PIXEL 2018 International Workshop on Semiconductor Pixel Detectors for Particles and Imaging (PIXEL2018)

東京大学 THE UNIVERSITY OF TOKYO

Estimation and imaging of recoil electron with event-driven SOI sensor and deep learning in Compton imaging system

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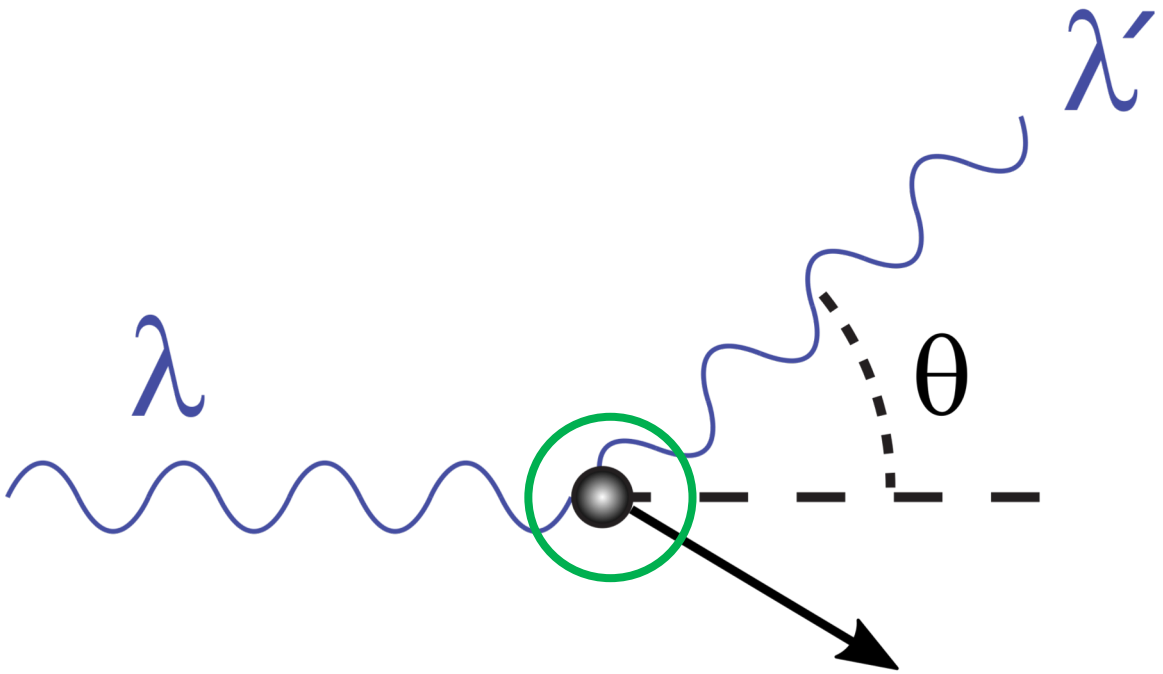
Outline

- Introduction
- Electron Tracking Compton Camera based on SOI
- Geant4 Simulation and estimation by deep-learning
- Summary

Compton Scattering

Scattering of a photon by a charged particle, usually an electron



The main role: recoil electron

Trigger-mode SOI pixel sensor

Electron tracking requirements

The length of electron ~ 300μm

effective track < ~100μm

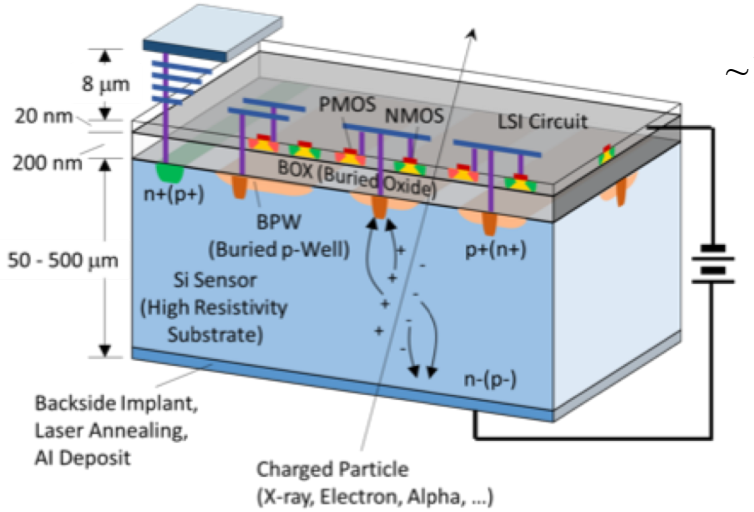
Record of electron trajectory

Coincidence judgment (absorber/scatterer)
>1kHz

○~10μm pixel size
（Energy measurement）

○Electron track pattern

○Trigger in coincidence
X CCD(frame mode)



~10μm

Properties:
Monolithic technology
Pixel size ~ <10μm
Integrated circuit

Lapis semiconductor

Trigger-mode SOI pixel sensor

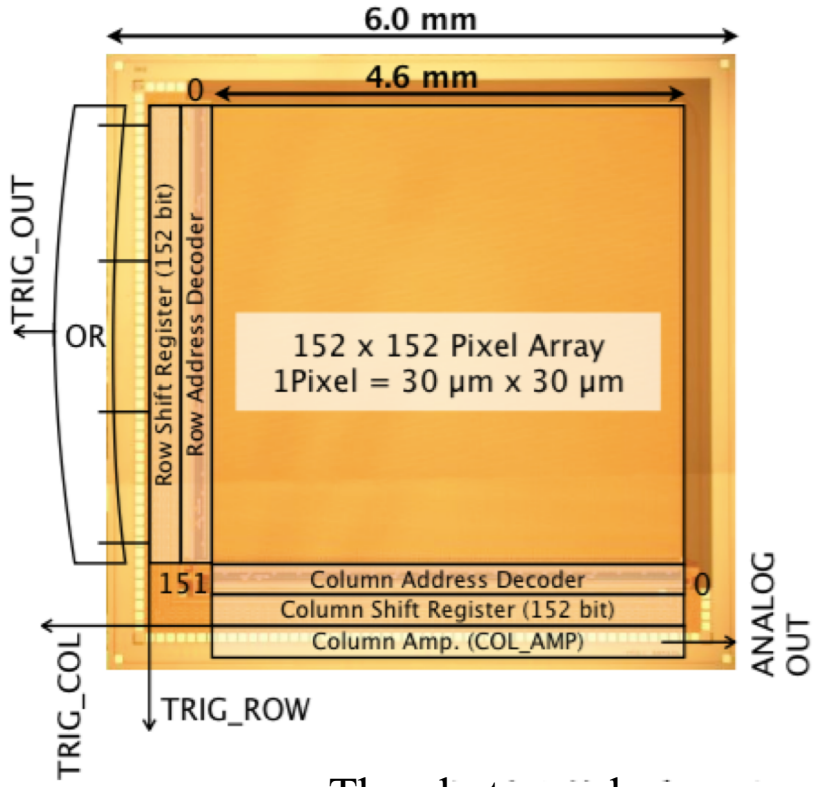
Developed in the collaboration of SOI pixel sensor group

SOI sensor:

