

Generation and measurement of gamma rays with axially symmetric polarization states via Compton scattering

Yoshitaka Taira ^{1,2,*} Yuxuan Yang ^{3,1,4} Toshiyuki Shizuma ⁵ and Mohamed Omer ^{6,†}

¹*Institute for Molecular Science, National Institutes of Natural Sciences, Okazaki 444-8585, Japan*

²*Graduate Institute for Advanced Studies, SOKENDAI, Okazaki 444-8585, Japan*

³*School of Physics, Zhengzhou University, Zhengzhou 450001, China*

⁴*Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China*

⁵*Kansai Institute for Photon Science, National Institutes for Quantum Science and Technology, Kizugawa 619-0215, Japan*

⁶*ISCN, Japan Atomic Energy Agency, Tokai 319-1195, Japan*



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Highly polarized gamma rays with linear or circular polarization are essential light sources for nuclear and particle physics experiments, astronomical detector evaluations, and relativistic electron beam diagnostics. In this study, we demonstrate gamma-ray generation via Compton scattering with unique polarization states, termed axially symmetric polarization. To investigate this, we developed a polarimeter for Compton gamma-ray sources to measure their two-dimensional polarization distribution. We found two methods to generate gamma rays whose polarization axis follows the azimuthal direction. The first method exploits the inherent azimuthal polarization of gamma rays produced using a circularly polarized laser. In this configuration, the gamma rays along the central axis are circularly polarized, while the linear polarization components in the outer region of the beam cross section are aligned azimuthally. The second method utilizes azimuthal polarization that arises in the outer region of the beam due to the incoherent superposition of multiple linearly polarized gamma rays with varying polarization axes, generated by an axially symmetric polarized laser. Additionally, our calculations indicate the feasibility of generating gamma rays with polarization axes oriented along the radial direction. This radial polarization, observed near the beam axis, results from the incoherent superposition of second harmonic gamma rays produced through nonlinear interactions induced by an intense axially symmetric polarized laser.

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I. INTRODUCTION

Polarization is one of the controllable degrees of freedom of light [1]. While linearly and circularly polarized light exhibit homogeneous polarization states across the beam cross section, recent advances in polarization control technologies have enabled the generation of light with spatially modulated polarization states, commonly referred to as structured light. A notable example is light with an axially symmetric polarization state, including radial and azimuthal polarization—collectively known as vector beams [2]. A laser whose polarization is distributed in the radial (azimuthal) direction is termed a radially (azimuthally) polarized laser. In both cases, the optical axis forms a polarization singularity, resulting in a characteristic doughnut-shaped intensity distribution. Vector beams have been successfully generated using various methods in the visible and near-infrared wavelength

ranges [3] and their extension into the ultraviolet and x-ray regions has also been proposed [4–6]. Axially symmetric polarized lasers have attracted substantial interest due to their unique optical properties, including sharper focusing compared to linearly polarized lasers [7], enhanced axial trapping efficiency in optical tweezers [8], and improved laser cutting efficiency relative to circularly polarized lasers [9]. Moreover, their strong longitudinal electric field component is considered promising for particle acceleration applications [10].

In the MeV energy region, polarized gamma rays can be generated either by bremsstrahlung or by Compton scattering (CS) between a polarized laser and a relativistic electron beam. In bremsstrahlung, linearly polarized gamma rays are produced through coherent bremsstrahlung [11], while circularly polarized gamma rays are generated using a polarized electron beam [12]. However, CS can produce gamma rays with a higher degree of polarization than bremsstrahlung. Using linearly or circularly polarized lasers, linearly and circularly polarized gamma rays with nearly 100% polarization can be achieved [13,14]. In addition to their polarization properties, gamma rays generated through CS offer other advantages, such as variable energy and low divergence angles (less than 1 mrad). Because gamma-ray energy varies with the scattering angle, gamma rays with an energy spread of only a few percent can be selected using a collimator. The generation of polarized gamma rays through CS is currently performed at several electron accelerator

*Contact author: yostaira@ims.ac.jp

†Formerly at: Physics Department, Faculty of Science, Assiut University, Assiut 71516, Egypt.

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facilities worldwide [14–17]. These sources support a wide range of applications, including nuclear physics experiments [18–20], polarized positron beam generation [21], polarized electron beam diagnostics [22], and the evaluation of detectors for polarized gamma rays [23,24]. Other applications of Compton gamma rays that do not directly exploit polarization include tomography [25,26], electron beam energy diagnostics [27], beam size measurements [28], and analysis of atomic-scale defects inside bulk materials using positron annihilation spectroscopy [29,30]. Recently, laser-accelerated electron beams have also been employed to generate gamma rays [31–35]. As discussed previously, the development and application of lasers with new polarization characteristics have been actively promoted. Extending these advances to the gamma-ray region—specifically, enabling the generation of axially symmetric polarized gamma rays, an unexplored area—could lead to new applications beyond those based on conventional linearly, circularly, and randomly polarized gamma rays.

This study experimentally and theoretically investigates methods for generating gamma rays with axially symmetric polarization states using 6.6 MeV gamma rays produced by 90° scattering between a 750 MeV electron beam and a Ti:Sa laser with an 800 nm wavelength. The experiments are conducted using an electron storage ring at the ultraviolet synchrotron orbital radiation (UVSOR) facility. To measure the polarization distribution of the gamma rays in detail, we have developed a Compton polarimeter capable of measuring the two-dimensional linear polarization distribution, in contrast to previous one-dimensional scanning methods [16,36]. The polarimeter covers a range of $0 \leq \gamma_0 \leq 1$ and $0 \leq \phi < 2\pi$, where γ_0 denotes the Lorentz factor of the electron beam, θ is the gamma-ray scattering angle, and ϕ is the azimuthal angle. The measured gamma-ray energy ranges from 3 to 6.6 MeV, as the energy decreases with increasing scattering angle. To assess the performance of the polarimeter, we first demonstrate that the polarization axis of linearly polarized gamma rays varies linearly with the polarization axis of a laser and that the two-dimensional polarization distribution changes across the gamma-ray beam cross section. Subsequently, we demonstrate that, at $\gamma_0 \theta = 1$, the polarization axis of gamma rays generated by a circularly polarized laser is oriented in the azimuthal direction. Although not widely recognized, gamma rays inherently exhibit an azimuthal polarization component. Near the beam center, gamma rays are circularly polarized; however, as the scattering angle increases, the polarization transitions to linear, with the polarization axis aligning along the azimuthal direction. Furthermore, we demonstrate that gamma rays generated by an axially symmetric polarized laser exhibit azimuthal polarization in the outer region, where the scattering angle is large. This behavior arises from the incoherent superposition of linearly polarized gamma rays with different polarization axes. The superposition is incoherent because electron bunches with finite longitudinal lengths do not produce phase-aligned gamma rays. Additionally, calculations indicate that radially polarized gamma rays can be generated around the central axis through the incoherent superposition of second-harmonic gamma rays produced by nonlinear interactions with an intense axially symmetric polarized laser.

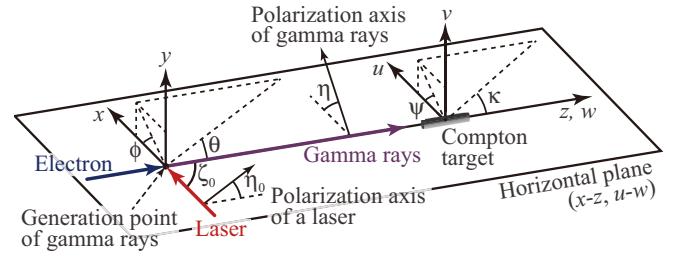


FIG. 1. Schematic of the coordinate system used in this study.

II. POLARIZATION CHARACTERISTICS OF GAMMA RAYS GENERATED BY LINEARLY AND CIRCULARLY POLARIZED LASERS

For UVSOR gamma rays, the energy of incident photons in the electron rest frame is 2.2 keV. This energy is substantially smaller than the electron rest energy, allowing the scattering process to be treated as being close to the Thomson scattering regime. Therefore, the polarization characteristics of the generated gamma rays can be calculated using classical electrodynamics based on the Liénard-Wiechert potentials. The Fourier component of the electric field emitted by an electron in an arbitrary orbit is given by (Sec. 14.5 in [37])

$$\mathbf{E} = -iC_0 \int_{-\infty}^{\infty} dt \{ \mathbf{n} \times (\mathbf{n} \times \boldsymbol{\beta}) \} e^{ik\{ct - \mathbf{n} \cdot \mathbf{r}_e(t)\}}. \quad (1)$$

Here,

$$C_0 = \frac{ek}{\sqrt{32}\pi^{3/2}\epsilon_0 R} e^{ikR}, \quad (2)$$

where e denotes the elementary charge, $k = \omega/c$ (with ω being the angular frequency of the emitted radiation), c represents the speed of light, ϵ_0 is the vacuum permittivity, R is the distance from the origin of the electron's motion coordinate system to the observation point, t is time, $\mathbf{n}$ is the unit vector pointing from the origin to the observation point, $\boldsymbol{\beta}$ signifies the ratio of the electron's velocity vector in the laser field to the speed of light, and $\mathbf{r}_e(t)$ is the trajectory of the electron inside the laser field. Equation (1) can be evaluated by solving the relativistic equation of motion for an electron in a polarized laser field. For instance, a transverse sinusoidal motion of electrons is induced along the polarization axis when interacting with a linearly polarized laser. In contrast, a spiral electron motion is induced by a circularly polarized laser [38]. This electron motion affects the polarization characteristics of the emitted electric field. As the detailed derivations are described in [38–41], only the final expressions for the electric fields emitted when a linearly or circularly polarized laser is injected at arbitrary angles are presented here. A schematic of the coordinate system used in this study is shown in Fig. 1.

