Development of SOI-GFAG Compton imager with recoil electron tracking capability

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The Tenth International Workshop
on Semiconductor Pixel Detectors for Particles and Imaging

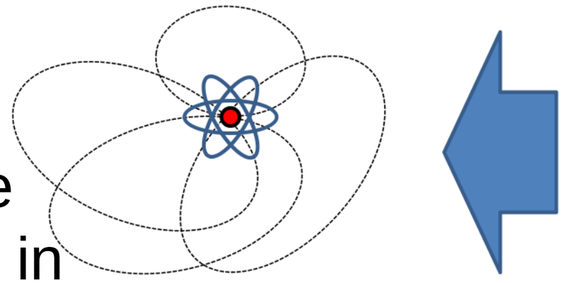
Outline

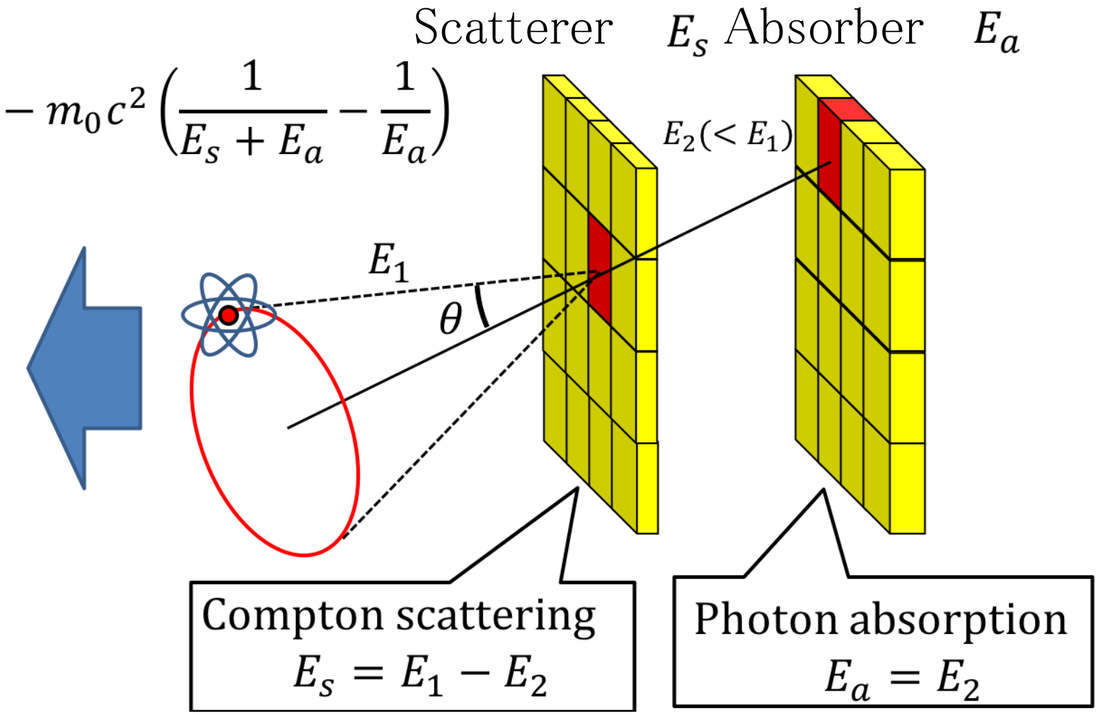
- Research Background
  - Compton imaging
  - Compton imaging in medical field
- Recoil electron Compton imaging
- Development of Compton camera with SOI fine-pitch pixel detector and GFAG scintillator detector
- Electron Trajectory in SOI pixel detector (XRPIX7)
- Summary

Research Background

◆ Compton imaging

- One of gamma-ray imaging techniques based on Compton scattering kinematics
- Scattering angle information can be calculated from deposited energies in a scatterer and an absorber
- No collimators required
- Wide photon energy range for imaging
- Wide field of view





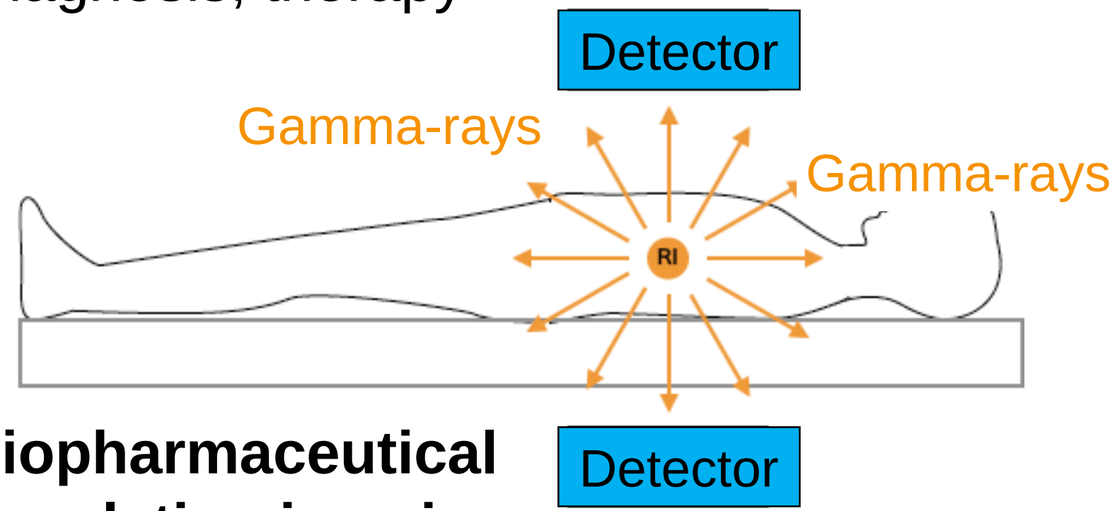
Application

→Astrophysics, Medical field, Nuclear field

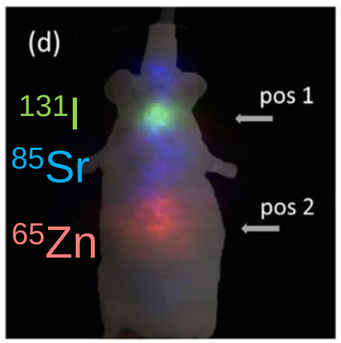
◆ Compton imaging in medical field

Nuclear Medicine

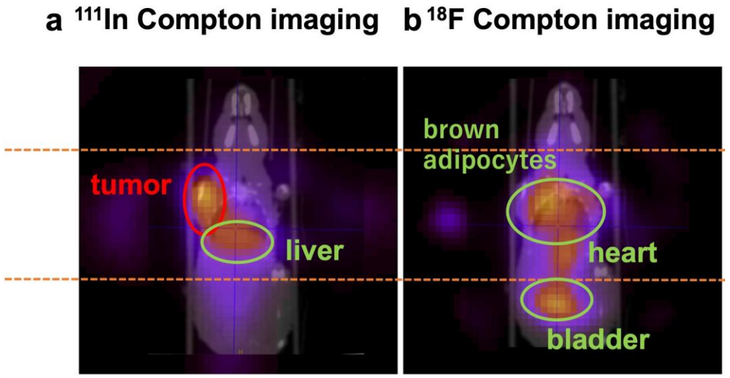
→Diagnosis, therapy



Radiopharmaceutical accumulation imaging



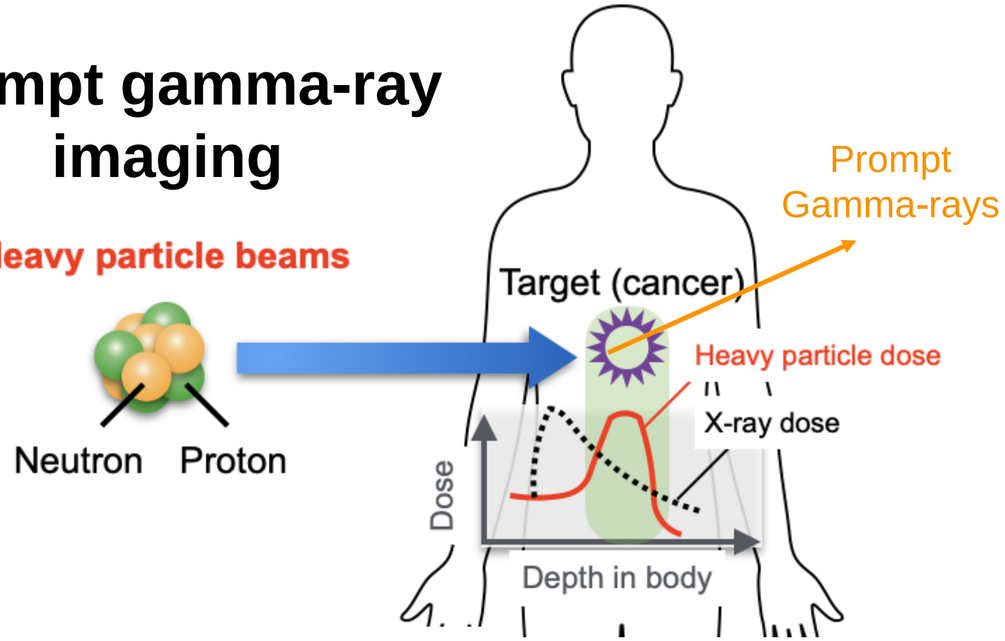
A. Kishimoto et al., Sci. Rep., (2017):2110