• n-type high resistivity CZ wafer ver. 1

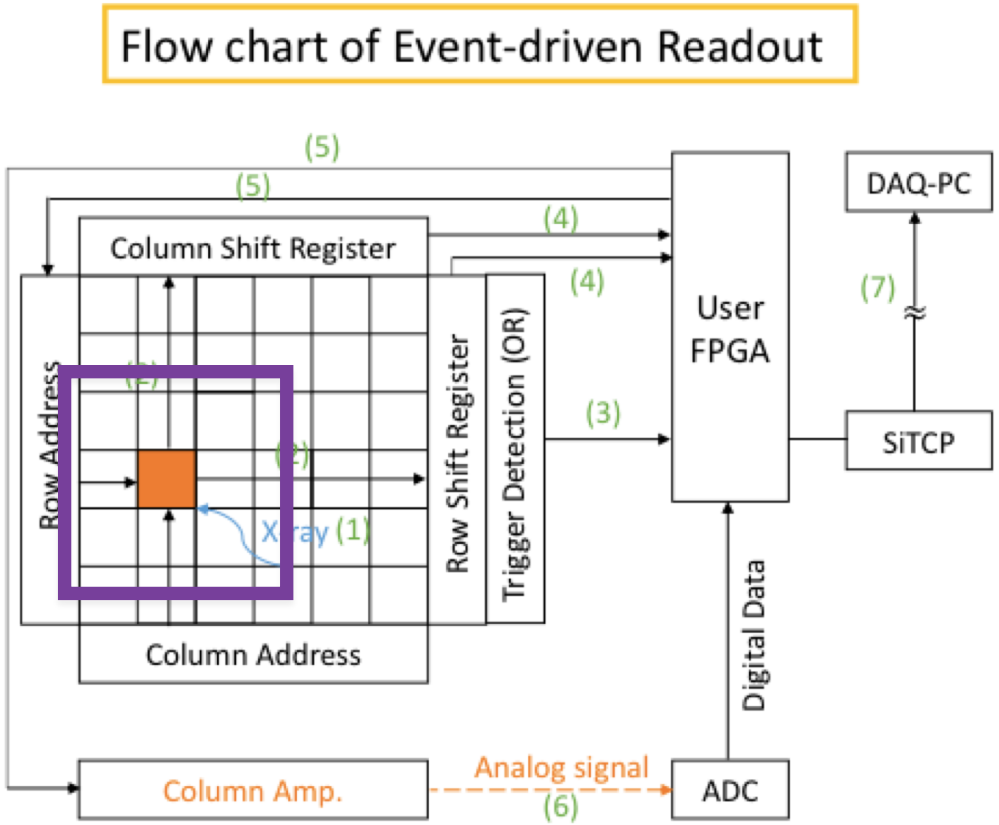
	NHR1(CZ)	NFZ
Chip Size	6.0 mm sq.	
Pixel Size	30 μm sq.	
BPW Size	12 μm sq.	
# of pixel ***	152 x 152	
Effective Pixel	144 x 144 (= 20,736)	
Effective Area	4.3 mm x 4.3 mm	
Thickness of Sensor ****	250 μm	500 μm
Resistivity	1.5 kΩ・cm	5 kΩ・cm
Power Supply *****	1.8V @ Core / 3.3V @ IO	
Back Bias (sensor)	5 - 500V <	

The physical properties



The photograph

Extraction of Compton Electron pattern



(1) Incident x-ray

(2) If the x-ray signal exceeds a threshold voltage, trigger signals are transferred to row and column direction

(3) Trigger output signal is generated

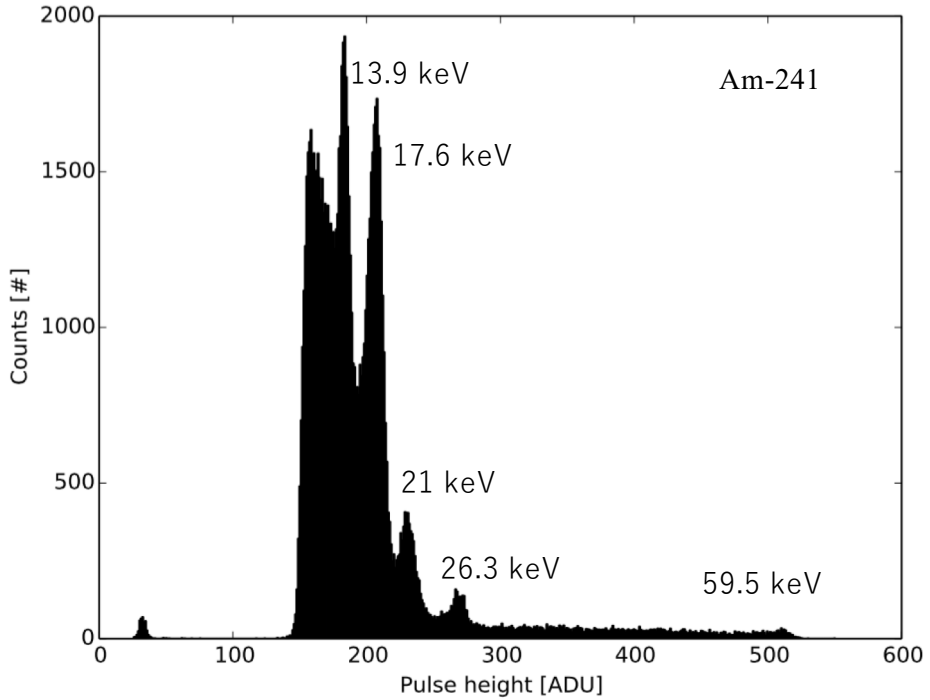
(4) By receiving the trigger output signal, user-FPGA start to read the address information from the row and column shift register

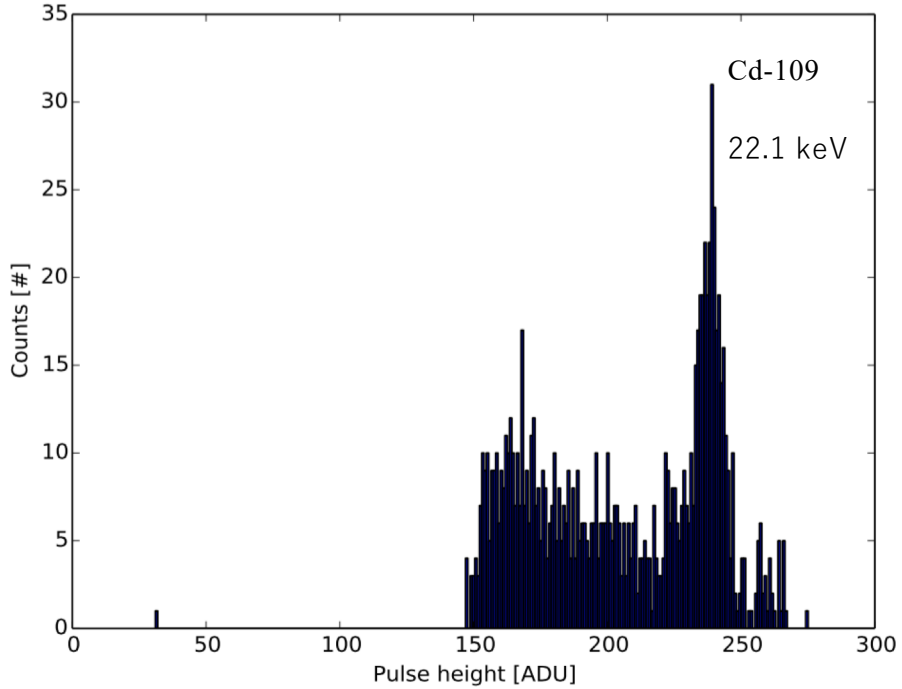
(5) The user-FPGA accesses the hit pixel directly by asserting the obtained address

(6) User-FPGA readout the analog voltage (signal and pedestal levels) through the ADC

