



Commissioning of laser electron gamma beamline SLEGS at SSRF

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Abstract The Shanghai Laser Electron Gamma Source (SLEGS) is a powerful gamma source that provides MeV gamma-ray beams for nuclear science and technology. It was developed as one of the 16 beamline stations in the Phase II Project of the Shanghai Synchrotron Radiation Facility. The slant-scattering mode is for the first time systematically employed in laser Compton scattering at SLEGS to produce energy-tunable quasi-monoenergetic gamma-ray beams. The SLEGS officially completed its commissioning from July to December 2021. Gamma rays in the energy range of 0.25–21.7 MeV with a flux of 2.1×10^4 – 1.2×10^7 photons/s and an energy spread of

2–15% were produced during the test. This paper reports the results from commissioning the SLEGS beamline.

Keywords SLEGS · Laser Compton scattering · Slant-scattering mode · Backscattering mode

1 Introduction

Photonuclear reactions form a unique field of nuclear physics and astrophysics because of their well-known electromagnetic interactions. As early as the 1960s and through the 1980s, the systematic study of the isovector giant dipole resonance was carried out in photoneutron cross-sectional measurements with a wide range of nuclei at the Saclay Laboratory, France, and Lawrence Livermore National Laboratory (LLNL), USA, using positron in-flight annihilation technology. However, a large discrepancy between the Saclay and LLNL data regarding the photoneutron cross sections has persisted [1–5], leading to the creation of the International Atomic Energy Agency (IAEA) photonuclear data library in 2019, which includes new data to resolve the long-standing discrepancy [3].

The laser Compton scattering (LCS) gamma source was developed based on the inverse Compton scattering of laser photons from relativistic electrons in the storage ring. It is currently the most advanced quasi-monoenergetic gamma-ray source and provides a new research opportunity to study photonuclear physics. Since the 1980s, the LCS beamline [6] of the National Institute of Advanced Industrial Science Technology (AIST) and the NewSUBARU BL01 LCS beamline of the University of Hyogo, both in Japan [7], as well as the high-intensity gamma source (HIγS) of the Triangle University Nuclear Laboratory (TUNL) in the USA, have been constructed to study

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nuclear physics [8]. The high-energy laser electron gamma source (LEGS) at the Stanford Linear Accelerator Center (SLAC) [9] and the laser electron photon beamline (LEPS/LEPS2) at SPring-8 are dedicated to hadron physics [10]. The TERAS LCS beamline was closed in 2013; after the installation of a new injection linac, and the operation of the NewSUBARU LCS beamline is currently limited to industrial applications. Currently, only the high-energy LPES/LEPS2 and low-energy HI γ S are in operation as major facilities. The laser electron gamma source the variable energy gamma-ray (VEGA) system in extreme light infrastructure–nuclear physics (ELI-NP) was re-designed in 2019, is currently under construction, and is scheduled to begin operation in 2023 [11].

The Shanghai Laser Electron Gamma Source (SLEGS) was first proposed in 1998 at the Shanghai Synchrotron Radiation Facility (SSRF). Nearly 20 years after the feasibility study and prototype development [12–19], it was approved in 2016 as one of the 16 beamlines in the Phase II project of the SSRF by the National Development and Reform Commission, People's Republic of China. Construction of the SLEGS beamline began in October 2019 and was completed in December 2021. The beamline passed the commissioning test in 2021 and will be open to users by the end of 2022 [20].

Using a CO₂ laser with a wavelength of 10.64 μ m and a maximum power of 100 W, high-intensity gamma-ray beams are generated in collisions with 3.5 GeV electrons in the SSRF storage ring. The SLEGS is designed to operate in two operating modes: One is the laser Compton backscattering mode at 180°, which is commonly used around the world to achieve the highest energy and polarization of gamma-ray beams; and the other is the laser Compton slant-scattering mode, which enables the energy of gamma-ray beams to be tuned by changing the collision angle between the laser and electron beams in a wide range, from 20° to 160°.

Slant scattering is a key technology for producing energy-tunable gamma-ray beams at synchrotron radiation

facilities operating at a fixed electron beam energy. In the past decade, SINAP-II [15–19] and UVSOR-II have played a pioneering role in the technical development of slant scattering. While UVSOR-II has succeeded in producing MeV gamma rays at limited slant-scattering angles ranging from 70° to 110° [21, 22], the gamma-ray beam production at SLEGS is systematically carried out in an innovative manner with a dedicated interaction chamber [23] and double collimator system [24, 25].

2 Research at SLEGS

SLEGS is designed to generate gamma-ray beams at energies ranging from 0.25 to 21.1 MeV in slant scattering at collision angles ranging from 20° to 160° and at a maximum energy of 21.7 MeV in backscattering at 180°. The full-spectrum flux ranges from $\sim 10^5$ photons/s at 20° to $\sim 10^7$ at 180°. A 2% energy resolution is achieved with a 1- to 2-mm collimator, which confines the emission angle of the gamma-ray beam to less than 0.5 mrad.

