Road to Build
Radiation Detector and Imager

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Contents

Definition

Definitions

What is Radiation?

"Particle or wave transmitting in space."

Definitions

Particle or wave transmitting in space."

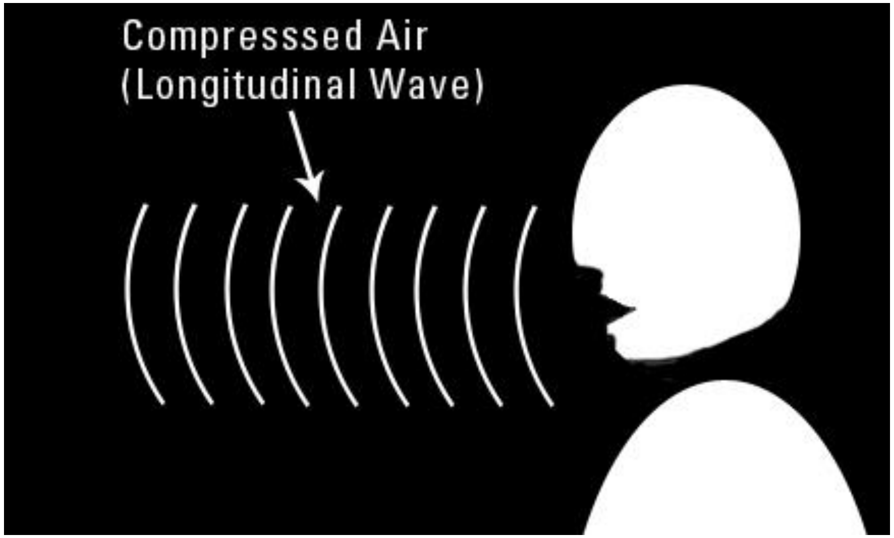
A stone is a particle....., But a Radiation ?

No! It should be subatomic.

Definitions

"Particle or wave transmitting in space."

Sound is a kind of waves….., But a Radiation ?



No! It cannot transmit in vacuum.

Definitions

"Subatomic particle or wave transmitting in space including vacuum."

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Definitions

What is Detection?

“Extraction of particular information from a larger stream of information without specific cooperation from or synchronization with the sender”

Then, What is Radiation Detection?

Definitions

What is Measurement?

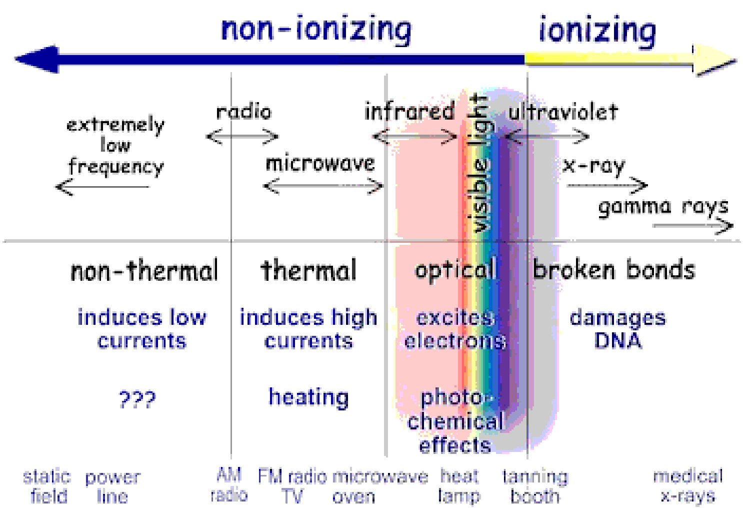
"Assignment of numbers to objects or events"

Then, What is Radiation Measurement?

How to Detect

Can you see radiation?

If not, how to see?



Make the Invisible Radiations to Visible

- Convert to electron and measure by electronics
- Convert to light and measure (or see) it
- Changed Chemical property (Color)
- Miscellaneous (Temperature, Damage, Fission)

How to Detect

1. Convert to electron and measure by electronics
   . Gas: ionization chamber, proportional and GM tube
   . Solid: Semiconductor, Scintillator (?)

2. Convert to light and measure (or see) it
   . Gas, Liquid, Solid: Scintillator, TLD

3. Measure change in chemical property (color)
   . Liquid: Fricke and cerium dosimeter
   . Solid: Glass dosimeter, X-ray film

4. Miscellaneous
   . Cerenkov*, Fission chamber, Damage, Superconductor

Measurement

1D

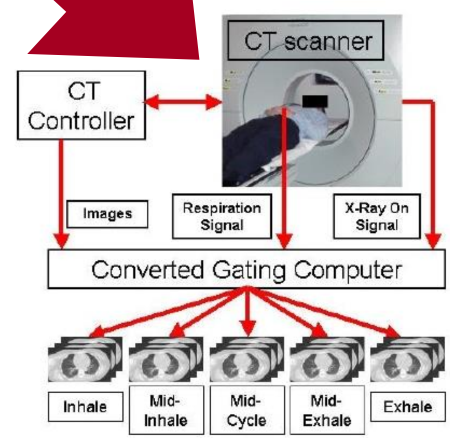
2D

0 dimension

(Detector, Statistics)

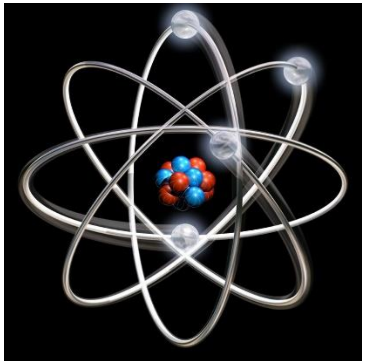
3D

4D



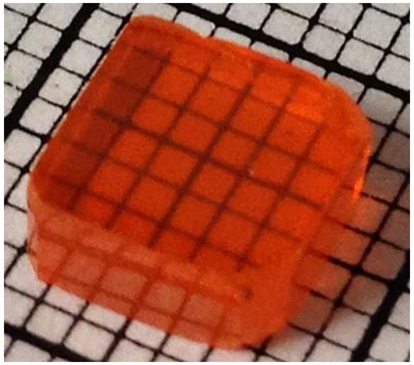
Important Factors to Build Radiation Devices

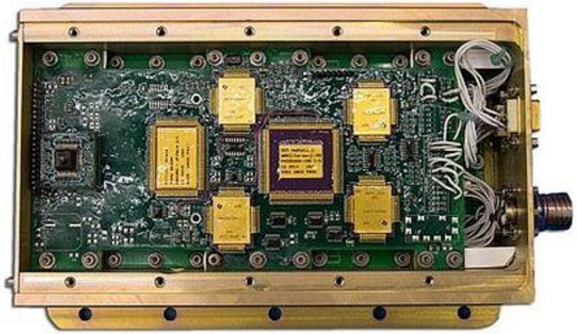
Important Factors to Build Radiation Devices



Physics

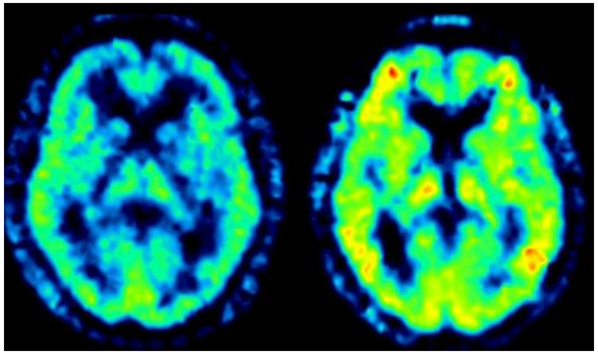
Material





Electronics

Software



Important Factors to Build Radiation Devices

Physics: Relatively Well known

Detector Material: Needs Time and Technique

Software: Commercially wide spread

Electronics: Commercial Devices but ASIC is unique skill

Important Factors to Build Radiation Devices

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Material

. Purity of Base Material (CdZnTe from Battery industry)
. Property of Tools such as glass tubes
. High performance of Devices -> Cost
. Time and Labor intensive (Find the Best conditions)
. Not only Idea but Technique (Sealing, Remove impurity)

Electronics

. Many Commercial Devices
. Many Custom-made-electronics applied for PMT, SiPM
. Only a few ASIC to process a number of small signals
Laborious and Limited Market (IDEAS, BNL, Kromek...)

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Researches for Radiation Devices in KOREA

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Discovery of Tl based scintillators

KNU group started a pioneer work in 2009 on Tl-based high-Z compounds and published $Tl_2LiGdCl_6:Ce^{3+}$ paper as a first Tl-based scintillator in 2015 and presented $Tl_2LiYCl_6:Ce^{3+}$ SCINT2015.

$Tl_2LiLnX_6:Ce$

- $Tl_2LiGdCl_6:Ce^{3+}$ [1]
- $Tl_2LiGdBr_6:Ce^{3+}$ [2]
- $Tl_2LiYCl_6:Ce^{3+}$ [3,4]
- $Tl_2LiLuCl_6:Ce^{3+}$ [5]
- $Tl_2LiScCl_6$:Pure

$Tl_xLnX_y:Ce$

- $Tl_2LaCl_5:Ce^{3+}$ [7]
- $Tl_2LaBr_5:Ce^{3+}$ [8]
- $Tl_2GdCl_5:Ce^{3+}$ [9]
- $TlGd_2Cl_7:Ce^{3+}$ [10]

$Tl_xAEX_y:Eu$

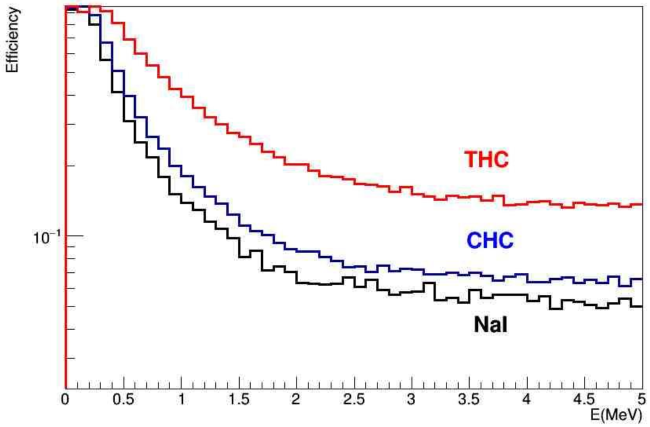
- $TlSr_2Br_5$: Pure [11]
- $TlCaCl_3$: Pure [12]
- $TlSr_2I_5:Eu^{2+}$ [13]

[1] H.J. Kim et al., J. Lumin., 164 (2015) 86–89.
[2] H. J. Kim et al., Rad. Measurem., 90 (2016) 279-281.
[3] H. J. Kim et al., IEEE Trans. Nucl. Sci., 63 (2) (2016) 439.
[4] G. Rooh et al., J. Cryst. Growth, 459 (2017) 163–166.
[5] G. Rooh et al., J. Lumin.,187 (2017) 347–351.
[7] H.J. Kim et al., J. Lumin., 186 (2017) 219–222.
[8] H.J. Kim et al., NIMA., 849 (2017) 72–75.
[9] G. Rooh et al., IEEE TNS., 65 (8) (2018) 2157
[10] A. Khan et al., IEEE TNS., 65 (8) (2018) 2152
[11] G. Rooh et al., Opt. Mater., 73 (2017) 523.
[12] A. Khan et al., Rad. Measurem., 107 (2017) 115.
[13] H.J. Kim et al., Opt. Mater., 82 (2018) 8

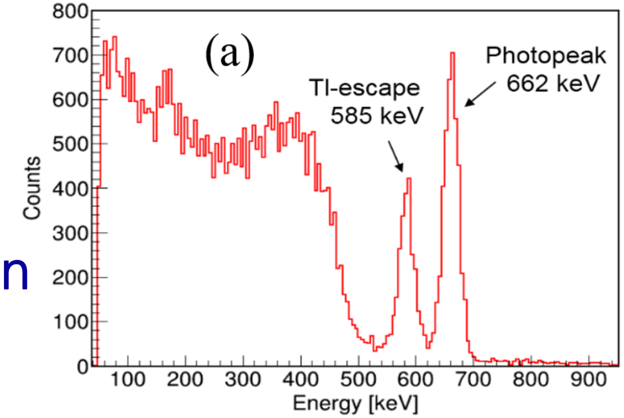
3 US and 1 EU patents, 1 is under review

Courtesy by Prof. Hongju Kim

New crystal scintillators 2018 by KNU



47.000 photons/MeV
4.3% energy resolution



Scintillation material	Effective atomic number	Density (g/cm3)	Light yield (ph/MeV)	Major decay time (ns)
NaI(Tl)	50.8	3.67	38000	250
CsI(Tl)	54	4.51	52000	1000
BGO	75.2	7.13	9000	300
LYSO	65	7.1	33000	40
Cs_2HfCl_6 (1)	58	3.86	54000	4100
Tl_2ZrCl_6 (2)	**69**	**4.65**	**47000**	**2700**
Tl_2HfCl_6	**71**	**5.25**	**32000**	**1000**
$LaBr_3$(Ce)	**44.1**	**5.08**	**89,000**	**16**

Courtesy by Prof. Hongju Kim

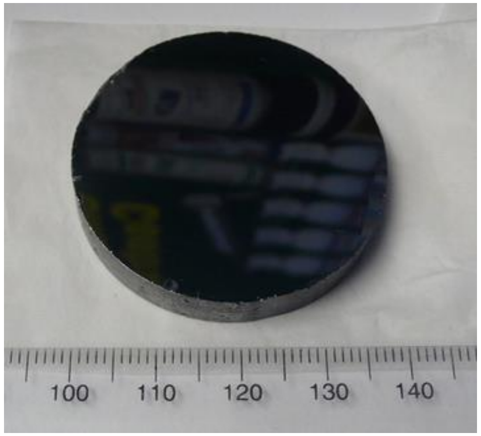
New semiconductor by Korea Univ.

1. Furnace

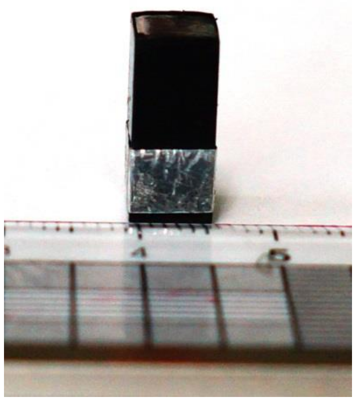
2. Ingot

3. Wire Sawing

4. Polishing



5. Wafer



6. Detector (15mm

Courtesy by Prof. Kihyun Kim

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New semiconductor by Korea Univ.

. CZT 단결정 성장 -> Cd 증기압이 가장 높아 Cd 빈자리 생성

. Cd 빈자리 보상을 위해 In, Al, Cl불순물을 도핑

-> 불순물은 전기적 특성을 저해하고, 구조적인 결함을 생성

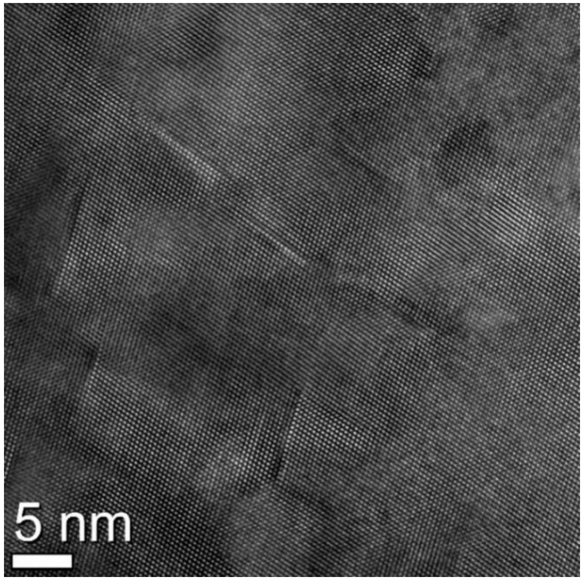
-> Cd 빈자리 결함농도를 낮출 수 있다면 불순물의 양도 감소됨.

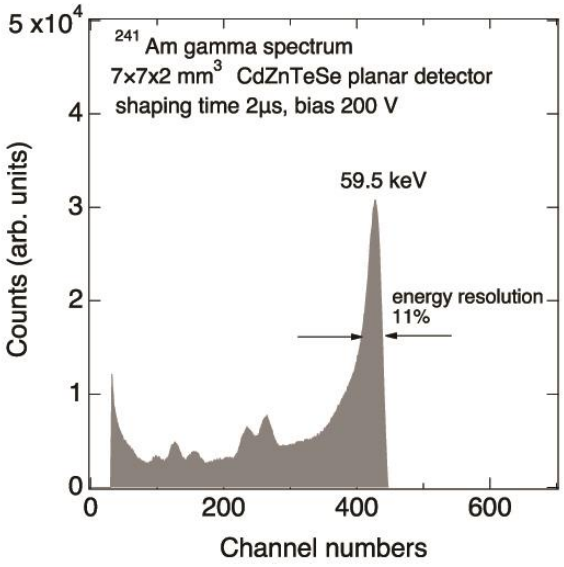
. Se의 녹는점은 Cd 보다 낮아, Se를 첨가하면 Cd 빈자리가 감소.

. CdZnTeSe 단결정 성장에 대한 예비 실험 시 -> 긍정적 결과

Courtesy by Prof. Kihyun Kim

New semiconductor by Korea Univ.





CdZnTeSe 단결정 결함 TEM사진 **Am-241 감마 스펙트럼**

. CdZnTe에 비해 dislocation 결함이 대략 10-15배 작음을 확인.

. 전기적 특성에 결정적인 Te inclusion 분포 및 크기가 위치에 따라 다름->연구대상

. CdSe 재료의 순도를 높여, CdZnTeSe 단결정을 성장할 경우,

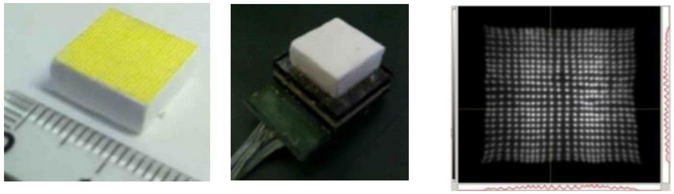
. 추가 연구를 통해 CdZnTe의 몇몇 단점을 극복할 수 있을 것으로 판단됨.

Courtesy by Prof. Kihyun Kim

Device Development by Korea Univ.

초고분해능 방사선 검출기 예시

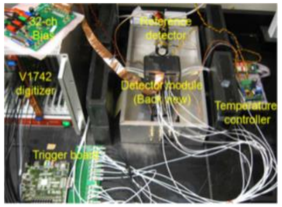
- 세계 최소형 핵의학(PET) 0.4 mm pixel array 검출기 개발
- 24x24 어레이 알고리즘으로 구별
- IEEE TNS, IEEE TRPMS 등 게재



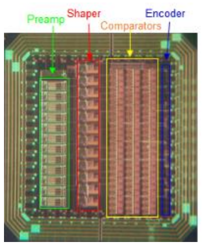
세계 최고분해능 핵의학 검출기 개발

방사선 검출기 회로 및 데이터획득장치 개발

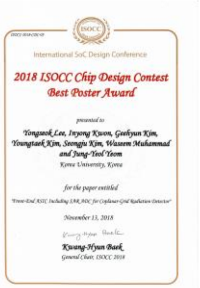
- 각종 방사선 검출기용 회로(ASIC주문형직접회로 포함) 및 데이터 획득 장치 (DAQ) 개발 등
- IEEE TNS, NIMA 등 논문 게재, 2018 ISOCC 국제학회 Best poster award 수상



DAQ



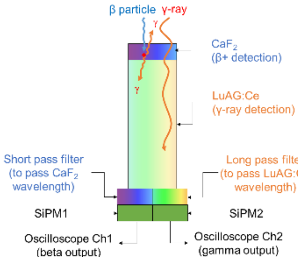
ASIC 회로



2018 ISOCC best poster award

새로운 방사선 검출기 개발

- 고성능 time-of-flight PET 검출기 개발
- 극한 환경(원전중대사고)용 방사선 검출기 개발 등
- NIMA, Phys. Med. Biol., Med. Phys. 등 다수 게재



2019 IEEE NPSS Seoul Chapter 공동심포지엄 우수구연발표상

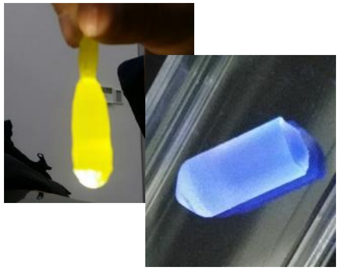
Courtesy by Prof. Jung-Yeol Yeom

Device Development by Korea Univ.