Equation (1) is first calculated in the spherical coordinate system (r, θ, ϕ) and then converted to the Cartesian coordinate system (x, y, z) . The x and y components of the electric field of the emitted gamma rays are expressed as

$$E_x = E_\theta \cos \theta \cos \phi - E_\phi \sin \phi \quad (3)$$

and

$$E_y = E_\theta \cos \theta \sin \phi + E_\phi \cos \phi. \quad (4)$$

The intensity distribution of the gamma rays is calculated as $2\epsilon_0 c R^2 |\mathbf{E}|^2$ (Sec. 14.5 in [37]). The degree of polarization is determined using the Stokes parameters (Sec. 7.2 in [37]). Specifically, the degree of horizontal linear polarization is given by $S_1/S_0 = (|E_x|^2 - |E_y|^2)/(|E_x|^2 + |E_y|^2)$ and the degree of circular polarization by $S_3/S_0 = (|E_x - iE_y|^2 - |E_x + iE_y|^2)/(|E_x - iE_y|^2 + |E_x + iE_y|^2)$.

$$E_\theta = i \sum_{n=1}^{\infty} \sum_{m=-\infty}^{\infty} C_0 \frac{N_0 \lambda_0}{c} \left[\frac{1}{\sqrt{2}} k_0 r_1 \cos \theta \cos(\phi - \eta_0) \{J_{n+2m+1}(p_1) J_m(p_2) + J_{n+2m-1}(p_1) J_m(p_2)\} - \beta_{1z} \frac{\sin \theta}{\cos \zeta_0} J_{n+2m}(p_1) J_m(p_2) \right] \quad (5)$$

and

$$E_\phi = -i \sum_{n=1}^{\infty} \sum_{m=-\infty}^{\infty} C_0 \frac{N_0 \lambda_0}{c} \frac{1}{\sqrt{2}} k_0 r_1 \sin(\phi - \eta_0) \{J_{n+2m+1}(p_1) J_m(p_2) + J_{n+2m-1}(p_1) J_m(p_2)\}. \quad (6)$$

Here, n and m are integers, with n representing the harmonic number of the emitted gamma rays ($n \geq 1$); $J_n()$ denotes the Bessel function of the first kind; N_0 signifies the number of laser field periods interacting with the electron; $k_0 = 2\pi/\lambda_0$ represents the laser wave number. The parameter r_1 is given by $r_1 = a_0/\{\sqrt{2}\gamma_0(1 + \beta_{z0})k_0\}$. The polarization angle of the laser, η_0 , defines the polarization state of the laser, with $\eta_0 = 0^\circ$ corresponding to horizontal polarization and $\eta_0 = 90^\circ$ corresponding to vertical polarization, as shown in Fig. 1. The quantities p_1 and p_2 are defined as $p_1 = \sqrt{2}k r_1 \sin \theta \cos(\phi - \eta_0)$ and $p_2 = k z_1(1 + \beta_{z0} \cos \theta - \beta_{x0} \sin \theta \cos \phi)$, respectively, where $z_1 = a_0^2/\{8\gamma_0^2(1 + \beta_{z0})^2 k_0\}$. The normalized initial electron velocities are given by $\beta_{x0} = \beta_0 \sin \zeta_0$ and $\beta_{z0} = \beta_0 \cos \zeta_0$, where β_0 is the initial electron velocity normalized to the speed of light and ζ_0 is the incident angle of the laser with respect to the electron beam in the x - z plane (Fig. 1). The longitudinal velocity component is expressed as $\beta_{1z} = \{4\gamma_0^2 \beta_{z0}(1 + \beta_{z0}) - a_0^2\}/\{4\gamma_0^2(1 + \beta_{z0})^2\}$.

The electric field for a circularly polarized laser is given by

$$E_\theta = i \sum_{n=1}^{\infty} C_0 \frac{N_0 \lambda_0}{c} e^{in\phi} \left(\frac{nk_0 \cos \theta}{k \sin \theta} - \beta_{1z} \frac{\sin \theta}{\cos \zeta_0} \right) J_n(p) \quad (7)$$

and

$$E_\phi = - \sum_{n=1}^{\infty} C_0 \frac{N_0 \lambda_0}{c} e^{in\phi} \frac{1}{2} k_0 r_1 \{J_{n-1}(p) - J_{n+1}(p)\}. \quad (8)$$

Here, $p = k r_1 \sin \theta$.

As illustrated in Figs. 2(a)–2(c), the spatial intensity distribution varies with polarization. The parameters used are as follows: $\gamma_0 = 1468$, $\lambda_0 = 800$ nm, $\zeta_0 = 90^\circ$, and $n = 1$, consistent with the experimental conditions at UVSOR. Linearly polarized gamma rays exhibit an azimuthally asymmetric spatial distribution, with a weak intensity node detected at $\gamma_0 \theta = 1$ along the laser polarization axis. Figures 2(d)–2(e) and 2(g)–2(h) present the degree of horizontal linear polarization and corresponding electric field vectors, respectively. These figures show that the polarization axis of the gamma rays coincides with that of the laser along the central axis, as well as along the lines $x = 0$ and $y = 0$. However, the

The approximate expression for the electric field in the spherical coordinate system for a linearly polarized laser is then derived. Here, we assume the conditions $\gamma_0 \gg 1$ and $a_0 \ll \gamma_0$, where $a_0 = eE_L \lambda_0/(2\pi m_e c^2)$ is the laser strength parameter, considered in this study to be much smaller than unity, E_L is the amplitude of the laser field, λ_0 is the laser wavelength, and $m_e c^2$ is the rest energy of the electron:

polarization direction varies across the beam's cross section. Figures 2(d) and 2(e) are consistent with results calculated using the differential scattering cross section of CS, as reported in previous studies [42–45]. In contrast, circularly polarized gamma rays display an azimuthally symmetric intensity distribution, as presented in Fig. 2(c). The degree of circular polarization and the corresponding electric field vectors are illustrated in Figs. 2(f) and 2(i), respectively. The degree of circular polarization varies with $\gamma_0 \theta$. Near the central axis, the polarization is circular, but it transitions to linear polarization at $\gamma_0 \theta = 1$. Notably, the gamma rays are azimuthally polarized along the $\gamma_0 \theta = 1$ line, as shown in Fig. 2(i). Although not explicitly stated, Fig. 6 in [45] similarly indicates azimuthal polarization of gamma rays in the outer regions. As discussed above, the spatial polarization distribution of gamma rays is characterized by $\gamma_0 \theta$. Since a large energy spread of an electron beam distorts the polarization distribution of gamma rays, it is important to use an electron beam with an energy spread of 1% or less for detailed measurement of the polarization distribution.

III. DESIGN OF A GAMMA-RAY POLARIMETER

A. Polarization detection of MeV gamma rays

In the visible wavelength range, the polarization axis and degree of polarization can be determined by measuring the transmitted power of light while rotating a polarizer. However, measuring gamma-ray polarization is challenging owing to the absence of effective polarizers that can function within the gamma-ray wavelength range. The primary interactions with matter in the few MeV energy regions are CS and pair production (PP). In both reactions, it is possible to detect the linear polarization of incident gamma rays. In the CS method, polarization is determined by irradiating a target with polarized gamma rays and observing the azimuthal modulation of the CS gamma rays [46–48]. In the PP method, a polarimeter is developed by measuring the azimuthal angles of electron-positron pairs before substantial multiple scattering occurs [23]. Alternatively, linear polarization can also be detected by measuring the azimuthal

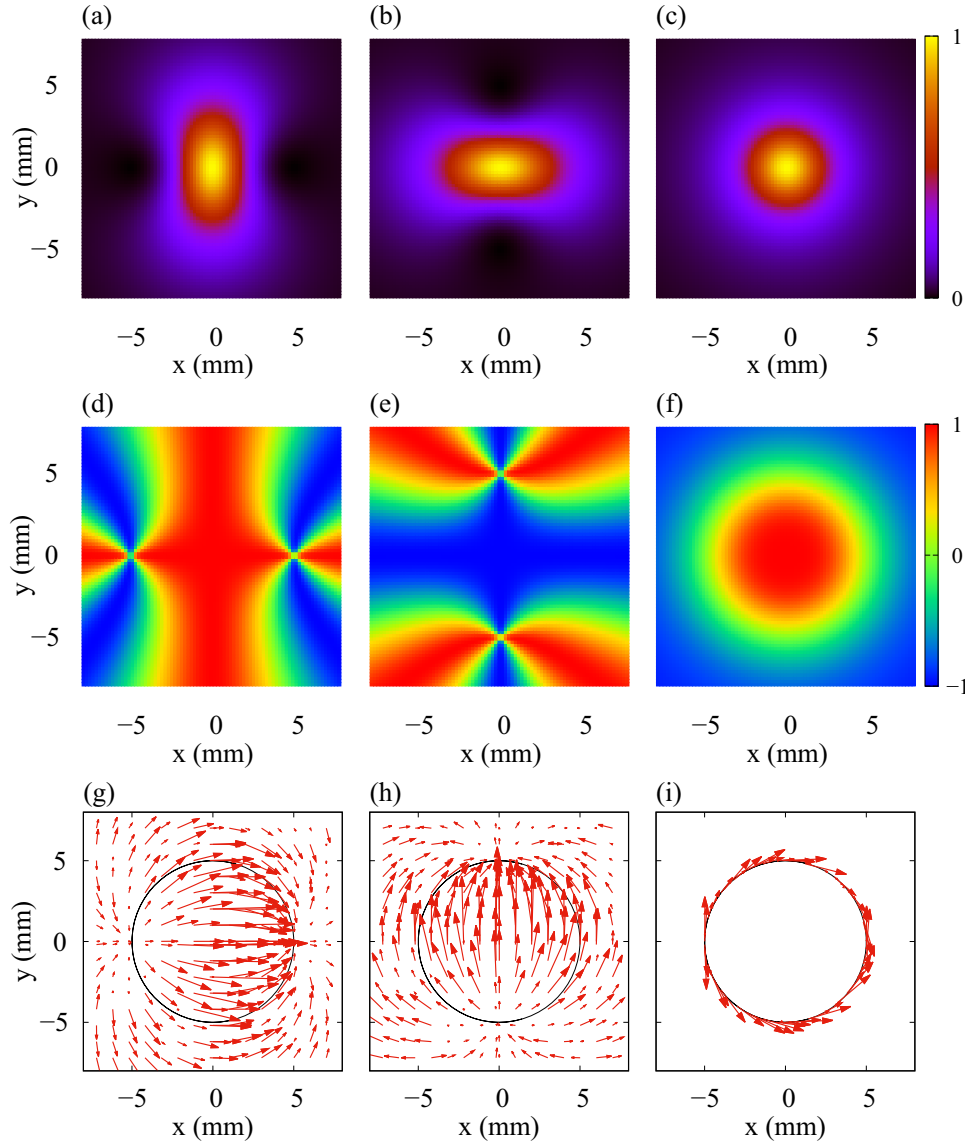


FIG. 2. (a)–(c) Normalized intensity distribution, (d), (e) degree of horizontal linear polarization, (f) degree of circular polarization, and (g)–(i) real part of the electric field vector of gamma rays, calculated at a distance of 7.3 m from the generation point using Eqs. (3)–(8). Panels (a), (d), and (g) present the calculated results for horizontal linear polarization ($\eta_0 = 0^\circ$), (b), (e), and (h) for vertical linear polarization ($\eta_0 = 90^\circ$), and (c), (f), and (i) for circular polarization. The degree of horizontal linear polarization is positive for horizontal polarization and negative for vertical polarization. The solid black line with a radius of 5 mm in panels (g)–(i) represents $\gamma_0\theta = 1$. The electric field vector for circular polarization is shown only along the line where $\gamma_0\theta = 1$. The calculation parameters are $\gamma_0 = 1468$, $\lambda_0 = 800$ nm, $\zeta_0 = 90^\circ$, and $n = 1$.

distribution of neutrons produced through the photodisintegration of deuterons [14].