The SLEGS serves as a multi-functional experimental platform for research in nuclear science and technology [20]. The research spectrum in basic research ranges from collective excitation of nuclei, nuclear equations of state, and the origin of elements to ultra-high-energy cosmic rays, while that in application research ranges from atomic energy, nuclear transmutation, and gamma imaging to national security.

3 SLEGS beamline

The SLEGS beamline is equipped with four main components, as illustrated in Fig. 1. The SLEGS is located in the BL03SSID of the SSRF experimental hall. A 3D drawing is provided in Fig. 2.

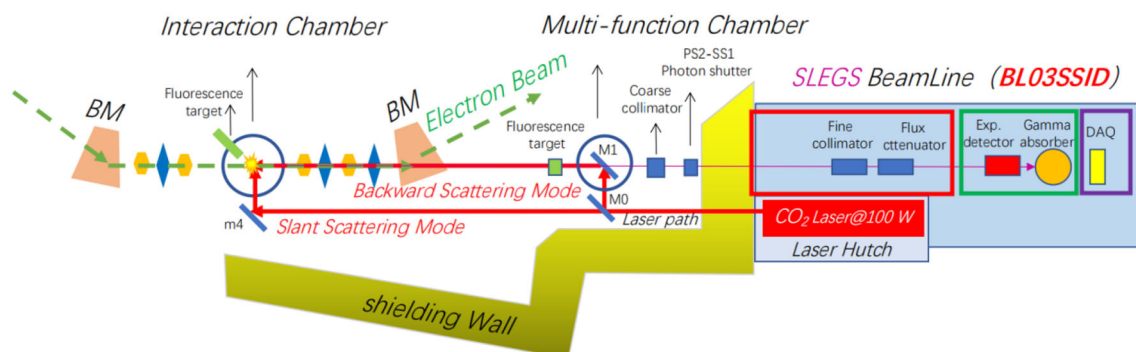


Fig. 1 (Color online) Schematic layout of the SLEGS beamline

Fig. 2 (Color online) 3D drawing of the SLEGS beamline. Top: Interaction chamber (a), multi-functional chamber (b), and coarse collimator (c) inside the SSRF vault. Bottom: Fine collimator (d), flux attenuator (e), experimental detector (f), and gamma absorber (g) in the SLEGS beamline

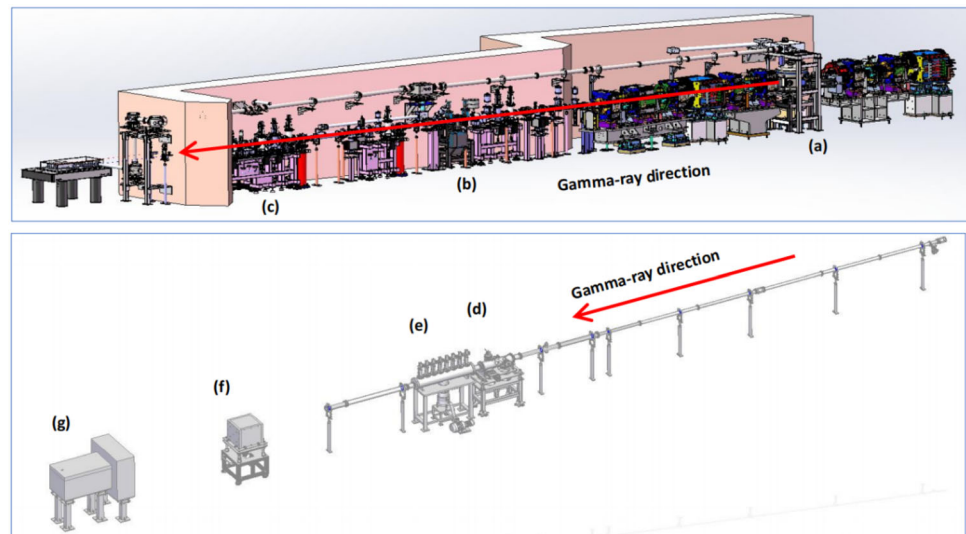
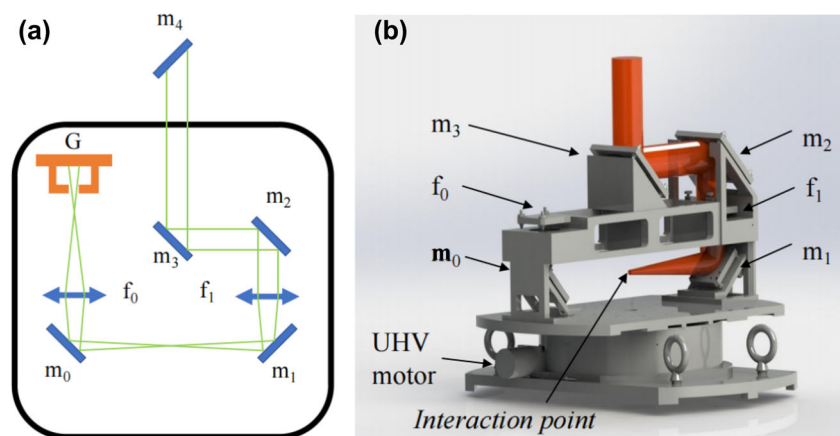


