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# Measurement of spatial polarization distributions of inverse Compton scattered gamma rays

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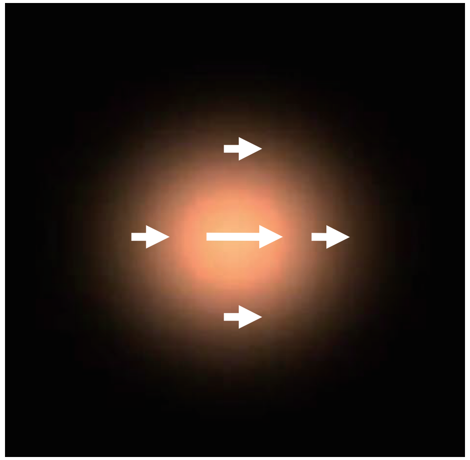
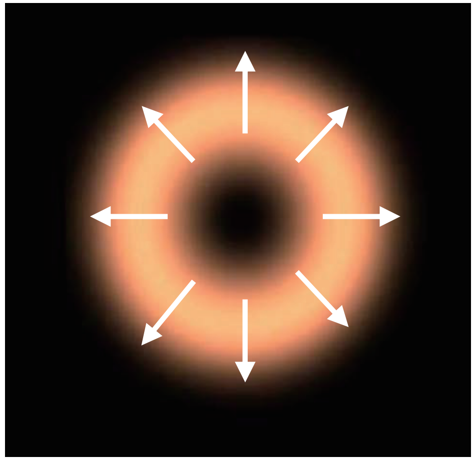
# Polarization of light

**Polarization is one of the controllable degrees of freedom of light.**

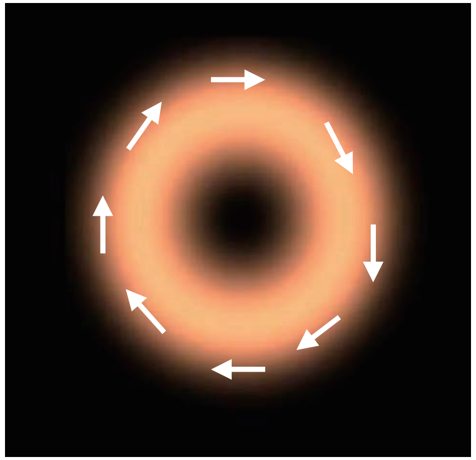
**X-polarized fundamental Gaussian mode**



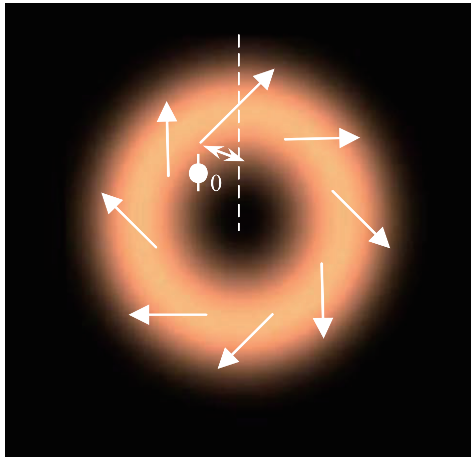
**Radially polarized mode**



**Azimuthally polarized mode**



**Generalized cylindrical vector beams mode**



Qiwen Zhan, Adv. Opt. Phot. 1 (2009) 1.

**A laser with axially symmetric polarization states (vector beams) have been generated using various methods and their extension into the ultraviolet and x-ray regions has also been proposed.**

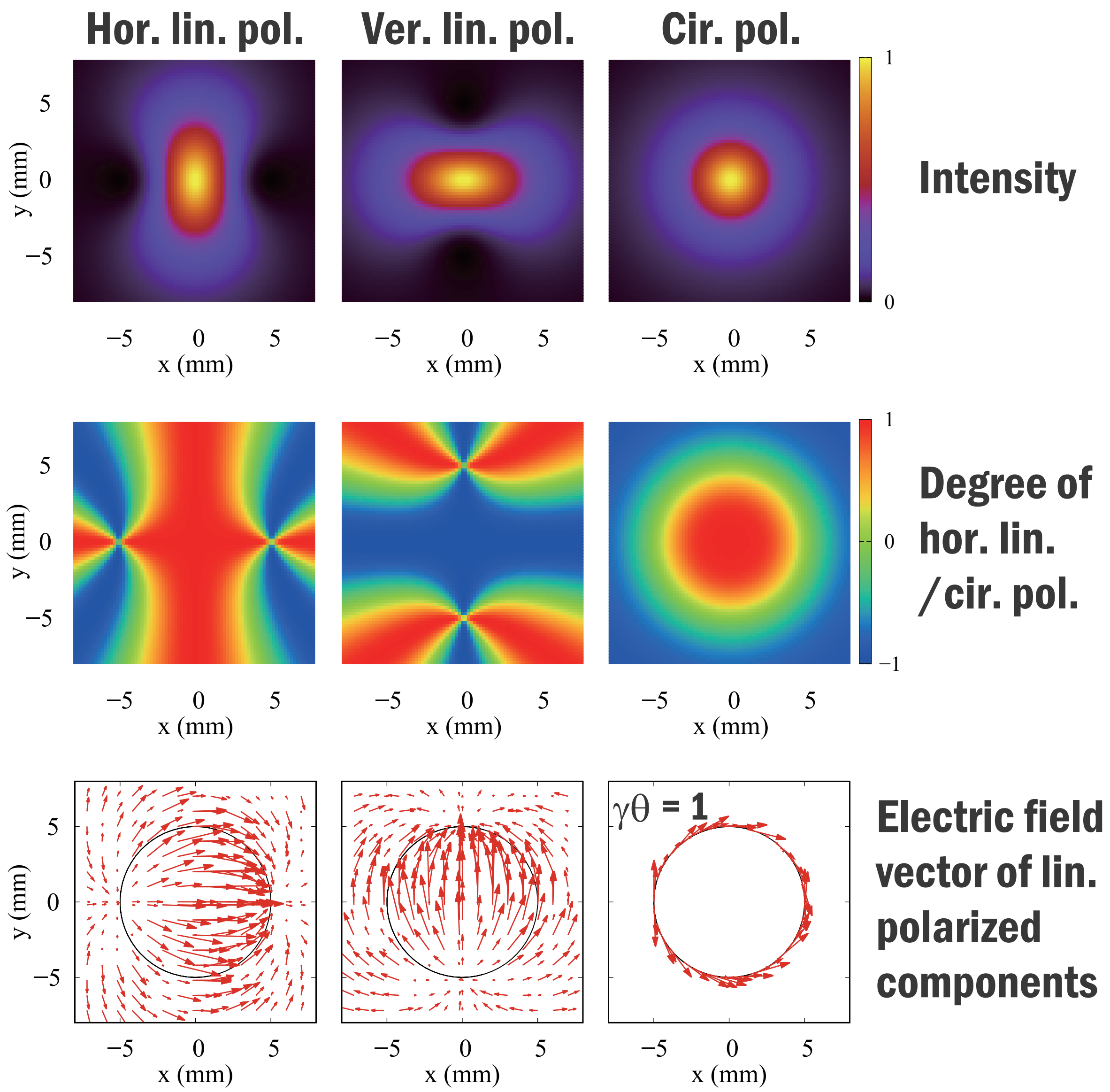
**Applications of vector beams: sharper focusing, z-polarization, improved laser cutting efficiency etc.**

# Generation of polarized gamma rays by Compton scattering


Two-dimensional intensity and polarization distribution changes across the gamma-ray beam cross section.

The polarization axis of linearly polarized gamma rays changes in the outer region.

