Non-destructive Isotope-Selective Imaging by Laser Compton Scattering Gamma-ray

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Acknowledgment

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- AIST
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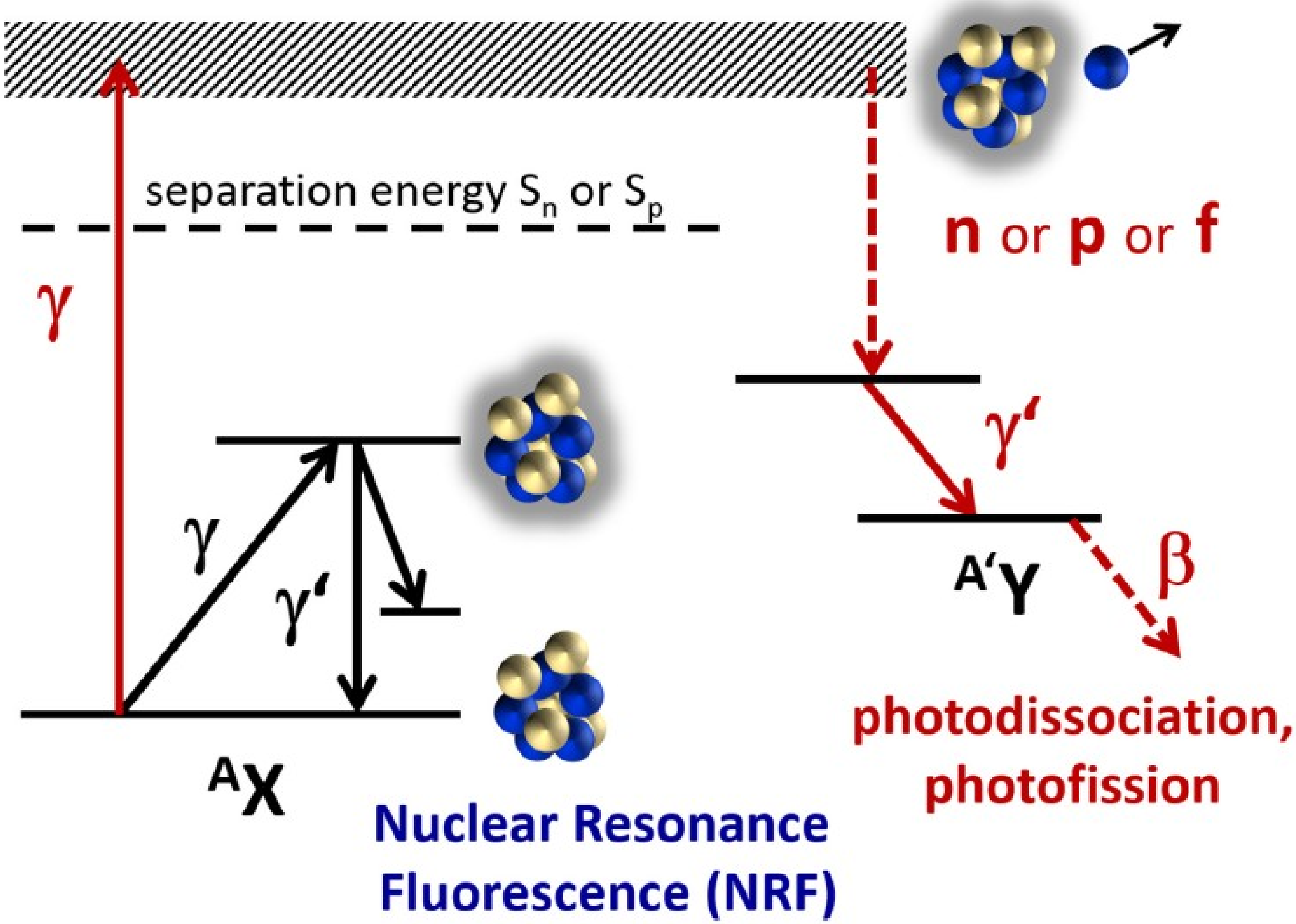
- UVSOR
  - M. Kato, Y. Taira

Contents

Why Gamma-rays?

- All matter in our universe has permanently been bombarded by photons.

- High energy photons (Gamma-rays) can cause photoexcitation and photodisintegration of atomic nuclei photoexcitation photodisintegration



A. Zilges, Prog. in Particle and Nucl. Phys. 122, 103903 (2022)

- **Real photon** vs Virtual photon (Coulomb force)
  - Pros: dipole excitation because of almost no momentum transfer, simple mechanism, cleaner environment
  - Cons: no high momentum transfer reaction, **no good Gamma ray sources**
    - RI sources: mono but discrete energy, weak yield
    - Bremsstrahlung: continuous spectrum, strong yield, poor polarization

Some milestones for the scientific exploitation of photonuclear reactions

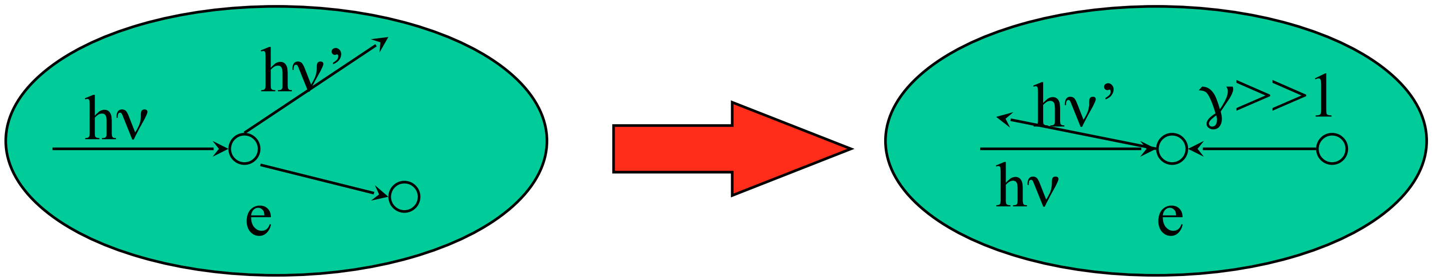
1937 – (p,γ) *reaction and subsequent photodissociation* (*Bothe, Gentner*)
1947 – *Bremsstrahlung from betatron* (*Baldwin, Klaiber*)
1953 – *Positron annihilation in flight* (*Colgate, Gilbert*)
1963 – *Laser Compton Backscattering* (*Milburn, Arutyunian, Tumanian*)
1969 – Bremsstrahlung from Van de Graaff accelerator (*Metzger*)
1983 – Tagged photons (*Knowles et al.*)
1980s – High-performance bremsstrahlung (*Kneissl, Richter*)
1990s – High-performance laser Compton backscattering (*Litvinenko, Ohgaki, Pietralla*)

A. Zilges, Prog. in Particle and Nucl. Phys. 122, 103903 (2022)

Stuttgart Dynamitron, S-DALINAC

https://www.ikp.tu-darmstadt.de/forschung_kernphysik/experimentelle_geraete/s_dalinac_details//

What's Laser Compton Backscattering Gamma-rays?



Compton Scattering

hν>hν'

Compton Backscattering

hν<<hν'

- Tunable Energy
- Quasi-monochromatic
- High Polarization
- Photon Yield….

AIST-LCS facility (1985-2011)

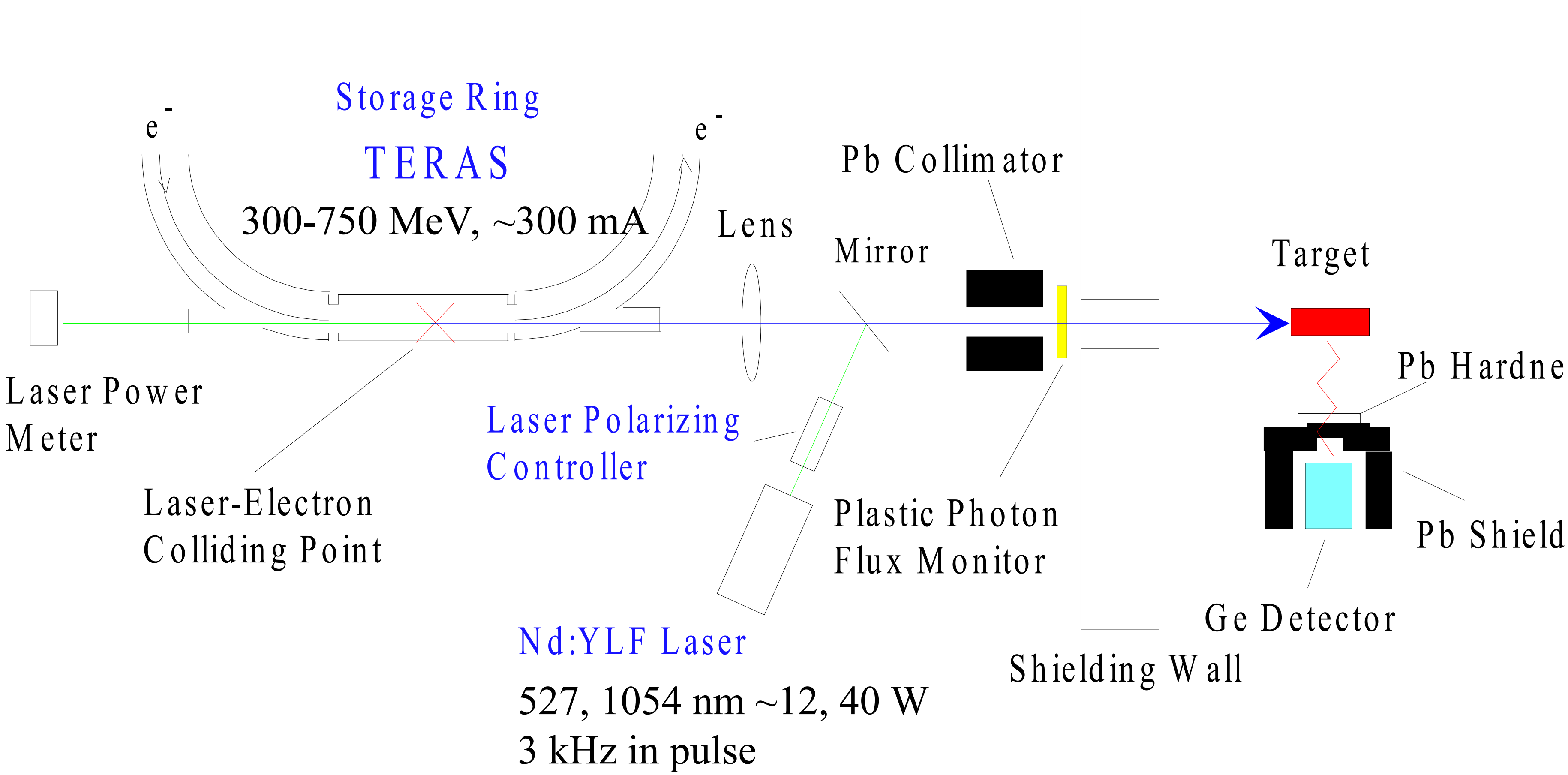
Mission

Establishment of a gamma-ray standard field in MeV region

Then

- Beam Diagnostic of the Electron Storage Ring
  - Electron Energy
  - Energy Spread
  - Beam Divergence
- Detector calibration
- Nuclear Physics
  - Polarized Photon Scattering => Dr. Shizuma
  - Photonuclear Reaction => Prof. Utsunomiya
- Industrial application
  - Gamma-CT => Isotope-CT
  - Positron => Prof. Taira

