Construction and Commissioning of the Shanghai Laser Electron Gamma Source

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Abstract

This paper describes the construction and commissioning status of the Shanghai Laser Electron Gamma Source (SLEGS) beamline station, one of the projects under the Shanghai Synchrotron Radiation Facility beamline initiative. The SLEGS gamma source facility supports fundamental research in nuclear physics, nuclear astrophysics, and other fields, as well as applied research such as gamma irradiation, gamma imaging, and gamma activation. The SLEGS beamline station passed its technical acceptance in December 2021, entered the commissioning phase in October 2022, and opened for user operations in September 2023. SLEGS is the world' s first facility to continuously tune gamma beam energy by varying the collision angle, featuring superior energy scanning precision, flux density, and efficient energy tuning capability. During the commissioning phase, the SLEGS beamline station focused on resolving online monitoring challenges for gamma beam energy spectrum and flux intensity, primarily accomplished experimental methodology studies for measuring photoneutron cross-sections using a Flat Efficiency Detector (FED), and conducted expansion and research on application platforms such as gamma imaging, gamma activation, and positron production. With the advancement of inverse Compton scattering technology and growing application demands, future laser Compton scattering light sources featuring short pulses, high polarization, high flux, and miniaturization will see enhanced development opportunities and will play a significant role in gamma source application research fields including nuclear physics, astrophysics, particle physics, polarization physics, as well as aerospace, medical detection, and energy development.

Full Text

Preamble

Article Title: Construction and Trial Operation of the Shanghai Laser Electron Gamma Source

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Abstract

This paper introduces the construction and trial operation of the Shanghai Laser Electron Gamma Source (SLEGS) beamline, a project of the Shanghai Synchrotron Radiation Facility (SSRF) Phase II. The SLEGS gamma source facility enables fundamental research in nuclear physics and nuclear astrophysics, as well as applied studies in gamma irradiation, gamma imaging, and gamma activation. The SLEGS beamline passed technical acceptance in December 2021, entered the trial operation phase in October 2022, and opened to users in September 2023. SLEGS is the world' s first laser Compton scattering gamma source to employ continuously variable collision angles for tuning gamma beam energy, offering the best energy scanning precision, flux density, and efficient energy regulation capability.

During the trial operation phase, the SLEGS beamline focused on solving the challenge of online monitoring of gamma beam energy spectra and intensity. The primary achievements include the development of experimental methodologies for measuring photoneutron cross-sections using a flat-efficiency detector (FED), as well as the expansion and investigation of application platforms for gamma imaging, gamma activation, and positron production. With the advancement of inverse Compton scattering technology and growing application demands, future short-pulse, high-polarization, high-flux, and compact laser Compton scattering sources will encounter better development opportunities and play important roles in gamma source applications across nuclear physics, astrophysics, particle physics, polarization physics, aerospace, medical testing, and energy development.

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1. Introduction

Following the invention of the laser in the 1960s, the concept of generating high-energy photons through laser collisions with relativistic electrons was proposed [1]. In 1978, Italy built the first laser Compton scattering (LCS) based gamma source facility, LADON [2]. Around 1984, the United States constructed the high-energy gamma facility LEGS [3], while Japan simultaneously built an LCS beamline based on the synchrotron radiation facility TERAS [4]. Subsequently, the United States established facilities including HIγS@TUNL [5], PLEIADES@LLNL [6], and T-RAY/M-RAY@LLNL [7]. After the 1990s, Japan successively built laser electron gamma source beamlines based on synchrotron radiation facilities SPring-8 [8], SAGA [9], UVSOR-II/III [10], and NewSUBARU [11]. Spain [12] and Canada [13] proposed similar LCS gamma source beamline concepts for their synchrotron radiation facilities, though these were never approved for construction. In 2016, the European Union proposed the ELI-NP project [15], which planned to construct an inverse Compton scattering gamma source branch (GBS) based on a linear electron accelerator; this was renamed VEGA in 2020 and remains under construction.

