WASEDA University 早稲田大学

金沢大学 KANAZAWA UNIVERSITY

PD24

Applications

Extracting high performance of energy information in photon-counting Computed Tomography

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Outline

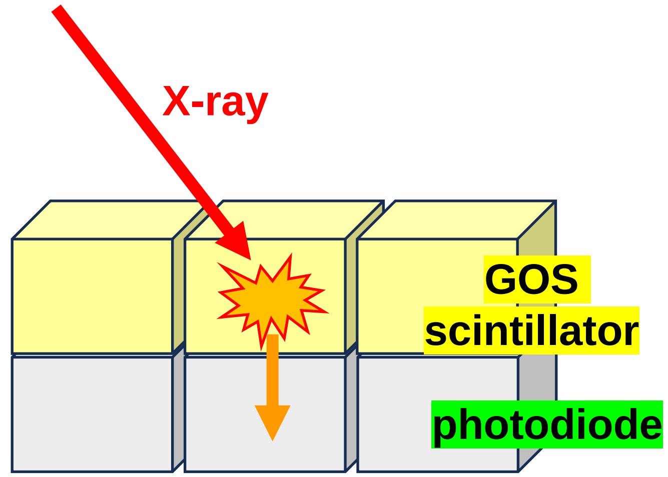
- Introduction
  - Conventional CT
  - Photon-counting CT (PCCT)
- Raise a problem of PCCT (energy information)
- Experiment using our PCCT system
- Provide new correction method for CT values
- Discussion about method and usability for PCCT
- Conclusion

Introduction ~Conventional CT~

Conventional CT

Use energy-integrated detector

└ GOS scintillator + Photodiode

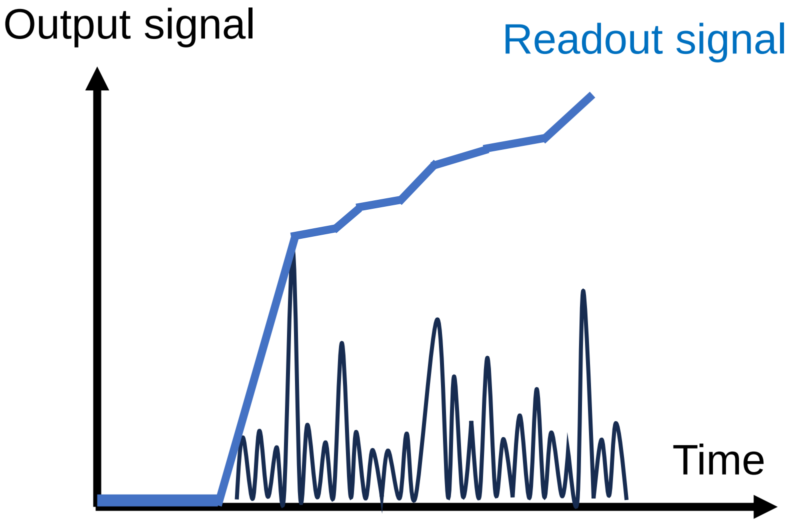


- ✓ Long decay time of GOS (≳ μs)
- ✓ High intensity of X-ray (~$10^{7\text{-}8}$ Hz/mm^2)

  ⇒ X-ray signals pile up

Readout mode : **current mode**

Integrate X-ray signal



This leads to …

- ✓ Lack of energy information = monochromatic image
- ✓ Require high radiation dose

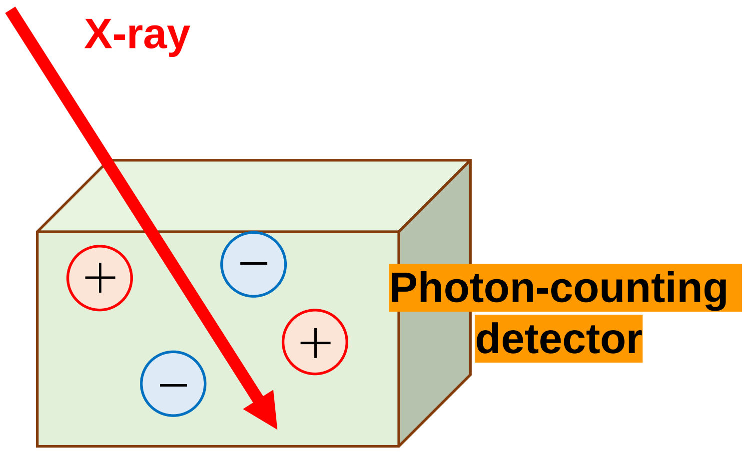
Introduction ~PCCT~

<u>Photon-counting CT (PCCT)</u>

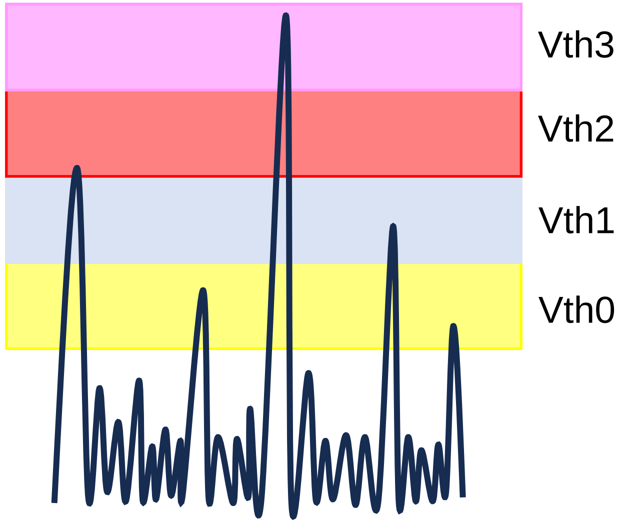
Use photon-counting detector

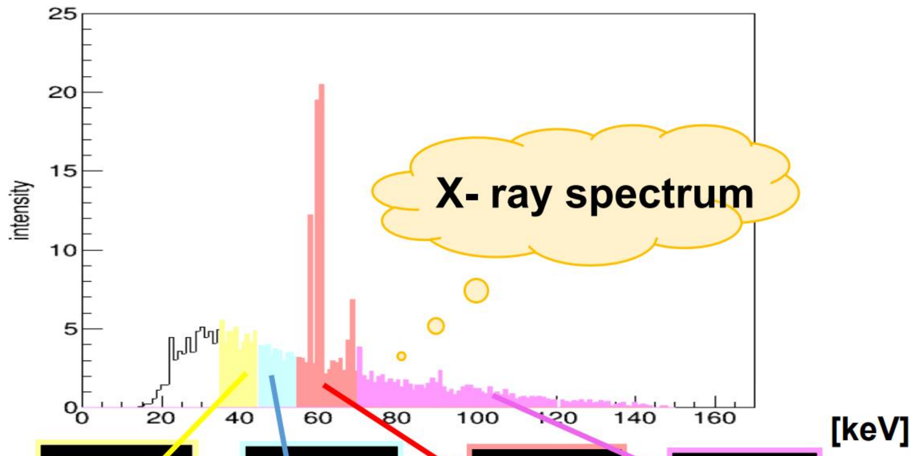
Readout mode : **pulse mode**

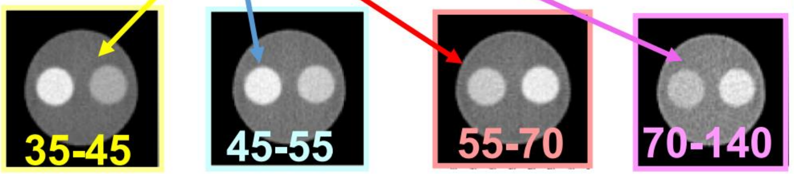
Set multiple energy thresholds



- ✓ Signals can be discriminated by energy bands (energy-resolved image)
  ⇒ Spectral analysis ○
- ✓ Cut dark current noise
  ⇒ SNR up
  ⇒ Reduce radiation dose







Introduction ~PCCT~

<u>Photon-counting detector (PCD)</u>

✓ Semiconductor detector

Mainly researched as PCD (CdTe, CZT)

○ High energy resolution

△ Expensive

△ Need to make pixels very small (high rate of X-ray)

(cf.) NAEOTOM Alpha
(Siemens Healthineer) … CdTe

✓ Scintillation detector

△ Low energy resolution

○ Reduce total cost

○ No need complex system

○ Compatible with conventional CT system

<u>Simple & Reasonable</u>
PCCT system

Our group : **develop scintillation-based PCCT**

PCCT system

Our PCCT system

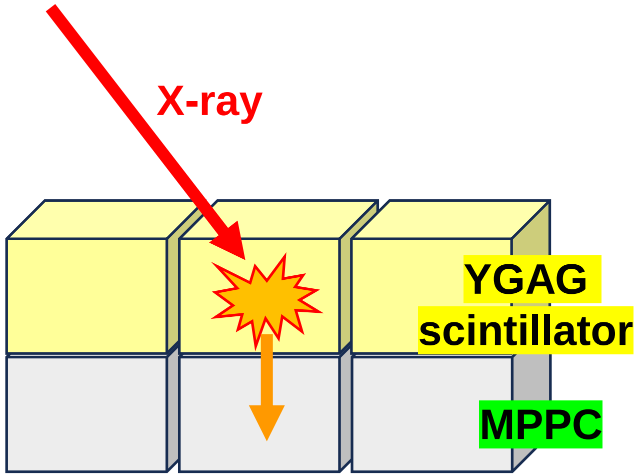
✓ Fast scintillator + MPPC detector

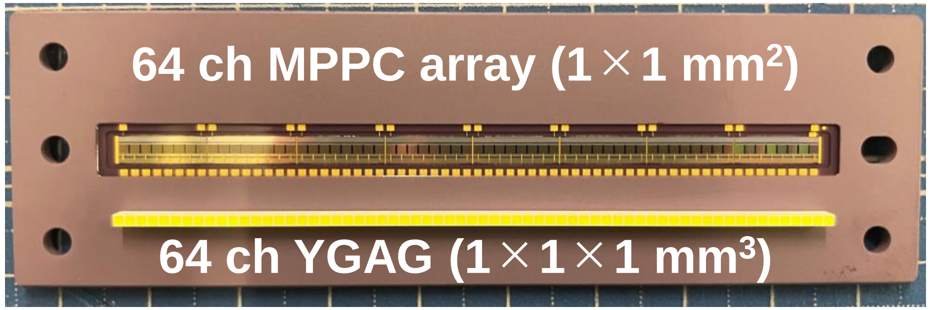
YGAG scintillator (ceramic)

- Decay time : ~ 70 ns
- Luminescence : 36000 photon/MeV
- Density : 5.38 g/cm^3
- Thickness : 1 mm

MPPC (SiPM)

- Internal gain : ~ 10^6
- Time response : ~ 10 ns
- Effective sensitive area : 1 × 1 mm^2
- Pixel pitch : 15 μm



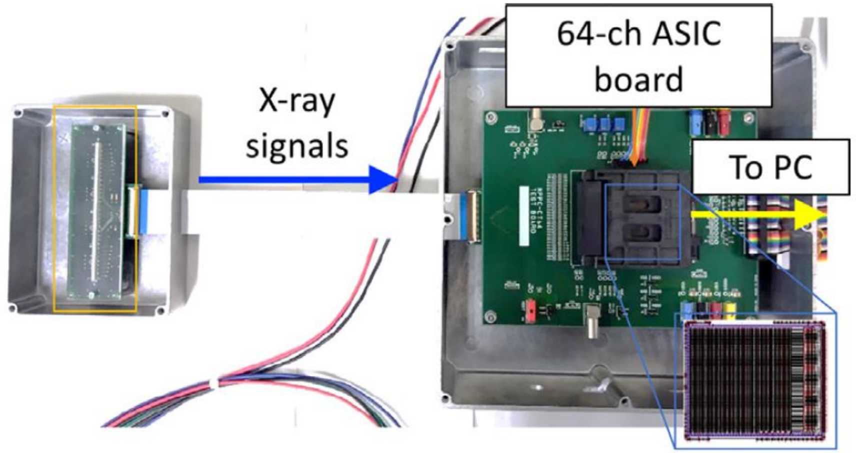


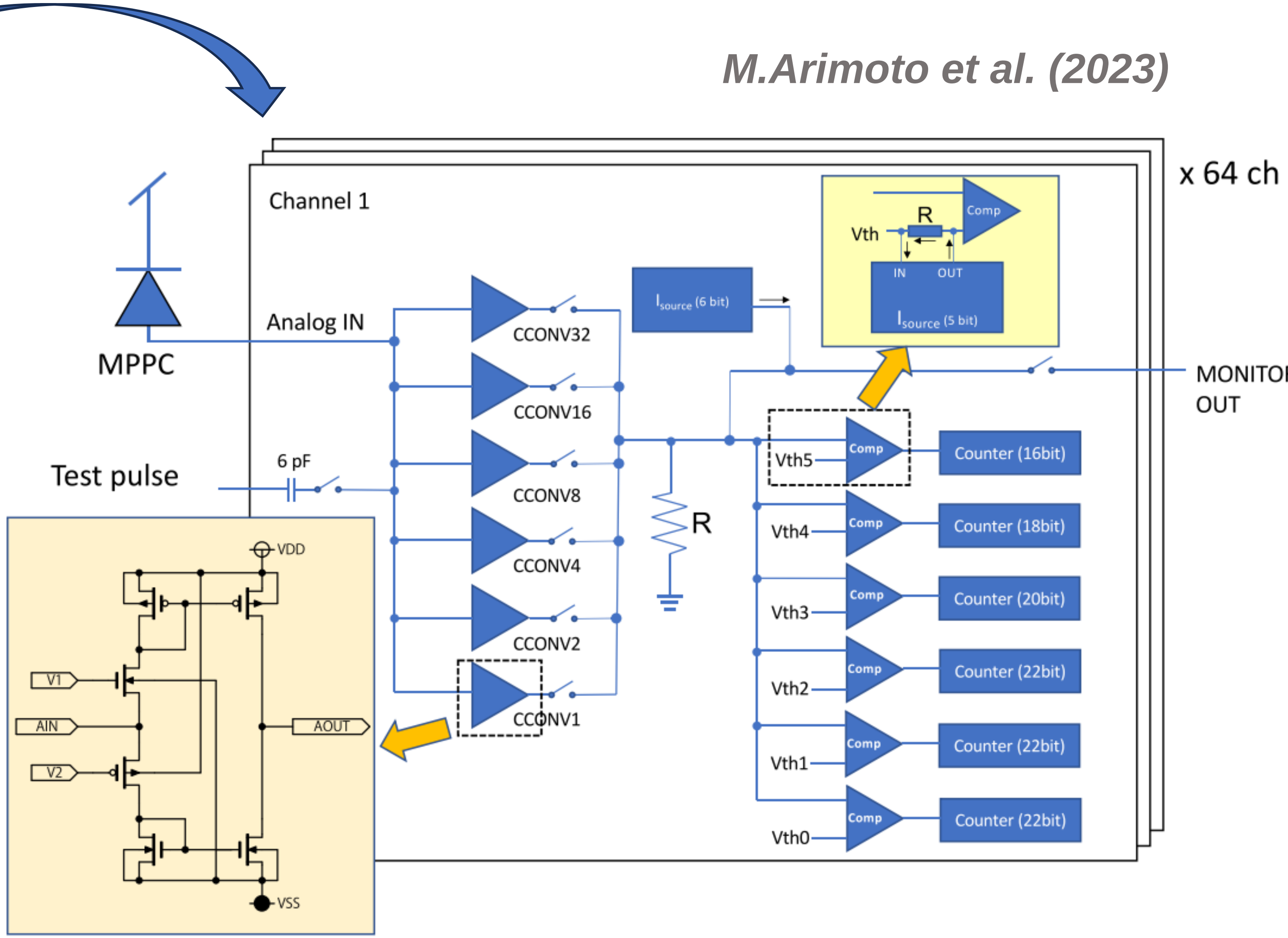
PCCT system

Our PCCT system

✓ 64ch-LSI

M.Arimoto et al. (2023)

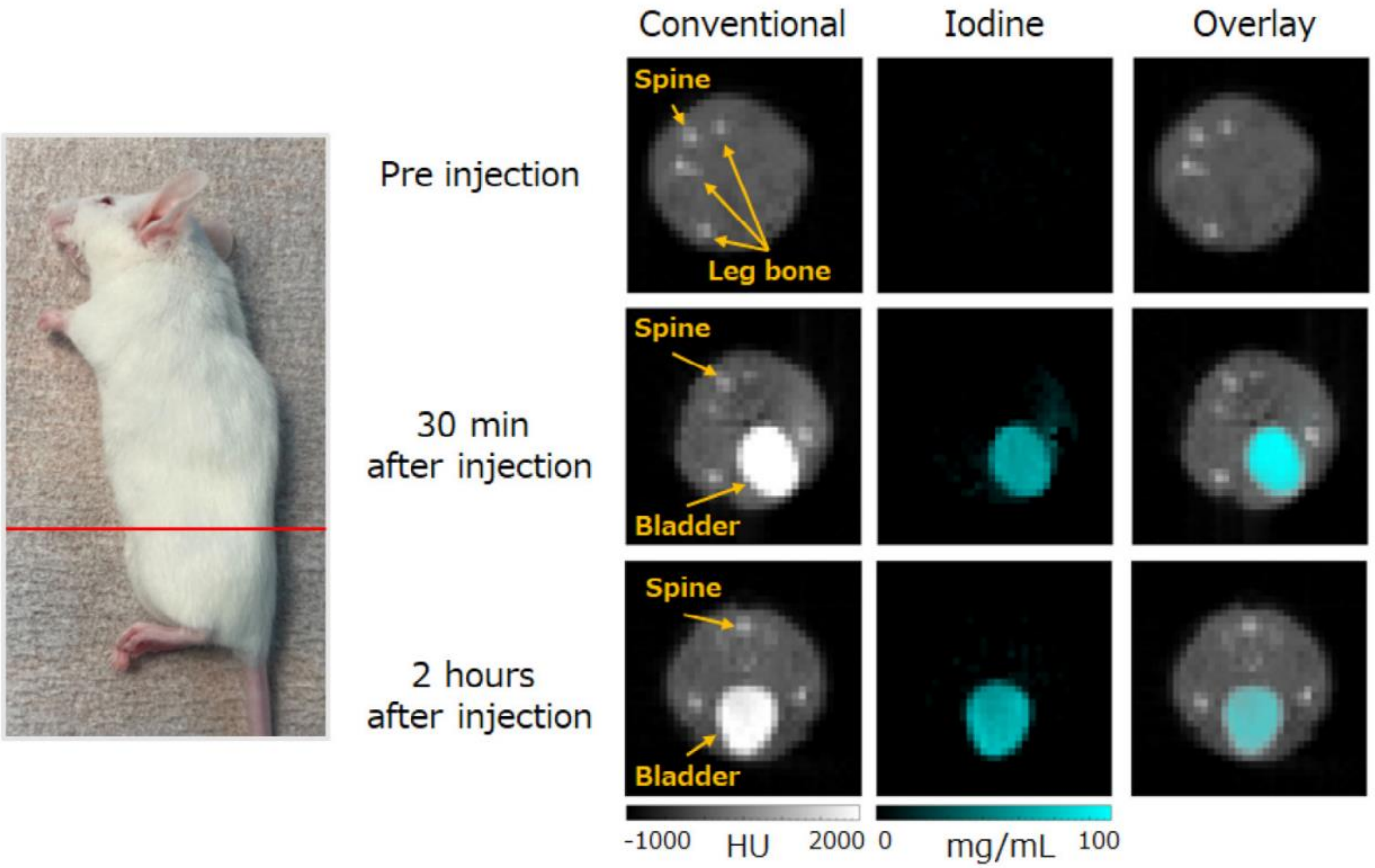




Signals are discriminated into 6 energy bins (Vth0 – Vth5)