AIST-LCS facility

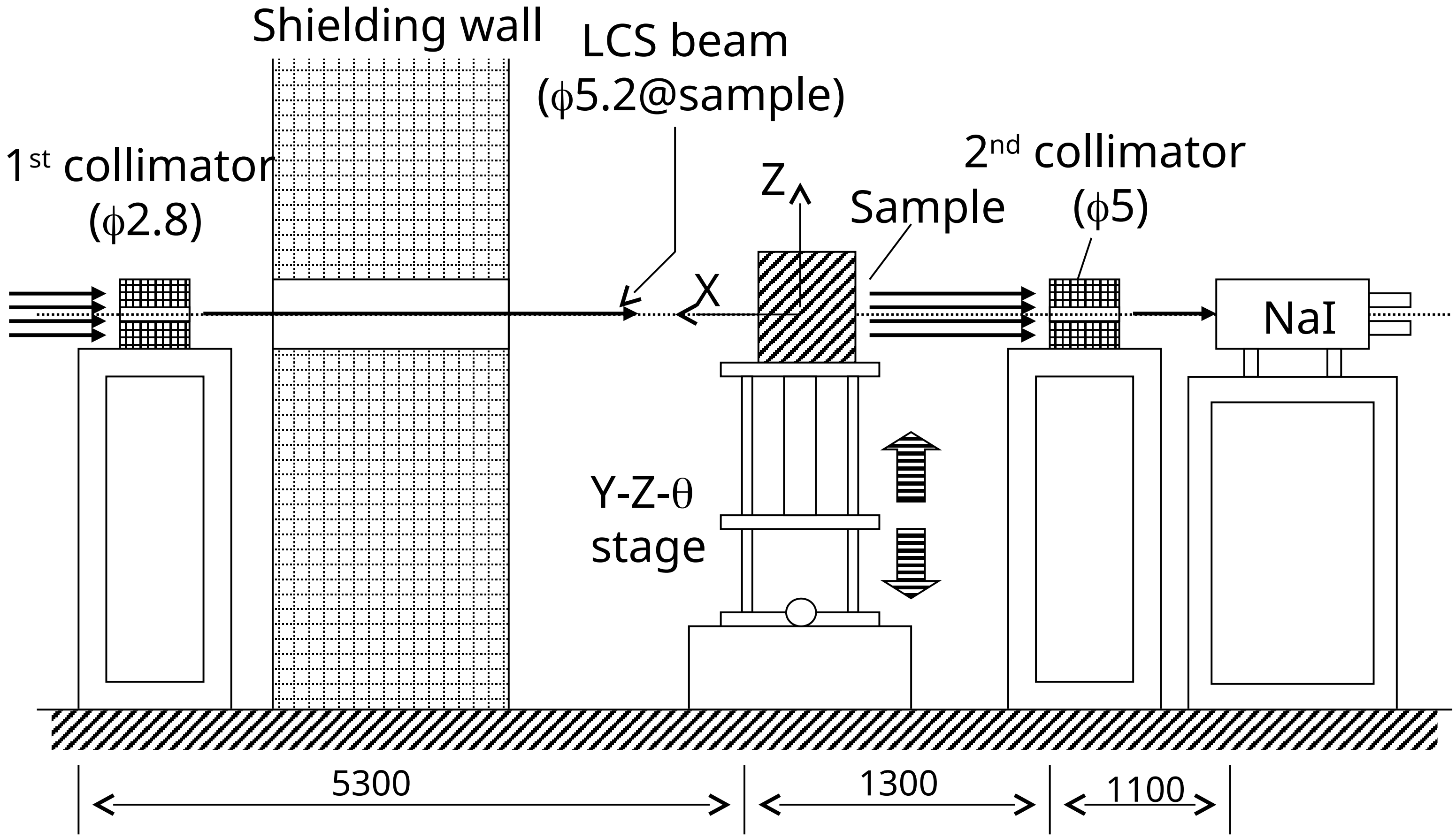


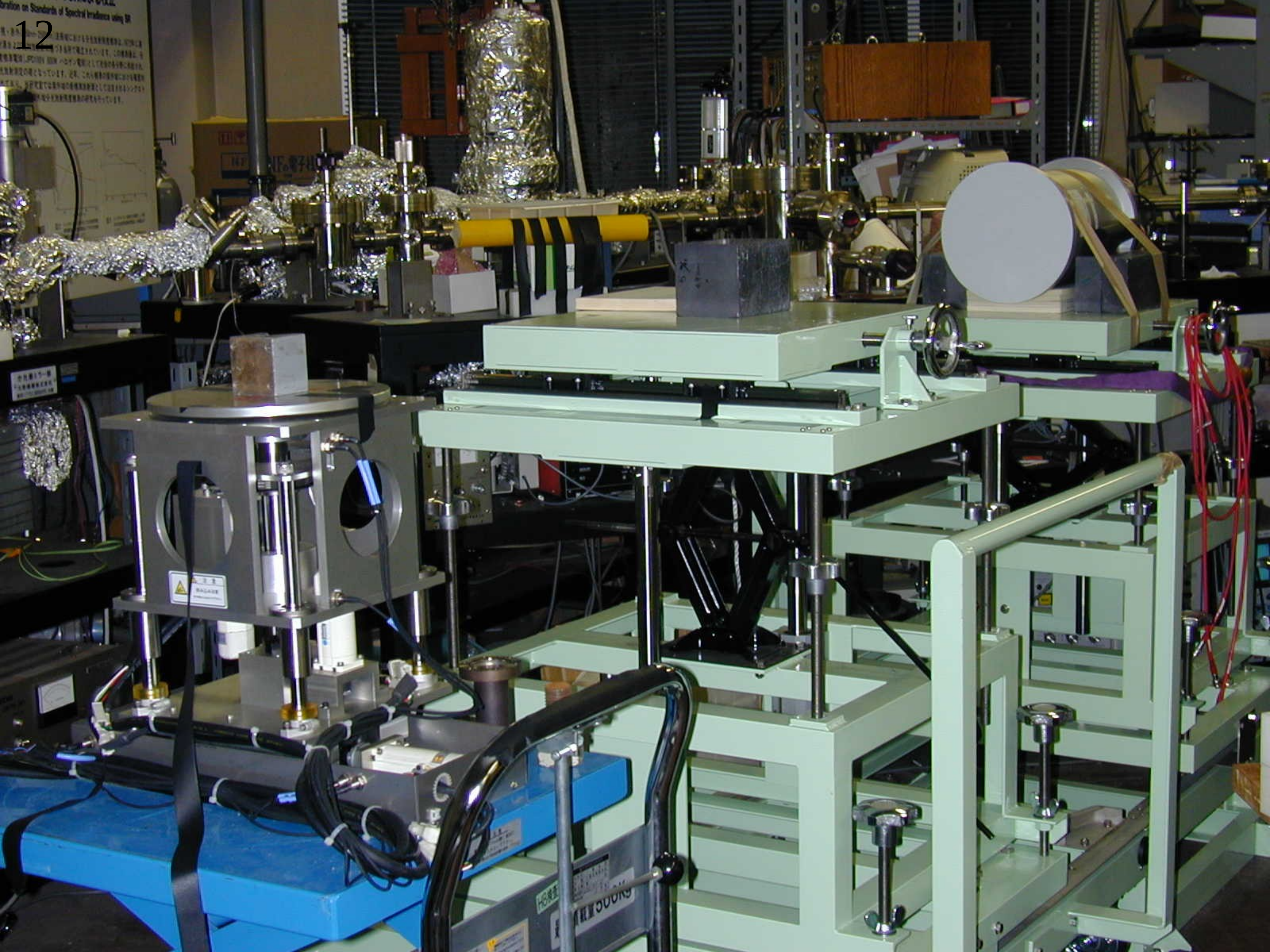
Simple and easy to understand, everybody feel that I can do this!

Electron Energy: 300 – 750 MeV

Few SR users!!!

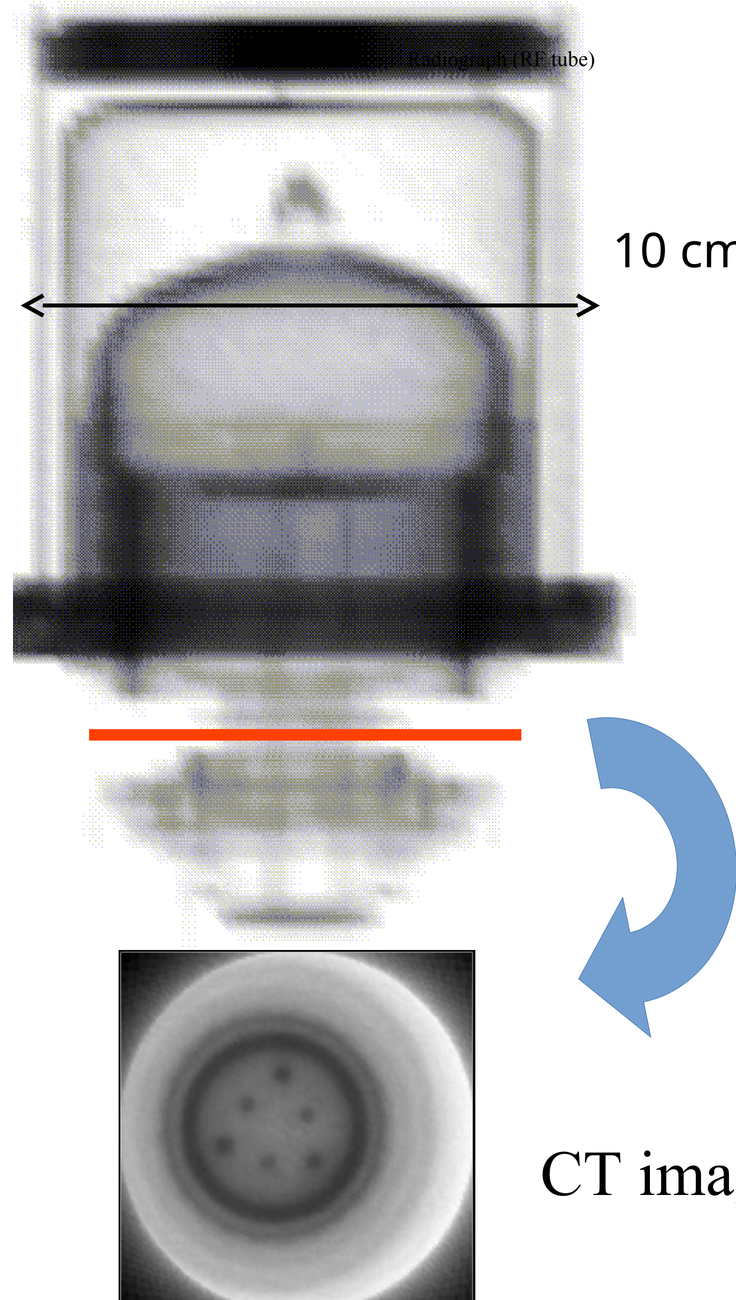
LCS Radiography and CT





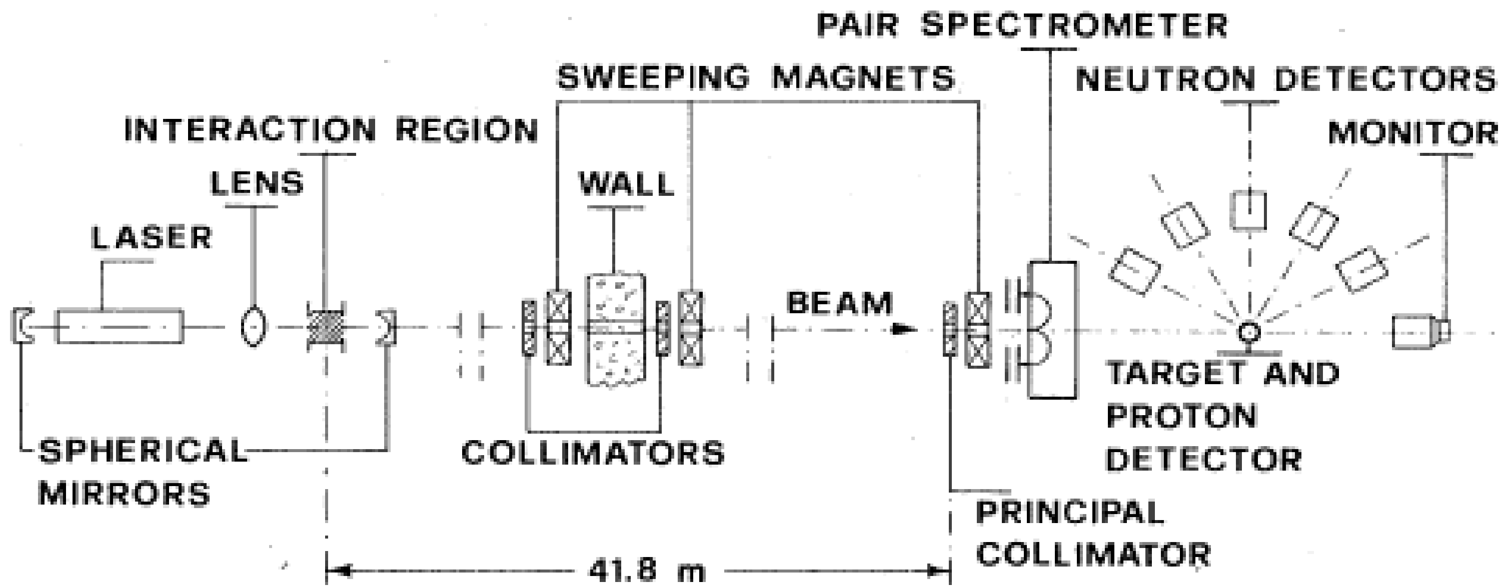
10 MeV Gamma Beam

H. Toyokawa, H. Ohgaki, IEEE Trans. NS, vol.49, 182 (2001)



CT image

Polarization asymmetry in the photodisintegration of the deuteron



LADON @ Frascati

E= 5 to 78.7 MeV
Polarization=99%

M.P. De Pascale, PRC vol.32, No. 6, 1830 (1985)

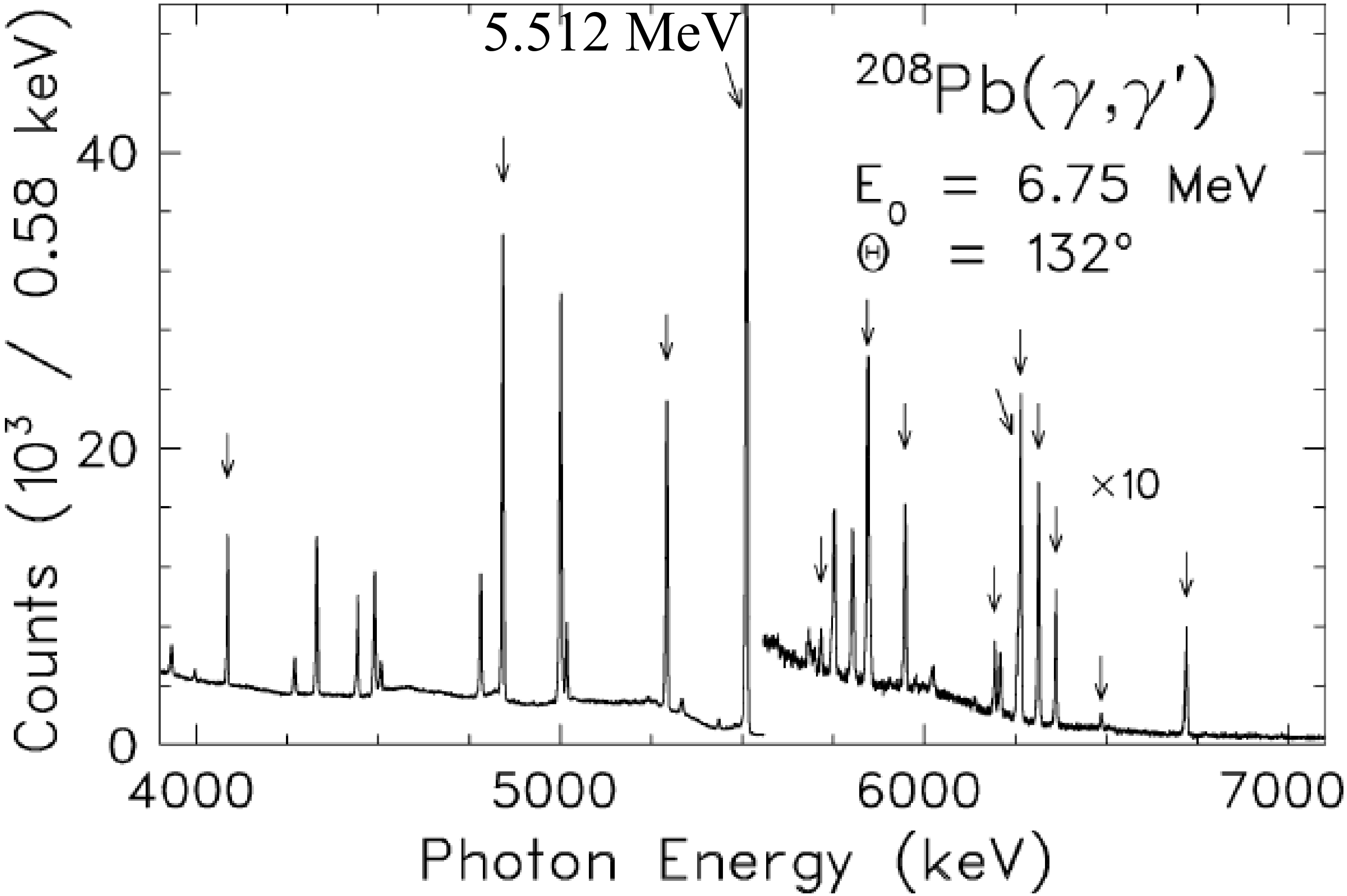
Linearly Polarized Photon Beam

NRF Asymmetry $A(\theta)=\frac{1}{p}\frac{\sigma(\theta,0)-\sigma(\theta,90)}{\sigma(\theta,0)+\sigma(\theta,90)}$

Multipolarity	Spin Sequence	$A(\theta=90°)$ $P=100\%$
E1	0^+-1^--0^+	-1
M1	0^+-1^+-0^+	+1
E2	0^+-2^+-0^+	+1

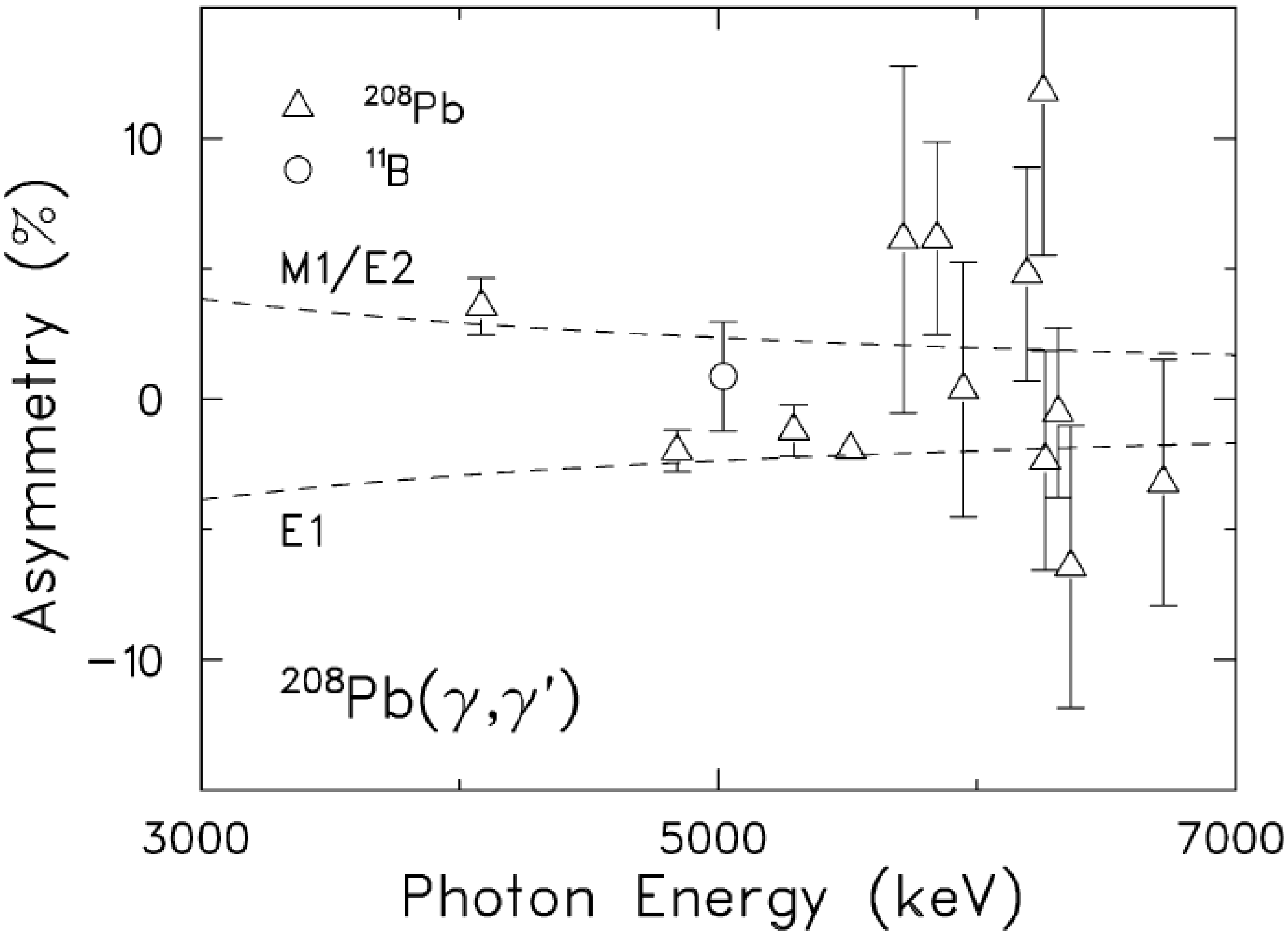
R.D.Heil et. al, Nucl. Phys.506(1990)p223.