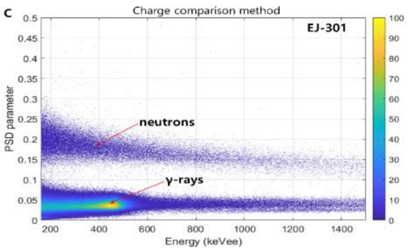
섬광결정 성장
- uPD 및 브리지먼 기법 이용한 섬광결정 성장
- 섬광체 가공, 후처리 및 표면 처리


μPD장비


Bridgman장비


섬광결정

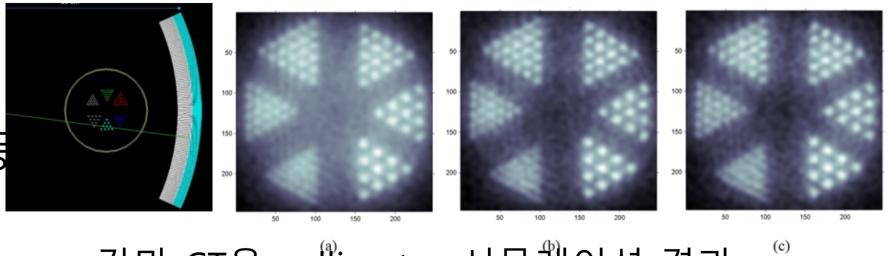
각종 신호 처리 알고리듬 개발
- Pulse shape discriminator (PSD, 파형구별법)을 이용한 감마-중성자 구별
- 고분해능 핵의학 검출기 depth-of-interaction (반응깊이) 구별 알고리듬 등



중성자, 감마 구별 결과

2017 방사선방어학회 우수논문

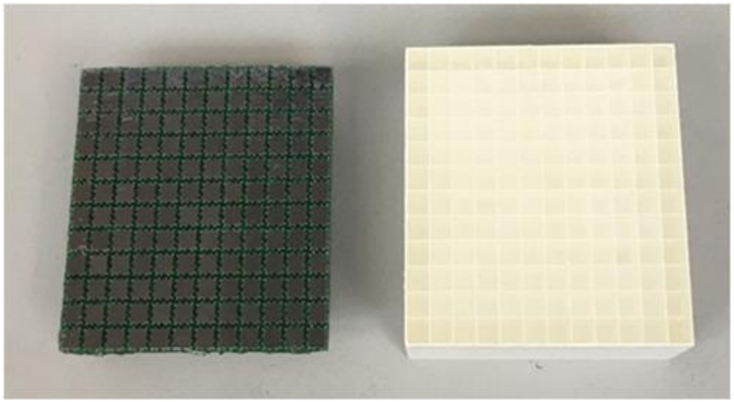
시뮬레이션 및 영상재구성
- GATE를 이용한 Gamma CT용 collimator 설계
- 핵의학영상기기 time-of-flight (TOF) 영상재구성 등



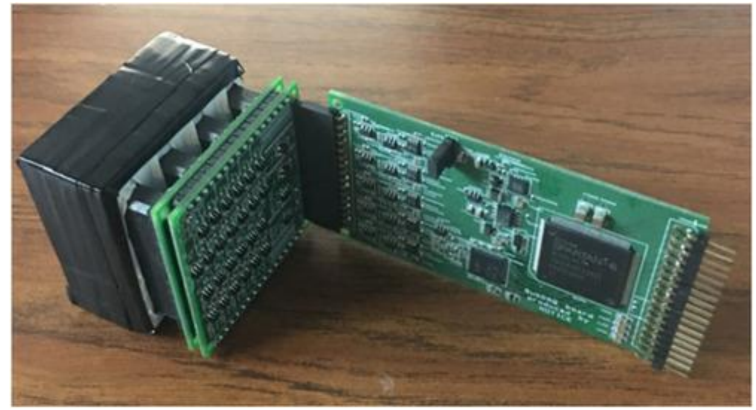
감마 CT용 collimator 시뮬레이션 결과

Courtesy by Prof. Jung-Yeol Yeom

Radiation Imager by JeJu Univ.

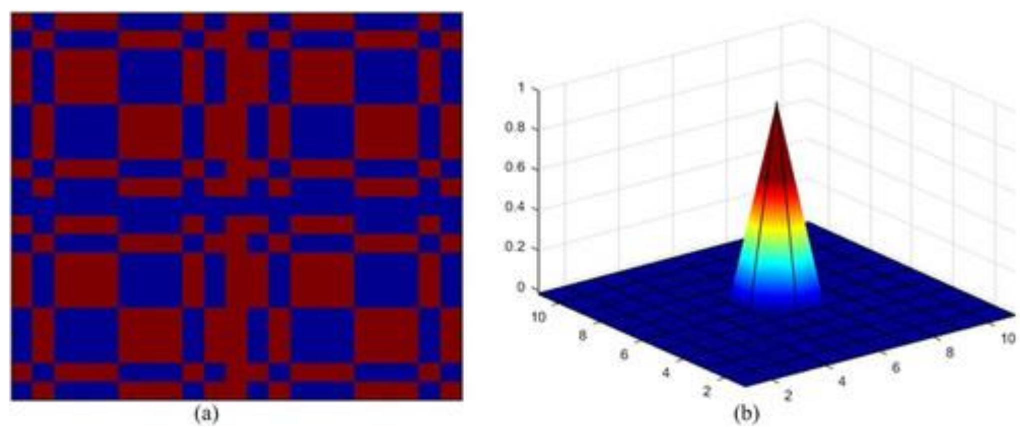


12 × 12 SiPM pixel array and 4×4×20 mm^3 pixelated CsI(Tl)



Detector system including DAQ board

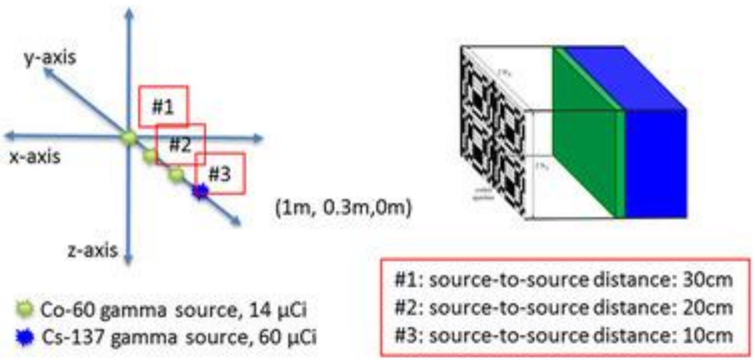
MURA mask fabricated
with a 3D printer and 20 mm thick tungsten pieces



21 × 21 MURA mask pattern (a) and its auto-correlated function plot with decoding pattern as delta function

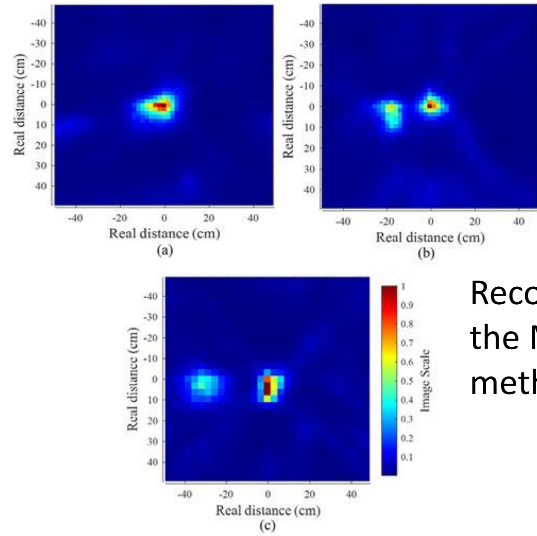
RSI 89, 033106 (2018) Prof. Manhee Jeong

Radiation Imager by JeJu Univ.

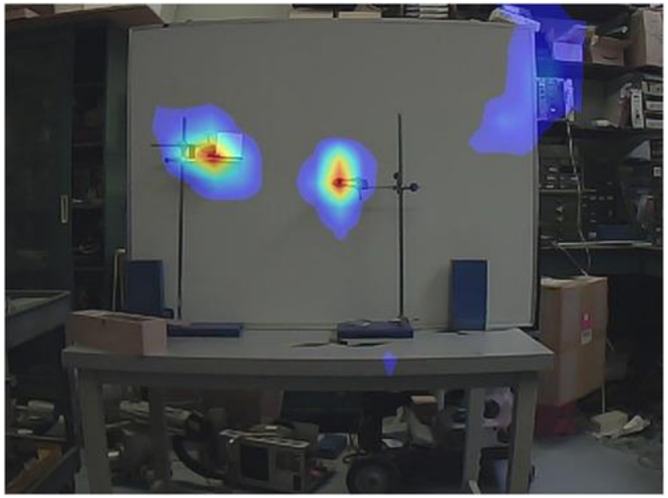


(a)

(b)



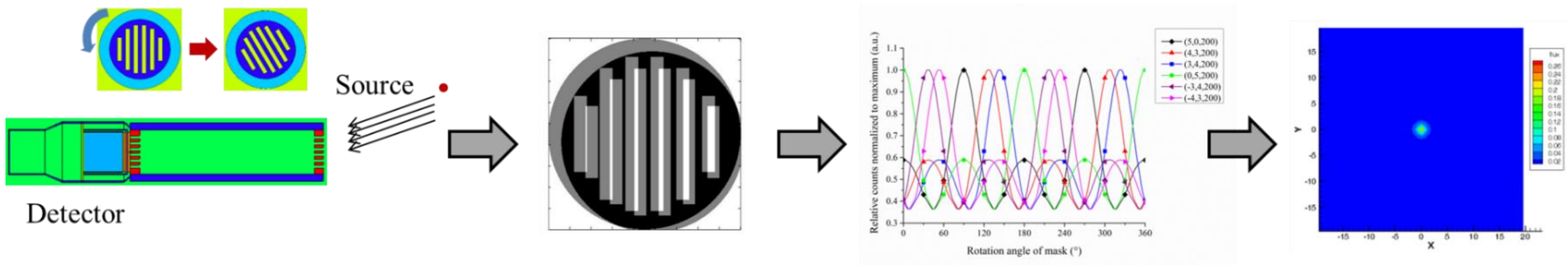
Reconstructed image with the MLEM reconstruction method



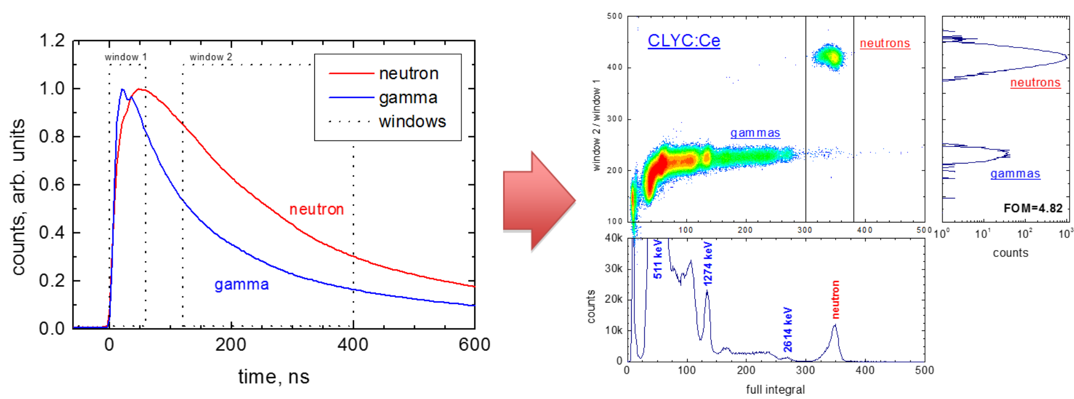
RSI 89, 033106 (2018) Prof. Manhee Jeong

Radiation Imager by Sejong Univ.

- Rotational Modulation Collimator (RMC)
  - Originally developed for X-ray and solar flare imaging in astronomy.
  - Does not require a position-sensitive radiation detector.
  - As collimators rotate, the open area made by slits change over time.



- PSD-capable Scintillators



Courtesy by Prof. Kihyun Kim

Radiation Imager by Sejong Univ.

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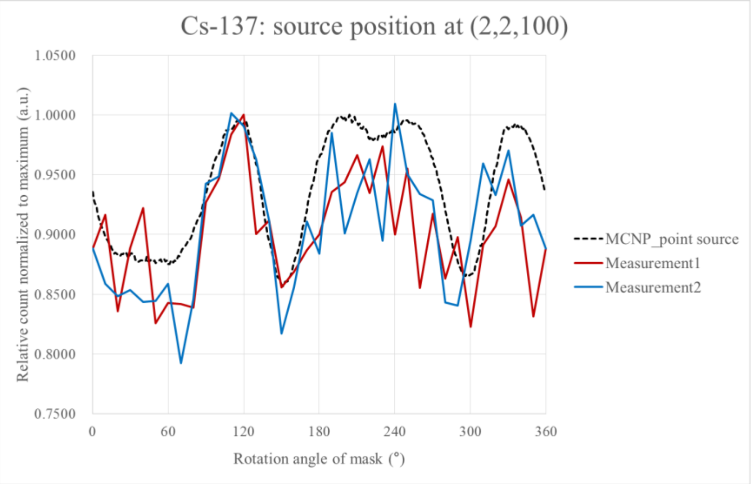
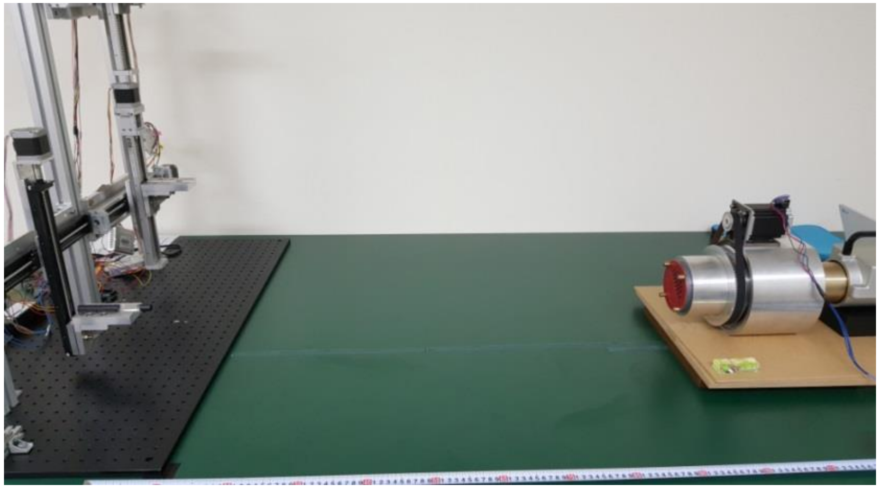
감마선원 계측 및 영상화 실험

- 감마선원을 이용한 RMC 영상화 실험
  - 비대칭 집속기 사용 (Pb 1 cm+ BPE 0.2 cm)
  - RMC와 방사선원 사이 거리: 1 m
  - 측정 선원: ^{137}Cs 10.23 μCi, ^{133}Ba 10.64 μCi (reference date 2016-04-01)

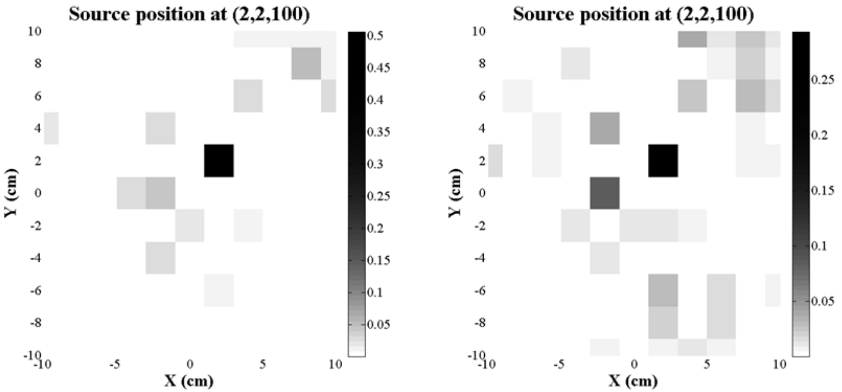
<Cs-137 선원에 대한 회전 변조 패턴>



<감마선원 계측 및 영상화 실험>



<재구성된 방사선원 분포 영상>



SNR=14.1 **SNR=10.5**

MLEM iteration 5,000회

Courtesy by Prof. Kihyun Kim

Radiation Imager by Sejong Univ.