Fig. 3 (Color online) Schematic of configuration of optical elements (a) and the rotating bracket (b)



- (1) 100-W CO₂ laser [26] and laser transport.
- (2) Interaction chamber for slant scattering and multi-functional chamber for backscattering.
- (3) Two-stage coarse and fine collimators and gamma flux attenuator.
- (4) Experimental hutch, experimental detector, gamma absorber, and data acquisition system

3.1 Laser transport and gamma production

A continuous-wave 10.64 μm CO₂ laser with a laser power of 100 W is located in the laser hutch located adjacent to the SSRF vault. The hutch is designed as a clean room for stable operation of the laser. The CO₂ laser can also be operated in pulse mode with an adjustable laser interval and pulse width, e.g., a 1-ms laser interval and 100- μs pulse width at 10 W with a 10% duty cycle.

Collisions between the 10.64 μm laser photons and 3.5 GeV electrons occur inside the interaction chamber, as

shown in Fig. 3, in two collision modes: laser Compton backscattering and slant scattering. The CO₂ laser beam passes through the multi-functional chamber with a ZnSe window, is bent by 90° through a water-cooled mirror, and undergoes a head-on collision in the backscattering mode. In contrast, the laser beam vertically enters the interaction chamber, passes through the optical elements (mirrors m_4 , m_3 , m_2 , and m_1 and convex lens f_1 , as shown in Fig. 3), and horizontally collides with the electron beam in the slant-scattering mode. The CO₂ laser is finally refocused and led to beam absorber G through mirror m_0 and convex lens f_0 . The optical elements are mounted on a rotating bracket so that the collision angle between the laser and electron beams can be changed from 20° to 160° through a safety stop angle at 90° [23].

3.2 Coarse and fine collimators

The energy spread and spot size of the gamma-ray beams at the target position are determined by the two-