(7) Obtained digital data is transmitted to the DAQ-PC

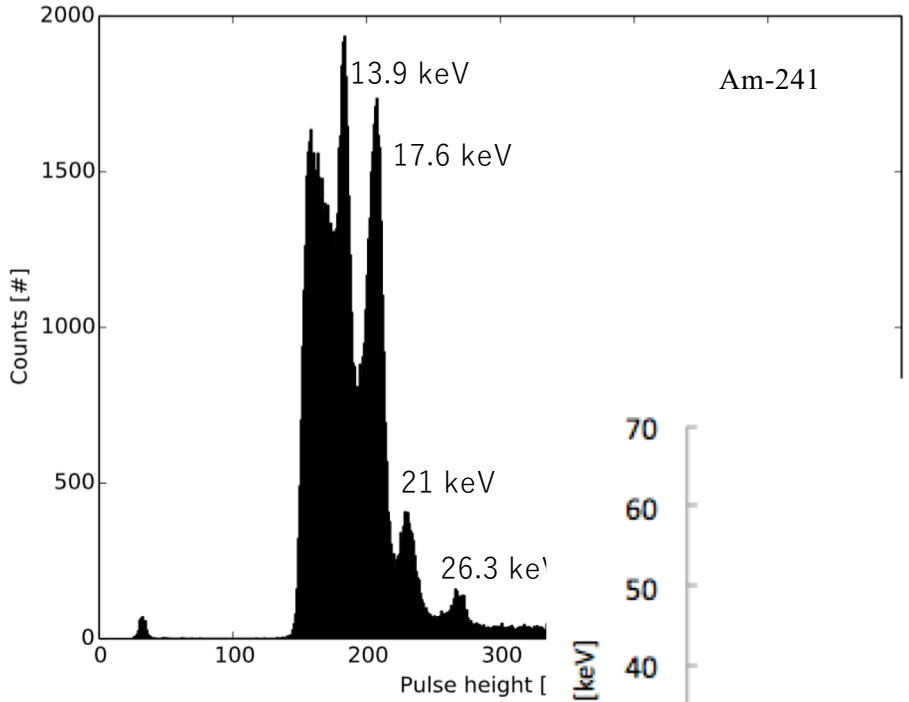
Energy spectrum in trigger-mode

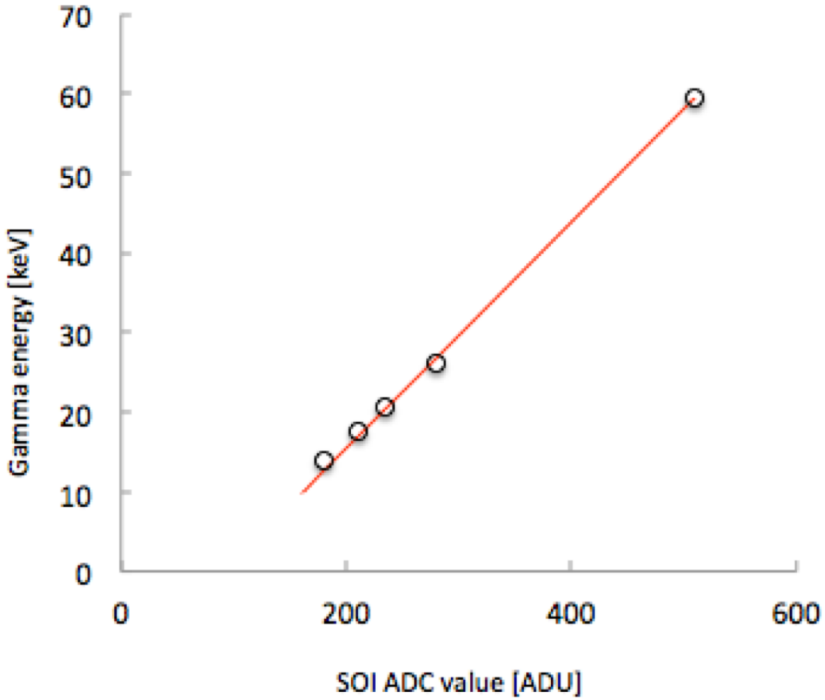


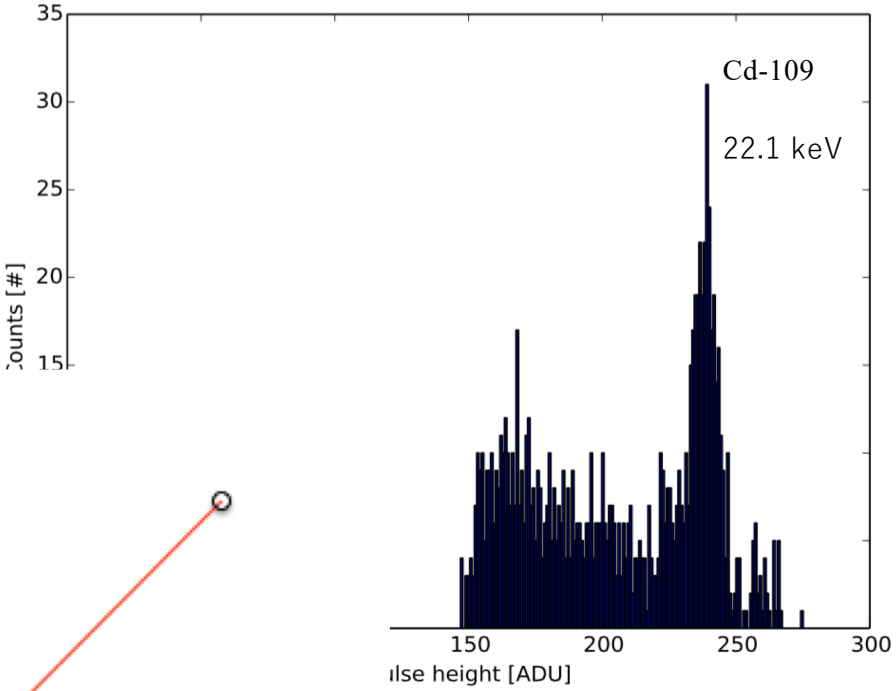


Vbias = 5V
Vth = 450mV
Room Temperature

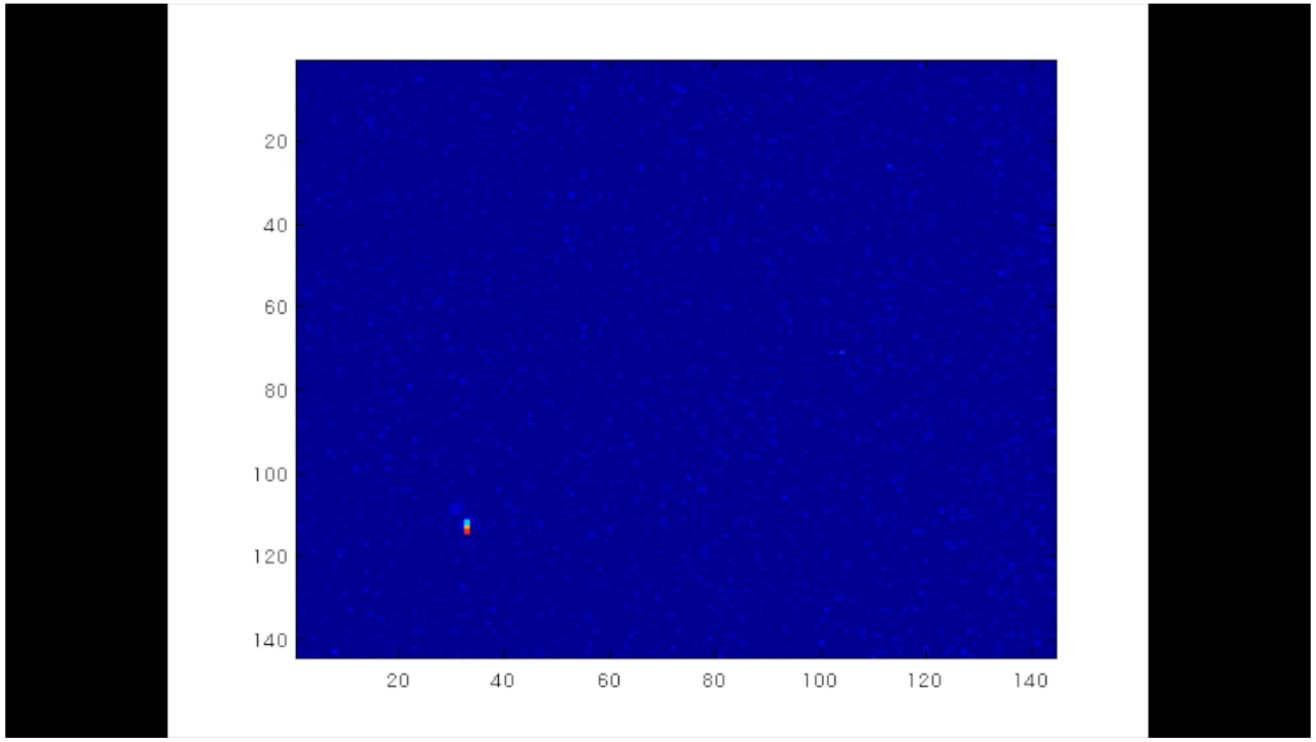
Energy spectrum in trigger-mode







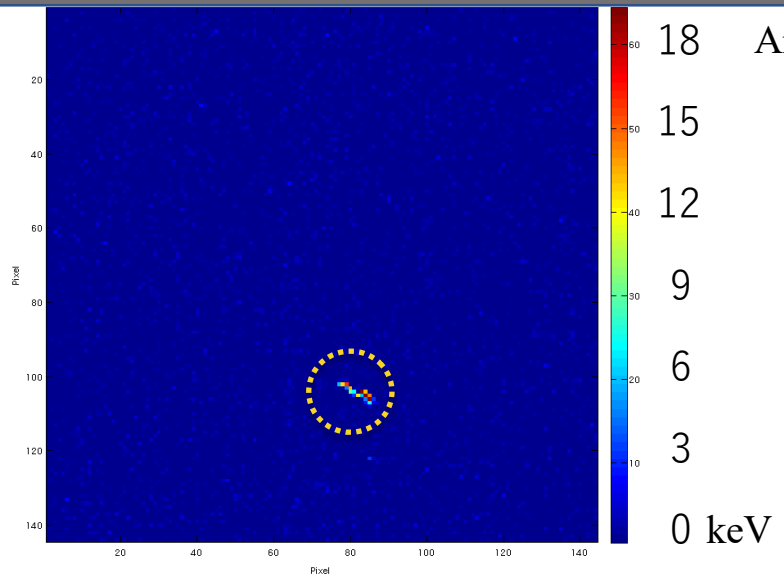
Compton recoil electron image



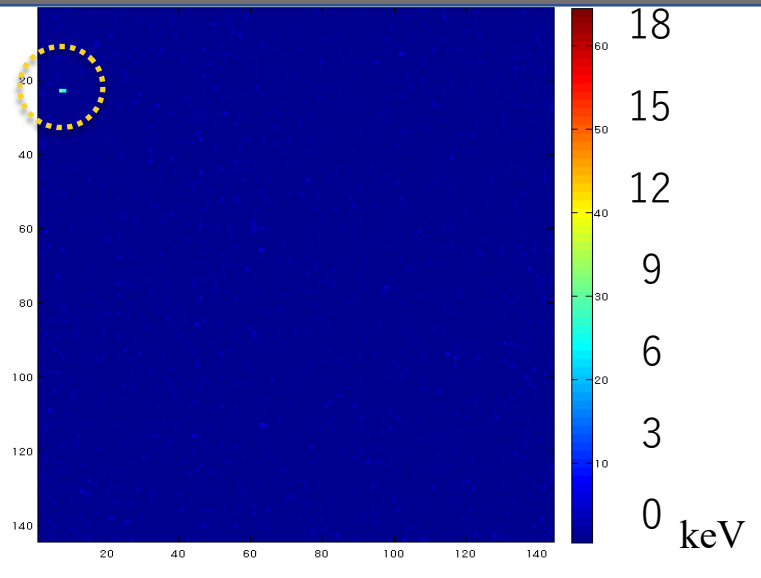
Vbias=5V
Room temperature
Integration time = 1000us