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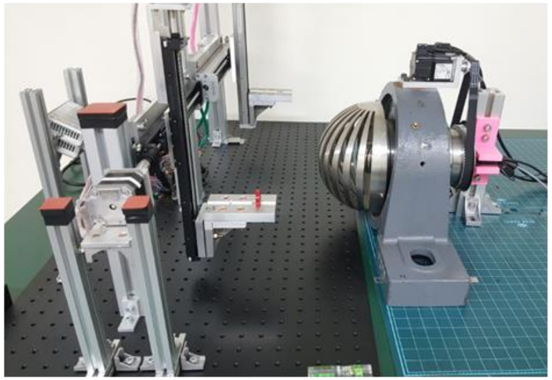
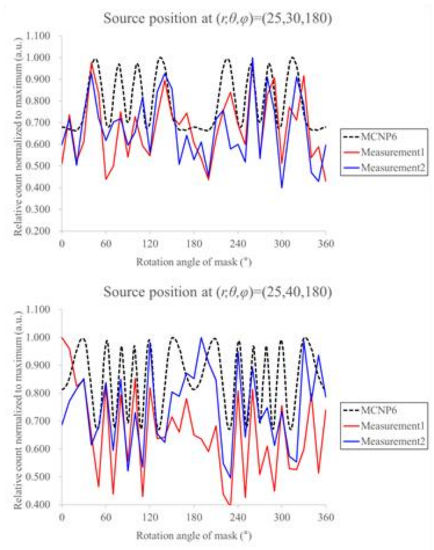
선원 세기/타입 변화에 따른 변조패턴

- **감마선원을 이용한 RMC 영상화 실험**
  - 선원위치: (r, θ, φ)=(25 cm, 30°, 180°),
    (25 cm, 40°, 180°)
  - 측정 선원: ^{133}Ba 89.52 μCi (D-type source, reference date 2018-08-01)
  - Dwell time: 10 min

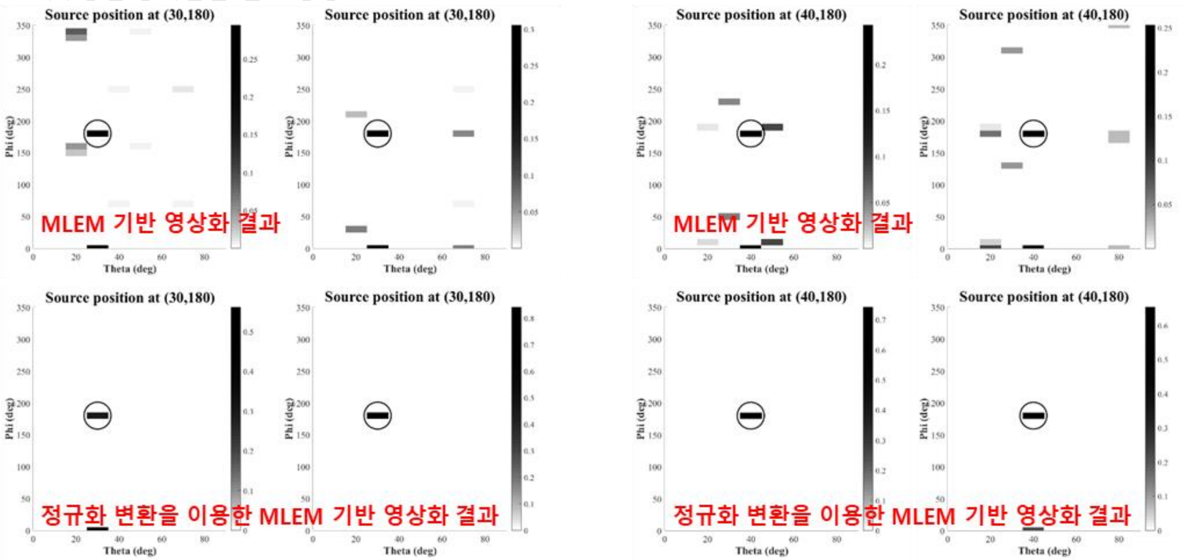
<감마선원 계측 및 영상화 실험>



<Ba-133 선원에 대한 회전 변조 패턴>

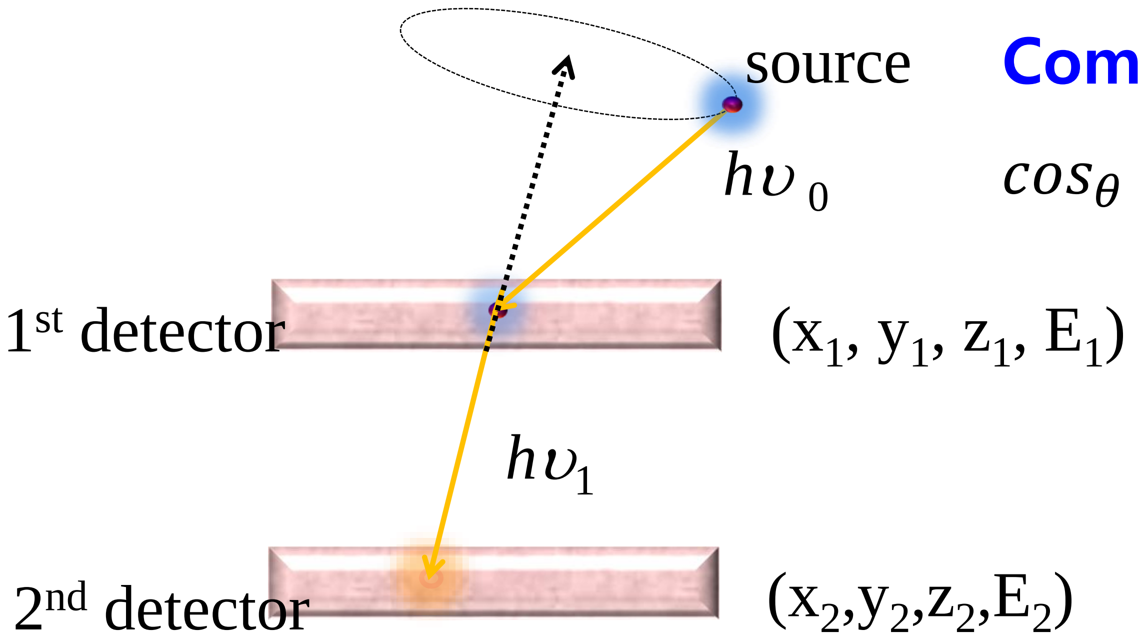


<재구성된 방사선원 분포 영상>



Courtesy by Prof. Kihyun Kim

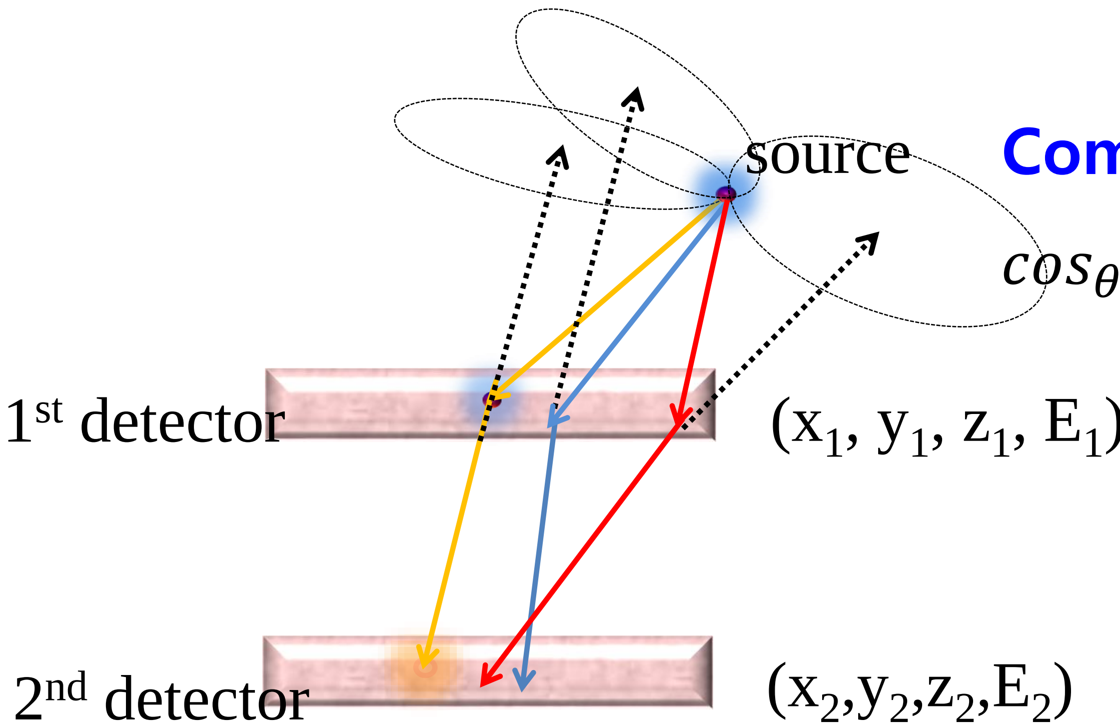
Radiation Imager by Korea Univ.



Compton Reconstruction

$$cos_{\theta} = 1 - \left(\frac{m_0 c^2}{h\nu_0} \cdot \frac{E_1}{(h\nu_0 - E_1)}\right)$$

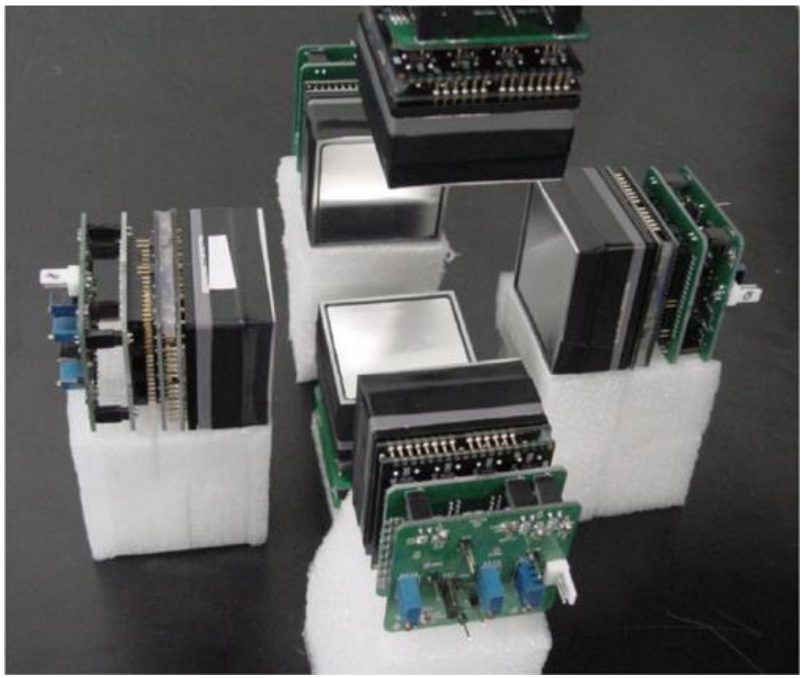
Radiation Imager by Korea Univ.



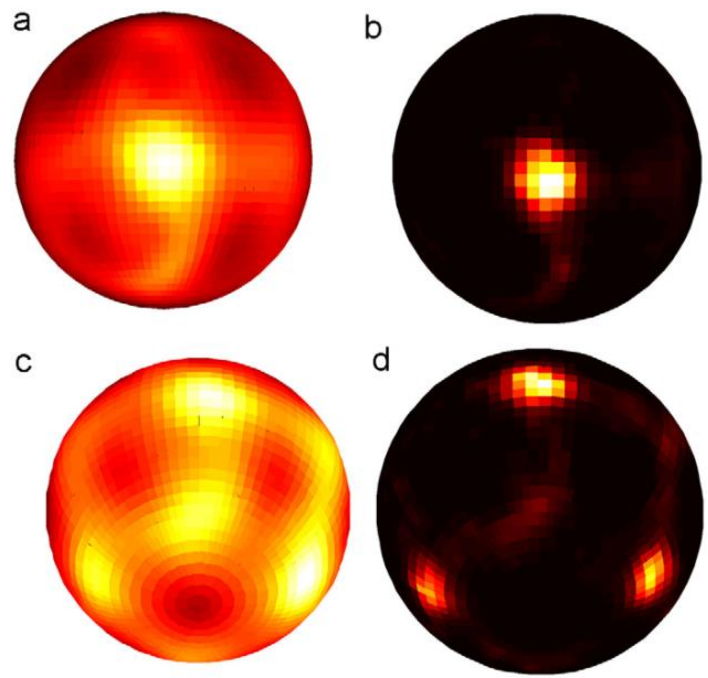
Compton Reconstruction

$$cos_{\theta} = 1 - \left(\frac{m_0 c^2}{h\nu_0} \cdot \frac{E_1}{(h\nu_0 - E_1)}\right)$$

Radiation Imager by Korea Univ.



1st 50th



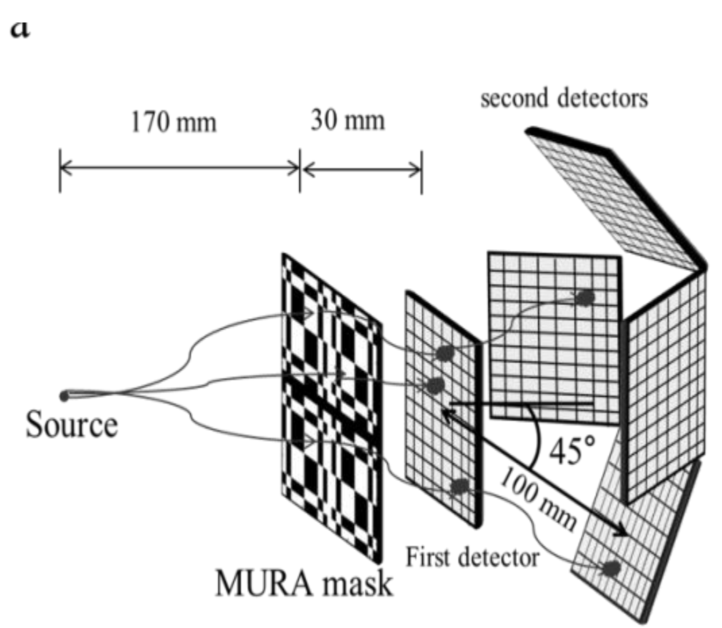
One source

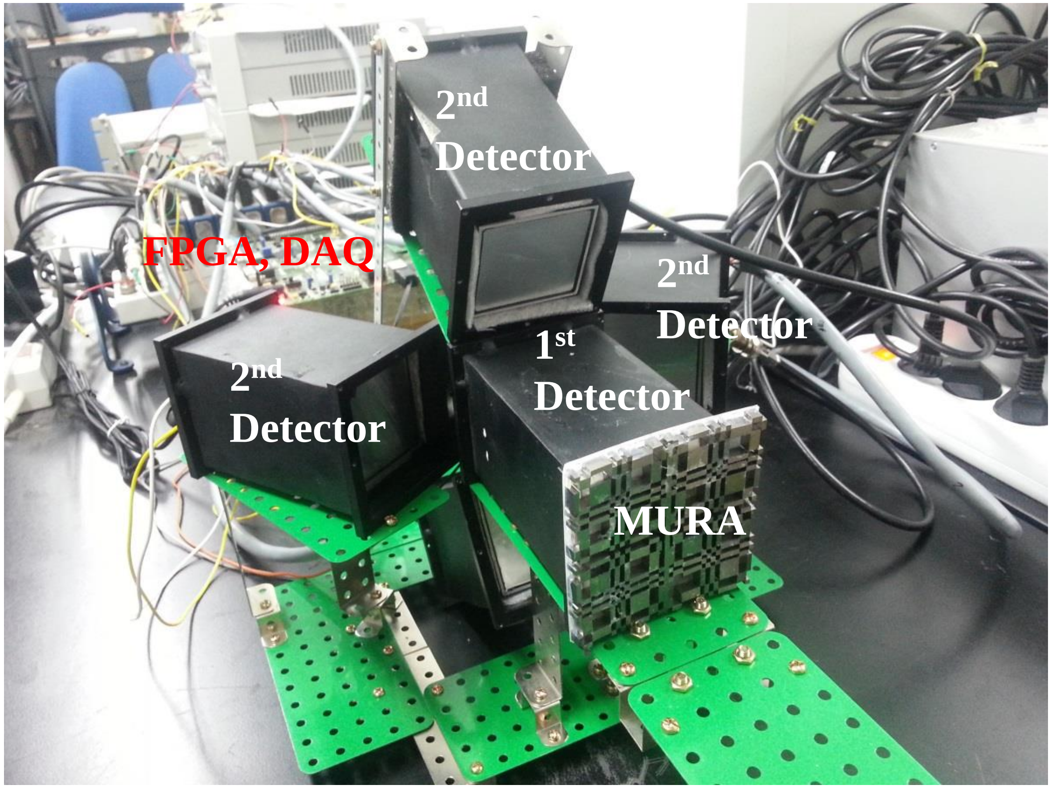
Three sources

Intrinsic Efficiency : 4.67×10^{-4}

Wonho Lee and Taewoong Lee, 2011, NIMA, 652, 33

Radiation Imager by Korea Univ.

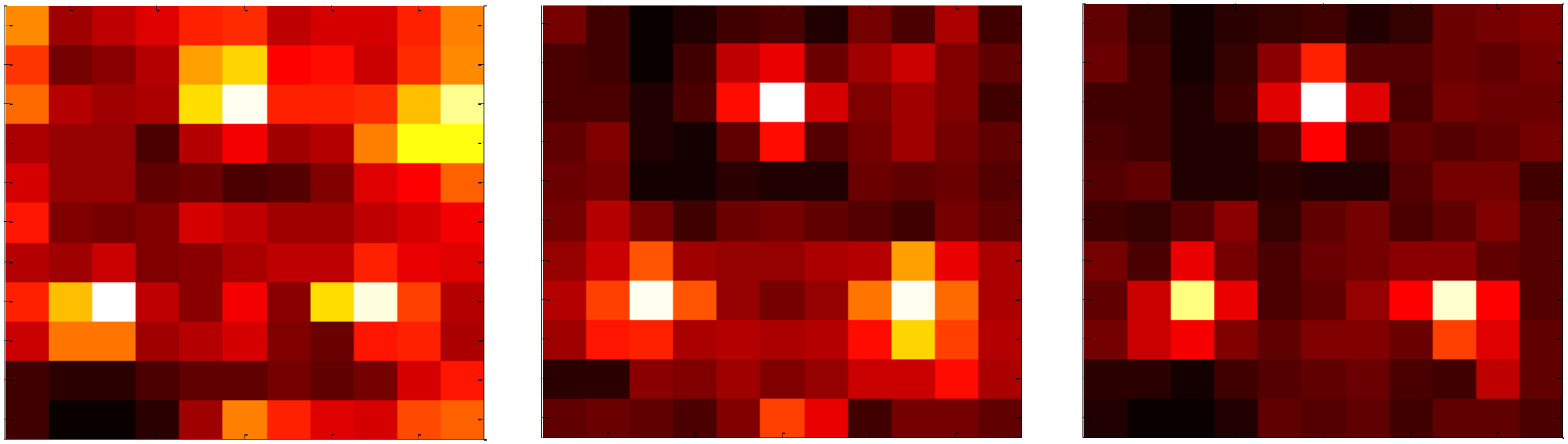


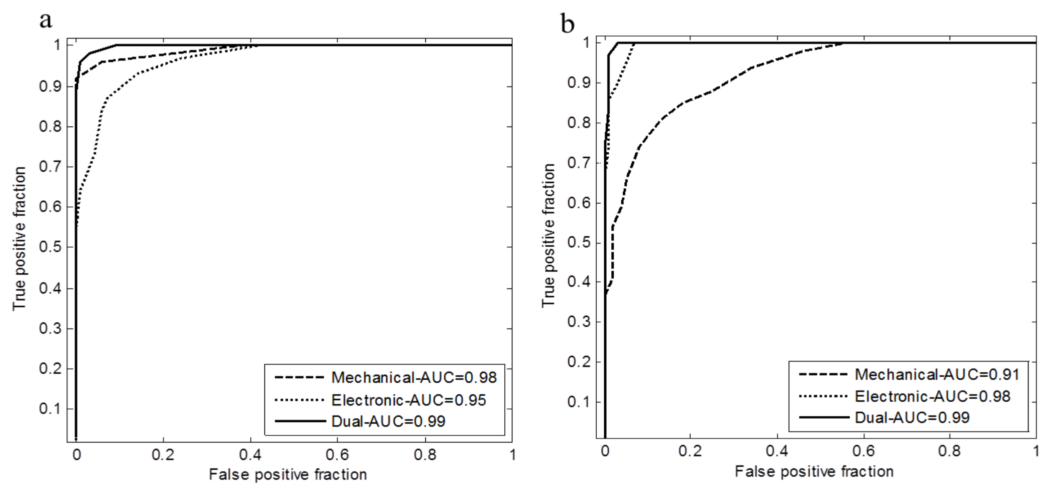


Taewoong Lee and Wonho Lee., 2014, NIMA 767, No.11, 5

Radiation Imager by Korea Univ.