The SLEGS beamline was constructed based on the Shanghai Synchrotron Radiation Facility (SSRF). In 2016, it received approval from the National Development and Reform Commission as one of 16 beamlines in the SSRF Phase II project [16]. Construction began in 2018, with completion and acceptance at the end of December 2021. Trial operation commenced in the second half of 2022, and the facility opened to users in September 2023 [17]. Similar domestic facilities include Tsinghua University' s compact VIGAS project [19], currently under construction following the TTX facility [18], and the photon collider conceptual design based on laser Compton scattering principles at the Institute of

High Energy Physics, Chinese Academy of Sciences [20-23]. In August 2023, Sun Yat-sen University' s feasibility study report for the "Gamma Photon Collider and Comprehensive Beam Facility (Phase I) Verification Device" was approved by the Ministry of Education. presents the main operational parameters and status of current international laser Compton scattering gamma source facilities.

Table 1. Operational Status of Laser Compton Scattering Gamma Source Facilities Worldwide
(BCS = Backward Compton Scattering; SCS = Slanting Compton Scattering)

Facility	Country	Mode	Energy Range	Energy Resolution	Flux (phs/s)	Status
HIγS	USA	BCS	~10^7	~5%@2mm	1996–present, operational [5]	
SLEGS	China	BCS/SCS	0.25-21.7 MeV	<1.5%@Collimator	2022–present, operational [16,17]	
VIGAS	China	BCS	-	<1.5%@Collimator	2025–, under construction [19]	
UVSOR-III LCS	Japan	BCS/SCS	-	~2.9%@2mm	2012–present, operational/applications [10]	
ELI-NP/VEGA	Europe	BCS	-	~0.5%@2mm	2023–, under construction [15]	
NewSUBARU-B01	Japan	BCS	-	~10%@3mm	2005-2021, partially closed [11]	
LEPS/LEPS2	Japan	BCS	-	<15%@tagging	1999/2013–present, operational [8]	

In 2009, a U.S. Department of Energy technical report [24] identified laser Compton scattering gamma sources as one of the four most promising future light sources, alongside synchrotron radiation and free-electron lasers, which already have multiple operational and under-construction facilities. Energy recovery linacs and laser Compton scattering gamma source facilities have gained increasing attention. In recent years, laser Compton scattering gamma sources have evolved toward application-oriented [25], free-electron laser dedicated [26], and linear accelerator + small ring + laser external cavity configurations [27]. Future compact laser Compton scattering gamma source facilities for applications will be the preferred choice.

Such quasi-monoenergetic gamma sources can conduct photonuclear reaction studies to reveal nuclear properties and nuclear force interactions, discover new collective motion phenomena, and explore the origin of heavy elements in the universe. Photonuclear reaction data are widely needed for reactor safety, medical testing, aerospace, and national defense. However, current photonuclear reaction research faces several challenges [28-29]:

1. Insufficient experimental photonuclear reaction research. In 2019, the International Atomic Energy Agency compiled 219 photonuclear reaction experimental datasets, with fewer than 60 added in the subsequent 20 years. Most photonuclear reaction cross-sections suffer from large errors and low precision.
2. In terms of applications, only the United States has built irradiation and medical isotope production platforms, while Europe is planning gamma irradiation and positron source facilities.
3. China has lacked suitable gamma source facilities, resulting in a gap in photonuclear reaction experimental research in recent years, with insufficient experimental techniques and talent in this field.

2. SLEGS Facility Overview

SLEGS employs an externally introduced CO_2 laser with 10.64 m wavelength and the 3.5 GeV electron beam from the SSRF storage ring, colliding at variable angles from 20° to 160° to generate gamma beams through inverse Compton scattering. Gamma energy is continuously tuned by varying the collision angle. High-energy and high-polarization gamma beams are produced through 180° Compton backscattering. The SLEGS layout is shown in [Figure 1: see original paper] [30].