Bioimaging examples using our PCCT system

D.Sato et al. 2023



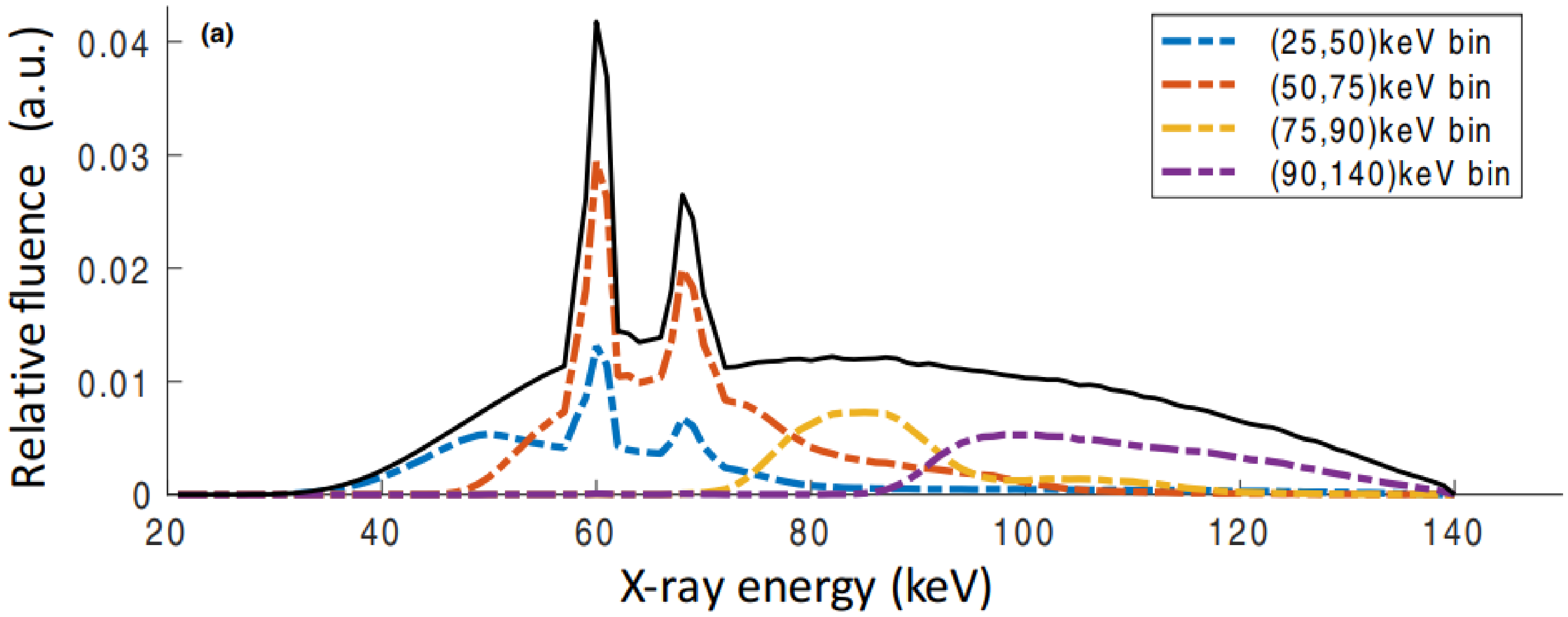
Confirmed iodine accumulation in bladder from in-vivo imaging using our system

Problem

Whether PCCT images can be acquired from individual energy bands as expected?

Study about detection spectrum (CdTe detector)
initial energy of X-ray photons counted in each energy bin

R.Symons et al. (2007)



Problem

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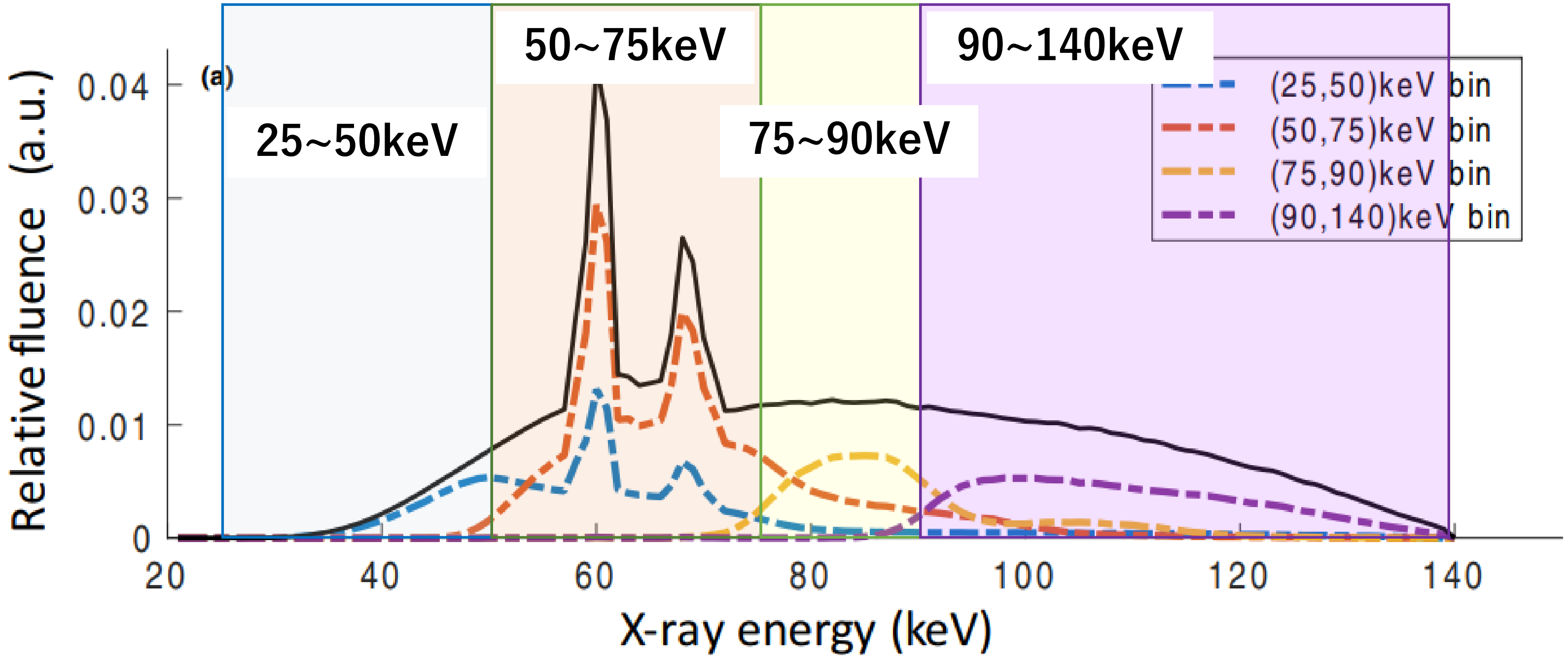
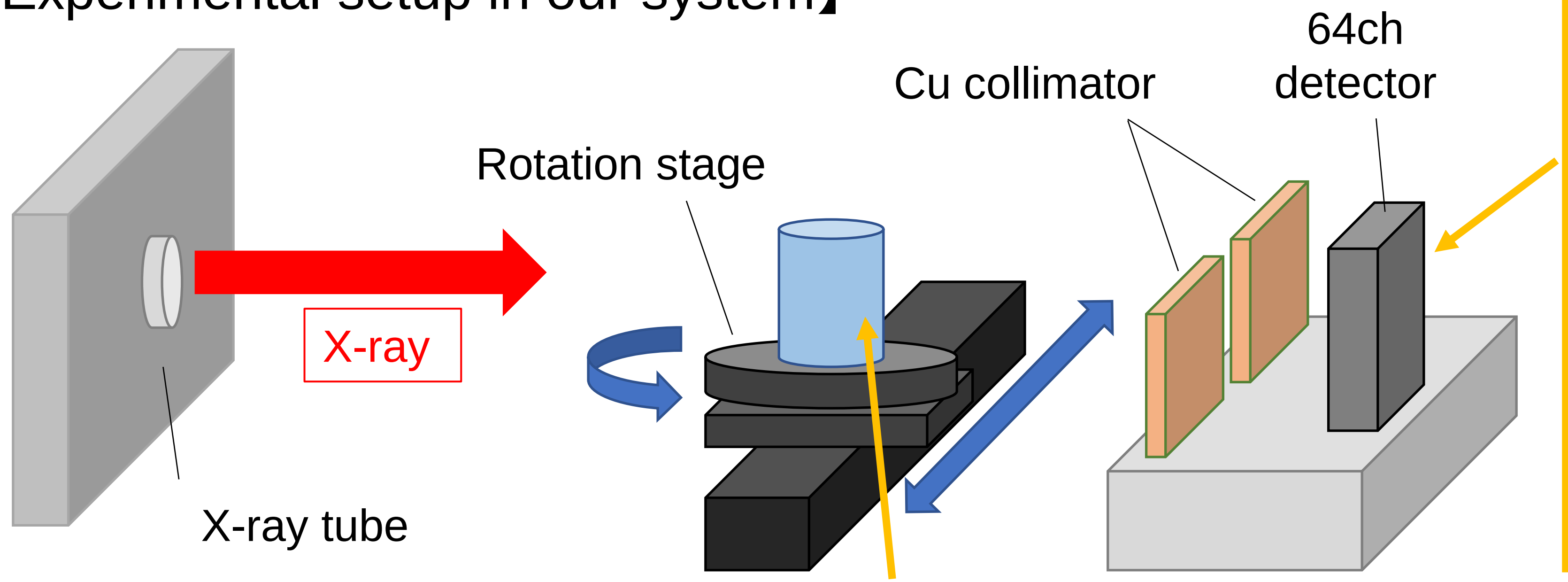


Spectrum separation between energy bins is not perfect (low-energy bands)

Experiment

Same problem in our PCCT system?

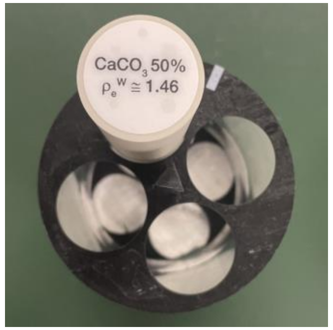
【Experimental setup in our system】



YGAG scintillator + MPPC

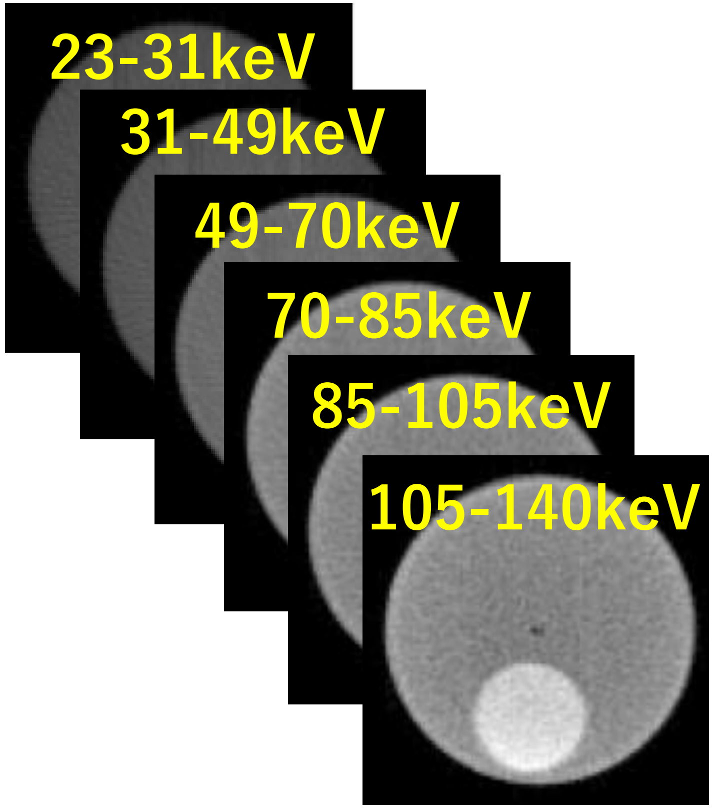
【Condition】
Tube voltage: 140kV
Tube current: 0.5mA
Exposure time: 500ms

【Phantom】
Advanced Electron Density Phantom ($CaCO_3$ 50%)

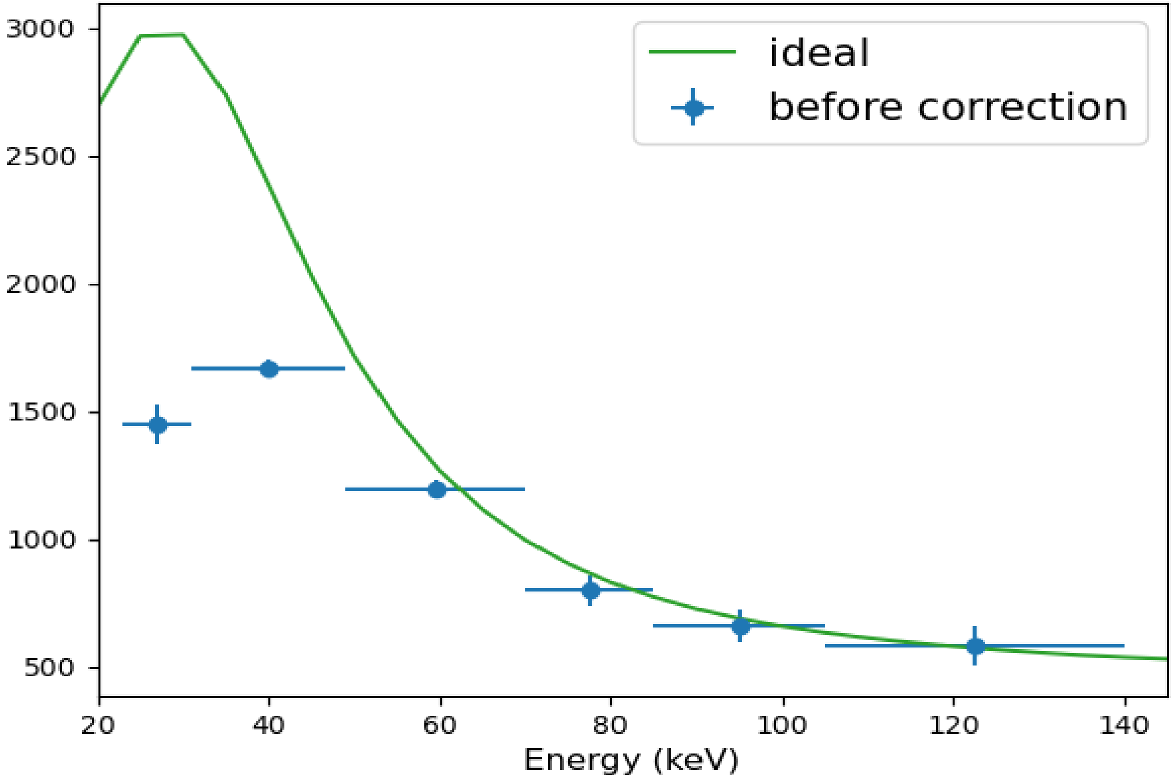


Result

CT images



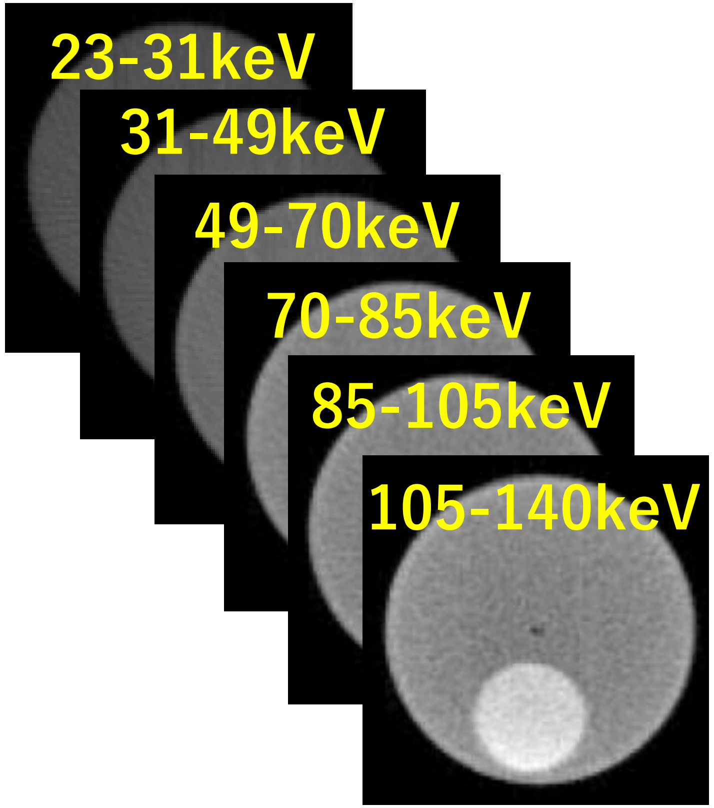
CT values (target region)



