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A Future Laser Compton Scattering (LCS) \(\gamma\)-Ray Source: SLEGS at SSRF

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The Shanghai Synchrotron Radiation Facility (SSRF) is a third-generation synchrotron radiation light source and will come into commission in April 2009. The project Shanghai Laser Electron Gamma Source (SLEGS), which is a high intensity \(\gamma\)-ray beamline based on Laser Compton Scattering (LCS) between relativistic electron bunches and a laser, has been proposed at the SSRF. According to our simulations, the SLEGS is expected to generate a polarized \(\gamma\)-ray beam of up to 22 MeV and \(10^{11}\) photons/s if using 3.5 GeV, 200–300 mA relativistic electrons and a 500 W CO\(_2\) polarized laser. Here we describe the status and the application prospects of SLEGS and its developed prototype.
**Introduction**

Studies of Compton scattering have a long history. Since Compton [1] presented a semi-quantum mechanical treatment of such an interaction in 1922, many theoretical calculations of the characteristics of Compton scattering have been developed. In 1963, Milburn [2] and Arutyunian and Tumanian [3] originally proposed the Laser Compton Scattering (LCS) scheme and accurately predicted the production of quasi-monochromatic photon beams by utilizing laser backscattered photons from an energetic electron beam. The basic properties of Laser Compton Scattered X-rays, such as photon energy and divergence, have been well studied, both theoretically [4, 5] and experimentally [6–9]. These properties are characterized by the Lorentz factor of the electrons ($\gamma$); namely, the ratio of the electron energy to the electron rest mass.

When photons interact with high energy electrons, low energy photons obtain higher energies at the expense of the electrons’ kinetic energies. This interaction results in the emission of a highly directed (peaked in the direction of the incident electron beam), mono-energetic, highly polarized and tunable $\gamma$-ray beam with a divergence on the order of a vertex angle of $1/\gamma$. The laser Compton $\gamma$/X-ray energies cover the region between 0 and $2\gamma^2 E_L$ ($E_L$: laser photon energy) at 90° for the interaction angle between electron and photon. However, monochromatic photons can be easily obtained with a collimator because the photon energy is determined uniquely by the scattering angle. Therefore, one can produce well directed and monochromatic photons by Laser Compton Scattering on a high-energy electron beam.

Intense LCS photon beams have been recently produced and used in various fields and purposes. For example, such a light source can be used to investigate photonuclear reactions, calibrate the energies and the efficiencies of detectors, measure the electron beam parameters such as beam energies, the transversal beam dimensions [10], and the electron beam polarization, generate medical images, etc. Early in 1969, Ballam et al. [11] at the Stanford Linear Accelerator Center (SLAC) performed a physics measurement using laser backscattered photons. Until now, several $\gamma$/X-ray facilities have been developed for use in many high-energy physics experiments in the world. Table 1 shows the main LCS facilities around the world and their basic parameters. The first $\gamma$-ray beamline for nuclear physics research [12] was developed at the 1.5 GeV ADONE storage ring at the Frascati National Laboratories. Using a Storage Ring Free-Electron-Laser, an early high flux ($10^6–10^{10}$ photons/s) polarized $\gamma$-ray source was achieved by the High Intensity

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**Table 1: Parameters of the LCS facilities [14] around the world**