[Figure 1: see original paper] *Schematic layout of the SLEGS facility. Inside the sawtooth shielding wall are the interaction chamber, multi-pass assembly, and coarse collimator. Outside are the fine collimator, attenuator, and experimental terminals.*

Table 2. Current Operational Parameters of SLEGS

Parameter	Value
Gamma energy range	0.25–21.7 MeV
Energy resolution	~5% (with collimator)

Parameter	Value
Integrated gamma flux	2.14$×10^{4}$ phs/s@20° to 2.45$×10^{6}$ phs/s@90° to 1.20$×10^{7}$ phs/s@180°
Angular divergence	0.38 mrad
Charged particle detector	Energy resolution 0.52%@5.5 MeV, position resolution 2 mm
High-efficiency gamma detector	Energy resolution 0.282%@662 keV, relative efficiency 95.5%

SLEGS is an independently developed, high-performance quasi-monoenergetic gamma source beamline in the MeV energy range. It is the world' s first laser Compton gamma source employing continuous angle-variation for rapid gamma beam energy switching. The SLEGS beamline comprises three systems: the source system, beamline system, and experimental station system.

The source system includes key components: the interaction point target chamber with internal laser optics, multi-pass assembly, and external laser beamline. The interaction point target chamber is located in the C03 short straight section of the storage ring, providing approximately 1.8 m of insertion device space created by the SSRF Phase II superconducting magnet upgrade. Similar to other insertion devices, the laser enters vertically from the top of the chamber and is redirected via a zigzag optical table to collide horizontally with the electron beam. The collision angle can be continuously varied by adjusting the optical table inside the chamber.

The multi-pass assembly is a small target chamber in the front-end region between the storage ring exit and the shielding wall. Its water-cooled mirror redirects the laser by 90° for horizontal injection while allowing gamma beam, synchrotron radiation, and bremsstrahlung emission through a slitted water-cooled copper mirror. The external laser beamline transports the laser from the laser source outside the sawtooth wall to the collision point inside the storage ring through a ~1 Pa low-vacuum pipeline, incorporating modules for power monitoring, beam expansion, transmission, polarization control, and scanning/focusing [31].

The beamline system includes coarse and fine collimators, copper attenuators, and local shielding. The coarse collimator at the front-end region end inside the sawtooth wall uses a water-cooled beryllium window to isolate the high vacuum. It features a fixed aperture design, while the fine collimator employs a camera shutter mode [32]. Considering future energy selection via outgoing gamma angle, SLEGS is developing an annular collimator design [33]. The coarse collimator effectively utilizes the storage ring' s sawtooth wall shielding, with the fine collimator and attenuator placed behind the optics hutch and surrounded by enhanced local shielding to reduce environmental radiation dose.

The experimental station system is located in the experimental hutch, separated from the beamline' s ~0.01 Pa low vacuum by an atmospheric beryllium window. Spectrometers typically operate under atmospheric conditions (except for photon-induced charged particle spectrometers). Four main types of photonuclear reactions are studied:

1. **(γ,γ/γ) reactions**: Configured with a Nuclear Resonance Fluorescence (NRF) gamma spectrometer consisting of two large coaxial High-Purity Germanium (HPGe) detectors, two HPGe CLOVER detectors, and eight large $LaBr_3$ detectors. Detailed parameters are in reference [34].
2. **(γ,n) reactions**: Configured with a ^{3}He flat-efficiency (FED) neutron spectrometer comprising 26 ^{3}He proportional counters filled to 2 atm, arranged in three concentric circles within a polyethylene moderator, achieving ~35–45% average efficiency at 1 keV–6 MeV. Detailed parameters are in reference [35]. Additionally, a Time-of-Flight (TOF) neutron spectrometer consists of 20 large liquid scintillator neutron detectors (EJ301) and eight $LaBr_3$ detectors, with details in reference [36].
3. **(γ,p/α) reactions**: Configured with a Light Charged Particle (LCP) spectrometer comprising 4–6 sets of Gridded Ionization Chambers (GIC), silicon microstrip detectors, and 3$\times$3 CsI arrays as telescope detectors, housed in a large vacuum target chamber. Telescope unit testing has been completed.
4. **(γ,Fission) reactions**: Currently not considered for measurement at SLEGS.