Bremsstrahlung beam



J. Enders, Nucl. Phys. A 724 (2003) 243–273

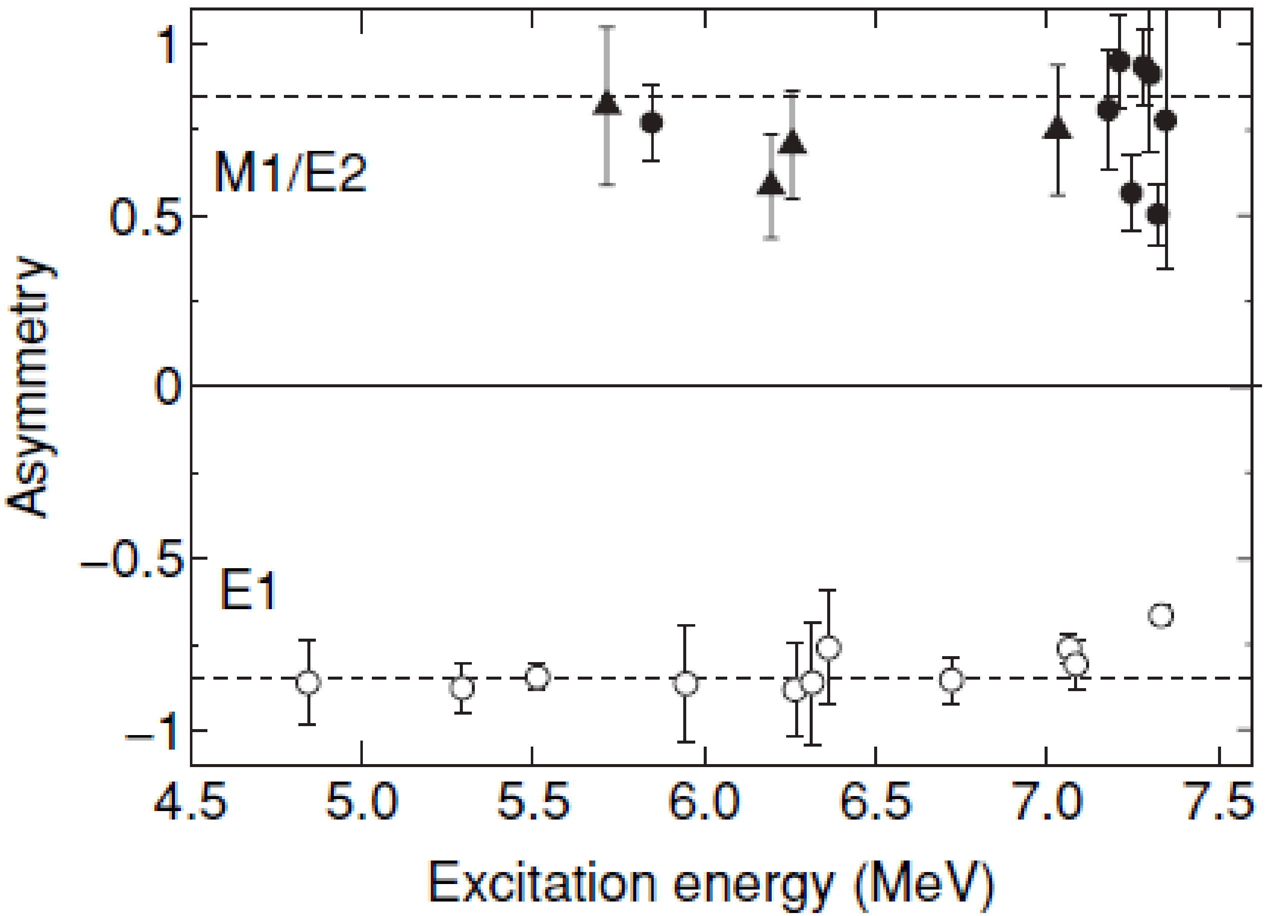
Bremsstrahlung beam



J. Enders, Nucl. Phys. A 724 (2003) 243–273

LCS beam

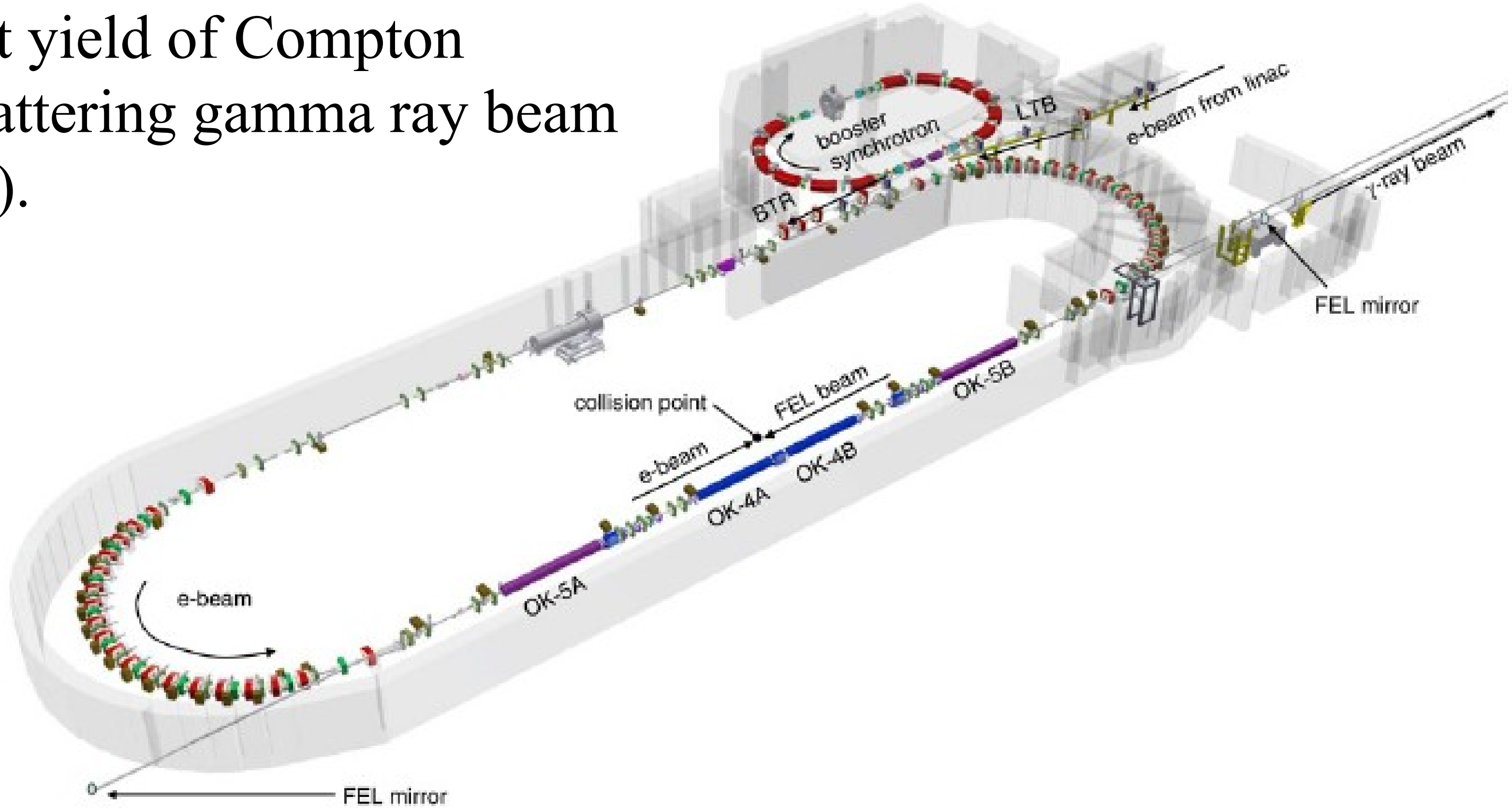
Fine structure of the magnetic-dipole-strength distribution in ^{208}Pb



T. Shizuma, Phys. Rev. C78, 061303(R) (2008)

HIγS - High Intensity γ-Ray Source

Highest yield of Compton backscattering gamma ray beam (~10^7/s).



H.R. Weller et al., Prog. Part. Nucl. Phys. 62 (2009) 257

Pygmy and core polarization dipole modes in 206Pb: Connecting nuclear structure to stellar nucleosynthesis

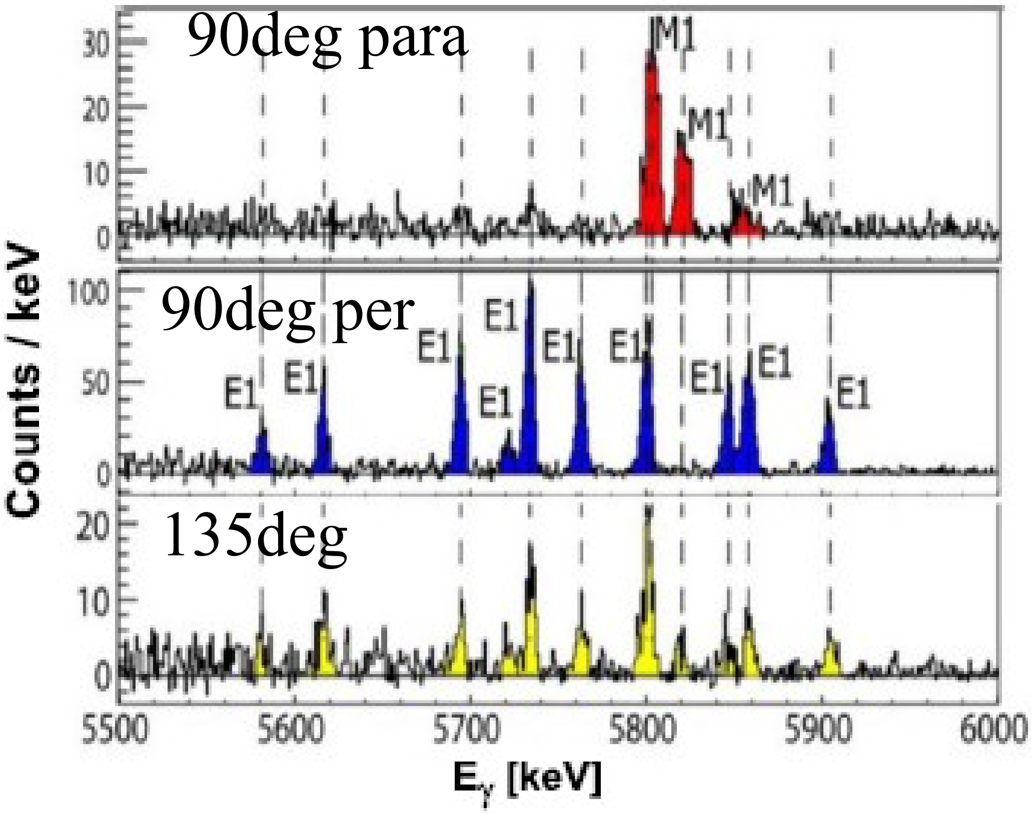


Table 1
Summary of the $E1$ and $M1$ strengths in ^{206}Pb.

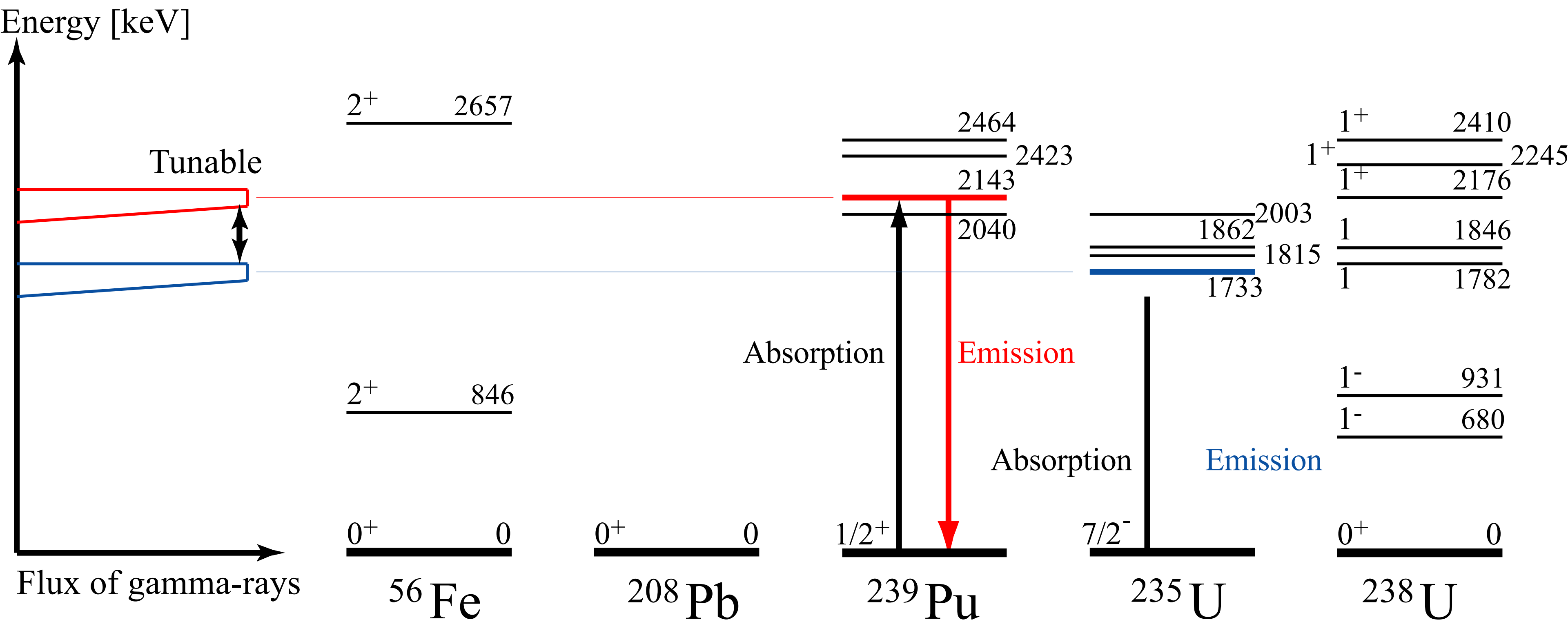
Parameter	Present data	EDF+QPM
Energy interval (MeV)	4.9–8.1	4.9–8.1
Number of $E1$ states:		
Within the exp. sensitivity[a]	100[a]	94
Total		340
$\Sigma B(E1)\uparrow$ (e^2fm^2)	0.9 ± 0.2	0.9
Number of $M1$ states:		
Within the exp. sensitivity[b]	26[b]	28
Total		170
$\Sigma B(M1)\uparrow$ (μ_N^2)	8.3 ± 2.0	8.9

[a] The sensitivity limit for a single $E1$ transition is $\sim 5 \times 10^{-4}$ e^2fm^2.
[b] The sensitivity limit for a single $M1$ transition is $\sim \times 10^{-2}$ μ_N^2.

@HIγS

A.P.Tonchev, Phys. Let. B773 (2017) 20-25

Novel Nondestructive Assay by LCS gamma-rays



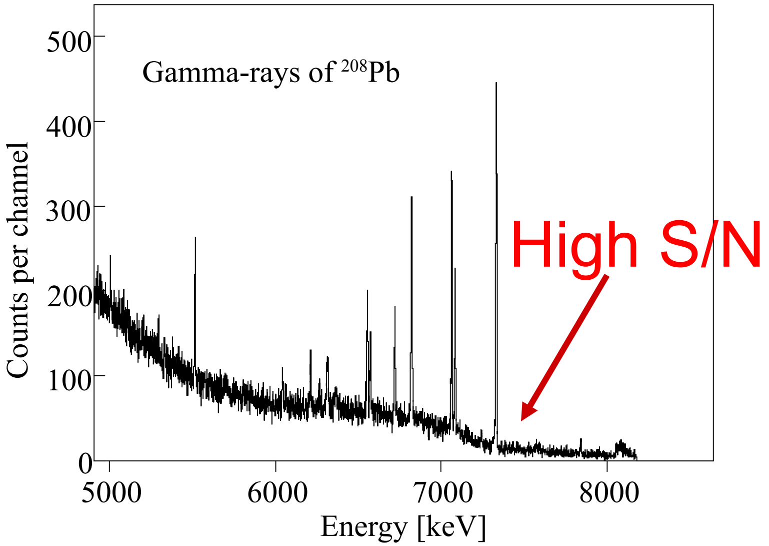
- •Only expected nucleus is excited and subsequently de-excites with emission of γ-ray.
- •With energy tunable monochromatic gamma-ray beam, we can detect selectively an isotope of interest.