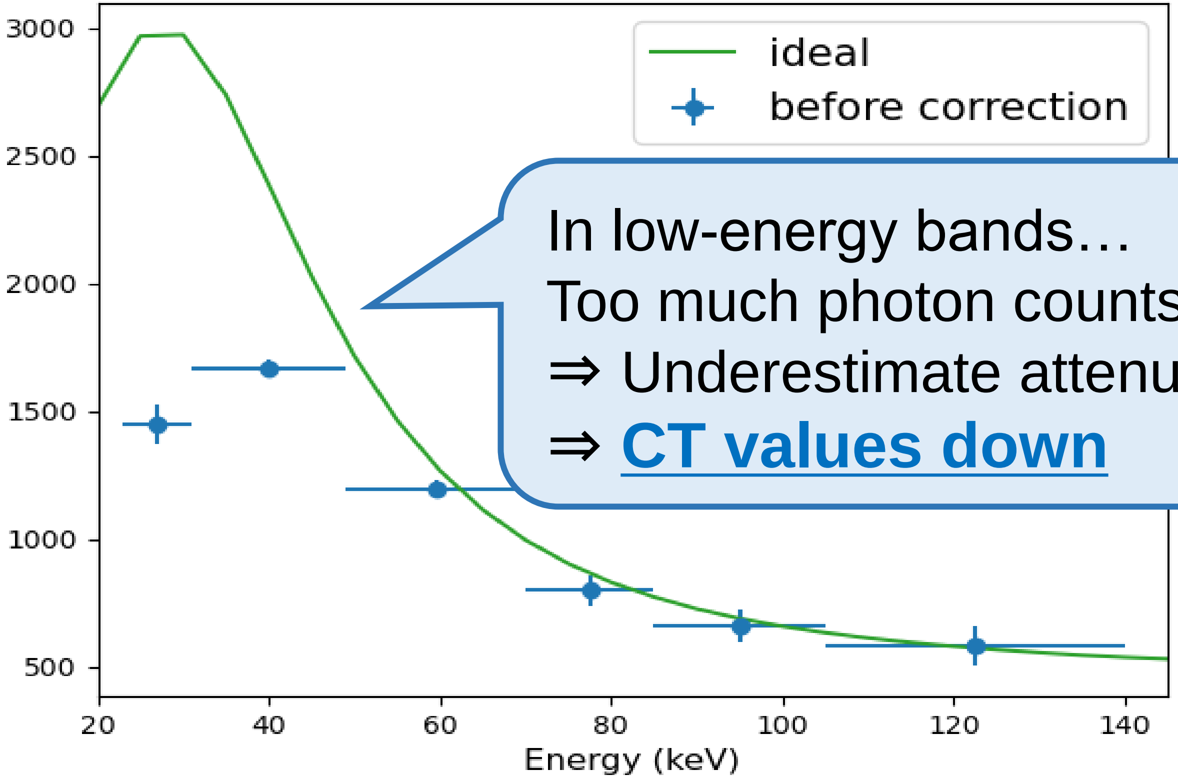
Underestimate CT values in low-energy bands

Result

CT images



CT values (target region)



In low-energy bands…
Too much photon counts (escape, scatter etc.)
⇒ Underestimate attenuation in phantom
⇒ **CT values down**

Underestimate CT values in low-energy bands

Correction method

Main reasons about deviation of CT values … escape, scatter events
⇒ correct the counts of photons

【Correction method】

① prepare photon count table ▶ ② apply correction

Correction method

Main reasons about deviation of CT values…escape, scatter events
⇒ correct the counts of photons

【Correction method】

① prepare photon count table ▶ ② apply correction

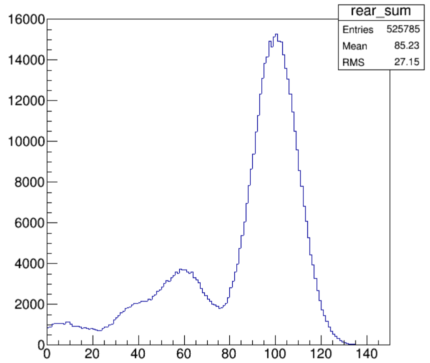
✓ Using Geant4 simulation

Inject monochromatic energy (30-140keV)
⇒ Make count table

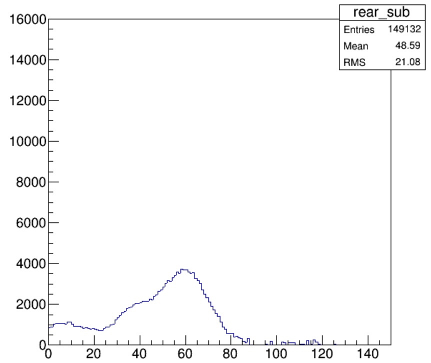
Measured energy bin count VS Inaccurate count (low-energy bands)

(e.g.) injection energy = 100 keV

Measured count



inaccurate count



Correction method

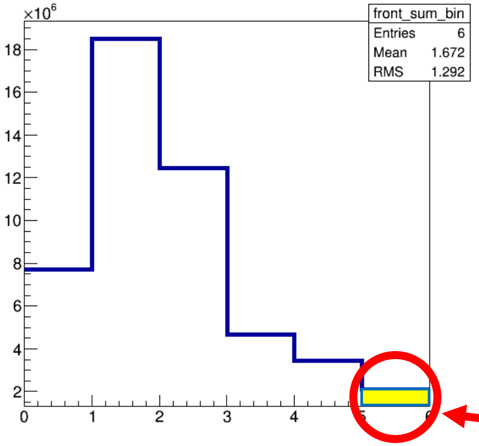
Main reasons about deviation of CT values…escape, scatter events
⇒ correct the counts of photons

【Correction method】

① prepare photon count table ▶ **② apply correction**

Correction 1st cycle

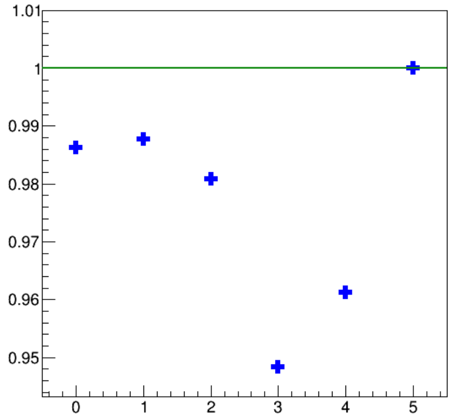
Measured count data



Check the highest bin

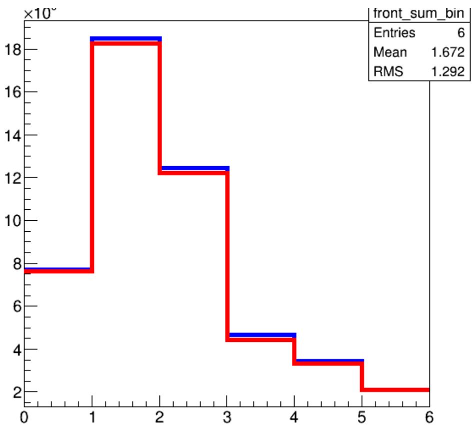
Estimate the ratio of inaccurate count (using table)

Correction factor



apply

Apply 1st correction



Correction method

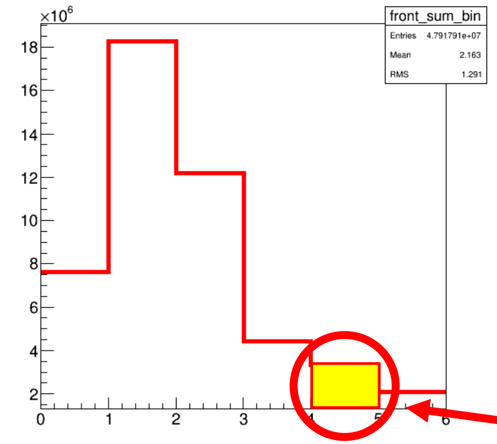
Main reasons about deviation of CT values…escape, scatter events
⇒ correct the counts of photons

【Correction method】

① prepare photon count table ▶ **② apply correction**

Correction 2nd cycle

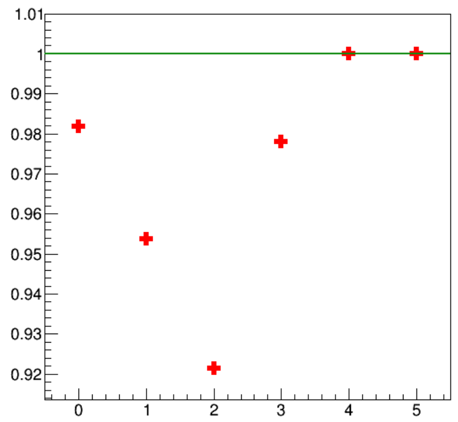
After 1st correction



Check the next bin

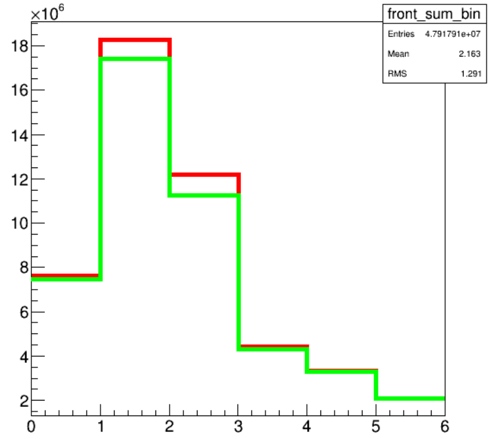
Estimate the ratio of inaccurate count (using table)

Correction factor



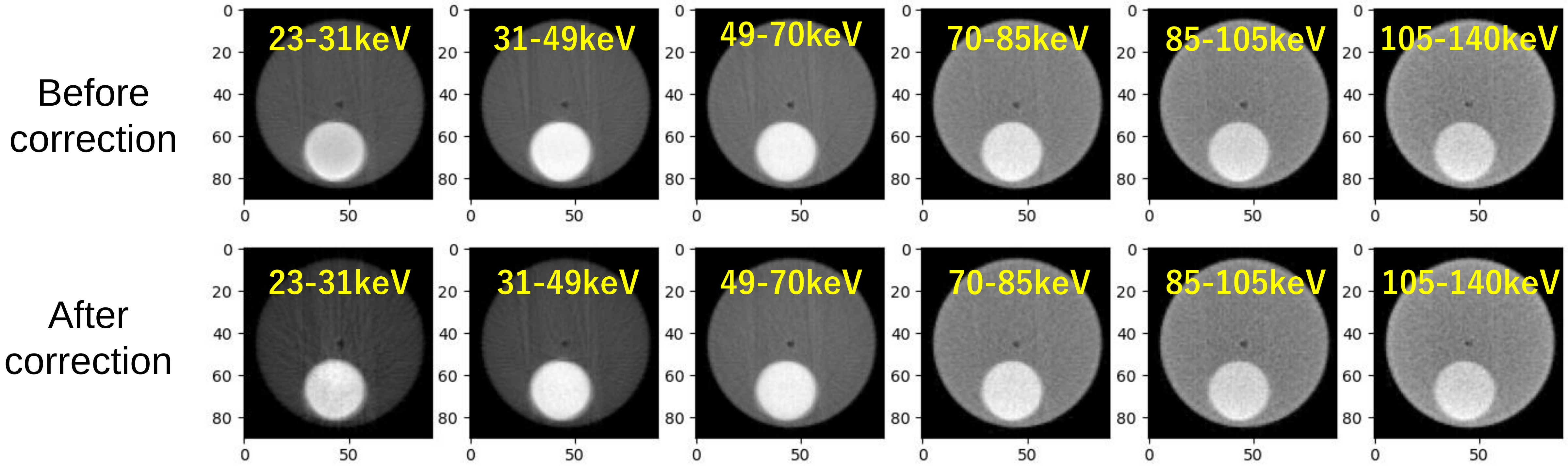
apply

Apply 2nd correction



Correction result

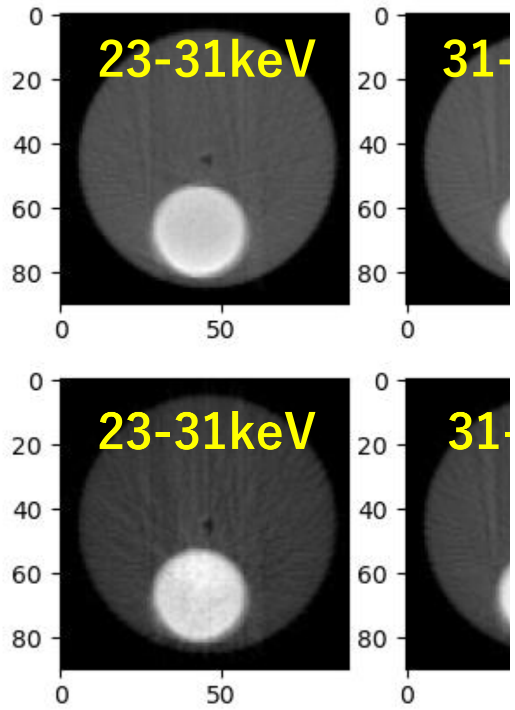
Applied this correction method to measured CT data

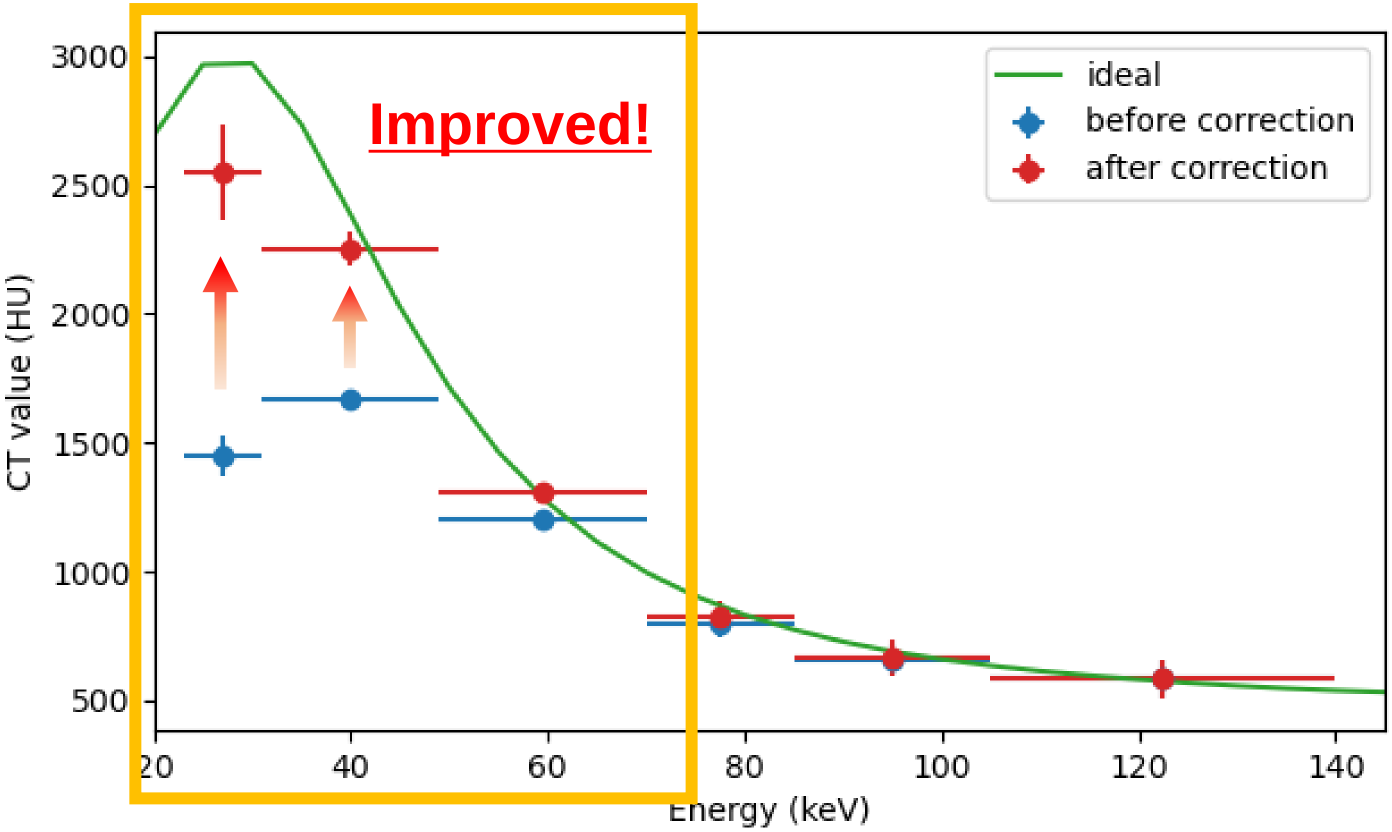


Improve contrast of CT images in low-energy bands

Correction result

Applied this correction method to measured CT data



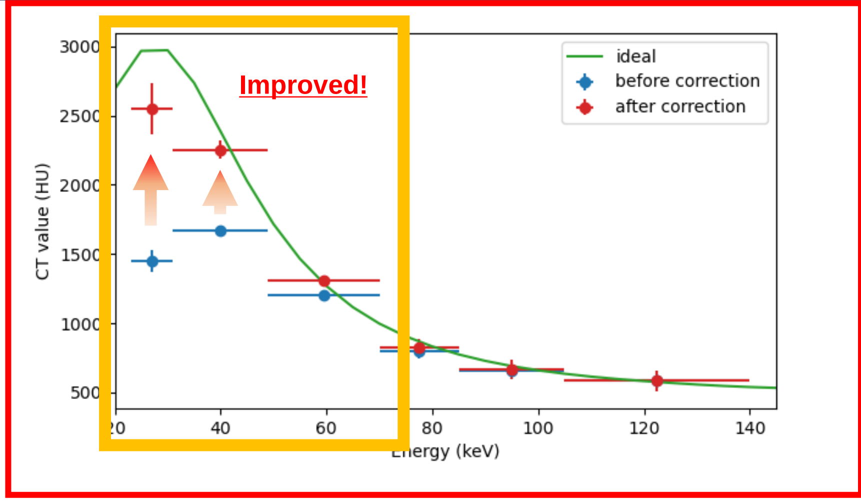


Improve the accuracy of CT values in low-energy bands
⇒ This method is effective

Correction result

The benefit of this correction method

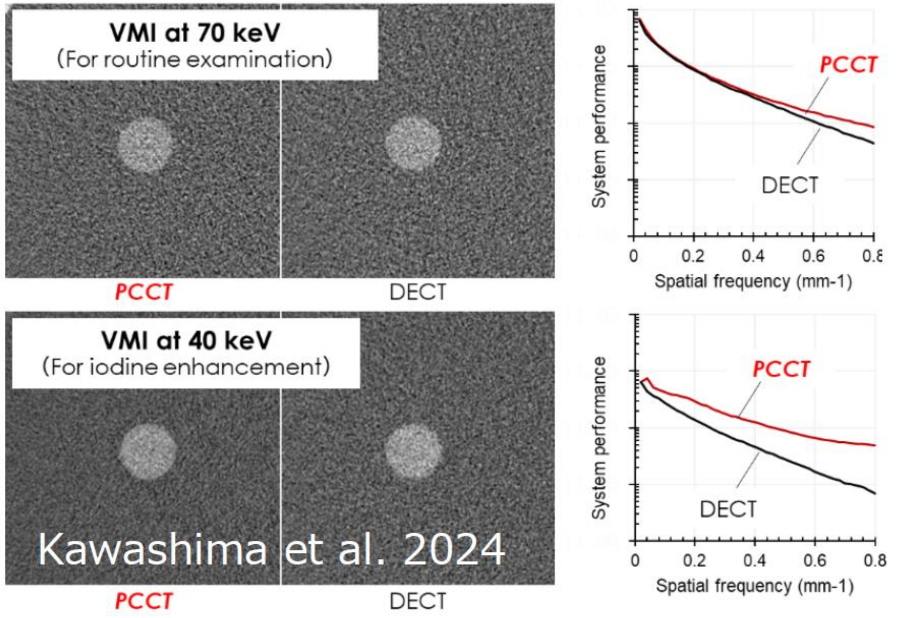
✓ It can be also applied for semiconductor detector only based on physics
(= independent of the type of PCD, phantoms)



✓ It can broaden usability of "accurate" energy information of PCCT

Some studies have suggested…
Low-energy images in PCCT has high performance

Contribute to clinical uses of low-energy information
(iodine contrast-enhancement examination etc.)