Coded aperture | Compton | Dual



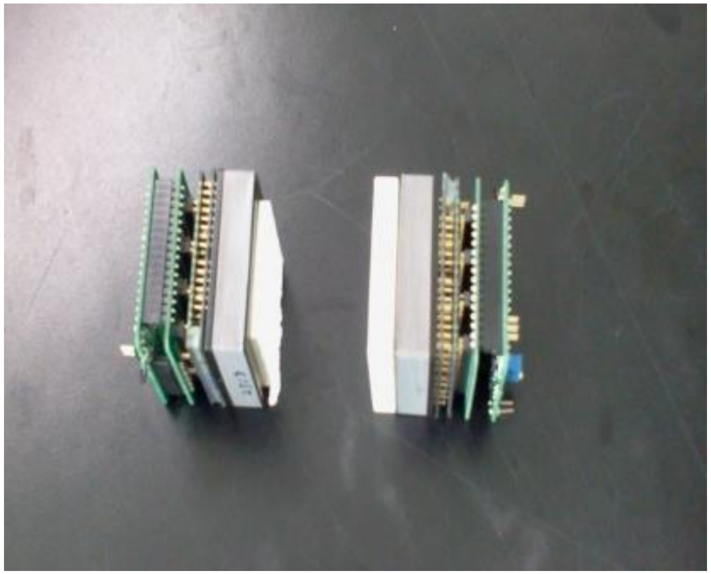


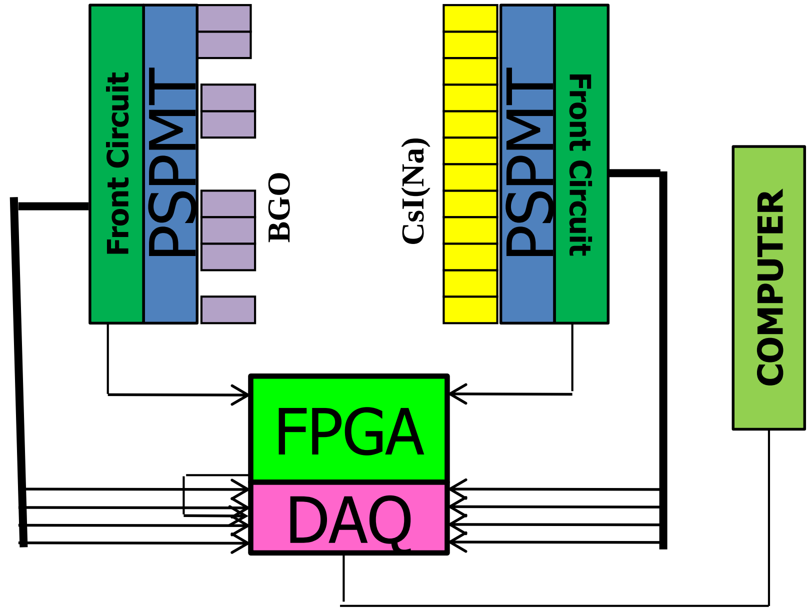
662 keV

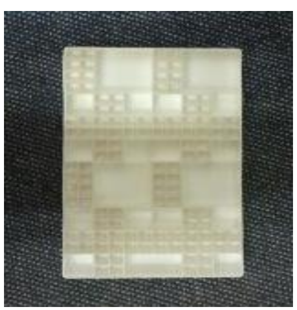
Taewoong Lee and Wonho Lee., 2014, NIMA 767, No.11, 5

Radiation Imager by Korea Univ.

Coded mask made by a scintillator array (BGO)






URA (SICCAS)


Planar (Hilgers)

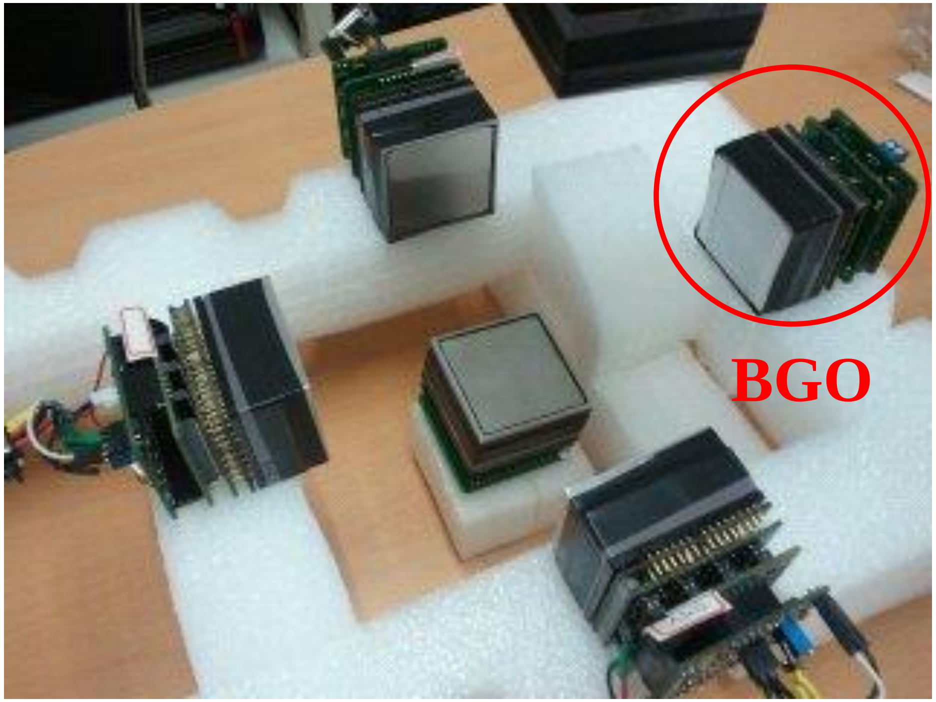

(Hamamatsu)


(Custom-made)


(Digilent)

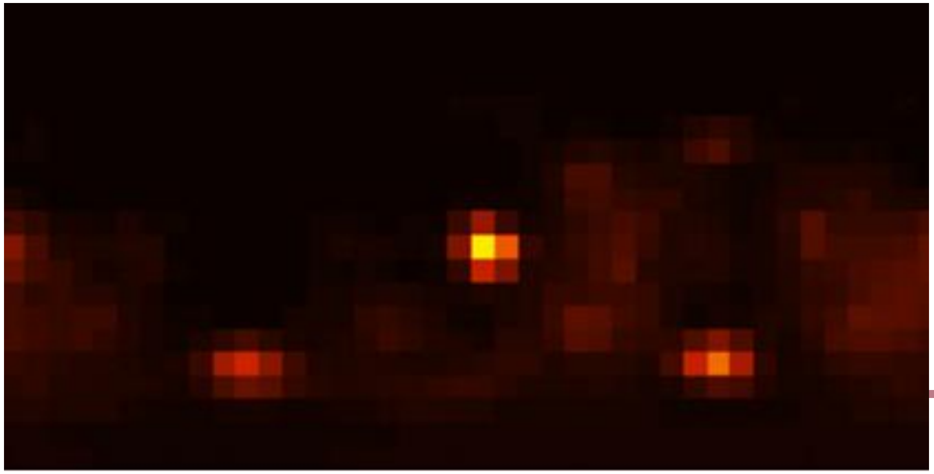

(NI)

Radiation Imager by Korea Univ.



Taewoong Lee, Wonho Lee*, 2014, IEEE TNS, **61**, No.1, 654-662

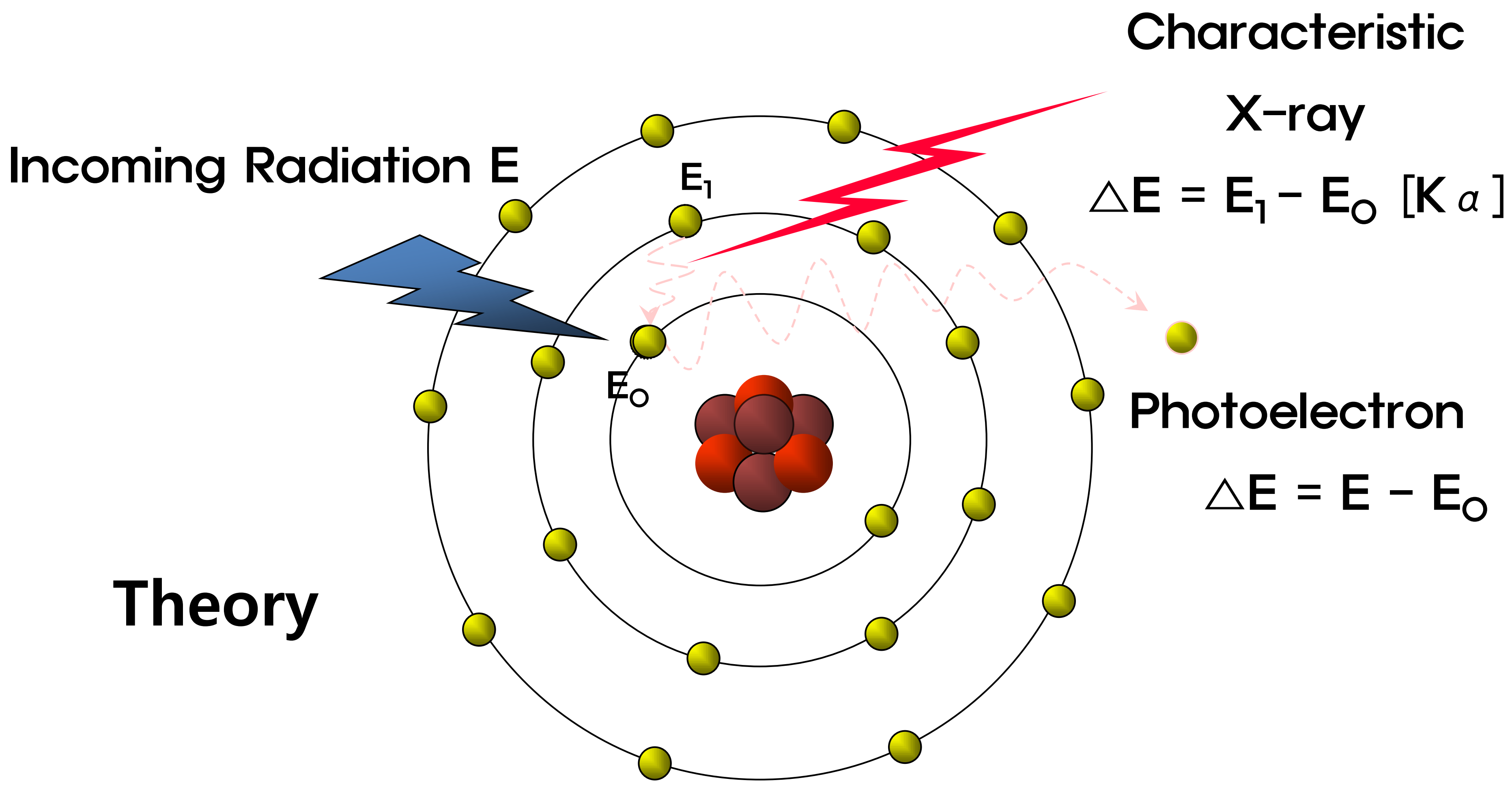
Taewoong Lee and Wonho Lee* 2014, ARI, **90**, 102-108



Three 662 keV sources

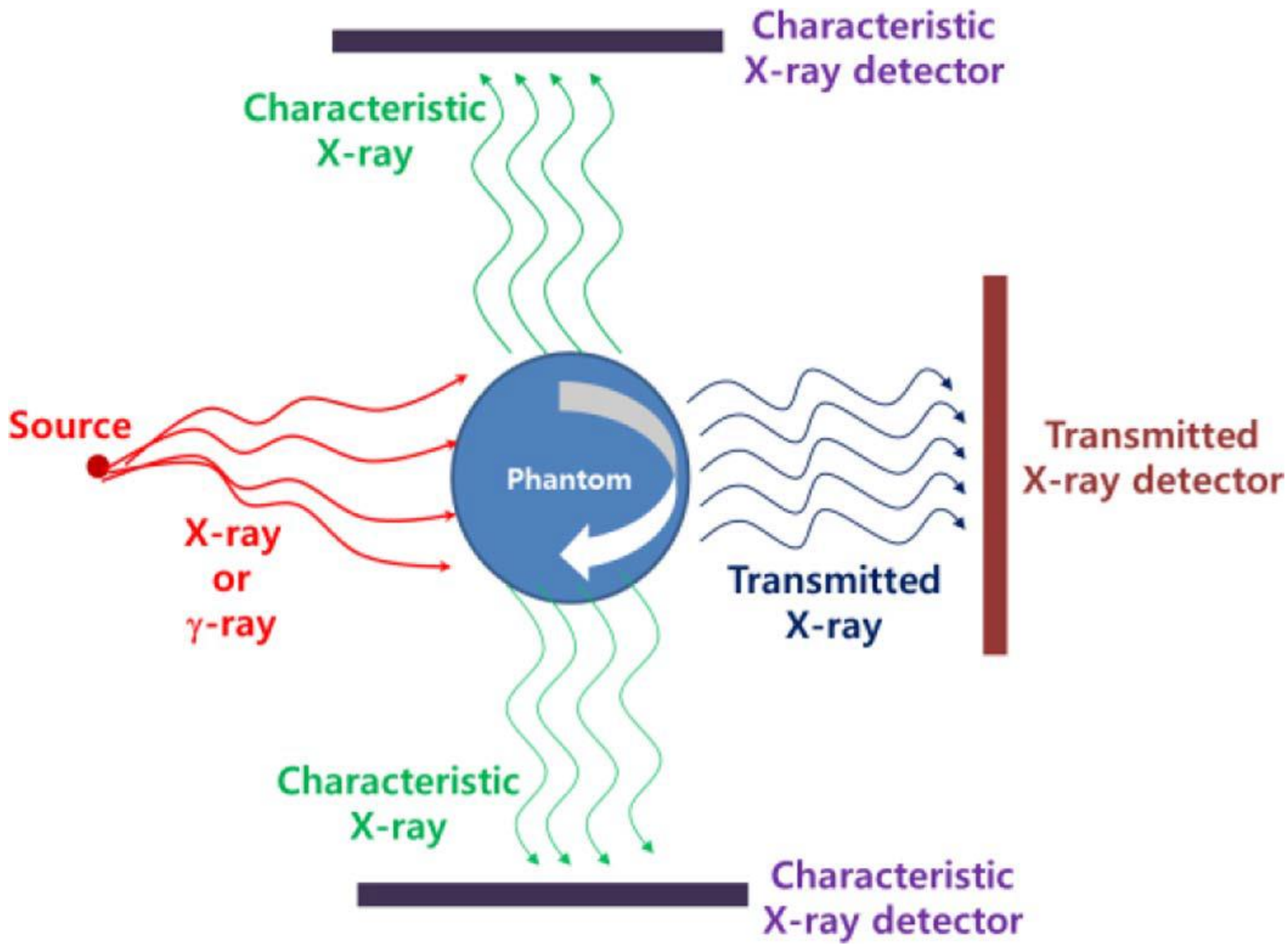
Current Researches of RMI Lab in Korea Univ.

Fluorescent X-ray Computed Tomography

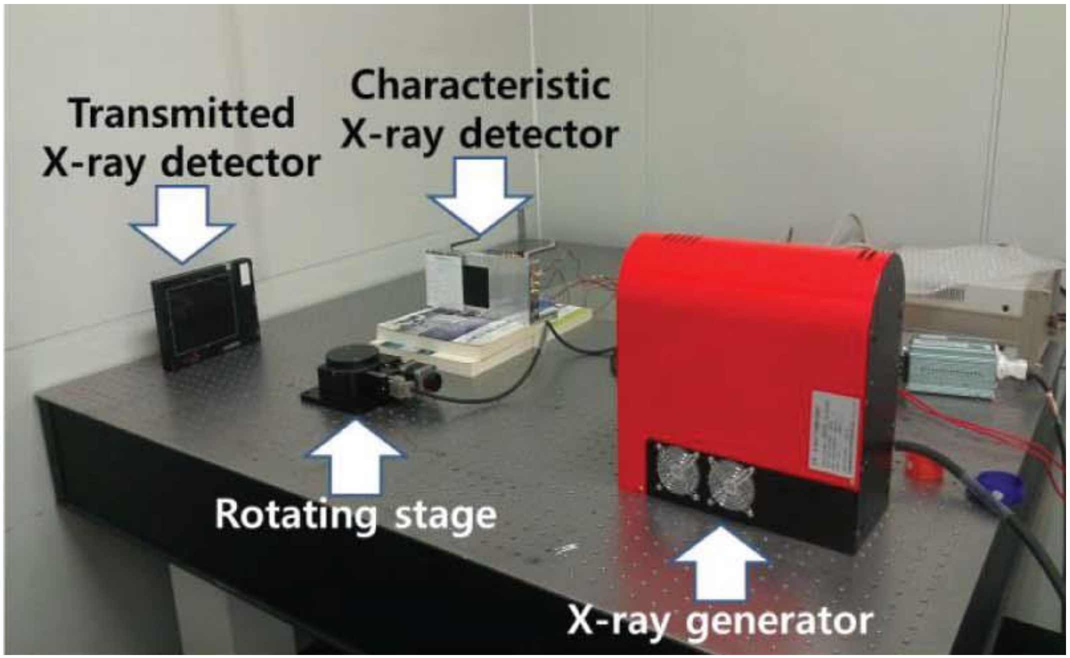


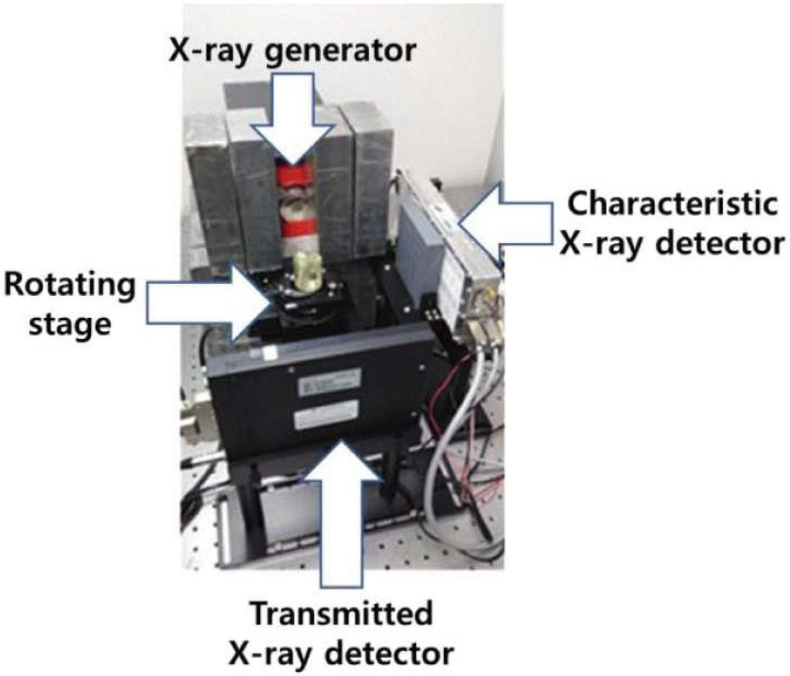
Theory

FXCT: Schematic Diagram



FXCT System Photos





Chanyeon *et al*, IEEE TNS, 63, NO. 3, JUNE 2016

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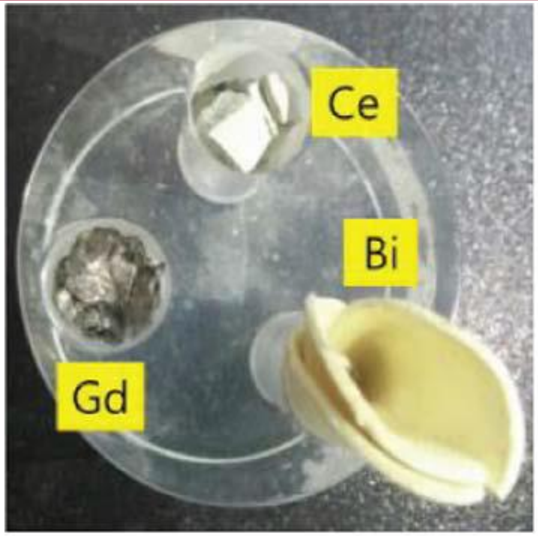
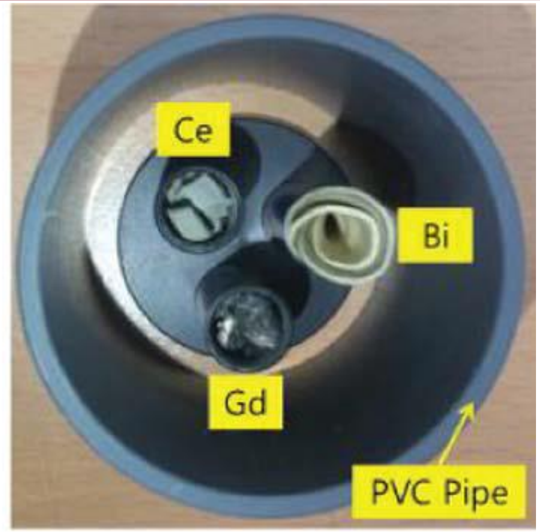
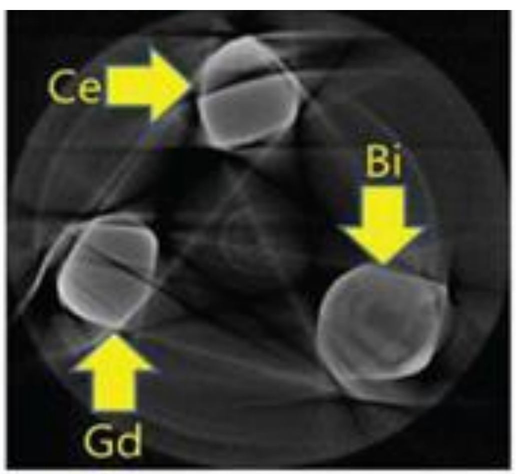
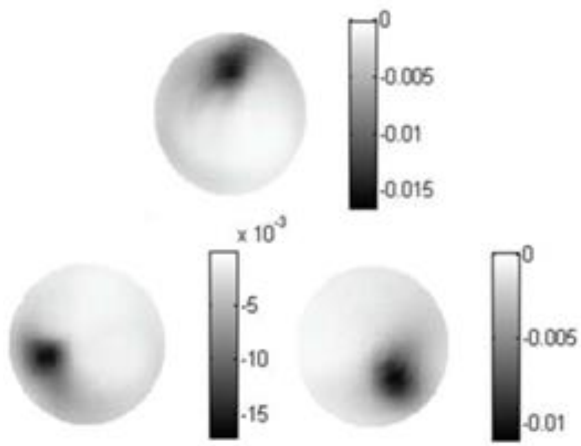
FXCT Experiment (1st generation)