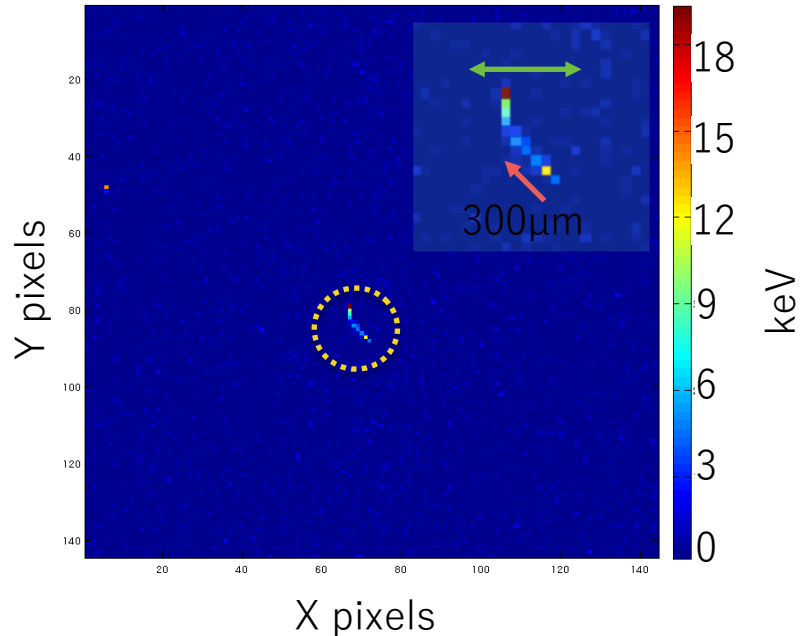
Compton Electrons in SOI sensor

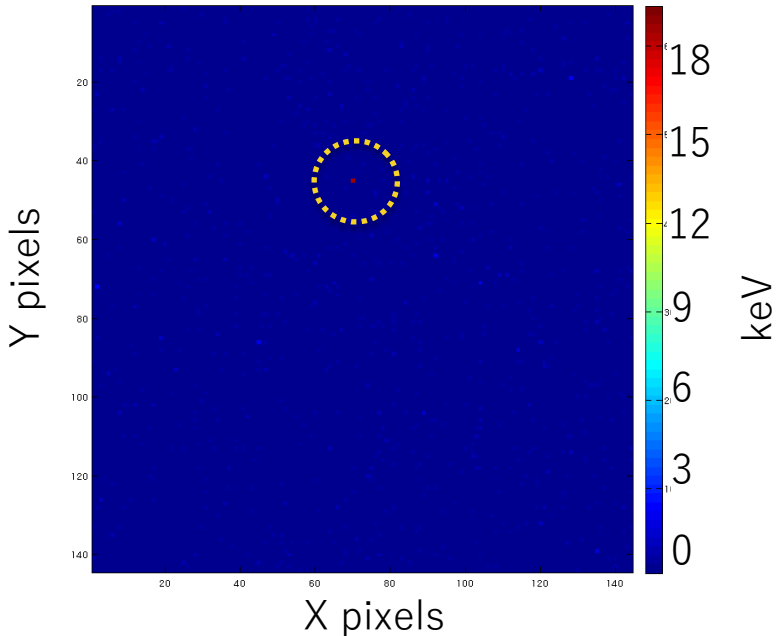
Co-60



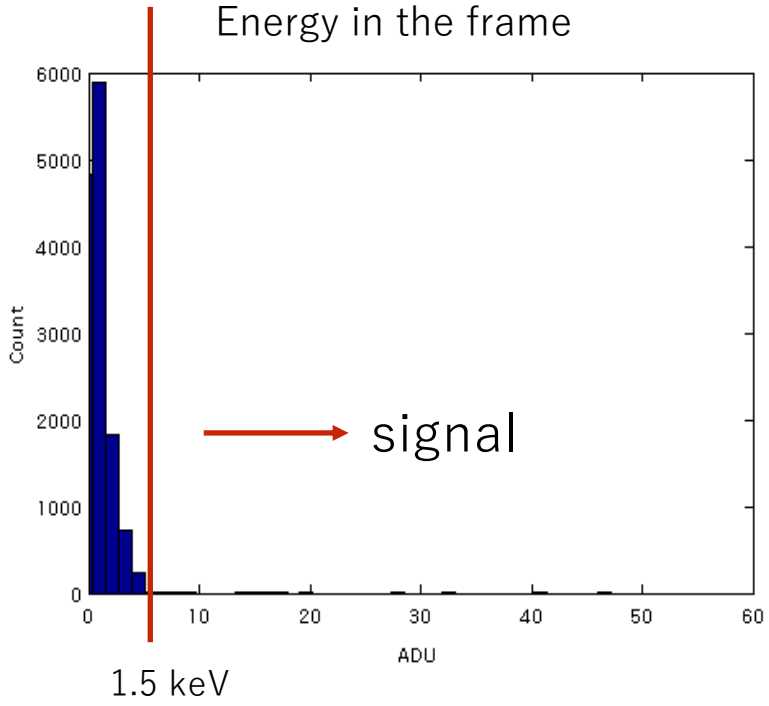
Am-241



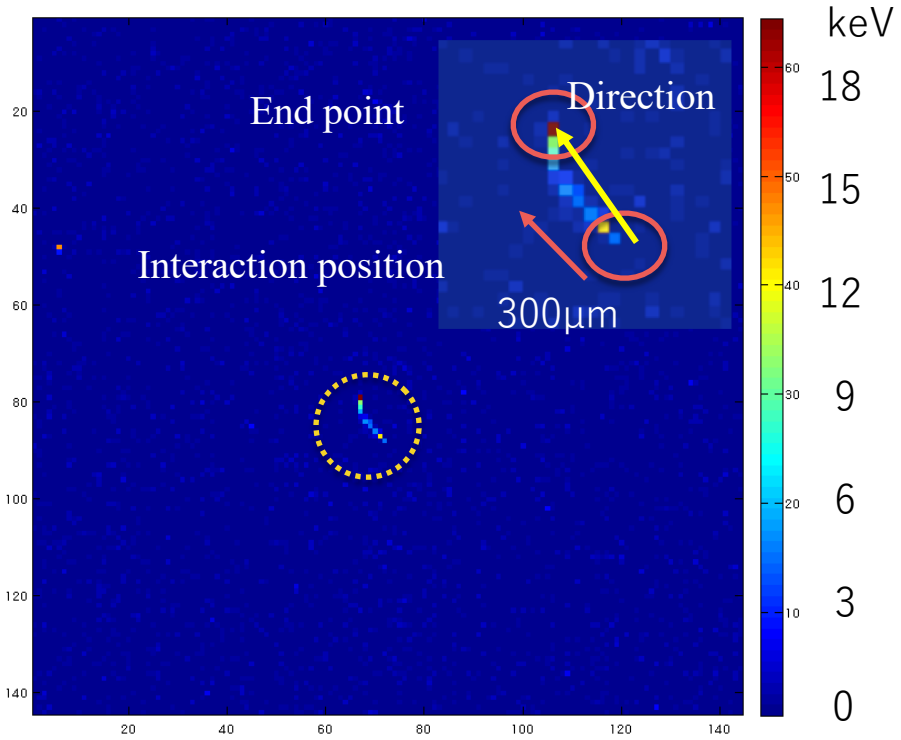




Example of Compton Electron in SOI sensors

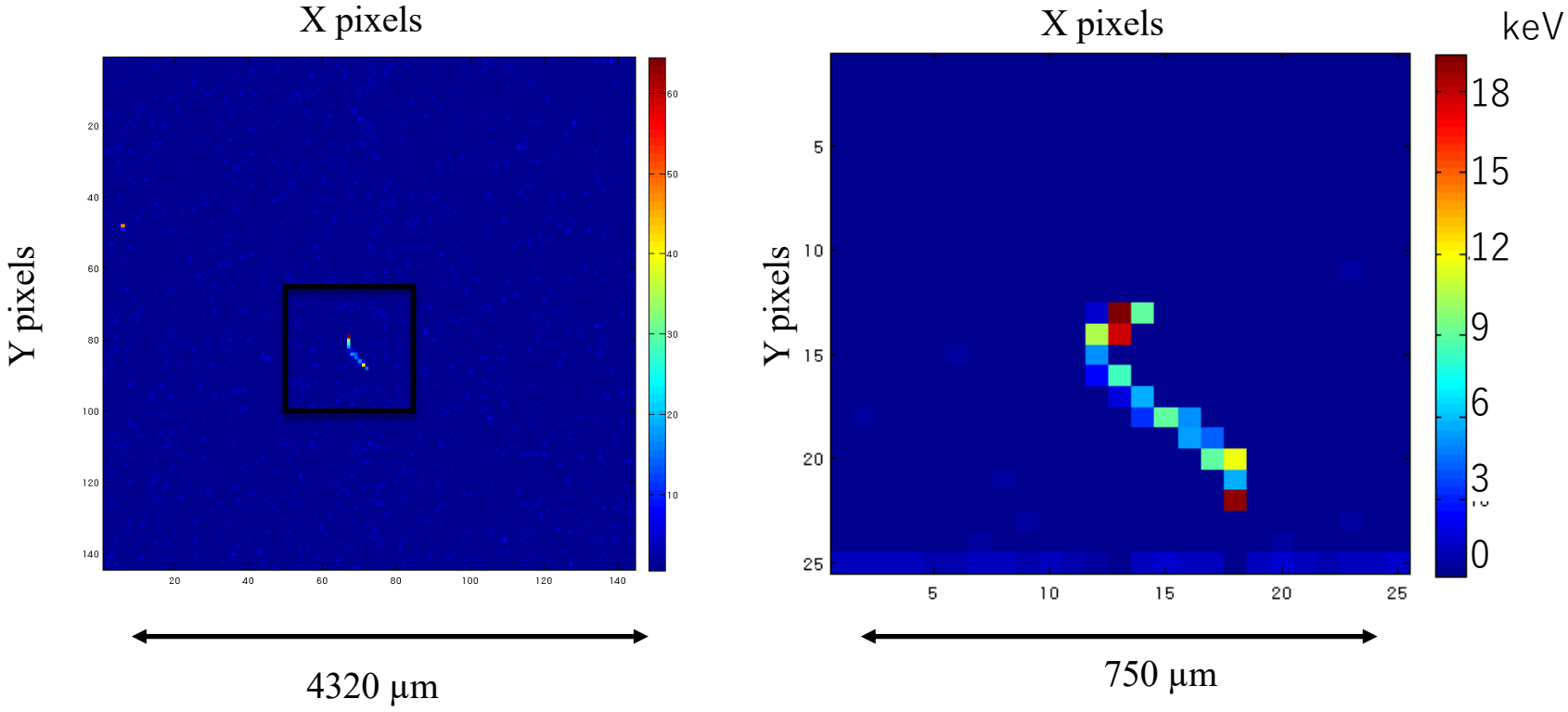


Threshold set



Typical pattern of electron track

Compton electron (25x25 pixels)



Frame-mode(144 x 144 pixels)

Trigger-mode (25 x 25 pixels)

The property of trigger-mode

- It is enough for the electron tracking (750 μm x 750 μm)
  Length of electron track is 300 μm
- A faster readout can be achieved (faster more than 30 times)