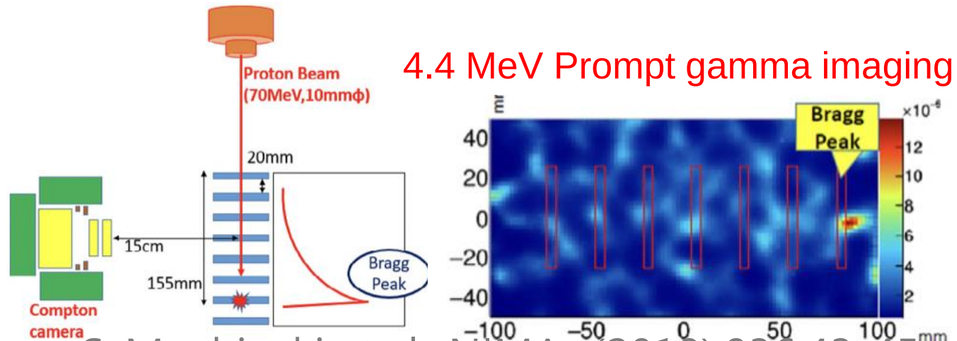


M. Yoenomachi et al., Sci. Rep., (2021):17933

Heavy particle therapy

Prompt gamma-ray imaging





S. Mochizuki et al., NIMA., (2019);936:43-45

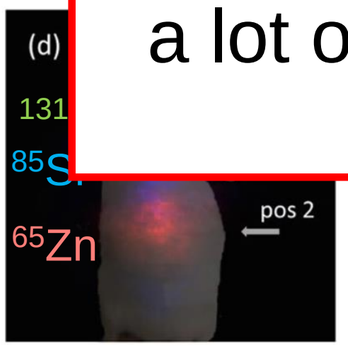
Research Background

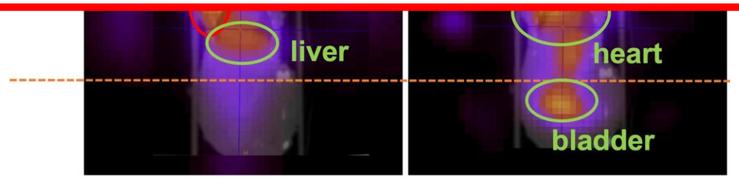
◆ Compton imaging in medical field

Nuclear Medicine

→Diagnosis, therapy

Radioph
accumul

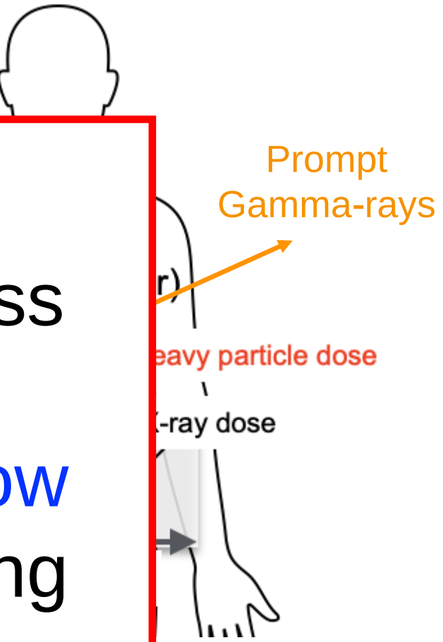




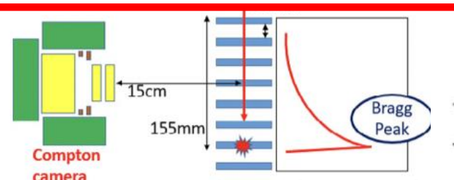
A. Kishimoto et al., Sci. Rep., (2017):2110

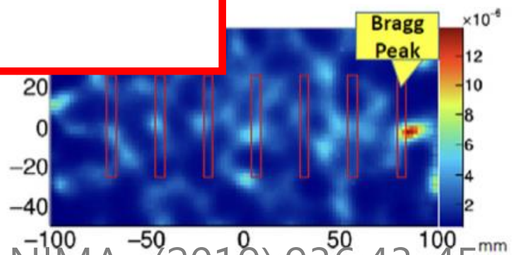
Heavy particle therapy

Prompt gamma-ray



t gamma imaging





M. Yamaguchi et al., Sci. Rep., (2021):17933

S. Mochizuki et al., NIMA., (2019);936:43-45

Compton imaging is a promising method in medical field due to the wide energy range and collimator-less imaging

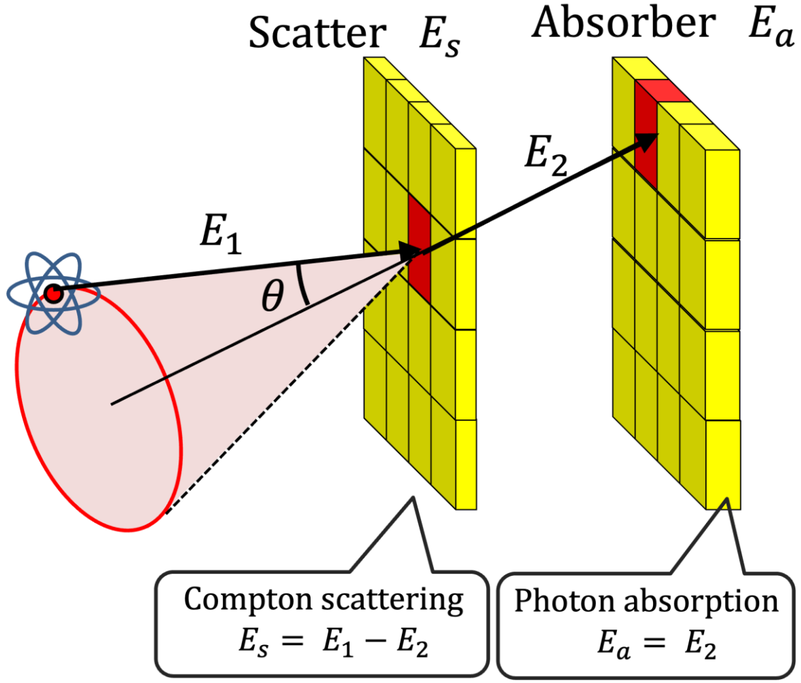
However, still in under research because of the low signal-to-background ration (SBR) caused by drawing a lot of Compton cones.

Recoil electron tracking Compton imaging

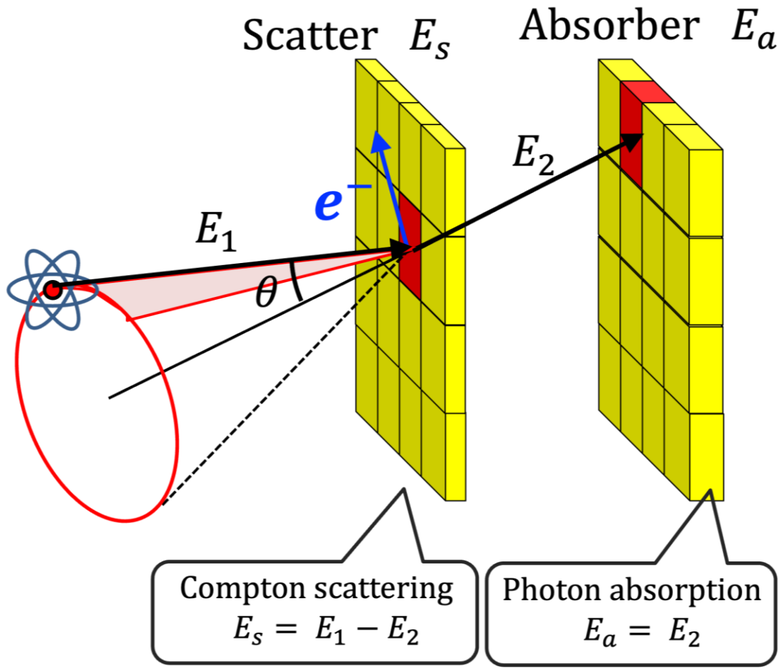
Measurement of a recoil electron trajectory when a photon is Compton scattered in a scatterer

⇒ Constrains the radionuclide position on from a Compton conical surface to **an arc surface**

Conventional imaging



Electron tracking imaging



Recoil electron tracking Compton imaging

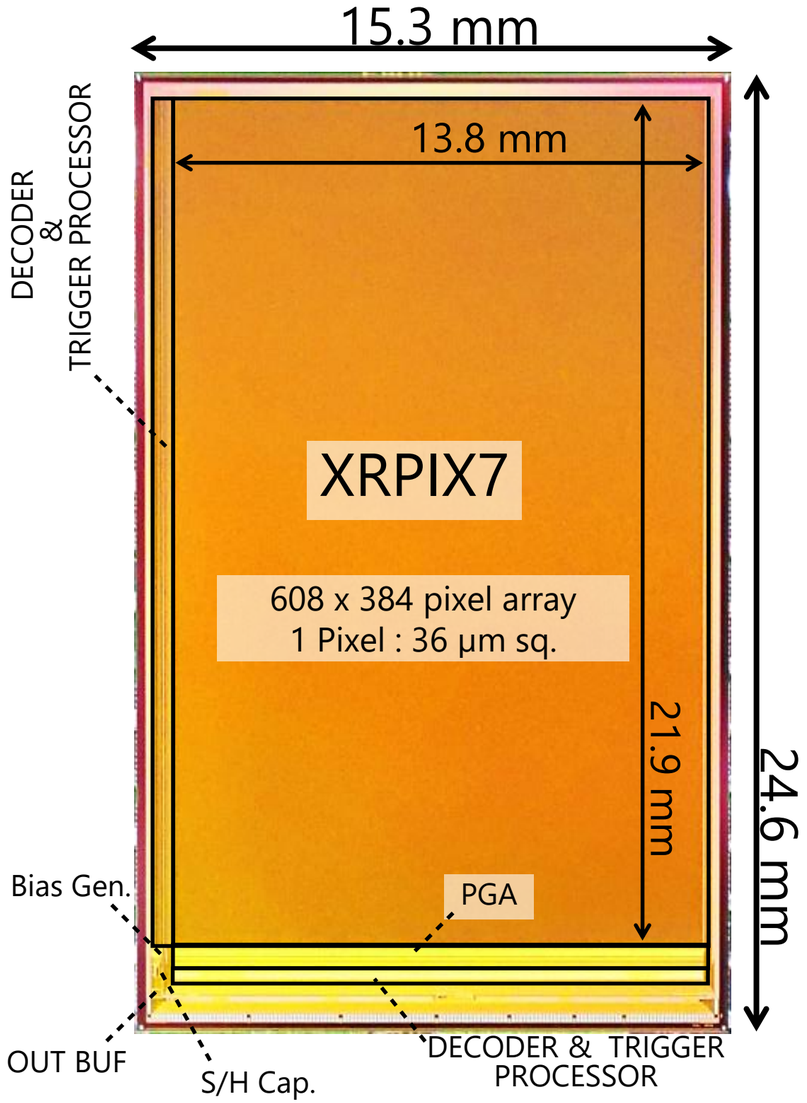
- Electron tracking Compton camera succeeded to be developed with gaseous detectors by Kyoto University Tanimori group for high energy gamma-ray astrophysics.
- For medical imaging, semiconductor detector is ideal
- However, the high spatial resolution (a few tens of μm) is required for electron tracking with a semiconductor detector

Objective

In this study, we developed a Compton imaging system with SOI (silicon on insulator) fine-pitch pixel sensor and GFAG scintillator detector for electron tracking Compton imaging

Overview of SOI pixel sensor (scatterer)

Silicon on Insulator (SOI) technique → Monolithic circuit integrated silicon sensor

