

A compact Compton backscattering setup to measure the electron beam energy at ANKA

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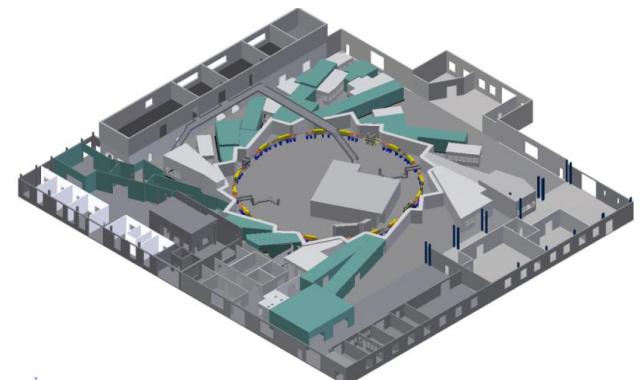


Outline

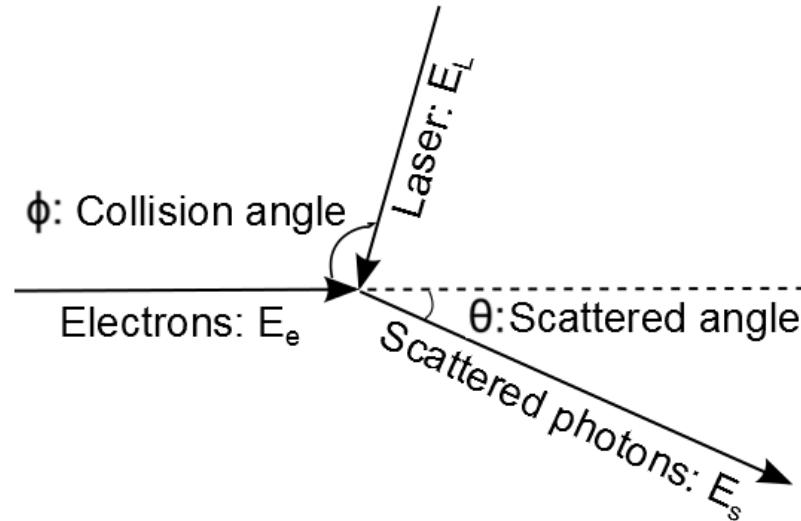
- Motivation
- Introduction and setup at ANKA
- CO₂ laser/optical system and detection system
- First results and preliminary analysis
- Conclusion and outlook

Motivation

- Circumference: 110.4 m
- Energies: ~0.5 GeV, 1.3 GeV, 1.6 GeV, 2.5 GeV
- So far, energy measurement only at 2.5 GeV: resonant spin depolarization*
 - * A.-S. Müller et al. Energy Calibration of the ANKA Storage Ring, EPAC 2004
- Lower energies: Compton Back-Scattering (CBS)
 - Absolute energy measurement
 - High accuracy
- Short bunch operation (1.3GeV, 1.6 GeV)
 - Parameters (e. g. the momentum compaction factor): highly nonlinear



Introduction to CBS



■ The energy of scattered photons E_s

$$E_s = \frac{E_L(1 - \beta \cos \phi)}{1 - \beta \cos \theta + E_e / E_L [1 - \cos(\theta - \phi)]}$$

E_L: energy of incoming laser photons

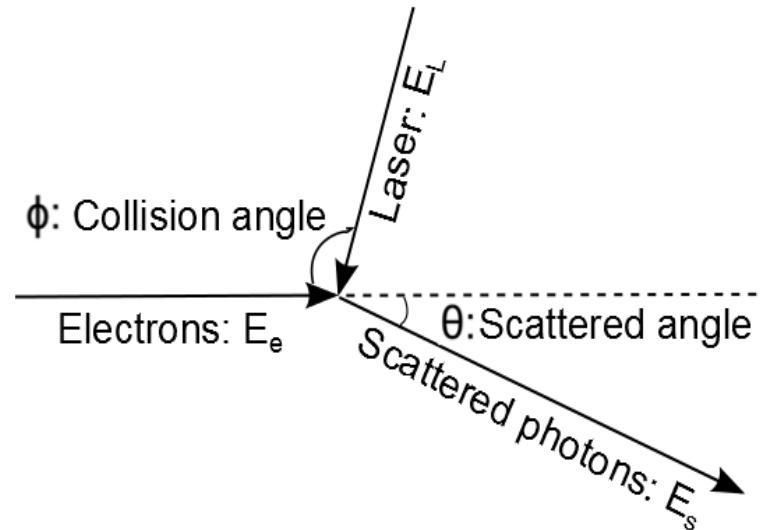
E_e: energy of electrons

β: electron velocity divided by speed of light

Introduction to CBS

- The energy of scattered photons E_s

$$E_s = \frac{E_L(1 - \beta \cos \phi)}{1 - \beta \cos \theta + E_L / E_e [1 - \cos(\theta - \phi)]}$$



- Maximum energy of the scattered photons (for $\theta=0$)

$$E_{\max} = \frac{E_L(1 - \beta \cos \phi)}{1 - \beta + E_L / E_e (1 - \cos \phi)}$$

$$\rightarrow E_e = \frac{mc^2}{2 \sin \frac{\phi}{2}} \sqrt{\frac{E_{\max}}{E_L}}$$

Known: mc^2 , E_L
Measured: Φ , E_{\max}

} E_e determined !

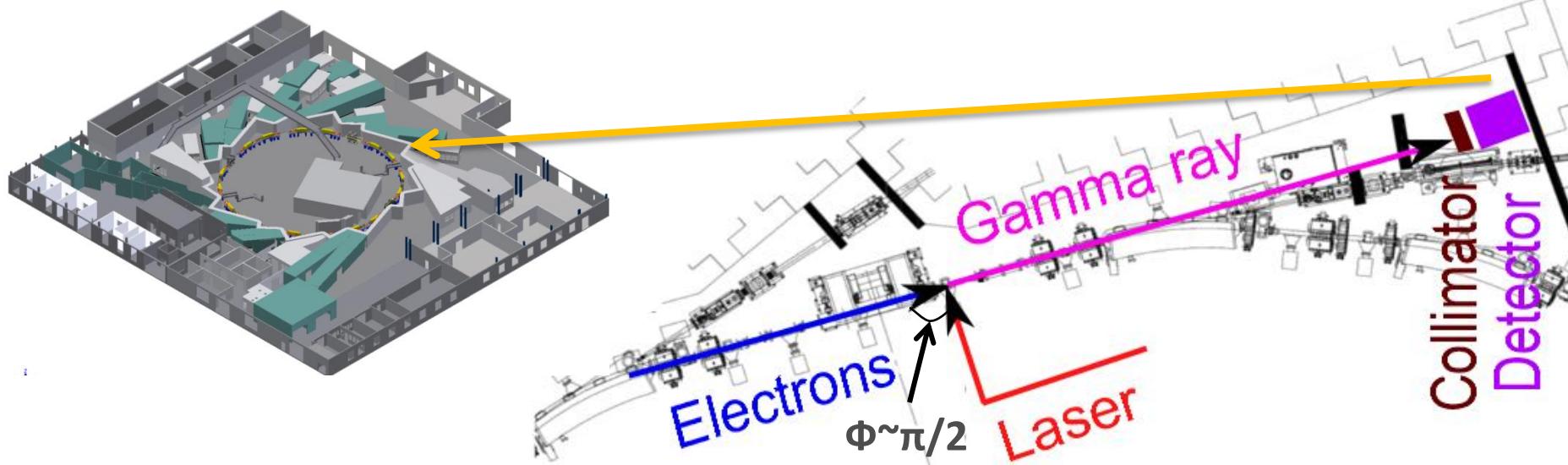
Advantages vs. challenges

- Conventional: head on collision
 - Dedicated beamline design
 - Components in vacuum
- Our approach: **transverse** scattering