<table>
<thead>
<tr>
<th>Facility name (Location)</th>
<th>Electron energy (GeV)</th>
<th>Laser energy (eV)</th>
<th>Photon energy (MeV)</th>
<th>Beam intensity (photons/s)</th>
<th>Operating time</th>
</tr>
</thead>
<tbody>
<tr>
<td>LADON [15–18] (Frascati, Italy)</td>
<td>1.5</td>
<td>2.45</td>
<td>5–80</td>
<td>$5 \times 10^5$</td>
<td>1978–1993</td>
</tr>
<tr>
<td>ROKK-1 [89] (Novosibirsk, Russia)</td>
<td>2</td>
<td>2.34–2.41</td>
<td>100–960</td>
<td>$2 \times 10^5$</td>
<td>1982</td>
</tr>
<tr>
<td>LEGS/NSLS [19] (BNL, USA)</td>
<td>2.2–2.8</td>
<td>2.41–4.68</td>
<td>110–450</td>
<td>$5 \times 10^6$</td>
<td>1987</td>
</tr>
<tr>
<td>ROKK-2 [20] (Novosibirsk, Russia)</td>
<td>2</td>
<td>2.41–3.53</td>
<td>140–220</td>
<td>$5 \times 10^6$</td>
<td>1987</td>
</tr>
<tr>
<td>At Teras [21] (Tsukuba, Japan)</td>
<td>0.8</td>
<td></td>
<td>1.6–8.7</td>
<td>$10^3–10^5$</td>
<td>1991</td>
</tr>
<tr>
<td>ROKK-1M [22] (Novosibirsk, Russia)</td>
<td>2</td>
<td>1.17–4.68</td>
<td>100–1600</td>
<td>$3 \times 10^6$</td>
<td>1993</td>
</tr>
<tr>
<td>GARAAL/ESRF [23,24] (Grenoble, France)</td>
<td>6</td>
<td>2.41–3.53</td>
<td>550–1500</td>
<td>$3 \times 10^6$</td>
<td>1995</td>
</tr>
<tr>
<td>HIGS [25,26] (Durham, USA)</td>
<td>1</td>
<td>2–12.5</td>
<td>$\leq 220$</td>
<td>$2 \times 10^8$</td>
<td>1997</td>
</tr>
<tr>
<td>TINAF [27] (Virginia, USA)</td>
<td>6</td>
<td>2.41–3.53</td>
<td>$\leq 1500$</td>
<td>$10^6$</td>
<td>2000</td>
</tr>
<tr>
<td>ELFE[90] (DESY, Germany)</td>
<td>15–30</td>
<td>2.41–3.52</td>
<td>3–20$\times 10^3$</td>
<td>$10^7$</td>
<td></td>
</tr>
<tr>
<td>LEPS [28] (Hyogo, Japan)</td>
<td>8</td>
<td>3.5</td>
<td>1500–2400</td>
<td>$2.5 \times 10^5$</td>
<td>2004</td>
</tr>
<tr>
<td>At NewSUBARU [29] (Hyogo, Japan)</td>
<td>1 (1.5)</td>
<td>1.17</td>
<td>17.6 (39.1)</td>
<td>$2.5 \times 10^5$</td>
<td>2004</td>
</tr>
<tr>
<td>At Spring-8 [30] (Hyogo, Japan)</td>
<td>8</td>
<td>0.01</td>
<td>2–10.2</td>
<td>$1.3 \times 10^3$</td>
<td>2007</td>
</tr>
<tr>
<td>SLEGS [31] (Shanghai, China)</td>
<td>3.5</td>
<td>0.117</td>
<td>$\leq 22$</td>
<td>108–1010</td>
<td>2010 or later</td>
</tr>
</tbody>
</table>

* $\gamma$-ray maximum energies and intensities are given for various existing and future facilities.
Gamma-Ray Source (HIGS) [13] at the Triangle Universities Nuclear Laboratory (TUNL).

The Shanghai Synchrotron Radiation Facility (SSRF) [32] is a third-generation synchrotron radiation light source and will come into commissioning in April 2009. The energy of the electrons in the storage ring is 3.5 GeV, which so far is the highest value of medium-energy light sources in the world. The SSRF consists of a 150 MeV Linac, a booster, a storage ring, and a number of experimental stations. The storage ring has 4 identical long straight sectors, 16 identical standard straight sectors, and 40 bending magnets. The Shanghai Laser Electron Gamma Source (SLEG), which will be one of the highest intensity beam lines of γ-ray based on the LCS method using relativistic electron bunches and a laser, has been proposed at the SSRF. It will be built at beamline BL20 – one of the long straight sections of the SSRF storage ring. γ-rays with energies up to a few hundred MeV can be generated. The properties of the SLEG beam are a high monochromatic intensity and a high degree of polarization.

In the following we describe the status, plans, simulation results, and several promising applications of SLEG. As a prototype of SLEG, an X-ray source has been installed at the terminal of a 100 MeV linear accelerator (linac). The first experiment has been performed using electron bunches of 107 MeV, 5 Hz, 1 ns, and 0.1 nC, and Nd:YAG laser pulses of 18 ns and 10 MW peak power. The LCS X-rays have been observed in our preliminary results. The setup of prototype is also presented.