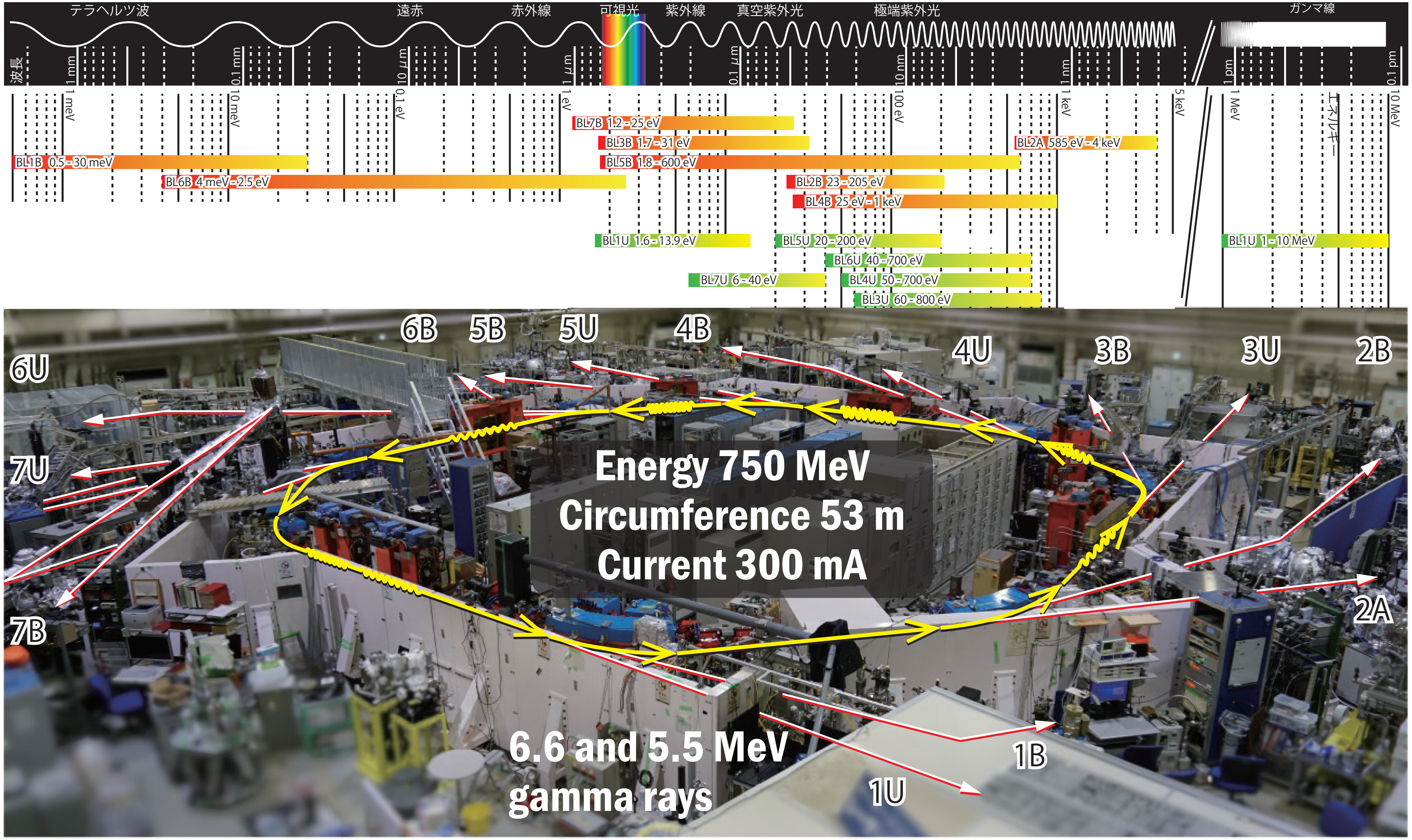
Gamma rays generated by a circularly polarized laser are circularly polarized near the beam center, but at $\gamma\theta = 1$, **the polarization axis of gamma rays is oriented in the azimuthal direction**.



# Purpose of this study

- Investigate the detailed spatial polarization distribution of polarized gamma rays.
- We have developed a Compton polarimeter capable of measuring the two-dimensional linear polarization distribution of gamma rays.
- We report experimental results on gamma rays generated using linearly, circularly, and axially symmetric polarized lasers.

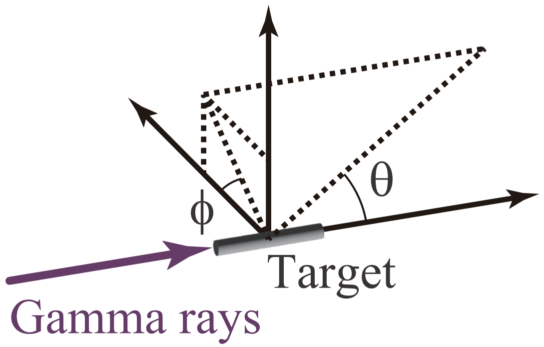
# UVSOR synchrotron facility, Okazaki, Japan

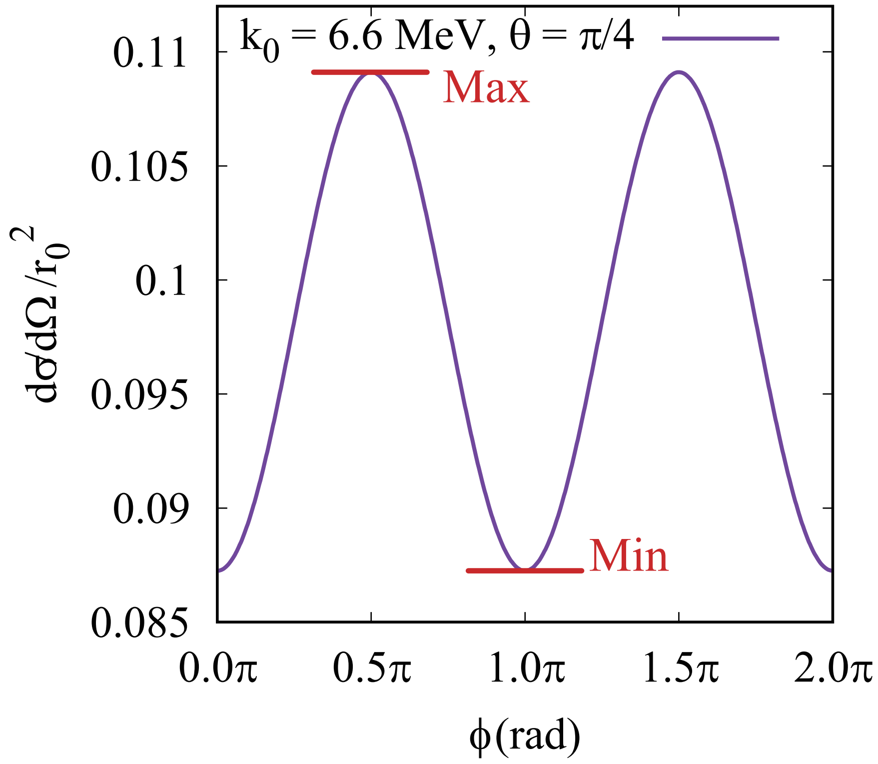


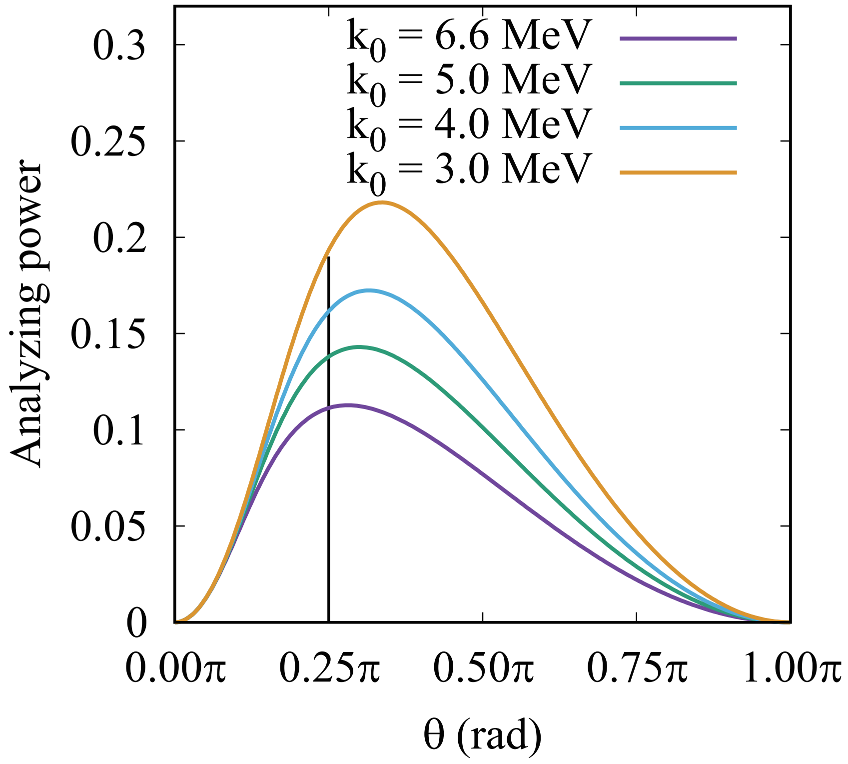
# Compton scattering when an initial gamma ray is polarized