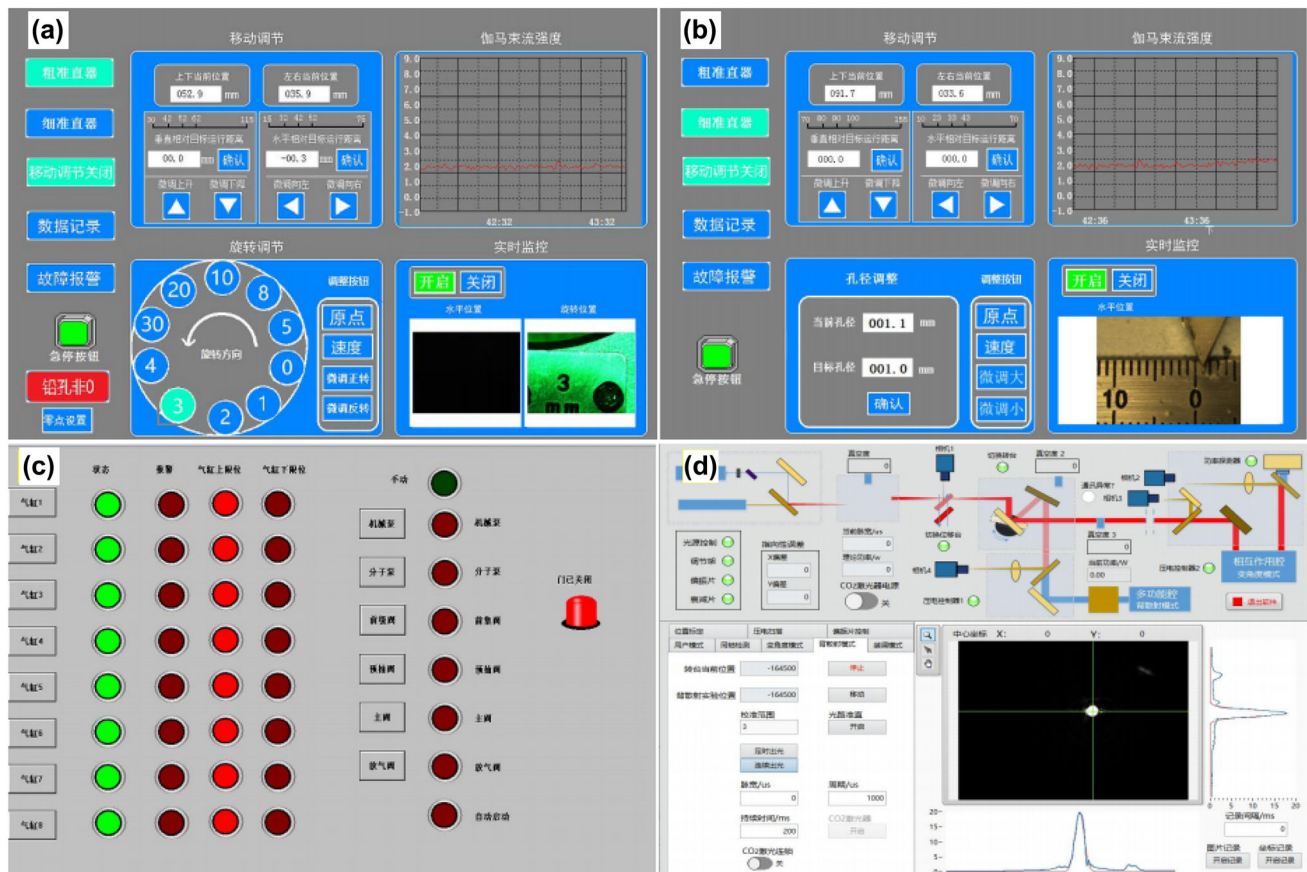


Fig. 5 (Color online) Interface displays for the coarse collimator (a), fine collimator (b), flux attenuator (c), and CO₂ laser (d)

4 Commissioning of the SLEGS beamline

Measurements of the gamma-ray beams during the commissioning of the SLEGS beamline were taken in an experimental hutch. At the end of the beamline, unreacted gamma rays entered the gamma absorber, which is made of thick concrete, Pb, and high-density polyethylene, as shown in Fig. 1.

4.1 Collimator alignment

The collimators must be aligned with respect to the gamma-ray beam axis. The collimator alignment was performed horizontally and vertically by maximizing the intensity of the gamma rays passing through the collimator. Figure 6a, b shows the gamma-ray intensity as a function of the vertical and horizontal positions of the coarse collimator, respectively. In this collimator position scan, a coarse collimator with an aperture of 2 mm was used along with a 20-mm fine collimator and a 100-mm flux attenuator. A $\Phi 3'' \times 4''$ ($\Phi 76.2 \text{ mm} \times 101.6 \text{ mm}$) LaBr₃(Ce) detector [27] was used to measure the gamma rays. The optimized position of the coarse collimator was found to be

(51.97 ± 0.04) mm vertically and (34.54 ± 0.03) mm horizontally. The laser electron collision position and fine collimator underwent the same adjustment process.

4.2 Gamma-ray beam spot

The SLEGS beamline is equipped with two beam spot monitors in the experimental hutch (Fig. 7): an X-ray camera called MiniPIX [28], shown in Fig. 7b, and a gamma spot monitor (GSM), shown in Fig. 7d. The MiniPIX consists of 256 × 256 silicon pixels with a pixel size of 55 μm × 55 μm and a silicon wafer thickness of 500 μm. The GSM involves a LYSO scintillator that is 70 mm in diameter and has a thickness of 2.5 mm, which collects the scintillation light generated by X- and gamma rays with a CCD/CMOS camera through a 45° plane mirror, with a 135° optical path as a reserved monitoring channel.

Figure 7a shows an example of a beam spot with a Bremsstrahlung background measured using MiniPIX. Figure 7c shows an example of the gamma beam spot measured with the GSM after subtracting the Bremsstrahlung background along with the horizontal (X) and

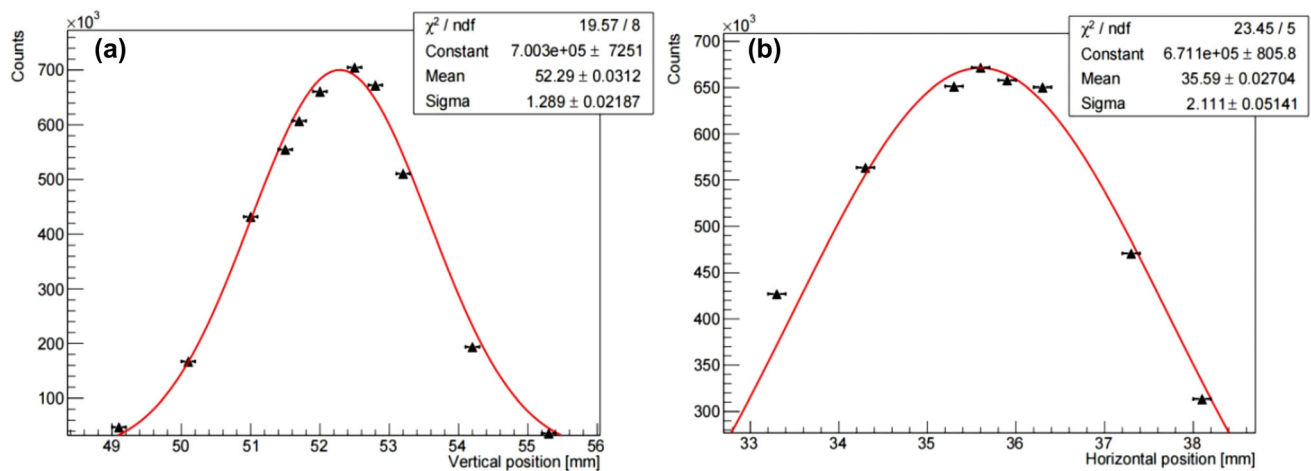


Fig. 6 Results for the vertical (a) and horizontal (b) scans of the coarse collimator