Transmission image



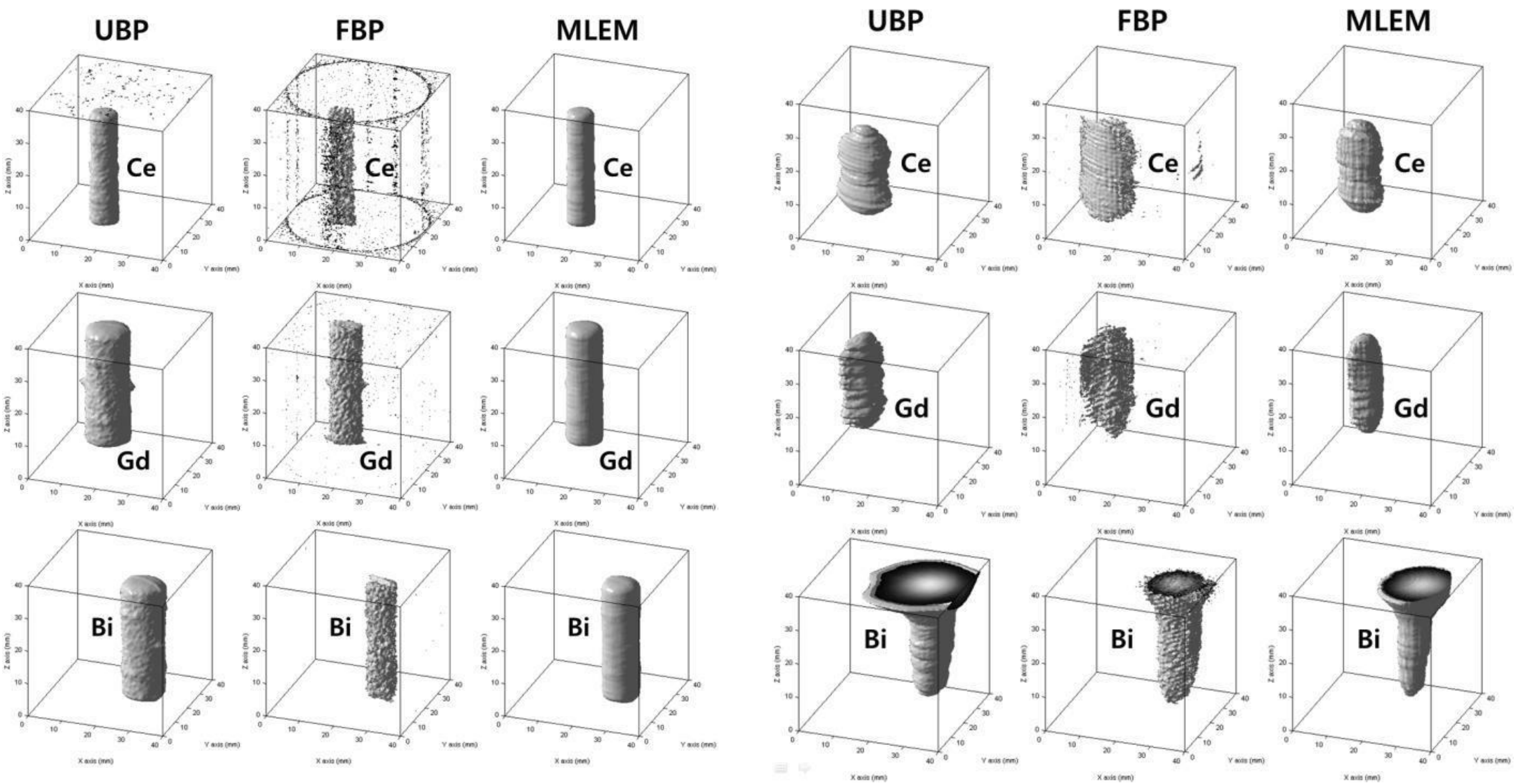
Characteristic image

Combined image

Chanyeon *et al*, IEEE TNS, 63, NO. 3, JUNE 2016

FXCT Experiment (1st generation)

3D Rendered Images



Simulation

Experiment

Chanyeon *et al*, IEEE TNS, 63, NO. 3, JUNE 2016

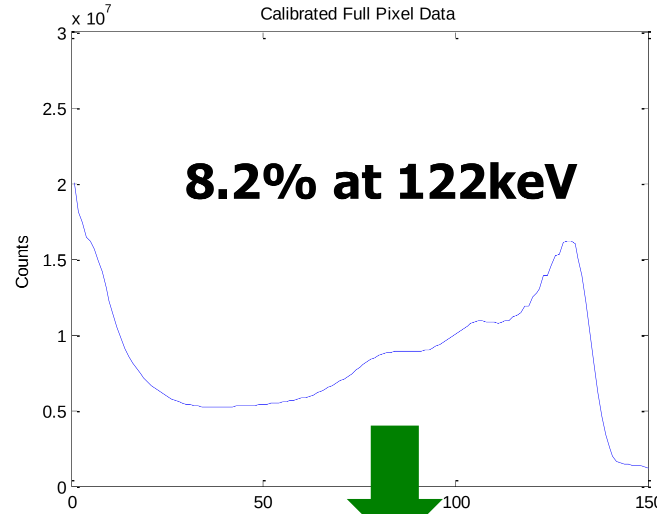
FXCT Experiment (1st generation)

Detectable Depth

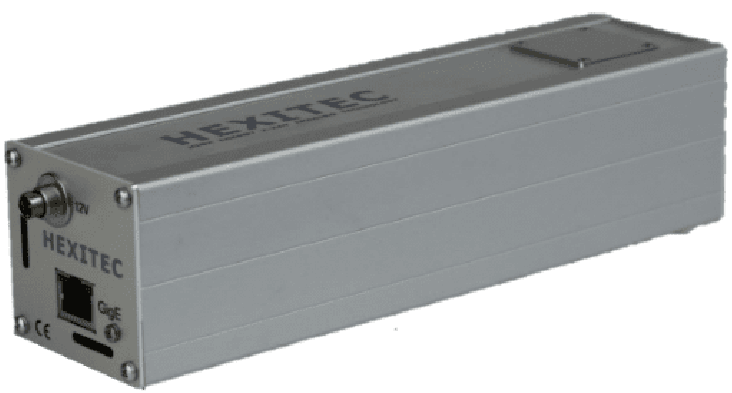
Pipe material	thickness [mm]			
	0.7	1.5	2.25	3
PVC	O	O	O	O
Al	O	O	O	O
Stainless Steel	O	O	X	X
Cu	O	X	X	X

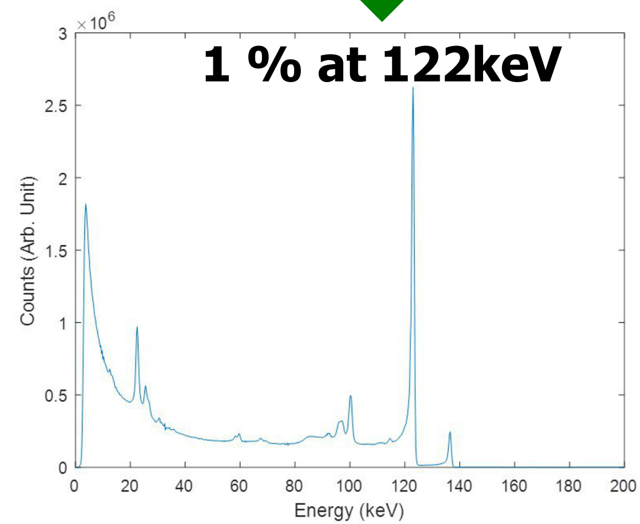
FXCT Experiment (1st -> 2nd Generation)

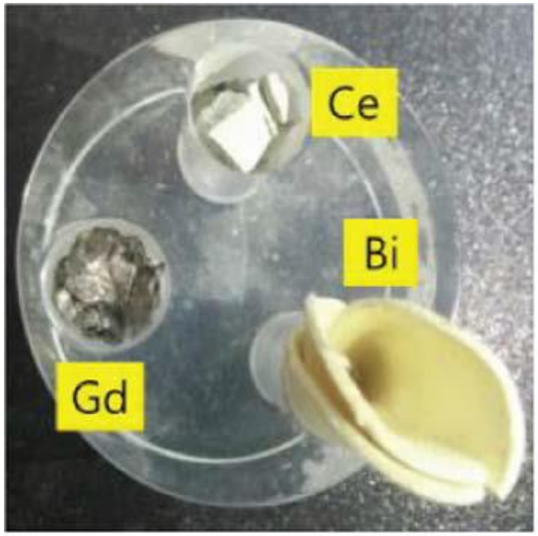
1st
Detector
AJAT

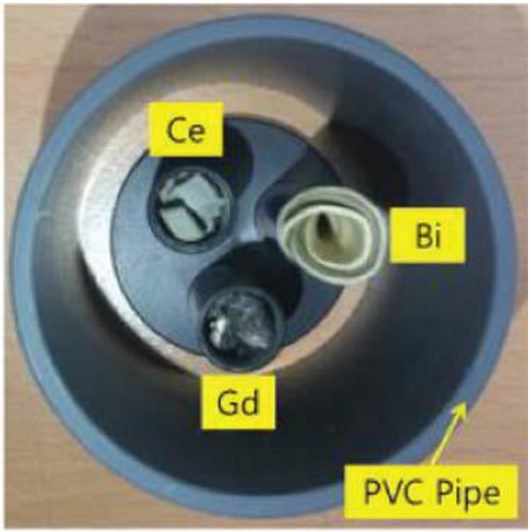


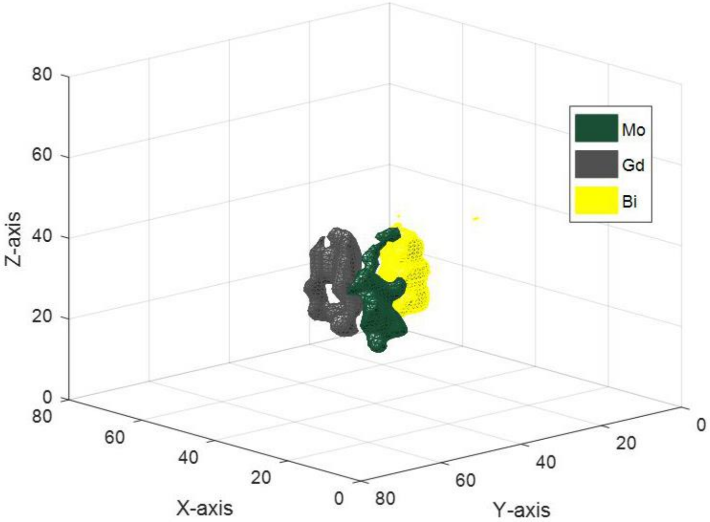
2nd
Detector
HEXITEC





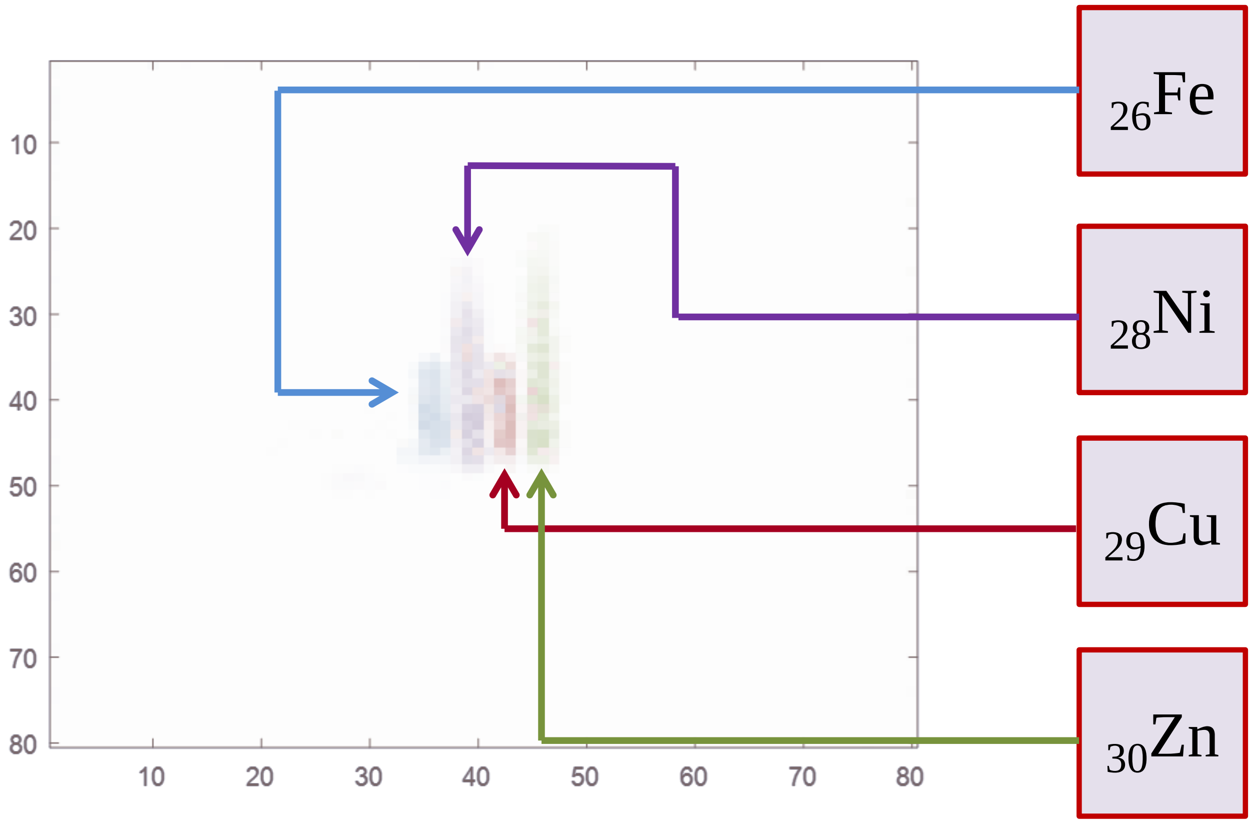

Ce
Bi
Gd


Ce
Bi
Gd
PVC Pipe


Mo
Gd
Bi
Z-axis
X-axis
Y-axis
0
20
40
60
80

FXCT Experiment (2nd Generation)

Even if ΔZ=1, they are discriminated from each other!