The total cross section for photodisintegration is approximately 0.002 barn in the few MeV region [49], whereas the cross section for CS is approximately 0.1 barn. Because the intensity of gamma rays generated at UVSOR is relatively low, choosing an interaction with a large cross section is preferable. Furthermore, in the 3–6.6 MeV energy range, CS dominates PP for interactions with most materials. Therefore, we develop a polarimeter based on the CS method in this study. To avoid confusion, CS gamma rays by stationary electrons are referred to as CS gamma rays and are clearly distinguished from CS gamma rays by relativistic electrons.

B. CS cross section of linearly polarized gamma rays

The differential scattering cross section for CS when the initial gamma rays are linearly polarized is given by [50]

$$\frac{d\sigma}{d\Omega}(\kappa, \psi) = \frac{r_0^2}{2} \left(\frac{E_1}{E_0} \right)^2 \left\{ \frac{E_1}{E_0} + \frac{E_0}{E_1} - 2 \sin^2 \kappa \cos^2(\psi - \eta) \right\}. \quad (9)$$

Here, $d\Omega = \sin \kappa d\kappa d\psi$, where κ denotes the scattering angle of a CS gamma ray relative to the initial gamma ray, ψ represents the azimuthal angle, and η denotes the polarization angle of the initial gamma ray (Fig. 1). In this equation, r_0 denotes the classical electron radius and E_0 and E_1 represent the initial

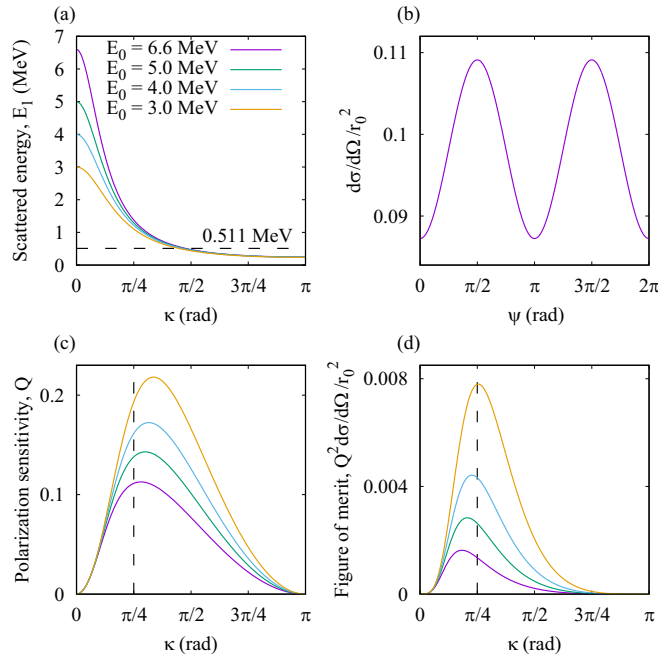


FIG. 3. (a) CS gamma-ray energy as a function of scattering angle for different initial energies. The dashed line indicates 0.511 MeV, corresponding to the energy of annihilation gamma rays. (b) Differential scattering cross sections along the azimuthal direction for $E_0 = 6.6$ MeV, $\kappa = 45^\circ$, and $\eta = 0^\circ$. (c) Q factor and (d) figure of merit as functions of scattering angle. The initial gamma-ray energies in (c) and (d) are the same as those shown in the legend of (a). The dashed lines in (c) and (d) represent 45° .

and scattered gamma-ray energies. The scattered gamma-ray energy E_1 as a function of the scattering angle is given by

$$E_1 = \frac{E_0}{1 + E_0(1 - \cos \kappa)/(m_e c^2)}. \quad (10)$$

The CS gamma-ray energy as a function of the scattering angle, calculated using Eq. (10), is depicted in Fig. 3(a). Figure 3(b) presents the differential scattering cross section along the azimuthal direction, calculated using Eq. (9) for $E_0 = 6.6$ MeV, $\kappa = 45^\circ$, and $\eta = 0^\circ$. The scattering cross section exhibits asymmetry in the azimuthal direction, with the maximum scattering occurring at 90° relative to the polarization axis of the initial gamma rays. Therefore, measuring the azimuthal distribution of CS gamma rays can determine the polarization axis of the initial gamma rays.

If the gamma rays are polarized along the $\eta = 0^\circ$ direction, then the polarization sensitivity—simply the Q factor—of a polarimeter is calculated as follows [51,52]:

$$Q = \frac{d\sigma/d\Omega(\kappa, \psi = 90^\circ) - d\sigma/d\Omega(\kappa, \psi = 0^\circ)}{d\sigma/d\Omega(\kappa, \psi = 90^\circ) + d\sigma/d\Omega(\kappa, \psi = 0^\circ)} = \frac{\sin^2 \kappa}{E_1/E_0 + E_0/E_1 - \sin^2 \kappa}. \quad (11)$$

The Q factor, calculated as a function of the scattering angle using Eq. (11), is illustrated in Fig. 3(c). The scattering angle at which the Q factor reaches its maximum depends on the initial gamma-ray energy. In the Thomson scattering region

($E_0 \ll m_e c^2$), the Q factor is maximum at 90° , but as the initial gamma-ray energy increases, the angle corresponding to the maximum Q factor decreases. For an initial energy of 3 MeV, the Q factor is maximum at 60° , while at 6.6 MeV, it peaks at 50° . Figure 3(d) shows the figure of merit, calculated as $Q^2 d\sigma/d\Omega$. When the initial energy is 3 MeV, the figure of merit is maximum at 46° and, at 6.6 MeV, it is maximum at 33° .

The intensity and energy of the gamma rays decrease in the region of $\gamma_0 \theta > 0$ relative to the central axis. To obtain a high figure of merit in the low-energy region, the detector for CS gamma rays was set at $\kappa = 45^\circ$. The energy of CS gamma rays at 45° is in the range of 1.1–1.3 MeV, as presented in Fig. 3(a). This energy range exceeds that of annihilation gamma rays, which are emitted isotropically, making it possible to discriminate between CS gamma rays and annihilation gamma rays during the measurement.

C. Configuration of the polarimeter

The polarimeter consisted of a lead collimator, a target, NaI scintillation detectors, and drive units for adjusting their positions and angles. The lead collimator, 1 mm in diameter and 180 mm in length, was placed along the gamma-ray beam axis and used to allow only a portion of the polarized gamma rays to pass through. These collimated gamma rays were then irradiated to a pure iron target, 5 mm in diameter and 50 mm in length. To determine the polarization axis, the azimuthal distribution of CS gamma rays was measured using NaI detectors (SP-10, Ohyo Koken Kogyo Co., Ltd.). A total of seven detectors were arranged in the azimuthal direction at 30° intervals, from $\psi = 0^\circ$ to 180° . Each NaI crystal measured 38.1 mm (1.5 in.) in diameter and 76.2 mm (3 in.) in length. All NaI detectors were fixed to face the center of the target, with the distance from the target center to the tip of each NaI crystal set at 150 mm. Consequently, the NaI crystals covered a scattering angle range of $39^\circ < \kappa < 51^\circ$. Gamma rays propagate with an angular spread of approximately $2/\gamma_0$ from the generation point. For UVSOR, this angular spread corresponds to a beam diameter of approximately 10 mm at a distance of 7.3 m; thus a 1 mm displacement of the collimator corresponds to an angle of $\theta = 0.2/\gamma_0$. Therefore, by performing a two-dimensional scan with the collimator, the spatial polarization distribution of the gamma rays can be measured.

D. EGS5 simulation

The polarimeter design was evaluated through simulations using actual gamma-ray parameters in the Monte Carlo simulation code EGS5 [53]. EGS5 simulates the transport of photons, electrons, and positrons through arbitrary geometries in the energy range from keV to several hundred GeV. The gamma-ray parameters used in the simulation were based on those described in Sec. II A of [54]. The initial energy and intensity distributions of the gamma rays were defined using theoretical models [55,56]. Relative uncertainties in the gamma-ray energy, arising from the electron beam energy spread (0.0526% rms) and the laser linewidth (0.53% rms) as presented in Table 1 of [57], were also incorporated into

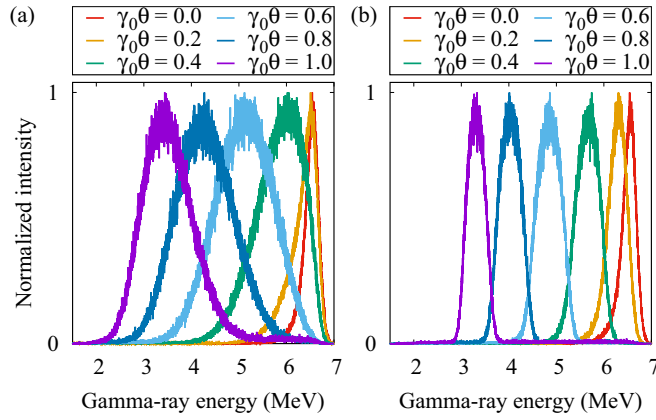


FIG. 4. Simulated energy spectra of gamma rays passing through a 1-mm-diameter collimator at various collimator positions. The collimator positions were scanned along the (a) x and (b) y axes. Each energy spectrum is normalized to its maximum value.

the simulation. The initial position and angular spread of the gamma rays were determined based on the calculated beam size and angular spread derived from the electron beam emittance [58]. The electron beam size was estimated to be 1.3 mm horizontally and 0.05 mm vertically [full width at half maximum (FWHM)], corresponding to an angular spread of 0.12 mrad horizontally and 0.02 mrad vertically. The laser beam, approximately 10 mm in diameter, was focused using a lens with a focal length of 150 mm and collided with the electron beam. Thus the dispersion of the laser's incident angle at the collision point had to be considered. In the simulation, the incident angle of the laser was modeled as a Gaussian distribution with a standard deviation of $\sigma_\alpha = 0.015$ rad.