Advantages	Challenges
Compact and integrated setup	Lower interaction time
Lower E_{\max} → Easier measurement	More sensitive to alignment errors
Versatile instrument	laser focusing and coupling in

- Aim: relative energy uncertainty ~a few 10^{-4}

Setup at ANKA



Electron beam:

- Short bunch mode E_e : 1.3 GeV
- Vertical size (RMS): 96 μm \longleftrightarrow
- Horizontal size (RMS): 1193 μm

Collimator:

- Tungsten collimator with central aperture
- 9.2 m after collision point

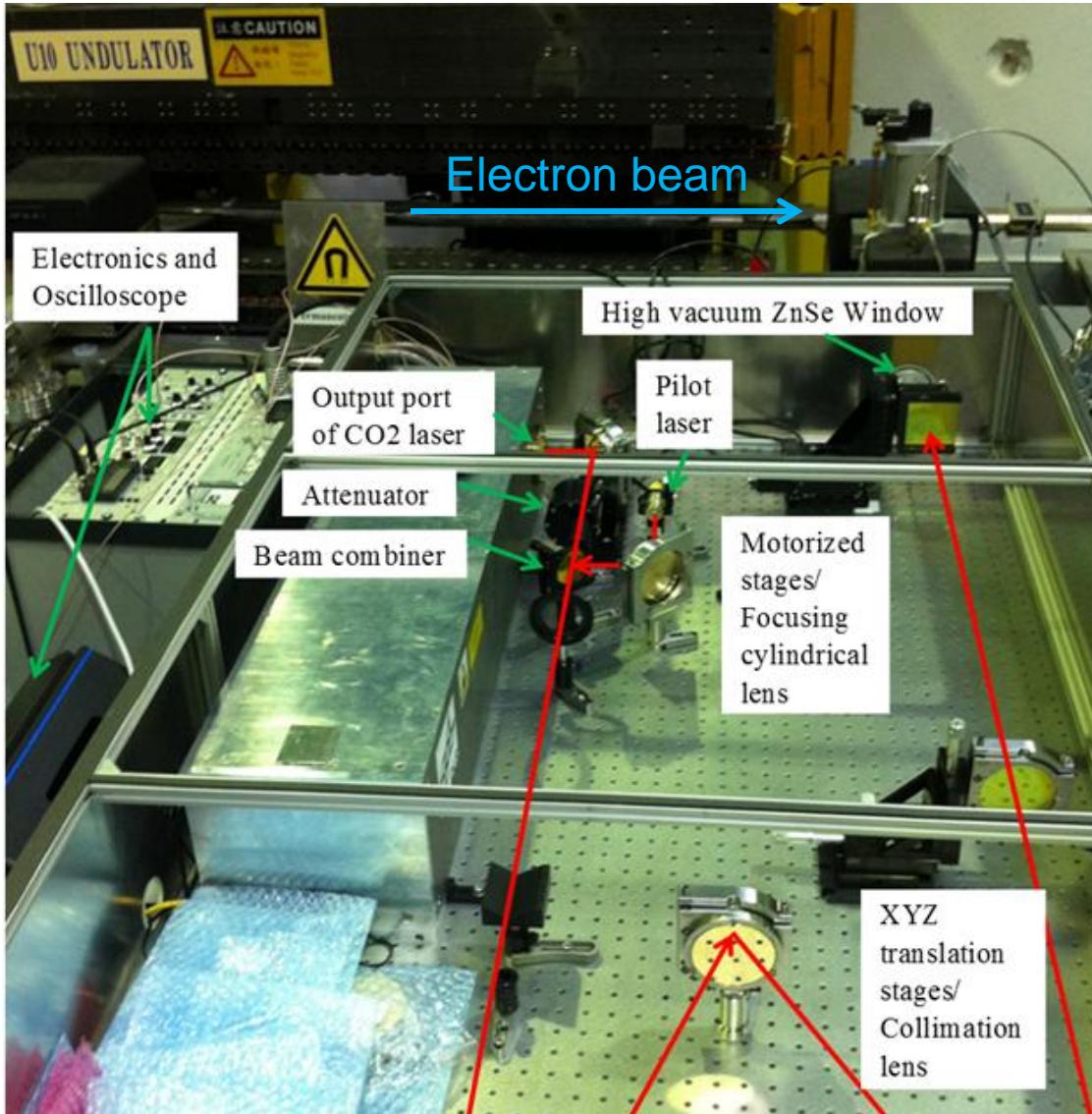
Laser:

- CW CO₂ Laser E_L : ~ 0.12 eV
- RMS radius: ~ 100 μm
- Stability $\Delta E_L / E_L$ better than 10^{-5}

Detector:

- High purity germanium (HPGe) detector
- Energy resolution $\sim 10^{-3}$
- Normal detectable range < 10 MeV

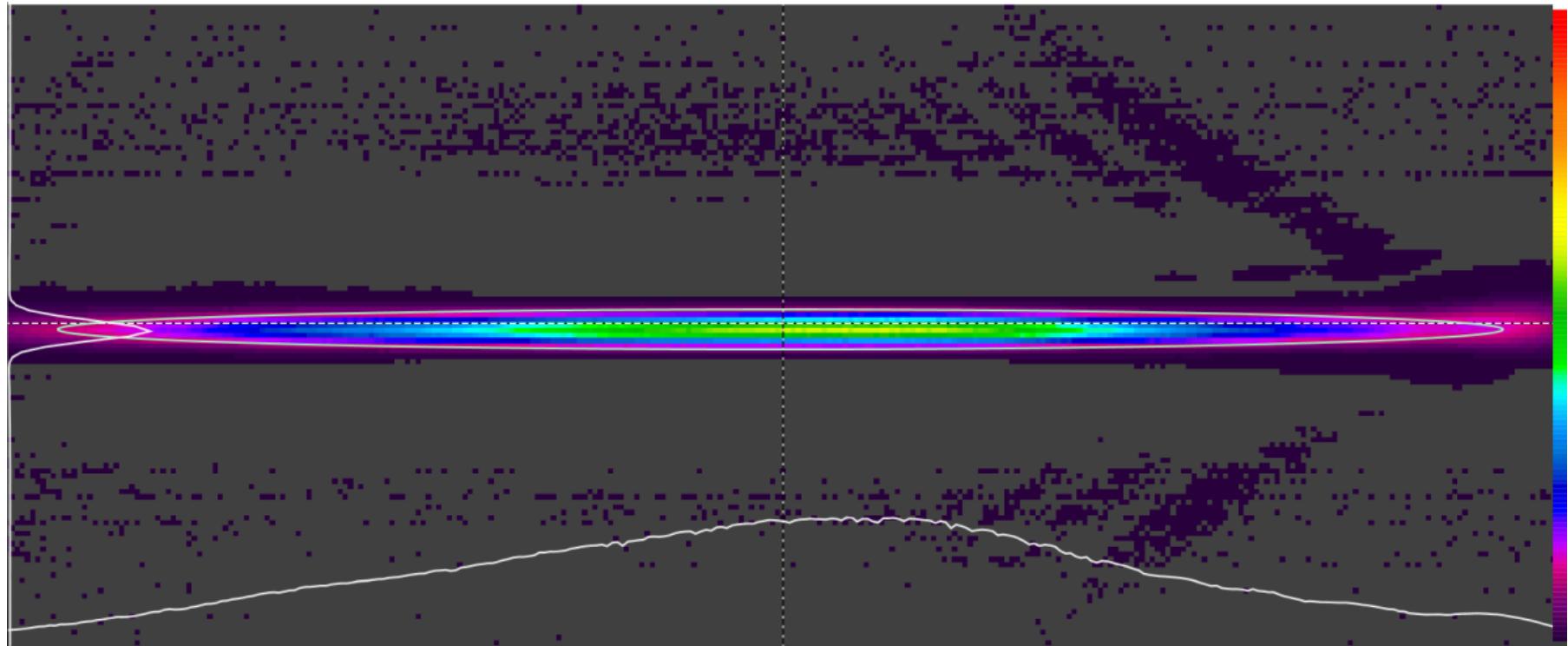
CO₂ laser and optical system



- CW, ~20W laser
- PID loop + Fabry-Perot cavity:
Specially stabilized frequency
→ $\sim 10^{-6}$ (DLR)
- Motorized focusing cylindrical lens → Control the focal position
- Laser coupling through ion pump