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\left(\frac{k}{k_0}\right)^2\left(\frac{k}{k_0} + \frac{k_0}{k} - 2\sin^2\theta\cos^2\phi\right)$$

$$\frac{k_0}{k} = 1 + \frac{k_0}{m_e c^2}(1-\cos\theta)$$



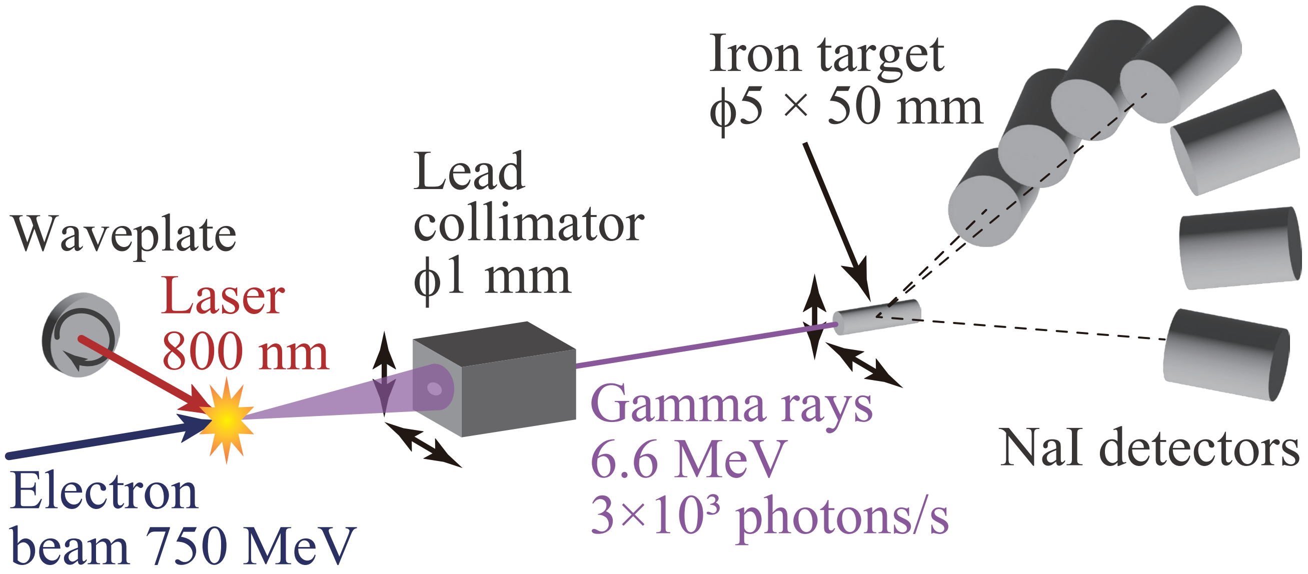



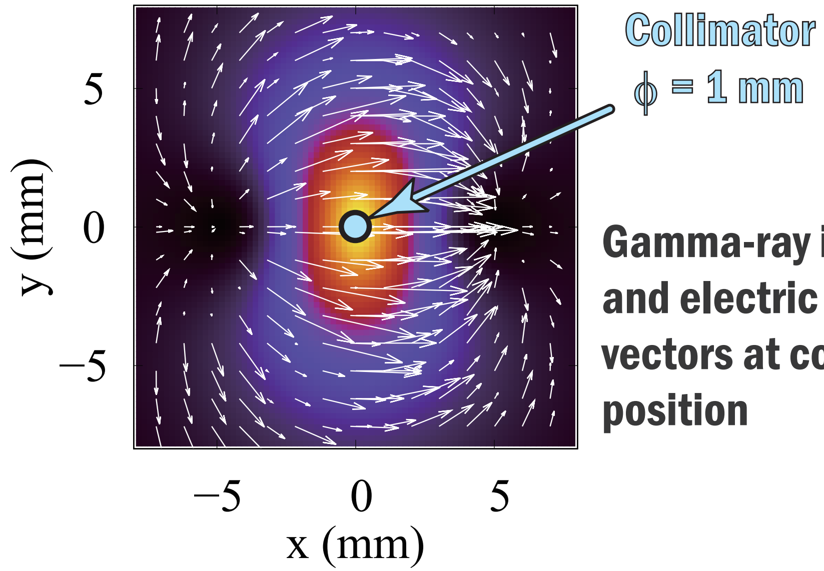

$$\text{Analyzing power} = \frac{\text{Max}-\text{Min}}{\text{Max}+\text{Min}}$$

**If initial gamma rays are linearly polarized, scattered gamma rays show asymmetry in the azimuthal direction, with a maximum at 90 degrees to the gamma ray polarization axis.**

# Development of a Compton polarimeter








Gamma-ray intensity and electric field vectors at collimator position

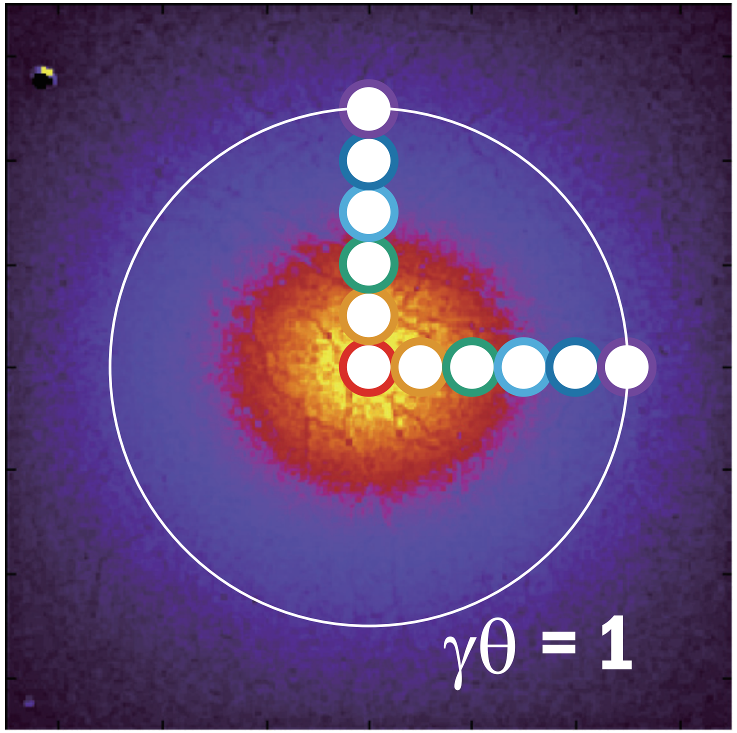
Seven NaI scintillation detectors are placed at $\theta$ = 45 degrees and every 30 degrees in $\phi$ direction to measure the scattered gamma rays from the target.

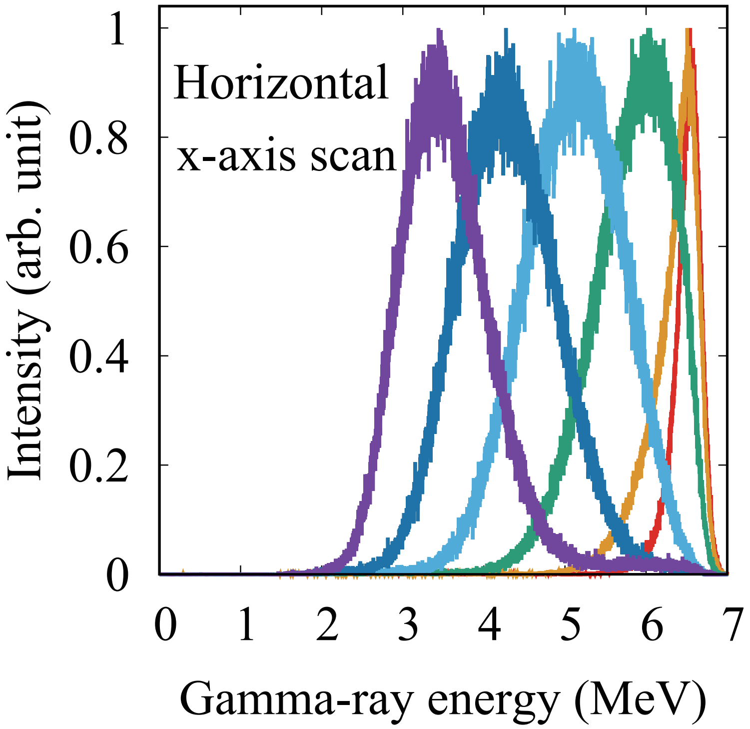
By passing a portion of gamma rays through a collimator, the polarization axis of gamma rays at that location can be measured.

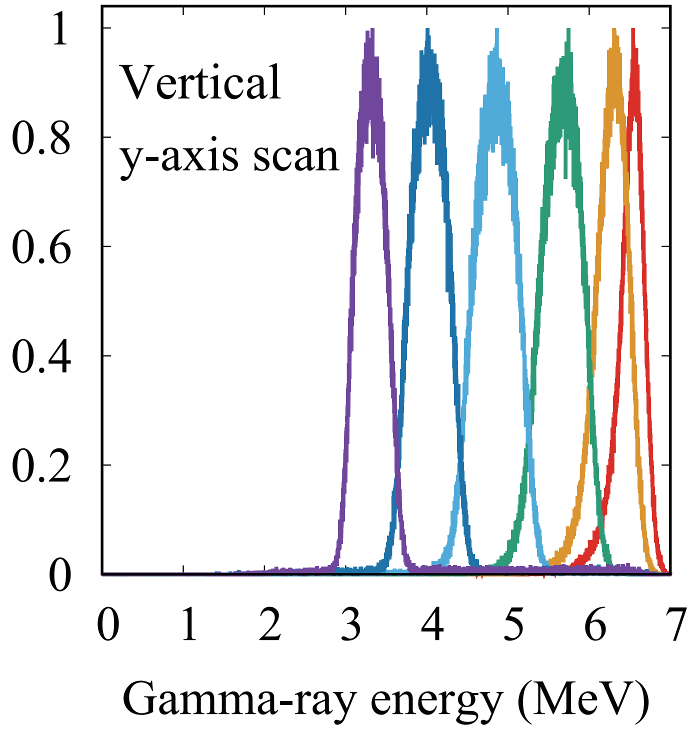
By scanning the collimator in two dimensions ($0 \leq \gamma\theta \leq 1$ and $0 \leq \phi < 2\pi$), the spatial polarization distribution of gamma rays can be measured.