Each spectrometer is equipped with independent detector electronics and waveform digitizers from CAEN (CoMPASS), Mesytec (MVME), and a self-developed data acquisition system [37], enabling up to ~120 channels of waveform sampling.

3. SLEGS Research Platforms

The scientific objectives of SLEGS are to conduct fundamental research in nuclear astrophysics, nuclear physics, and polarization physics through photonuclear reactions, particularly addressing major scientific questions of significant value. The facility also performs application-oriented basic research related to strategic needs in aerospace, defense, and nuclear energy, including precise calibration of aerospace gamma detectors, investigation of key photonuclear cross-sections for nuclear energy, and studies of nuclear waste transmutation cross-sections. SLEGS is expected to become a multifunctional experimental platform integrating basic and applied physics.

Key research directions include: 1. Investigating the mechanism of heavy element production in stellar evolution—one of the 11 unsolved problems in physics. 2. Precise measurement of resonance and cluster structures—a natural laboratory for testing nuclear many-body theory and nuclear forces. 3. Research on gamma transmutation of nuclear energy and waste—a strategic requirement for national sustainable energy development. 4. Studying reaction product polarization angular distributions using polarized gamma beams—an important tool for fundamental symmetry research.

To expand the comprehensive applications of SLEGS' s quasi-monoenergetic gamma beams, the beamline also incorporates applied research platforms:

1. **Device irradiation effects platform**: With rapid development in semiconductors and microelectronics, new materials, structures, processes, and physical principles are being applied in device fabrication, creating urgent demand for radiation effects research. This requires continuous, tunable monoenergetic irradiation sources covering application-relevant particle energy spectra and dose rates to study device radiation effects under different radiation types, energies, and dose rates.

2. **MeV-energy tunable positron source platform**: Pair production from gamma-matter interaction provides a method for generating fast positron sources. When gamma photon energy exceeds twice the electron rest mass (1.022 MeV), gamma photons convert to electron-positron pairs in atomic nuclear Coulomb fields. Positron annihilation spectroscopy is a non-destructive detection method at atomic scales.

3. **High-energy gamma detector calibration platform**: Current calibration of gamma detectors above 3 MeV primarily uses radioactive isotope standard sources. Monoenergetic de-excitation gamma rays from accelerator (p,γ) reactions can also be used, but this method has limited energy range and points and requires extensive accelerator beam time. SLEGS provides continuously tunable gamma beams from 3–21.7 MeV for energy calibration.

4. **Gamma imaging technology platform**: Using X-ray-sensitive silicon pixel detectors (MiniPIX) and gamma beam spot monitors (GSM), SLEGS can conduct gamma imaging and related technology research.

5. **Gamma activation technology platform**: Gamma activation can excite stable targets into radioactive isotopes that emit characteristic gamma rays measured by low-background HPGe detectors, enabling determination of activation beam intensity or target nucleus cross-sections.

Additionally, SLEGS can conduct applied research on gamma transmutation key technologies. As a complement to neutron transmutation, gamma transmutation is highly effective for specific high-level radioactive wastes such as ^{131}I. Combined neutron-gamma transmutation can significantly improve overall transmutation efficiency.

4. SLEGS Construction and Commissioning

The SLEGS laser optical path is divided into external and internal sections. The external path includes the CO_2 laser, He-Ne alignment laser, laser power monitor, beam expansion and focusing optics, and polarizer. To avoid air turbulence effects, the external path is designed as a low-vacuum pipeline transporting the beam 20 meters into the storage ring' s collision point target chamber and multi-pass assembly. [Figure 2: see original paper] shows the SLEGS optical system schematic.