Advantages

A combination of LCS gamma-rays and NRF provides

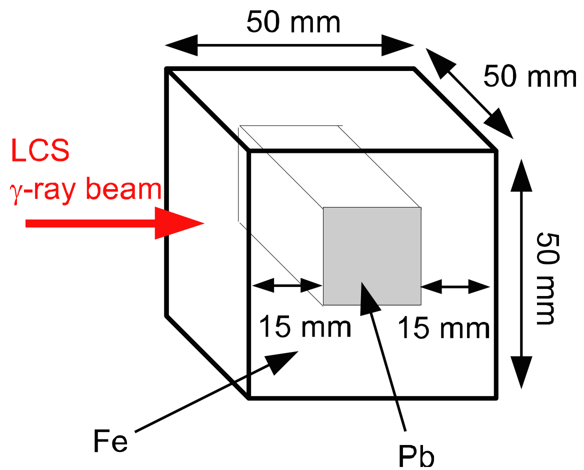
- Detection of isotopes of all the elements of Z>2
- High S/N ratio at peak
- With about 2-MeV gamma-rays we can detect Pu, U through thick shields, iron, lead, and water.
- No production of radioactive materials by 2-MeV gamma-rays

Example of detection of Pb-208 with a LCS gamma-rays



T.Shizuma,et al., Phys. Rev. C 78, 061303(R) (2008)

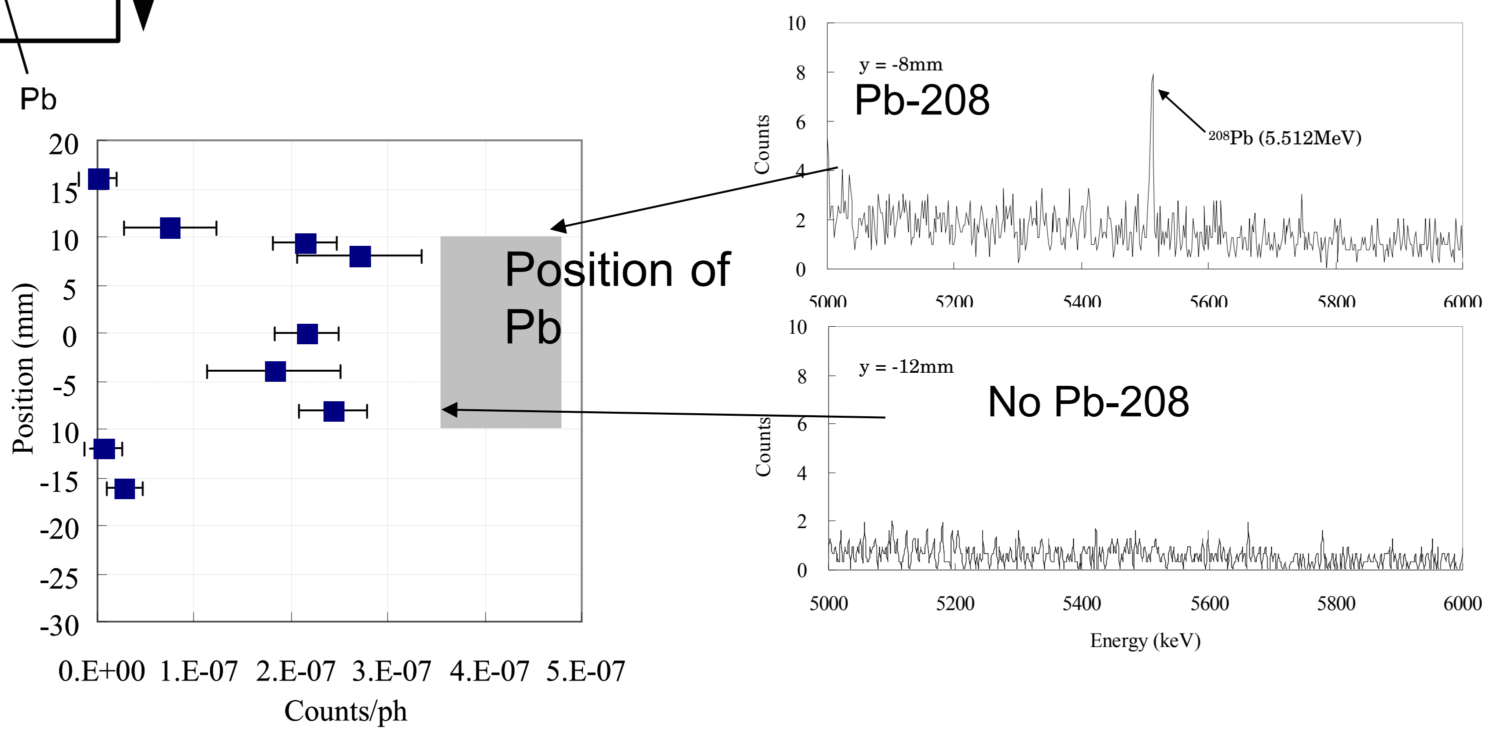
Detection of a hidden isotope



Pb-208 hidden by 15mm iron plate.

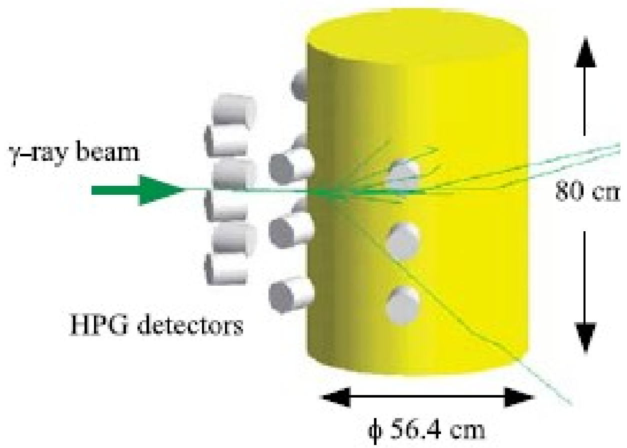
Exciting 5.512 MeV level

Imaging!?



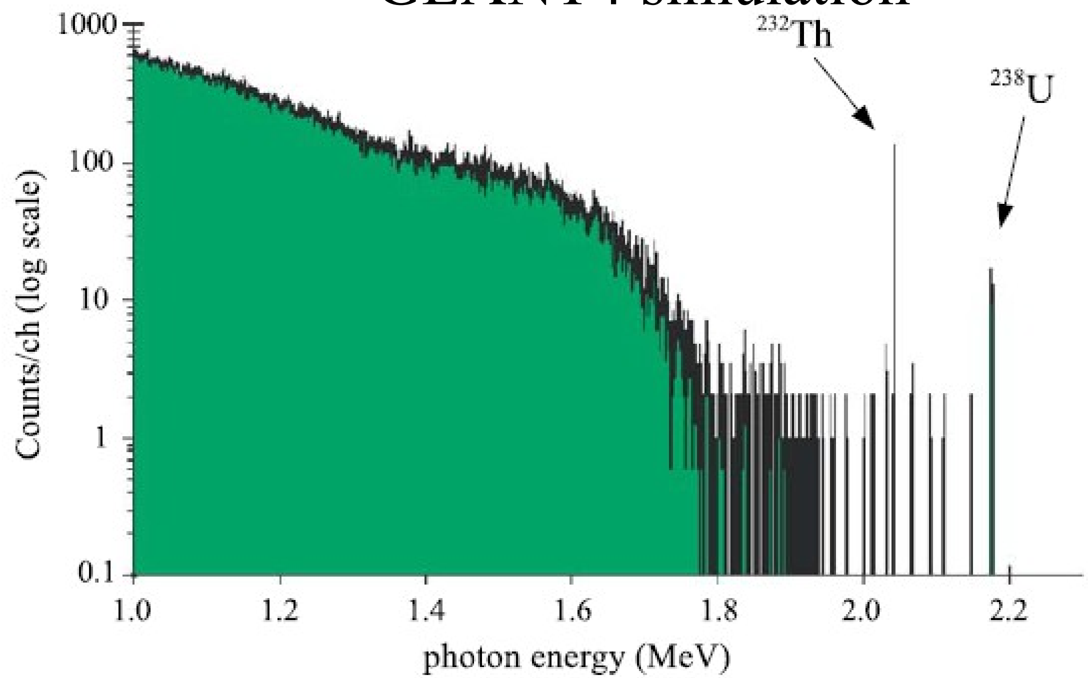
N. Kikuzawa et al., Applied Physics Express 2, 036502 (2009).

Detection of radioactive isotopes by using laser Compton scattered γ-ray beams



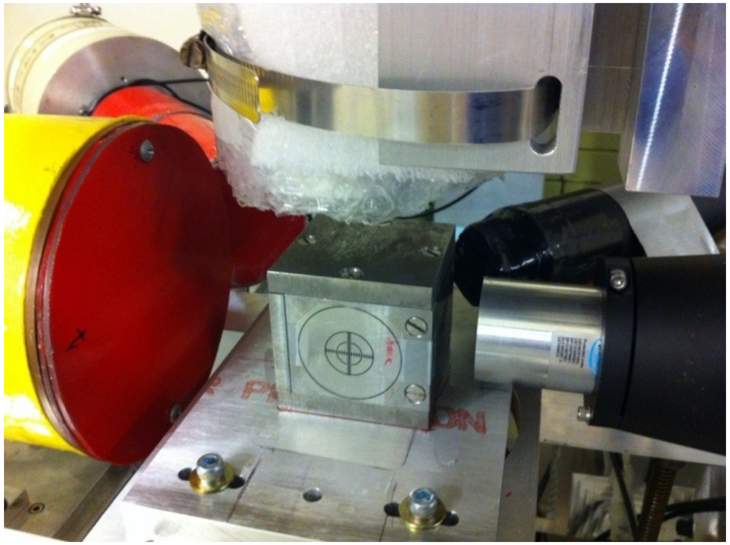
200L drum, 18 Ge

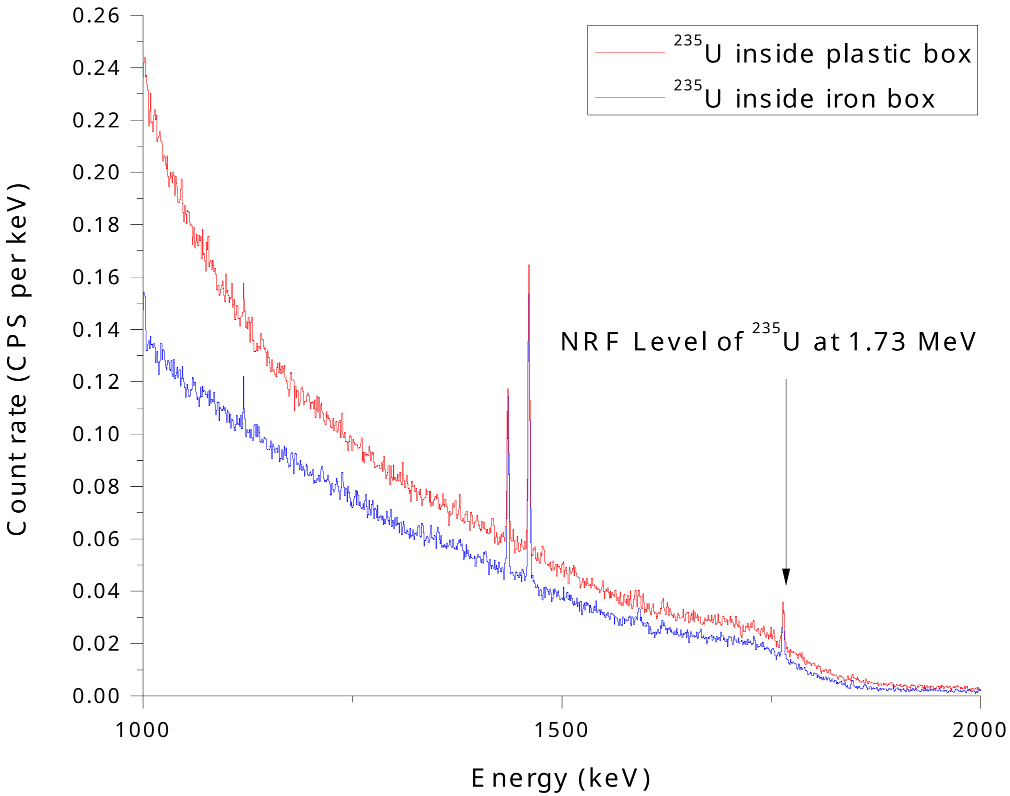
GEANT4 simulation



R. Hajima, NIM A608 (2009) S57

NRF Experiment in HIγS





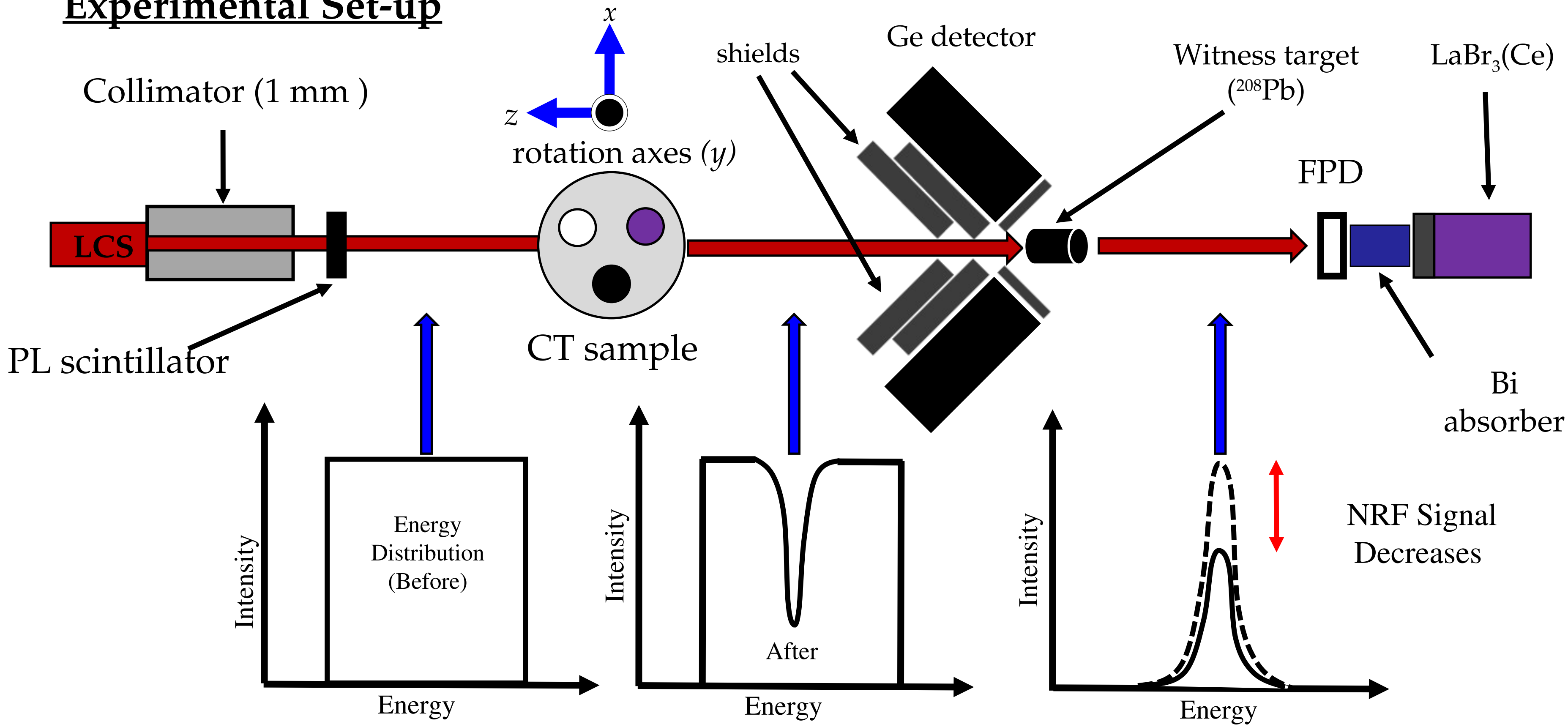
Sep. 2011

Hidden ^{235}U was detected!