# EGS5 simulation -Gamma-ray energy spectra-

**Simulated energy spectra after passing through a 1-mm-diameter collimator at various collimator positions.**




**rms $e^-$ beam size and angle**
**$\sigma_x$ = 0.58 mm, $\sigma_y$ = 0.02 mm**
**$\sigma_x'$=0.05 mrad, $\sigma_y'$ = 0.01 mrad**

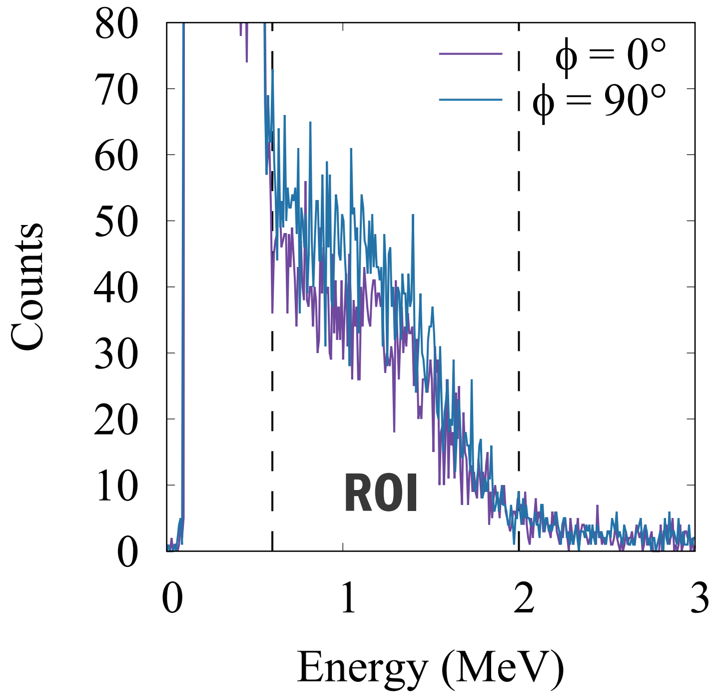
**Energy range: 3 to 6.6 MeV**

**Due to the larger horizontal emittance of the electron beam, the energy width is broader in the horizontal direction than in the vertical direction.**

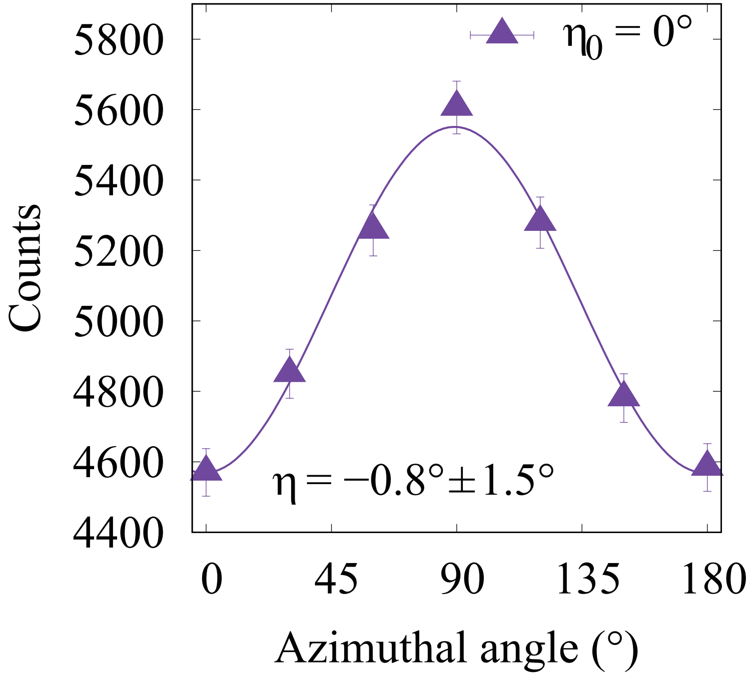
# Linear polarization at the central axis (meas.)

**The collimator was fixed at the center of the gamma-ray beam.**

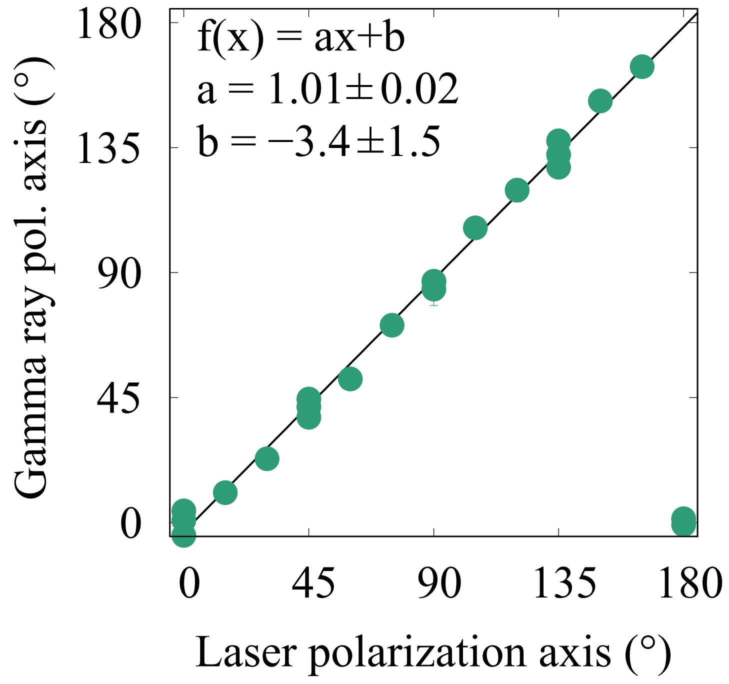
**Energy spectra of NaI detectors placed at $\phi$ = 0 and 90 deg.**




**Azimuthal distribution of detector counts in ROI.**

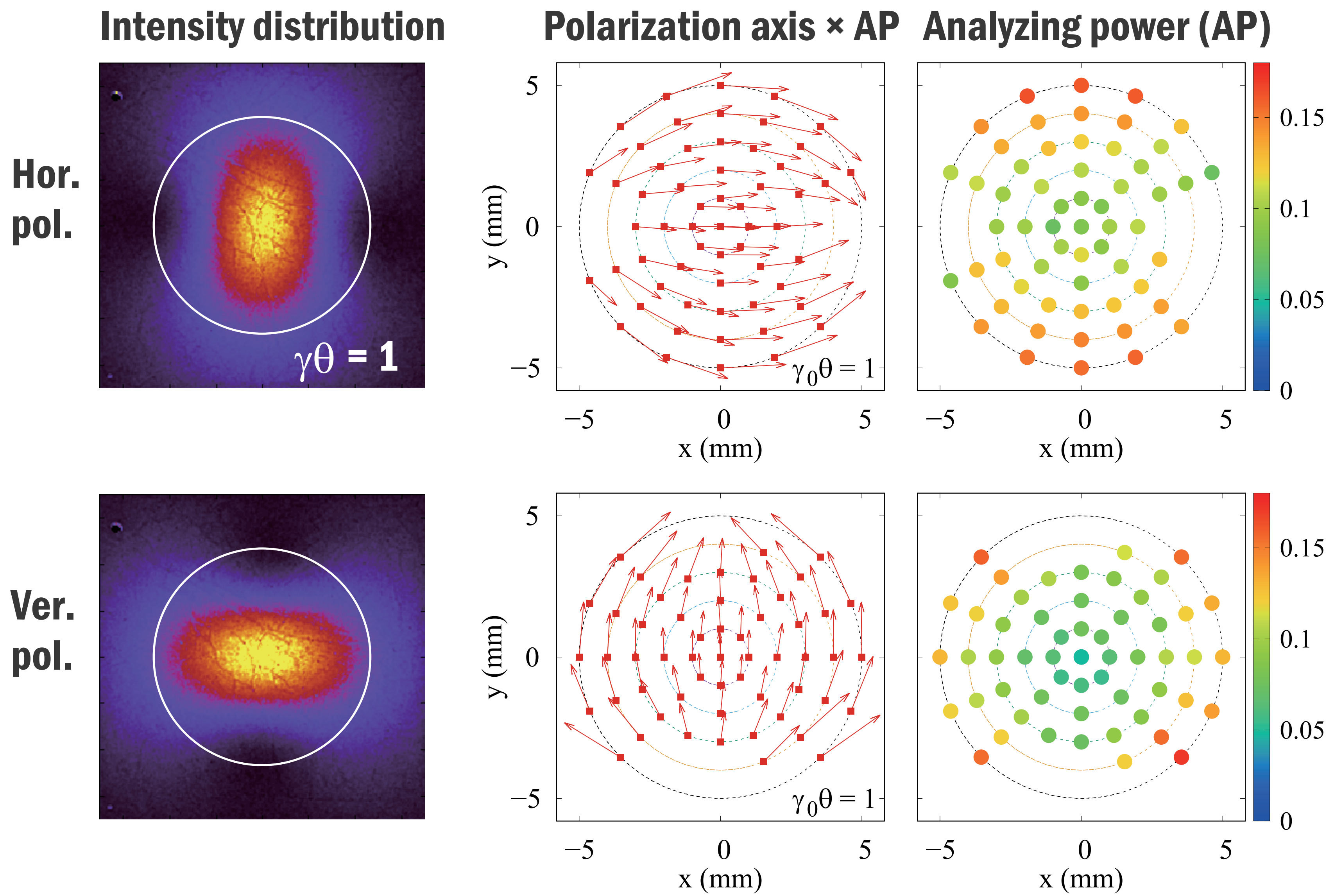



**Change in the gamma-ray polarization axis**




**The standard deviation of repeated measurements: 1° to 4°**

# Gamma rays generated by *linearly* polarized lasers (meas.)




It was clearly measured that the polarization axis of linearly polarized gamma rays changes with the position of the cross section.