Conclusion & Future works

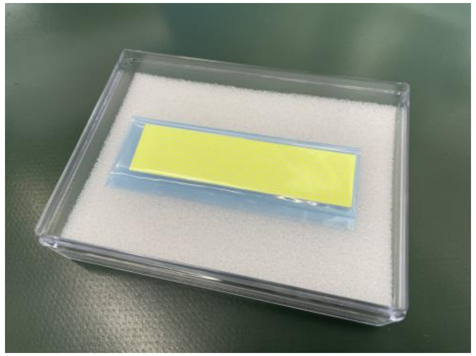
Conclusion

・Confirmed inaccuracy of low-energy PCCT data
・Improved image contrast & CT values applying our correction method
・Provide the possibility of medical applications of PCCT energy information with high accuracy

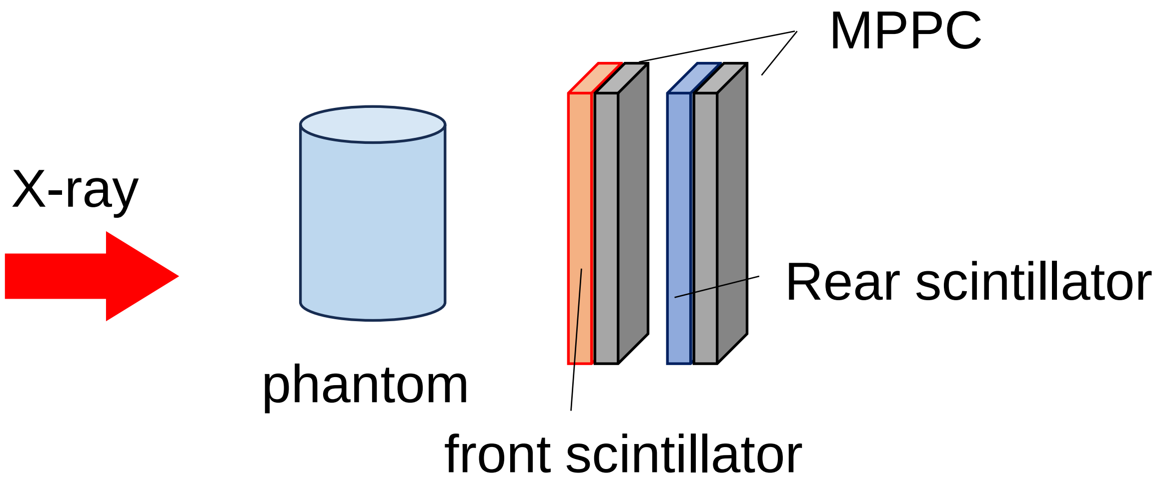
Future works

・Expand detector area (2D)

2D scintillator array



・dual layer PCCT system

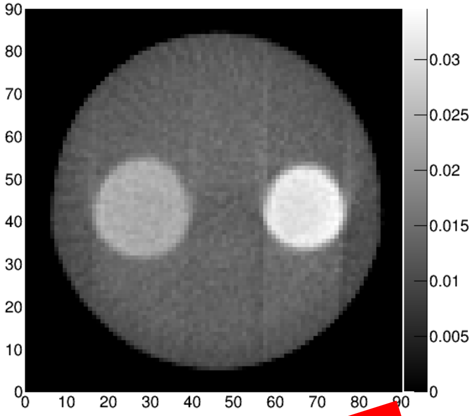


Appendix

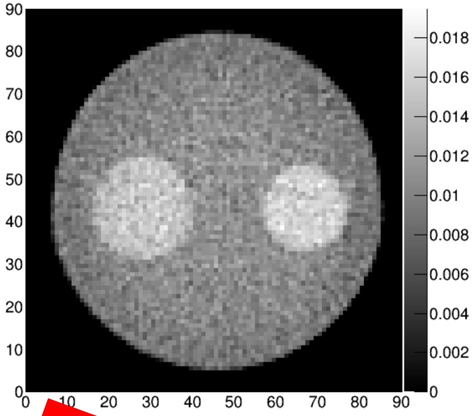
Appendix

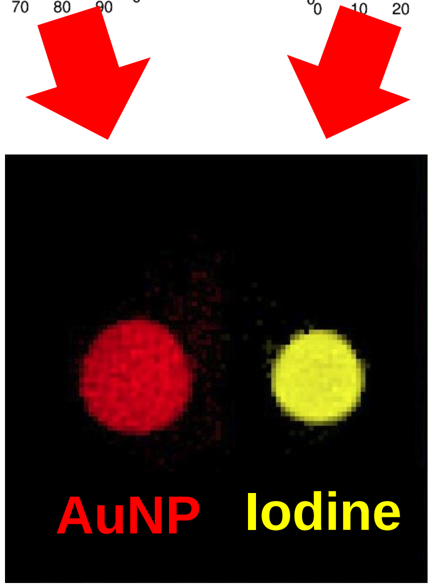
K-edge imaging

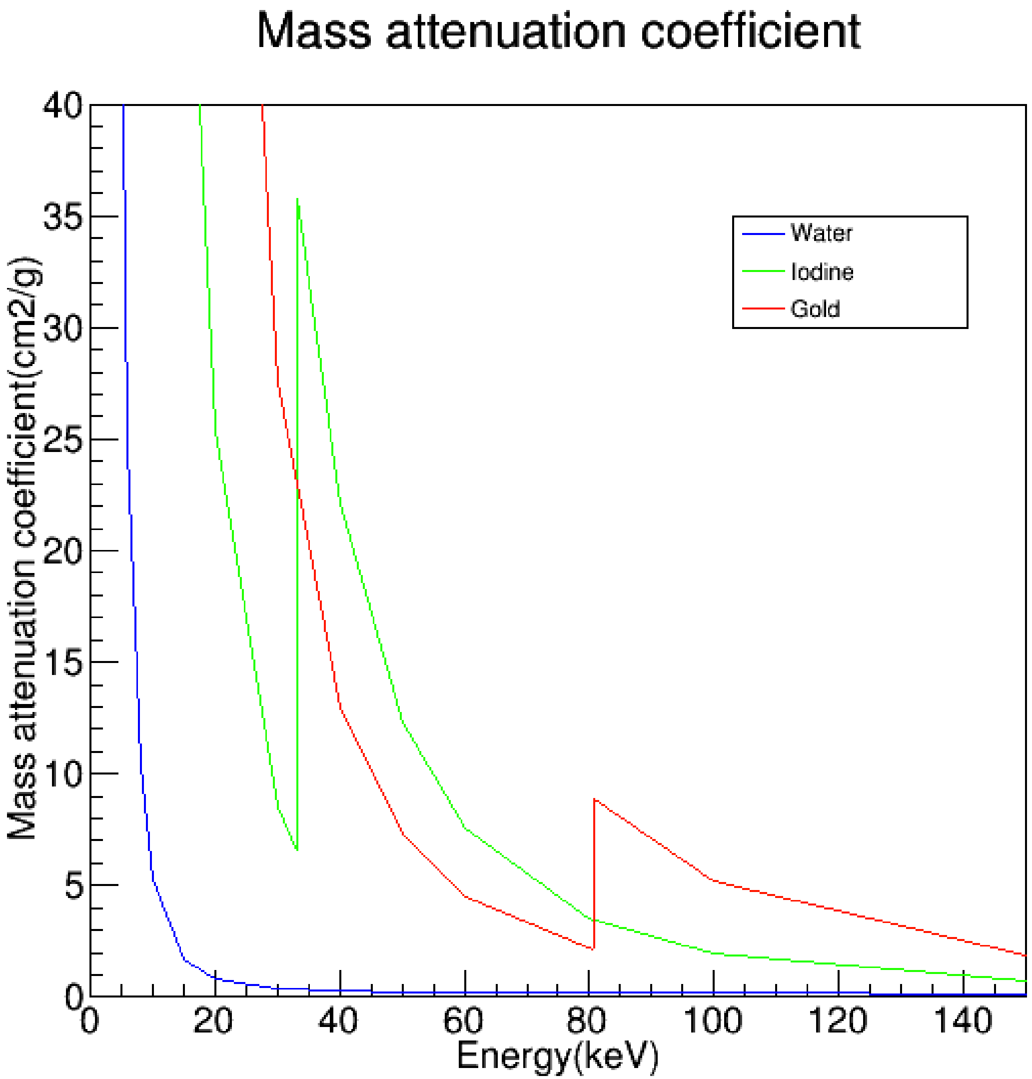
Low-energy image



High-energy image

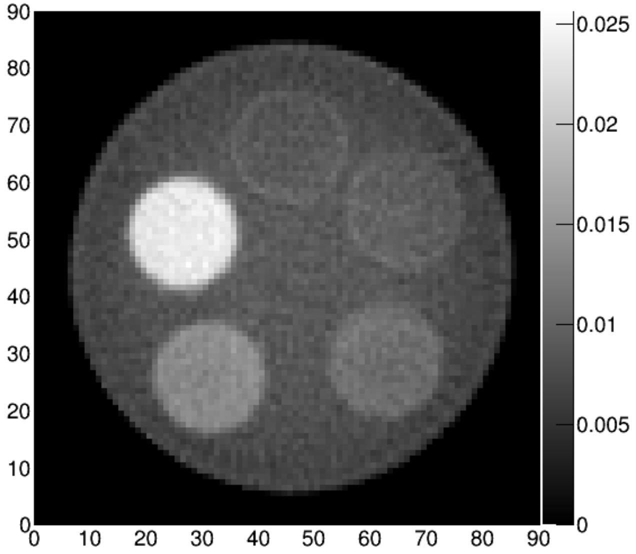


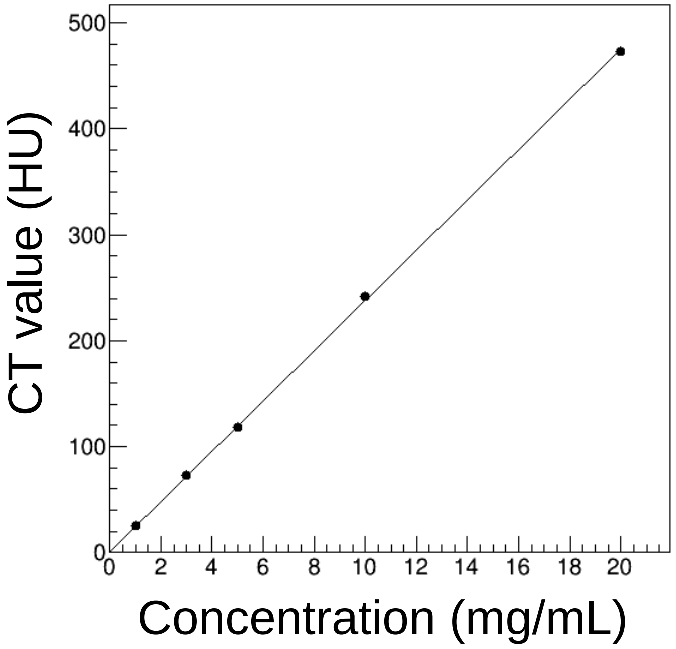




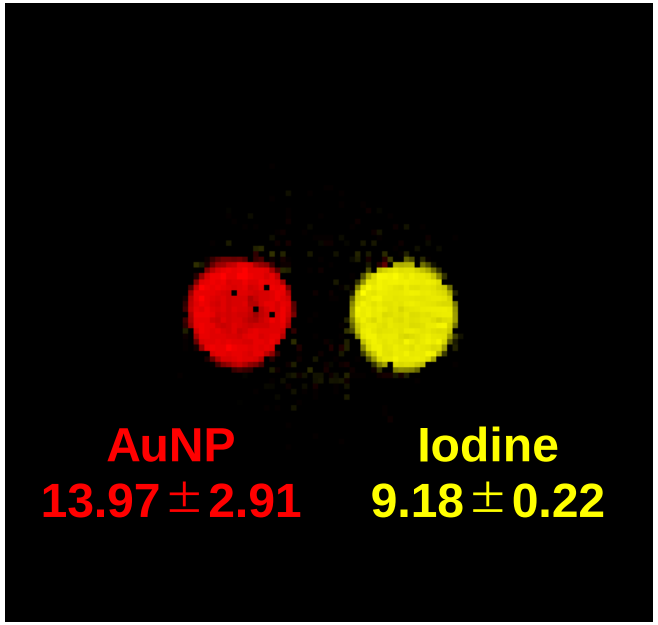
Concentration estimation

CT image
(various concentration)





(e.g.) Concentration map
Iodine 10mg/mL
AuNP 10mg/mL

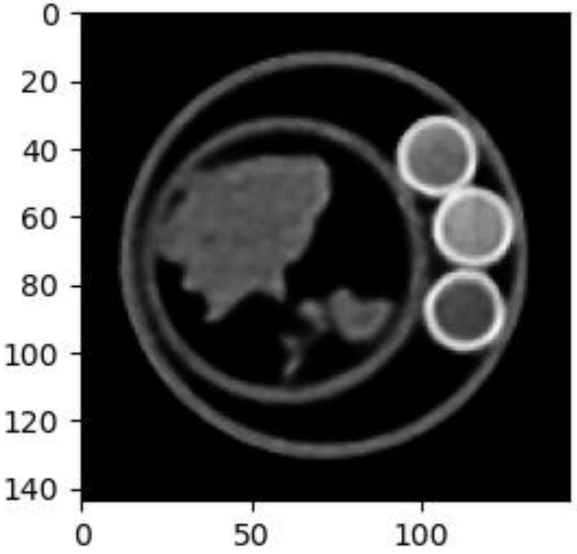


Appendix

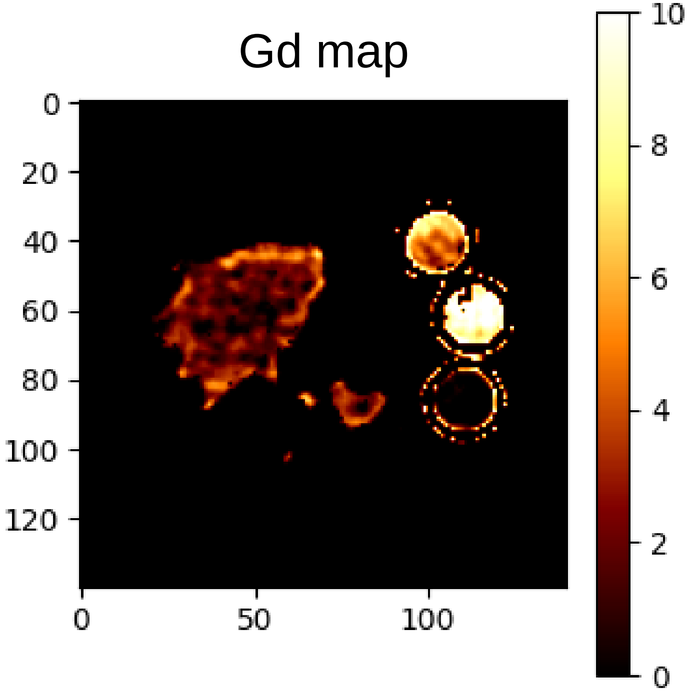
Ex-vivo imaging using our PCCT system

Liver and spleen of mouse (Gd agents injected)

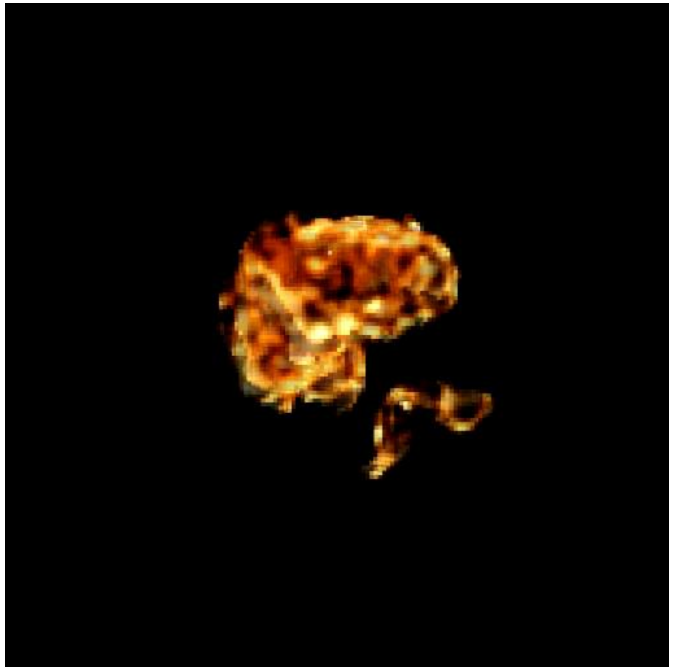
CT image



Gd map

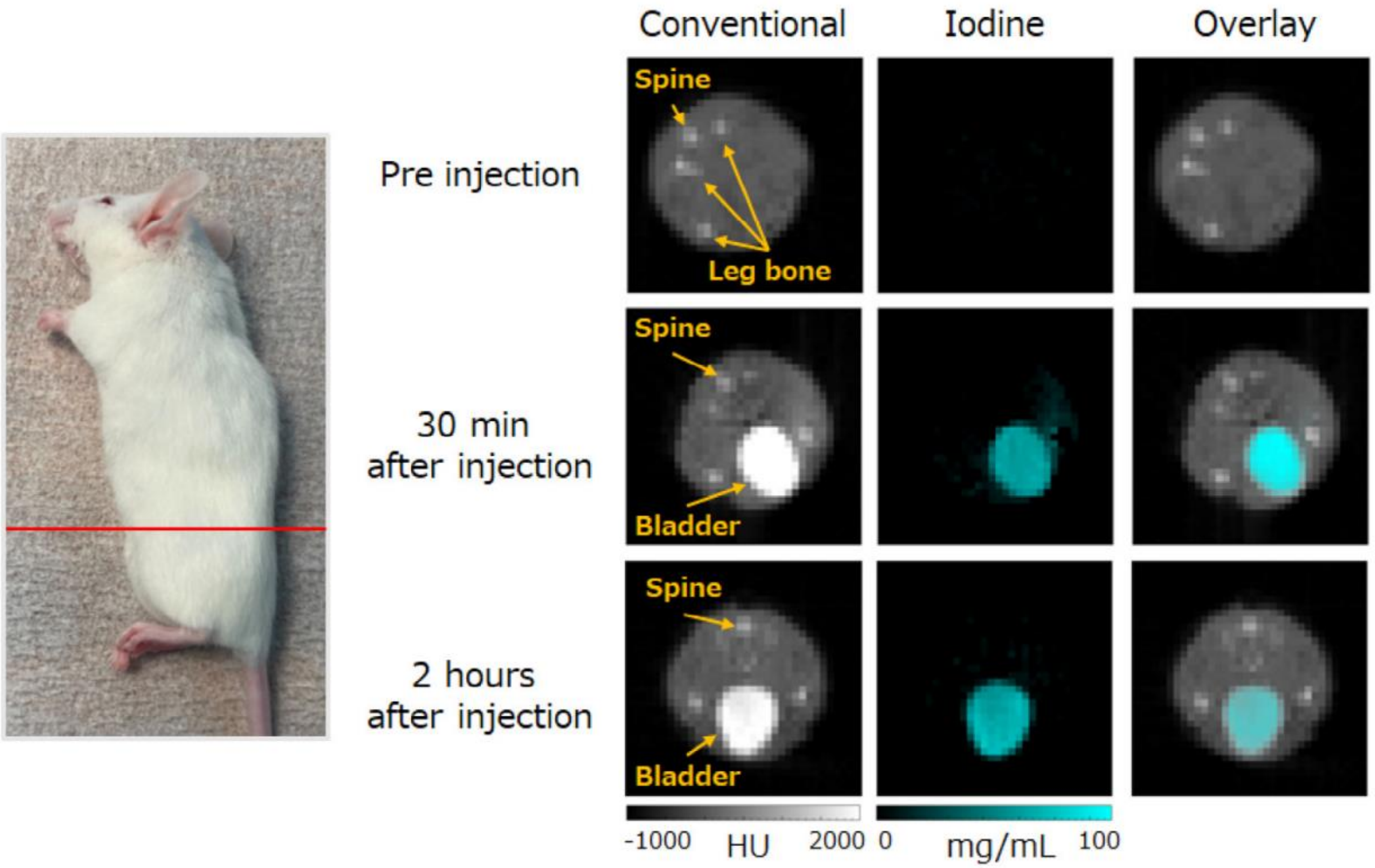


3D reconstruction



Bioimaging examples using our PCCT system

D.Sato et al. 2023



Confirmed Iodine accumulation in bladder from in-vivo imaging using our system

Appendix

Previous study

PCCT : NAEOTOM Alpha
(Siemens Healthineers)
DECT : SOMATOM Force
(Siemens Healthineers)