The energy spectra of gamma rays obtained by scanning a 1-mm-diameter collimator along the x and y axes, from $\gamma_0\theta = 0$ to 1, are presented in Fig. 4. Due to the larger horizontal emittance of the electron beam, the energy width is broader in the horizontal direction than in the vertical direction.

Two simulation results that substantially influenced the polarimeter design are discussed here. We calculated events where CS or PP occurred inside the target, followed by energy loss in the NaI crystal. The energy resolution of the NaI crystal was assumed to be 9% at FWHM. In these calculations, gamma rays were treated as unpolarized.

(i) Azimuthal scattering distribution due to target misalignment. The azimuthal scattering distribution resulting from the displacement of the target was evaluated. Figures 5(a) and 5(b) show events in which 0.6–2 MeV of energy was deposited in the NaI crystals when only the target was displaced along the u and v directions, with the collimator and NaI detector positions held fixed. The figures demonstrate that the azimuthal distribution is uniform when the target is positioned at the origin. However, as the target is displaced, asymmetric distributions emerge. Figure 5(c) shows the energy loss spectra measured by the NaI crystals positioned at $\psi = 0^\circ$ and 90° when the target is displaced by $u = -1$ mm. This asymmetry occurs independent of the polarization of the gamma rays, thus distorting the azimuthal modulation originating from polarization. Displacement of the target alters the transverse thickness of the target as viewed from the

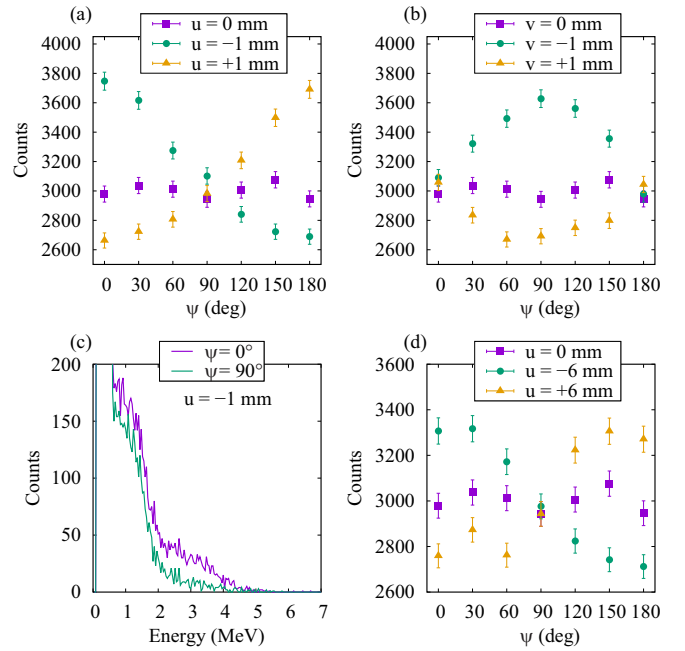


FIG. 5. Calculated distribution of energy losses in each NaI crystal when the target was moved along the (a) u and (b) v directions, with the collimator and NaI detector positions fixed. (c) Energy loss spectra measured by the NaI crystal located at $\psi = 0^\circ$ and 90° when the target displacement was $u = -1$ mm. (d) Calculated distribution of the number of energy losses when the seven NaI crystals were placed along the u direction without moving the collimator or target. Error bars in (a), (b), and (d) represent statistical errors.

gamma-ray beam, making the thickness thinner in the direction opposite to the displacement. This change increases the fraction of high-energy electrons and positrons ejected from the target and directly incident on the NaI crystal, resulting in an asymmetric azimuthal distribution.

(ii) Azimuthal scattering distribution due to NaI crystal displacement. The azimuthal scattering distribution was also enhanced when only the seven NaI detectors were displaced in the u direction, while keeping the collimator and target positions fixed. Figure 5(d) shows the resulting azimuthal distribution. 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 to maintain alignment and symmetry.

E. Measurement system

An overview of the measurement system is shown in Fig. 6. The NaI detectors were operated at +600 V and connected to the preamplifier power supply unit (N5424, CAEN S.p.A.), as each detector includes a built-in preamplifier. The output from the preamplifier was directly connected to a four-channel digital multichannel analyzer (MCA, DT5781, CAEN S.p.A.). Two MCAs were used to acquire data from the seven NaI detectors. The MCAs were controlled via CoMPASS software supplied by CAEN. The target and NaI detectors

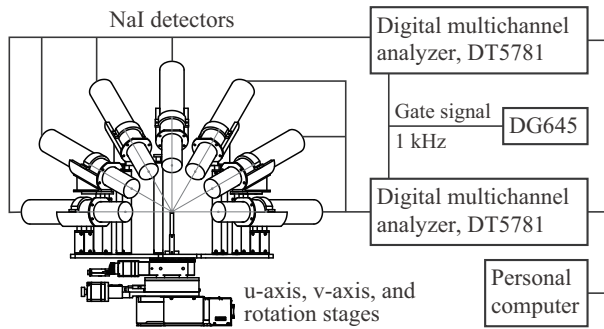


FIG. 6. Overview of the measurement system. Y. Miyazaki provided the drawings of the NaI detectors and three-axis stage at the Equipment Development Center (EDC) of the Institute for Molecular Science (IMS). The drawings of the stages were obtained from the websites of Thorlabs, Inc. [59] and Suruga Seiki Co., Ltd [60].

were mounted on a common plate, which was attached to a three-axis automated stage system capable of u - v scanning and u - w plane rotation. A CdTe image sensor (AdvAPIX TPX3, Advacam s.r.o.) was also fixed to the same plate to monitor the gamma-ray beam position. Key performance characteristics of the CdTe sensor include a pixel size of $55 \times 55 \mu\text{m}^2$, an effective area of $14.08 \times 14.08 \text{ mm}^2$, and a sensor thickness of 1 mm.

In addition to the laser-induced gamma rays, bremsstrahlung gamma rays generated by interactions between the electron beam and residual gas in the storage ring were also directed at the target. To selectively measure the laser-induced CS gamma rays, a gate signal synchronized with the laser was generated using a digital delay generator (DG645, Stanford Research Systems) and fed into the MCA.

IV. MEASUREMENT

A. Preparation of measurement system

1. Measurement overview

A schematic of the spatial polarization distribution measurement setup is shown in Fig. 7. The lead collimator was

placed 7.3 m downstream from the gamma-ray source point. The gamma rays irradiated to the CdTe image sensor, the 5-mm-thick aluminum plate of the sensor case, and the target. The azimuthal distribution of CS gamma rays was measured using seven NaI detectors. To shield scattered radiation from the collimator and the vacuum window downstream of the collimator (not shown in Fig. 7), a 100-mm-thick lead block was placed upstream of the target. The gamma rays passed through a 20-mm-square hole in the lead block to reach the target. The distance from the gamma-ray source to the target was 1.3 times greater than the distance to the collimator. Therefore, as the collimator moved, the target moved 1.3 times farther relative to the displacement of the collimator. As previously described, the target, NaI detectors, and CdTe image sensor were mounted on the same plate, ensuring synchronized movement during scanning. To monitor the intensity and energy of the gamma rays, the transmitted gamma rays were measured using a LaBr₃ detector.

2. Generation of a polarized laser

The method for generating a polarized laser is described in detail in Sec. III A of [54] and is briefly summarized here. The linearly polarized laser was operated synchronously with the radio frequency acceleration cavity of the storage ring [56]. The laser was injected into the vacuum chamber horizontally at 90° via a quartz window attached to a straight section of the storage ring. The focusing lens, as mentioned in Sec. III D, was positioned in front of the quartz window. The laser parameters at the collision point were as follows: wavelength = 800 nm, pulse energy = 2.2 mJ, pulse width (FWHM) = 1.8 ps, beam waist $w_0 = 13 \mu\text{m}$ for linear and circular polarization, and $w_0 = 14 \mu\text{m}$ for axially symmetric polarization. Twelve electron bunches orbit the electron storage ring at a frequency of 5.6 MHz and the laser interacts with one of the bunches at a repetition rate of 1 kHz. Two rotating waveplate stages were installed upstream of the focusing lens. By changing the combination of waveplates attached to the rotating stages, lasers with different polarization states could be generated.

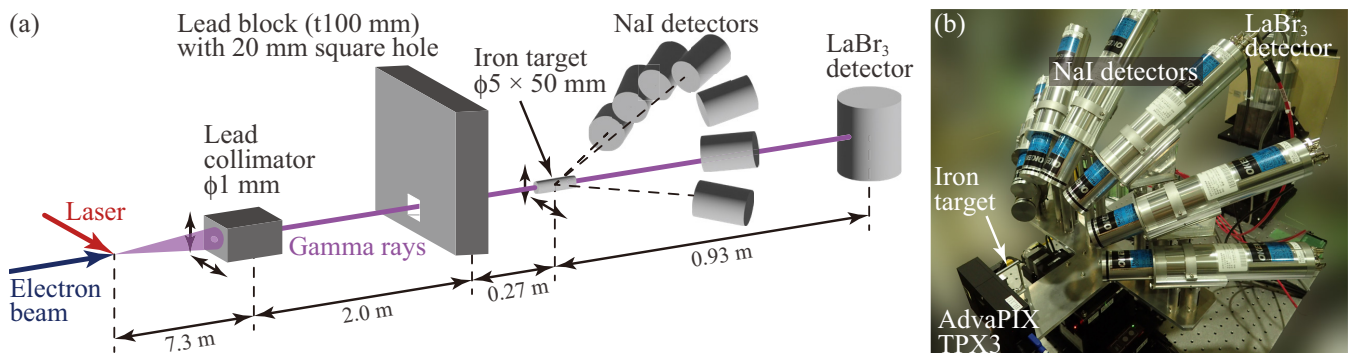


FIG. 7. (a) Schematic of the spatial polarization distribution measurement of polarized gamma rays. Gamma rays transmitted through a quartz window (not shown), which separated the vacuum from the atmosphere, passed through a 1-mm-diameter collimator and irradiated the target. A CdTe image sensor was installed upstream of the target to measure the gamma-ray position (not shown). CS gamma rays were generated primarily from the aluminum plate of the CdTe sensor case and the target was measured using seven NaI detectors. Gamma rays transmitted through the target were measured with a LaBr₃ detector. A 50-mm-thick lead block was placed upstream of the LaBr₃ detector to attenuate the gamma-ray intensity (not shown). (b) Photograph of the measurement system.

(i) Linearly polarized laser: a $\lambda/2$ waveplate was attached. By rotating the $\lambda/2$ waveplate, the polarization axis of the laser could be adjusted to any desired angle.