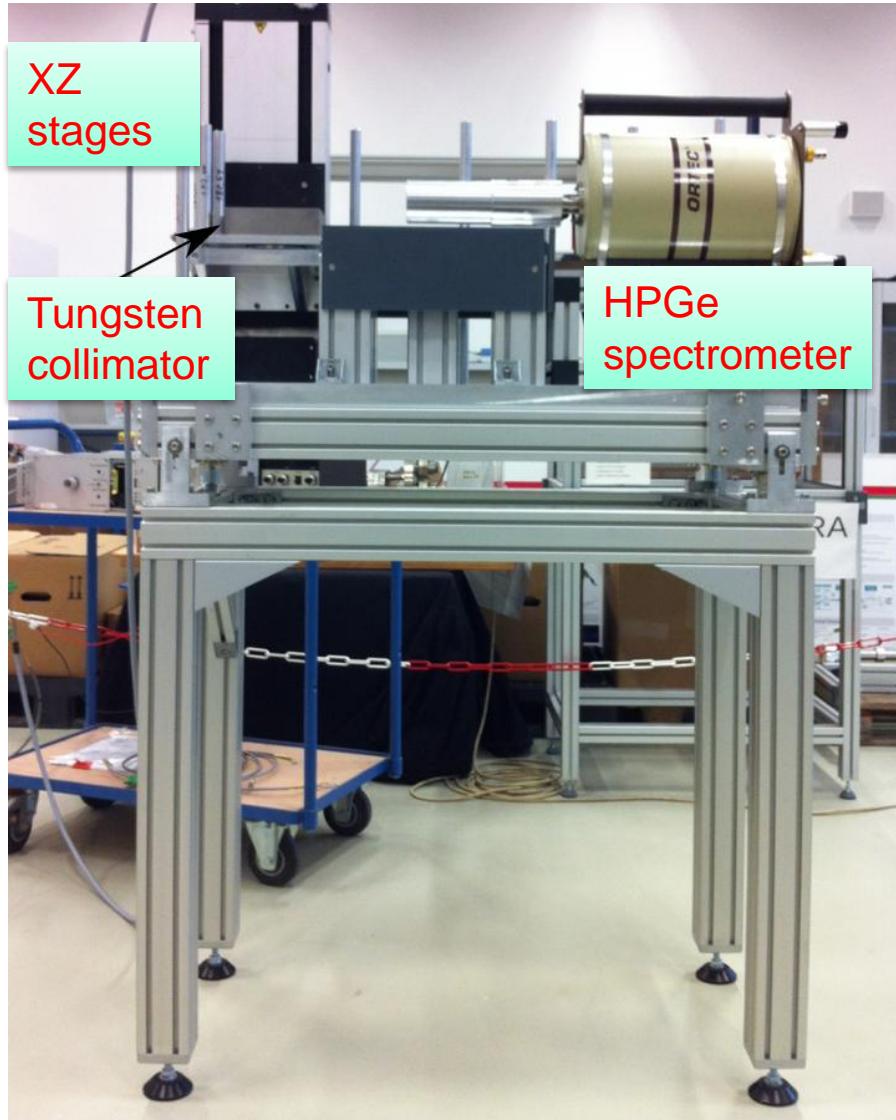


Focal beam size



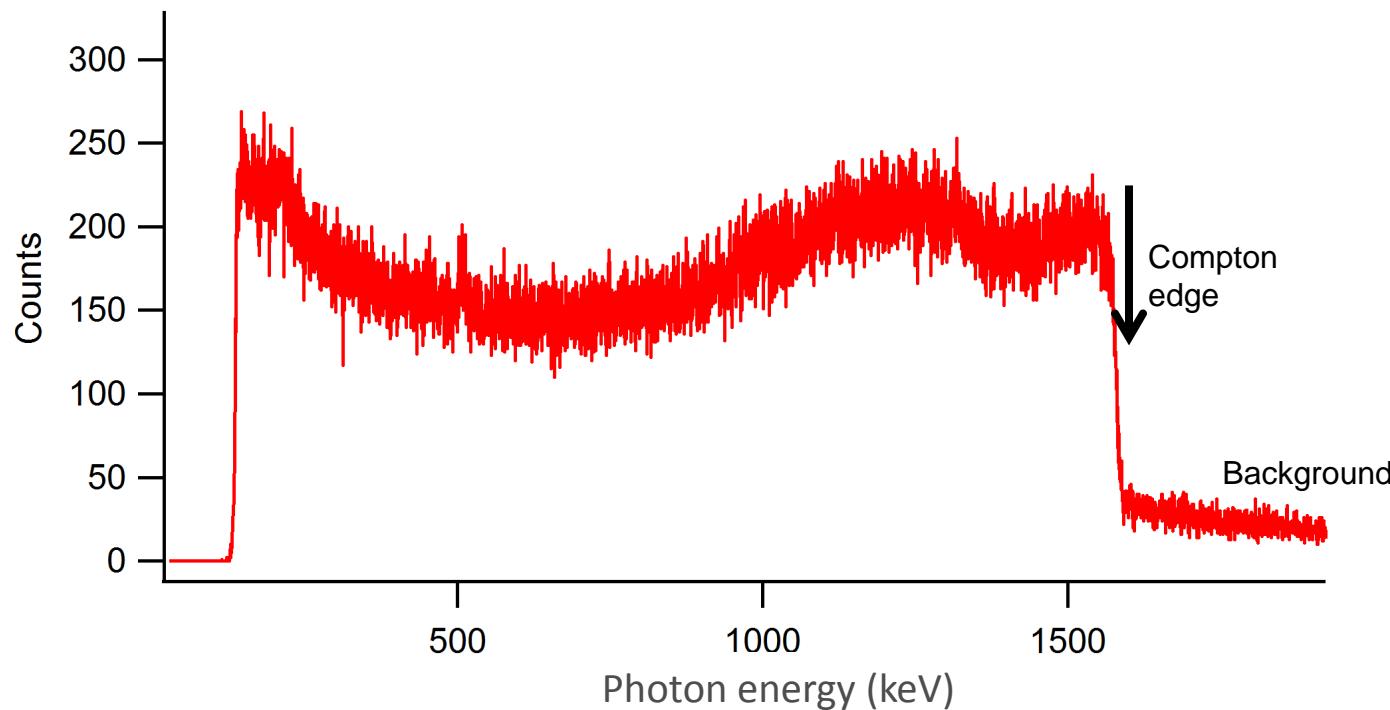
Vertical focal beam size
 (4σ) : **618 μm**

Gamma ray detection system



- ORTEC HPGe spectrometer
(38% nominal relative efficiency)
- Crystal section shielded by lead blocks
- Motorized tungsten collimator
- Capability to be pre-aligned by laser tracker