Plan and status of SLEG

The construction of the SSRF, including 7 beamlines in the first phase, is scheduled for completion in April 2009. The 7 beamlines were installed in early 2008. The storage ring is designed to store 300 mA at 3.5 GeV. An electron beam of 200 mA with more than 13 hours lifetime was achieved for the first time at 22:16 on Sept. 30, 2008, at SSRF. Currently, three beamlines are in operation [33].

The aim of SLEG is the construction of a beamline at SSRF which extends the keV energy range of common synchrotron radiation sources into the MeV range. γ-rays up to 22 MeV will be produced by Compton backscattering of CO2 laser photons on the electrons circulating in the storage ring. 

Figure 2: Paths of the laser beam, electron bunches, and the generated γ-rays.
storage ring. Intensities as high as $10^9$-$10^{10}$/s can be achieved without affecting the SSRF performance. The $\gamma$-ray beam will have a high degree of linear or circular polarization (80–100%) with respect to the polarization direction of laser beam. An energy resolution of 1.5% can be achieved. These beam characteristics can be used to explore many interesting fields.

SLEGS is located at the BL20 straight section of the storage ring. The entire facility consists of the BL20 front-end of the storage ring, a laser hutch, an experimental room, and a $\gamma$-ray beam dump. All of them are located outside the shielding wall. Figure 1 presents the schematic diagram of the entire facility.

The optical system consists of a continuous laser, a beam expander, mirrors, and focusing lenses. After a polarized laser beam is produced in the laser hutch downstream of the BL20 front-end, the laser beam is expanded, directed toward BL20 by a set of reflecting mirrors, and then focused onto an interaction region inside the SSRF storage ring. To facilitate that the laser beam overlaps with the electron bunches, the laser beam is co-axial with a visible laser, which is already adjusted to overlap with the electron bunches using a YAG crystal target and a XC-56 Sony video camera. After scattering, $\gamma$-rays are generated within a small forward cone along the direction of incident electrons and go back into the experimental room. The remaining electrons are bent by bending magnets toward the storage ring’s next section, while the transmitted laser beam that passes through the interaction region is inspected by a set of monitors, which provide feedback and control signals. Figure 2 shows the paths of the laser beam, electron bunches, and the generated $\gamma$-rays.

In order to achieve a high intensity LCS photon beam, many high power lasers can be selected. Compared to others, the CO$_2$ laser has several advantages: 1) it is well developed, compact, and offers high quality; 2) high output power that promises a high flux of LCS $\gamma$-ray; 3) relatively low cost and low technical risk; and 4) it is easy to manage and control. Thus, the CO$_2$ laser is the best option for SLEGS. The intrinsic wavelength of the CO$_2$ laser is 10.64 $\mu$m.

Table 2: Basic parameters of the CO$_2$ laser

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength ((\mu)m)</td>
<td>10.4–10.8</td>
</tr>
<tr>
<td>Peak power (MW)</td>
<td>500</td>
</tr>
<tr>
<td>Rise/fall time ((\mu)s)</td>
<td>&lt;90</td>
</tr>
<tr>
<td>Stabilization of power (%)</td>
<td>$\pm$8</td>
</tr>
</tbody>
</table>

Figure 3: General arrangement of the experimental set-up, which contains an electron beam source, a laser system and an X-ray beam monitor. A combination of a RF photocathode and a linac was used as electron source. A pulsed ND:YAG laser system was used for interaction with the electron beam. The repetition rates of e-bunch and laser pulse were 5 Hz and 2.5 Hz, respectively. This was synchronized to the RF of the electron beam, which was 2836 MHz.
and the corresponding photon energy \((E_L)\) is 0.117 eV. Basic parameters of the CO\(_2\) laser that will be used in SLEGS are listed in Table 2.

**Prototype of SLEGS**

It is crucial to build a prototype for designing SLEGS, setting it up smoothly, and accomplishing it on time. The prototype of SLEGS provides a test for running SLEGS with non-backward LCS processes as well. Unlike SLEGS, the prototype of SLEGS is a keV X-ray source and the laser used for the LCS process is a pulsed beam. With high intensity photon fluxes, these kinds of X-ray sources have a great future in applications because they are very compact and portable compared to a synchrotron radiation light source.