(ii) Circularly polarized laser: a $\lambda/4$ waveplate was attached.

(iii) Axially symmetric polarized laser: both a $\lambda/2$ waveplate and an s-waveplate (RPC-0800-12-AR, Altechna) were attached. The s-waveplate, fabricated by inscribing self-organized nanogratings inside fused silica glass using a femtosecond laser [61], acted as a space-variant retarder, converting linear polarization into axially symmetric polarization [62]. Radial polarization was generated when the alignment mark printed on the s-waveplate was oriented vertically and a vertically linearly polarized laser was injected into the s-waveplate. Azimuthal polarization was generated by rotating the $\lambda/2$ waveplate to inject a horizontally linearly polarized laser. The measurement result of the axially symmetric polarized laser near the interaction point is presented in Fig. 2 of [54].

3. Alignment of the collimator using circularly polarized gamma rays

The angle and position of the collimator were adjusted to ensure that it was parallel to the gamma-ray beam axis and aligned with the central axis. Circularly polarized gamma rays—whose spatial distribution is nearly concentric—were used for this alignment. When the stored electron beam current was 200 mA in top-up multibunch mode, the gamma-ray intensity at the generation point was estimated to be 3×10^2 photons per pulse, corresponding to 3×10^5 photons per s. This gamma-ray intensity was the same as that used for polarization measurements. The pulse width of the gamma rays was calculated to be 5 ps (FWHM).

Initially, the collimator angle was adjusted by placing the CdTe image sensor near the target location and measuring the spatial distribution of the gamma rays. The lead blocks, target, and the NaI and LaBr₃ detectors were not installed during this measurement. The collimator angle was varied in the u - w and v - w planes to achieve the broadest possible spatial distribution. Figure 8 shows the spatial distribution of gamma rays after passing through the collimator; the measured results agree with the spatial distribution calculated using EGS5. As the CdTe sensor was not directly sensitive to gamma rays but instead registered energy losses from secondary electrons and positrons, the EGS5 simulation calculated the locations of CS and PP. As shown in Fig. 8, the edge shape of the spatial distribution is more gradual in the horizontal direction than in the vertical direction. This difference is attributed to the larger horizontal emittance of the electron beam compared with the vertical emittance.

Next, the collimator position was determined by scanning the collimator along the u - and v -axis directions and measuring the energy spectra of the gamma rays. The energy spectrum was measured using a high-purity germanium detector (HPGe, GC14022, Mirion Technologies, Inc.) placed downstream of the collimator. The germanium crystal had a diameter of 86.0 mm and a length of 92.0 mm, with a relative detection efficiency of 140% at 1.332 MeV. The preamplifier output of the HPGe detector was connected to a spectroscopy

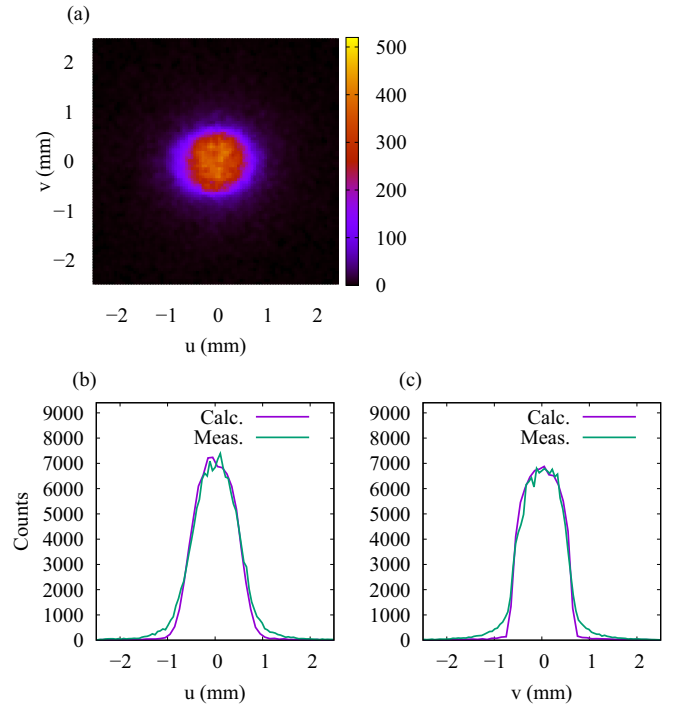


FIG. 8. (a) Spatial distribution of gamma rays after passing through the 1-mm-diameter lead collimator, measured using the CdTe image sensor. The background measured without laser injection was subtracted. The number of detected events per pixel was approximately 400 per 20 min. If the gamma-ray intensity is increased by a factor of 3000, the sensor is estimated to be saturated because more than one event per pixel would be detected due to the incidence of one gamma-ray pulse. (b),(c) Line intensity distribution of gamma rays along the (b) u and (c) v axes. The spatial distribution calculated using EGS5 is also displayed. In the u (v) axis direction, the range $-0.55 \leq v(u) \leq +0.55$ mm was integrated and shown.

amplifier and its output was fed into an MCA to record the energy spectrum. A gate signal was also input into the MCA to synchronize the detection. Energy calibration was performed using gamma rays from ^{60}Co (1173 and 1332 keV) and ^{40}K (1461 keV). The CdTe image sensor was not installed during this measurement. The measurements were conducted at a stored electron beam current of 4 mA—lower than the typical operating current of 200 mA—to reduce pile-up effects. The energy spectrum of gamma rays was recorded while scanning the collimator along the u and v axes. The collimator position corresponding to the maximum gamma-ray intensity was taken as the gamma-ray beam center.

Figure 9(a) measured energy spectra with the laser on and off when the collimator was aligned with the gamma-ray center. Due to the low electron beam current and the use of a gate signal, the spectrum contained almost no background gamma rays from bremsstrahlung. Counts above the maximum gamma-ray energy of 6.6 MeV were attributed to pile-up effects, where two gamma rays were detected simultaneously within the time resolution of the HPGe detector. Figure 9(b) presents the energy spectrum including the pile-up effect, calculated using EGS5. The energy resolution of the HPGe detector was determined to be 0.2% (FWHM). The

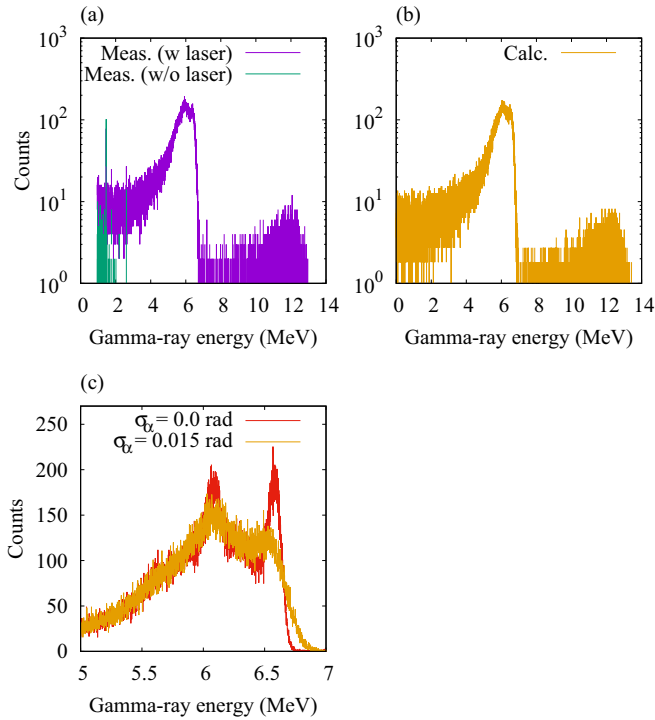


FIG. 9. (a) Measured and (b) calculated energy spectra when the central axis of the gamma rays was aligned with a 1-mm-diameter collimator and (c) calculated energy spectra with $\sigma_\alpha = 0$ and 0.015 rad.

measured energy spectrum is consistent with the EGS5 simulation result. Figure 9(c) is the magnified view of the energy spectrum in the 5–7 MeV range, showing the two peaks at 6.0 and 6.5 MeV. The lower-energy peak corresponds to the single escape peak. Usually, the intensity near the Compton edge rises sharply; however, at UVSOR, the Compton edge is gradual due to dispersion in the laser incident angle, as discussed in Sec. IIID. The Compton edge becomes sharp only when $\sigma_\alpha = 0$ rad as shown in Fig. 9(c).

4. Alignment of the target

The angle of the target in the v - w plane was adjusted by tilting the optical breadboard on which the three-axis automated stage was mounted. A level was used to achieve an angular accuracy of less than 0.1° . Alignment in the u - w plane was adjusted by measuring the transmitted gamma-ray intensity distribution with a CdTe image sensor placed downstream of the target. The edge of the target was aligned with the gamma-ray central axis and the rotation stage was rotated in 0.1° increments to identify the angle that maximized the derivative of the intensity distribution.

To align the gamma-ray center with the center of the target, the target edge was first aligned near the gamma-ray center and the transmitted distribution was measured. The target was then shifted 5 mm to align the opposite edge. The position showing a symmetric spatial distribution was identified and the gamma-ray center was determined to be 2.5 mm from that point. This procedure was repeated along the u and v axes to complete the alignment.

B. Polarization axis of gamma rays by changing the polarization axis of a linearly polarized laser

To evaluate the performance of the developed polarimeter, the polarization axis of gamma rays was measured while systematically varying the polarization axis of a linearly polarized laser. The collimator was fixed at the center of the gamma-ray beam. The laser polarization axis was adjusted from 0° to 180° in 15° increments by rotating the $\lambda/2$ waveplate. To assess reproducibility, measurements were repeated three times at 45° intervals. Each measurement at a given angle was conducted over a 20 min period.

The azimuthal distribution of CS gamma rays was obtained by integrating the counts within the region of interest (ROI) between 0.6 and 2 MeV from energy spectra measured using NaI detectors. Energy calibration of the NaI detectors was performed using gamma rays at 511 keV, 662 keV (from ^{137}Cs), and 1173 and 1332 keV (from ^{60}Co). Due to slight differences in the detection efficiencies of the seven NaI detectors, corrections were necessary. The correction factors were determined by measuring circularly polarized gamma rays, which have a uniform azimuthal scattering distribution. The maximum correction reached 2.4%. The corrected azimuthal distribution was fitted using the following function, modified from Eq. (9) [52]:

$$C(\psi) = B - A \cos \{2(\psi - \eta)\}, \quad (12)$$

where A and B are fitting parameters. The modulation factor, also referred to as analyzing power, is defined as A/B . It can be expressed as $A/B = P_0 Q$, where P_0 is the degree of linear polarization and Q is the polarization sensitivity, as given by Eq. (11) [52]. Since the gamma-ray energy at any given position within the beam cross section is independent of the polarization type, the polarization sensitivity remains constant. Thus the analyzing power varies only with the degree of linear polarization.