The CBS spectrum of 1.3 GeV electron beam



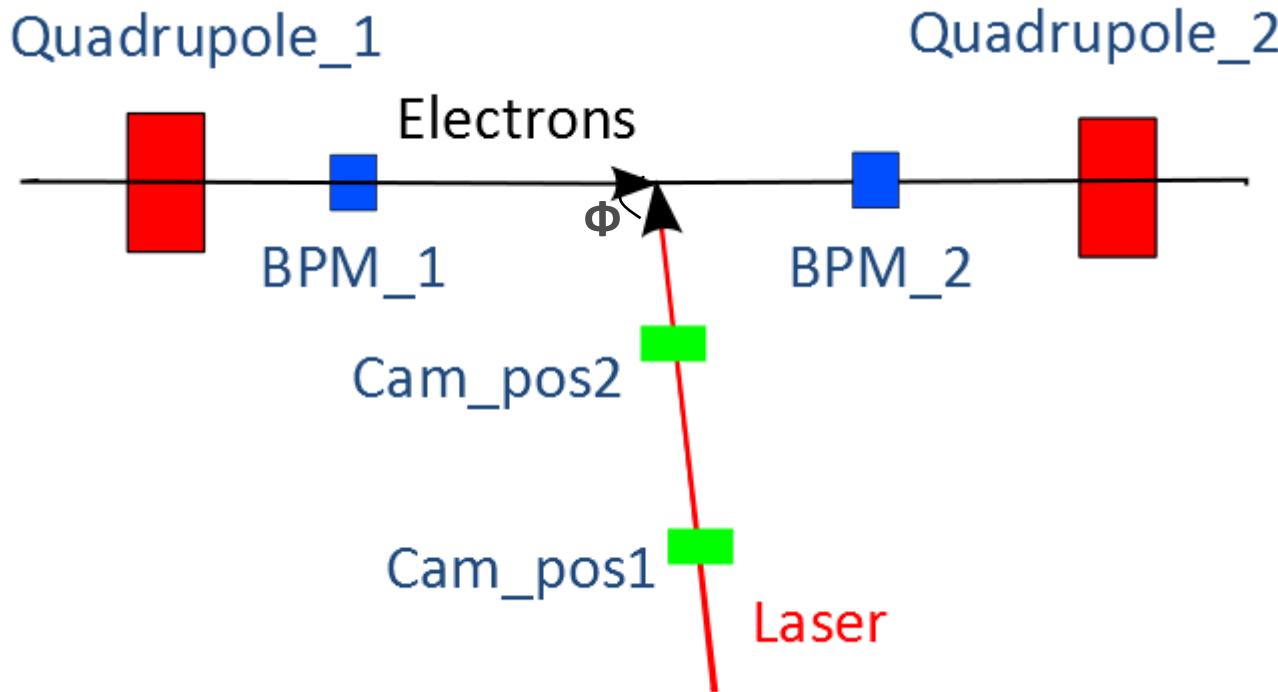
- 10 mA electron beam
- Acquisition time 120 s
- S/N ~ 3

The uncertainty of the method

$$E_e = \frac{mc^2}{2 \sin \frac{\phi}{2}} \sqrt{\frac{E_{\max}}{E_L}} \quad \rightarrow \quad \frac{\sigma_{E_e}}{E_e} = \sqrt{\left[\frac{\sigma_{E_L}}{2E_L} \right]^2 + \left[\frac{\sigma_\phi}{2 \tan(\phi/2)} \right]^2 + \left[\frac{\sigma_{E_{\max}}}{2E_{\max}} \right]^2}$$

- $\frac{\sigma_{E_e}}{E_e}$: Relative uncertainty of electron beam energy
- $\frac{\sigma_{E_L}}{E_L}$: The relative uncertainty of laser photon energy ($\sim 10^{-6}$)
- $\frac{\sigma_\phi}{\tan(\phi/2)}$: The angular deviation of electron orbit and laser beam path
- $\frac{\sigma_{E_{\max}}}{E_{\max}}$: The relative uncertainty of average E_{\max}
 - Systematic error of the edge measurement from the HPGe detector calibration: $< 10^{-4}$
 - Statistic error by spectrum edge fitting of E_{\max}

Determination of collision angle Φ



Laser direction (degree)	91.61 ± 0.02
Electron orbit (mrad/degree)	-0.6 / -0.03
Collision angle Φ (degree)	91.58 ± 0.02
$\frac{\sigma_\phi}{\tan \phi / 2}$	3×10^{-4}

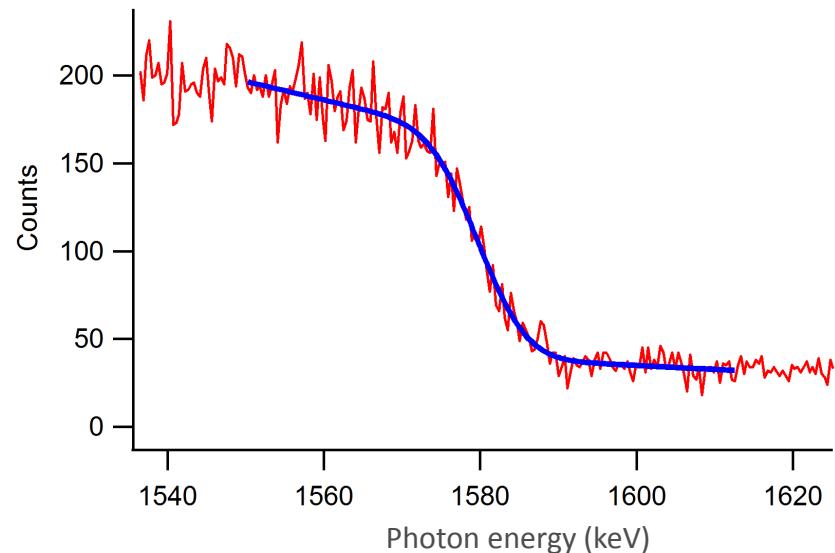
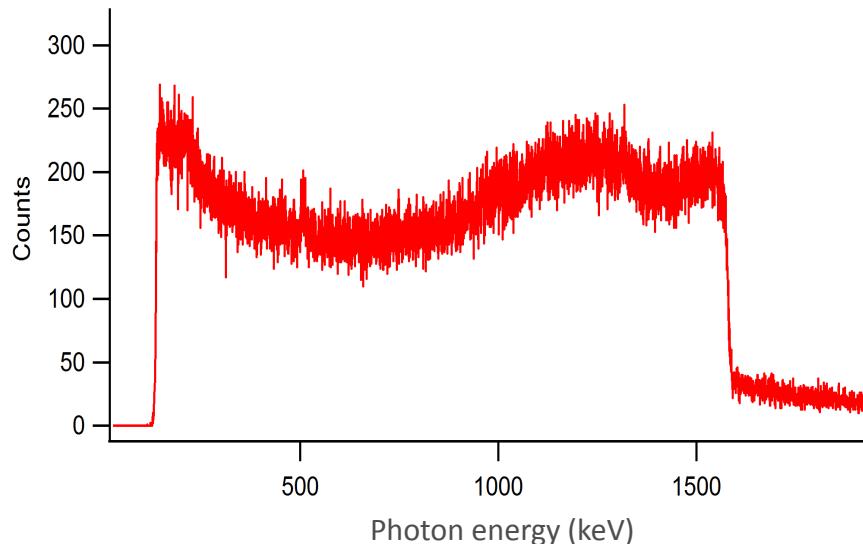
Determination of average E_{\max} by edge fitting

$$f(x) = \frac{1}{2} [p_2(x - p_0) + p_3] * erfc(\frac{x - p_0}{\sqrt{2}p_1}) - \frac{p_1 p_2}{\sqrt{2\pi}} \exp[-\frac{(x - p_0)^2}{2p_1^2}] + p_4(x - p_0) + p_5$$

$$erfc(x) = 1 - erf(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} \exp(-t^2) dt$$

- p_0 : position of the edge E_{\max}
- p_1 : width/ standard deviation of the edge
- p_2 : slope above the edge
- p_3 : amplitude of the edge
- p_4 : slope below the edge
- p_5 : background offset