M. Omer et al, JJAP, vol.52, 10, 106401-1-4 (2013)

Isotope Selective CT Imaging

Experimental Set-up



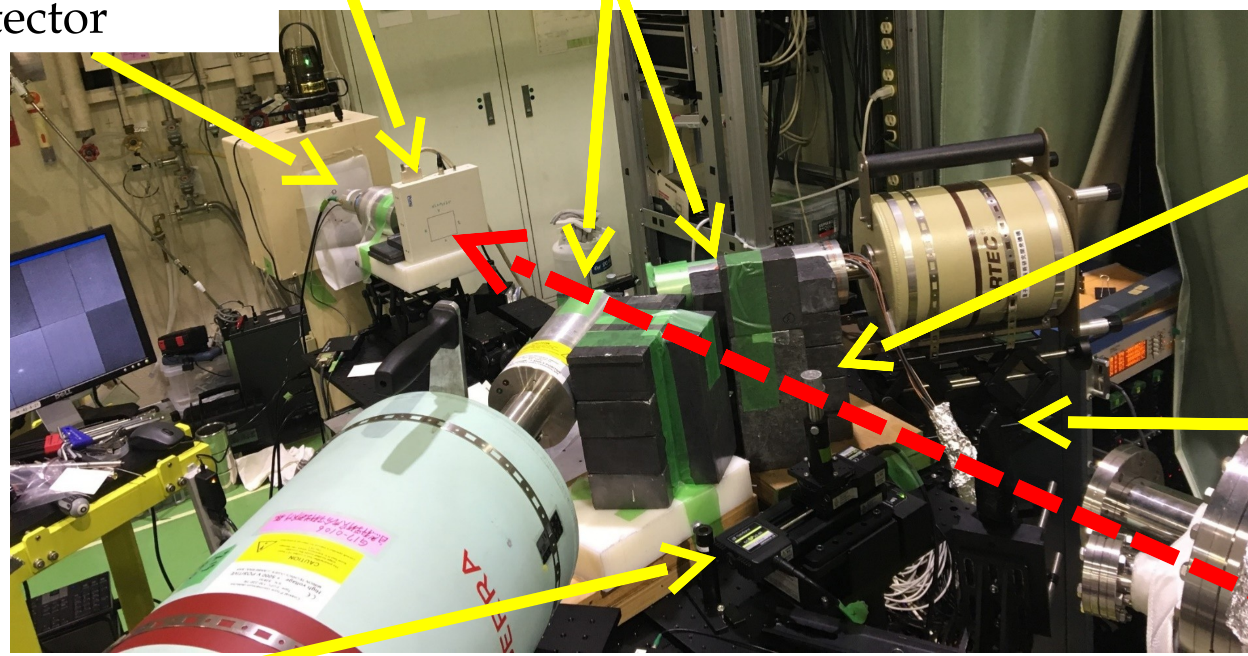
K. Ali et al., IEEE Trans. NS, vol 67, 1976 (2020)

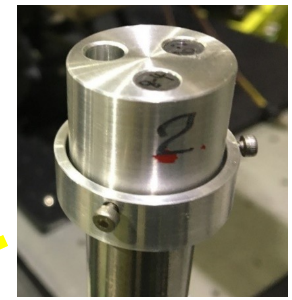
Experimental Set-up in BL1U, UVSOR-III

$LaBr_3$ (Ce) Detector

FPD

HPGe Detector





CT target

Plastic Scintillator

LCS Gamma-rays

Movable stage

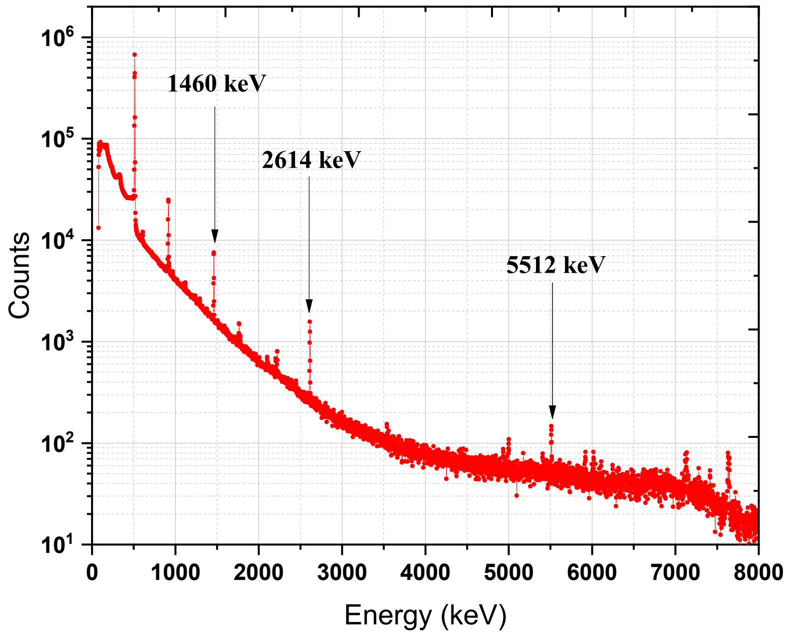
LCS gamma-rays for 2D NRF-CT

LCS beam parameters	3D NRF-CT
diameter	$2-mm$
e- energy	$746 \pm 1\ MeV$
e- current	$300\ mA$
Laser power	$36\ W\ (CW)$
Laser wavelength	$1.896\ \mu m$
Polarization	$Random$
LCS intensity	$10\ photons/s/eV$

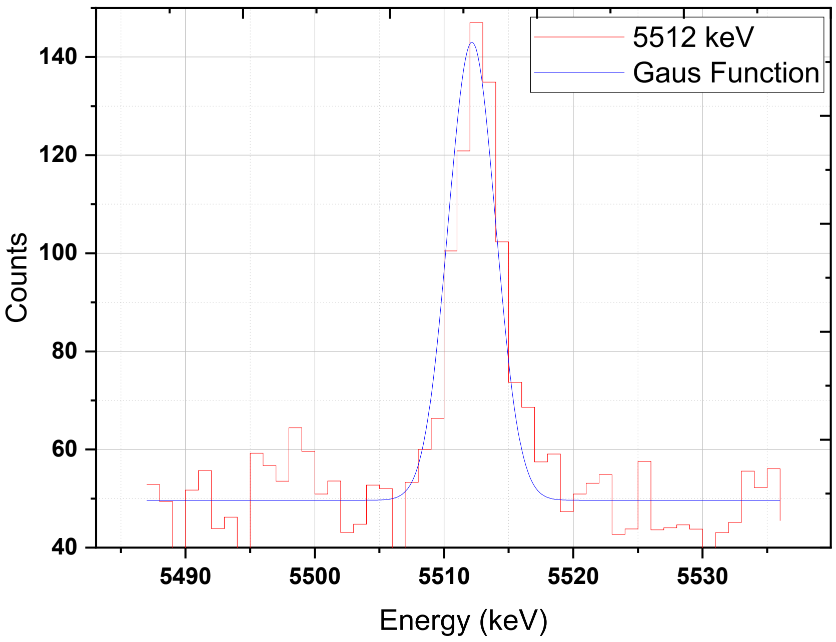
Isotope Selective CT Imaging

Ge Spectra

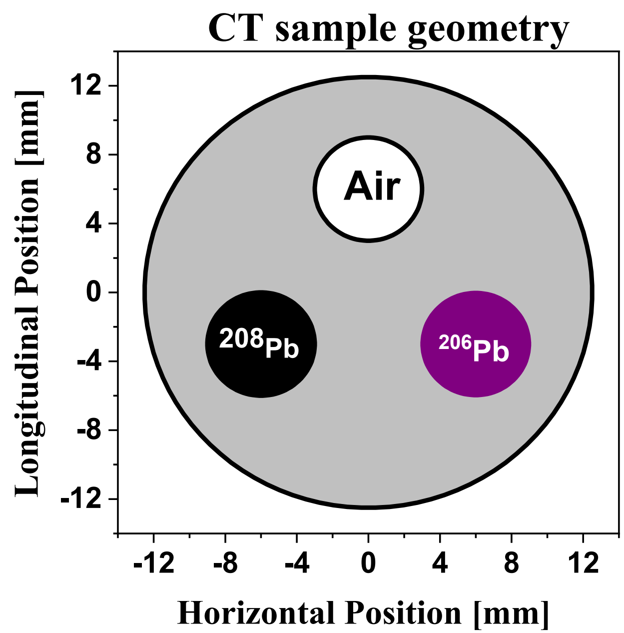
HPGe detectors (2 Spectrum in $\Delta = 2\ keV$)

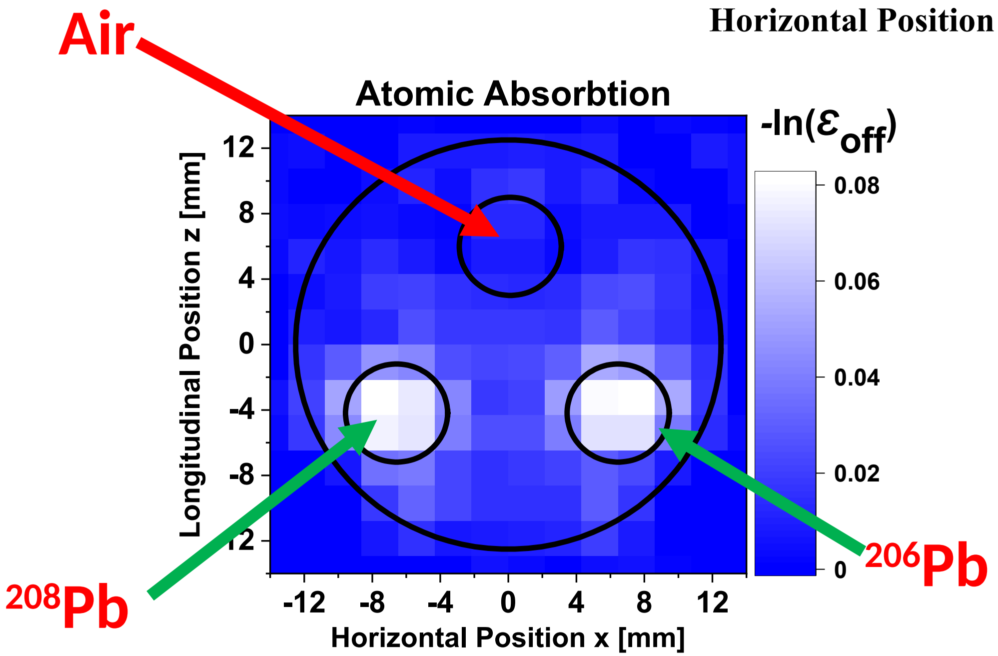


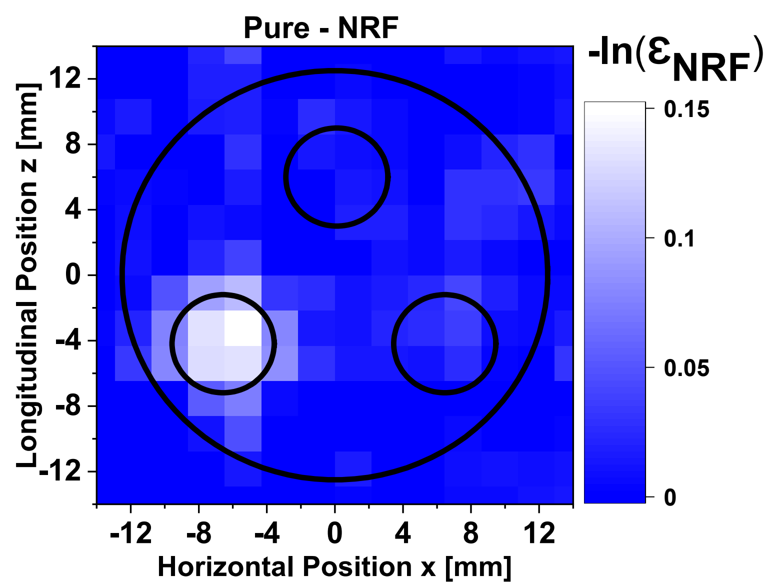
NRF of ^{208}Pb at (5512 keV)



Isotope Selective CT Imaging (2D)

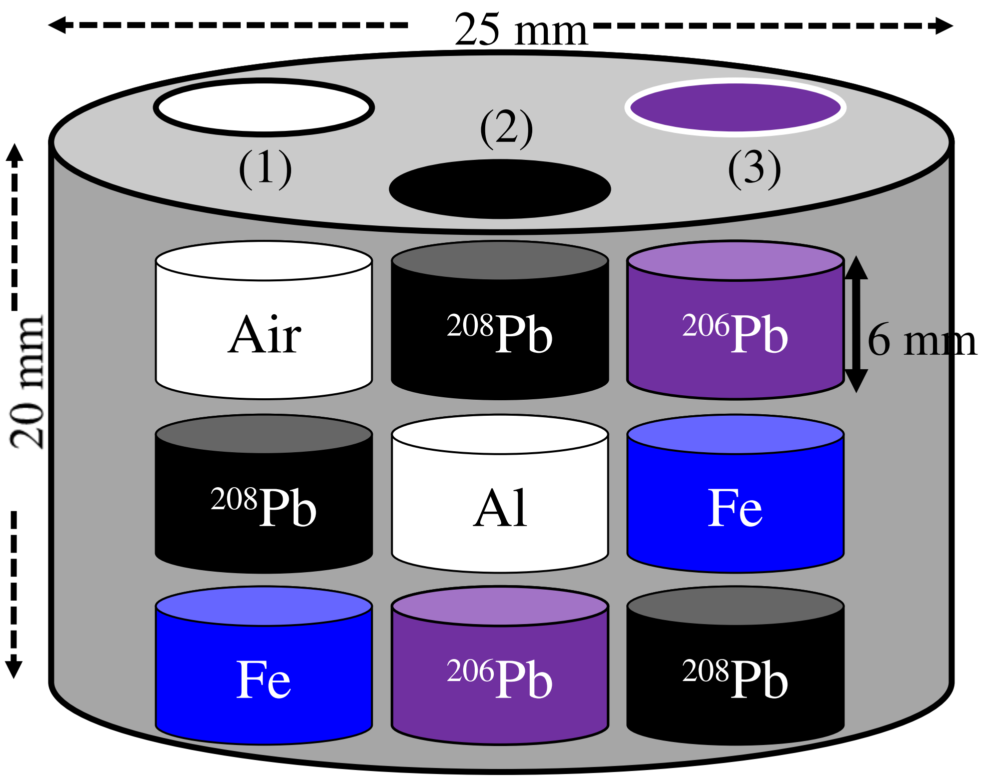






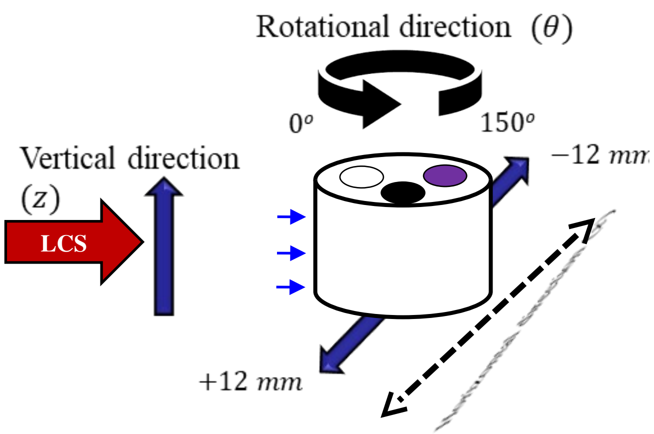
3D Isotope Selective CT Imaging

CT Sample



Scanning plan in 2D

Direction	Step size	Range	No. of points
θ	30°	30° ~150°	6
x	4 mm	$-12 \sim +12$ mm	7
z	@ $z = 3, 11, 17$ mm		3 Layers
Acquiring Time for one position			20 min.
Overall measurement time			48 hours