C. Spatial polarization distribution of gamma rays

The spatial distribution of gamma-ray polarization was measured by scanning the collimator, target, and NaI detectors in two dimensions from the center of the gamma-ray beam axis. Measurements were performed for five laser polarization types: horizontal linear, vertical linear, circular, radial, and azimuthal. While most measurements were conducted during multibunch operation of the electron storage ring, vertical linear and some circular polarization measurements were conducted during single-bunch operation, where only one electron bunch circulated the ring. Measurements were taken at $\gamma_0\theta$ intervals of 0.2 for $0 \leq \gamma_0\theta \leq 1$ in the θ direction and at 22.5° for $0.6 \leq \gamma_0\theta \leq 1$ and at 45° for $0.2 \leq \gamma_0\theta \leq 0.4$ in the ϕ direction. Because gamma-ray intensity decreases with increasing $\gamma_0\theta$, the measurement time was adjusted accordingly—for instance, 20 min at $\gamma_0\theta = 0$ and 2 h at $\gamma_0\theta = 1$. Due to time constraints, some low-intensity positions were not measured. The total measurement time for all five polarization states amounted to 271 h.

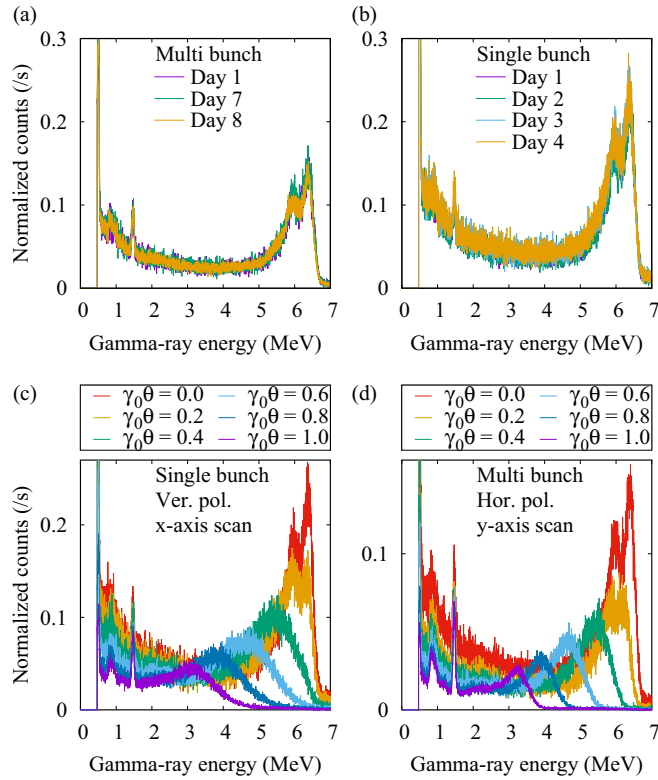


FIG. 10. (a), (b) Measured energy spectra of gamma rays using the LaBr₃ detector when the collimator was centered during (a) multibunch and (b) single-bunch operation. (c), (d) Measured energy spectra at different collimator positions along the (c) x axis and (d) y axis. The operation modes and gamma-ray polarization were (c) single bunch with vertical polarization and (d) multibunch with horizontal polarization, respectively. The counts in all figures were normalized by the measurement time.

D. Gamma-ray monitor using the LaBr₃ detector

Gamma-ray intensity varied with changes in the overlap between the electron beam and the laser. Vertical positional fluctuations in the electron beam, on the order of tens of micrometers over several hours, led to reductions in gamma-ray intensity. Periodic monitoring using a LaBr₃ detector was performed and, when a decrease in intensity was detected, the laser position was adjusted to maintain a constant gamma-ray output. Figures 10(a) and 10(b) present the LaBr₃ detector energy spectra obtained on different days with the collimator centered. Based on the total counts between 3 and 6.6 MeV, the standard deviation in gamma-ray intensity variation was estimated to be less than 6%. Furthermore, the intensity during single-bunch operation was approximately 1.5 times higher than that during multibunch operation, due to the shorter electron bunch length in single-bunch mode.

Figures 10(c) and 10(d) present the energy spectra measured at different collimator positions. A gradual decrease in the energy of the collimated gamma rays was observed as the collimator was moved outward. The broader energy spread during horizontal shifts was attributed to the large emittance of the electron beam, as discussed previously in Fig. 4. Gamma rays generated by axially symmetric polarized lasers exhibited similar spectral changes.

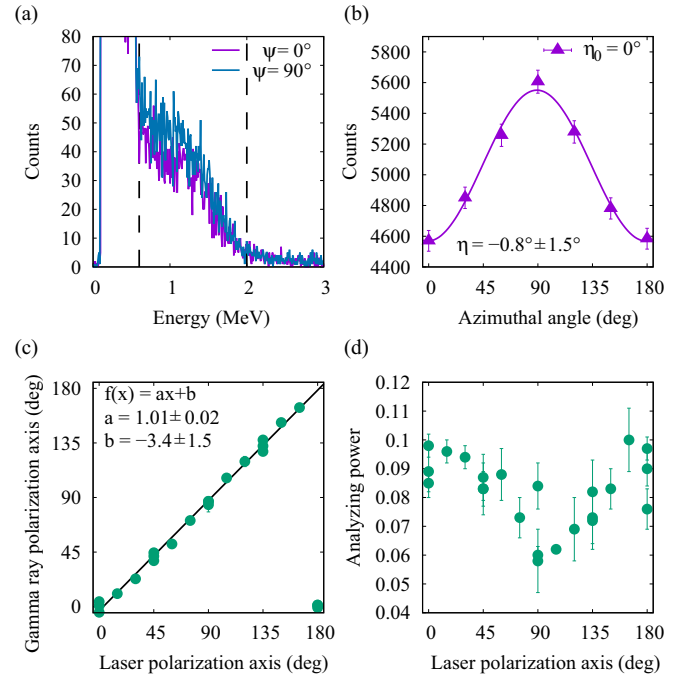


FIG. 11. (a) Energy spectra of NaI detectors placed at azimuthal angles of 0° and 90° when $\eta_0 = 0^\circ$. The dashed line represents the ROI. (b) Azimuthal distribution of detector counts. The gamma-ray polarization axis was measured as $\eta = -0.8^\circ \pm 1.5^\circ$. (c) Change in the gamma-ray polarization axis and (d) analyzing power as the laser polarization axis varied.

V. RESULTS AND DISCUSSION

A. Polarization axis of gamma rays by changing the polarization axis of the linearly polarized laser

The energy spectra measured with the NaI detectors when the laser was horizontally linearly polarized are shown in Fig. 11(a). Because the gate signal synchronized with the laser was input into the MCA, the measurement data exhibited a high signal-to-noise ratio. For instance, when the collimator was in the center position, the average count in the ROI per 10 min was 2.7×10^3 counts. Conversely, when the laser was turned off and the target was irradiated only with bremsstrahlung gamma rays, the average counts decreased to 2. Additionally, when the laser was on, but the target and CdTe image sensor were removed, the average counts increased to 44. This background count likely resulted from direct radiation entering the NaI detectors from upstream, as well as backscatter from the downstream lead block. These results suggest that the CS gamma rays generated from the target by laser-induced gamma rays contributed most of the measured counts.

Figure 11(b) shows the measured counts of CS gamma rays as a function of the azimuthal angle. Clear azimuthal modulation is observed, with maximum counts occurring at 90° relative to the gamma-ray polarization axis. Figures 11(c) and 11(d) present the variation of the polarization axis and analyzing power of the gamma rays as a function of the laser polarization axis. The standard deviation of repeated measurements of the gamma-ray polarization axis, taken at laser

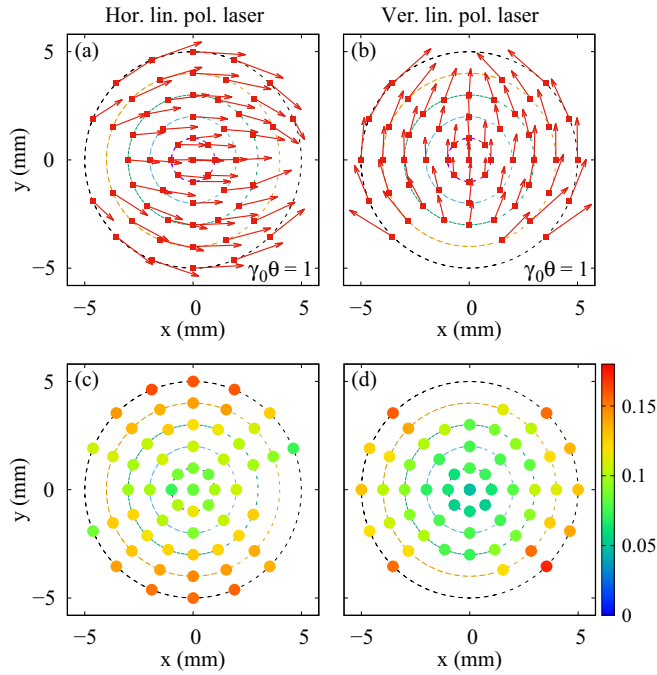


FIG. 12. (a), (b) Spatial polarization distribution of polarized gamma rays measured in two dimensions while scanning the collimator position. The arrow direction represents the polarization axis (the direction of the electric field vector) and the arrow length represents the product of the magnitude of the normalized polarization axis and the analyzing power. The circular dotted lines represent the range of $\gamma_0\theta$ from 0.2 to 1.0 in 0.2 increments. The outermost dotted line represents $\gamma_0\theta = 1$. (c), (d) Measured analyzing power. Panels (a) and (c) correspond to horizontal linear polarization, while panels (b) and (d) correspond to vertical linear polarization.

polarization angles of 0° , 45° , 90° , 135° , and 180° , ranged from 1° to 4° .

B. Spatial polarization distributions of gamma rays

1. Gamma rays generated using a linearly polarized laser

Figure 12 presents the measured spatial polarization distribution of linearly polarized gamma rays. Figures 12(a) and 12(b) show the distribution of the product of the magnitude of the normalized polarization axis and the analyzing power, while Figs. 12(c) and 12(d) display the measured analyzing power. Similar to the theoretical calculations in Figs. 2(g) and 2(h), the measurements demonstrate that the polarization axis varies depending on the position within the gamma-ray beam cross section.