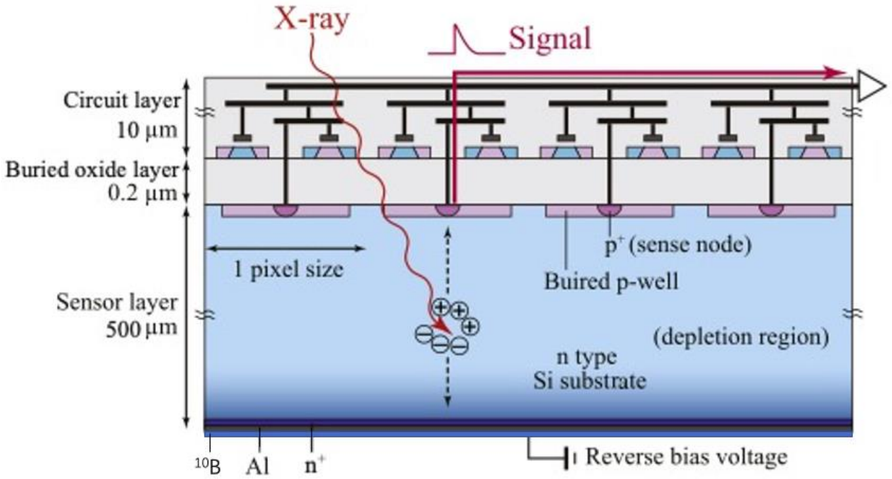


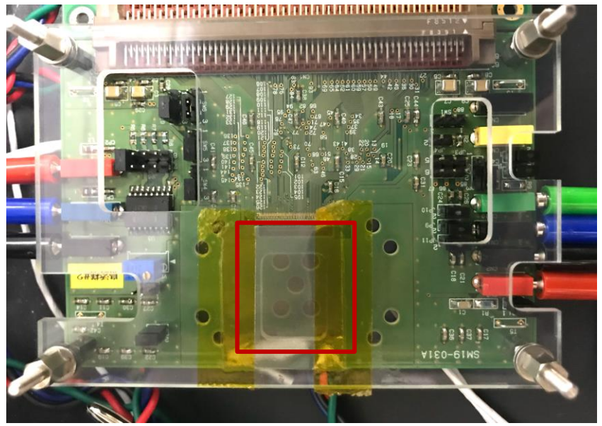
Large area X-ray SOI sensor "XRPIX7"

Sensor information

- Chip size : 24.6 mm x 15.3 mm
  (Active area : 21.9 mm x 13.8 mm)
- Pixel size : 36 μm sq.
- Pixel number : 608 x 384 (= ~233k)
- Sensor thickness : 300 μm

Event driven mode → coincidence detection





Overview of GFAG scintillator detector (absorber)

Detector

8 x 8 array GFAG scintillator + SiPM

- **8 x 8 array detector**
  Pitch size : 3.2 mm x 3.2 mm
- **GFAG scintillator (C&A corp.)**
  Pixel size : 2.5 x 2.5 x 5 mm^3
- **SiPM (Hamamatsu S13361-3050)**
  Active area : 3.0 x 3.0 mm^2

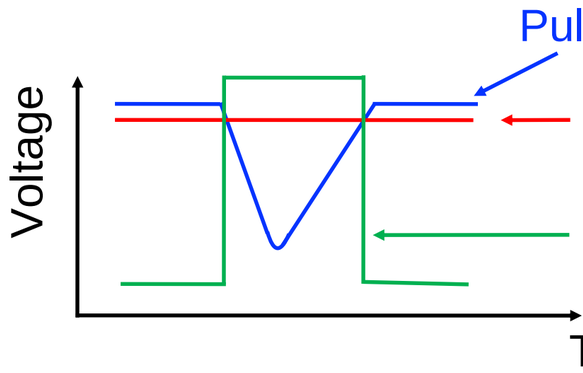
	GFAG (Ce)
Light yield [photon/MeV]	25,000~35,000
Decay time [ns]	≤ 40
Density [g/cm^3]	~6.7
Other	・No intrinsic γ-ray background ・No hygroscopicity

Signal process

64 ch slew rate limited ToT ASIC (application specific integrated circuit)

Ref: C&A HP (https://www.c-and-a.jp/index_jp.html)

ASIC power supply (2.5V, 1.25V)
IC chip power supply (3.3V)

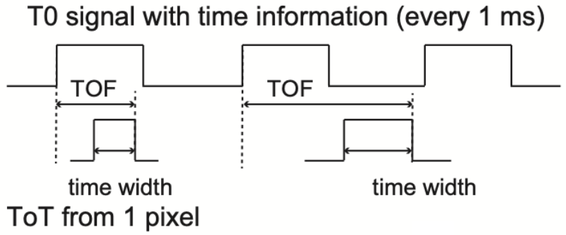


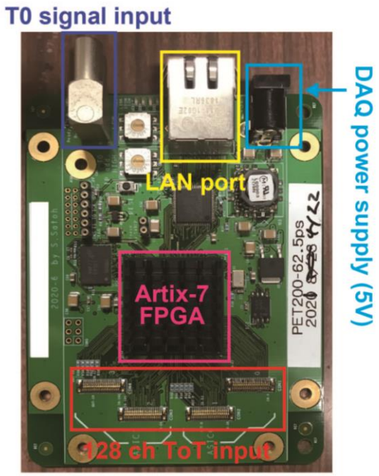
- ✓ Good linearity between energy and ToT
- ✓ Parallel signal process

Data acquisition (DAQ) system

FPGA-based 128 ch parallel ToT-DAQ (PETnet) [5]

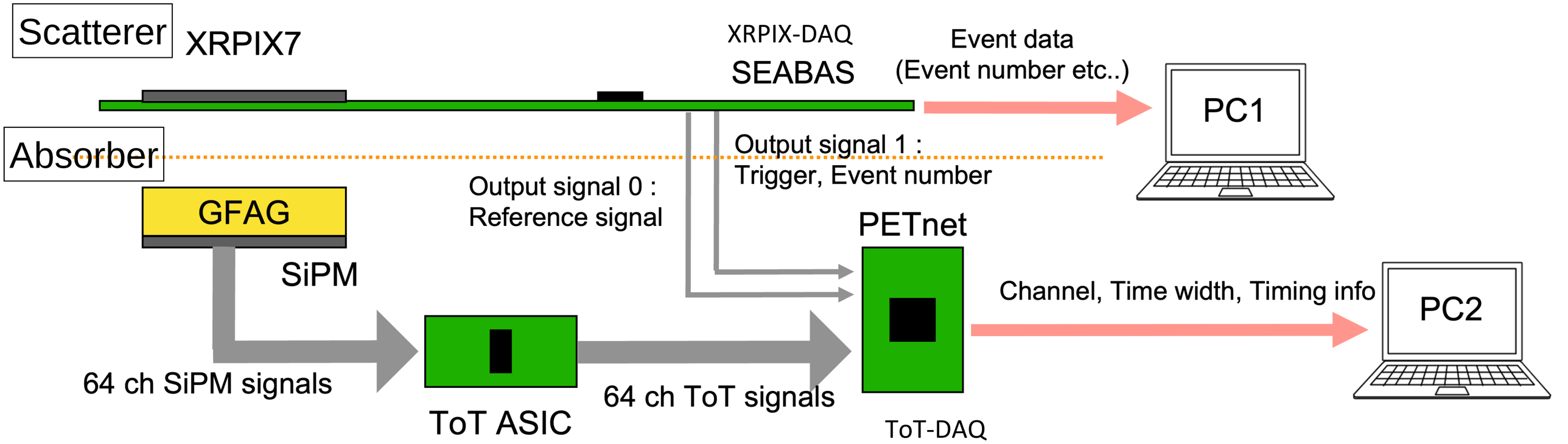
- 62.5 ps sampling
- List mode data
  - T0 data (Absolute time information)
  - Event data (channel, time width, TOF)





[5] S. Sato et al., "Development of multichannel high time resolution data acquisition system for TOT-ASIC", IEEE

Overview of SOI-GFAG Compton camera system



✓XRPIX7 data information (trigger, event number) was also recorded in PETnet (DAQ)

XRPIX-DAQ : list-mode data (event number, pixel information, pulse height, etc)

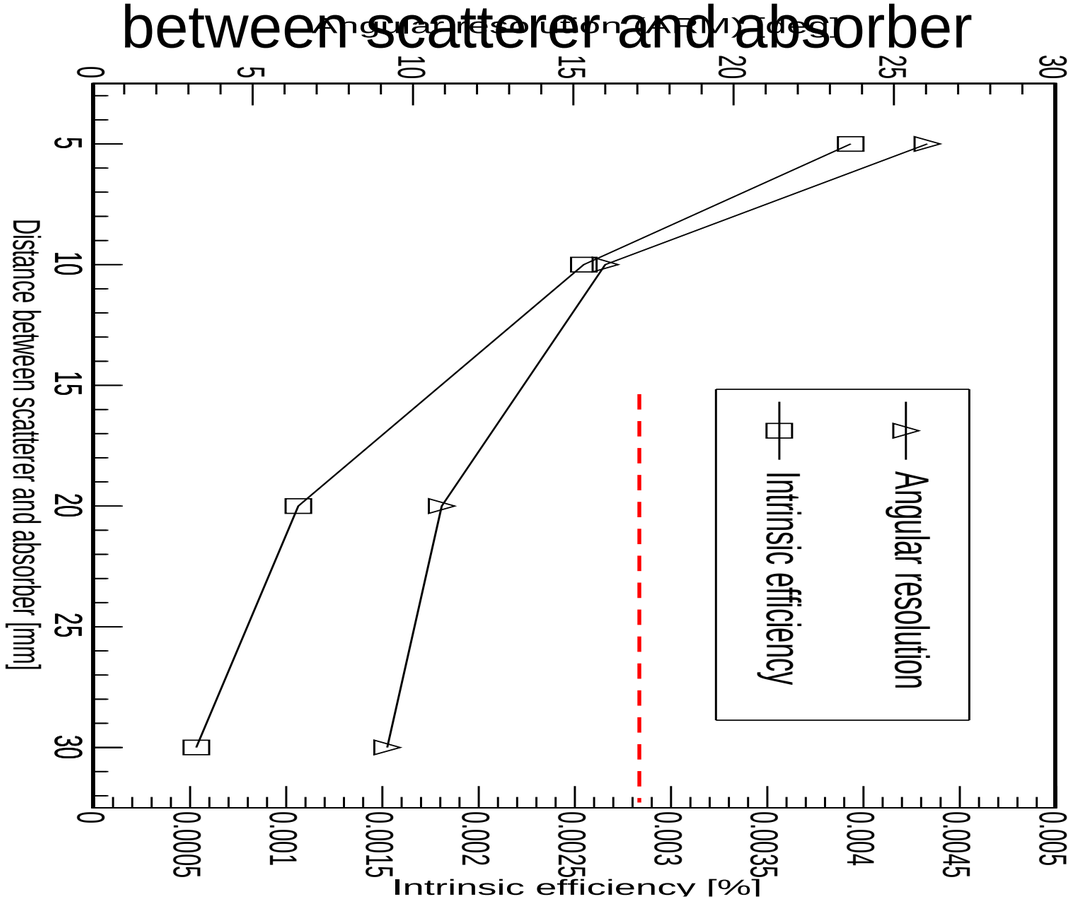
ToT-DAQ : list-mode data

- ➢ T0 data
- ➢ Event data
  - GFAG ToT signals
  - XR7 output signals (trigger, event number signals)