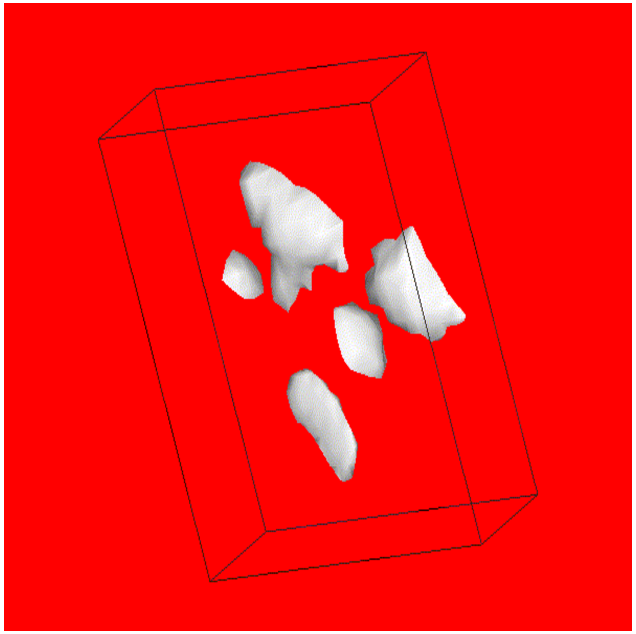


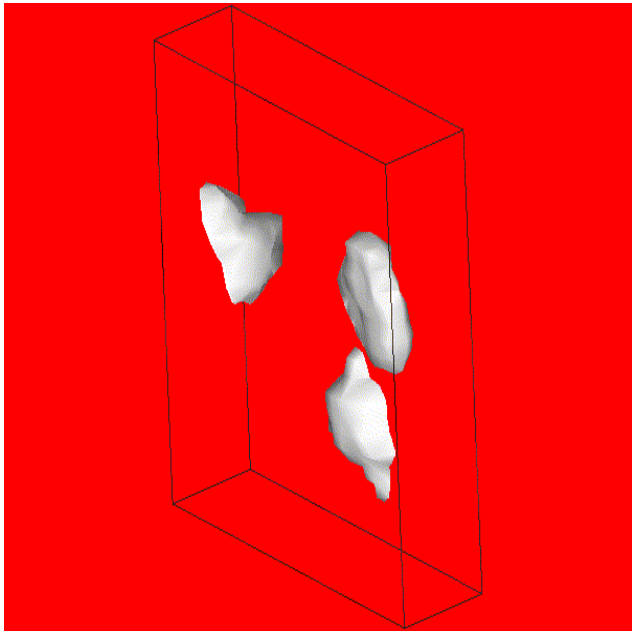
3D Isotope Selective CT Imaging

3D gamma-CT

MicroAVS

3 D NRF-CT





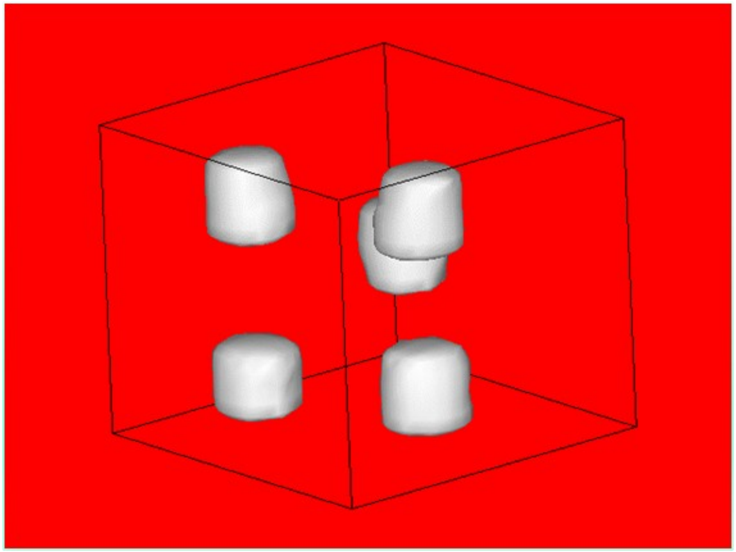
K. Ali et al., Applied Sciences, vol. 11, no.8, 3415 (2021)

Fusion Visualization Technique (FV)

3D NRF-CT (low resolution, isotope information)
x 3D Gamma-CT (high resolution)

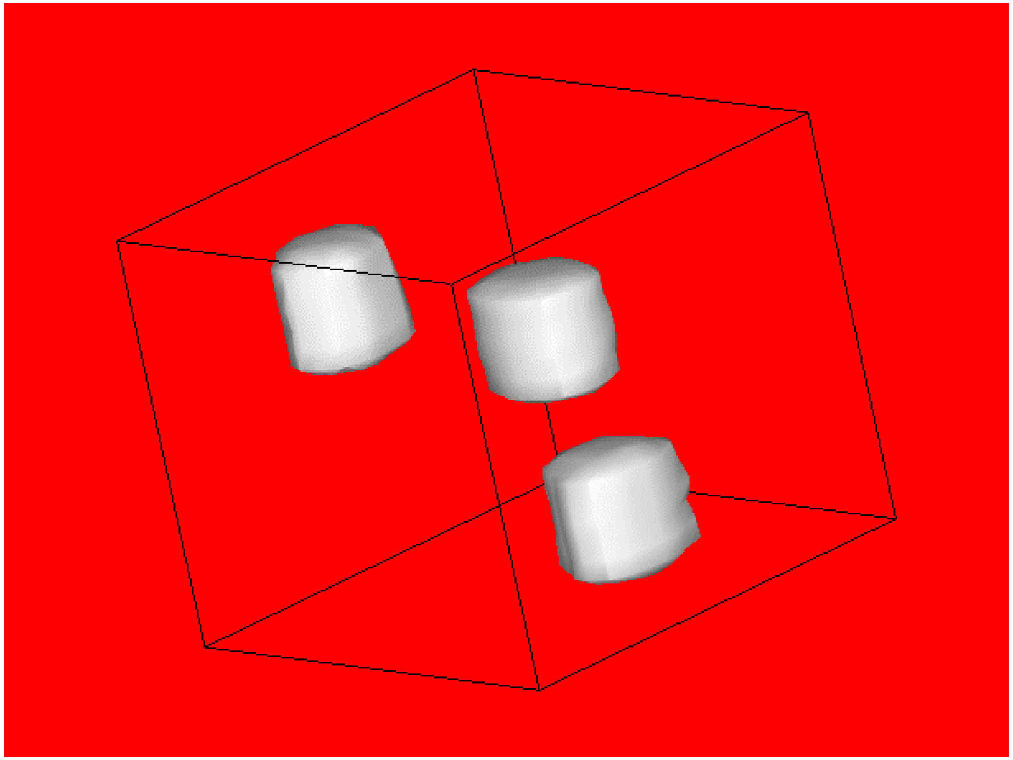
MicroAVS

3D gamma-CT image



1 mm pixel resolution

3D NRF-CT image



K. Ali et al., Applied Sciences, vol. 11, no.24, 11866 (2021)

Summary

- ❖ Briefly introduced LCS gamma-ray
- ❖ Successfully demonstrated NRF(isotope)-CT imaging
- ❖ Resolution of 4 mm/pixel and 3 layers with a data acquisition time of approximately 50 hours.

  => 1 mm/pixel using fusion visualizing

Challenge for LCS gamma rays

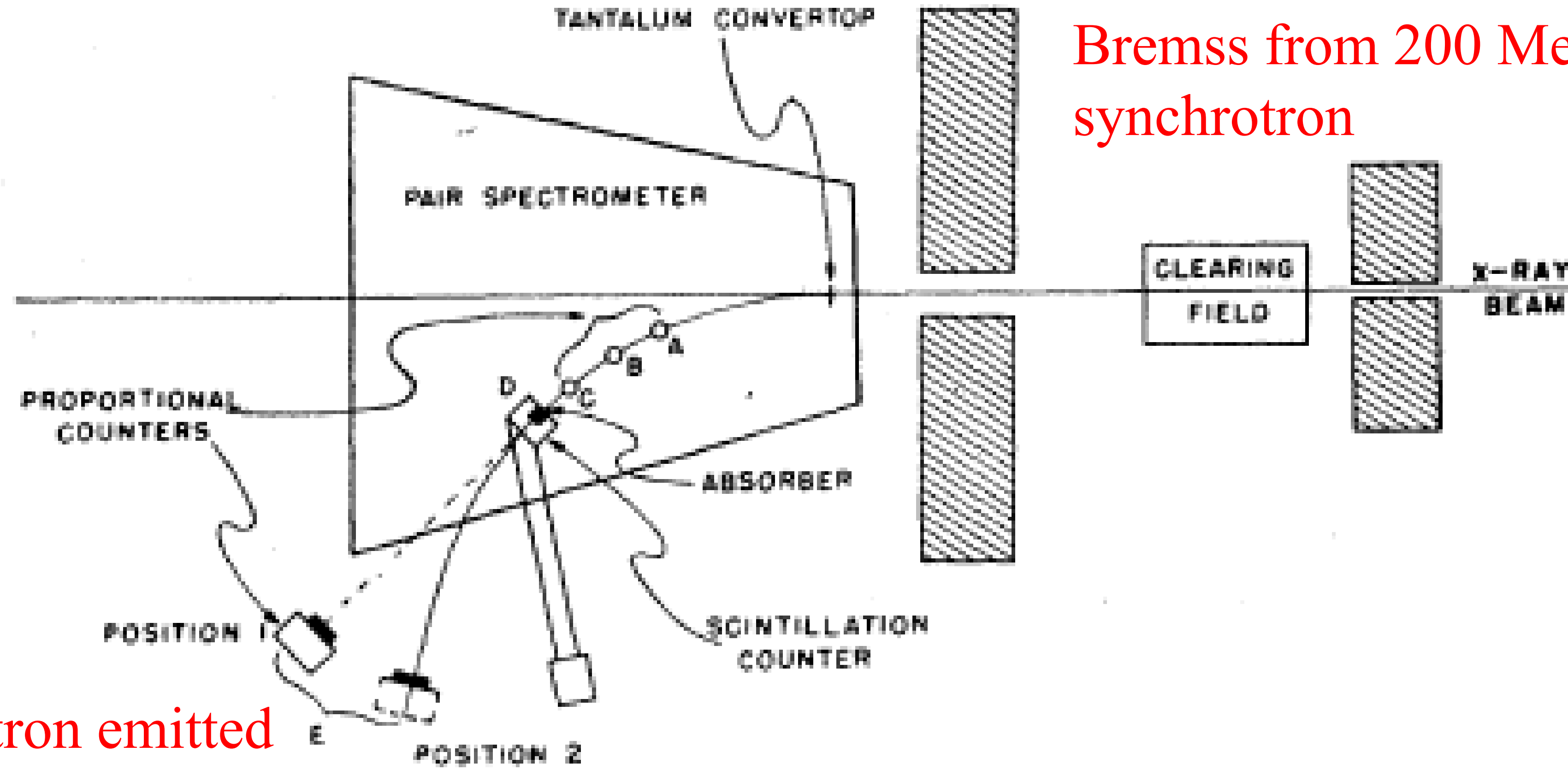
- Intensity of gamma ray beam: ELI-NP
- Energy tunability: SLEGS
- Facility size: laser acceleration

for NRF-CT

- Multiple isotopes
- Quantitative evaluation

Positron emitter

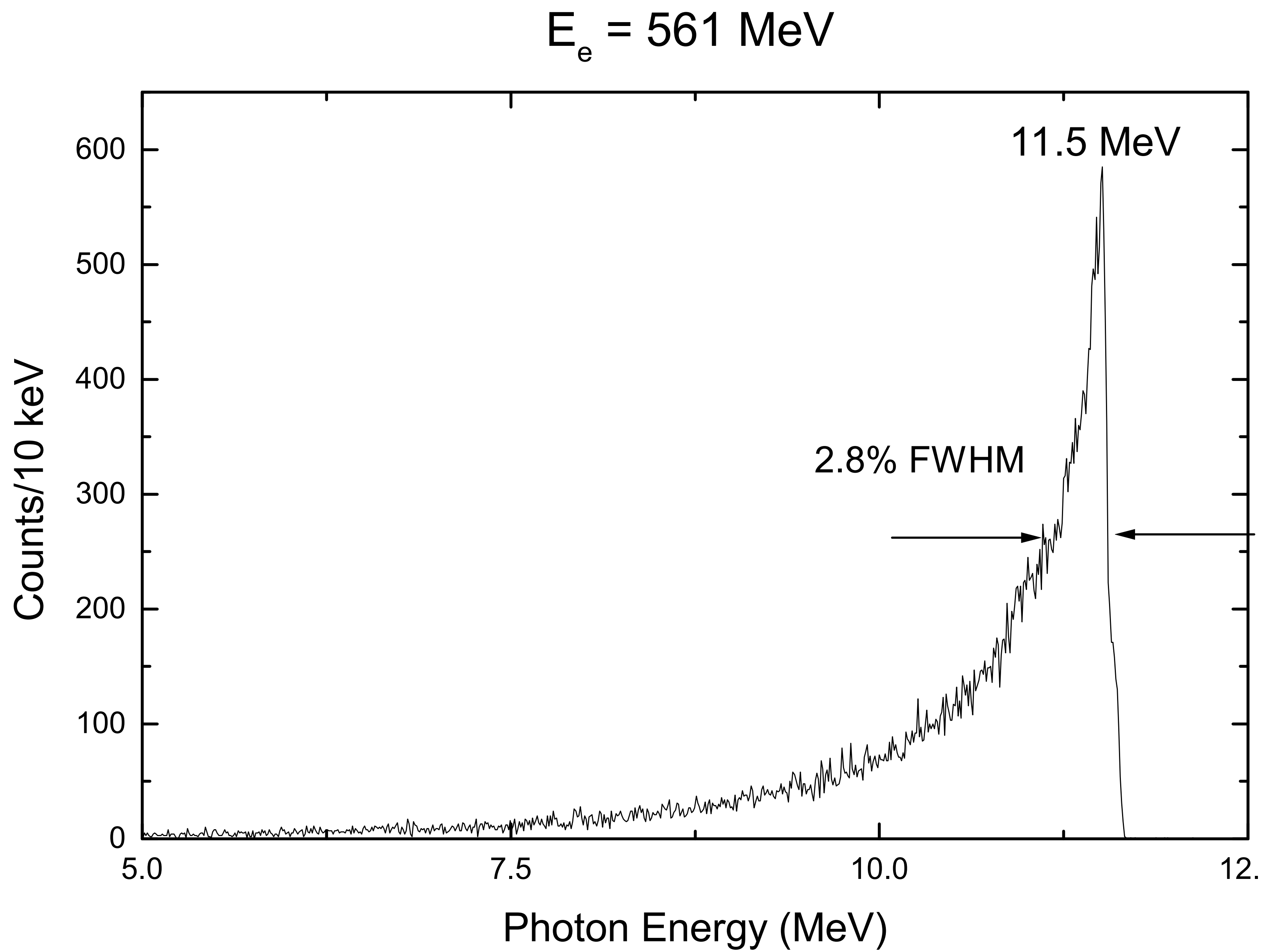
Bremss from 200 MeV synchrotron



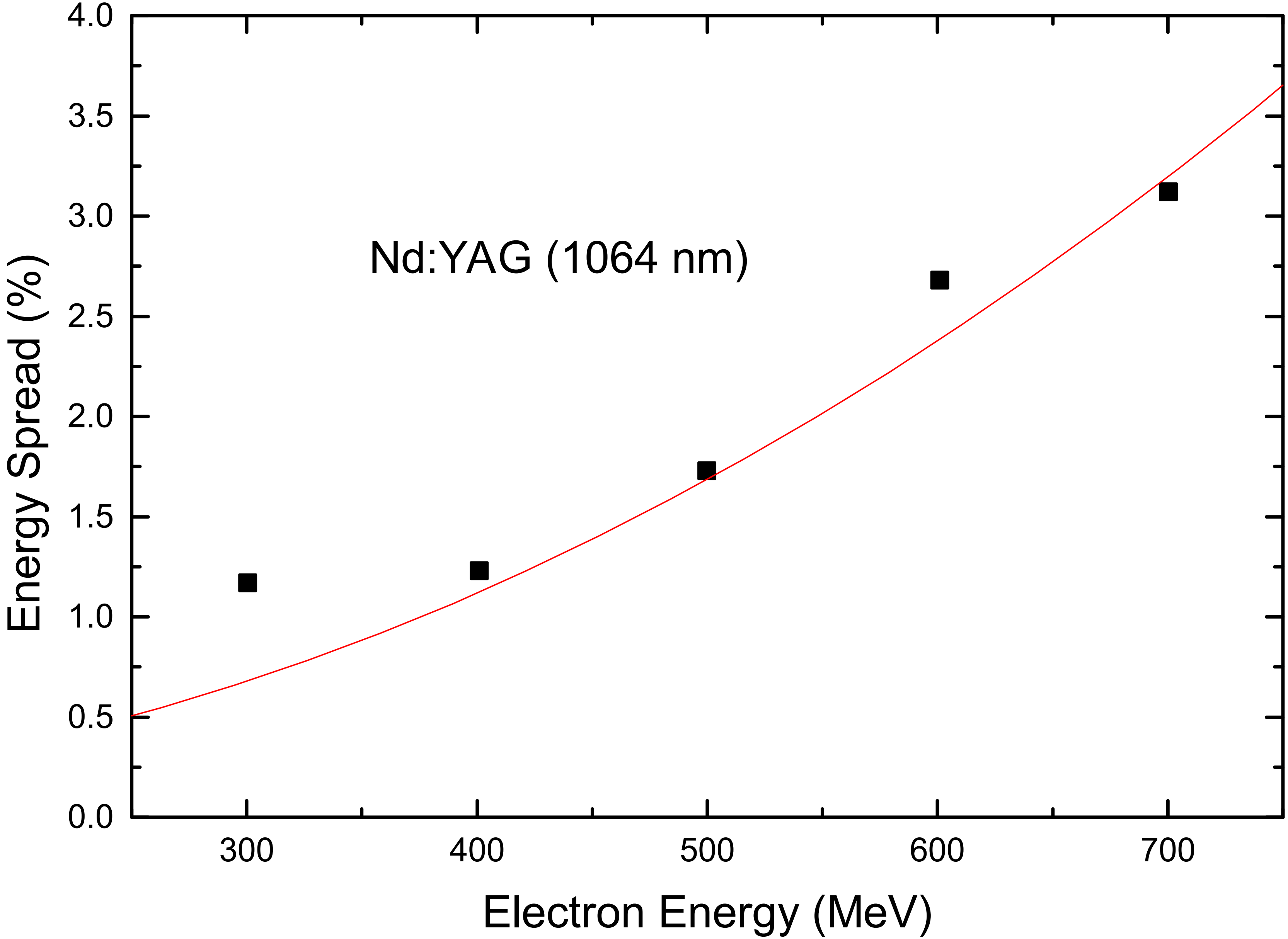
Positron emitted photons

FIG. 1. Experimental arrangement.