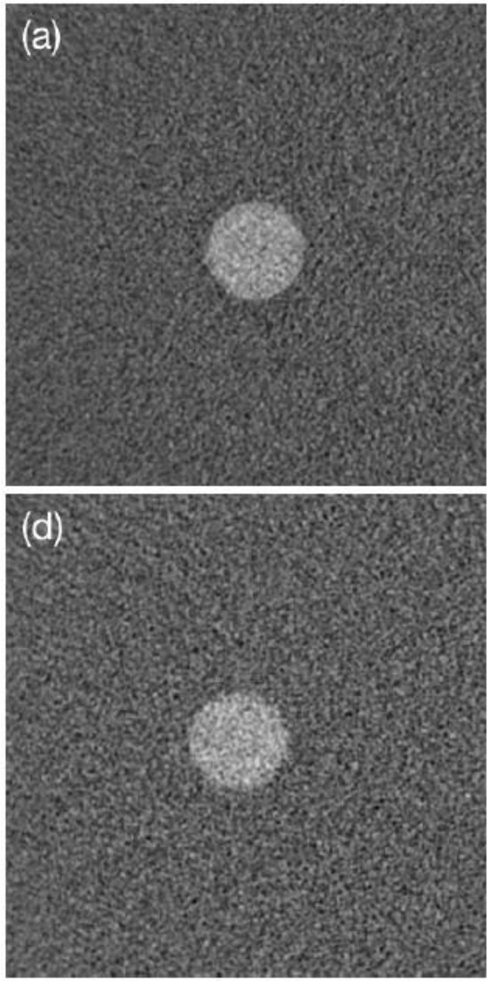
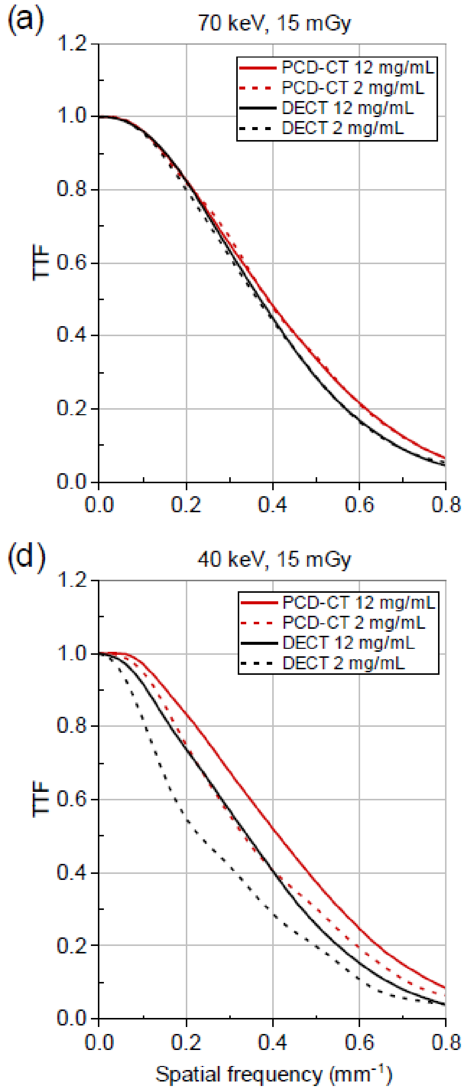


Image (a) : VMI 40keV for PCCT
Image (d) : VMI 40keV for DECT

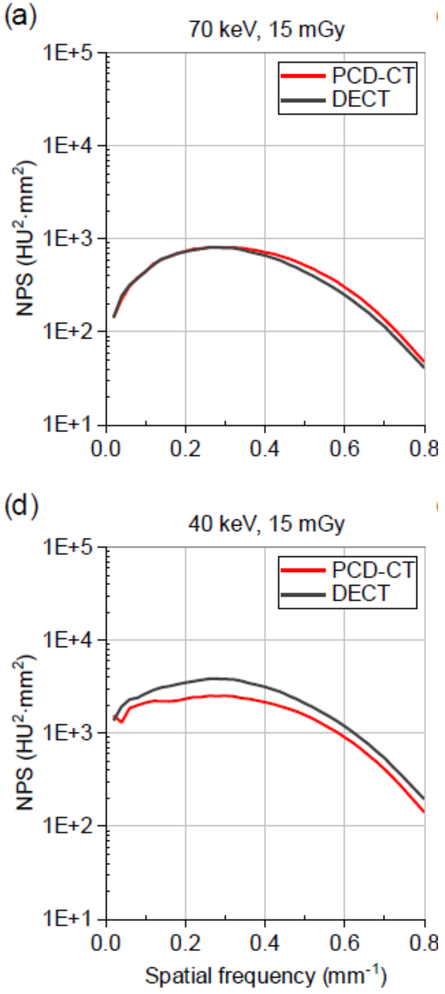
H. Kawashima et al. 2024

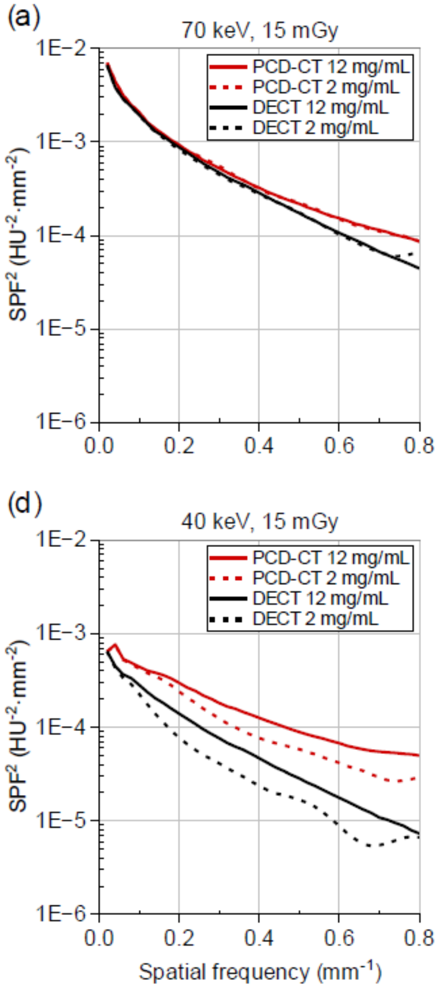


Appendix

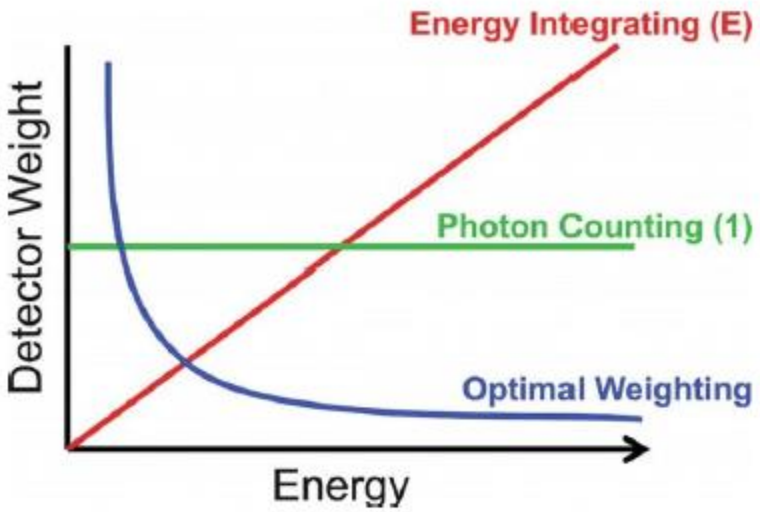
Previous study

H. Kawashima et al. 2024





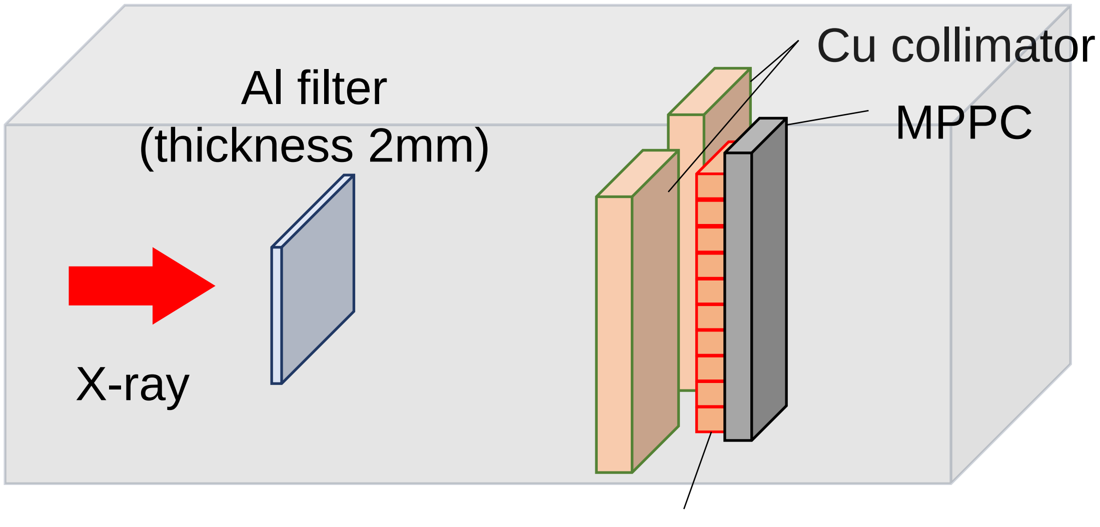
Energy weighting



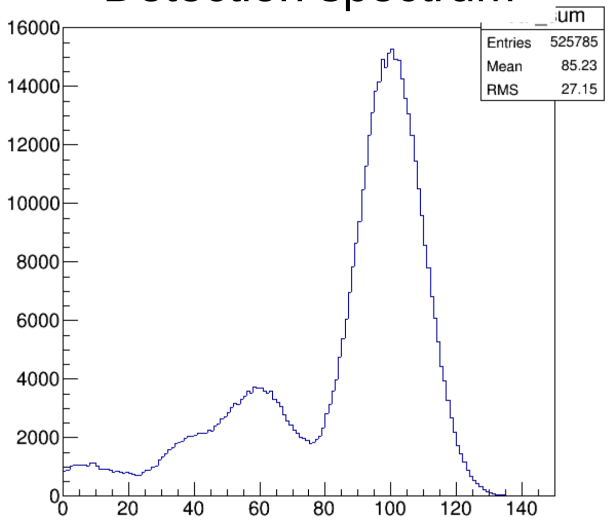
Appendix

Low-energy count

Inject 100 keV X-ray (monochromatic)

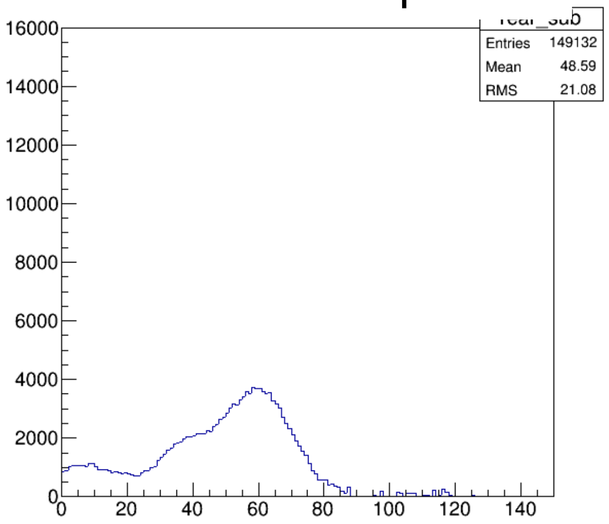


Detection spectrum



Subtract “real peak”
(already known injection energy,
energy resolution)

Inaccurate component



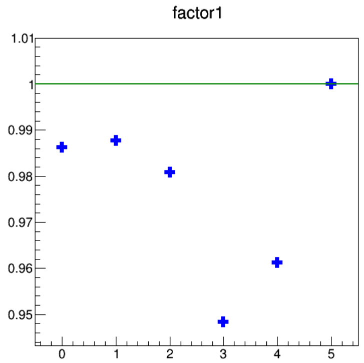
Appendix

Count table format (image)

Inaccurate count (Vth0 – Vth5)

Injection energy (true)

	Total count	Vth0	Vth1	Vth2	Vth3	Vth4	Vth5
Vth0	X(0)						
Vth1	X(1)	A(1, 0)					
Vth2	X(2)	A(2, 0)	A(2, 1)				
Vth3	X(3)	A(3, 0)	A(3, 1)	A(3, 2)			
Vth4	X(4)	A(4, 0)	A(4, 1)	A(4, 2)	A(4, 3)		
Vth5	X(5)	A(5, 0)	A(5, 1)	A(5, 2)	A(5, 3)	A(5, 4)	



Corrected count (cycle, Vth) = measured count (cycle) $\times$ A(cycle, Vth) / X (Vth)

Correction factor: A(cycle, Vth) / X (Vth)

(e.g.) 1st cycle correction

Corrected count (1, 0) = measured count (0) $\times$ A (5, 0) / X (5)

Corrected count (1, 1) = measured count (1) $\times$ A (5, 1) / X (5) …

Appendix

-

Detector specification

	Decay time (ns)	Luminescence (photon/MeV)	Density (g/cm^3)	Effective atomic number
GOS	3000	50000	7.34	32.0
YGAG	70	36000	5.38	25.8
GAGG	100	56000	6.70	21.8
LYSO	40	30000	7.10	27.4

Appendix

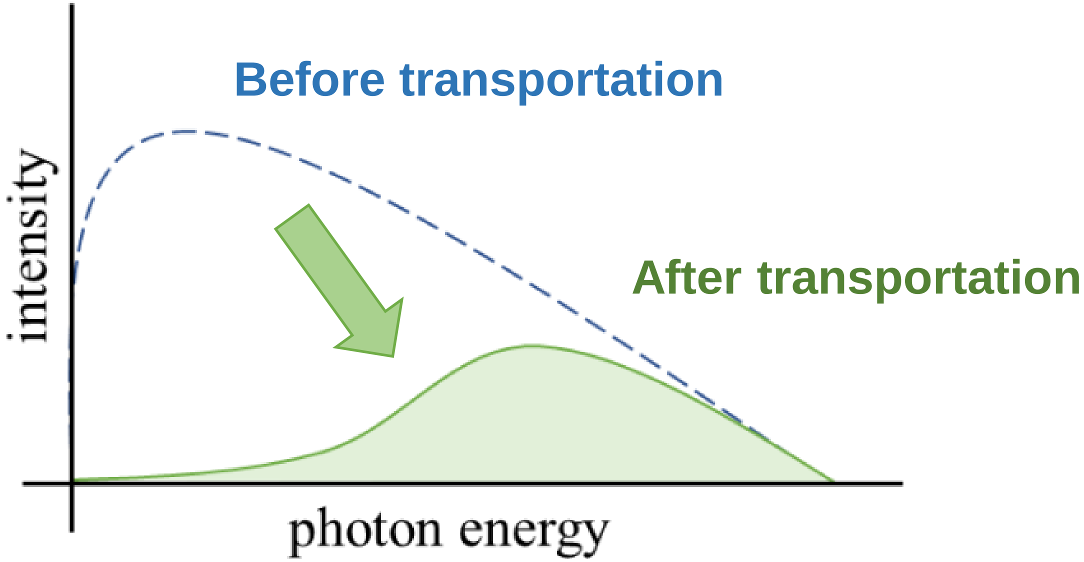
Detector specification

	$\mu\tau$ (electron) (cm^2/V)	$\mu\tau$ (hole) (cm^2/V)	Density (g/cm^3)	Effective atomic number
CdTe	3.3×10^{-3}	2×10^{-4}	5.85	50.0
CdZnTe	3×10^{-3}	5×10^{-4}	5.80	43.3

detector	Energy resolution
CdTe	3% @662keV
CdZnTe	7% @140keV
GOS	10% @662keV
YGAG	40% @60keV
GAGG	8% @662keV
LYSO	11% @662keV