The measured polarization axes closely reproduced the theoretical values.

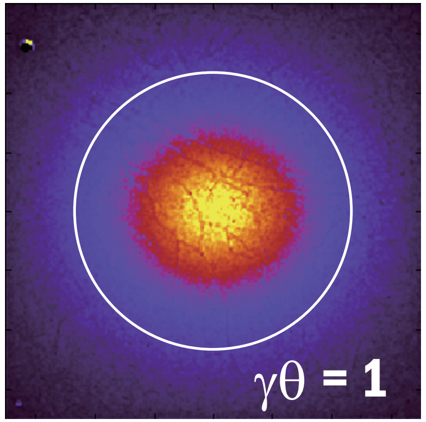
The developed polarimeter is considered to be operating effectively.

Y. Taira et al., PRR 7 (2025) 033130.

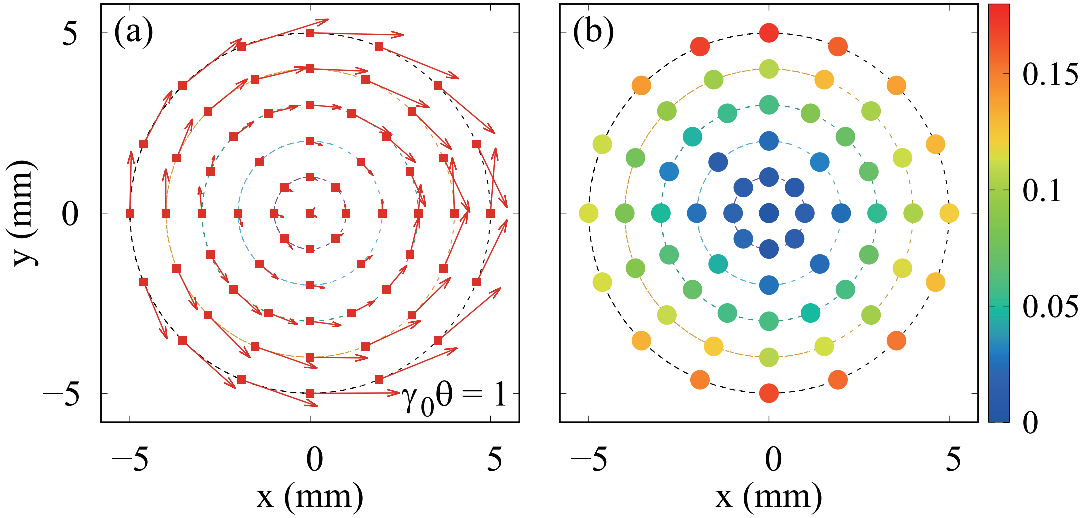
# Gamma rays generated by a *circularly* polarized laser (meas.)

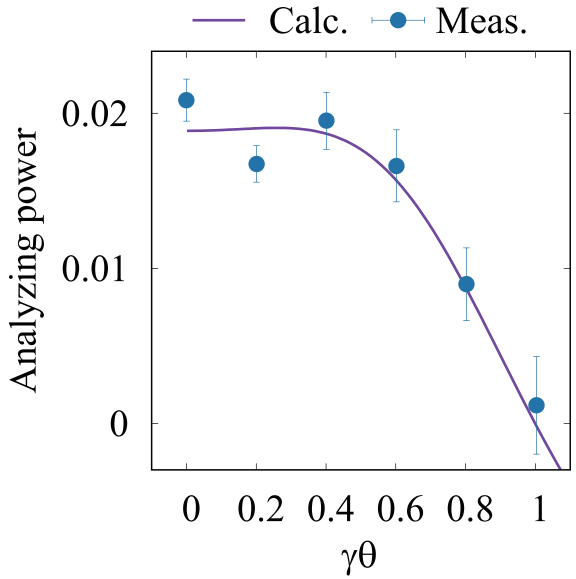
Intensity distribution

Cir. pol.




Polarization axis × AP　Analyzing power (AP)




Results measured by magnetic Compton scattering

AP was close to zero along the central but comparable to the values observed for linearly polarized gamma rays along the $\gamma\theta = 1$ line.

The polarization of gamma rays is circular at the central axis and becomes linearly polarized at $\gamma\theta = 1$.

We have demonstrated that the linear polarization component of gamma rays was azimuthal polarization as theoretical calculations indicate.

Y. Taira et al., PRA 107 (2023) 063503, Y. Taira et al., PRR 7 (2025) 033130.

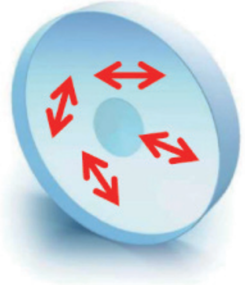
# Generation of an axially symmetric polarized laser

## S-waveplate (Altechna)

Standart waveplate

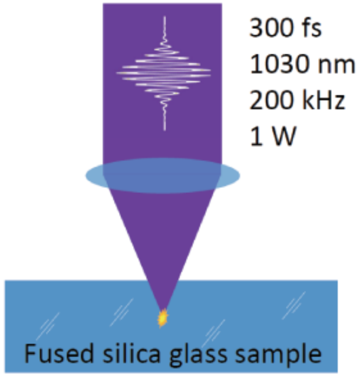
1. $\Theta$ = constant
2. $\Gamma$ = constant

