3 ^{99m}Tc capillaries
  - Activity: 29.8 MBq
  - Example of more realistic shape source
- Measured using static probe.
  - Parallel configuration
  - Distance between chips: 2.1 mm
  - Distance from source: 11 cm



Scattering Detector Output
(integrated 1 s)



Absorbing Detector Output
(integrated 100 ms)



Second Measurement: ^{99m}Tc

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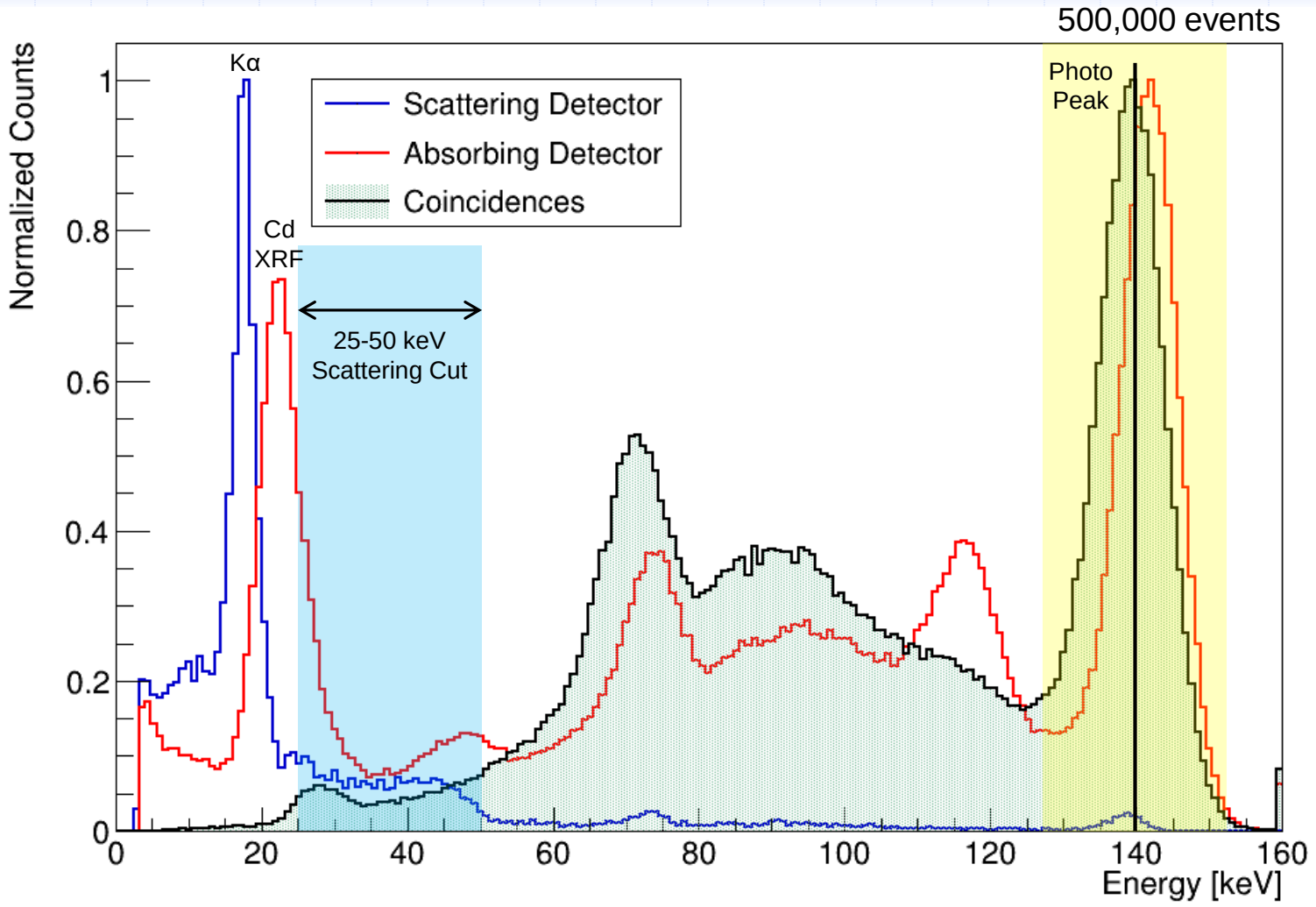
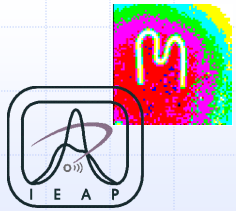


Conclusion



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- Designed a new Timepix3 Compton camera.
- Verified device geometry using series of simulations.
- Benchmarked reconstruction software to ensure sufficient performance.
- Performed first measurements with experimental prototype.

- Further work:
  - Implement iterative reconstruction algorithm (LM-MLEM),
  - Additional X-ray fluorescence suppression,
  - More realistic simulations (PCB, noise, multiple detectors),
  - Utilization of multiple view angles, larger sensitive area, tiled chips,
  - Study of depth resolution.

- Applications:
  - Medical imaging (SPECT),
  - Homeland security,
  - Decontamination

Thank you for your attention.

Petr Mánek, petr.manek@utef.cvut.cz

References:

- Mánek P. *A system for 3D localization of gamma source using Timepix3-based Compton cameras.* Master's thesis. Charles University, 2018.
- Lojacono X. *Image reconstruction for Compton camera with application to hadrontherapy.* Imaging. Ph.D. thesis. INSA de Lyon, 2013.
- Burian P. et al. *Katherine: Ethernet Embedded Readout Interface for Timepix3.* JINST, 2017.