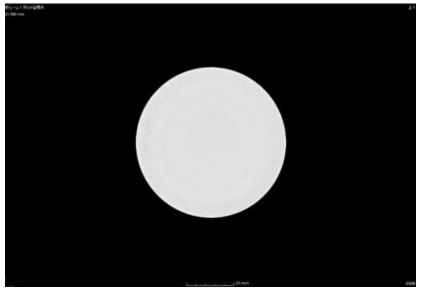
Appendix

Beam hardening effect

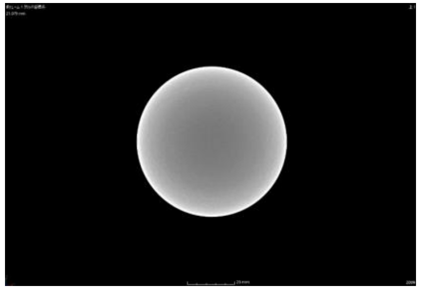


Low-energy X-ray tend to be attenuated well (not so penetrate)

Effective energy of X-ray spectrum increase after transportation



BH weak

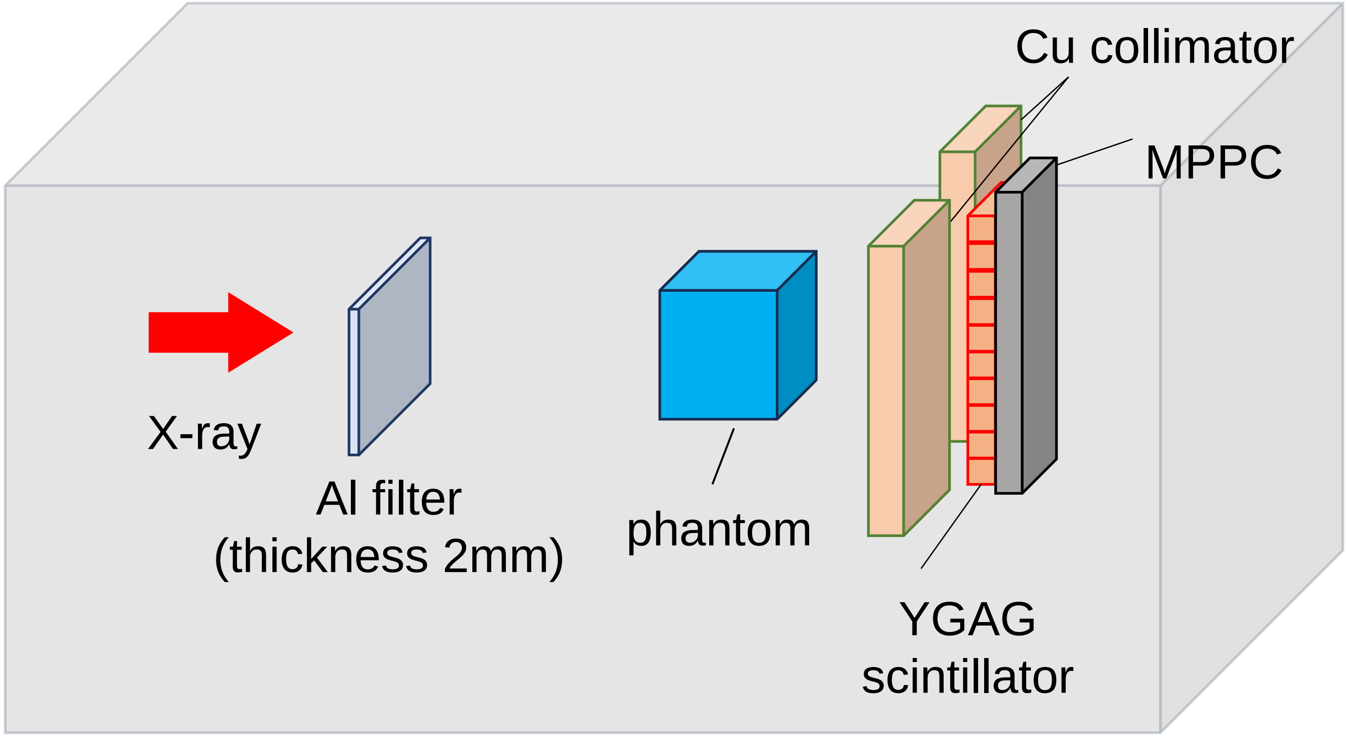


BH strong

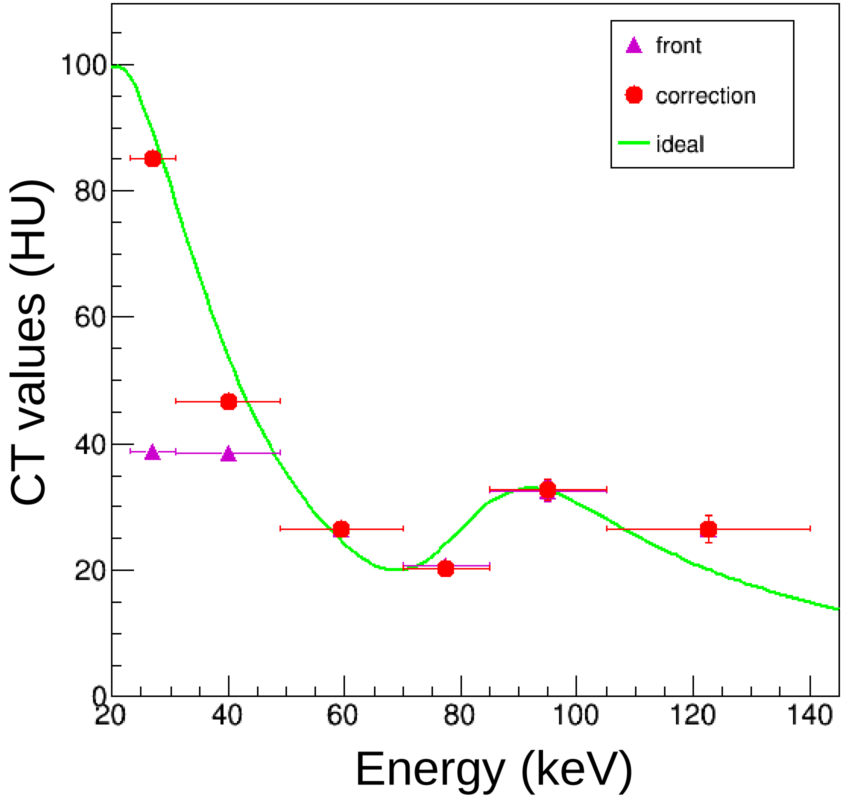
On CT images, artifact, inaccuracy of CT values

Appendix

Simulation study



AuNP 1mg/mL

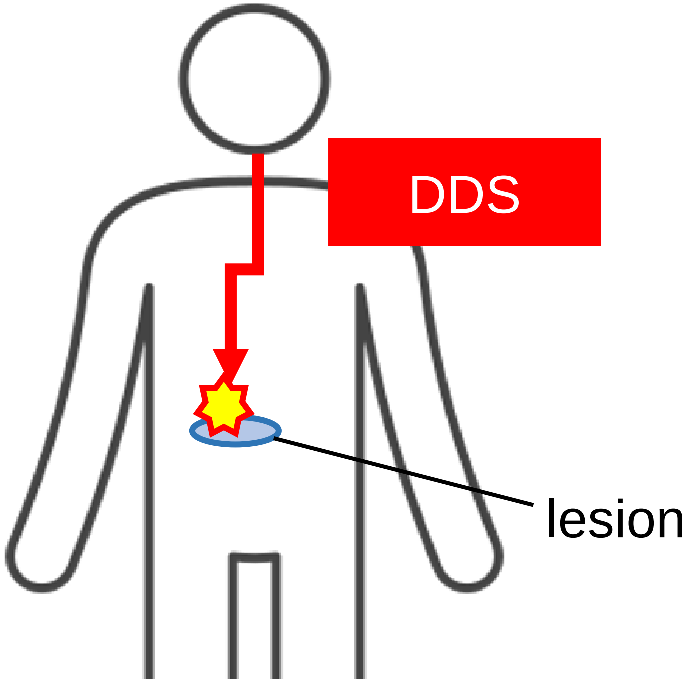


Incident X-ray follows $\propto E^{-1}$
(cf. Endo et al. (1997))

Also confirmed the effectiveness in simulation

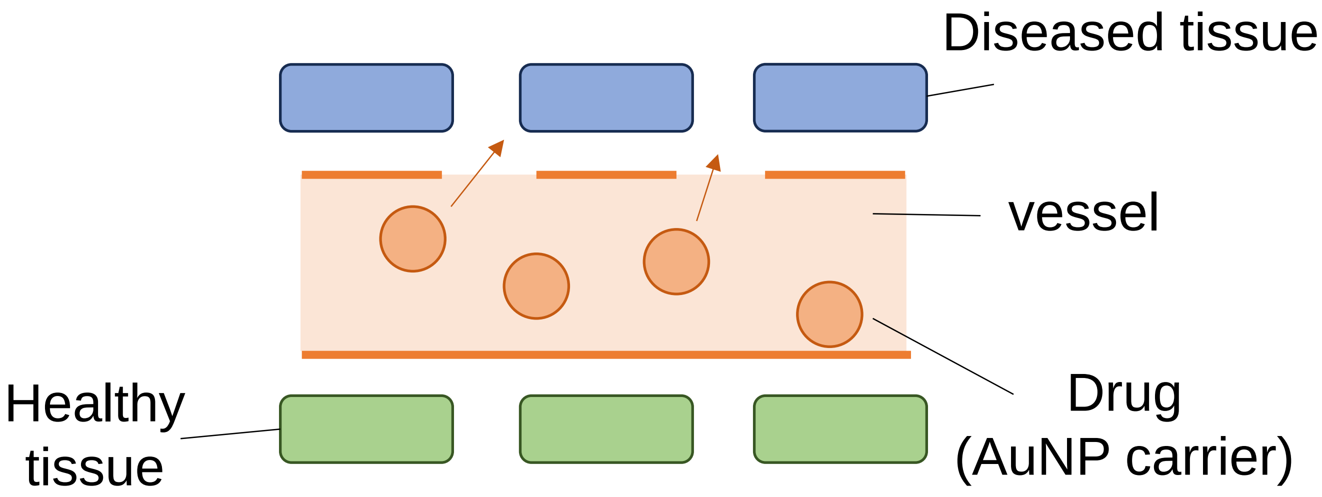
Drug Delivery System (DDS)

therapeutic approach that selectively delivers drugs to the diseased tissue or area in the body for targeted action



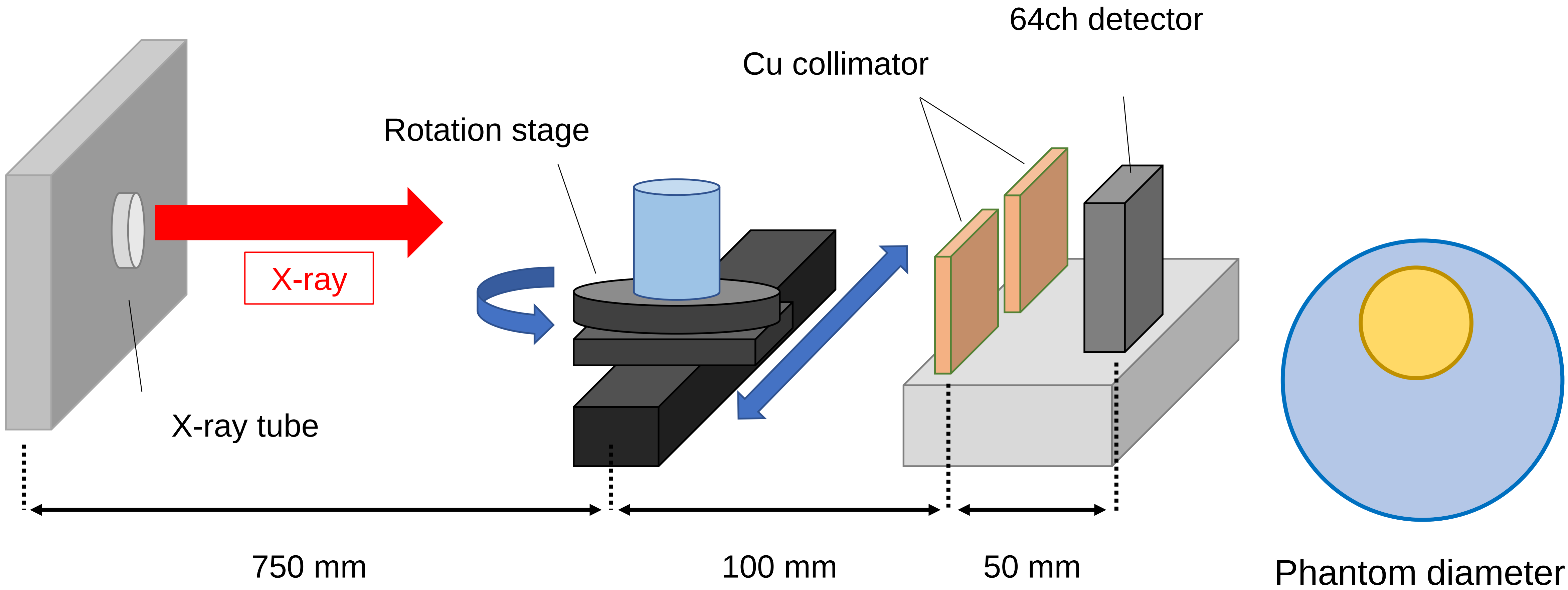
Gold nanoparticle (AuNP)
as one of the carriers

EPR effect



Appendix

Experimental setup (in detail)



Phantom diameter
Water : 90 mm
Target : 28 mm

Appendix

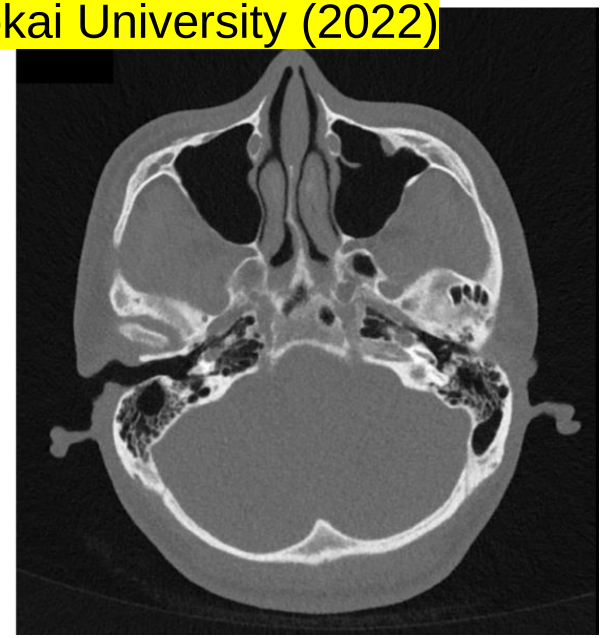
Radiation dose

Compared to conventional CT…
Total radiation dose ⇒ 1/10 ~ 1/15

(e.g.) sinus CT scan

Article from Tokai University (2022)

PCCT→



↓ Conventional CT

Table 1 Dose results of CT protocols used in this national survey on CT radiation doses

Protocol name	Clinical indication	Relative frequency (%)	Median scan range (mm)	Median (P75) DLP (mGy cm)	Median (P75) E_{103} (mSv)	Ratio max/min E
Brain	Haemorrhage	23.8	155	813.7 (935.6)	1.5 (1.8)	3.3
Sinus	Sinusitis	9.0	116	105.7 (133.4)	0.2 (0.3)	4.9
Neck	Standard	2.3	252	329.9 (404.3)	1.7 (2.1)	2.2
Neck-thorax-abdomen	Standard	0.7	880	985.1 (1,117.6)	13.8 (15.6)	1.7
Thorax	Standard	6.6	313	320.0 (346.5)	4.6 (5.0)	2.8
Thorax-liver	Lung cancer	4.1	401	542.0 (608.1)	8.1 (9.1)	2.7

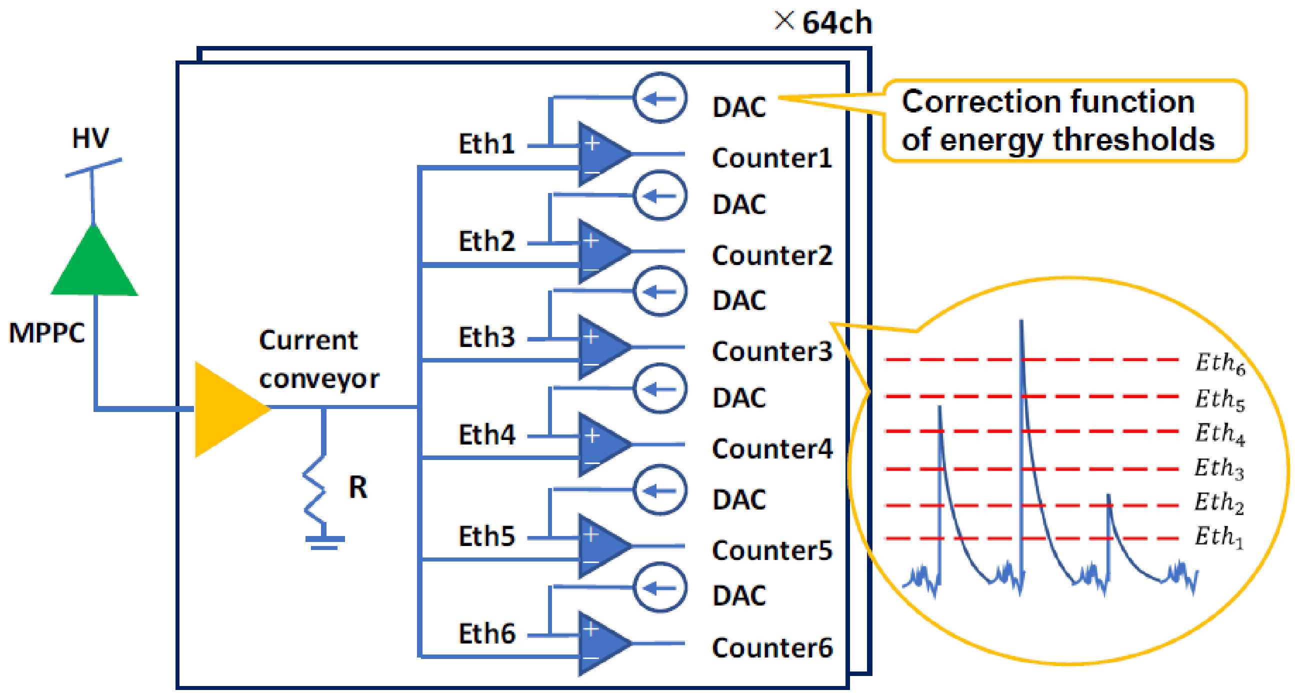
A.J. van der Molen et al. 2013

Appendix

LSI specification

M.Arimoto et al. (2023)

parameters	
channel	64 ch
Operation voltage	±1.65 V
Power consumption	~230 mW
Dynamic range	0 - 0.8 V
Non-linearity	~1.3 %
Rate tolerance	~a few MHz/ch