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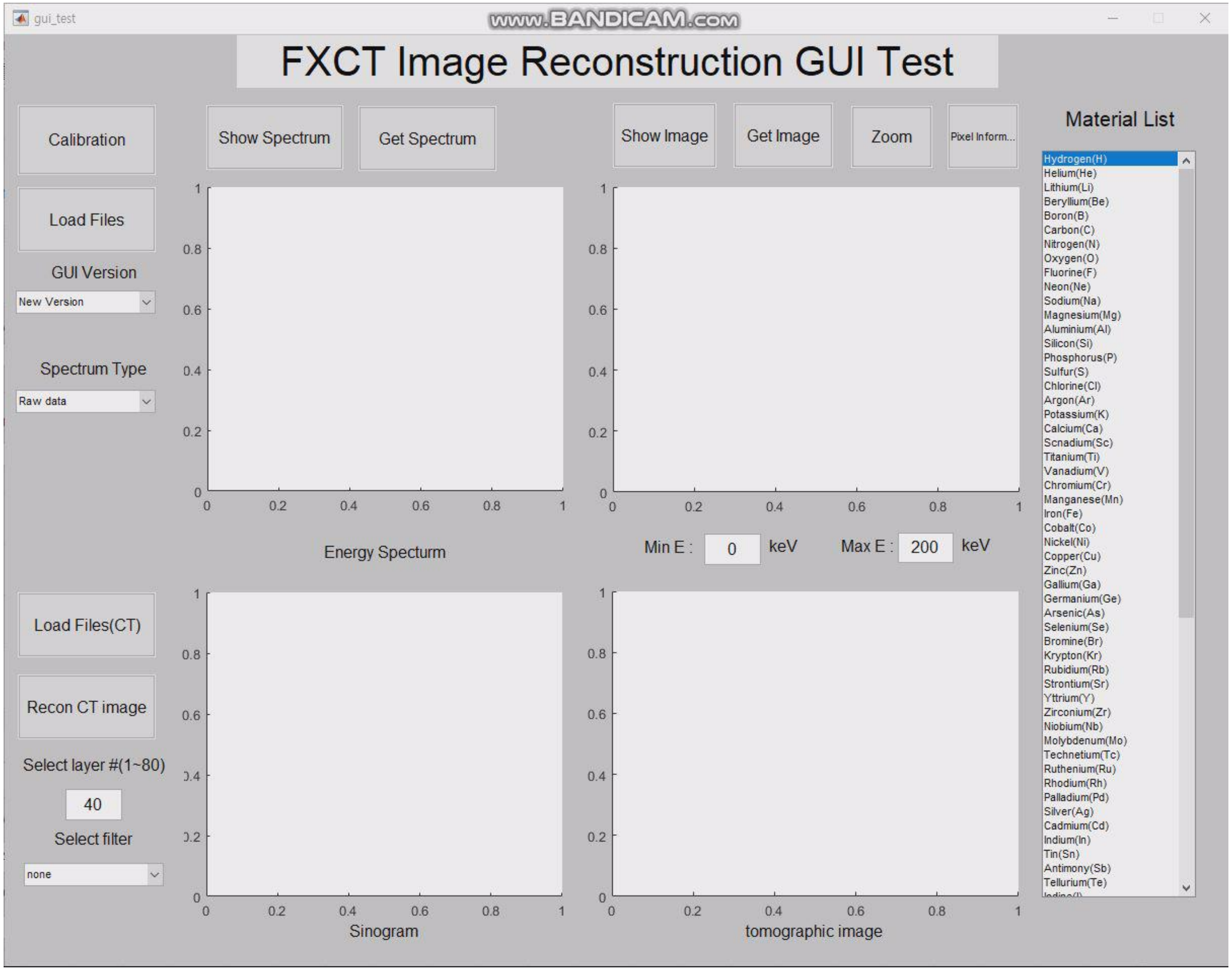
FXCT Experiment (2nd Generation)

Detected and Analyzed Materials

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	$_{1}$H																	$_{2}$He
2	$_{3}$Li	$_{4}$Be											$_{5}$B	$_{6}$C	$_{7}$N	$_{8}$O	$_{9}$F	$_{10}$Ne
3	$_{11}$Na	$_{12}$Mg											$_{13}$Al	$_{14}$Si	$_{15}$P	$_{16}$S	$_{17}$Cl	$_{18}$Ar
4	$_{19}$K	$_{20}$Ca	$_{21}$Sc	$_{22}$Ti	$_{23}$V	$_{24}$Cr	$_{25}$Mn	$_{26}$Fe	$_{27}$Co	$_{28}$Ni	$_{29}$Cu	$_{30}$Zn	$_{31}$Ga	$_{32}$Ge	$_{33}$As	$_{34}$Se	$_{35}$Br	$_{36}$Kr
5	$_{37}$Rb	$_{38}$Sr	$_{39}$Y	$_{40}$Zr	$_{41}$Nb	$_{42}$Mo	$_{43}$Tc	$_{44}$Ru	$_{45}$Rh	$_{46}$Pd	$_{47}$Ag	$_{48}$Cd	$_{49}$In	$_{50}$Sn	$_{51}$Sb	$_{52}$Te	$_{53}$I	$_{54}$Xe
6	$_{55}$Cs	$_{56}$Ba	$_{57}$La	$_{72}$Hf	$_{73}$Ta	$_{74}$W	$_{75}$Re	$_{76}$Os	$_{77}$Ir	$_{78}$Pt	$_{79}$Au	$_{80}$Hg	$_{81}$Tl	$_{82}$Pb	$_{83}$Bi	$_{84}$Po	$_{85}$At	$_{86}$Rn
7	$_{87}$Fr	$_{88}$Ra	$_{89}$Ac	$_{104}$Rf	$_{105}$Db	$_{106}$Sg	$_{107}$Bh	$_{108}$Hs	$_{109}$Mt	$_{110}$Ds	$_{111}$Rg	$_{112}$Cn	$_{113}$Uut	$_{114}$Uuq	$_{115}$Uup	$_{116}$Uuh	$_{117}$Uus	$_{118}$Uuo
란탄족					$_{58}$Ce	$_{59}$Pr	$_{60}$Nd	$_{61}$Pm	$_{62}$Sm	$_{63}$Eu	$_{64}$Gd	$_{65}$Tb	$_{66}$Dy	$_{67}$Ho	$_{68}$Er	$_{69}$Tm	$_{70}$Yb	$_{71}$Lu
악티늄족					$_{90}$Th	$_{91}$Pa	$_{92}$U	$_{93}$Np	$_{94}$Pu	$_{95}$Am	$_{96}$Cm	$_{97}$Bk	$_{98}$Cf	$_{99}$Es	$_{100}$Fm	$_{101}$Md	$_{102}$No	$_{103}$Lr

연구실 보유	구매 진행중	화합물 형태 보유	측정 불가	미구매예정 (가격)	상업적 취급 X

FXCT Experiment (2nd Generation)



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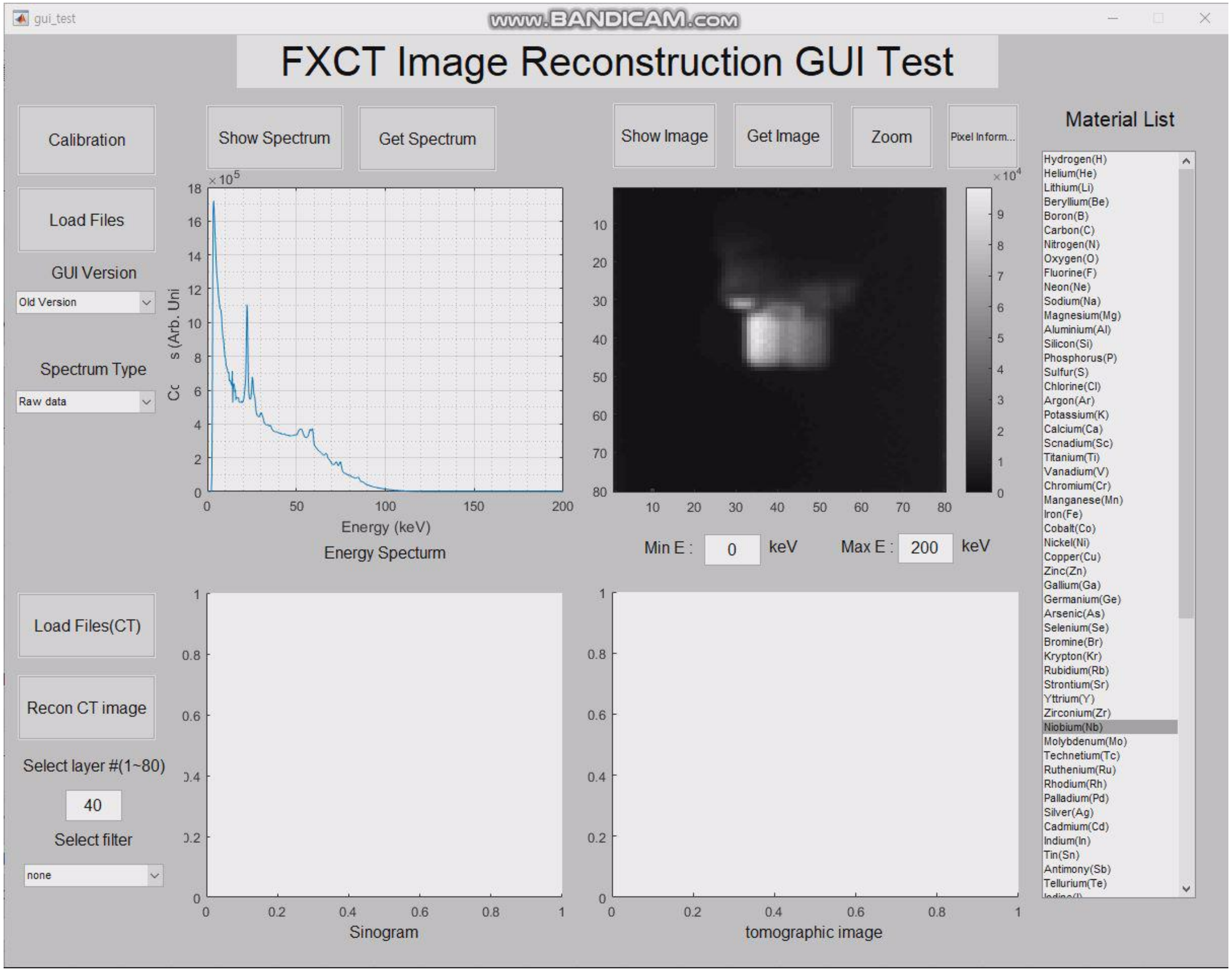
FXCT Experiment (2nd Generation)



- 유약분석 결과

유약	구성성분
투명유	Ti, Zn, Ba, Pr
상아철	Ti, Fe, Ba, Gd
민트결정	Ti, Fe, Cu, Ba
진주유	Ti, Nb, Ba
옥색유	Ti, Nb
루호유백	Ti, Nb, Ba, Pr
백매트	Nb

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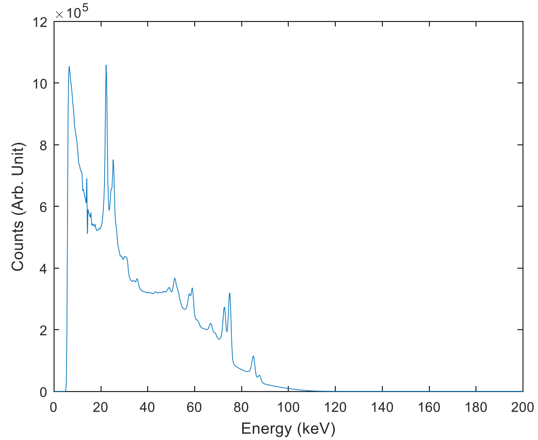
FXCT Experiment (2nd Generation)

- 아두이노 회로 실험 결과



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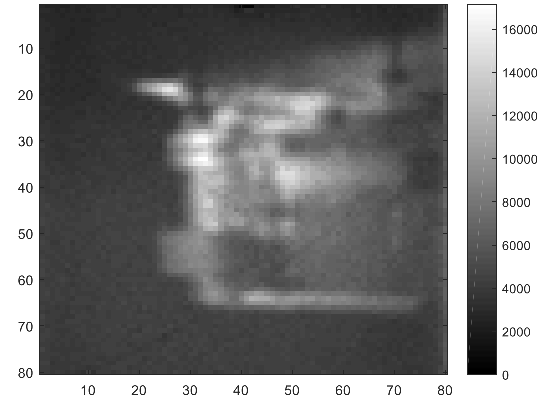

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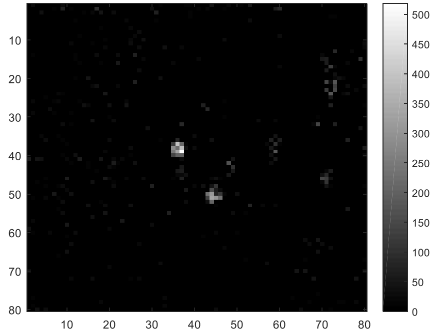

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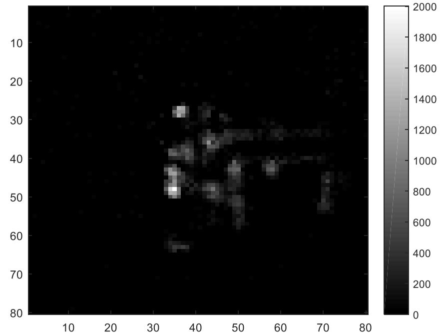

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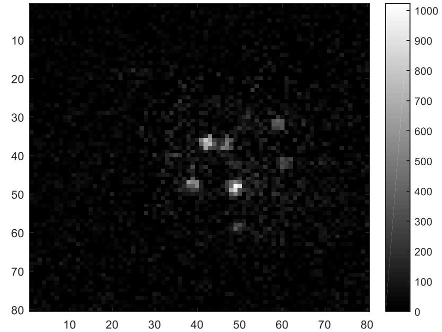

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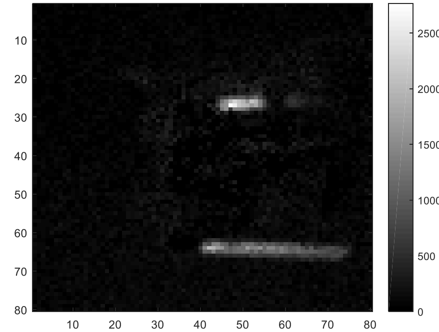


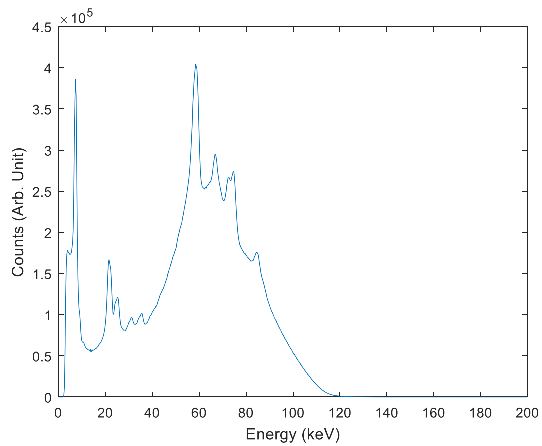
<Sb 영상>

FXCT Experiment (2nd Generation)

Gold ???

FXCT Experiment (2nd Generation)

- Purse clip



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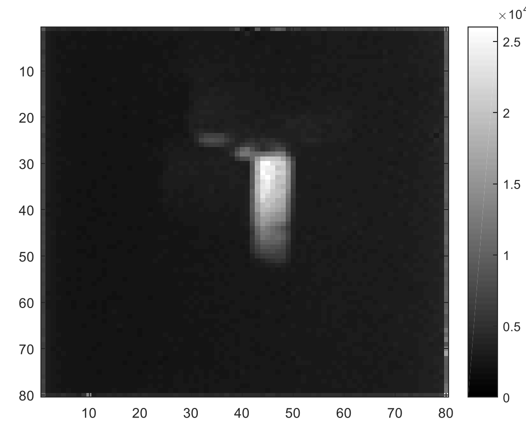

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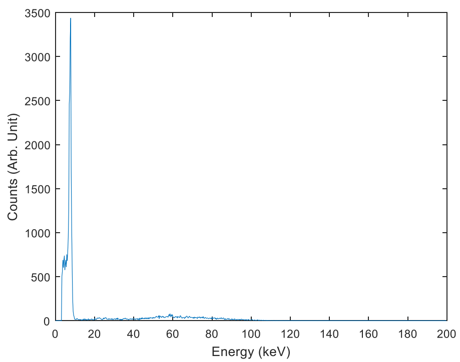

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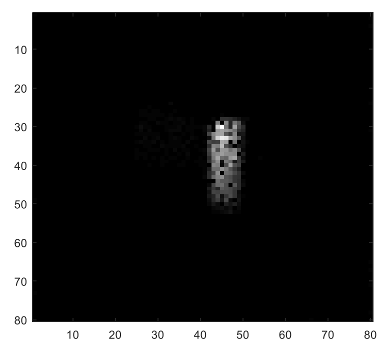

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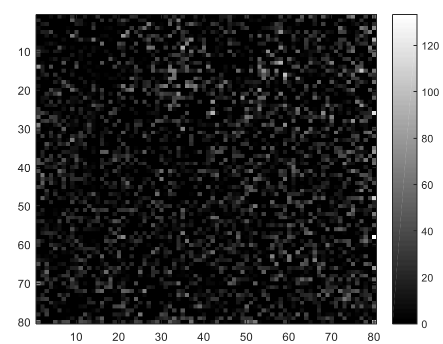
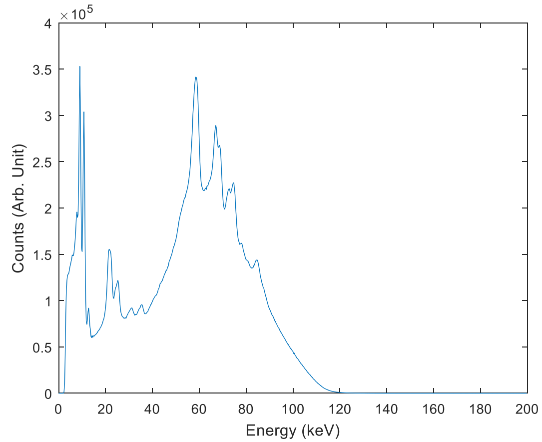


<Au 영상>

FXCT Experiment (2nd Generation)

- Gold Plate



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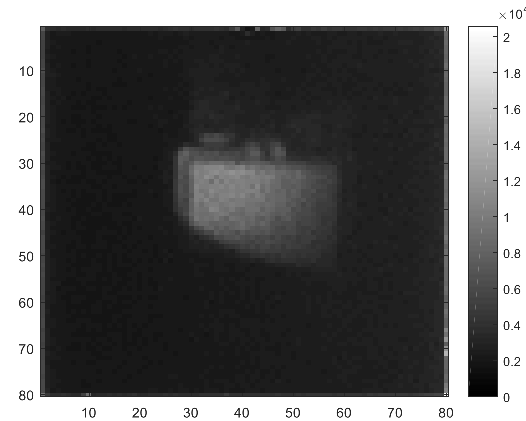

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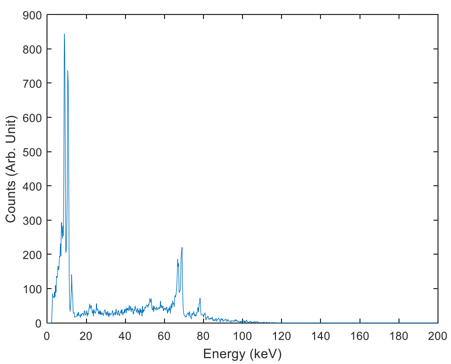

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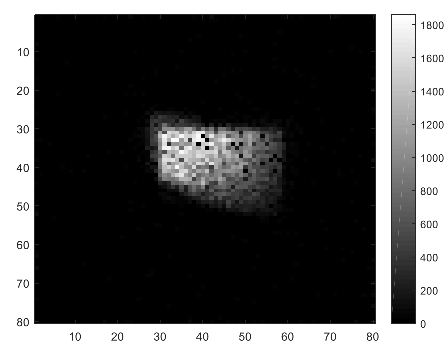

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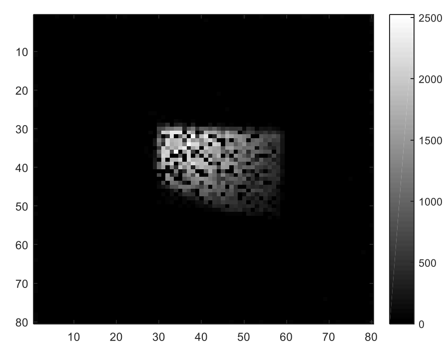

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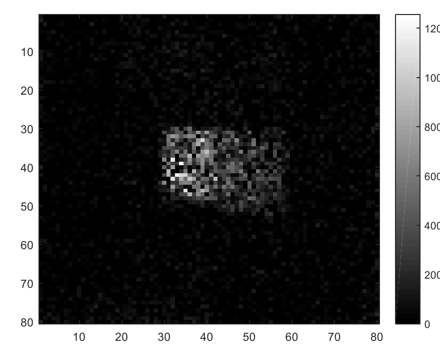
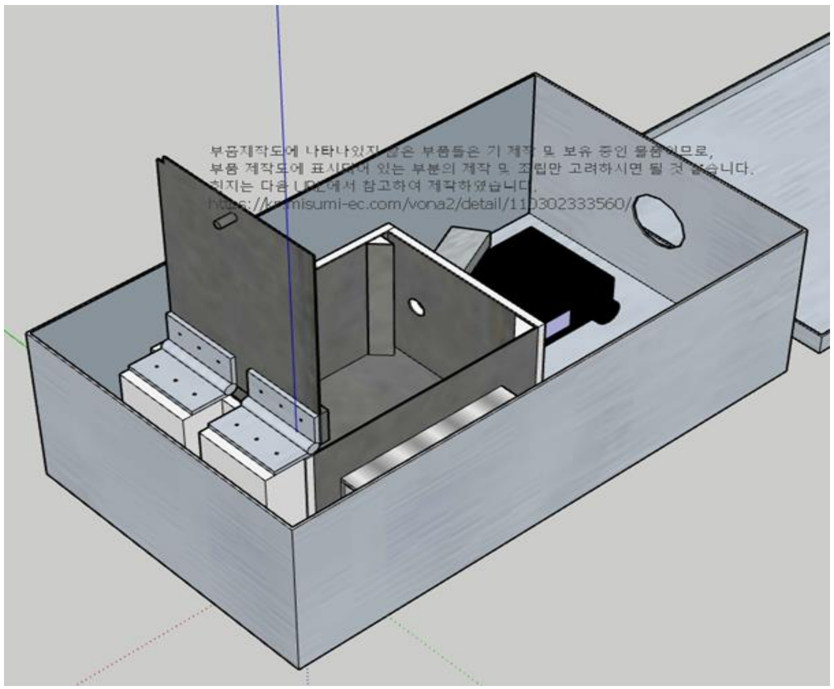