Determination/ uncertainty of edge fitting



- Coefficient values \pm one standard deviation

$$p_0 = 1579.9 \pm 0.4$$

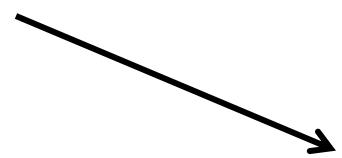
$$p_1 = 4.9 \pm 0.4$$

$$p_2 = -0.8 \pm 0.2$$

$$p_3 = 125 \pm 6$$

$$p_4 = -0.2 \pm 0.2$$

$$p_5 = 39 \pm 4$$



$$\frac{\sigma_{E_{\max}}}{E_{\max}} = 2 \times 10^{-4}$$

- $\chi^2 = 197.125$; $N_{\text{ndf}} = 158$;

Preliminary result for 1.3 GeV electron beam

$$mc^2 = 0.5109989 \text{ MeV}$$

$$E_L = 0.1211591 \text{ eV}$$

$$\phi = 91.58^\circ$$

$$E_{\max} = 1579.9 \text{ MeV}$$

$$E_e = \frac{mc^2}{2 \sin \frac{\phi}{2}} \sqrt{\frac{E_{\max}}{E_L}} \rightarrow E_e = 1287.2 \text{ MeV}$$

$$\frac{\sigma_\phi}{\tan \phi / 2} = 3 \times 10^{-4}$$

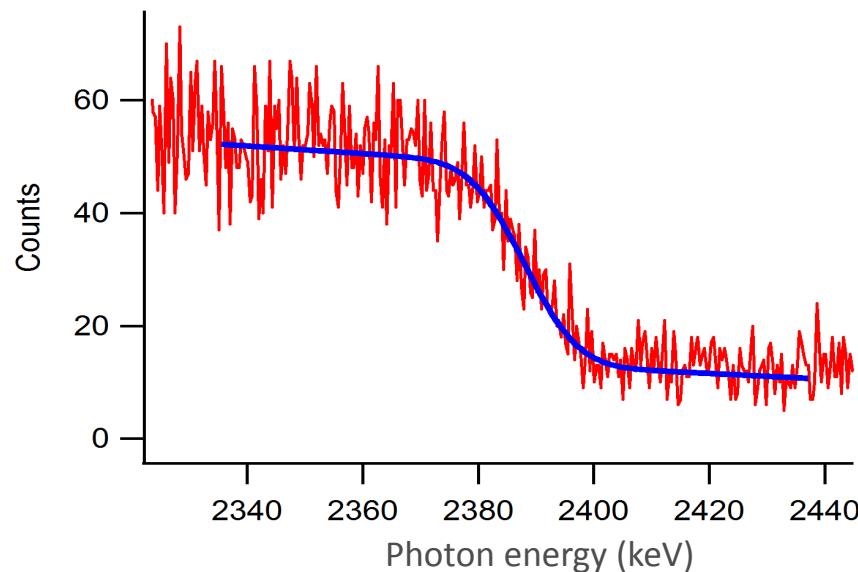
$$\frac{\sigma_{E_{\max}}}{E_{\max}} = 2 \times 10^{-4}$$

$$\frac{\sigma_{E_L}}{E_L} \sim 10^{-6}$$

$$\left. \begin{aligned} \frac{\sigma_{E_e}}{E_e} &= \sqrt{\left[\frac{\sigma_{E_{\max}}}{2E_{\max}} \right]^2 + \left[\frac{\sigma_{E_L}}{2E_L} \right]^2 + \left[\frac{\sigma_\phi}{2 \tan \phi / 2} \right]^2} \\ &\rightarrow \frac{\sigma_{E_e}}{E_e} = 2 \times 10^{-4} \end{aligned} \right.$$

$$E_e \pm \sigma_{E_e} = 1287.2 \text{ MeV} \pm 0.2 \text{ MeV}$$

Preliminary result for 1.6 GeV electron beam



- $p_0 = 2387.5 \pm 0.9 \rightarrow \frac{\sigma_{E_{\max}}}{E_{\max}} = 4 \times 10^{-4}$

- Chi-sq = 275.487; N_{ndf} = 261;

$$\Rightarrow \frac{\sigma_{E_e}}{E_e} = 3 \times 10^{-4}$$

$$\Rightarrow E_e \pm \sigma_{E_e} = 1582.2 \text{ MeV} \pm 0.4 \text{ MeV}$$

Conclusion and outlook

- For the first time, transverse CBS setup for electron beam energy measurement (1.3 GeV and 1.6 GeV)
- Preliminary analysis as proof of principle study
- Further detailed research on
 - BPM calibration and reading accuracy
 - Uncertainty caused by HPGe detector calibration
 - Improvement of laser direction determination
 - Improvement of statistic uncertainty by edge fitting
- Measurement of other energies, e.g. 0.5 GeV and 2.5 GeV (cross check with spin resonant depolarization)
- Potential complimentary energy measurement method at ANKA

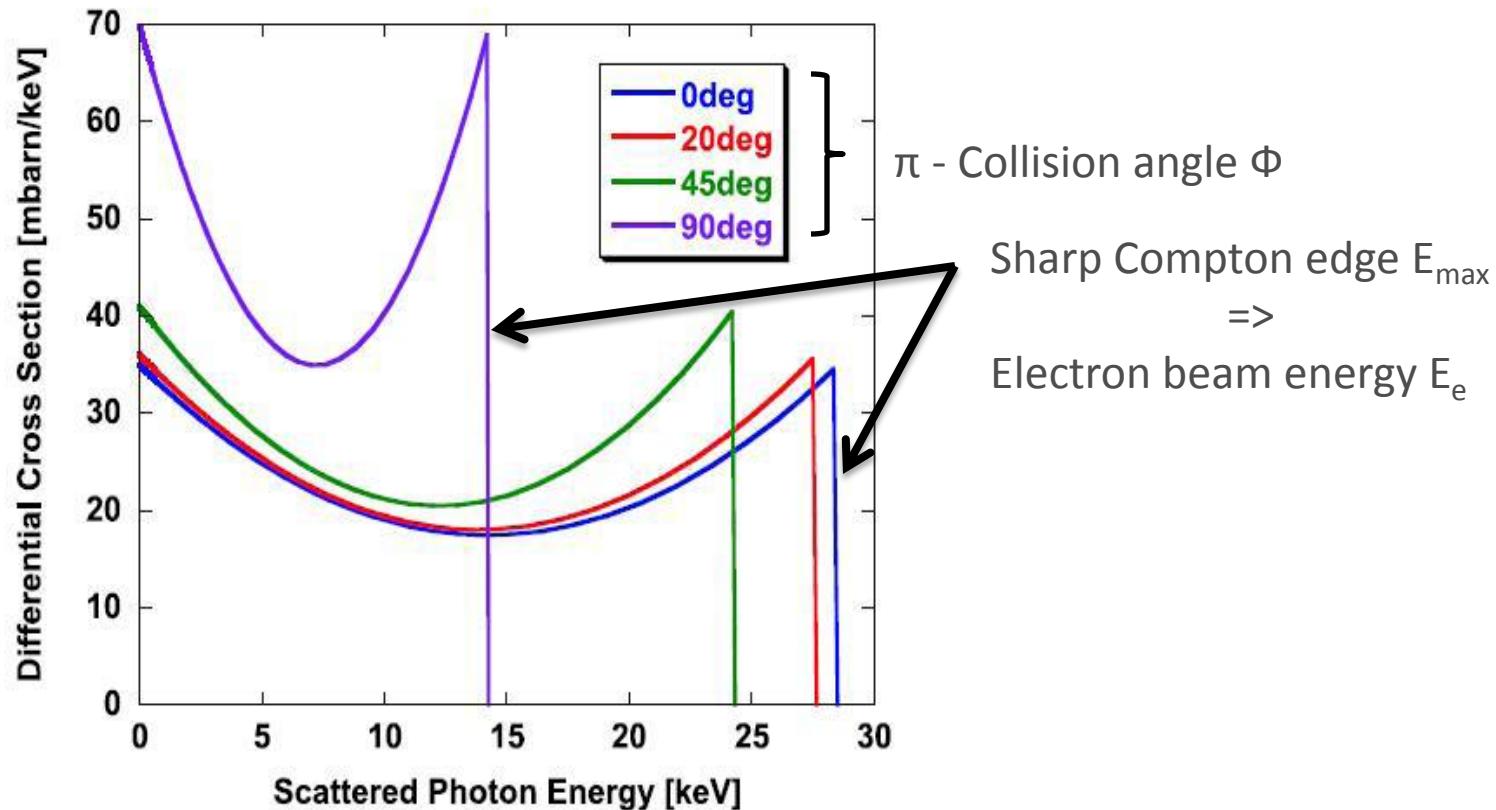
Acknowledgement

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Thanks !