  full-frame readout: 20736 pixels
  25 x 25 readout: 625 pixels

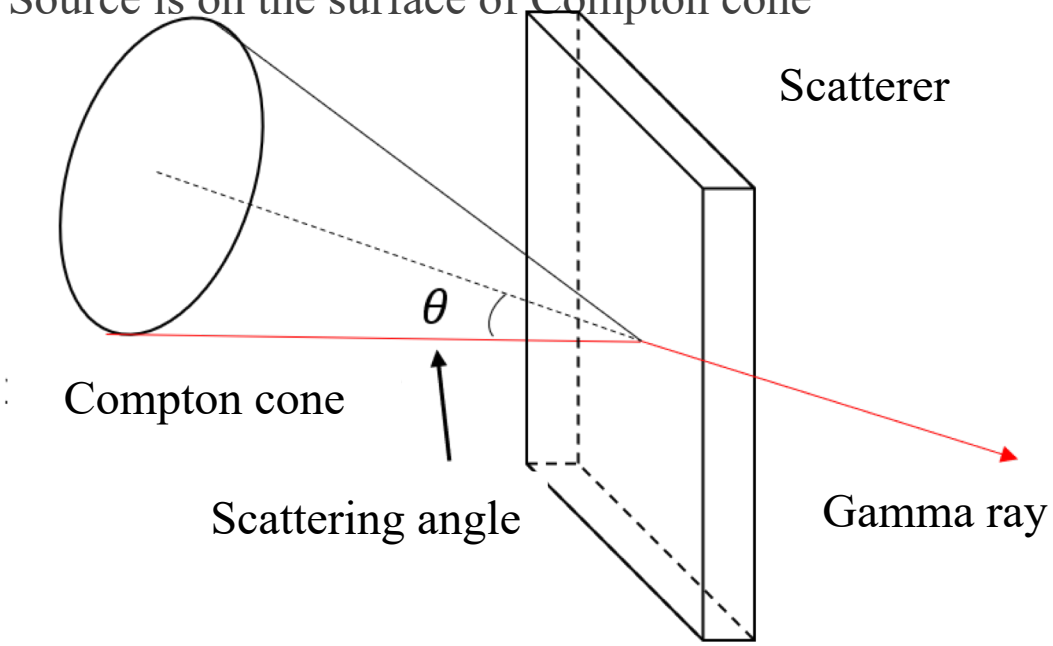
Compton Imaging

Conventional

Through the γ ray energy before and after scattering,

Compton cone can be built.

Source is on the surface of Compton cone



$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_0 c^2}(1 - \cos\theta)}$$

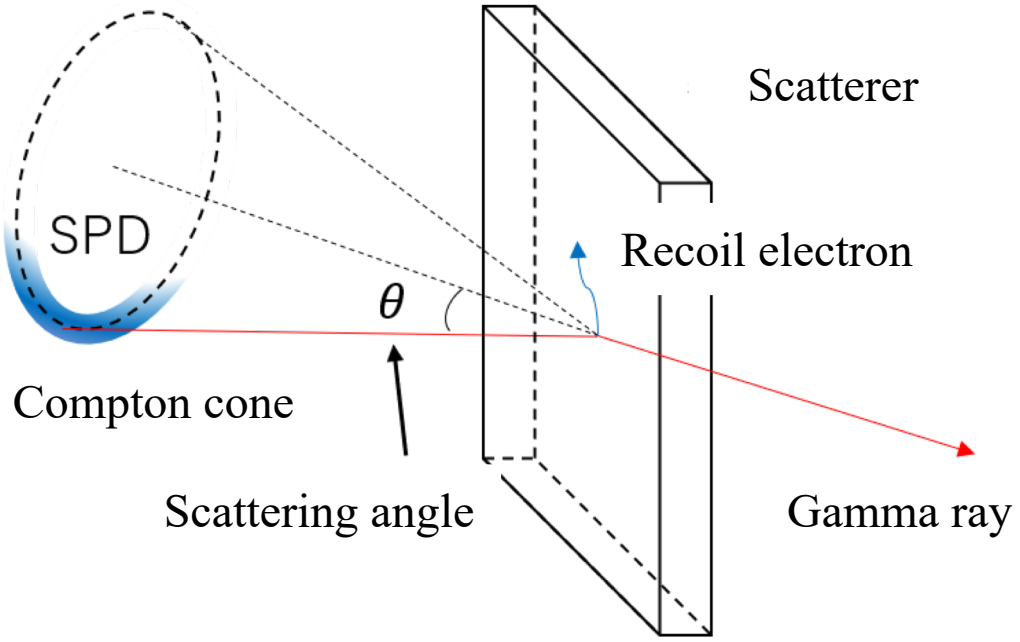
E_γ: Energy of pre-γ ray

E'_γ: Energy of scattered γ ray

Electron-tracking

Not only the γ ray information,

But the with the electron information



$$\vec{s}_0 = \left(\cos\theta - \frac{\sin\theta}{\tan\alpha}\right)\vec{p} + \frac{\sin\theta}{\sin\alpha}\vec{e}$$