A comparison between the measured and calculated values along the $x = 0$ and $y = 0$ lines, where the polarization axes of the linearly polarized gamma rays and the laser coincide, is presented in Figs. 13(a) and 13(b). The polarization axis was calculated as $\eta_c = \tan^{-1}\{\text{Re}(E_y)/\text{Re}(E_x)\}$ using Eqs. (3)–(6). It was observed that the polarization axis of the gamma rays varied by 90° between horizontal and vertical polarizations. The distribution of the difference between the measured and calculated polarization axes, $\delta\eta = \eta_m - \eta_c$, across all measurement points is shown in Figs. 13(c) and 13(d). The small mean and standard deviation values indi-

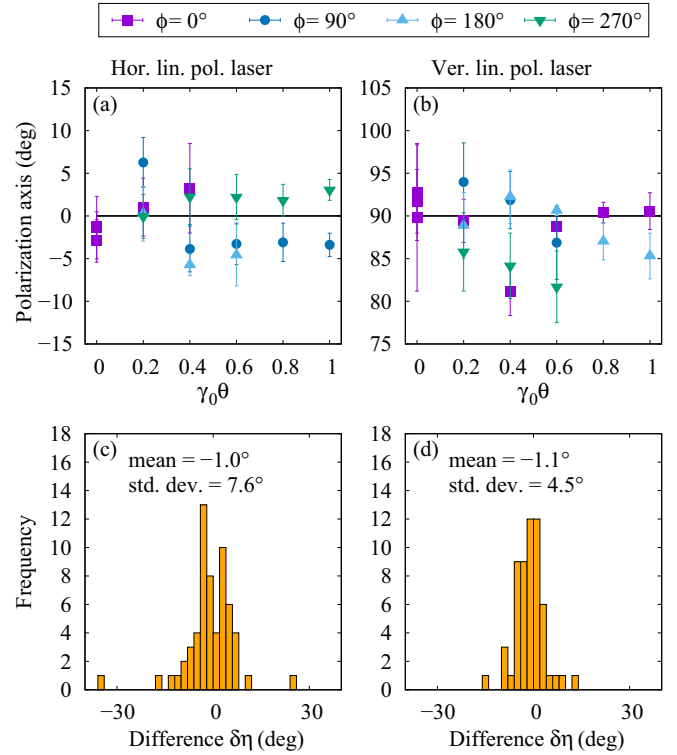


FIG. 13. (a), (b) Gamma-ray polarization axis along the $x = 0$ and $y = 0$ lines. The solid black lines represent the theoretical values calculated from Eqs. (3)–(6). (c), (d) Histogram of the difference between the theoretical and measured gamma-ray polarization axes. The mean and standard deviation values are shown in each panel. The laser polarization state in each panel corresponds to that shown in Fig. 12.

cate that the measured polarization axes closely reproduce the theoretical values. Therefore, the developed polarimeter is considered to be operating effectively.

One potential application for these gamma rays is the evaluation of astronomical detectors for polarized gamma-ray measurements. This application requires gamma rays of varying energies. As the gamma rays at UVSOR are generated at a fixed electron beam energy, laser wavelength, and injection angle, the only way to vary the gamma-ray energy is by shifting the collimator position [63]. Therefore, measuring the spatial polarization distribution of linearly polarized gamma rays is crucial for understanding their polarization characteristics when adjusting the collimator.

2. Gamma rays generated using a circularly polarized laser

The measured spatial polarization distribution of gamma rays generated using a circularly polarized laser is shown in Figs. 14(a) and 14(b). As seen in Fig. 14(b), the analyzing power of the circularly polarized gamma rays was close to zero along the central but comparable to the values observed for linearly polarized gamma rays along the $\gamma_0\theta = 1$ line. This result indicates that the polarization of gamma rays is circular at the central axis and becomes linearly polarized at $\gamma_0\theta = 1$, consistent with Fig. 2(f). Similar polarization behavior has been confirmed through magnetic CS, which is sensitive to

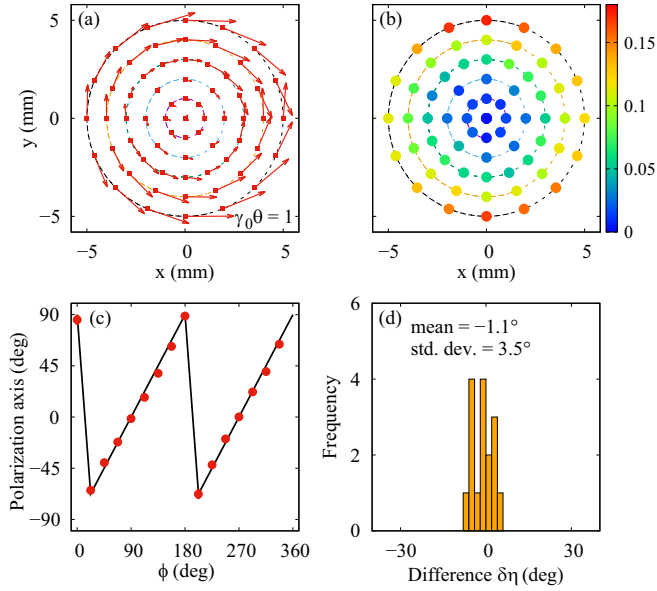


FIG. 14. (a) Spatial polarization distribution of gamma rays generated using a circularly polarized laser, with arrow definitions identical to those in Fig. 12. (b) Measured analyzing power. (c) Polarization axis along the $\gamma_0\theta = 1$ line. The solid black line represents the theoretical value calculated from Eqs. (3), (4), (7), and (8). (d) Histogram of the difference between theoretical and measured polarization axis values.

circular polarization [16]. A comparison of the measured and calculated polarization axes along the $\gamma_0\theta = 1$ line is presented in Fig. 14(c). Notably, the linearly polarized component generated by the circularly polarized laser was clearly azimuthally polarized, as shown in Figs. 14(a) and 14(c). The distribution of the difference between the measured and calculated polarization axes along the $\gamma_0\theta = 1$ line is presented in Fig. 14(d). The close agreement between the measured and theoretical values indicates the successful reproduction of the expected polarization properties.

3. Gamma rays generated using a radially or azimuthally polarized laser

The spatial intensity distribution of gamma rays produced by radially and azimuthally polarized lasers was previously discussed in [54] and is briefly summarized here. The measured spatial intensity distributions, obtained using a CdTe image sensor placed upstream of the collimator, are shown in Figs. 15(a) and 15(b). These distributions differed from those of linearly polarized gamma rays. Specifically, the nodes observed near $\gamma_0\theta = \pm 1$ along the laser polarization axis in linearly polarized cases [Figs. 2(a) and 2(b)] were absent. Additionally, gamma rays produced by axially symmetric polarized lasers showed a slightly broader spatial distribution in certain directions. This expansion was likely caused by the nonuniform spatial intensity distribution of the axially symmetric laser. For radial polarization, the horizontal polarization component was stronger than the vertical component, while for azimuthal polarization the vertical component was stronger than the horizontal. As a result, the gamma-ray distribution expanded vertically in the case of radial polarization

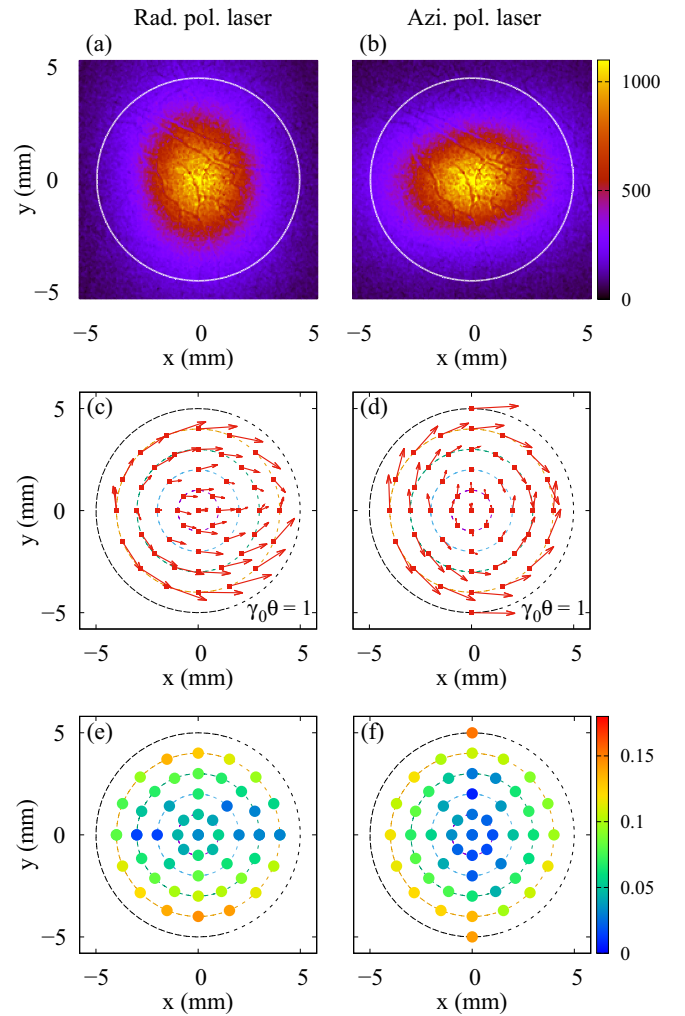


FIG. 15. (a), (b) Measured spatial intensity distribution of gamma rays generated using an axially symmetric polarized laser. The background measured without laser injection was subtracted. The white circular line represents the condition $\gamma_0\theta = 1$. (c), (d) Spatial polarization distribution of gamma rays, with arrow definitions identical to those in Fig. 12. (e), (f) Measured analyzing power. For gamma rays generated by the radially polarized laser, measurements were repeated twice at the same positions of $\gamma_0\theta = 0, 0.6$, and 0.8 along the $x = 0$ line. Panels (a), (c), and (e) show results for gamma rays generated by the radially polarized laser and panels (b), (d), and (f) show results for gamma rays generated by the azimuthally polarized laser.

and horizontally in the case of azimuthal polarization. This behavior is consistent with the characteristic expansion occurring at 90° relative to the laser polarization axis, as indicated in Figs. 2(a) and 2(b).