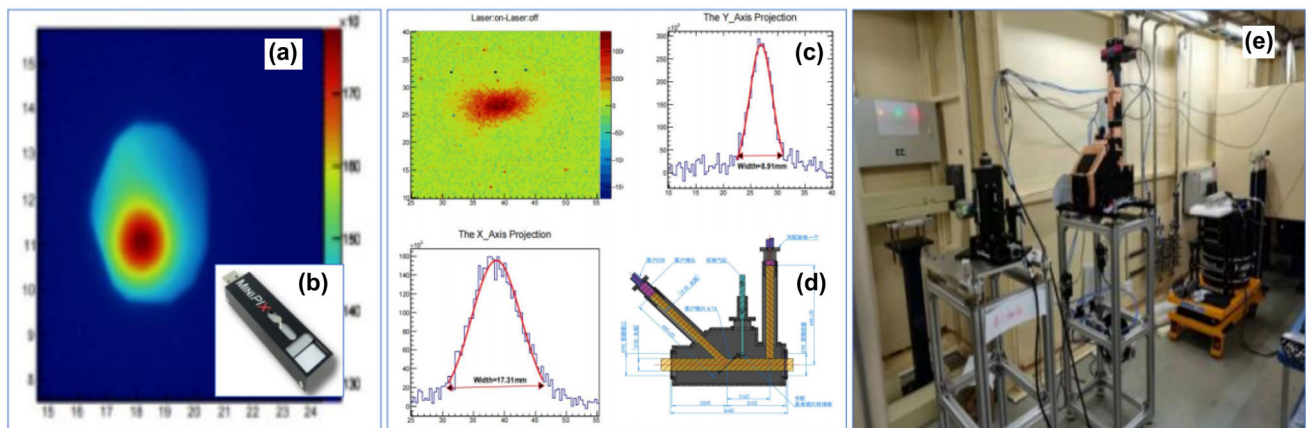


Fig. 7 (Color online) Bremsstrahlung beam spot (a) and MiniPIX (b) inset, gamma beam spot (c) and GSM (d) inset, and photograph of MiniPIX and GSM (e) in the experimental hut

vertical (Y) distributions. The gamma beam spot size in the full width at the tenth maximum (FWTM) is horizontally 17.31 mm and vertically 8.91 mm. Because the GSM is placed approximately 38 m from the gamma production point, the calculated gamma-ray emission angles are 0.46 mrad in the X direction and 0.25 mrad in the Y direction.

4.3 Energy profile and flux of gamma-ray beams

A Saint-Gobain lanthanum bromide ($\text{LaBr}_3(\text{Ce})$) detector 3'' (76.2 mm) in diameter and 4'' (101.6 mm) in length with an energy resolution of approximately $\sim 3\%$ at 661 keV [27] was used as the energy profile and flux monitor detector in the commissioning run. A BGO detector 76.2 mm in diameter with a length of 200 mm from SICCAS [29], located in the gamma absorber, was used to monitor the gamma flux. The flux value was fed back to the control system of the collimator and laser for online recording and display and will be used for automatic

correction of laser power output in the future. Figure 8a shows a typical response function of the $\text{LaBr}_3(\text{Ce})$ detector with respect to the gamma-ray beam, where a 3-mm coarse collimator, 3-mm fine collimator, and 1-mm additional lead external collimator were used, but without the flux attenuator. The background gamma spectrum is shown by the green line, where the lower-energy synchrotron radiation and higher-energy Bremsstrahlung are seen, as well as internal radiation from ^{138}La in the $\text{LaBr}_3(\text{Ce})$ detector. Figure 8b shows the background-subtracted spectra measured at 20° , 90° , and 180° .

We systematically measured the response functions of the $\text{LaBr}_3(\text{Ce})$ detector to gamma-ray beams produced by slant scattering. The background-subtracted spectra are shown in Fig. 9. The gamma-ray energy follows the kinematics of laser Compton slant scattering. The production of gamma-ray beams was confirmed in the energy range of 0.25–21.1 MeV in slant-scattering mode from 20° to 160° and at 21.7 MeV in backscattering at 180° .