✓Compton coincidence events (scatterer and absorber) were extracted in offline analysis

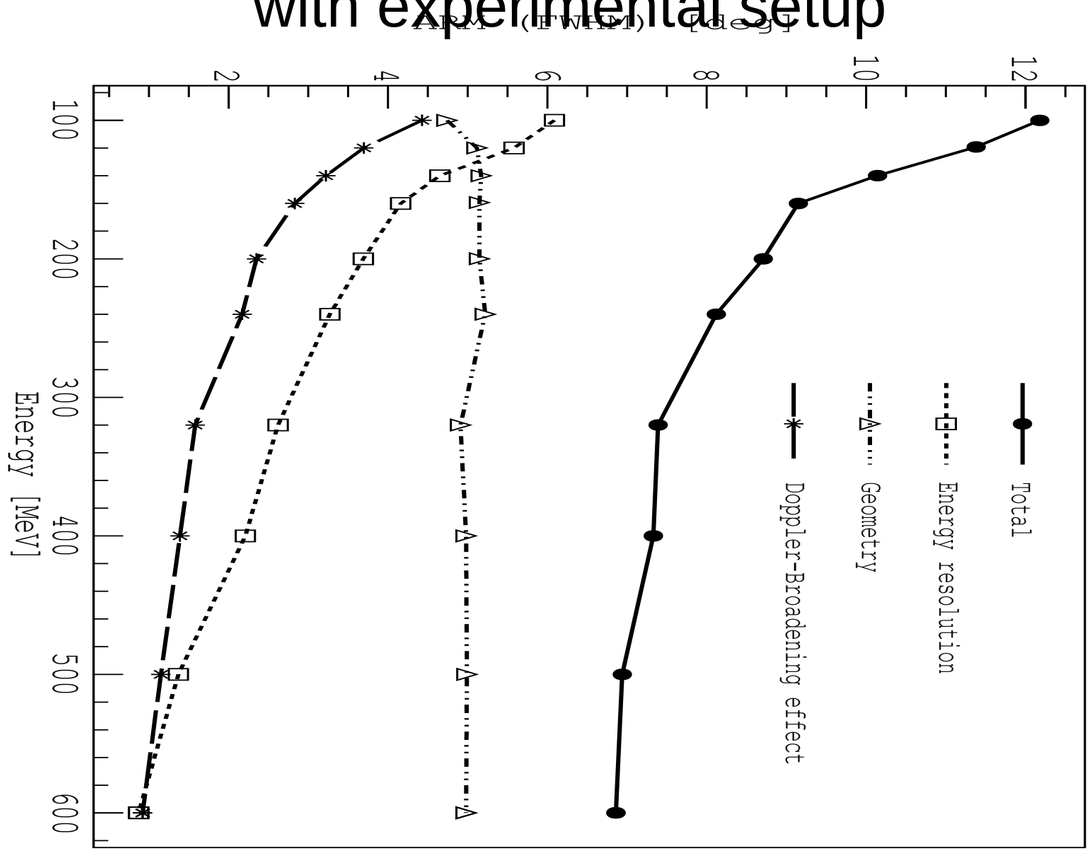
Simulated angular resolution by geant4 toolkits

Angular resolution vs Intrinsic efficiency by changing distance between scatterer and absorber



➡ We put absorber as close as a scatterer to ensure the efficiency

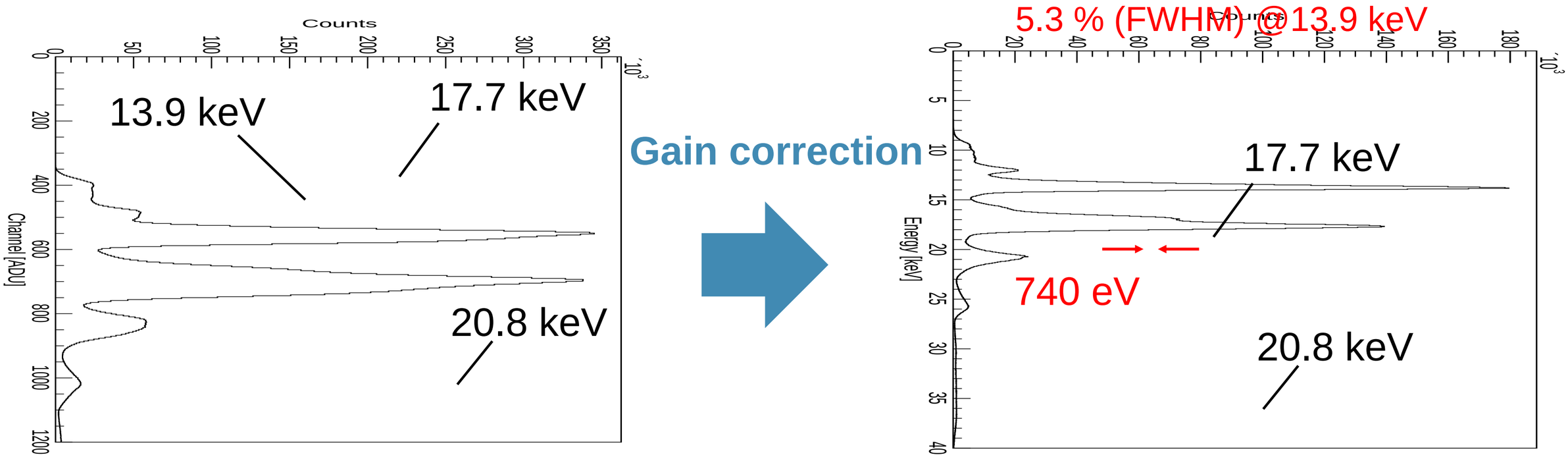
Parameter contributions to angular resolution with experimental setup



➡ The geometry contribution is dominant

Basic performance of XRPIX7

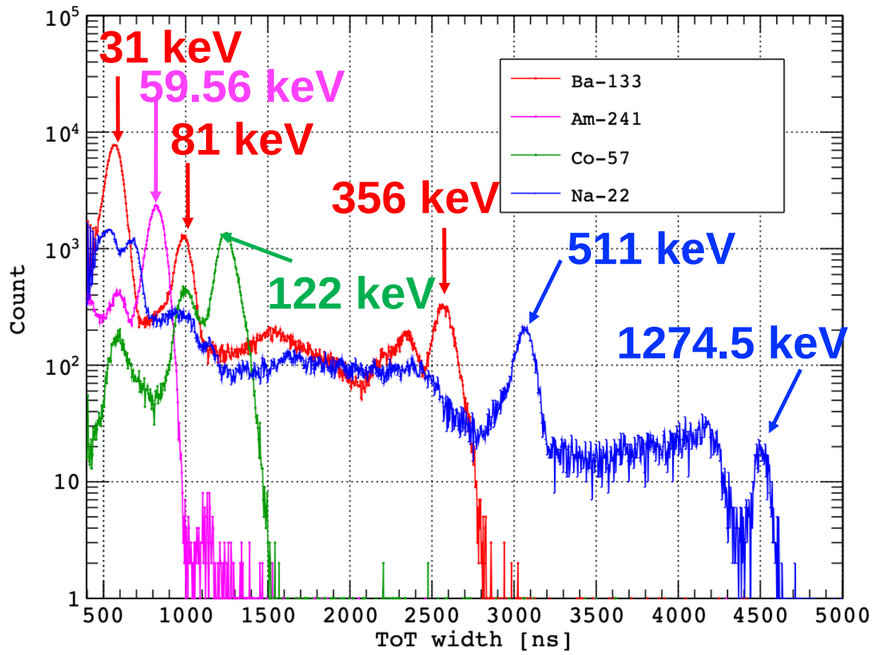
^{241}Am spectrum of all pixels



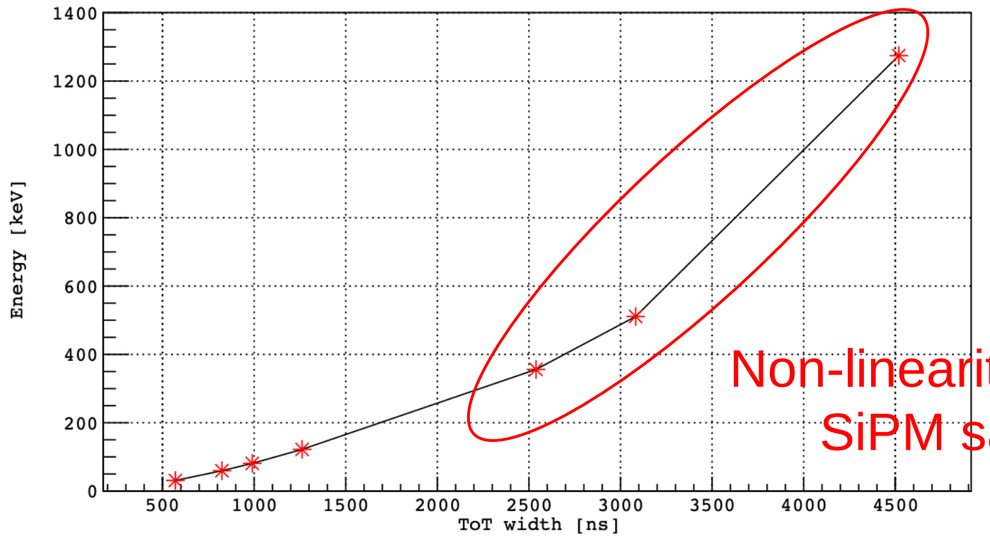
- Temperature : 0 deg
- Vdet : -25V (not full depletion)

Basic performance of GFAG detector system

ToT spectra



Linearity (ToT vs Energy)