<Au 영상>

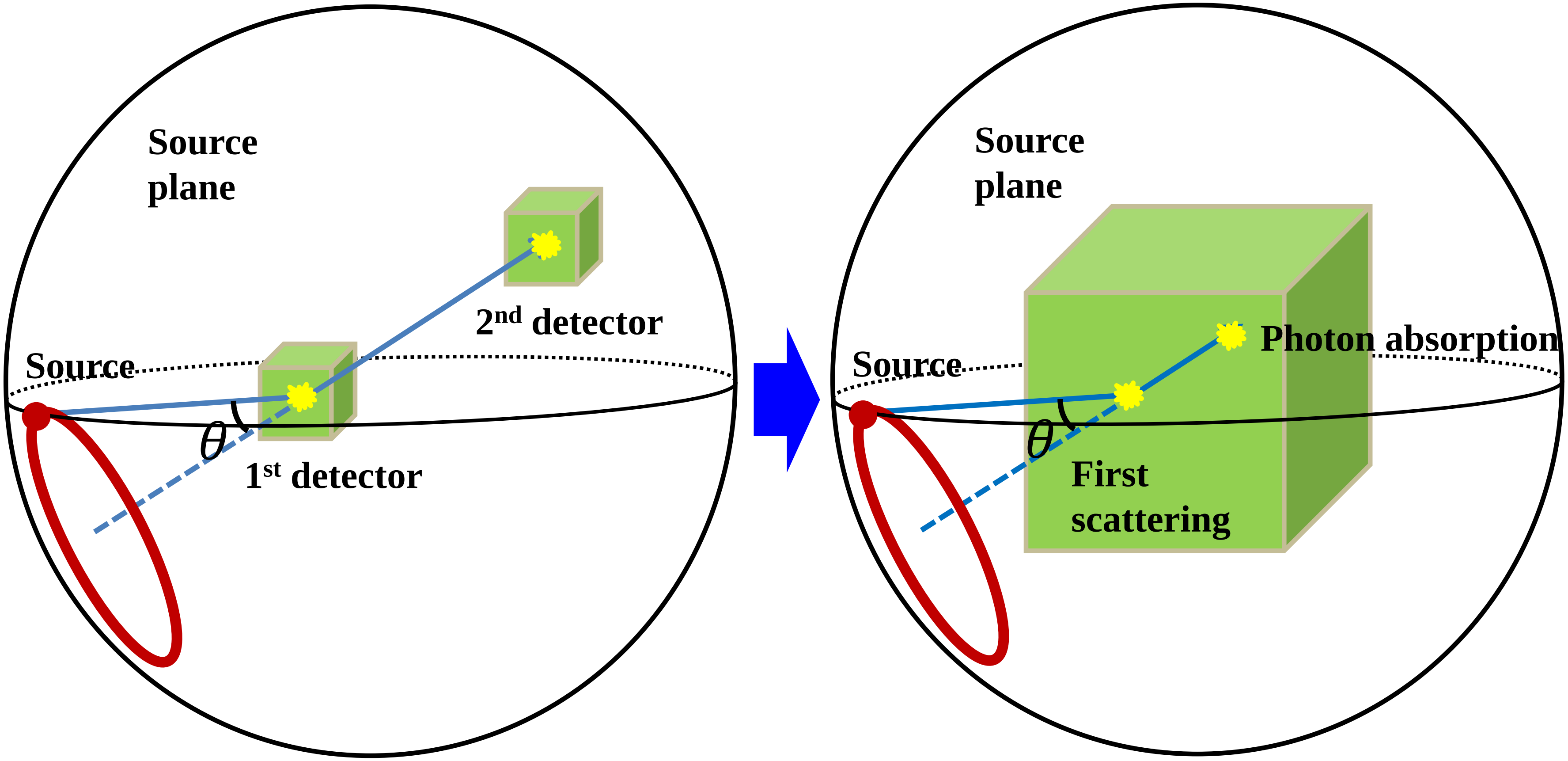
FXCT Experiment (2nd Generation)

- Mobile FXCT



Portable X-ray tube (50 kV), Field Application

CdZnTe 4π Compton Imager

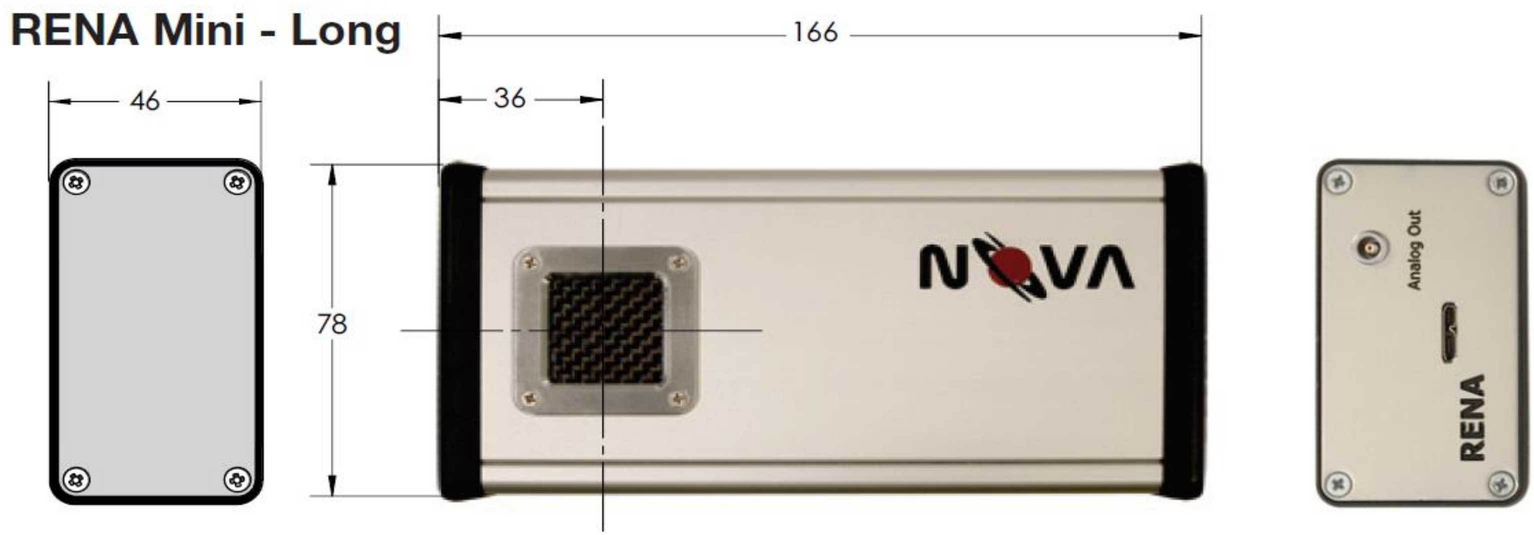


Conventional structure

Single detector

CdZnTe 4π Compton Imager

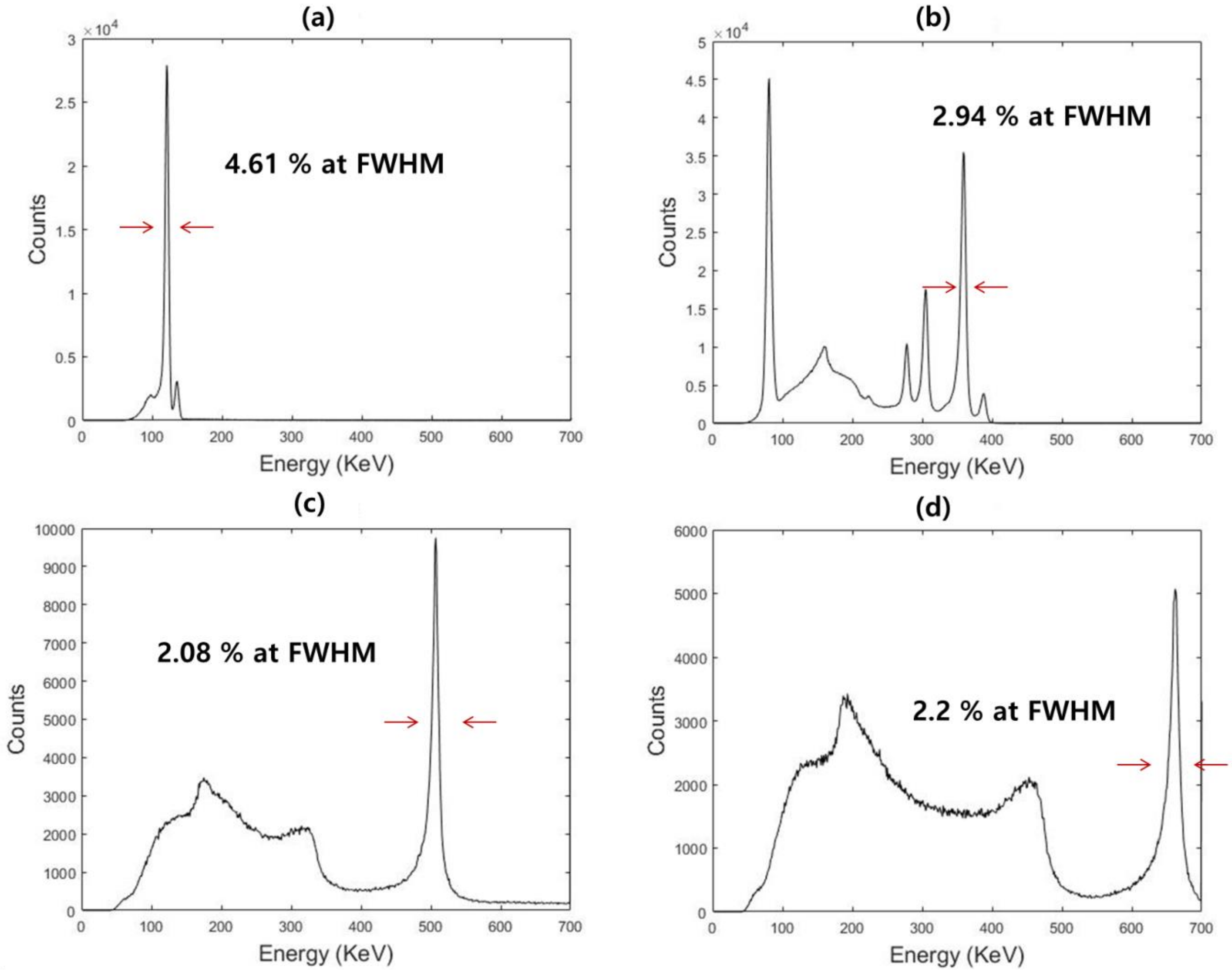
- **Rena-mini™ development kit with pixelated CZT from Kromek**



Parameter	Description/Value
Sensor type	Cadmium Zinc Telluride
Sensor size	20 mm × 20 mm × 5 mm (8 × 8 pixel pattern)
Energy range	20 keV - 3 MeV
Channel	64 channels for anode 1 channel for cathode (total 72 channels available)
Timing resolution	≤10 ns
Maximum count rate	10^5 count/s
Power consumption	≤6 mW/channel

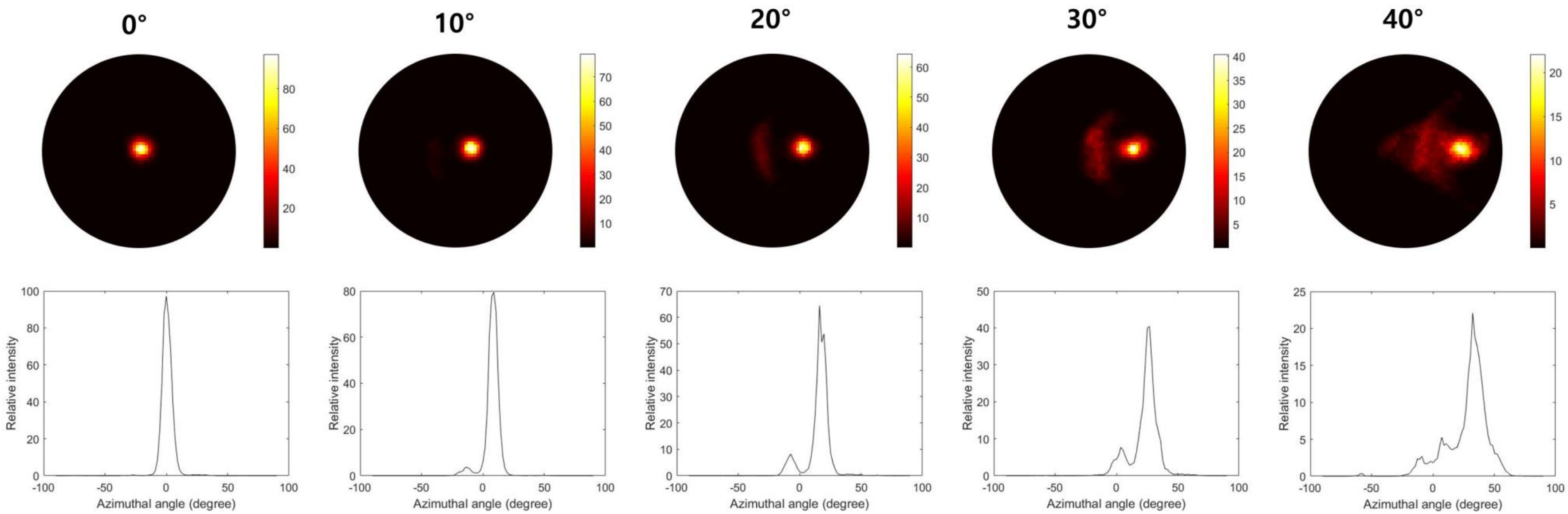
CdZnTe 4π Compton Imager

Total energy spectrum after drift time correction



CdZnTe 4π Compton Imager

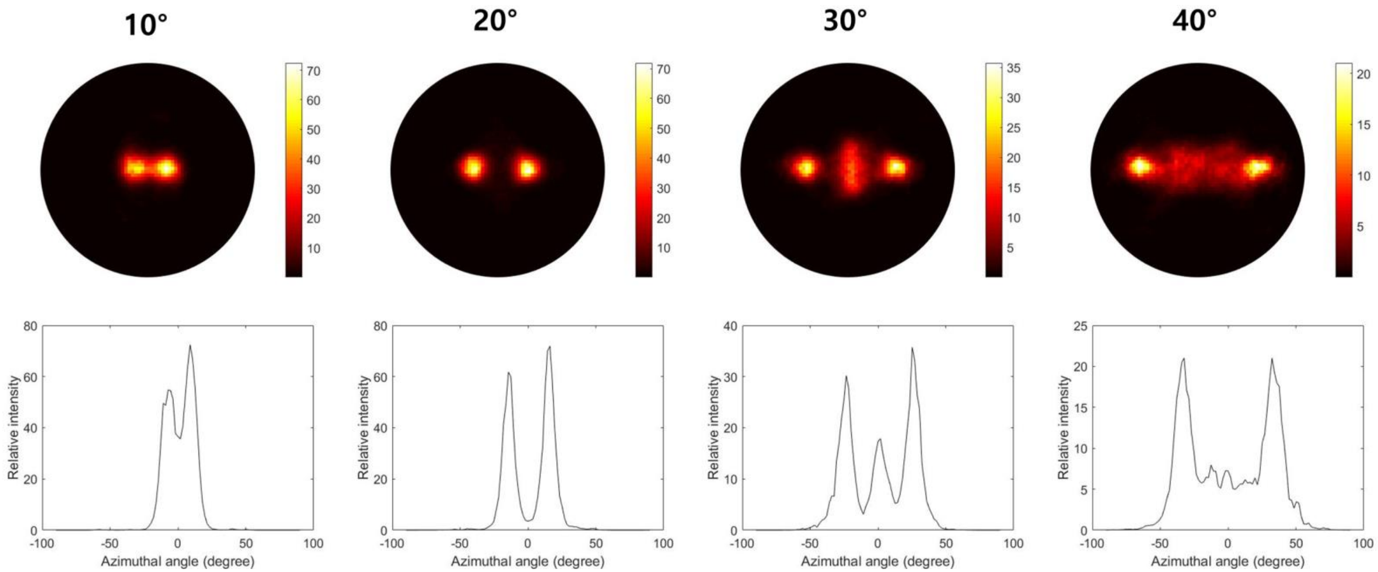
Image reconstruction for offset source (^{137}Cs)



Offset angle	FWHM	Source position (ERROR)	Intrinsic efficiency
0°	8.15°	0° (0%)	6.70×10^{-4}
10°	8.37°	9° (10%)	6.11×10^{-4}
20°	8.51°	16.2° (19%)	6.15×10^{-4}
30°	9.00°	27° (10%)	5.84×10^{-4}
40°	12.74°	32.4° (19%)	5.83×10^{-4}

CdZnTe 4π Compton Imager

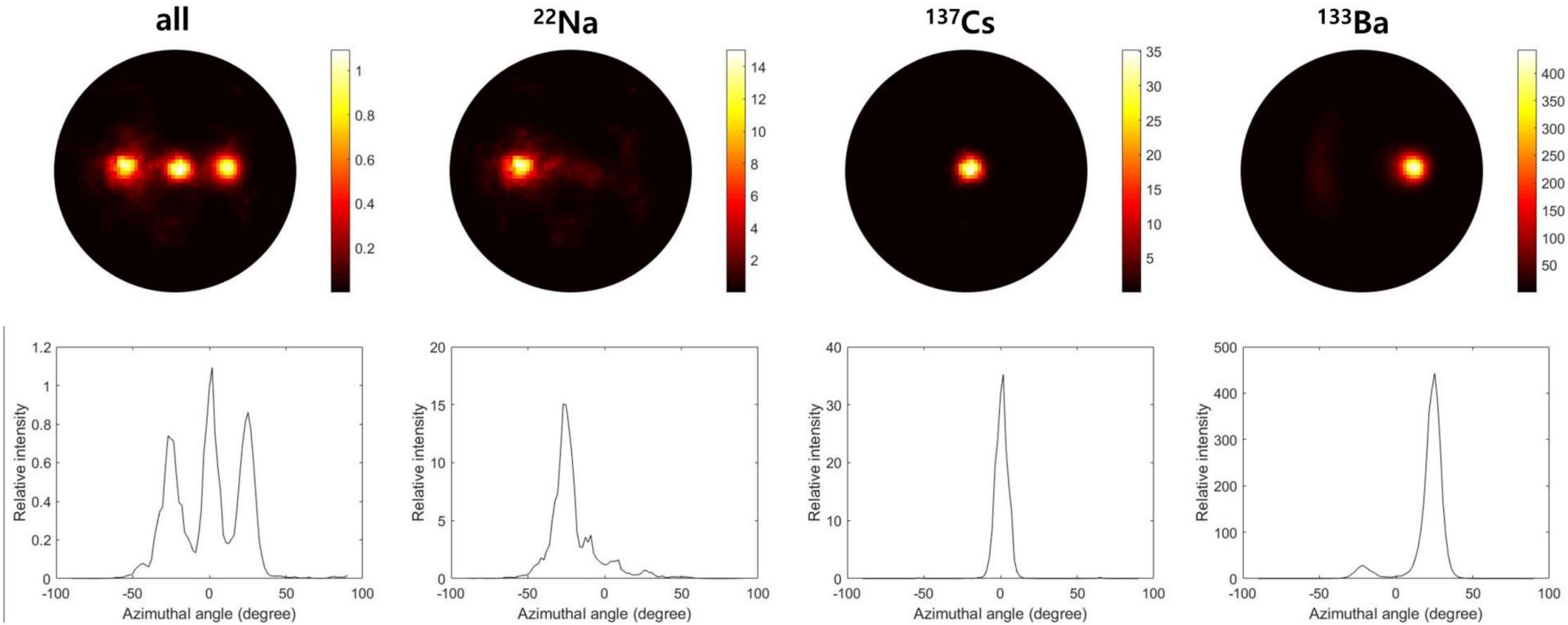
Image reconstruction for two ^{137}Cs sources