The X-ray source, the prototype of SLEGS, has been installed at the terminal of a 100 MeV linear accelerator (linac) at the Shanghai Institute of Applied Physics (SINAP). Electron bunches with the charge of about 0.1 nC within a 1–2 ns pulse width (FWHM) are generated at a 5 Hz repetition rate by the linac. They are accelerated up to 107 MeV by a 2856 MHz klystron and transported using bend magnets and quadrupoles to the interaction region inside the LCS chamber.

The more detailed experimental arrangement is shown in Figure 3. Using the four quadrupole magnets, the electron beam is focused at the center of the chamber, where it is scattered against the laser beam. Steering magnets combined with the quadrupole magnets are used to...
adjust the beam position. On the left side of the LCS chamber in Figure 3, a 30°-bending magnet deflected the electron beam onto a beam dump, away from the forward scattered X-rays.

Regarding the optical system, we have employed two pulsed Nd:YAG lasers and their optics are visible at the bottom of Figure 3. After the Nd:YAG laser beam is produced, 99% of photons pass through the spectroscope (a kind of grating) and are expanded, and the left 1% is reflected by it. The EPM1000 power and energy meter (Coherent, Inc.) is placed 30 cm away from the spectroscope and is used to measure the energy of some reflected photons for monitoring the stability of the laser energy, shown in Figure 5. Near the EPM1000, a PIN photo diode detector is also used to determine the pulse width of the Nd:YAG laser beam by measuring the other reflected photons. After being reflected by several mirrors and going through the wall of the 100 MeV Linac hall, the 99% beam is focused by a lens and finally incident into the LCS chamber with 40° incident angle of the laser with respect to the electron brunch. A He-Ne Laser at the right of Figure 4 is used to align the whole laser optical system.

In order to get the detailed timing information of the electron signal, we put a Wall Current Monitor (WCM) in front of the LCS chamber. With the help of the PIN detector and the WCM, we can measure the time difference between laser pulses and electron bunches (see Figure 6) so that we can synchronize them by adjusting the time difference during the experiment.

We did SLEGS prototype experiments twice using two lasers. Both lasers are Nd:YAG lasers but with different peak powers and pulse widths. The main parameters of the used lasers are listed in Table 3.

Because the signal to background ratio is quite small due to the bremsstrahlung background from the 100 MeV electrons, the LCS process is designed to happen for every other electron pulse. Therefore one can extract the yield of the LCS X-ray by subtracting the yield with LCS process from the yield without LCS process. The produced LCS X-ray has been observed in our preliminary results. The experimental details and the results will be published elsewhere.

Simulation results

In order to obtain the features of the γ-ray emerging from SLEGs from simulations, the following realistic conditions are used: 1) 10.64μm CO2 laser with an average power of 1W; 2) 3.5GeV electron beam and its profile at BL20 in SSRF; and 3) 300mA electron beam current. We have developed a C++ program using the Monte Carlo method to simulate the generation of the LCS γ-rays. Some important calculation and simulation results are presented here:

- The differential cross section and the energy of LCS photons as functions of the scattering angle (Figure 8);
- Estimated flux of the LCS γ-ray beam as a function of the collimation angle Θ (Figure 9);
- Energy spectra of the LCS γ-ray beam at different collimation angles (Figure 10); and
- Polarization as a function of the γ-ray energy (Figure 11).

More details are given in [31]. The relativistic framework that is considered for the LCS process shown in Figure 7.

Here $E_i$ and $E_{i'}$ in Figure 7 are the kinetic energies of incident and scattered electron, $E_l$ and $E_s$ are the energies of incident and scattered laser photon, and $\theta_i$ is the incident laser angle with respect to the electron beam direction. As $\theta_i$ equals $\pi$, this process is called Backward Compton Scattering (BCS). During the scattering, the X-ray emerges at a small angle $\theta$ with respect to the electron beam direction, and the electron emerges at the angle $\phi$. The basic mechanism of LCS can be found in Refs. [34–36].

Figure 5: Measured pulse energy as a function of time. The error bar includes system error and statistical error.