Calculation of CBS energy spectrum



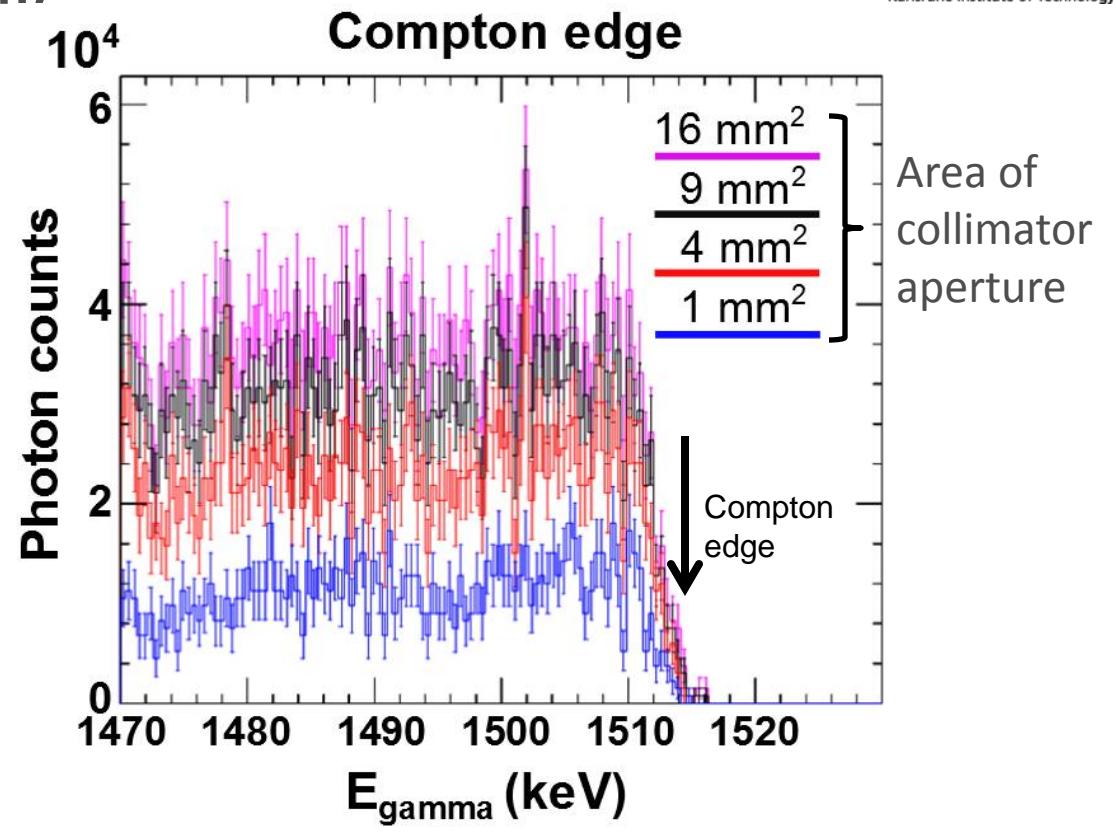
Energy spectrum of scattered photons produced by 1064 nm laser and 40 MeV electrons*

* XIN Tianmu, Physics department of Peking University, master's thesis, 2009

Simulation of CBS signal with CAIN2.35

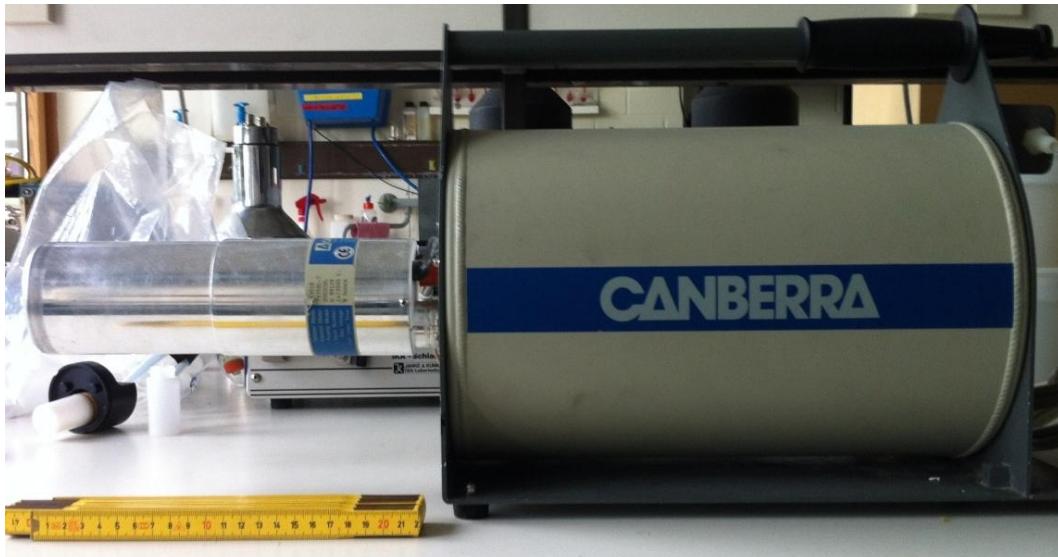
(developed by KEK, Japan)

- Electron beam current:
40 mA
- CW laser power: 10 W
- Acquisition: 20 min

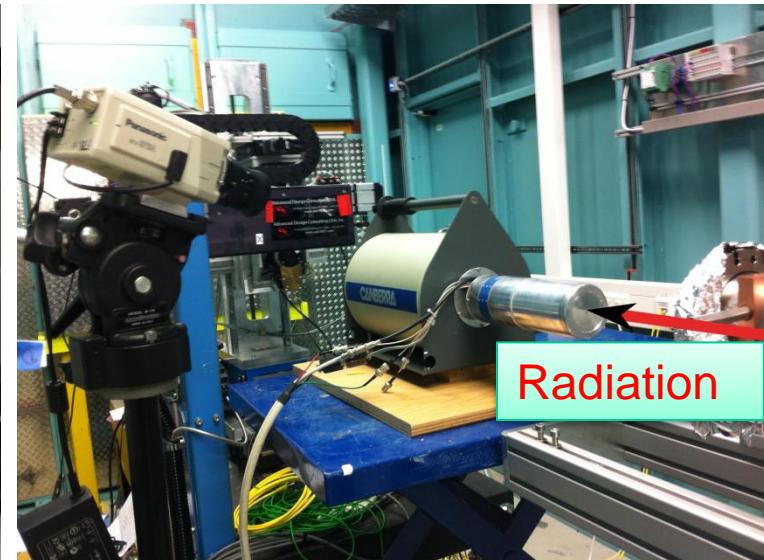


- 4 mm² aperture collimator
~5% detection efficiency
- } more than 2000 photons/keV recorded for analysis