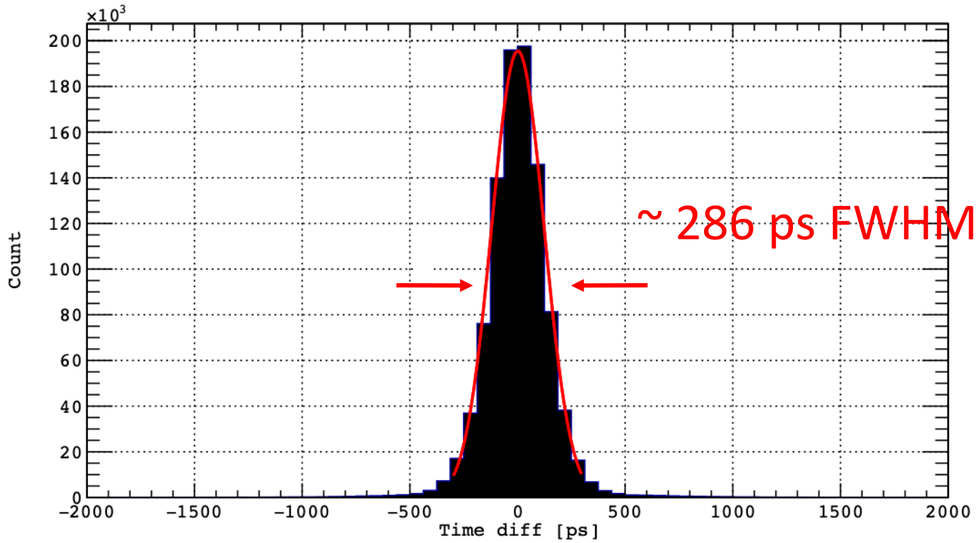


Non-linearity caused by SiPM saturation

Energy resolution

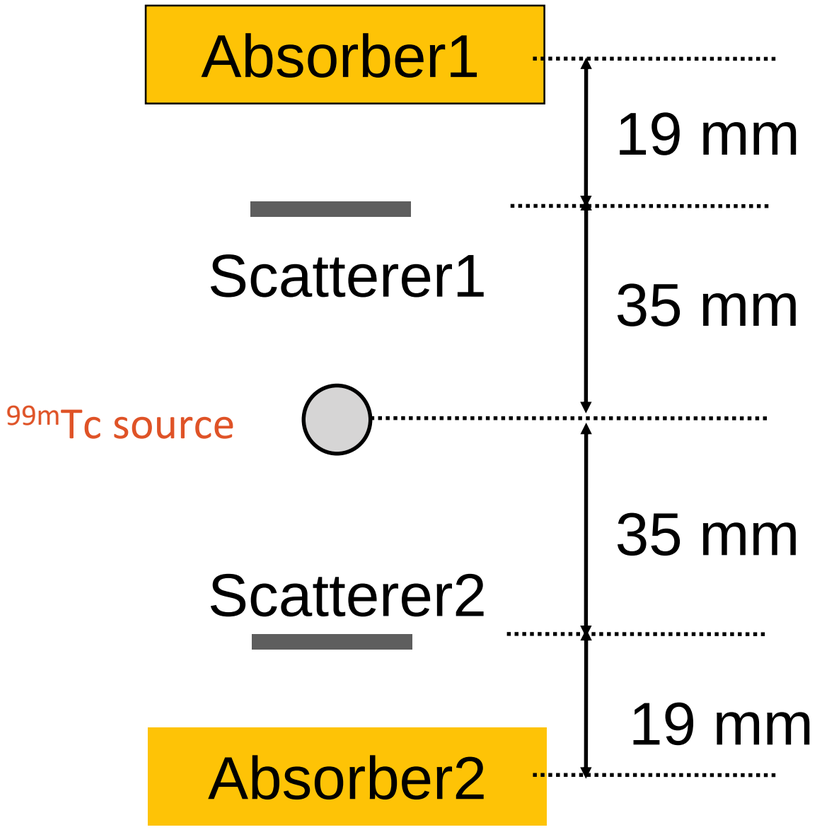
Energy [keV]	Energy resolution (FWHM) [%]
122	18.2
511	11.7
1274.5	5.6

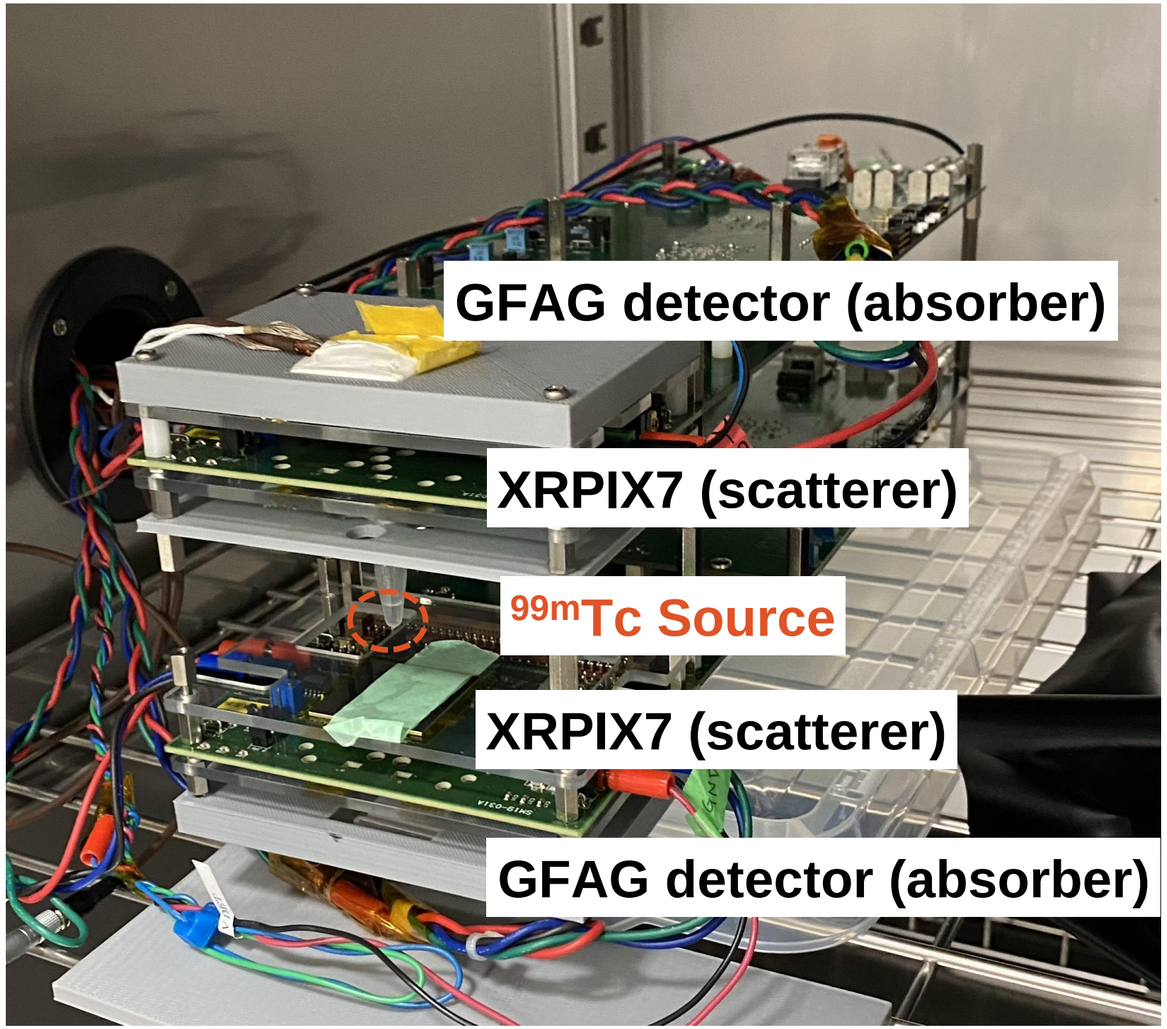
System time resolution (GFAG detector + ASIC + DAQ)