SPD : Scatter Plane Deviation

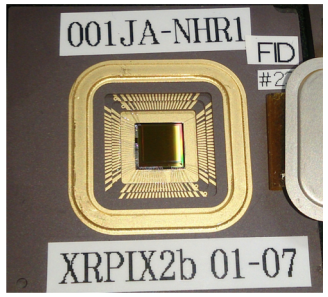
$\vec{s}_0$: Gamma ray direction

$\vec{e}$: Electron direction

$\vec{p}$: Scattered γ ray

α: angle between $\vec{e}$ and $\vec{p}$

Electron-tracking Compton Camera



SOI

e-

γ'

GAGG

MPPC

Trigger (TRIG_O)

Coincidence Flag

Pattern Readout

Trigger

DAQ/FPGA

Coincidence Decision

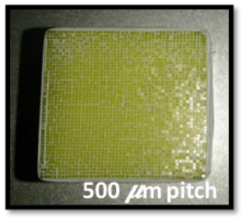
Electron pattern

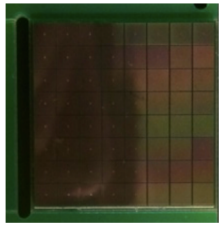
scatter energy

absorber energy

PC

Image reconstruction





GAGG 3 x 3 x 6 mm pixel array

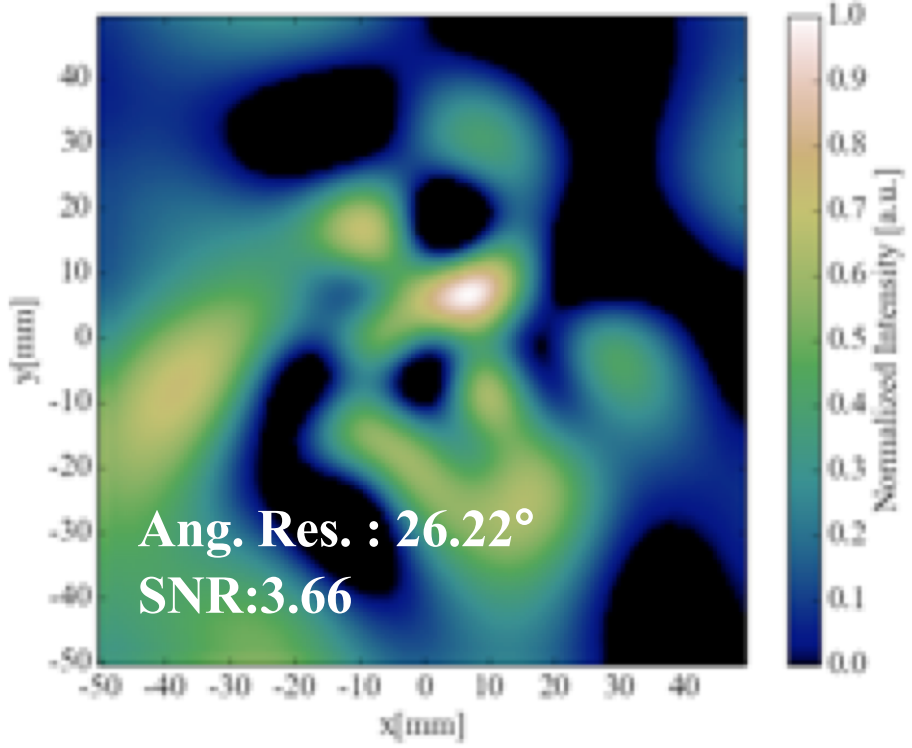
TSV-MPPC Hamamatsu(8 x 8 array 3mm)

The whole structure

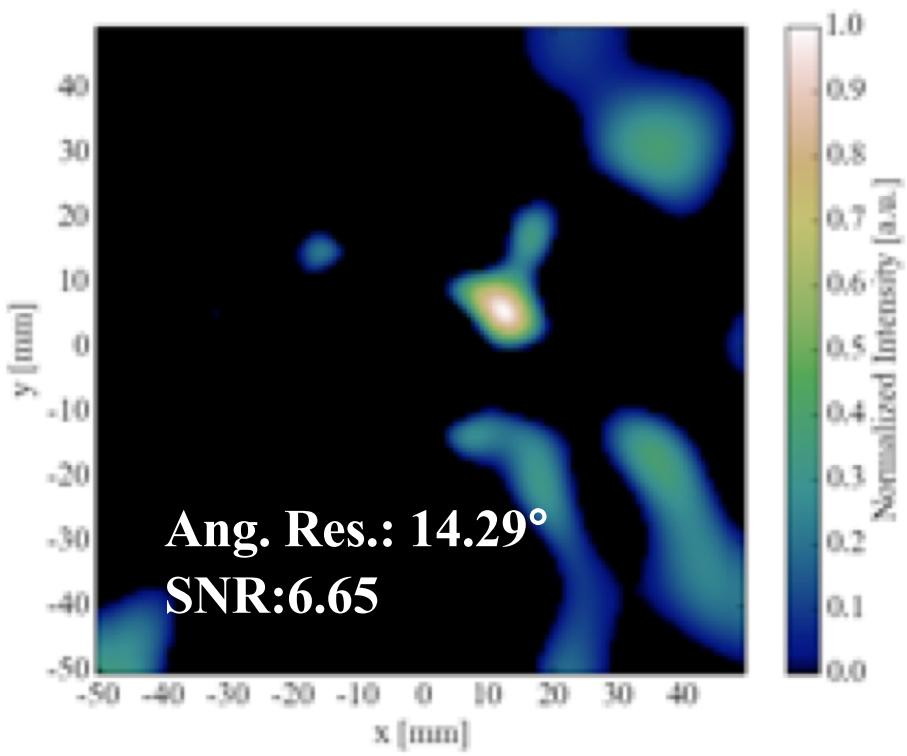
Electron-tracking Compton Image

2-D Reconstruction

without Electron Tracking



with Electron Tracking



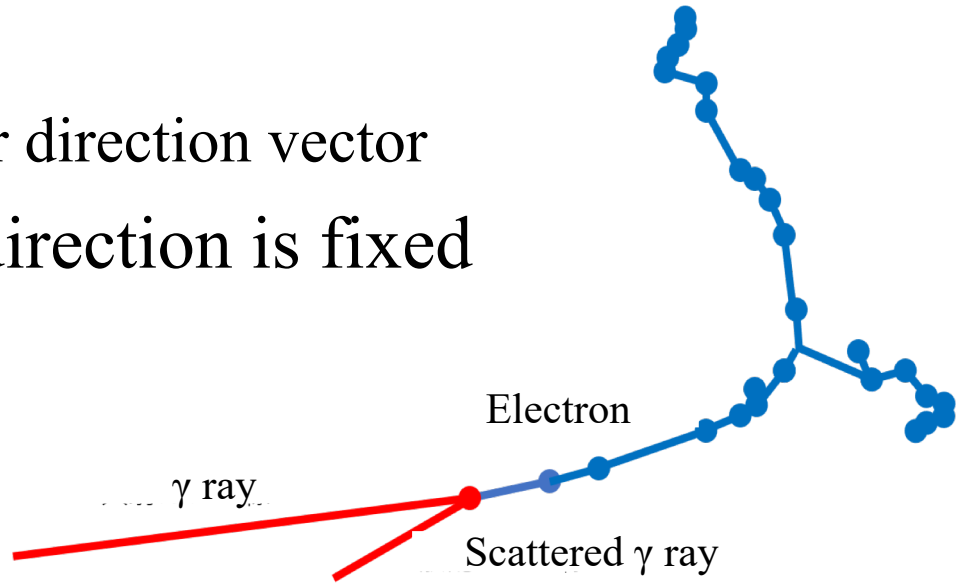
Both Angle resolution and SNR are improved with Electron Tracking

SNR: Signal Noise Ratio

Simulation of Compton Electron in Geant4

- Geant4: A simulation software used for interaction of particles.
- Setting: **Source**: ^{137}Cs **Energy**: 662keV
  Particle: Gamma ray **Detector**: Silicon Pixel Detector
- The electron information

  their coordinate, the change of energy, their direction vector
- The position of source and radiation direction is fixed