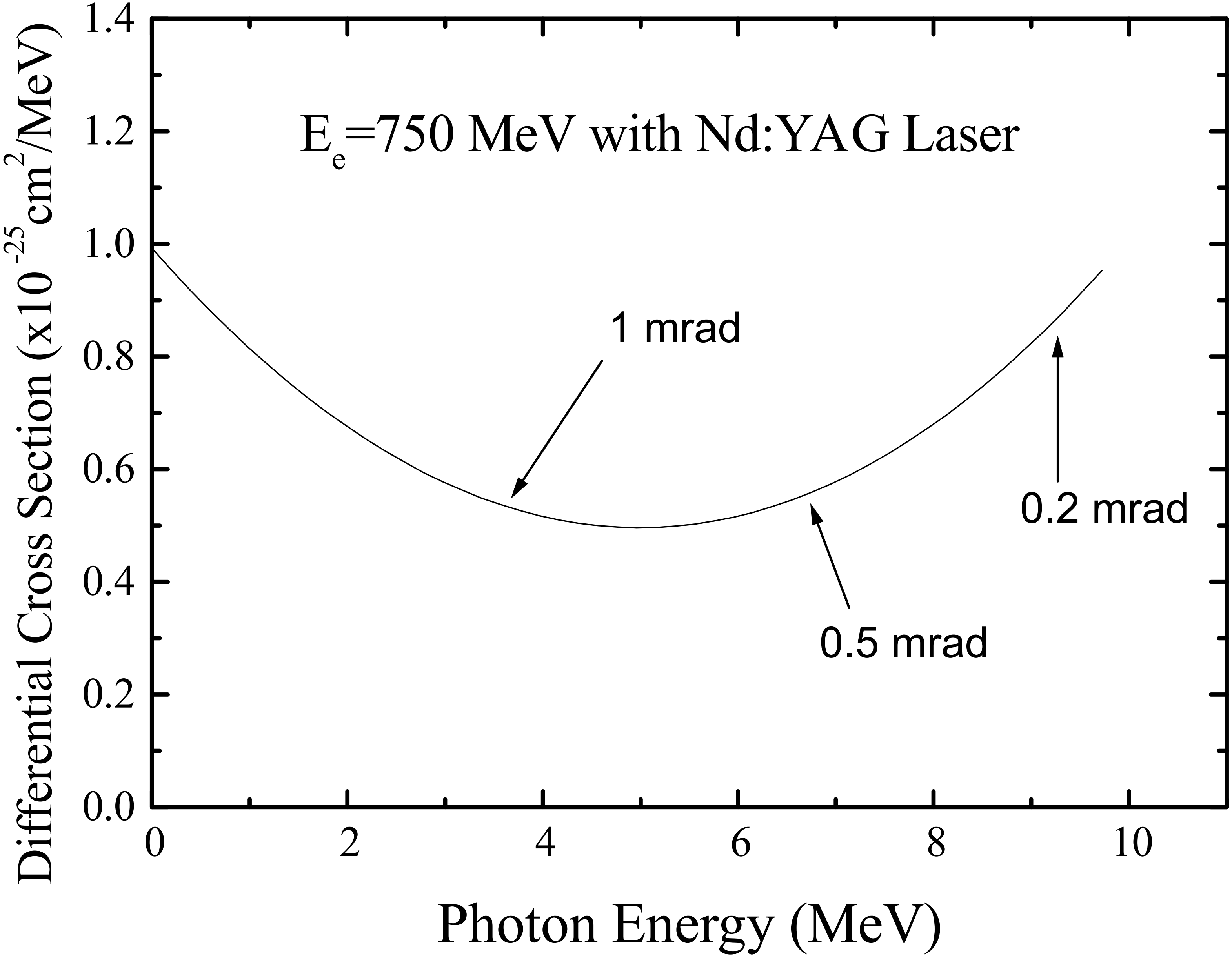
S.A.Colgate, Phys. Rev. vol 89, No. 4, 790 (1953)



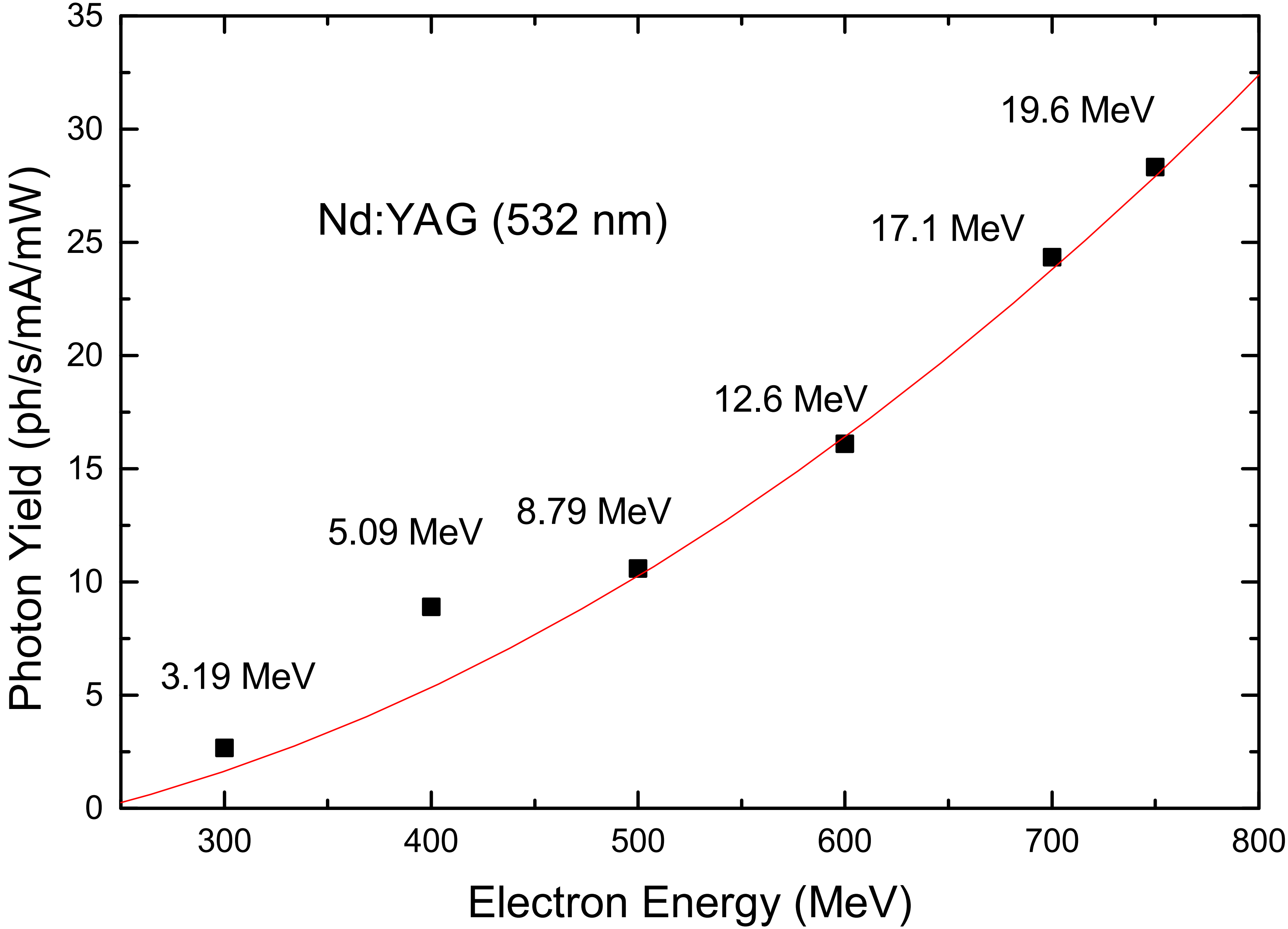
E$_e$ = 561 MeV
11.5 MeV
2.8% FWHM
Counts/10 keV
Photon Energy (MeV)
0
100
200
300
400
500
600
5.0
7.5
10.0
12.5



Nd:YAG (1064 nm)
Energy Spread (%)
Electron Energy (MeV)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
300
400
500
600
700



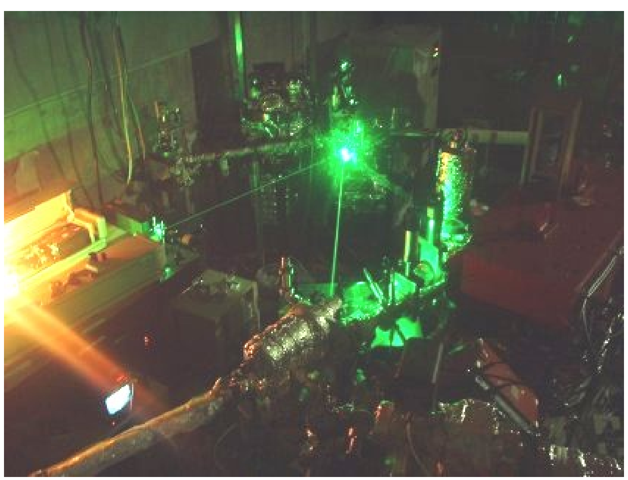
E_e=750 MeV with Nd:YAG Laser
1 mrad
0.5 mrad
0.2 mrad
Differential Cross Section (x10^-25 cm^2/MeV)
Photon Energy (MeV)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
2
4
6
8
10



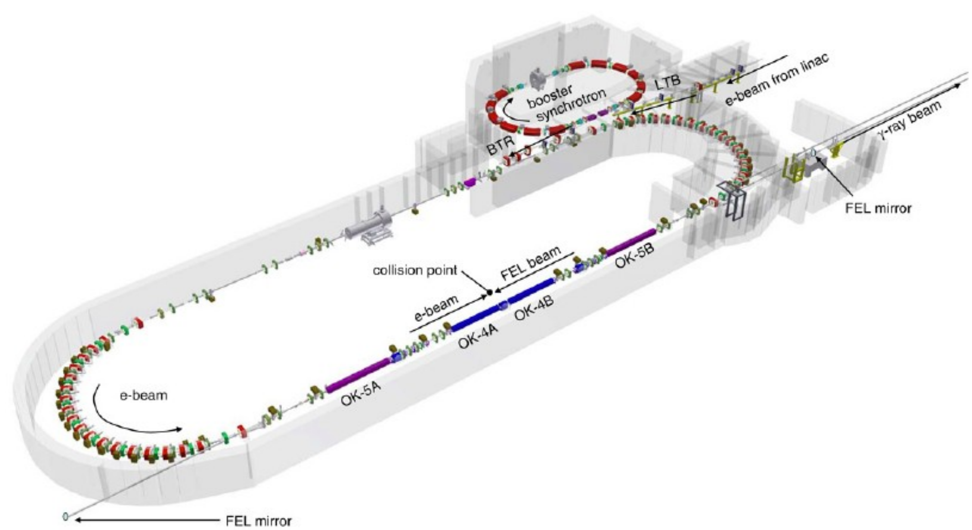
Photon Yield (ph/s/mA/mW)
Electron Energy (MeV)
Nd:YAG (532 nm)
3.19 MeV
5.09 MeV
8.79 MeV
12.6 MeV
17.1 MeV
19.6 MeV
0
5
10
15
20
25
30
35
300
400
500
600
700
800

Non-destructive Inspection of hidden SNM by using Laser-Compton Backscattering Gamma-ray induced NRF