Space variant waveplate

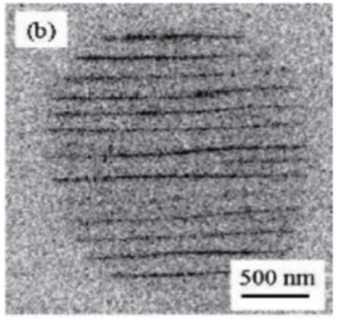


1. $\Theta(x,y)$
2. $\Gamma(x,y)$

**Fast axis angle $\Theta$**
**Retardance $\Gamma$**




300 fs
1030 nm
200 kHz
1 W

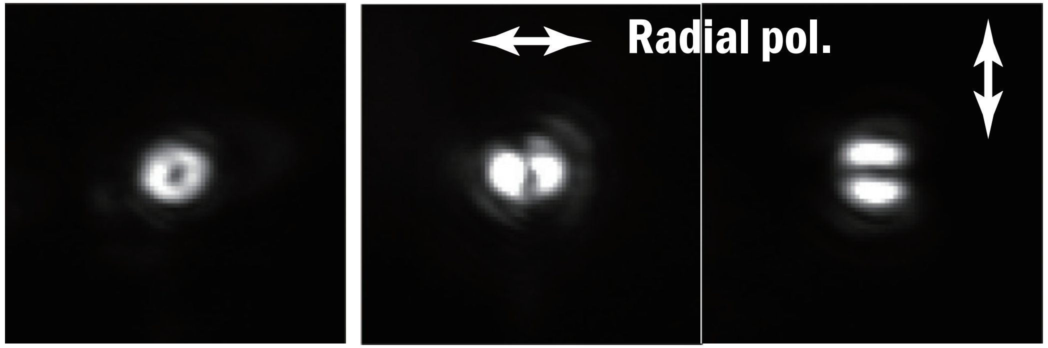



Top view

**Nanograting**

**Axially symmetric pol.** ◀ **Linear polarization**

w/o polarizer    w polarizer




**Optical vortex (TC = ±1)** ◀ **Circular polarization**

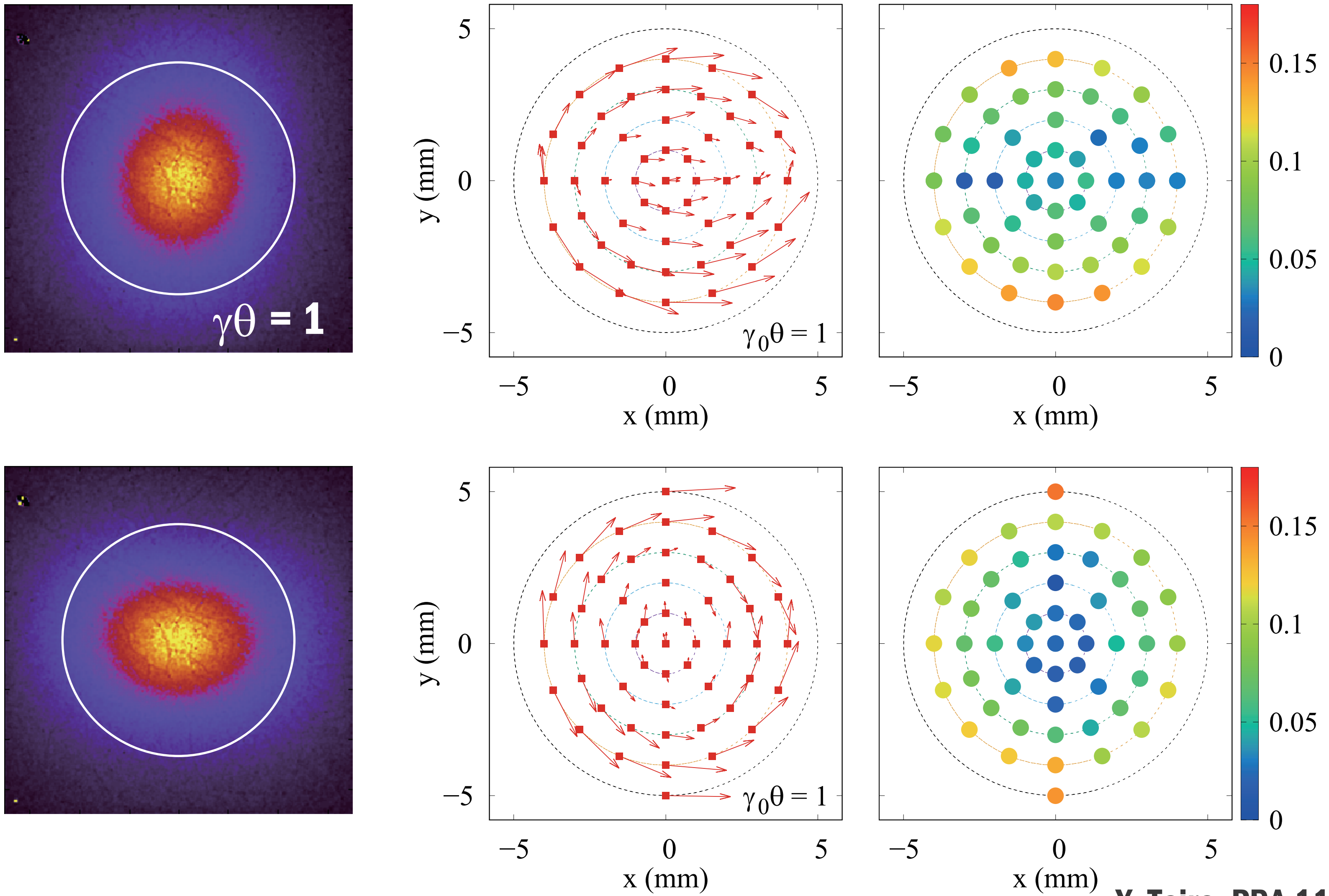
**Triangular aperture width 1 mm**

# Gamma rays generated by *rad.* and *azi.* polarized lasers (meas.)

Intensity distribution | Polarization axis × AP | Analyzing power (AP)

Rad. pol.

Azi. pol.




Different from the results for linear polarization.

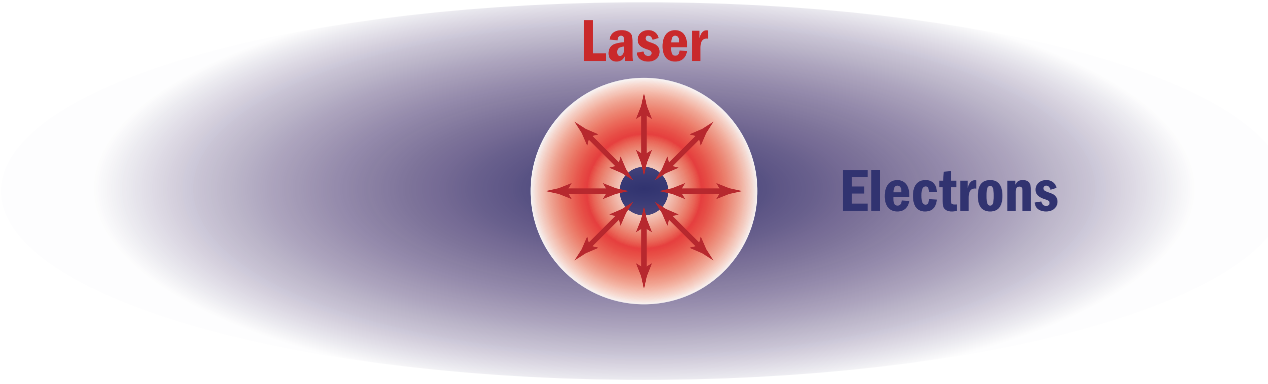
In both cases, the polarization of gamma rays is found to be azimuthal polarization in the outer region.

Furthermore, the analyzing power around the central axis is smaller than that of linearly polarized gamma rays.

This indicates that the degree of linear polarization around the central axis is low.

Y. Taira, PRA 110 (2024) 043525, PRR 7 (2025) 033130.

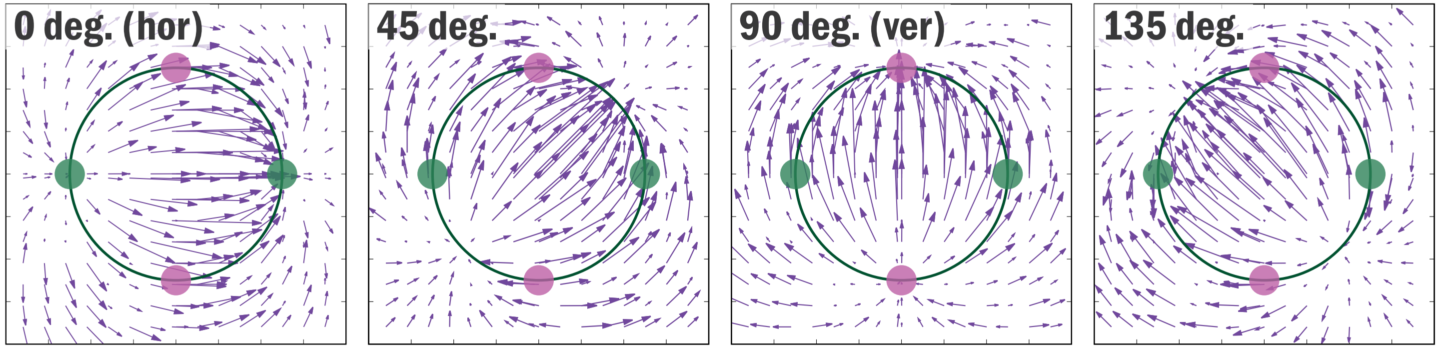
# Incoherent superposition of gamma rays (calc.)




Individual electrons interact with the entire axially symmetric polarized laser.

Electrons can be assumed to interact with electromagnetic fields whose polarization axis changes depending on their position.

**Linearly pol. gamma rays with different polarization axes are generated.**

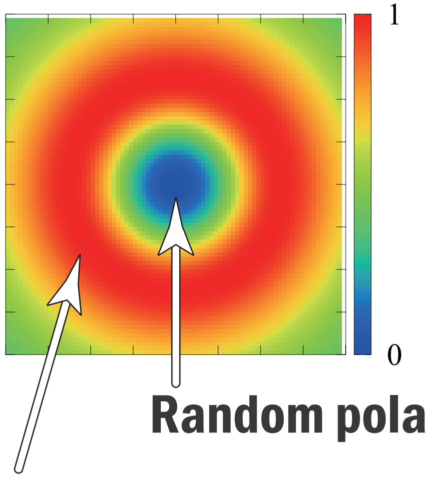



● Always horizontally polarized

● Always vertically polarized

Incoherent superposition

**The degree of linear polarization**




Random polarizeation

Azimuthal polarization

# Summary

- Using the developed gamma-ray polarimeter, we demonstrated the following.

  The polarization axis of linearly pol. gamma rays changes with the beam cross-section position.

  Gamma rays generated by a circularly polarized laser possess an inherent azimuthally polarized component in the outer region.

  Gamma rays generated using an axially symmetric polarized laser are not axially symmetric polarized gamma rays.

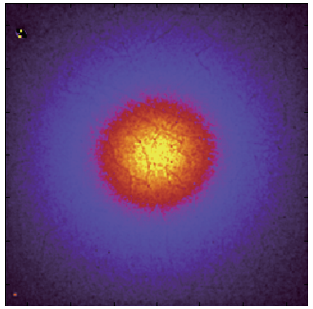
    The polarization state of gamma rays can be understood as an incoherent superposition of linearly polarized gamma rays with changing polarization axes.

- Future developments

  Is “coherent superposition” of gamma rays possible?

  Applications of gamma rays with unique polarization states.