Figure 6: Time difference between laser pulse and electron bunch as a function of time. The red line is the expected ideal time difference; the error bar includes system error and statistical error.
from which the energy of scattered photon \((E_s)\) can be simply obtained by

\[
E_s = \frac{4\gamma^2E_L}{1 + 4\gamma^2E_L/m_0c^2 + \gamma^2\theta^2}
\]  

(1)

where \(\gamma\) is the ratio of the total electron energy and rest energy: \(\gamma = E/m_0c^2 = 1/\sqrt{1 - \beta^2}\), which is the relativistic factor of the incident electron, \(\beta\) is the ratio between the electron and light velocities, and \(m_0\) is the electron mass at rest. The differential LCS cross-sections in the laboratory frame can be calculated using the Klein–Nishina formula [37] in the electron at rest (ER) frame. It can be written as

\[
d\sigma = \frac{\pi\rho_0^2}{\sin\theta d\theta} \frac{1 - \beta^2}{(1 - \beta\cos\theta)^2} R^2 \left( R + \frac{1}{R} - 1 + \cos^2\theta_{ER} \right)
\]

(2)

where \(\rho_0\), \(R\) and \(\theta_{ER}\) are the classical electron radius, the ratio between energies of the scattered and the incident photons, and the scattering angle in the ER frame, respectively. \(\theta_{ER}\) can be calculated from \(\theta\) in the laboratory frame by the Lorentz transformation. The differential cross-sections and the energies of LCS photons have the same trends in terms of scattering angle in Figure 8. They rapidly decrease as the scattering angle increases in a small scattering angle regime, such as \(0 < \theta < 0.2\) mrad.

The simulation results based on the differential LCS cross-section are shown in Figs. 9–11. The estimated LCS \(\gamma\)-ray flux from our simulation shown in Fig. 9 slowly increases as the corresponding collimation angle increases. When a 500 W laser and non-collimation are applied, then the flux can achieve \(10^{9–10}\) photons/s. Meanwhile, energy spectra of the LCS \(\gamma\)-ray beam at different collimation angles are also studied. In Figure 10, one can see that the non-collimation yield of the \(\gamma\)-ray is slightly higher at both ends of the energy spectrum. Around 10 MeV \(\gamma\)-ray energy the corresponding yield is the smallest. However, if the collimation angle is applied, for example, \(\Theta = 0.04\) mrad, only \(\gamma\)-ray energies larger than 15 MeV can be generated (see Figure 10), and its energy resolution is 1.5%. Therefore, one can obtain a quasi monochromatic \(\gamma\)-ray source by employing a proper collimator.

Because a high degree of polarization gamma source has a wide range of applications, we simulated the polarization of SLEGS also. In Figure 11, assuming a 100% circularly polarized CO\(_2\) laser, the degree of circular polarization of the LCS \(\gamma\)-ray decreases from 100% to -100% as the \(\gamma\)-ray energy increases from 0 MeV to 22 MeV. On the contrary, when a 100% linear polarized CO\(_2\) laser is used, the corresponding degree of linear polarization increases from 0% to 100% as the \(\gamma\)-ray energy increases from 0 MeV to 22 MeV. So the collimated SLEGS \(\gamma\)-ray with \(\Theta = 0.04\) mrad shown in Figure 10 will have roughly 80% circular or linear polarization.

In conclusion, according to the simulation results, SLEGS can be a polarization and energy-tunable, high flux \((10^{9–10})\) \(\gamma\)-ray source when a 500 W polarized CO\(_2\) laser is used.

Applications

Generally, \(\gamma\)-rays are a consequence of natural processes. They may have their origin in atomic nuclei. They are produced on earth in natural or induced by radioactive processes. They are also produced in astrophysical phenomena (e.g., stellar evolution processes), which release enormous energies. However, in recent years artificial \(\gamma\)-ray sources were produced in several laboratories and institutes around the world. \(\gamma\)-ray sources produced by LCS methods (see Table 1) have especially good characteristics of high intensity, monochromatic radiation, and a high degree of polarization. In the near future, as one of this kind of gamma sources, SLEGS will open up the possibility to conduct a wide range of fundamental studies such as nuclear physics, particle physics, and astrophysics. At the same time SLEGS will have particular characteristics that make it useful for industrial and medical applications.