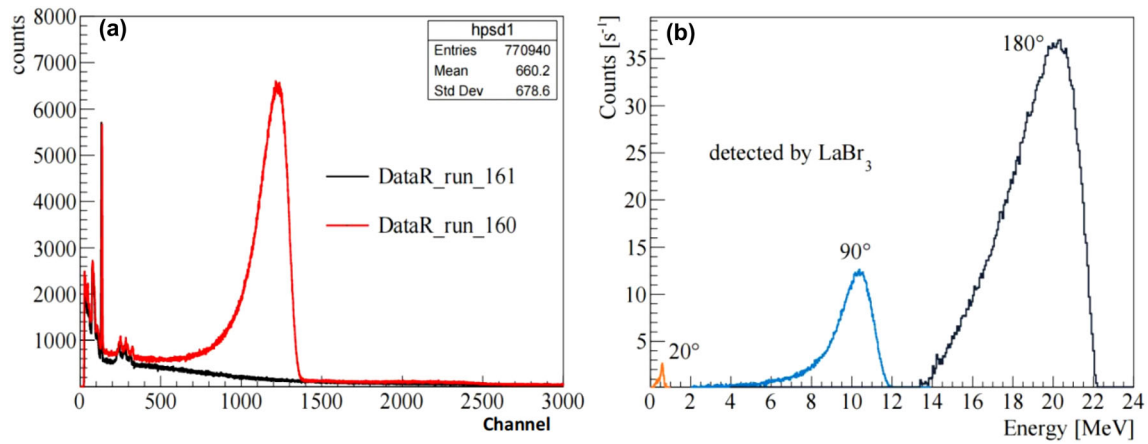


Fig. 8 (Color online) Typical response function of the LaBr₃(Ce) detector to a gamma-ray beam (a) and background-subtracted spectra at 20°, 90°, and 180° (b)

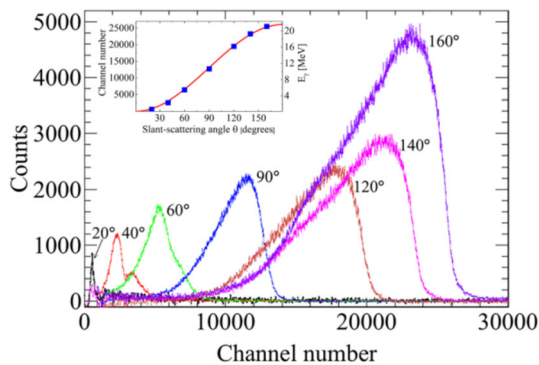


Fig. 9 (Color online) Response functions of the LaBr₃(Ce) detector to gamma-ray beams produced in the slant-scattering mode and background gamma rays to be subtracted. The inset is a comparison of the angle and energy measurements with the theoretically calculated curves

The total gamma-ray flux is an important parameter in the commissioning of the SLEGS beamline. The gamma flux required to be approved is the total flux at the gamma production point integrated over the entire gamma energy spectrum for the electron beam current $I_e = 300$ mA (design value). The background-free gamma-ray flux ϕ was measured using a LaBr₃(Ce) detector at $I_e = 200$ mA (test value). After normalizing the measured flux ϕ by $F = \phi / [\eta_D \times \eta_A \times \eta_C] \times [300 \text{ mA} / 200 \text{ mA}]$ with the detection efficiency η_D of the LaBr₃(Ce) detector, transmission rate η_A of the attenuator, and transmission rate η_C of the collimator hole, the total flux is shown in Fig. 10. The maximum flux at an electron current of 300 mA and a laser power of 100 W can reach approximately 10^5 photons/s at 20° and 10^8 photons/s at 180°.

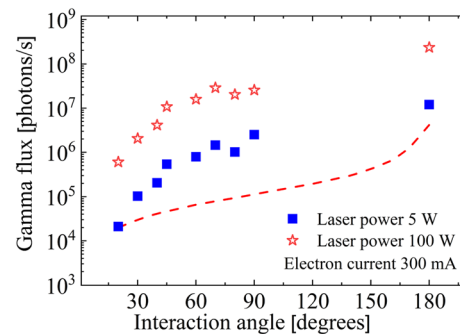
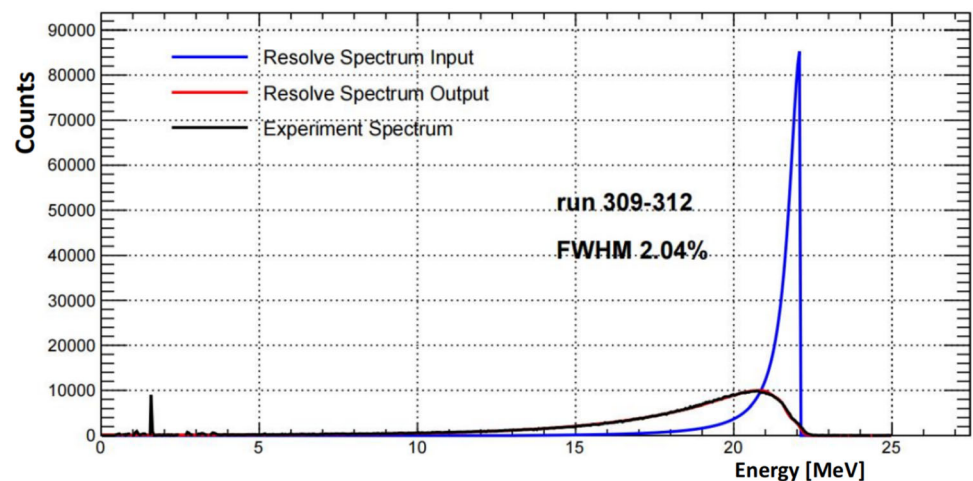