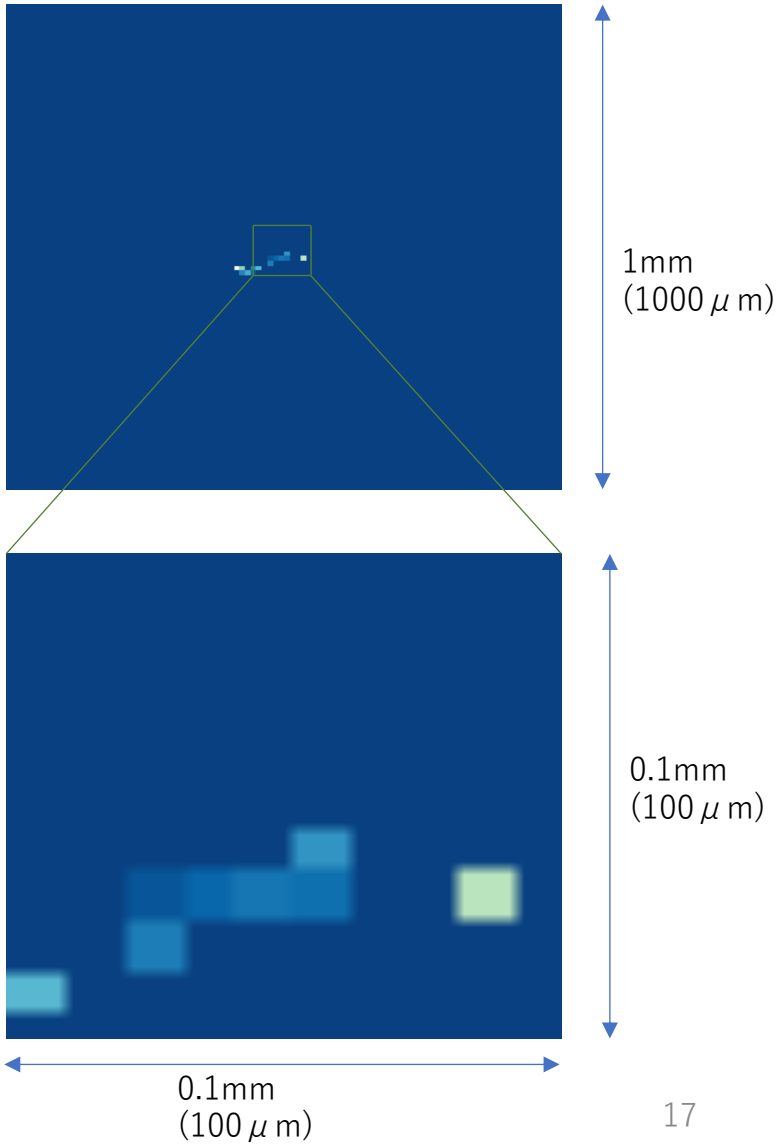


Simulation Result Example

Data Generation

- Image data generation for deep-learning
- The information of deposited charge in each pixel is recorded
- Pixel size in silicon detector

  = 10 μm or 30 μm

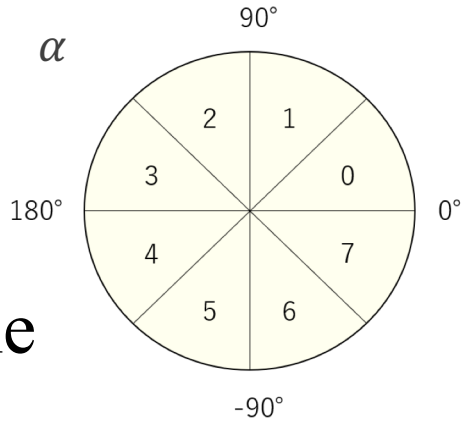


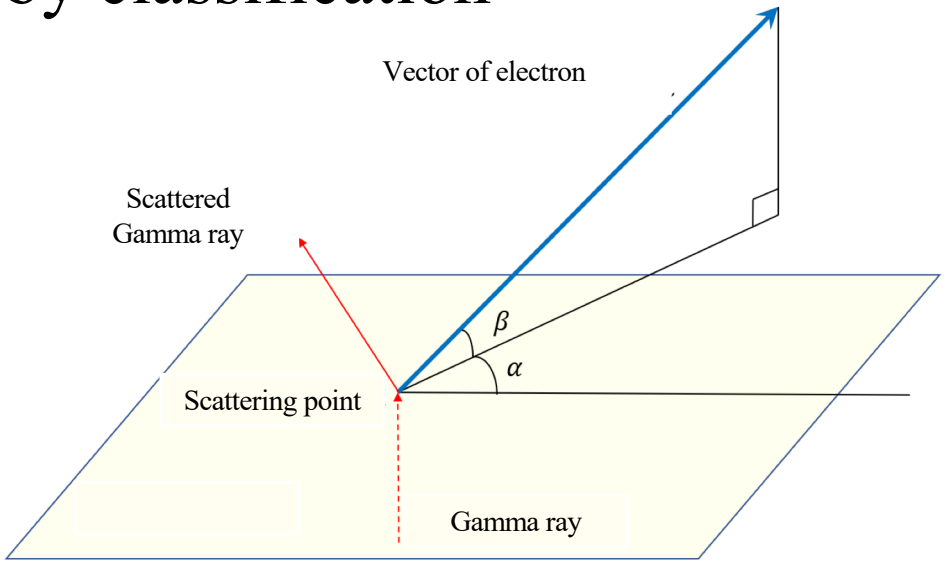
Data Generation

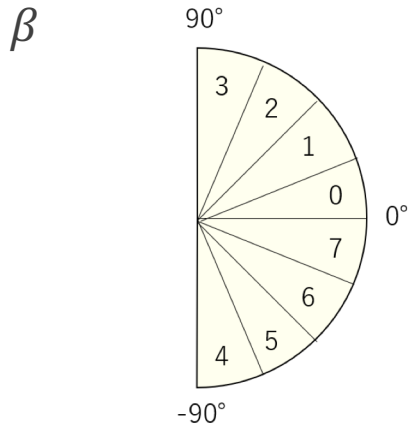
- Angle in plane and depth direction

  α、β are defined

- Each image are classified in to 8 same groups
- SPD: the extend of direction vector because of the error made by classification







Deep-learning

- One of the machine-learning with deep layer
- Input: image of Compton electron; Output: the predicted direction
- The network is trained with many data generated by Geant4 simulation
- Advantage
  - Once learning completed, only though the input of image, its direction vector can be forecasted
  - The accuracy will be increased if the data used for learning increase

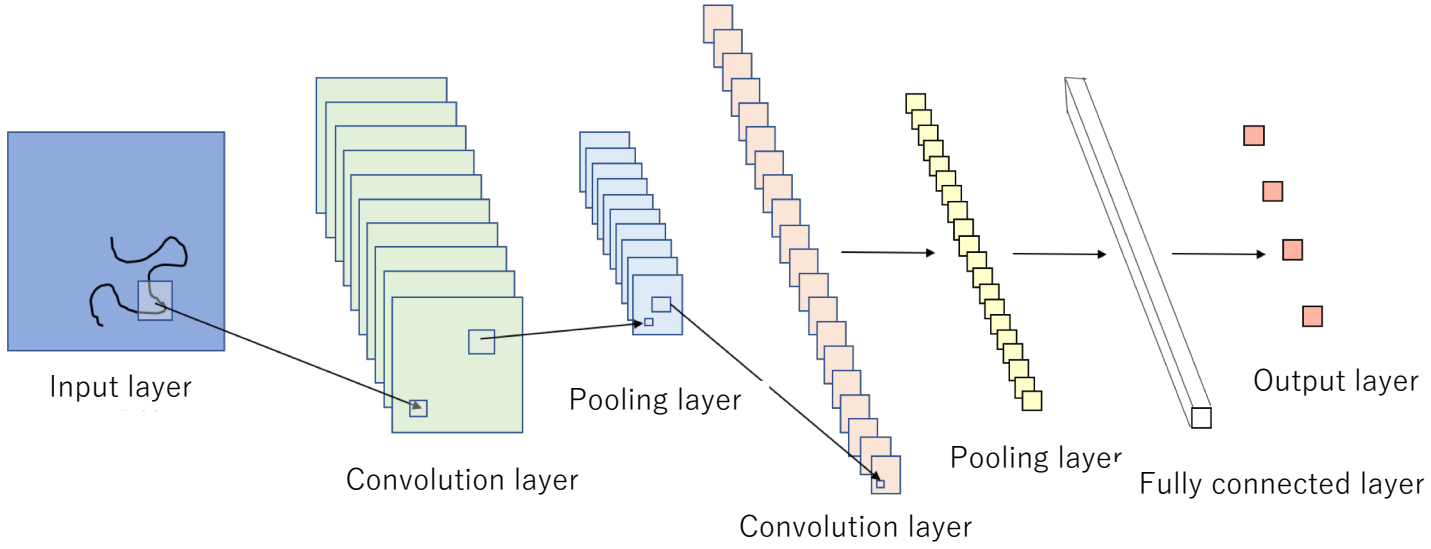
Deep-learning

- Convolutional Neural Network (CNN), which is common in image processing field are used.
- Combination of