The measured spatial polarization distributions of the gamma rays are shown in Figs. 15(c)–15(f). Figures 15(c) and 15(d) present the distribution of the product of the magnitude of the normalized polarization axis and the analyzing power, as depicted in Figs. 15(e) and 15(f). Near the central axis of the gamma-ray beam, the polarization axis was oriented horizontally for gamma rays generated by the radially polarized laser and vertically for those generated by the azimuthally

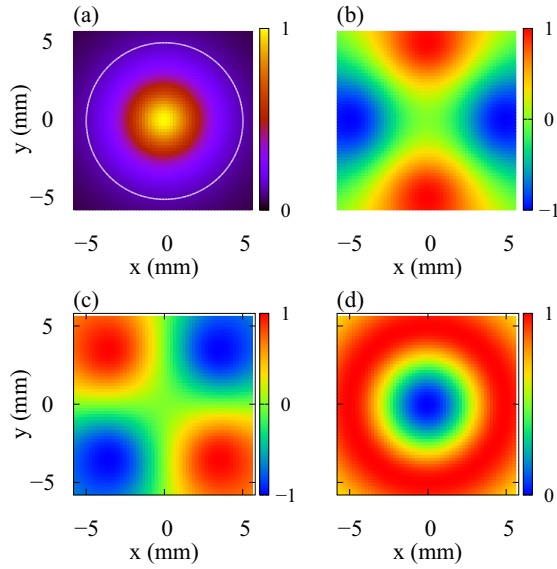


FIG. 16. (a) Normalized intensity distribution and the degree of (b) horizontal linear polarization, (c) 45° linear polarization, and (d) linear polarization of gamma rays averaged over rotation of the polarization axis, calculated using Eqs. (3)–(6). The white circular line in (a) represents $\gamma_0\theta = 1$. Calculation parameters are the same as those used in Fig. 2.

polarized laser. This observation reflects the nonuniform spatial intensity distribution of axially symmetric polarized lasers described earlier. Although the orientation of the polarization axis near the central axis differed between the two laser types, the gamma rays were azimuthally polarized in the outer regions where $\gamma_0\theta$ is large. Furthermore, the analyzing power near the central axis was lower than that observed for linearly polarized gamma rays shown in Figs. 12(c) and 12(d), implying a reduced degree of linear polarization at the center.

The polarization characteristics of the gamma rays can be interpreted as follows. Because the electron beam size was larger than the laser beam size, individual electrons interacted with the entire spatial profile of the axially symmetric polarized laser. Thus relativistic electrons effectively interacted with electromagnetic waves whose polarization axes varied depending on the electron position. Consequently, linearly polarized gamma rays with varying polarization axes were generated and the measured polarization state reflects an incoherent superposition of these gamma rays. Around the central axis, random polarization occurred due to the superposition of polarization axes rotating over 180°, resulting in a reduced degree of linear polarization. In contrast, the outer regions remained azimuthally polarized because the asymmetric intensity and polarization distributions prevented randomization. For example, at the position $\gamma_0\theta = 1$ and $\phi = 0$, the intensity for horizontally polarized gamma rays was nearly zero, while vertically polarized gamma rays were dominant, as shown in Fig. 2. Similar behavior observed at other positions supports the conclusion that the outer region was azimuthally polarized.

We verified these measurement results through theoretical calculations using Eqs. (3)–(6). The spatial intensity distribution of gamma rays was calculated as $2\epsilon_0 c \langle R^2 |\mathbf{E}|^2 \rangle$.

The degree of polarization was evaluated using the Stokes parameters (Sec. 7.2 in [37]): the degree of horizontal linear polarization $S_1/S_0 = (\langle |E_x|^2 \rangle - \langle |E_y|^2 \rangle) / (\langle |E_x|^2 \rangle + \langle |E_y|^2 \rangle)$, the degree of 45° linear polarization $S_2/S_0 = 2\langle \text{Re}(E_x^* E_y) \rangle / (\langle |E_x|^2 \rangle + \langle |E_y|^2 \rangle)$, and the degree of linear polarization as $\sqrt{S_1^2 + S_2^2}/S_0$. In standard calculations (Secs. 7.2 in [37]), the angle brackets $\langle \rangle$ represent time averaging over a comparatively long period. However, in this case, averaging was performed by rotating the gamma-ray polarization axis from 0° to 180°. Figure 16(a) shows the intensity distribution of gamma rays, revealing a concentric spatial pattern. The degree of polarization is presented in Figs. 16(b)–16(d). Figure 16(b) illustrates that horizontal (vertical) polarization dominates at $\phi = 90^\circ$ and 270° ($\phi = 0^\circ$ and 180°), while Fig. 16(c) shows that 45° (135°) linear polarization is dominant at $\phi = 135^\circ$ and 315° ($\phi = 45^\circ$ and 225°). These results indicate that the outer region exhibits azimuthal polarization. Near the central axis, the degree of polarization is reduced due to random polarization, as shown in Fig. 16(d). Overall, the theoretical calculations are consistent with the measured results.

C. Possible generation of radially polarized gamma rays

New possibilities emerge from this calculation. In this study, experiments were conducted under conditions where a_0 was sufficiently smaller than unity. However, when a laser with high peak power is employed and a_0 approaches 1, higher harmonic gamma rays are generated due to nonlinear Thomson scattering phenomena. The energy of the generated gamma rays is proportional to the harmonic order and their spatial distribution and polarization characteristics also change accordingly. Nonlinear effects have been studied theoretically [38,39,64–67] and the generation of higher harmonics has been experimentally confirmed [68–70]. Figures 17(a) and 17(b) show the spatial intensity and polarization distributions of second-harmonic gamma rays ($n = 2$), calculated under the condition $a_0 = 1$ using Eqs. (3)–(6), when the laser is horizontally and vertically polarized. The intensity at the central axis vanishes and two peaks appear along the polarization direction.

The results of similar calculations corresponding to Fig. 16 are shown in Figs. 17(c)–17(f). These figures demonstrate that the intensity distribution exhibits a doughnut-shaped spatial pattern [Fig. 17(c)], consistent with axially symmetric polarization, and the polarization state is radially polarized, as shown in Figs. 17(d) and 17(e). Thus it is possible to generate radially polarized gamma rays through the incoherent superposition using an intense axially symmetric polarized laser. However, because the degree of linear polarization is less than 1, as shown in Figs. 17(d)–17(f), we can state that the gamma rays are only partially radially polarized. Since both fundamental and harmonic gamma rays are simultaneously generated along the same axis, energy discrimination would be necessary to isolate the purely radially polarized gamma rays.

VI. CONCLUSIONS

In this study, we experimentally and theoretically demonstrated that a portion of the gamma-ray beam cross section,

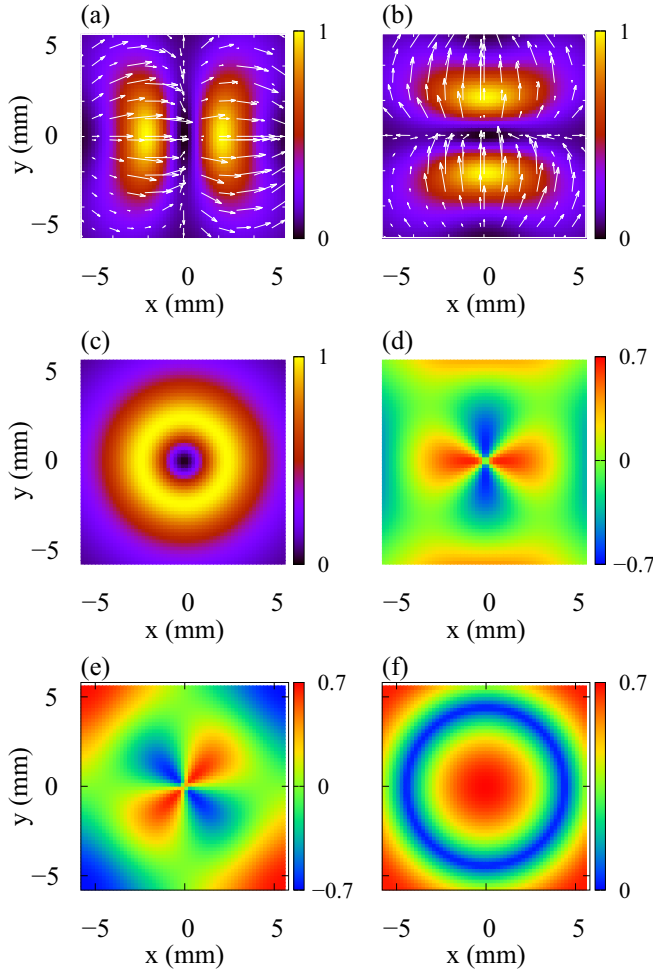


FIG. 17. Normalized intensity distribution of second-harmonic ($n = 2$) gamma rays calculated using Eqs. (3)–(6) with $a_0 = 1$, when the laser is (a) horizontally polarized and (b) vertically polarized. Other calculation parameters are the same as those in Figs. 2 and 16. The white arrows in the panels represent the real part of the electric field vector. (c) Normalized intensity distribution and the degree of (d) horizontal linear polarization, (e) 45° linear polarization, and (f) linear polarization of second-harmonic gamma rays averaged over rotation of the polarization axis.

generated via CS by relativistic electrons, exhibits axially symmetric polarization. The gamma rays were produced using a 750 MeV electron beam and a polarized laser with a wavelength of 800 nm. The gamma rays were collimated using a 1-mm-diameter lead collimator and irradiated onto a polarimeter composed of a target and seven detectors arranged azimuthally. The polarization axis of the gamma rays was measured from the asymmetry in the azimuthal scattering intensity distribution of CS gamma rays. By simultaneously moving the positions of the collimator and polarimeter, the

two-dimensional polarization distribution of the gamma rays was measured.

The polarization distribution of linearly polarized gamma rays was first measured to evaluate the performance of the developed polarimeter. The measurements confirmed that the polarization axis varied with the beam cross-section position, consistent with theoretical predictions. Subsequently, the spatial polarization distributions of gamma rays generated by a circularly polarized laser and an axially symmetric polarized laser were measured. Gamma rays generated by a circularly polarized laser were shown to possess an inherent azimuthally polarized component and it was demonstrated that the gamma rays were azimuthally polarized along the $\gamma_0\theta = 1$ line. Additionally, for gamma rays generated by an axially symmetric polarized laser, it was observed that the degree of linear polarization was low near the central axis and the gamma rays were azimuthally polarized in the outer region. This polarization behavior could be reproduced by calculating the incoherent superposition of linearly polarized gamma rays with varying polarization axes. In either case, azimuthally polarized gamma rays in the outer region can be selectively utilized by employing a doughnut-shaped collimator with an absorber near the central axis. Furthermore, calculations indicated that radially polarized gamma rays around the central axis could be produced through the incoherent superposition of second-harmonic gamma rays.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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