Fig. 10 Total gamma flux at the production point. The red dotted line is the theoretical calculated value with a 5 W laser and 300 mA electron current

4.4 Energy distribution of gamma-ray beams

The electron beam energy of the SSRF storage ring is 3.5 GeV. Because of this high electron beam energy, the energy of the gamma-ray beams produced in the laser Compton scattering strongly depends on the emission angle. Thus, the energy spread (resolution) of the gamma-ray beam is highly sensitive to the angular acceptance, defined by the collimator aperture. The black line in Fig. 11 shows the experimental response function of the LaBr₃(Ce) detector to gamma rays produced in backscattering at 180°. Assuming that the energy distribution of the gamma-ray beam incident on the detector is given by a truncated Breit–Wigner function, which is indicated by the blue line, we performed a Geant4 simulation of the response function of the LaBr₃(Ce) detector to the gamma-ray beam. The results are indicated by the red line in Fig. 11. It is clear that the Geant4 simulation reproduces the experimental response function well (black line). Phenomenologically, as the scattering angle decreases in slant-scattering mode, the incident gamma-ray spectra of

Fig. 11 (Color online) Experimental response function of the $\text{LaBr}_3(\text{Ce})$ detector to a gamma-ray beam produced in backscattering mode at 180° (black line), a truncated Breit–Wigner function (blue line) assumed for the energy distribution of the gamma-ray beam, and a Geant4 simulation of the $\text{LaBr}_3(\text{Ce})$ response function (red line) to the gamma-ray beam (blue line)



the Gaussian function better fit the experimental response function in the Geant4 [30] simulation. In this phenomenological study, it was found that an energy resolution of 2–15% could be obtained with a collimator aperture of 1–3 mm.

A thorough study of the energy resolution of the gamma-ray beam requires more realistic Geant4 simulations, in which gamma-ray beams are kinematically produced in laser Compton scattering, transported through the collimator system, and incident on the $\text{LaBr}_3(\text{Ce})$ detector. The energy distribution of the gamma-ray beam produced in laser Compton scattering depends on the electron beam emittance, which is an important parameter for reproducing the experimental response function. A thorough analysis using more realistic Geant4 simulations will be conducted in the near future.

4.5 Experimental spectrometers

We have developed four types of experimental spectrometers (sometimes called detector arrays), as shown in Fig. 12: a gamma nuclear resonance fluorescence (NRF) spectrometer, neutron flat-efficiency detector (FED) spectrometer, neutron time-of-flight (TOF) spectrometer, and light charged particle (LCP) spectrometer. The four experimental spectrometers are used for the photon elastic/inelastic scattering reaction, photoneutron reaction, and photolight charged particle reaction, respectively. The spectrometer for the photofission reaction is not involved in the current construction stage. The photonuclear reaction experiment can also employ a combination of two spectrometers, such as FED combined with an NRF spectrometer, which will be used in the $(\gamma, n\gamma)$ experiment [31].

The NRF gamma spectrometer consists of two large-volume coaxial HPGe detectors, two clover HPGe detectors [32], and eight $3''$ (76.2 mm) $\times$ $4''$ (101.6 mm) $\text{LaBr}_3(\text{Ce})$ detectors [28]. The neutron FED consists of

twenty-six ^3He counters [33] embedded in a polyethylene moderator [34]. The TOF neutron spectrometer consists of twenty $\Phi 5''$ (127 mm) $\times$ $2''$ (50.8 mm) EJ301 [35] liquid scintillation detectors. The LCP (p,d,t, α) spectrometer consists of 4–6 groups E–E telescope detectors comprising a grid ionization chamber (GIC) [36], silicon strip detector (SSD) [37], and CsI (Tl) crystal [36] mounted in a large high-vacuum experimental chamber, as shown in Fig. 12d.

5 Results of the commissioning of the SLEGS beamline

The SLEGS beamline started the first test run at a small electron beam current of 10 mA in July 2021 and finished the debugging of the gamma beam generation in the back-and slant-scattering modes at 200 mA. The performance of the SLEGS beamline in generating gamma-ray beams and the experimental spectrometer was approved by the Chinese Academy of Sciences (CAS) [38] in December 2021, completing the construction of the SLEGS beamline station. The results obtained during the commissioning run are summarized in Table 1.