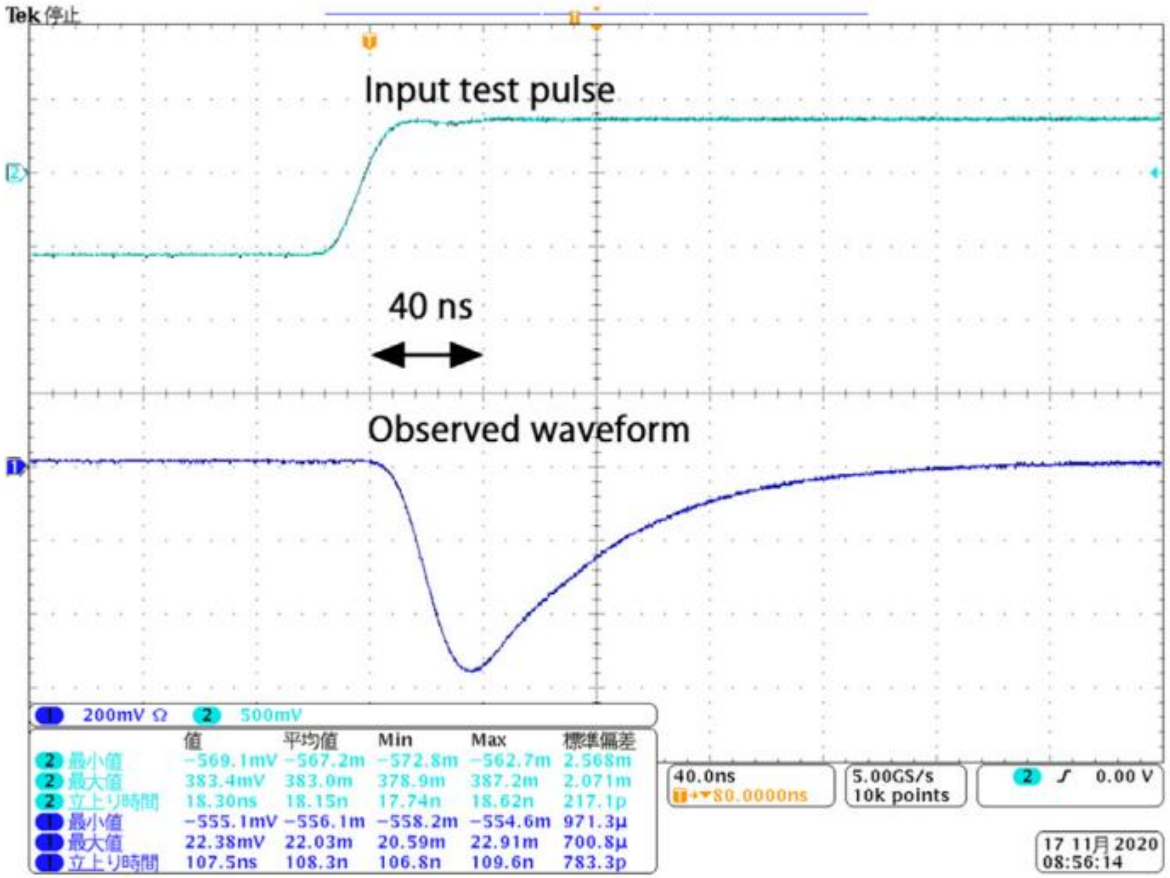


Appendix

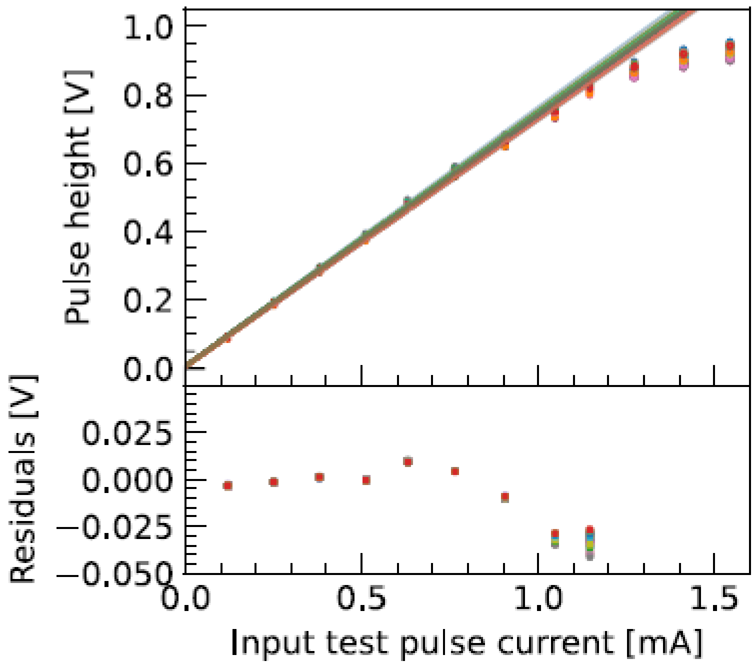
DAQ performance

M.Arimoto et al. (2023)

- Observed output waveform



- Signal linearity performance (test pulse)

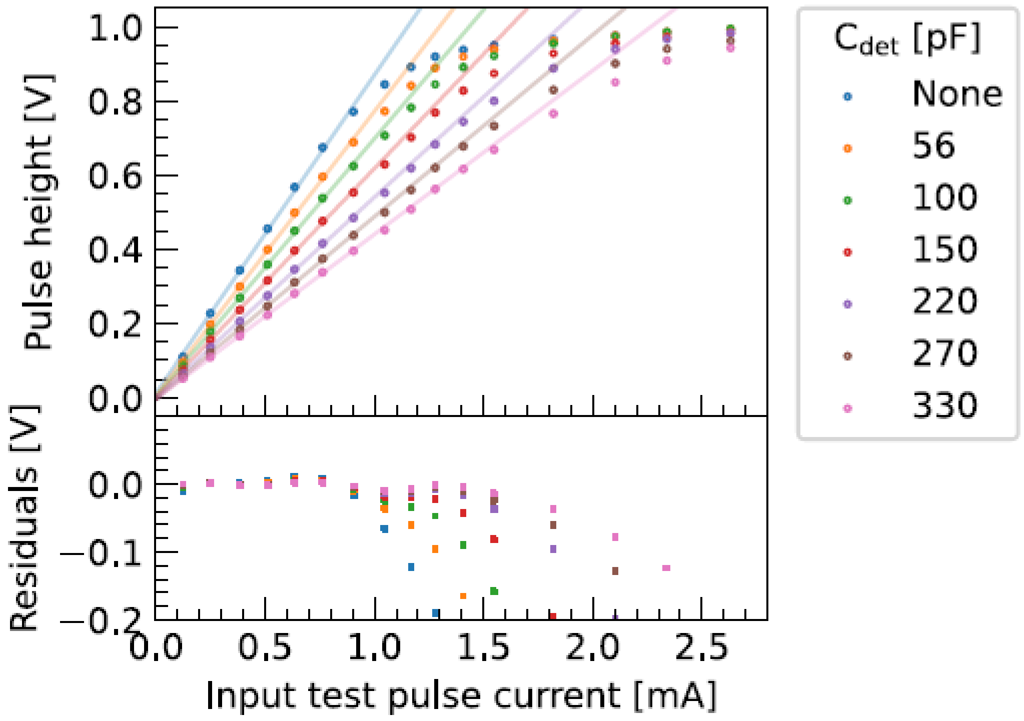


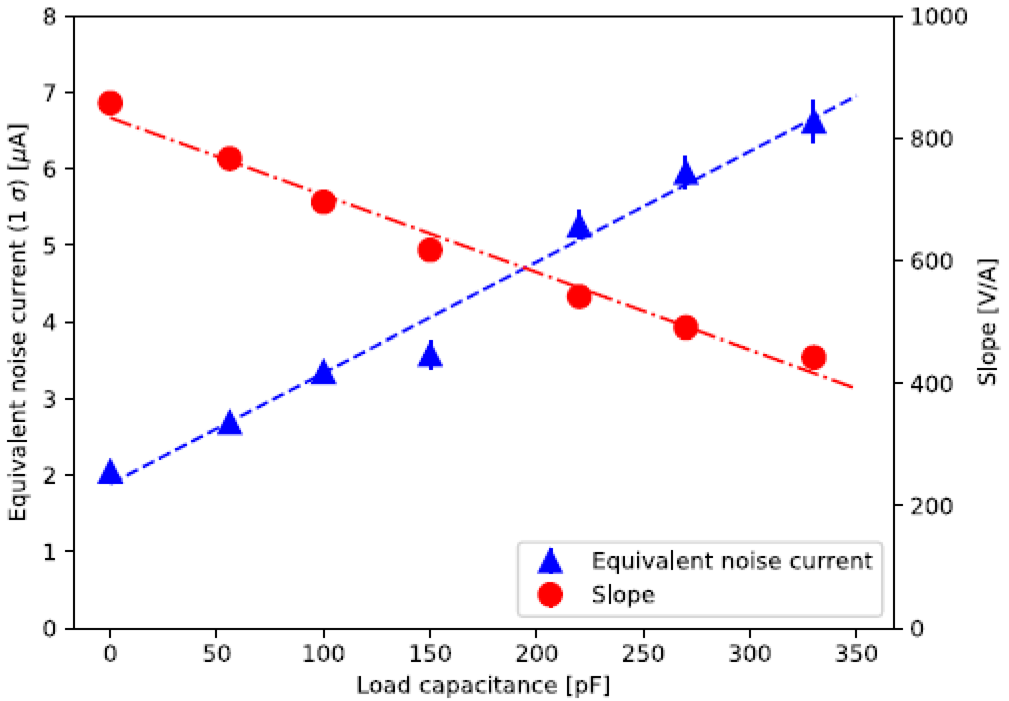
Appendix

DAQ performance

M.Arimoto et al. (2023)

- ☐ Measured linearity performance (change load capacitance)



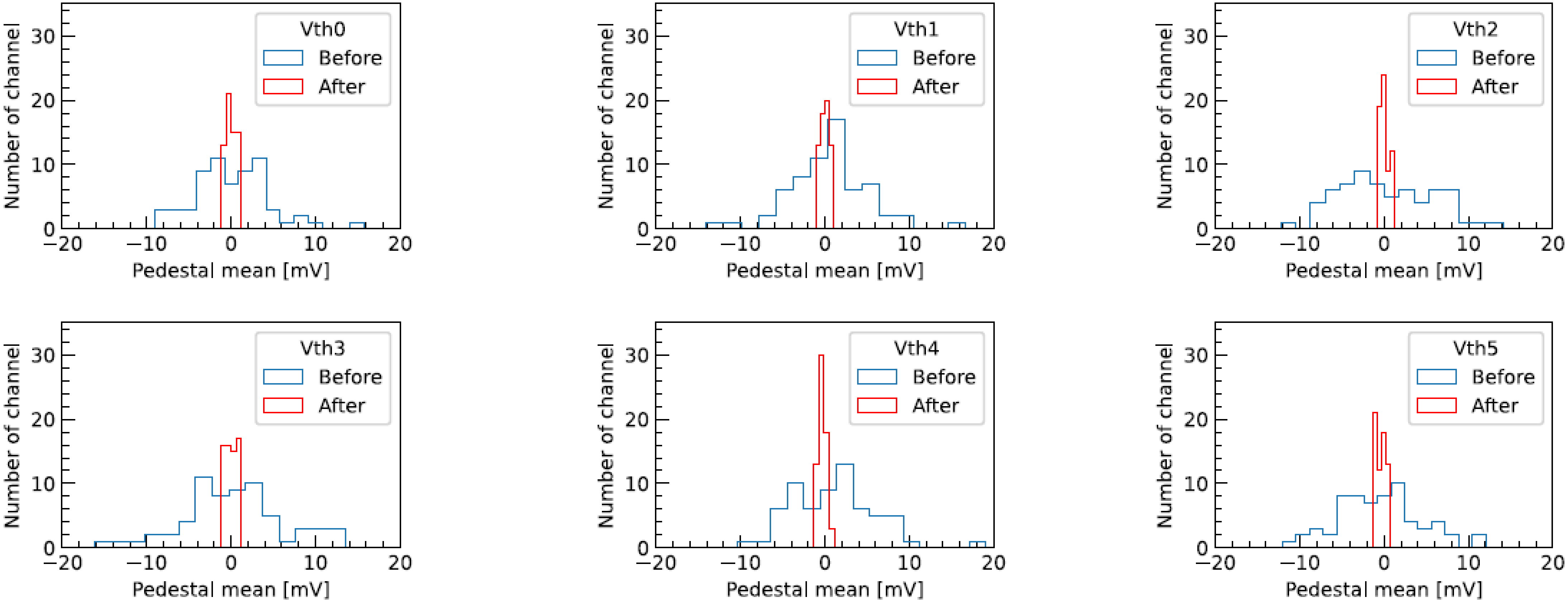


Appendix

DAQ performance

M.Arimoto et al. (2023)

- ☐ Pedestal distribution



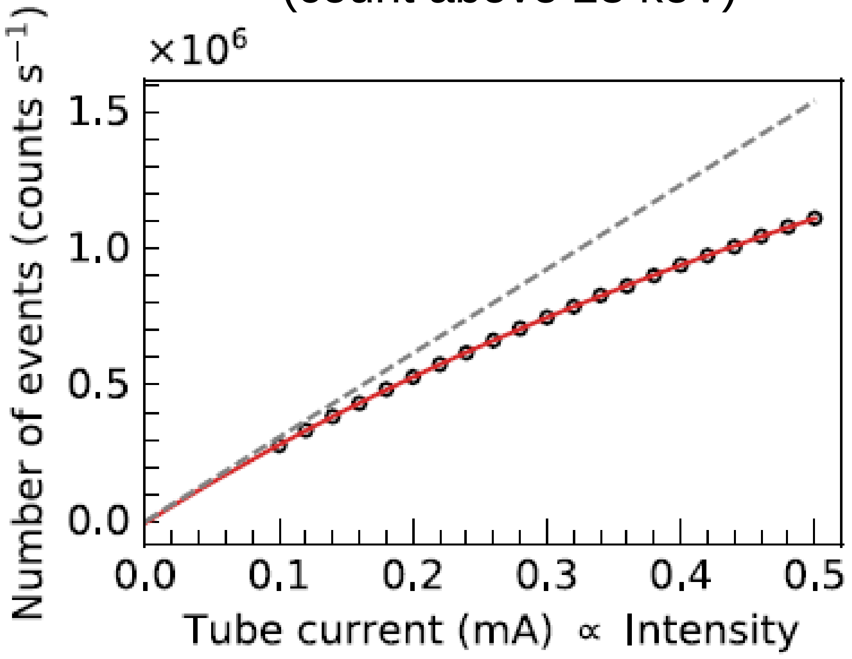
-

System performance

M.Arimoto et al. (2023)

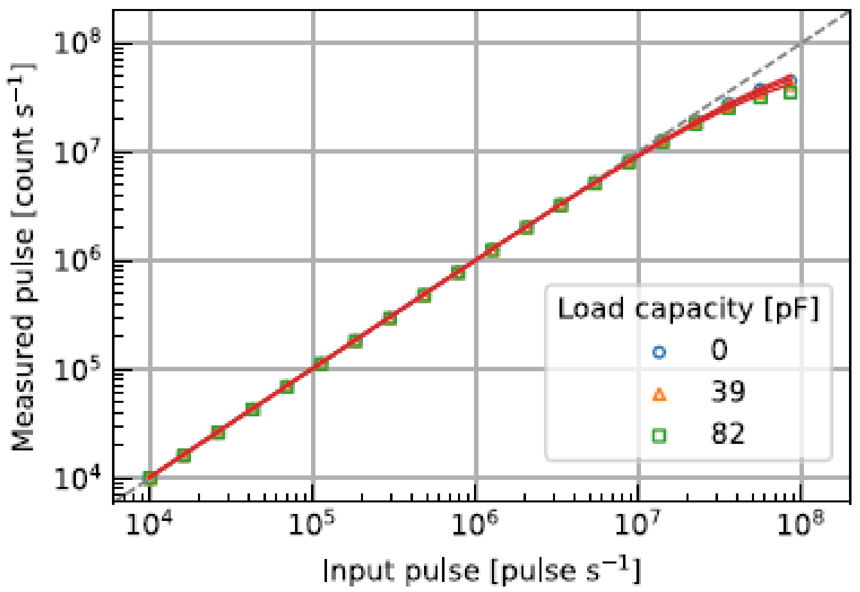
□ Count rate tolerance

Sensor + LSI
(count above 23 keV)



Dead time ~ 250 ns
⇒ ~ 4 MHz

Only LSI
(using high-speed function generator)



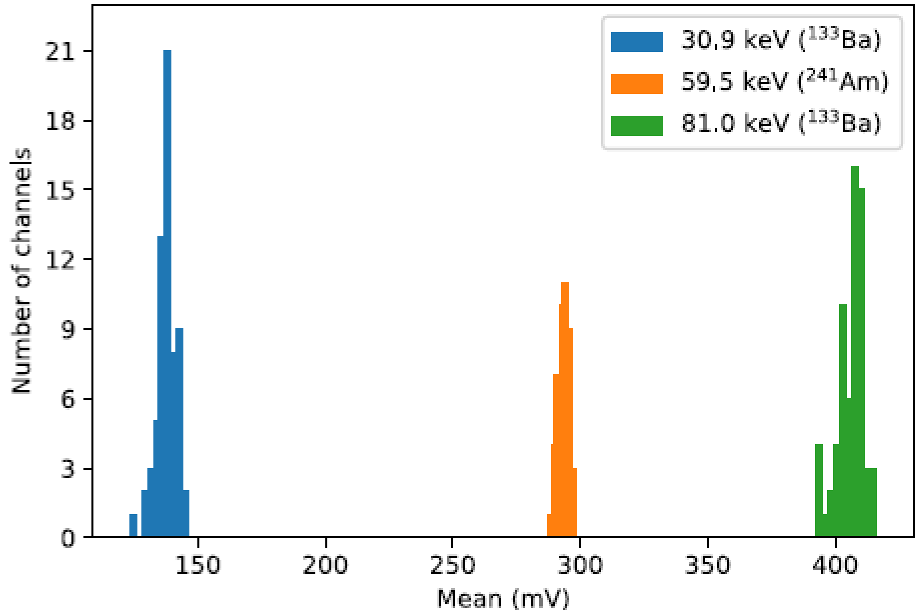
Dead time ~ 10 ns
⇒ ~ 100 MHz

Appendix

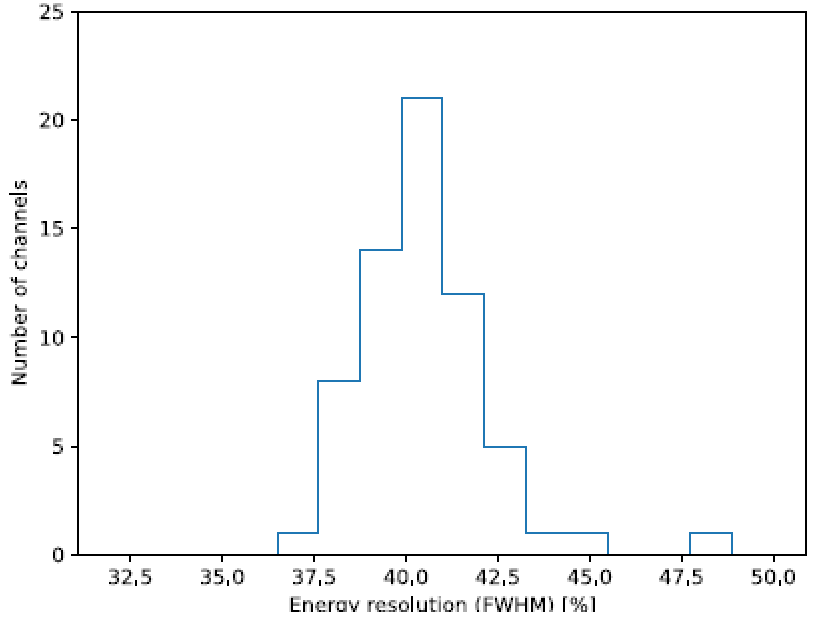
System performance

M.Arimoto et al. (2023)