The large number of applications restricts us to list keywords only; however, details can be found in the references. To the best of our knowledge, possible detailed studies and applications include:

<table>
<thead>
<tr>
<th>Table 3: Main parameters of the Nd:YAG laser in two experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters of laser</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Wavelength (nm)</td>
</tr>
<tr>
<td>Peak power (MW)</td>
</tr>
<tr>
<td>Pulse width (ns)</td>
</tr>
<tr>
<td>Stabilization of (ns)</td>
</tr>
<tr>
<td>Stabilization of power (%)</td>
</tr>
</tbody>
</table>
1. Fundamental research, e.g. in nuclear physics, particle physics, and astrophysics

1.1. Studies of nuclear structure [38]
- Nuclear vibration and excitation modes: Isovector Giant Dipole Resonance (IVGDR), Isovector Electric Giant Dipole/Quadruple Resonance (IVGDQR) and so on;
- Magnet dipole excitation (inversion spin M1 excitation, orbit collectivity magnet dipole M1 excitation, and orbit and spin dipole response to well deformed nuclei [39]), and electric dipole excitation [40–45] (two-phonon excitation, and quadruple-eight-pole particle states) by Nuclear Resonance Fluorescence (NRF) [46] technique;
- Isospin effects in nuclear structure;

1.2. Applications in nuclear astrophysics
- Nucleosynthesis;
- The process of radioactive capture through the Coulomb dissociation;
- The direct measurement of photonuclear reaction cross-section in low energy region [50,51];
- Cross-section measurements for some crucial nuclear reactions in stellar evolution [52–56].

2. Industrial applications
- Molecule and atom velocities and binding property of anisotropic solid system;
- \(\gamma\)-ray activation analysis [69–71] such as elemental analysis and defect analysis;
- Studies of radiation effects on material and biology [72–73]. Polarization has a great effect on material structure and its property, \(\gamma\)-ray produced by Laser Compton Scattering (LCS) has linear or circular polarization [74], which does not belong to other \(\gamma\)-ray sources. It can provide a new tool in this research field.
- Electron beam diagnostics and their application using LCS method in a storage ring [75–78], including precision measurements of electron energy, divergence and spatial distribution of the electron density, and the measurements of electron polarization [79];
- Disposal of nuclear waste material by triggering photonuclear reaction [46,80];
- Building ultra-high-intensity light sources and \(\gamma\)/X-ray lasers [81,82].

1.3. Studies of symmetry and exotic phenomenon
- Parity violation measurements with a high intensity photon beam [57–63];
- Study of non-commutative quantum field [64–67].

1.4. Studies of a few-body system [68] or spin polarization phenomenon in nuclear physics
- Study of light nucleus force (such as three body forces);
- Study of nucleus (nucleon) polarizabilities.

Figure 8: The differential cross-section (upper panel) and the energy (lower panel) of LCS photons as functions of the scattering angle.

Figure 9: The estimated flux of the LCS \(\gamma\)-ray beam as a function of the collimation angle \(\theta\).
3. Medical applications

- Nuclear medicine and γ-ray imaging technique, including Compton Scattering Tomography, γ-ray transillumination imaging technique, etc. [83,84] (the American TUNL had the idea of developing this field using High Intensity Gamma Source (HIGS));
- Cancer therapy by a γ-ray beam [85–88].

Conclusions

The construction of the Shanghai Electron Laser Gamma Source (SLEGS) will be finished around 2010. If a few hundred watts CO₂ laser is employed, a γ-ray beam with an energy of several MeV can be provided by this facility. Intensities as high as $10^9–10^{10}$ photons/s can be achieved without affecting the SSRF performance. The γ-ray beam will have a high degree (80–100%) of linear or circular polarization and its energy resolution of 1.5%. Therefore, the SLEGS is a very promising project and has a bright future in various applications, covering the range from fundamental research to applied science. The novel facility will open up new fields for synchrotron radiation research.

Acknowledgments

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Figure 10: The energy spectra of the LCS γ-ray beam at different collimation angles. The histograms filled with gray scale stand for $\Theta = 0.04, 0.1, 0.3, 0.5$ and $1.0$ mrad, respectively. The histogram filled with white represents the energy spectrum of the γ-ray beam.
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