Offset angle	FWHM	Source position (ERROR)	Intrinsic efficiency
10°	8.10°	7.2° (28%)	7.11×10^{-4}
	7.58°	9° (10%)	
20°	8.13°	14.4° (28%)	7.07×10^{-4}
	7.54°	16.2° (19%)	
30°	7.56°	23.4° (22%)	5.76×10^{-4}
	7.20°	25.2° (16%)	
40°	7.66°	32.4° (19%)	4.87×10^{-4}
	7.04°	32.4° (19%)	

CdZnTe 4π Compton Imager

Image reconstruction for multiple sources (Simultaneous measurement)

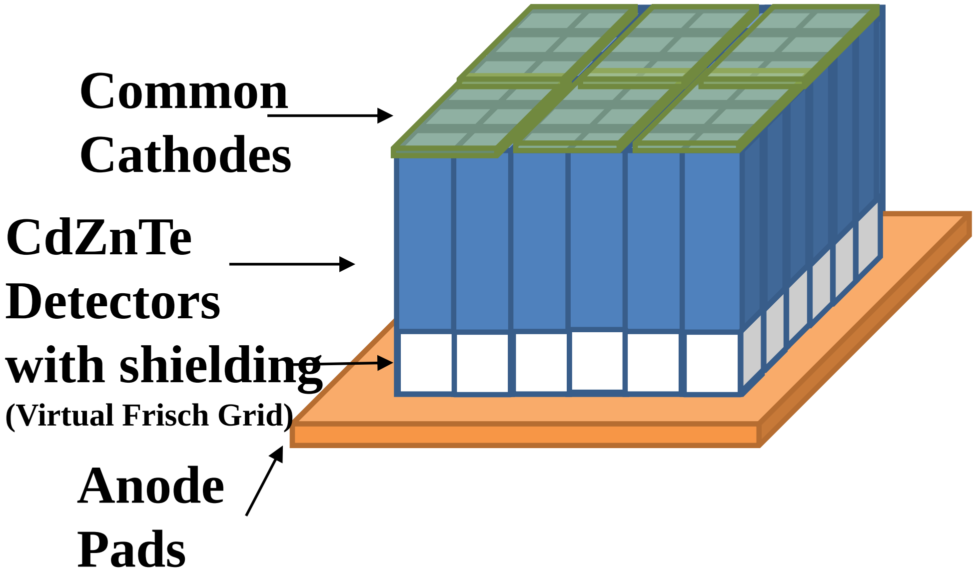


CdZnTe 4π Compton Imager

It is difficult to make a very large one. (>6 cm^3)

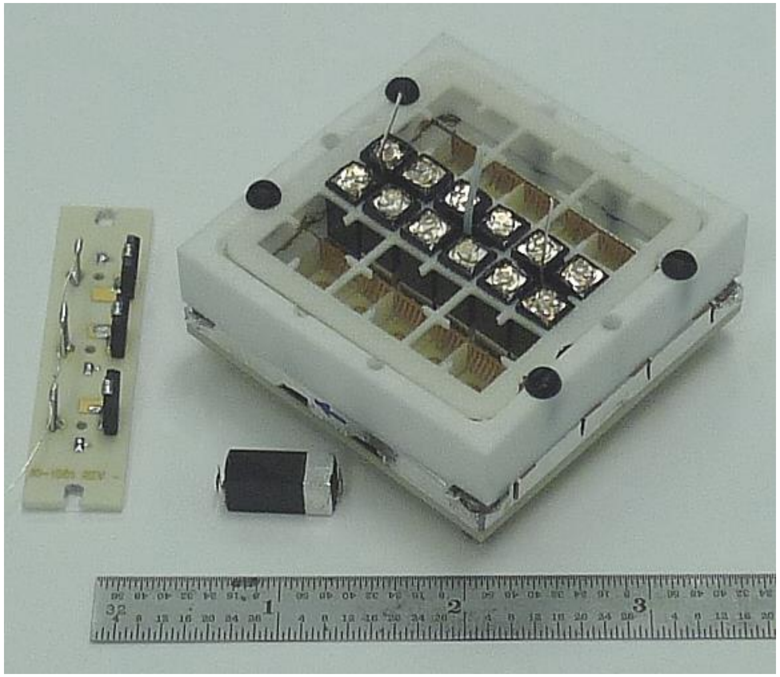
But it is easy make a small one.
(≅ 0.5 cm^3)

and **Make a Large Array by Segmentation!** **(≅ 20 cm^3)**
with specialized electrodes

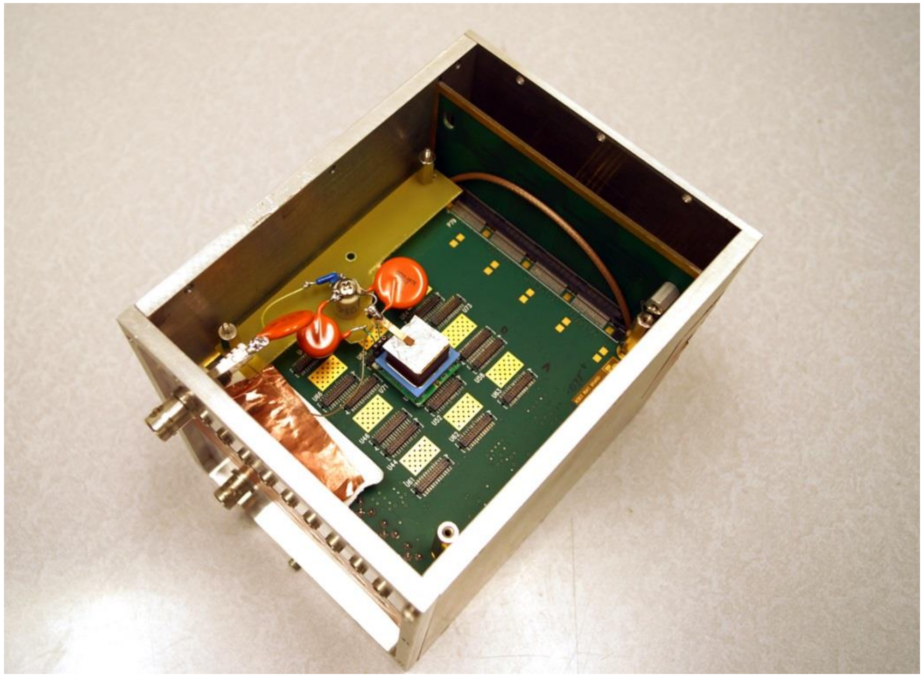


CdZnTe 4π Compton Imager

BNL



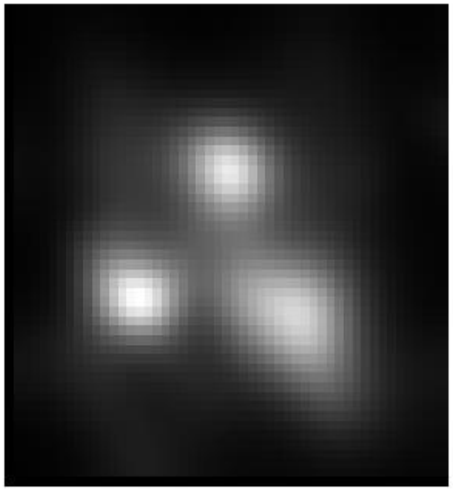
Detector Array

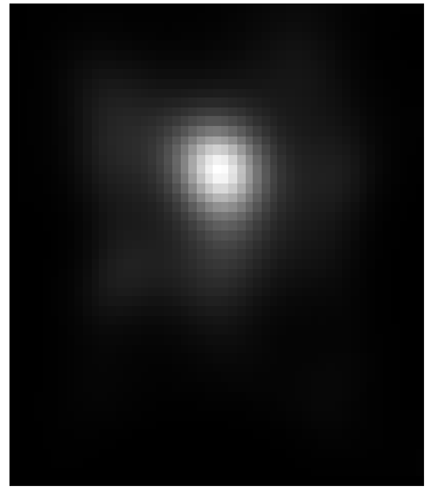


ASIC and HV connection

CdZnTe 4π Compton Imager

All Three Sources

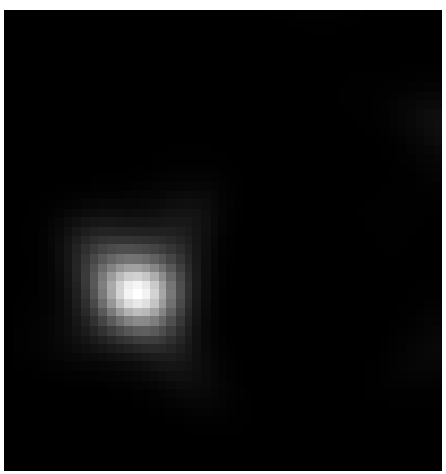


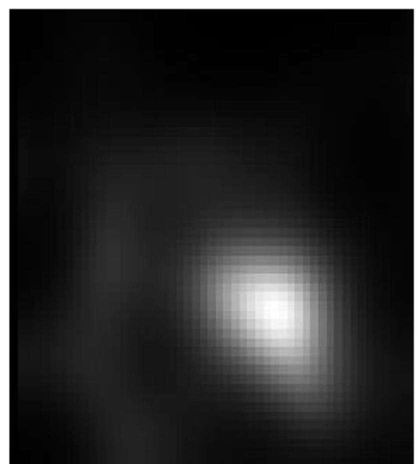


^{137}Cs (662 keV)

MLEM, 50th Iteration
50° between sources

^{60}Co (1173, 1332 keV)





^{133}Ba (356 keV)

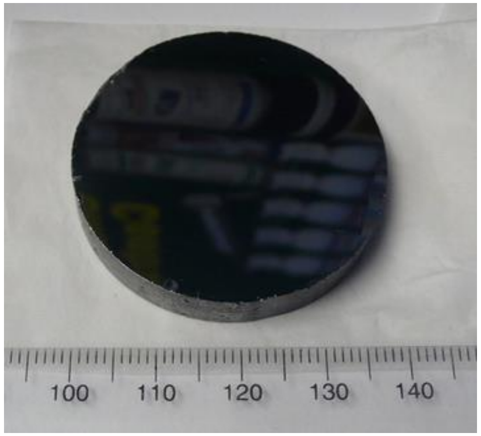
CdZnTe 4π Compton Imager

1. Furnace

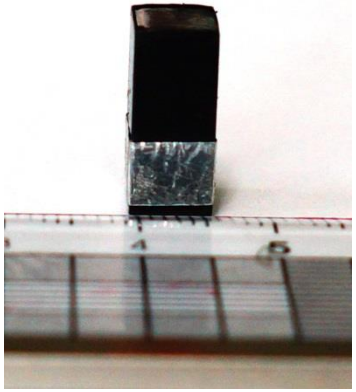
2. Ingot

3. Wire Sawing

4. Polishing



5. Wafer



6. Detector (15mm)

Courtesy by Prof. Kihyun Kim

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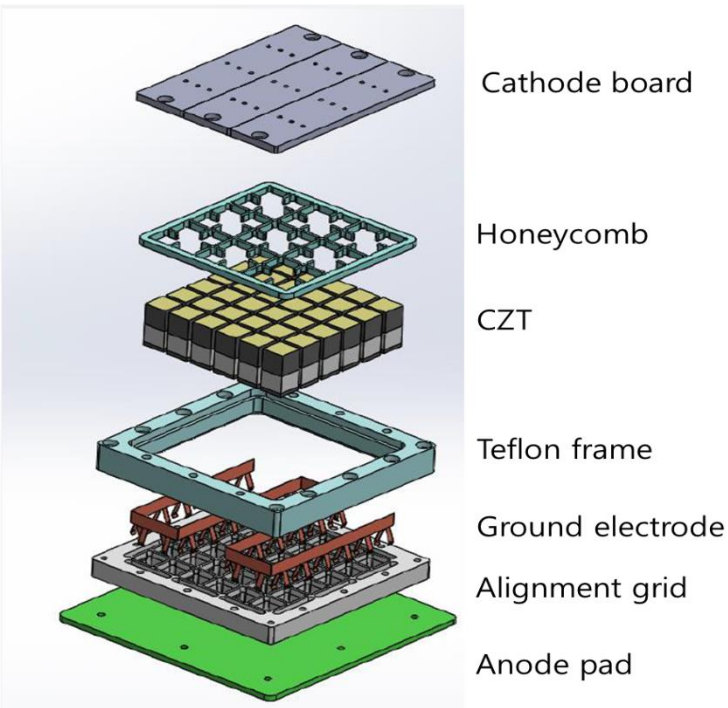
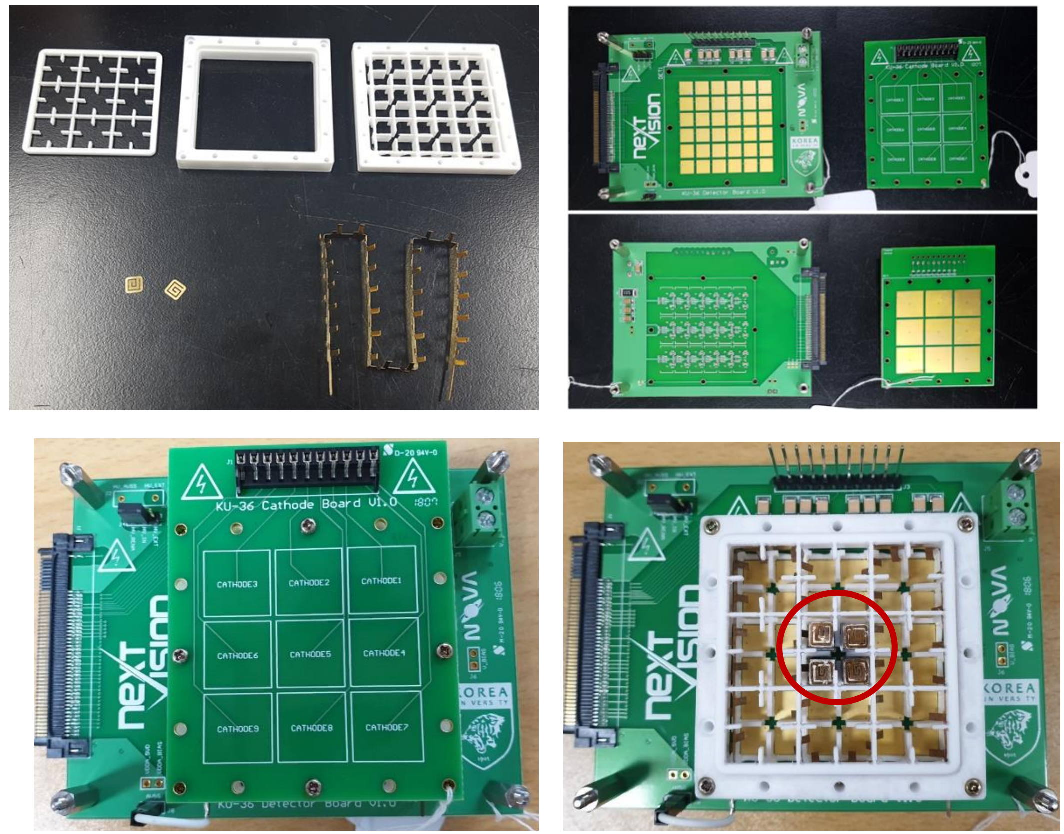
CdZnTe 4π Compton Imager



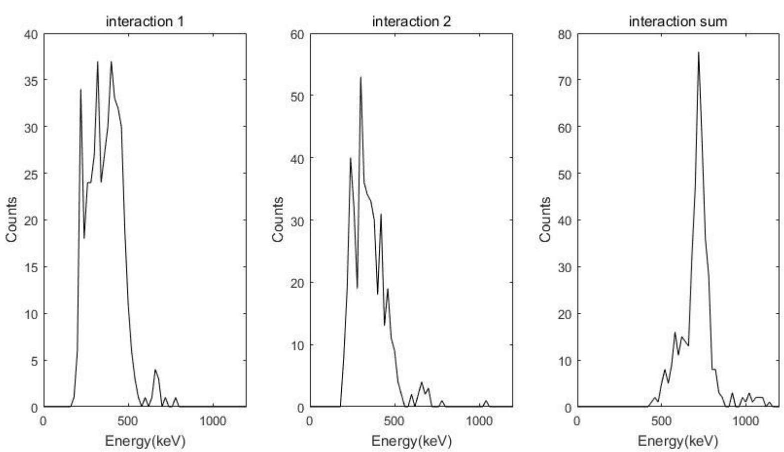
Schematic Diagram



Assembled System

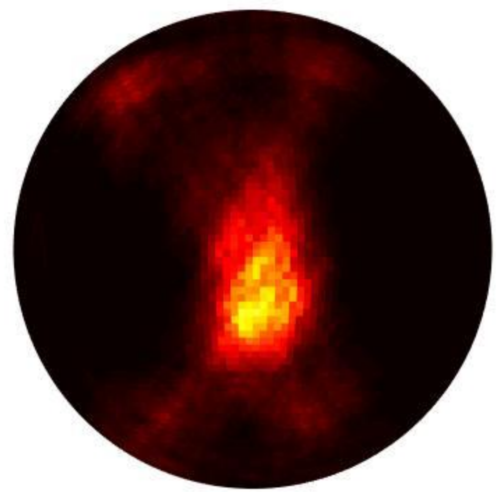
CdZnTe 4π Compton Imager

Assembled System



Energy Spectrums

(1st 2nd and Sum events)



4π Reconstructed Image

(Side exposure, 10 min, 10 uCi, 5 cm)

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Conclusion and Discussion

- Detection system is a Base for Radiation Application
- Researches for Detection System in Korea
- Current Research in RMI of Korea Univ.
- Specially Demanding Points in Korea Technology
  - Detector Material
  - Analog Signal Integrated Circuit (ASIC)
  - More than 20 – 30 years of Research on the Topics
    . Compete with Small but Strong Companies
    . Domestic Market is limited

Solution?

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Conclusion and Discussion

- Solution?
  - Continuous Support
    - World Leading Small Companies needs >30 years
    - Technician as well as Idea
    - Venture (Startup) Companies (Univ.)
  - Cooperation
    - Academy-Research-Industry
    - Connection between Researchers
    - No Negative Competition <- Large Gross Sum
    - International Research