Background measurement setup



HPGe detector: Canberra GX3018

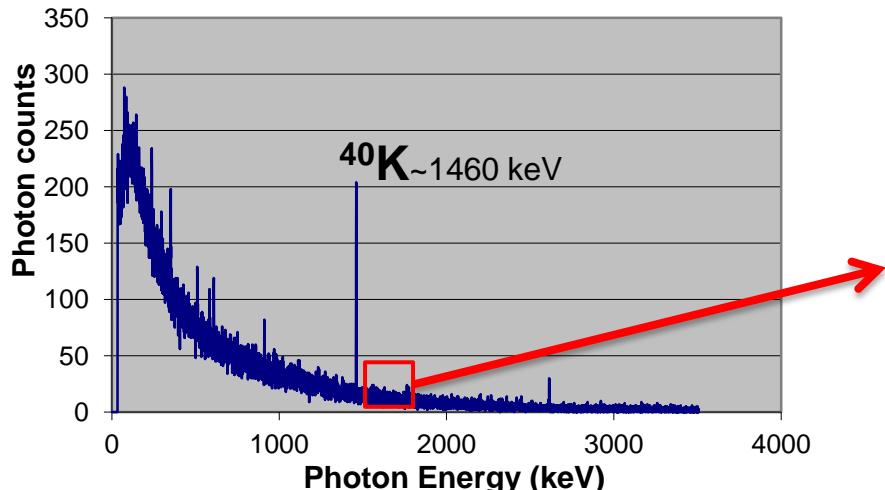


Measurement at IMAGE beamline

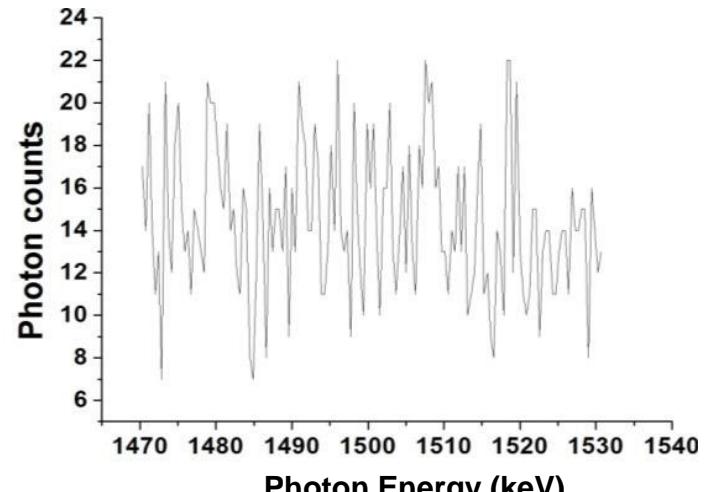
- Energy resolution: 1.80 keV (FWHM) at 1.33 MeV
- ~5% total absorption efficiency for ~1.5 MeV photons

Background measurement result

4 mm² slits, E_e: 1.3 GeV, I_e: 1.1 - 0.82 mA, acquisition time: 2000s



(a) whole spectrum

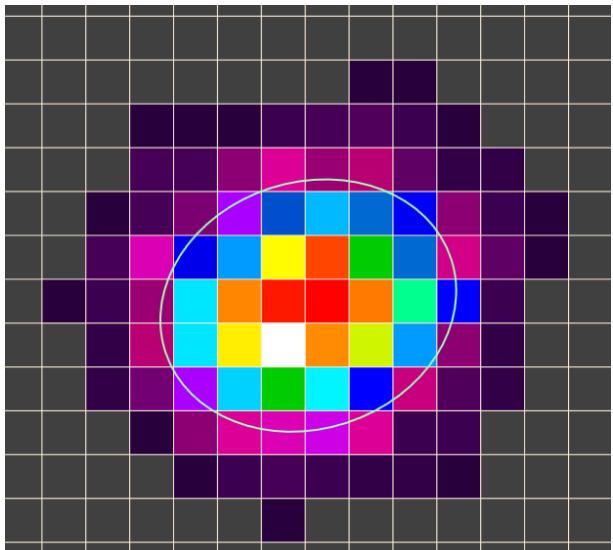


(b) CBS edge

■ Background measurement vs. simulation of CBS photons

→ *Signal - to - noise > 2.5 expected*

Determination/uncertainty of CO₂ laser direction



Centroid position (10000 samples)

	Pos1	Pos2
X center of samples (um)	13555	13486
ΔX (4 σ) (um)	1243.2	551.46
Distance between camera position 1 and 2 (m)		1.17948
Angle to RL by laser tracker (degree)		91.617

- Accuracy of Laser tracker (Leica Absolute Tracker AT402)
Maximum Permissible Error (>4 Sigma): +/- 15μm+6μm/m → negligible
- Angular uncertainty of laser centroid movement: 0.3 mrad=0.02°
- Laser orientation relative to RL: 91.61° ± 0.02°

Determination/uncertainty of electron beam orbit

Electron orbit		
	BPM1	BPM2
X position (mm)	0.327651	-0.381331
Distance between BPM 1 and 2 (m)		1.17948
Angle relative to RL (mrad/degree)		-0.6 / -0.03

- Mismatch between magnetic center and mechanical center of quadrupoles: 0.05 mrad
- Deviation by orbit drift during measurement <0.01 mrad
- Accuracy of BPM by beam based alignment method: < 0.1 mrad/0.006 °

$$\rightarrow \text{Interaction angle } \Phi = 91.58 \pm 0.02^\circ \rightarrow \frac{\sigma_\phi}{\tan \phi / 2} = 3 \times 10^{-4}$$

Electron beam orbit for 1.6 GeV

Electron orbit		
	BPM1	BPM2
X position (mm)	0.355972	-0.173986
Distance between BPM 1 and 2 (m)		1.17948
Angle relative to RL (mrad/degree)		-0.45 / -0.026