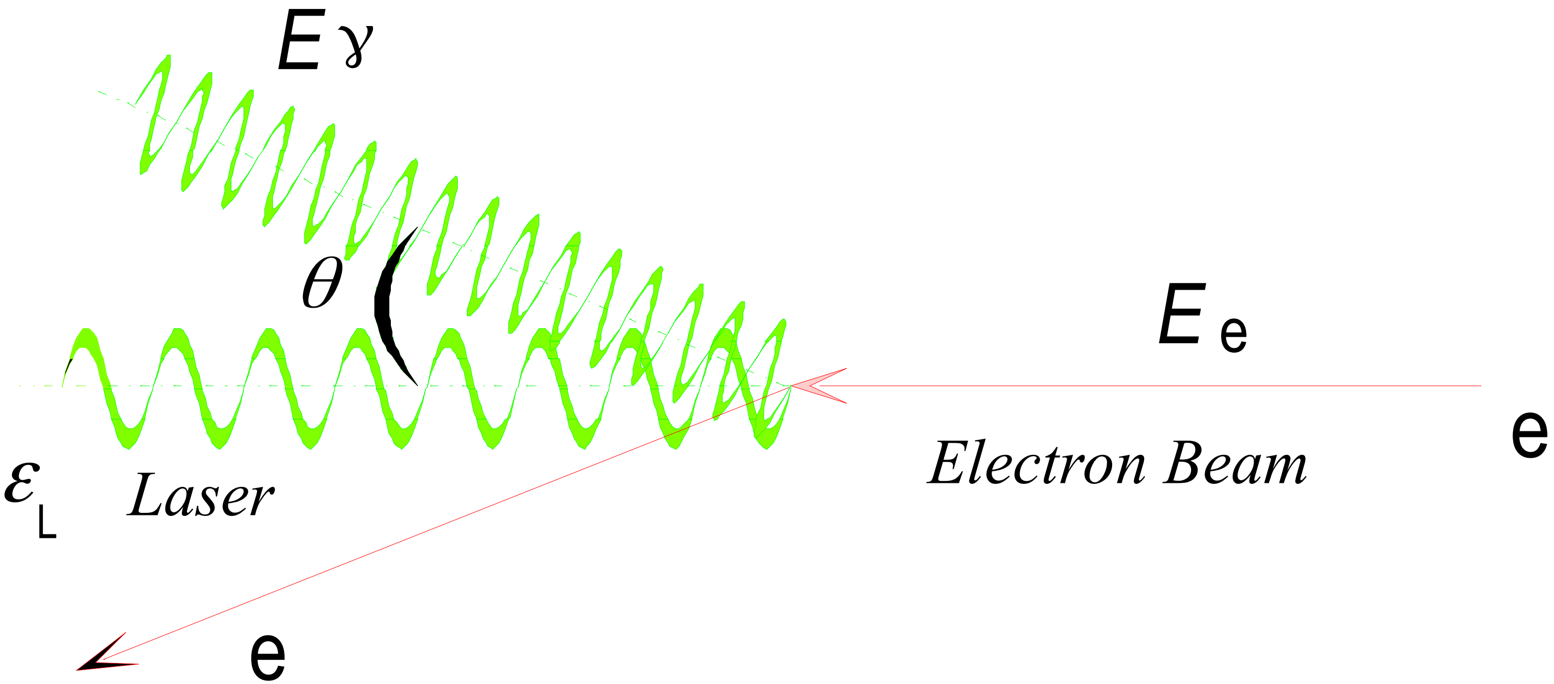
TERAS



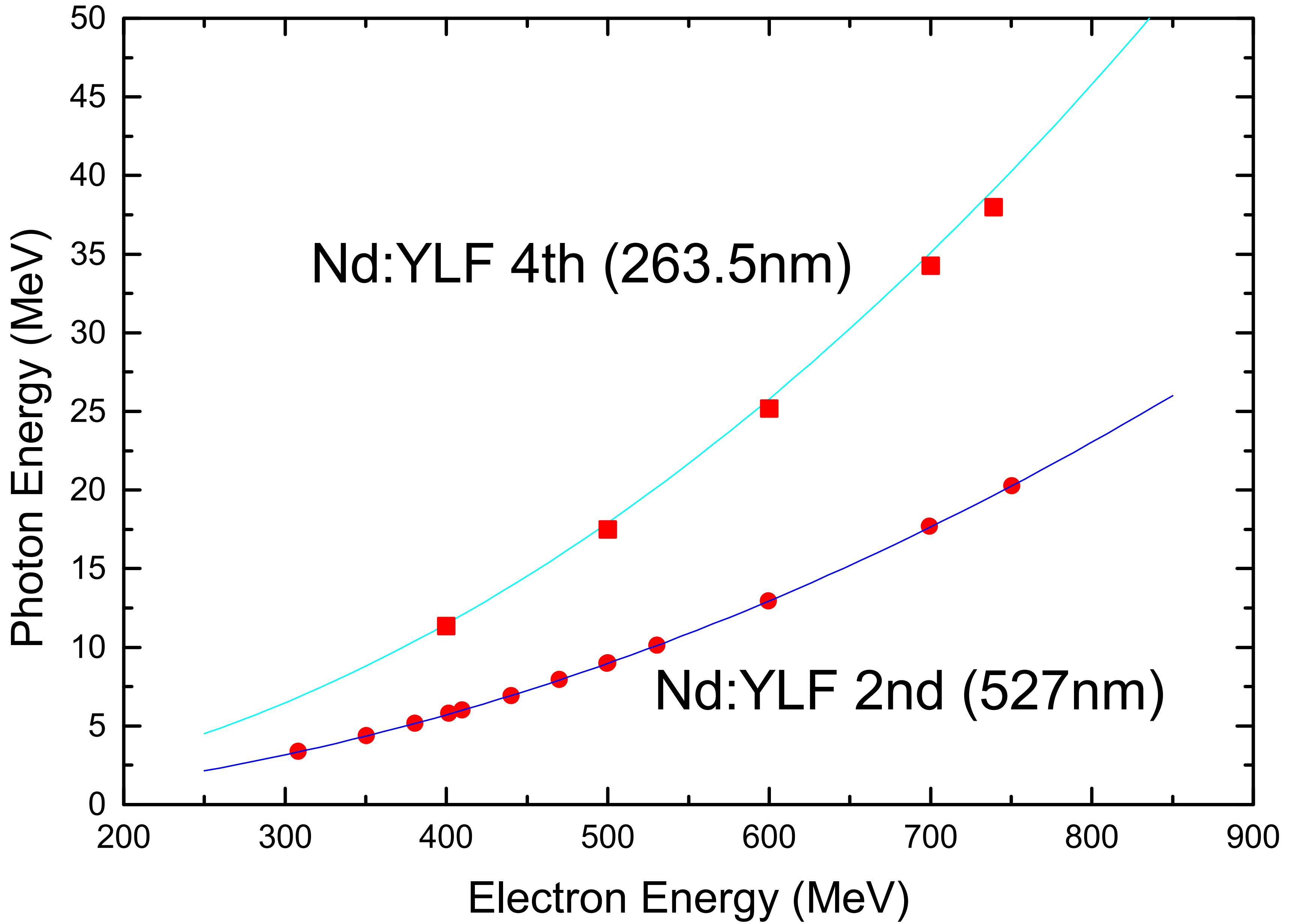
HIγS



• Energy



$$E_g = \frac{e_L}{1 - \beta \cos q + e_L \left(1 - \cos\left(q_L - q\right)\right) / E_e}$$



Nd:YLF 4th (263.5nm)
Nd:YLF 2nd (527nm)
Photon Energy (MeV)
Electron Energy (MeV)
0
5
10
15
20
25
30
35
40
45
50
200
300
400
500
600
700
800
900

- Energy Spread (Monochromaticity)

$$\Delta E / E \cong \sqrt{\left(2\frac{\Delta E_e}{E_e}\right)^2 + (\gamma\Delta\theta)^4}$$

$$\Delta\theta^2 = \theta_e^2 + \theta_c^2$$

Angular divergence of electron beam

Solid angle of a collimator

- Photon Yield

$$Y = \frac{2 N_e N_L \sigma L}{A \tau c}$$

N_e :Number of electrons

N_L :Number of photons in laser beam

σ :Cross section

L :Effective interaction length

A :Beam profile

τ :Pulse length

• Polarization

$$\frac{ds}{d\Omega}(v, c) = \frac{r_0^2}{2}\left(\frac{E}{E_0}\right)^2\left(\frac{E_0}{E} + \frac{E}{E_0} - 2\sin^2 v \cos^2 c\right)$$

r_0:Classical radius of electron

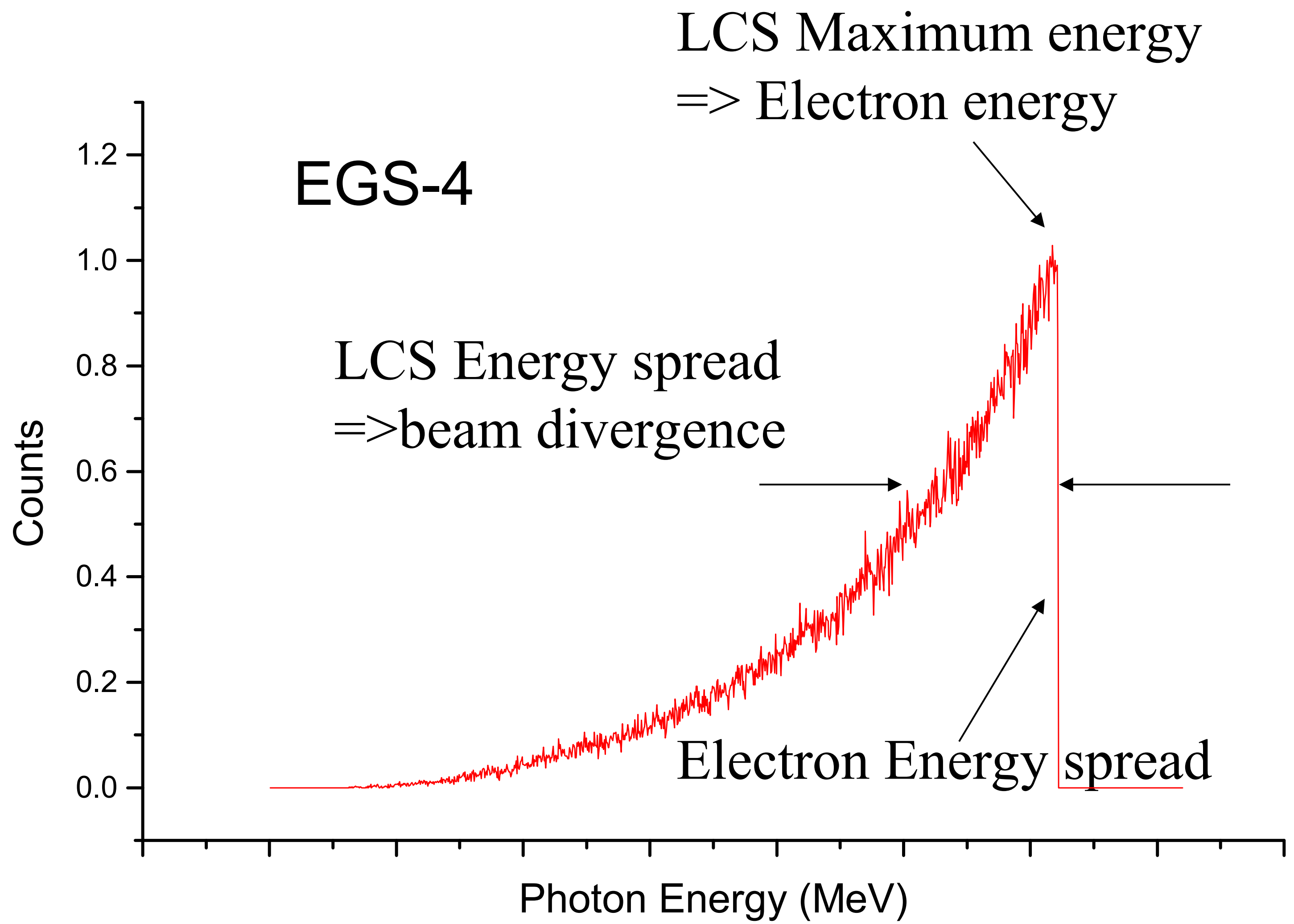
E_0,E:Photon energy(initial, final state)

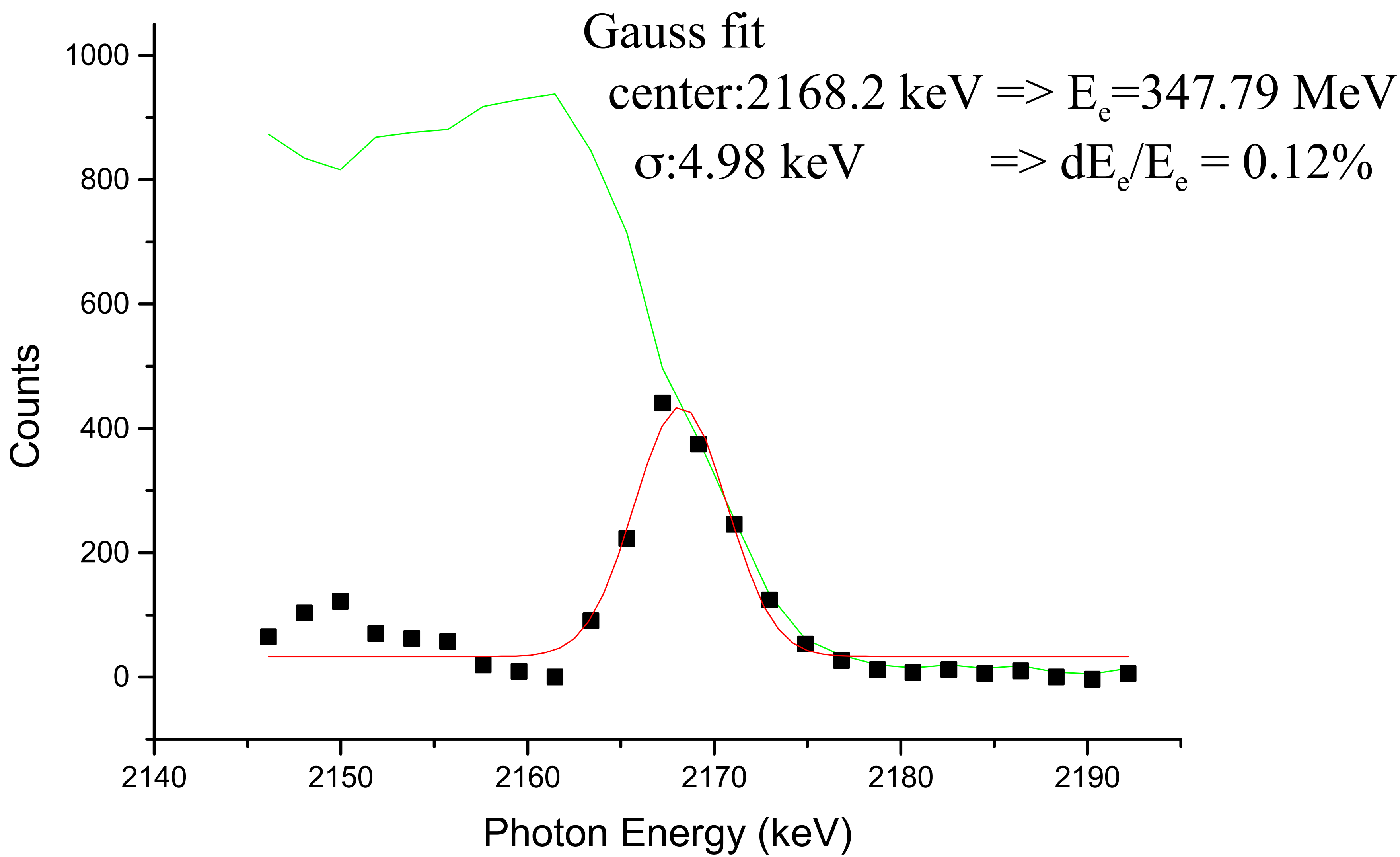
ν :Photon polarization axis

χ :Compton scattering angle

~100% polarization in backward scattering (χ~π)

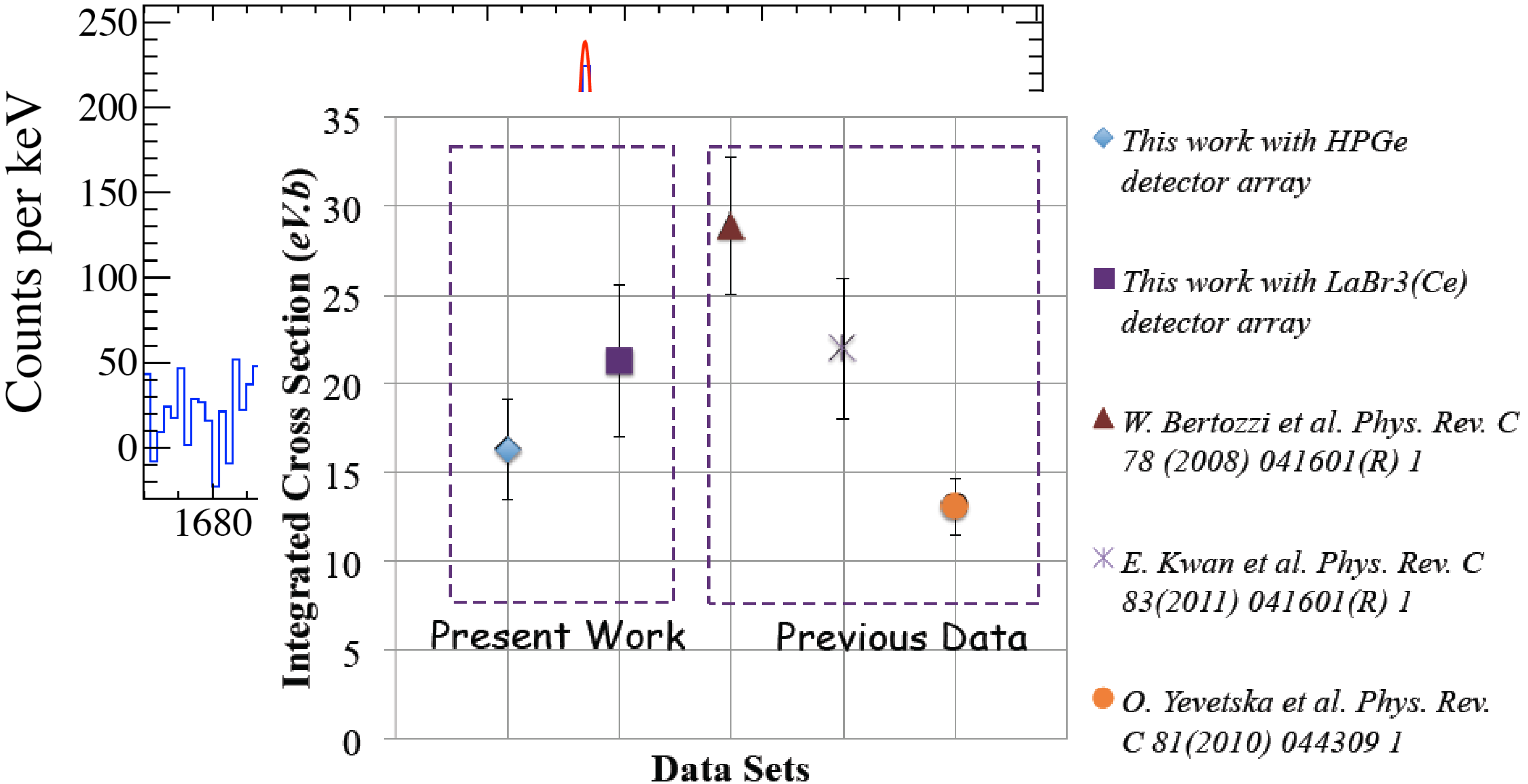
Beam Diagnostic





Gauss fit
center:2168.2 keV => E_e=347.79 MeV
σ:4.98 keV => dE_e/E_e = 0.12%
Counts
1000
800
600
400
200
0
2140
2150
2160
2170
2180
2190
Photon Energy (keV)

^{235}U Cross-section Measurement



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