- Photo peak distribution



- Energy resolution distribution

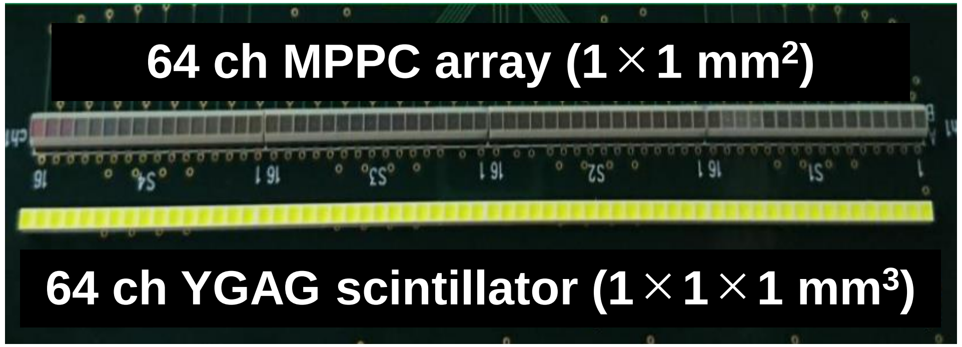


Energy resolution = 40.5 ± 1.5%

Appendix

MPPC specification

parameters	
Fill factor	83%
Window	Epoxy
Reflective index	1.59
Peak sensitivity wave length	460nm
Photo detection efficiency	32%
Dark current rate	120kcps
Crosstalk probability	<1%
Terminal capacitance	60pF



Introduction ~DECT~

Dual-energy CT (DECT)

Acquire two energy information

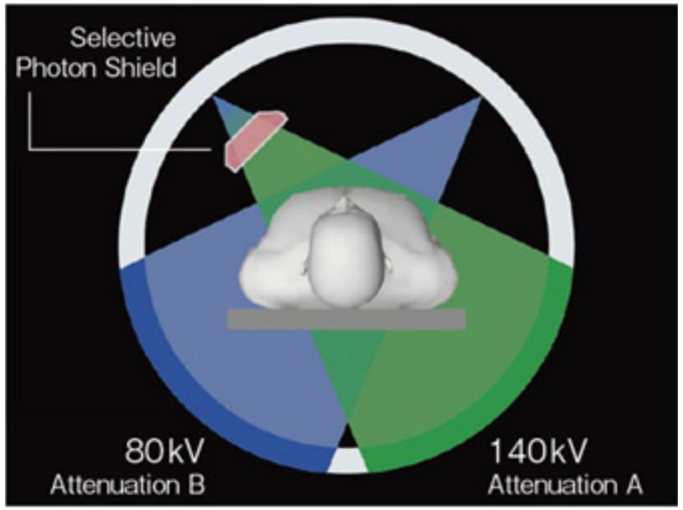
Type of DECT

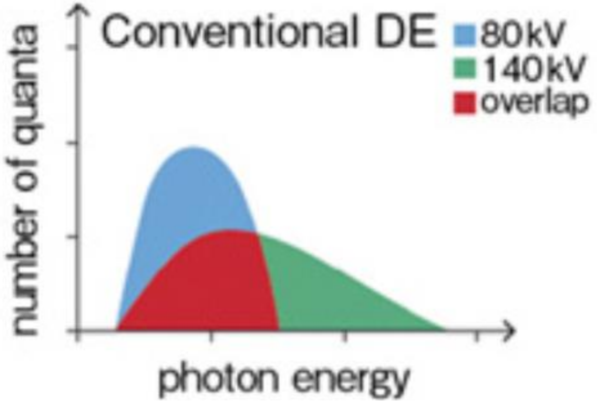
・dual source

・kV-switching

・dual layer etc.

From Siemens Japan





✓ Overlapping energy spectrum

✓ Only two CT values for material decomposition

Introduction ~PCCT~

Photon-counting detector (PCD)

✓ Semiconductor detector
mainly researched as PCD (CdTe, CZT)

(cf.) NAEOTOM Alpha (Siemens Healthineer) … CdTe

○ high energy resolution
△ Expensive
△ Need to make pixels very small (high rate of X-ray)

In PCCT…
Set many energy bands
⇒ insufficient photon counts in each band
⇒ statistical image noise (quality down)

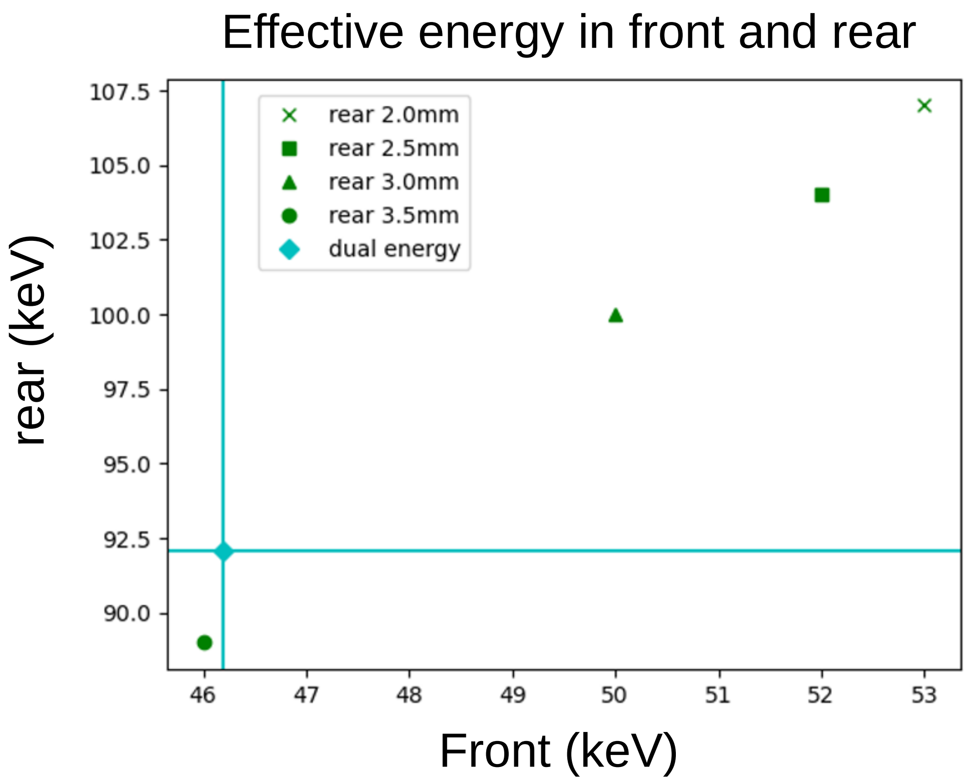
▶ Don’t need extreme high energy resolution ?

Our group : **develop scintillation-based PCCT**

Dual-layer PCCT system

① Optimize the thickness balance between front and rear (simulation)

Thickness condition : front + rear = 4.0mm

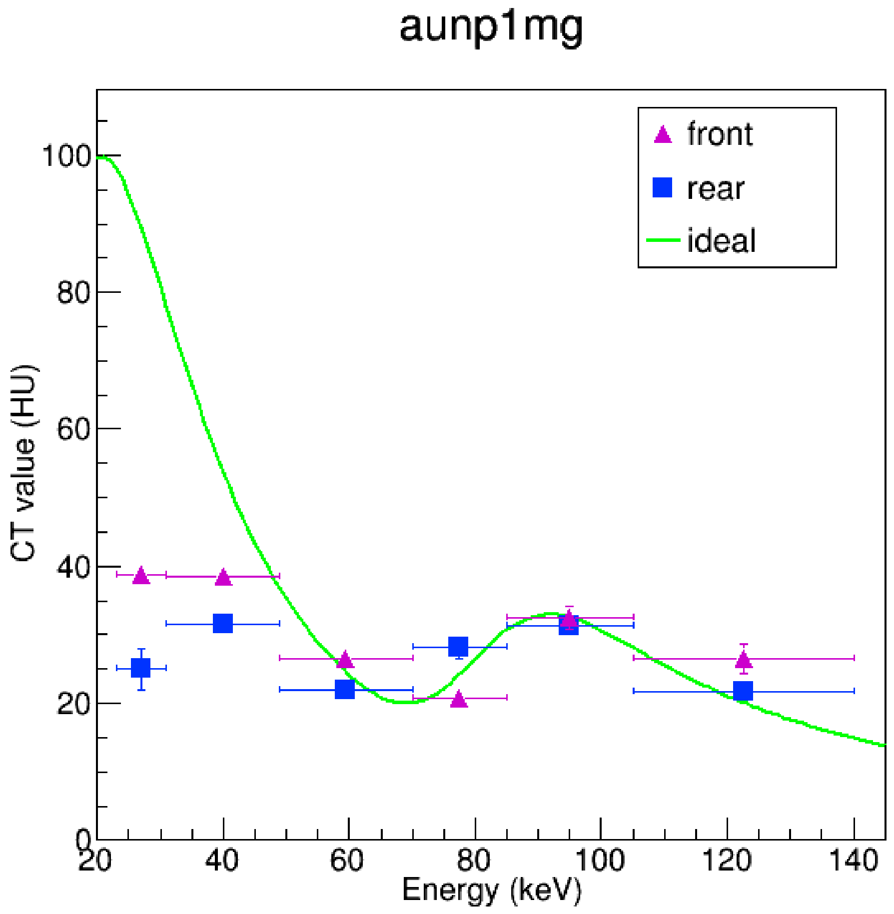


The nearest plot from "dual energy"
= front 0.5mm & rear 3.5mm
(best balance)

Appendix

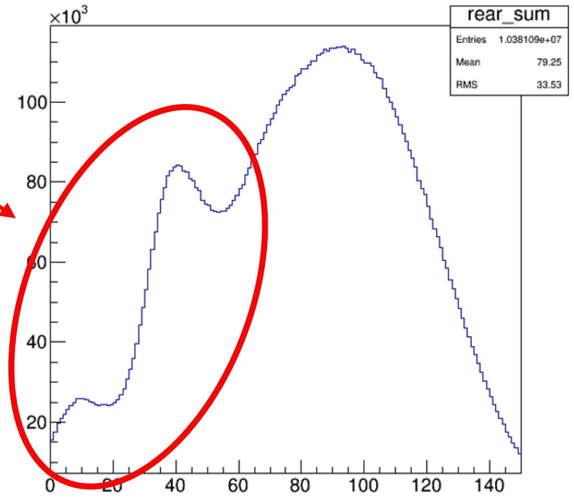
Dual-layer PCCT system

② Investigate the accuracy of CT values



The accuracy in high-energy acquired from rear is better than front

In rear spectrum, inaccurate component is contaminated in low-energy bands



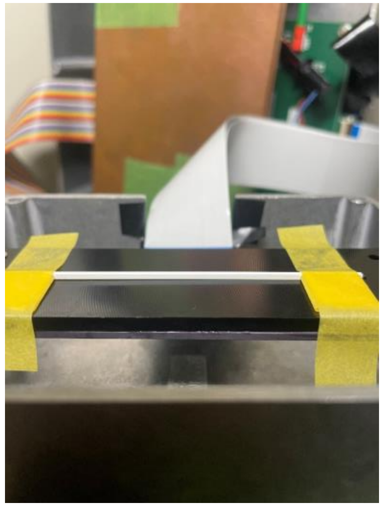
Appendix

Dual-layer PCCT system

Experimental setup

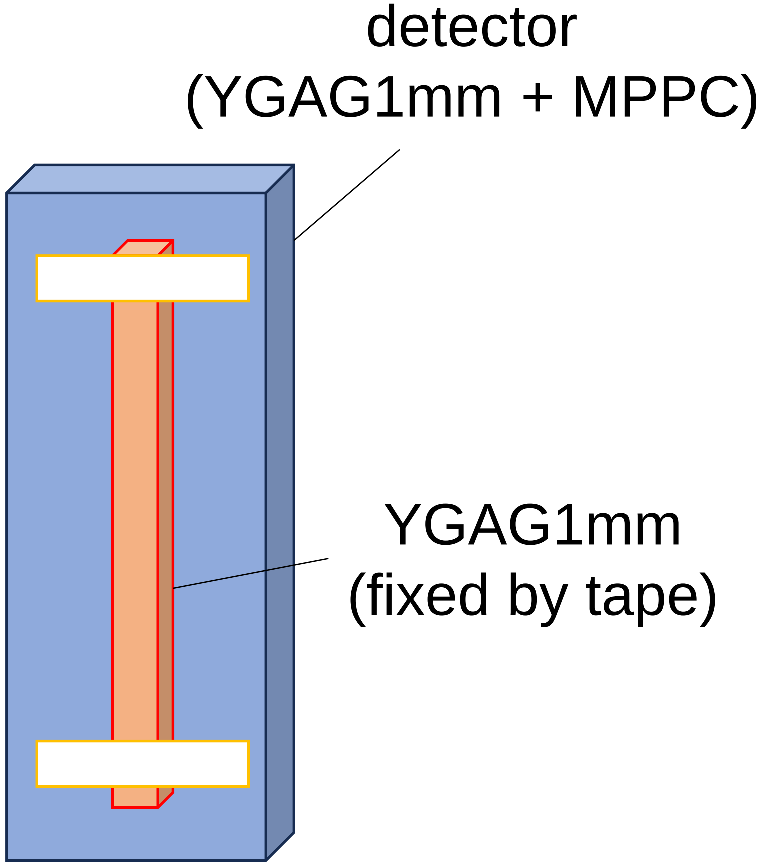
Front scan
(front view)

Rear scan
(front view)



Rear scan
(side view)

In the case of “Rear scan”

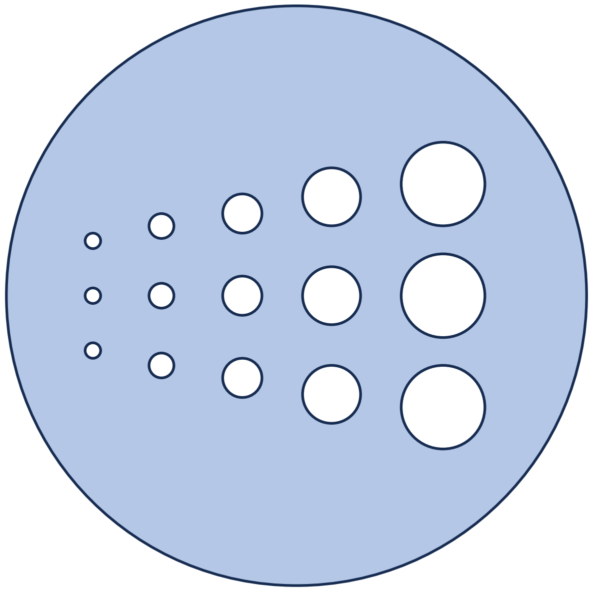


Appendix

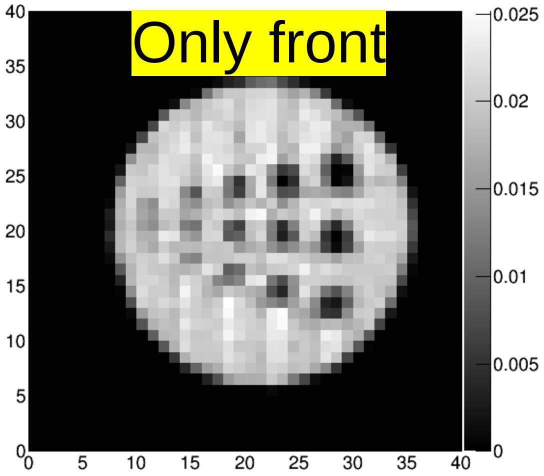
Dual-layer PCCT system

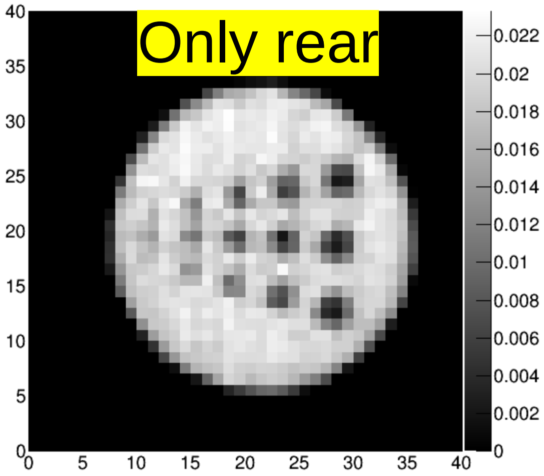
✓ Sub pixel shift CT scan

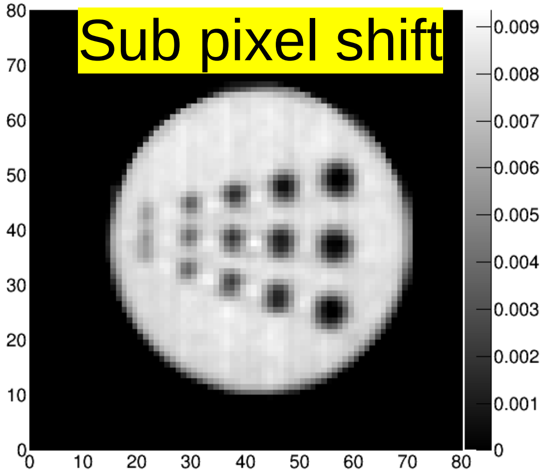
phantom



Hole size (diameter)
3.0, 2.5, 2.0, 1.5, 1.0 mm







Appendix