- Collision angle $\Phi = 91.59 \pm 0.02^\circ$

- $$\frac{\sigma_\phi}{\tan \phi / 2} = 3 \times 10^{-4}$$

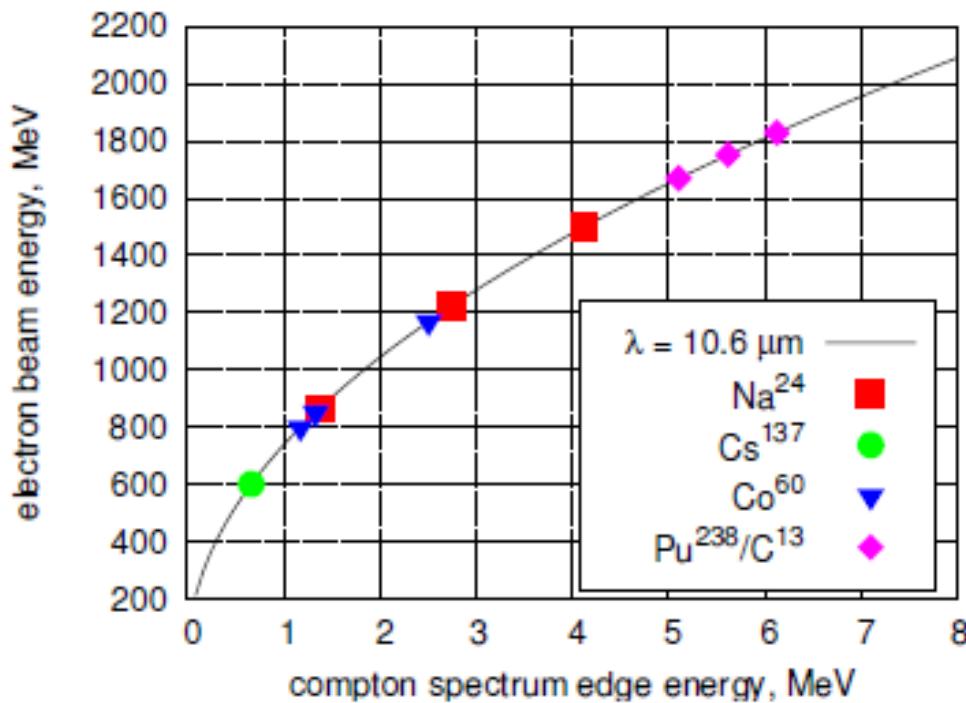
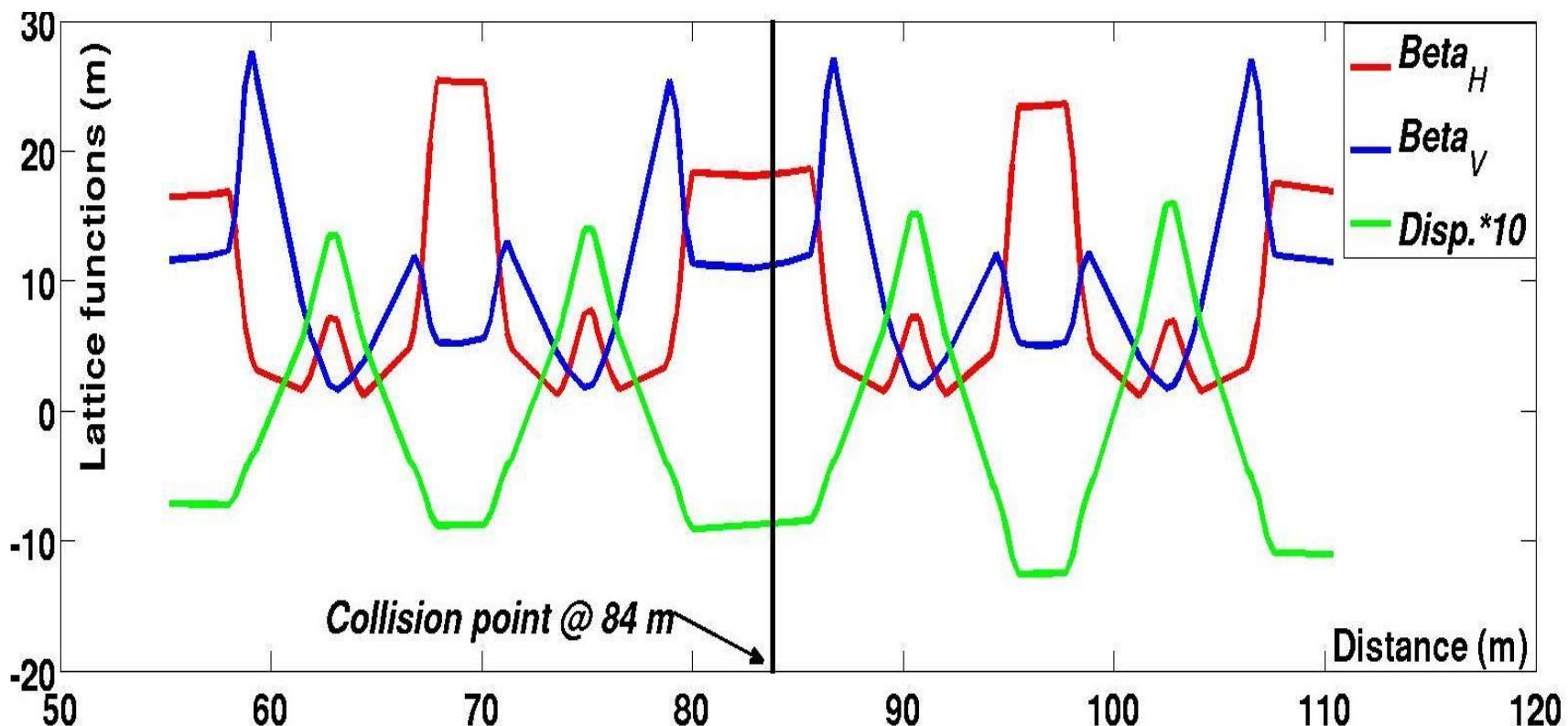


Figure 2: Relation between ω_{max} and ε (solid line). Dots is the energies of γ -active radionuclides (reference lines for HPGe detector calibration).

* M.N. Achasov et al., the beam energy calibration system for the BEPC-II collider, arXiv: 0804.0159v1 (2008).



The aim of the method

For $E_e \gg mc^2 \gg E_L$ and $\gamma = E_e/mc^2 \gg 1$,

$$\beta = \sqrt{1 - \gamma^{-2}} = \sqrt{1 - \frac{m^2 c^4}{E_e^2}} \approx 1 - \frac{m^2 c^4}{2E_e^2} \quad \Rightarrow \quad E_{\max} \approx \frac{E_e^2 \sin^2 \frac{\phi}{2} + \frac{m^2 c^4}{4} \cos \phi}{E_e \sin^2 \frac{\phi}{2} + \frac{m^2 c^4}{4E_L}}$$

For $\phi \sim \pi/2$

$$E_{\max} \approx \frac{E_e^2}{E_e + \frac{m^2 c^4}{4E_L \sin^2 \frac{\phi}{2}}} \quad \rightarrow \quad E_e = \frac{E_{\max}}{2} \left(1 + \sqrt{1 + \frac{m^2 c^4}{E_{\max} E_L \sin^2 \frac{\phi}{2}}} \right) \approx \frac{mc^2}{2 \sin \frac{\phi}{2}} \sqrt{\frac{E_{\max}}{E_L}}$$

The aim of the method

The width of the Compton edge ΔE_{\max}

$$\frac{\Delta E_{\max}}{E_{\max}} \simeq 2 \frac{\Delta E_e}{E_e} \oplus \frac{\Delta E_L}{E_L} \oplus \frac{\Delta R(E_{\max})}{R(E_{\max})} \oplus \frac{\Delta \phi}{\tan \phi / 2}$$

$\Delta \phi$ [Orbit drift during measurement $< 10^{-5}$
Beam angle of electrons a few 10^{-5} (H); $\sim 10^{-6}$ (V)
Beam angle of laser $<< 10^{-4}$ (H); 10^{-3} (V)

Relative uncertainty of electron beam energy

$$\frac{\sigma_{E_e}}{E_e} \simeq \frac{\sigma_{E_{\max}}}{2E_{\max}} \oplus \frac{\sigma_{E_L}}{2E_L} \oplus \frac{\sigma_\phi}{2 \tan \phi / 2}$$

σ_ϕ [Orbit drift during measurement $< 10^{-5}$
Misalignment due to precision of BPM 10^{-5} - 10^{-4} ; due to laser
 10^{-5} ?

The aim of the method

Statistic error from the edge fitting

$$\frac{\sigma_{E_{\max}}}{E_{\max}} \approx \sqrt{\frac{2\Delta E_{\max} / E_{\max}}{E_{\max} \frac{dN_{\gamma}}{dE_s}(E_{\max})}}$$

$\frac{dN_{\gamma}}{dE_s}(E_{\max}) \sim >10^3 / \text{keV}$ depending on how good the colimator can be aligned in real environment

$$\frac{\Delta E_{\max}}{E_{\max}} \sim 10^{-3}$$

$$\frac{\sigma_{E_{\max}}}{E_{\max}} \sim \text{a few } 10^{-5}$$

Systematic error of the edge measurement comes from the HPGe detector calibration $10^{-5} - 10^{-4}$

- Aim: relative energy uncertainty $\sim 10^{-4}$

Comparison between background and signal

- Compton edge: 1490 – 1515 keV
 - CBS gamma signal
 - Background radiation
- } \propto electron beam current x detection time
@ low electron current
- *Signal - to - noise?*

Average photon count rate (photons/mA/s)		
	16 mm ²	4 mm ²
Slits/collimator area		
Background (measured)	0.779	0.478
Signal (simulated, ~5% detection efficiency)	1.98	1.32

S/N > 2.5 expected