  Convolution layer to extract local characteristics

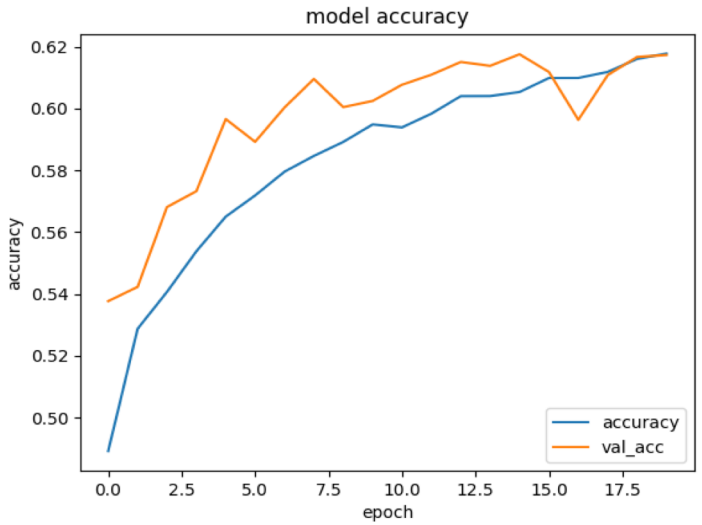
  Pooling layer to minimize the size while maintaining the characteristics

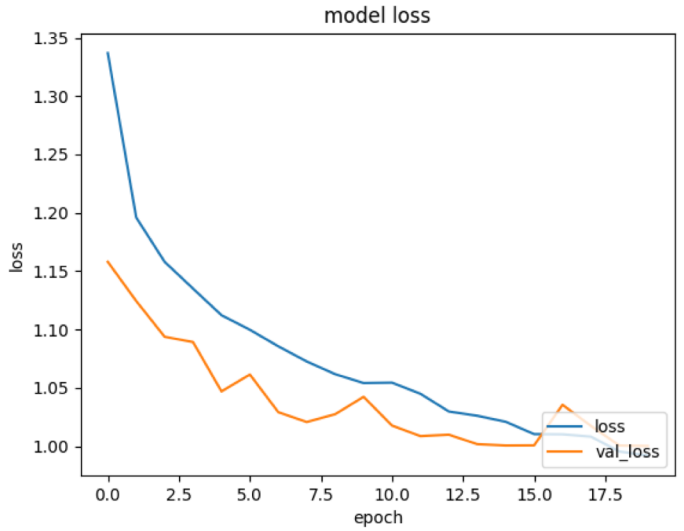
Deep-learning



Deep-learning

- Learning
  - After inputting image and correct group (including input and output) to model, change the parameters in order to get a correct output
  - The number of data: 10μm -> 80050 / 30μm -> 68779
  - Learnt 20 times





The relationship of model accuracy and model loss with number of times
α, pixel size=10

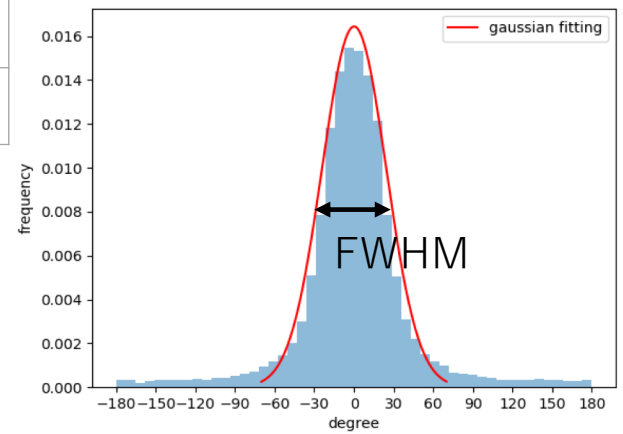
Deep-learning

- Learning
  - After input image and correct group (including input and output) to model, change the its parameter of in order to get a correct output
  - The number of data: 10μm -> 80050 / 30μm -> 68779
- Forecast
  - Using the input of unknown image to get a forecast image
  - The number of data : 10μm -> 39429 / 30μm -> 33877
- Evaluation
  - Calculate accuracy with the comparison of forecast class and correct class
  - Accuracy = (number of correct forecast data)/(number of all data)

Result and Conclusion

- The accuracy and SPD with CNN method

Method	Pixel Size	α	β	SPD(α)	SPD(β)
CNN	10μm	61.76%	48.48%	57.5	36.3
CNN	30μm	47.52%	49.51%	73.0	35.6



- Full Width at Half Maximum(FWHM)：The error between forecast vector and correct vector

From the result, we decided to use 10 μm which has higher accuracy for imaging

Result and Conclusion

- Reconstruction

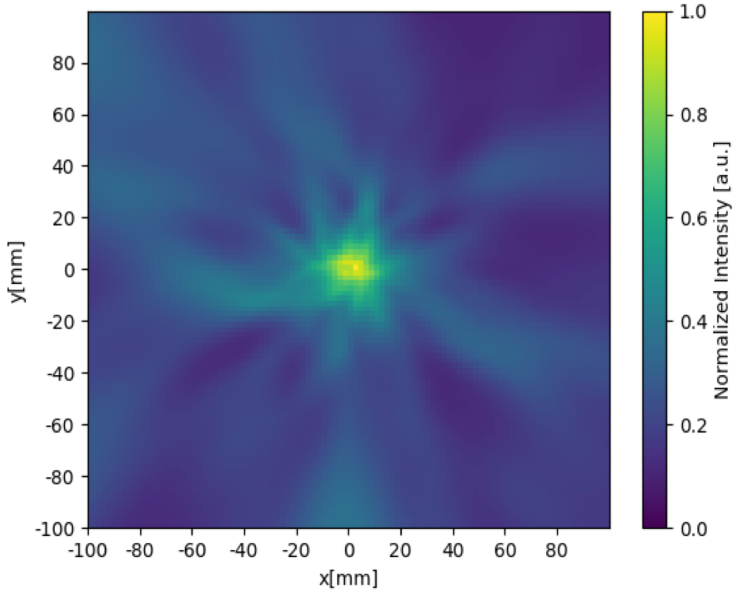


Fig.1 Without electron

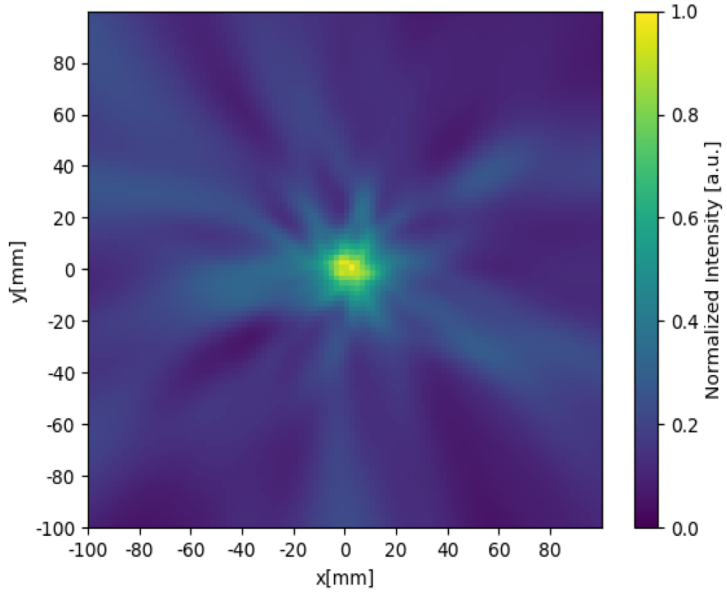


Fig.2 With electron achieved from deep-learning

The background of Fig.2 is clearer, which means noise is less

Result and Conclusion

The evaluation of image

- Signal Noise Ratio(SNR)
- Position Resolution

Electron	SNR(X)	SNR(Y)	PR(X)	PR(Y)
Without	3.99	3.47	32.3mm	26.4mm
With	4.83	5.15	30.4mm	23.6mm

SNR increased significantly. It is good for the separation of source and background

Summary

- Electron Tracking Compton imaging could be useful to make high SNR image in Compton imaging

- Deep learning could be used to estimate the direction of Compton electrons in SOI based small pixel silicon sensors