~ 286 ps FWHM

Experimental setup of ^{99m}Tc Compton imaging



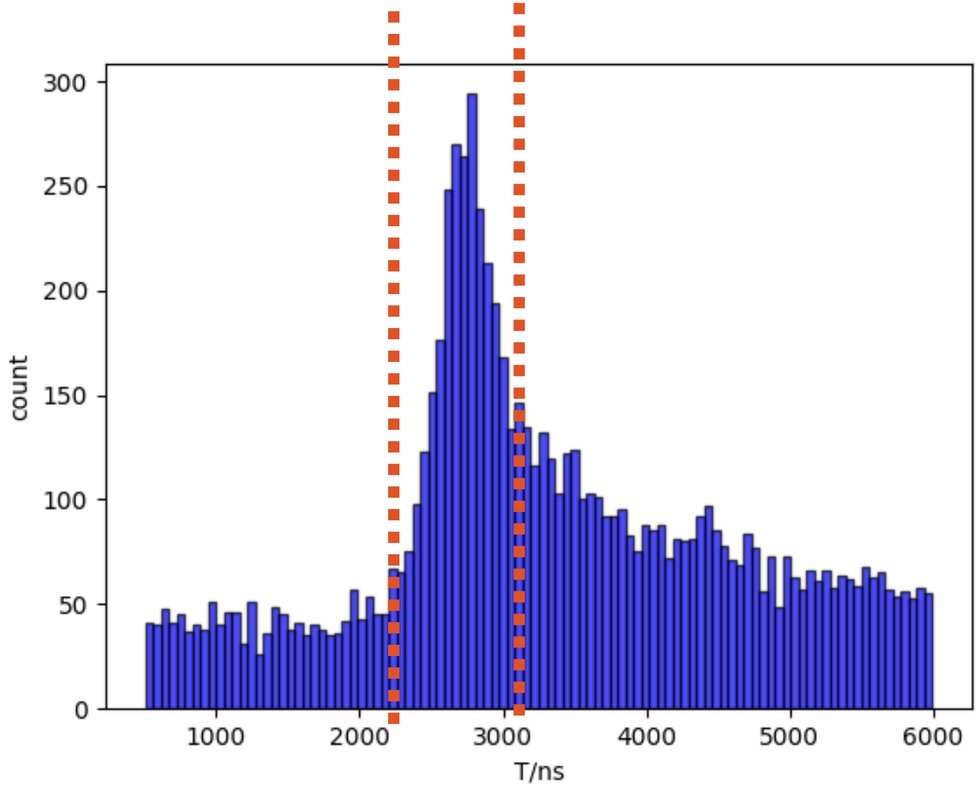


- Temperature: 0 deg
- XRPIX Bias: -25V
- SiPM Bias: -55V

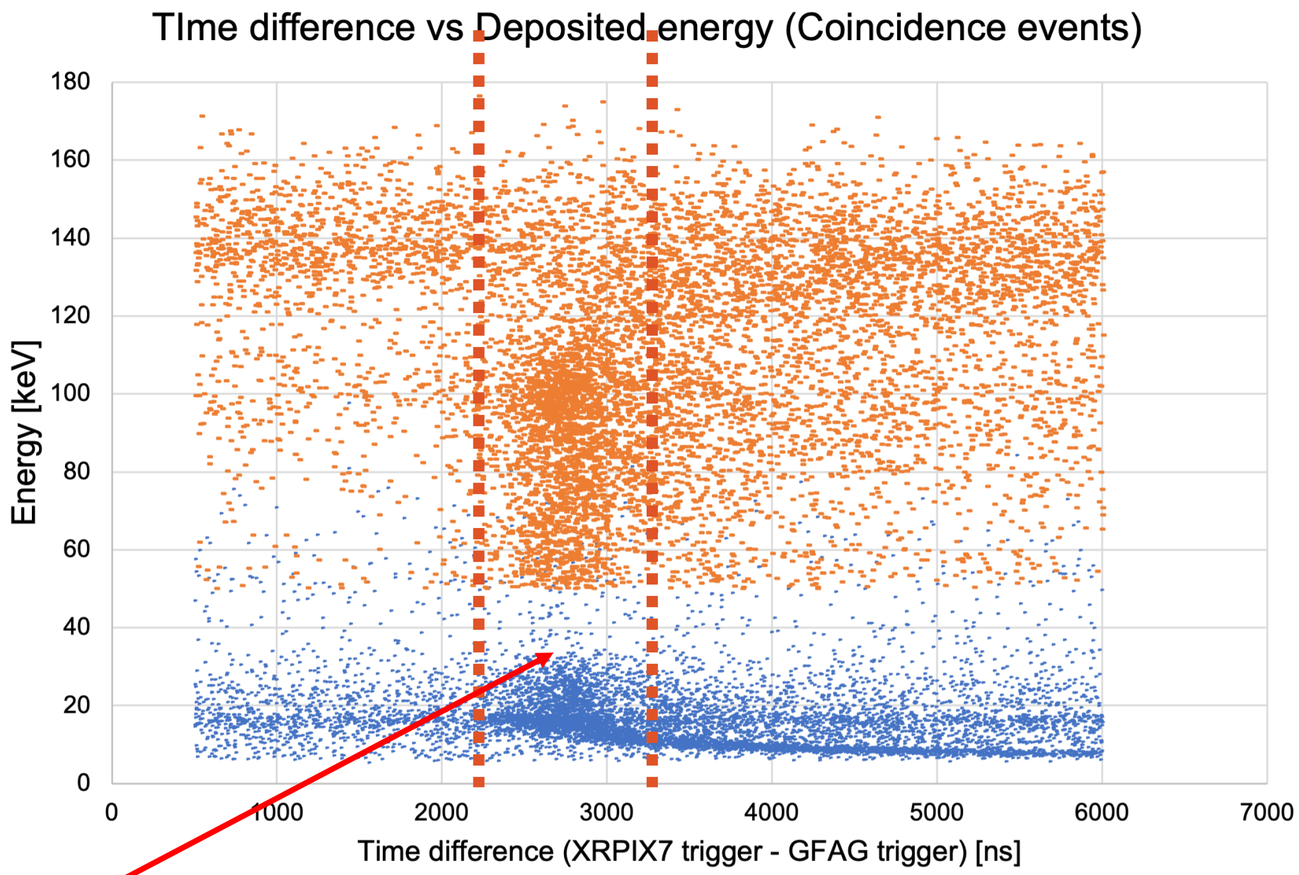
- Activity: ~1 MBq
- Measurement time: ~12.8 h

Result of ^{99m}Tc Compton imaging

Time difference spectrum (XR7 trigger – GFAG trigger)



Time difference vs Energy



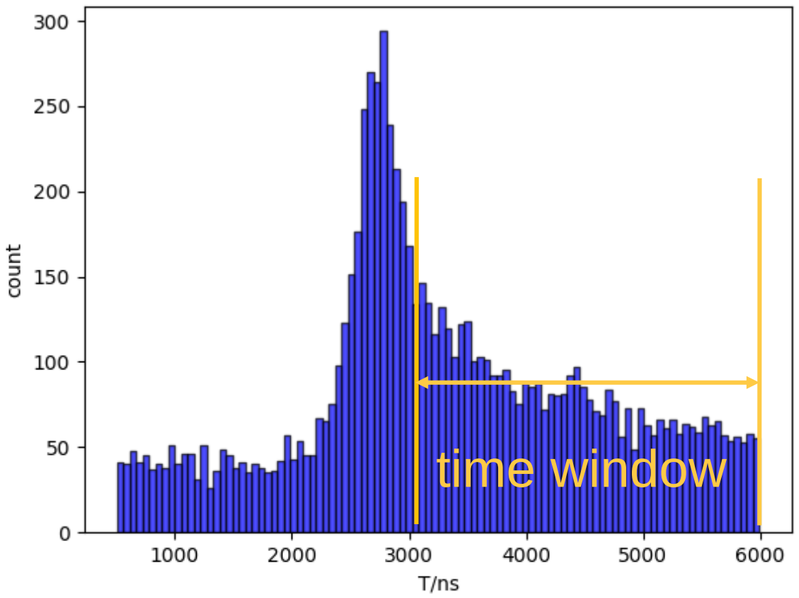
Back scattering events

Blue: Scatterer event (XRPIX7)

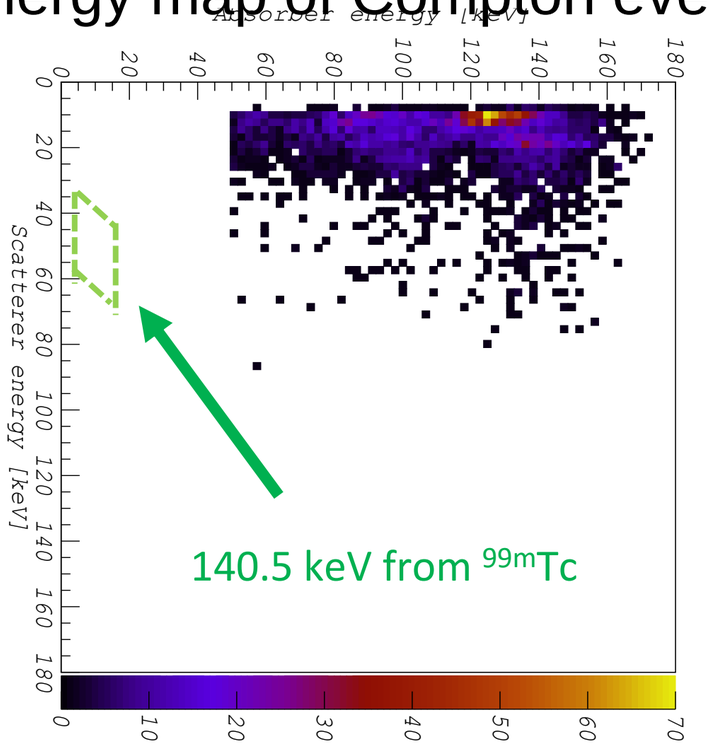
Orange: Absorber event (GFAG)

Result of ^{99m}Tc Compton imaging

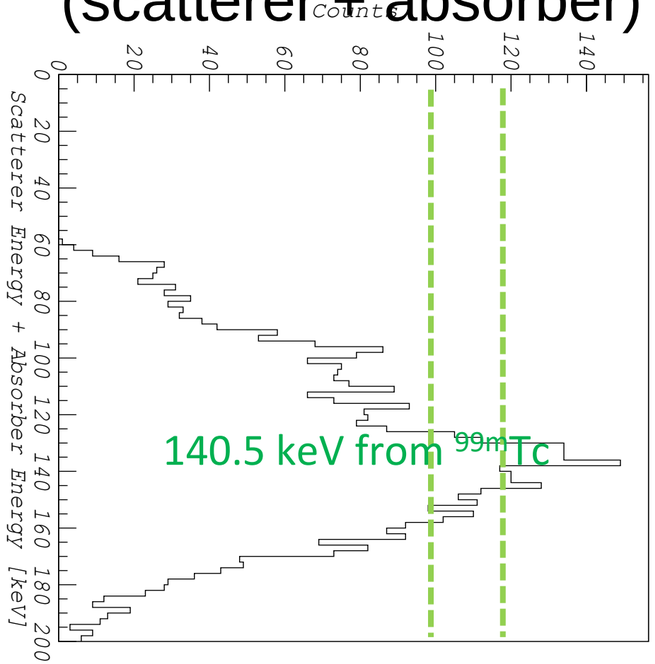
Time difference spectrum
(XR7 trigger – GFAG trigger)



Energy map of Compton events

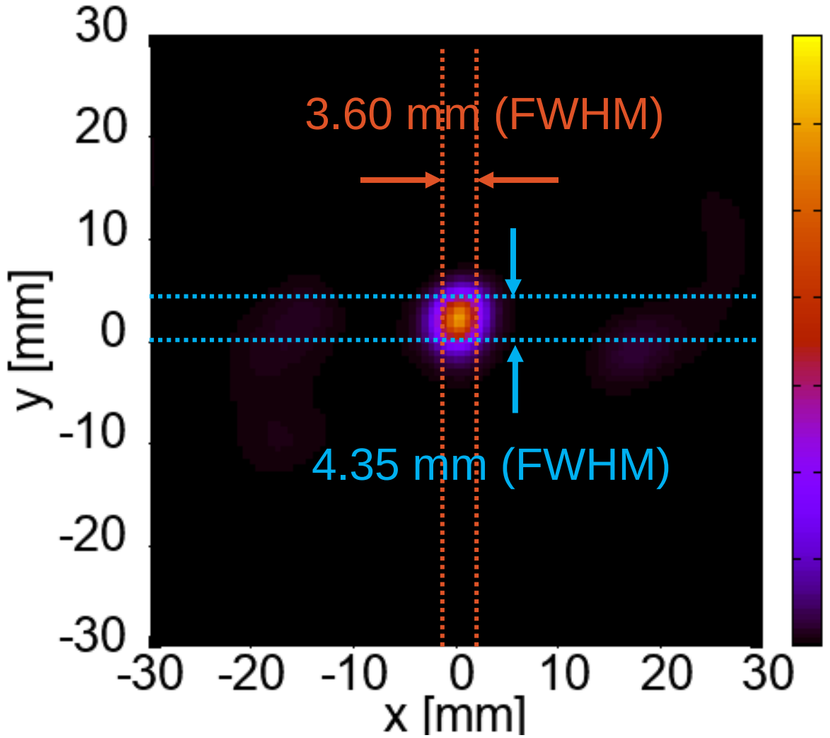


Energy spectrum
(scatterer + absorber)

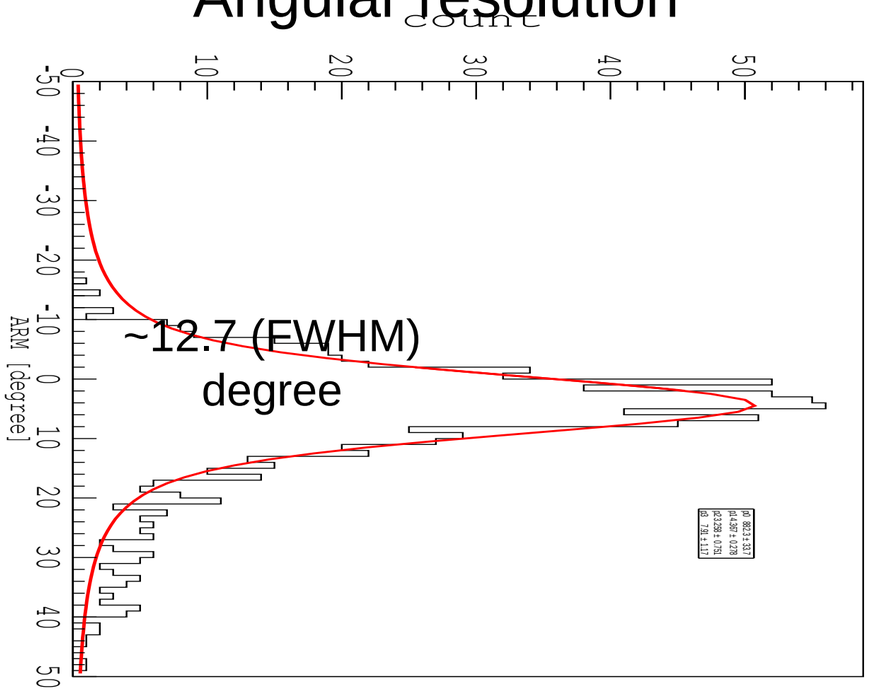


Result of ^{99m}Tc Compton imaging

140.5 keV Compton imaging



Angular resolution



Detection efficiency

Intrinsic detection efficiency	SOI-GFAG Compton-PET camera
140.5 keV Compton imaging	4.3×10^{-6}