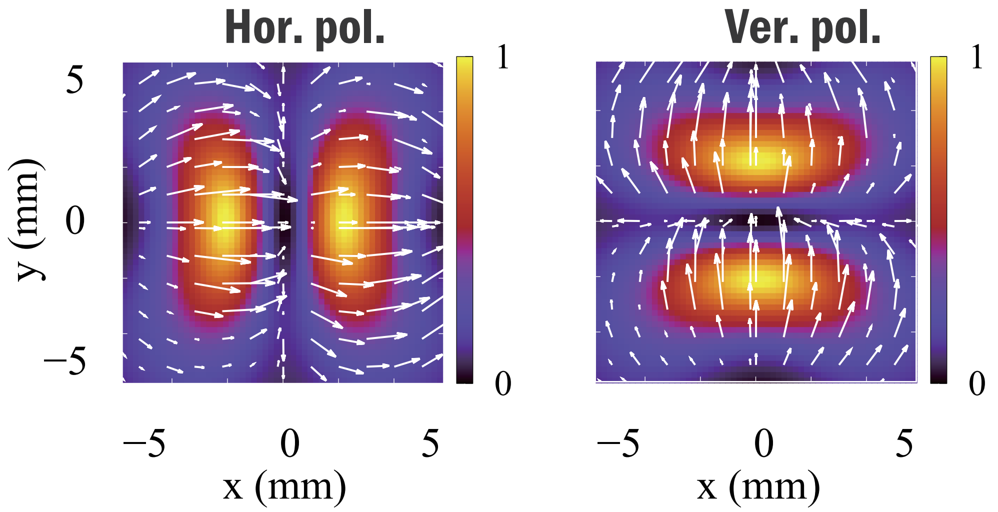
  Is the gamma ray generated using an optical vortex laser a gamma-ray vortex?



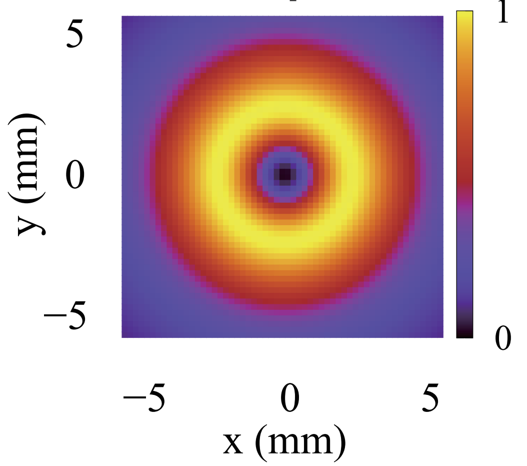
Thank you for your attention!

# Incoherent superposition of 2nd harmonic gamma rays (calc.)

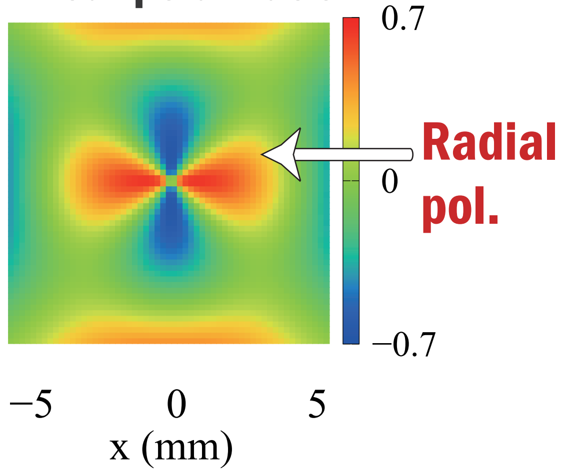
**Intensity distribution and electric field vectors**




**Intensity distribution averaged over rotation of pol. axis**




**The degree of horizontal linear polarization**




When a laser with high peak power is employed and $a_0 \sim 1$, higher harmonic gamma rays are generated due to nonlinear phenomena.

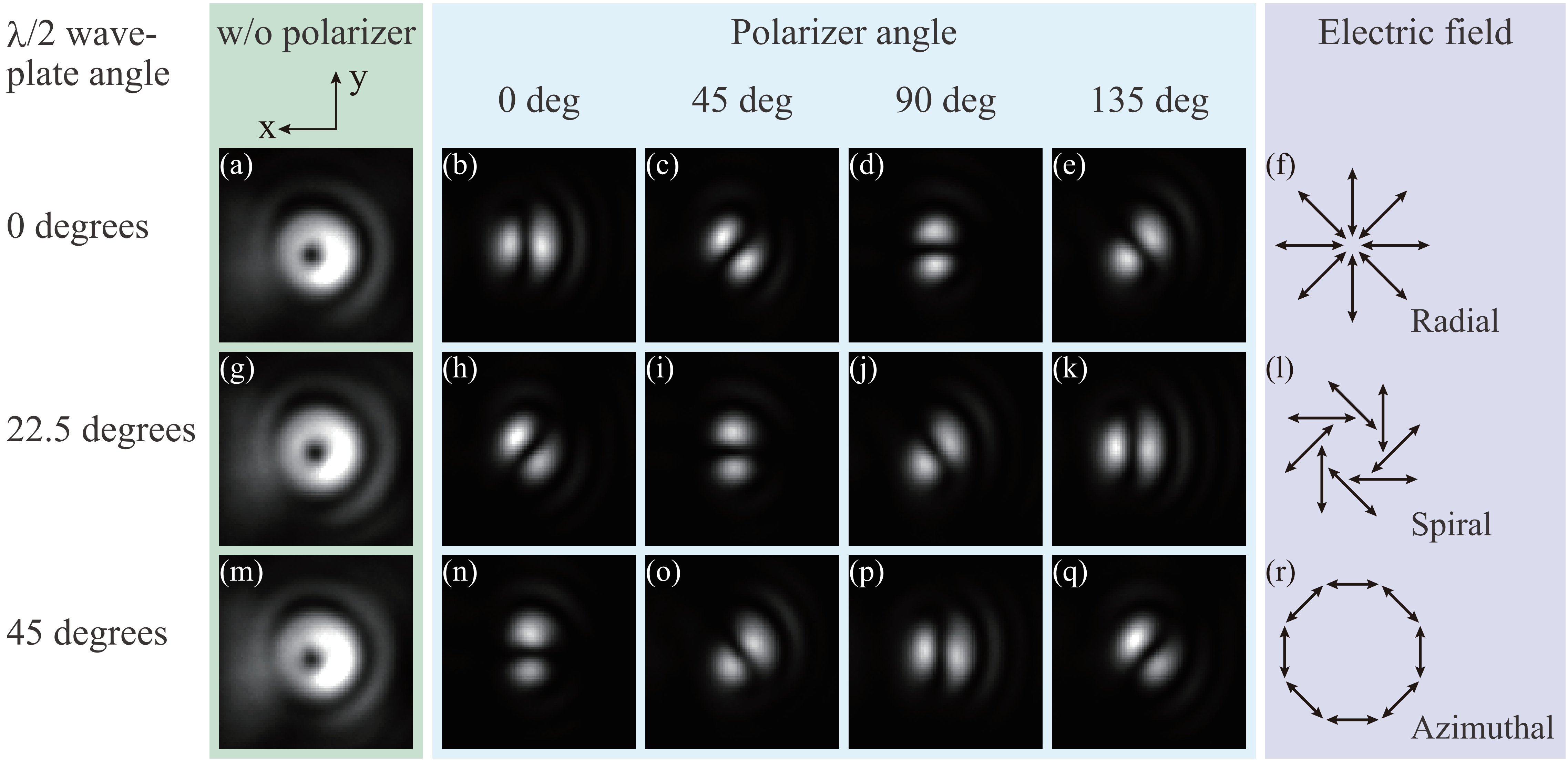
High-harmonic gamma rays exhibit variations in spatial intensity and polarization distribution.

For 2nd harmonic gamma rays, the intensity at the central axis vanishes, and two peaks appear along the polarization direction.

Consider the incoherent superposition of 2nd harmonic gamma rays generated using an intense axially symmetric polarized laser.

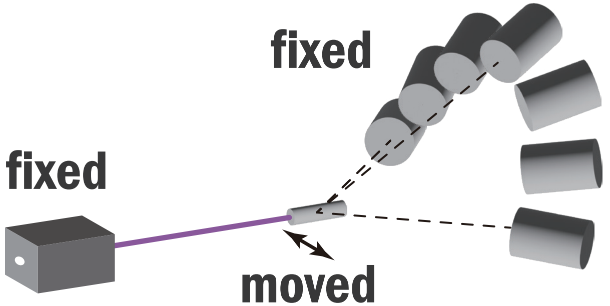
This calculation revealed that the intensity distribution exhibits a doughnut shape, and the polarization state is radial polarization.