Table 2 shows the situation of several LCS facilities worldwide and a comparison of the main gamma parameters. Currently, only $\text{HI}\gamma\text{S}$ and SLEGS can provide MeV gamma rays for nuclear physics research.

6 Summary and prospects

The completion of the SLEGS beamline station was approved by the Chinese Academy of Sciences (CAS) in December 2021 after the successful commissioning run. Gamma-ray beams are produced in the energy range from 0.25 to 21.1 MeV in the laser Compton slant-scattering mode with $10.64 \mu\text{m}$ CO_2 laser photons at scattering angles



Fig. 12 (Color online) Four types of experimental spectrometers available in the SLEGS experimental station: gamma nuclear resonance fluorescence spectrometer (a), neutron flat-efficiency

detector spectrometer (b), neutron time-of-flight spectrometer (c), and light charged particle spectrometer (d)

from 20° to 160° , and at a maximum energy of 21.7 MeV in laser Compton backscattering mode at 180° . The slant-scattering mode is employed in the SLEGS beamline to systematically produce gamma-ray beams.

Two-stage coarse and fine collimators are used to produce fine pencil-like quasi-monochromatic gamma-ray beams. The gamma-ray integrated flux is 2.1×10^4 photons/s at 20° , 2.5×10^6 photons/s at 90° , and 1.2×10^7 photons/s at 180° . The energy spread of the gamma-ray beam is 2–15% when the gamma-ray emission angle is confined to less than 0.45 mrad at 38 m using the

collimator system. Four types of spectrometers, which may reflect the versatility of nuclear physics experiments [39–44], are available at the SLEGS experimental station. The SLEGS beamline will be open to users by the end of 2022. In recent years, some large nuclear scientific facilities have started construction and been put into operation, including the back-streaming neutron (Back-n) source [45, 46] at the China Spallation Neutron Source (CSNS), the High-Intensity Heavy-ion Accelerator Facility (HIAF) [47–49] and CSR External-target Experiment (CEE) [50], Collinear Laser Spectroscopy (CLS)[51, 52], and the new

Table 1 Commissioning results for SLEGS

Commissioning item	Final measured results
<i>Beamline</i>	
Energy	0.25–21.7 MeV
Resolution	~ 2–15% (with collimator)
Full-spectrum integrated gamma flux	~ 2.1×10^4 photons/s at 20° ~ 2.5×10^6 photons/s at 90° ~ 1.2×10^7 photons/s at 180° (for 300 mA e- and 5 W CO ₂ laser)
Angular divergence	< 0.45 mrad
<i>Experimental station</i>	
Charged particle Detector	Energy resolution < 0.5% at 5.5 MeV Position resolution ≤ 2 mm
High-efficiency gamma detector	Energy resolution < 0.3% at 662 keV Relative efficiency > 94%

Table 2 Current operation of LCS facilities around the world

Facility/LCS name	Collision mode	Energy range	Gamma flux	Energy resolution	Current operating status
TUNL/HI γ S (USA)	BCS	1–100 MeV	10^{6-9} phs/s	(0.8–10)%	1996-, open
SSRF/SLEGS (China)	BCS/SCS	0.25–21.7 MeV	10^{5-8} phs/s	< 5% @ 2 mm	2022-, open
ELI-NP/VEGA (Europe)	BCS	0.2–19.5 MeV	~ 2.5×10^8 phs/s @ 10 MeV	≤ 0.5 @ 2 mm	Under construction
NewSUBARU/BL01 (Japan)	BCS	1–76 MeV	~ 10^7 phs/s	~ 10% @ 3 mm	2007-, LCS, limited operation
UVSOR-III/BL01 (Japan)	BCS/SCS	1–5.4 MeV	~ 10^7 phs/s	~ 2.9% @ 2 mm	2015-, open
SPRING-8 /LEPS&LEPS2 (Japan)	BCS	1300–2900 MeV	10^{6-7} phs/s	< 15% @ tagging	1999-, open

BCS back Compton scattering mode, SCS slant Compton scattering mode

Beijing Radioactive Ion-beam Facility (BRIF) [53]. The completion of these facilities or devices will surely push China's nuclear physics basic and applied research to the next level.

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Author contributions All authors contributed to the study conception and design. Material preparation, and data collection and analysis were performed by Long-Xiang Liu, Hang-Hua Xu, Long-Long Song, Xi-Guang Cao, Zi-Rui Hao, Kai-Jie Chen, Sheng Jin, Yu-Xuan Yang, Xin-Rong Hu, Xin-Xiang Li, and Pan Kuang. More scientific guidance by Wen-Qing Shen and Yu-Gang Ma. The first draft of the manuscript was written by Hong-Wei Wang, Gong-Tao Fan, and Hiroaki Utsunomiya, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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