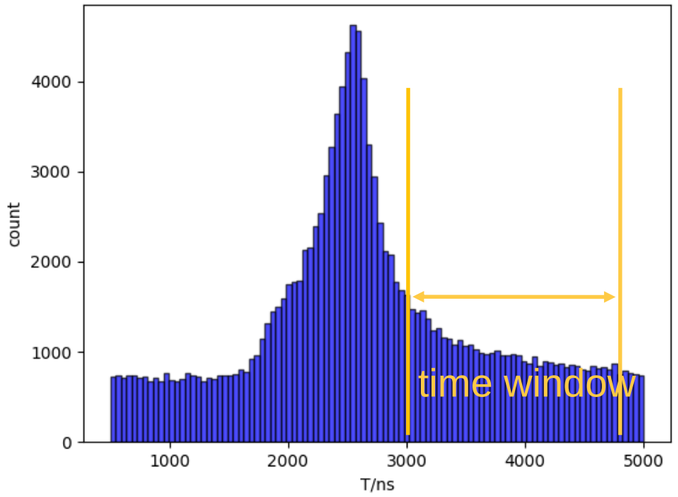
Reconstruction parameters

- MLEM*
- Iteration number: 100
- 5 keV < Esca < 20 keV
- 126.5 keV < Etotal < 154.6 keV

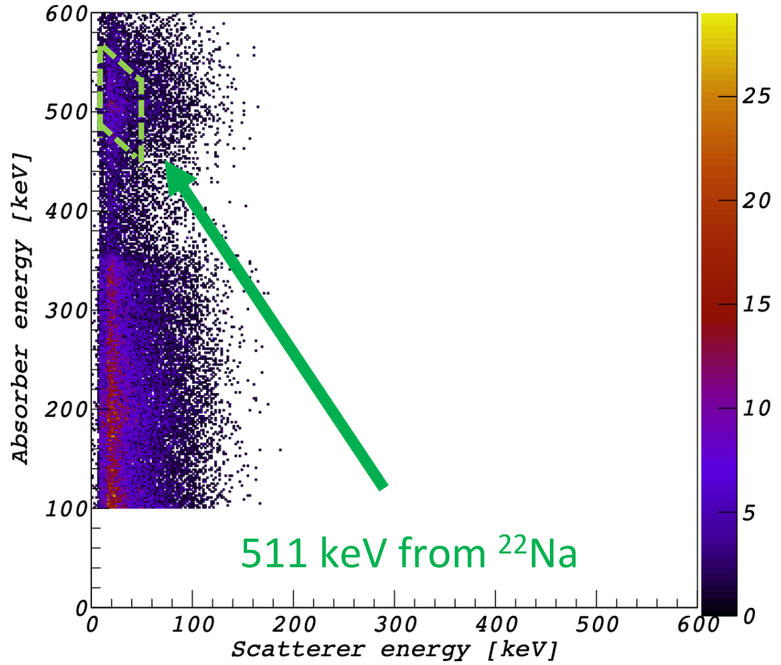
*Maximum likelihood estimation method

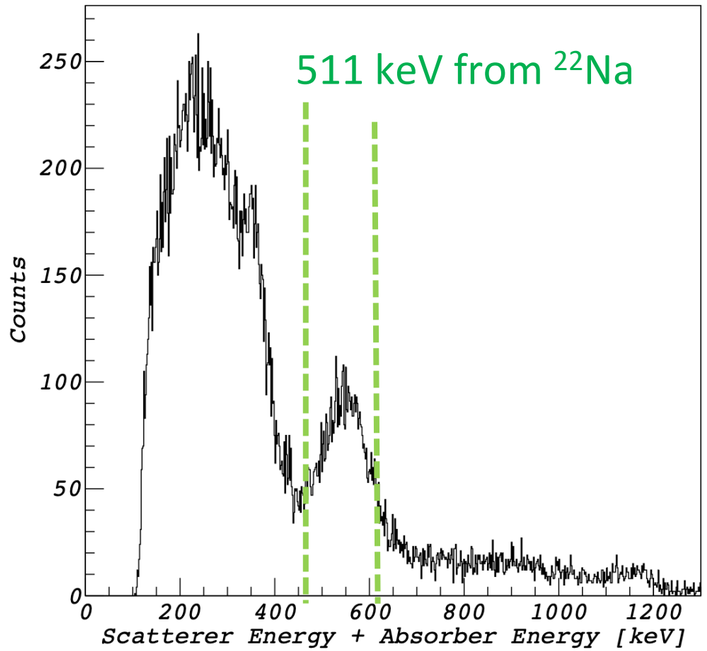
Succeeded to perform low energy (140.5 keV) gamma-ray Compton imaging

^{22}Na conventional Compton imaging

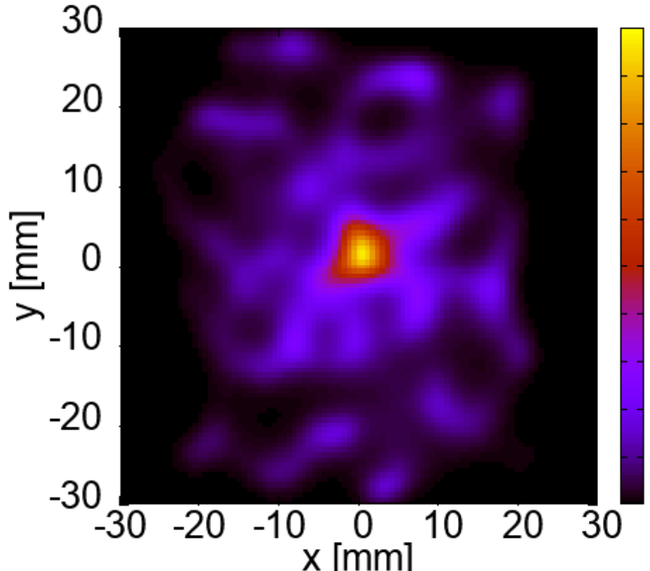


Energy map of Compton events





511 keV Compton imaging



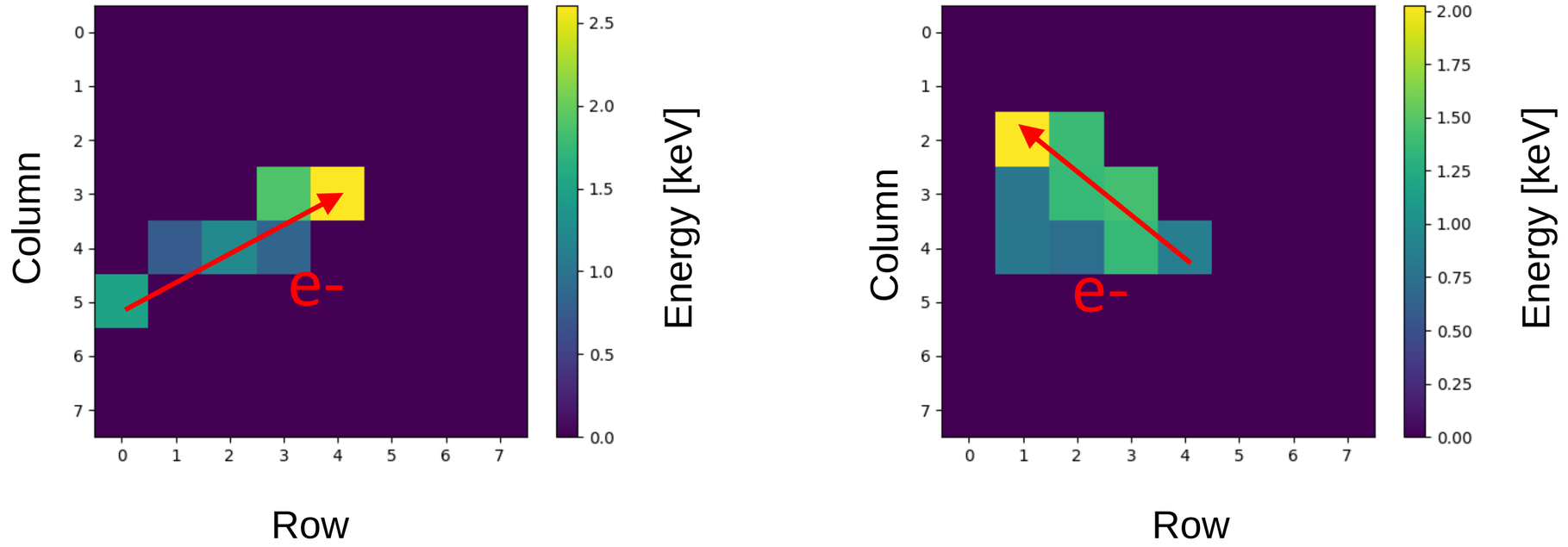
Reconstruction parameters

- MLEM
- Iteration number: 30
- 5 keV < Esca < 25 keV
- 408 .8keV < Etotal < 613.2 keV

Intrinsic detection efficiency	SOI-GFAG Compton-PET camera
511 keV Compton imaging	1.7×10^{-6}

Electron Trajectory in XRPIX7

Recoil electron trajectories of 511 keV gamma-ray



XRPIX7 could detect some of recoil electron trajectories of 511 keV gamma-ray. For future work, we need to establish the method to extract the correct electron trajectory because XRPIX7 can measure only 2D trajectory.