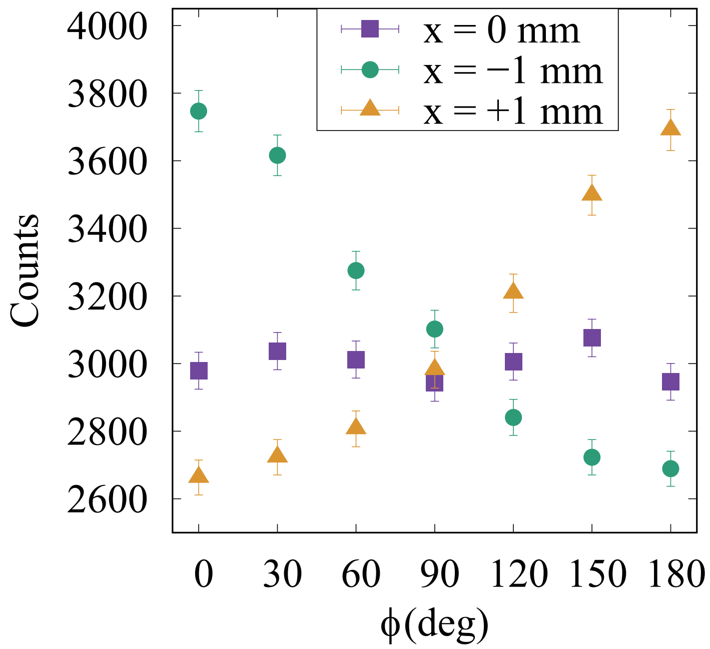
# Spatial distribution of the axially symmetric laser



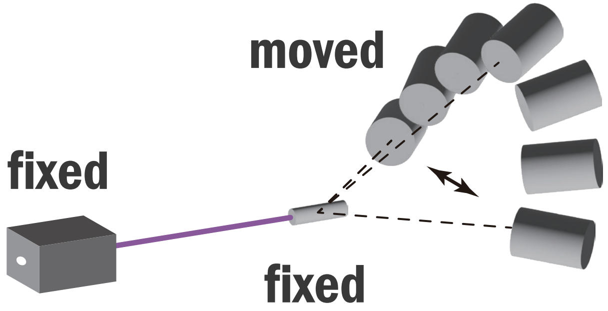

Y. Taira, PRA 110 (2024) 043525.

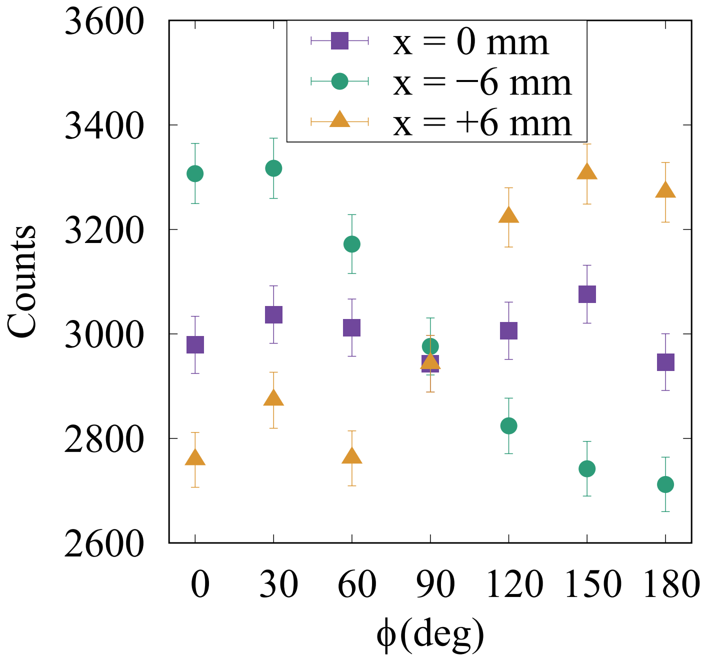
# EGS5 simulation -Displacement of target and detectors-




**The distribution becomes asymmetric because the number of electrons and positrons ejecting from the target increases.**

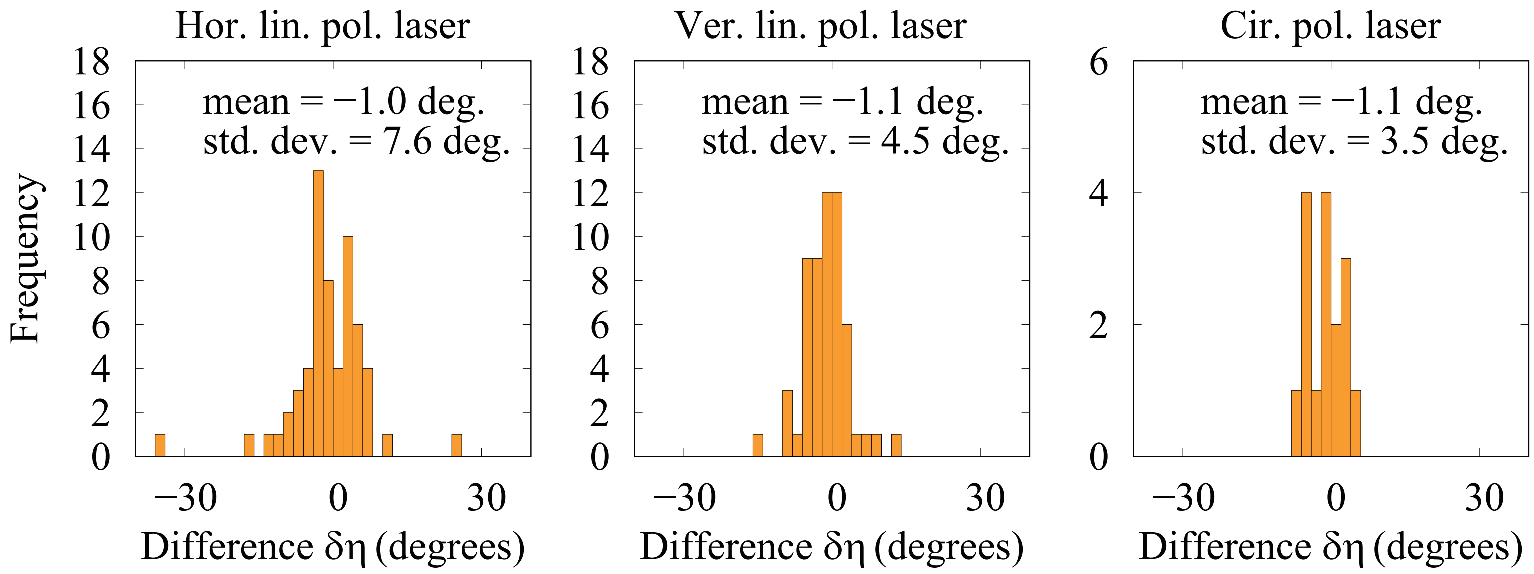



**The change in the effective solid angle of each detector due to displacement causes asymmetry in the scattering distribution.**

**Based on these simulation results, the polarimeter was designed such that when the collimator moves, the target and seven NaI detectors are displaced.**

# Gamma rays generated using *lin.* and *cir.* polarized lasers

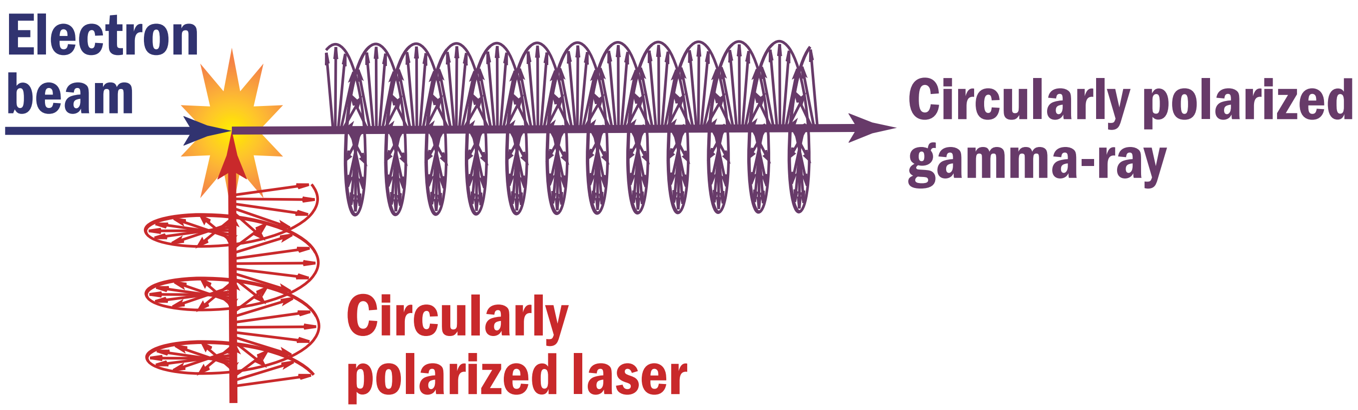



**Histogram of difference between theoretical and measured values of gamma-ray polarization axis**

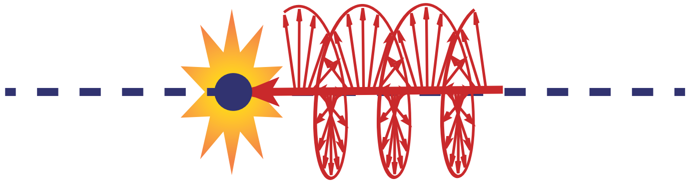
**The measured polarization axis distribution reproduces the theoretical calculation well because the mean and standard deviation of the differences are small.**

# Polarization of a laser for 90-degree collision

## Laboratory frame




## Electron rest frame



In an electron rest frame, the laser appears to be incident from the front due to Lorentz transformation.
Furthermore, if the Lorentz factor is sufficiently large, the laser remains circularly polarized.
Therefore, circularly polarized gamma-rays are generated even in a 90 degree collision.

J. D. Jackson, Classical Electrodynamics third edn. Chapter 11.
Y. Taira and M. Katoh, The ApJ 860 (2018) 45., Y. Taira et al., PRA 107 (2023) 063503.