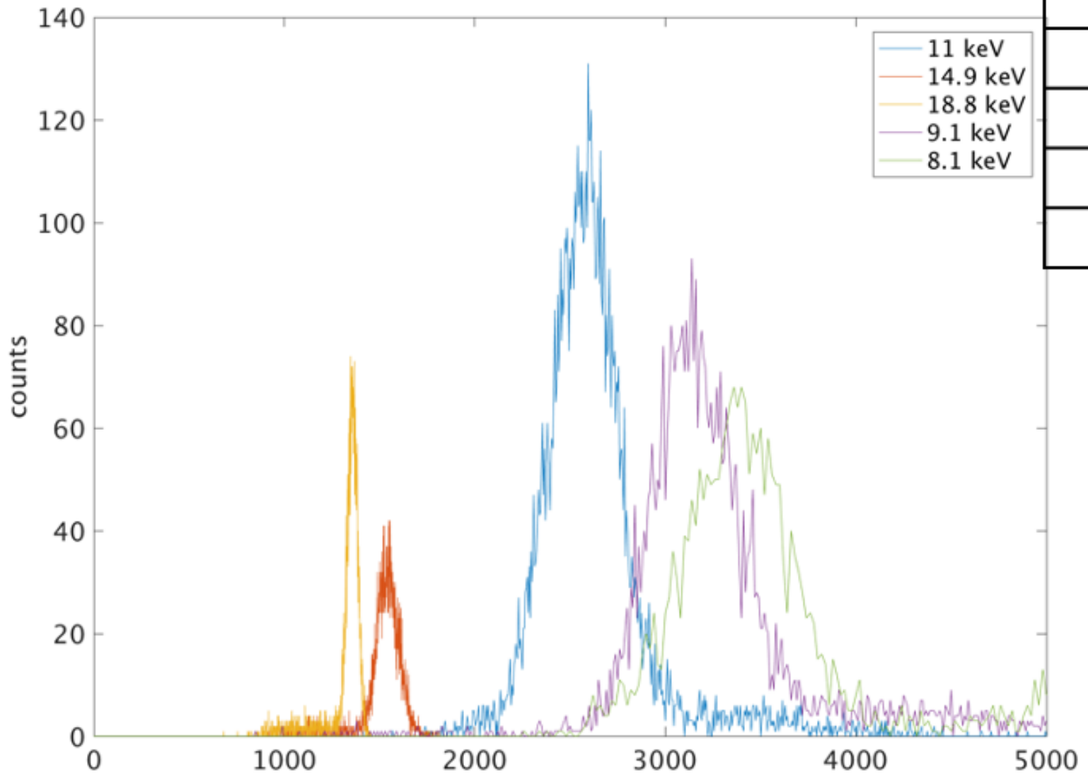
Summary and future works

- We are developing a Compton-PET hybrid camera consisting of SOI pixel sensor (XRPIX7) GFAG scintillator detector
- We succeeded to perform low energy gamma-ray Compton imaging of 140.5 keV (^{99m}Tc), and high energy gamma-ray Compton imaging of 511 keV (^{22}Na)
- Gain and count rate corrections of XRPIX7 will improve the reconstructed images
- XRPIX7 can detect a recoil electron trajectory of 511 keV gamma-ray (but not full depletion)
- We are going to evaluate the next large area SOI sensor "XRPIX-X" and utilize it as a scatterer.

Thank you for your attention

Time response of XRPIX7

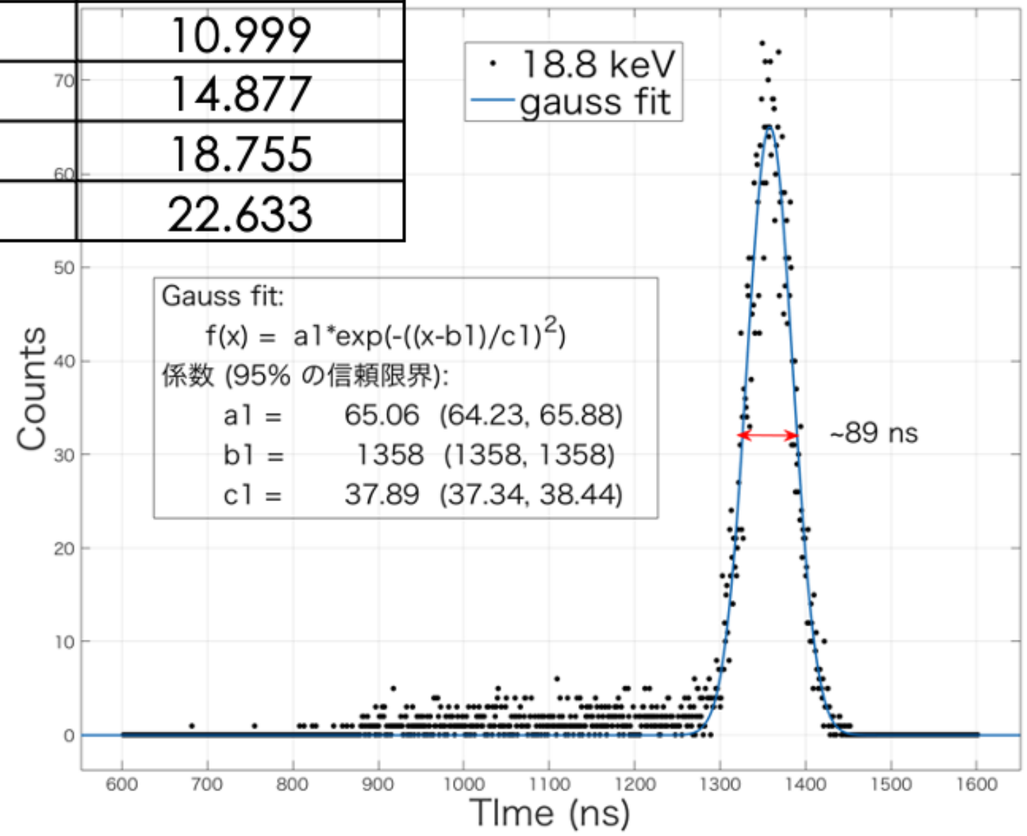
Pulsed laser irradiation



Time difference between a laser trigger and XRPIX7 trigger (ns)

Time response of XRPIX7

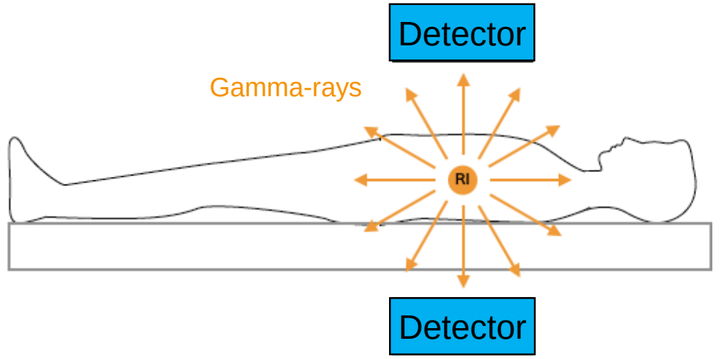
intensity	Energy(keV)
975	8.0905
1000	9.06
1050	10.999
1150	14.877
1250	18.755
1350	22.633



Research Background

Nuclear Medicine

One of medical specialty to diagnose and treat disease by injecting a radioactive agent into our body



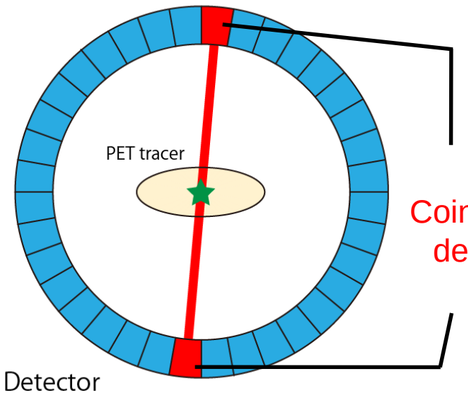
Conventional imaging modality ・・**PET** * and **SPECT** **

* Positron emission tomography
** Single photon emission computed tomography

PET

- **Positron emitter** (511keV annihilation gamma-rays)
- Early detection of malignant tumors

^{18}F-FDG (annihilation gamma) etc…

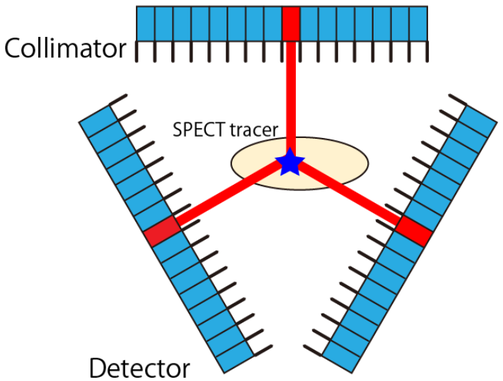


Glucose imaging

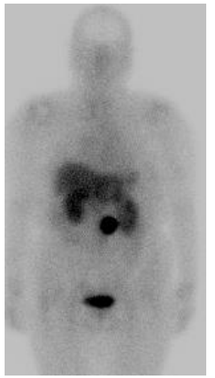
SPECT

- **Single photon emitters** (～400 keV)
- Blood flow, molecular dynamics, antibody imaging

^{99m}Tc (141keV),^{67}Ga (300keV), ^{111}In (171,245keV) etc..



Receptor imaging



Purpose of development of SOI-GFAG Compton-PET imager

Problems in GAGG-SiPM Compton-PET hybrid camera

- Visualization of low energy gamma-rays (< 200 keV) is difficult

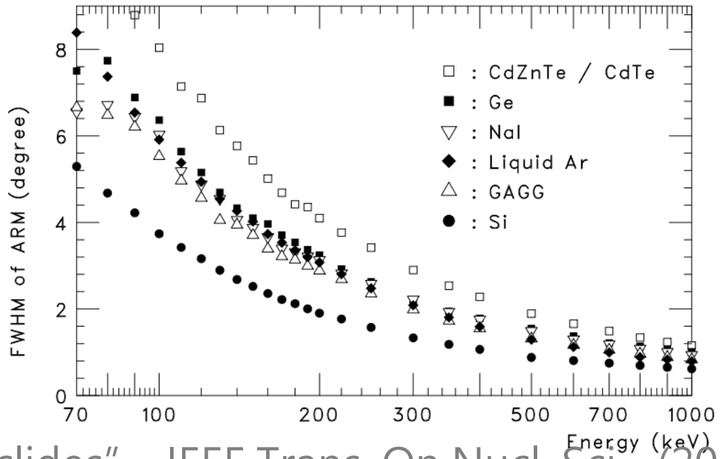
  Other SPECT nuclides emit single photons with energies of 50 – 200 keV
  (Ex: ^{99m}Tc →141 keV, ^{123}I → 159 keV, ^{201}Tl → 71, 145, 167 keV)

  Major causes : Energy resolution (~29% FWHM @ 31 keV), optical crosstalk

- Low angular resolution (~17 ° @ 245 keV)

  For example, Si/CdTe Compton camera → ~5° @ 245 keV
  Contributions: Energy resolution, position resolution, doppler broadening effect

Contribution of the doppler broadening effect to the angular resolution [4]



We are developing a SOI-GFAG Compton-PET hybrid camera to **perform low energy gamma-ray Compton imaging (< 200 keV)** and **potentially improve an angular resolution**.

u et al., "Tomographic Imaging by a Si/CdTe Compton Camera for ^{111}In and ^{131}I Radionuclides" , IEEE Trans. On Nucl. Sci., (2021)