[Figure 2: see original paper] *Schematic of the SLEGS optical system, divided into internal and external optical paths.*

[Figure 3: see original paper] displays engineering designs and site photos of four experimental spectrometers: Nuclear Resonance Fluorescence (NRF) gamma spectrometer [31], Flat-Efficiency (FED) neutron spectrometer [32], Time-of-Flight (TOF) neutron spectrometer [33], and Light Charged Particle (LCP) spectrometer. Due to limited space at the experimental station, SLEGS detectors are arranged compactly, as shown in [Figure 4: see original paper] (wide-angle view from left to right): TOF scintillator detectors, FED spectrometer and electronics rack, $LaBr_3$ detectors, X-ray beam spot monitor (MiniPIX), gamma beam spot monitor (GSM), and gamma beam absorber at the beamline end.

[Figure 3: see original paper] *Engineering designs (top) and corresponding site photos (bottom) of the NRF, FED, TOF, and LCP spectrometers.*

[Figure 4: see original paper] *Site photo of TOF and FED spectrometer layout in the SLEGS experimental hutch (wide-angle view): A) TOF spectrometer stand with EJ301 scintillator detectors, B) FED spectrometer stand and electronics rack, C) Partial $LaBr_3$ detectors and stand for NRF spectrometer, D) GSM beam spot monitor, and E) gamma beam dump.*

On December 25, 2021, SLEGS completed technical acceptance testing and entered the trial operation phase [27]. Initial commissioning included beam intensity and energy spectrum measurements at different collision angles (corresponding to gamma energies), with 1° rotation corresponding to 0.25 keV energy change:

1. **Precise gamma spectrum and flux measurement with spectral deconvolution**: As shown in [Figure 5: see original paper] (top left), gamma yield (flux) distributions were measured at different laser powers (5 W/100 W) with 200 mA electron beam current. The 5 W measurement shows ~10^5 phs/s with a 2 mm coarse collimator aperture and ~10^6 phs/s with a 3 mm aperture; the 100 W curve is equivalent calculation, with dashed lines showing theoretical simulation results. The top right panel shows measured gamma spectra at different angles ($LaBr_3$ measurement). Bottom panels compare simulated gamma spectral deconvolution with actual $LaBr_3$ measurements at 90° and 180°.

[**Figure 5: see original paper**] *Flux and spectral analysis from SLEGS commissioning: (a) gamma yield distribution, (b) gamma spectra at different angles, (c) 90° gamma spectrum deconvolution, and (d) 180° gamma spectrum deconvolution.*

2. **Photoneutron cross-section measurement methodology, gamma activation, and gamma imaging research**: Using the ^{3}He-based FED spectrometer, systematic methodological studies of photoneutron measurements were conducted ([Figure 6: see original paper]a, 6b), including neutron detection efficiency calibration, gamma flux verification via activation measurement, experimental hutch background elimination, and neutron spectrum deconvolution. Photoneutron cross-section measurements have been completed at multiple angles with a 2 mm coarse collimator, with further data analysis ongoing. Additionally, SLEGS has conducted methodological studies on gamma activation and imaging ([Figure 6: see original paper]c, 6d), with results to be published separately.

[**Figure 6: see original paper**] *Photoneutron cross-section measurement (a,b), gamma activation analysis (c), and gamma imaging (d, imaging of a hollow lead pendant) during SLEGS commissioning.*

5. User Access and Future Prospects

SLEGS opened for user proposals in March 2023. Proposals can be submitted anytime, with two annual review deadlines: March 31 (for beam time allocation July-December) and September 31 (for January-June). The SSRF user proposal process is:

1. Register at the “CAS Major Scientific Infrastructure Sharing Service Platform” : https://lssf.cas.cn
2. Select “Facility Display” → “Public Research Facilities” → “Shanghai Synchrotron Radiation Facility”
3. Follow the “Research User Login/Register” prompt at the top right
4. After login, select “New Proposal” and choose Regular/Key/Emergency Proposal
5. Complete the research content form and affix official institutional seal

SLEGS Technical Innovations: 1. First laser Compton scattering facility with both slanting incidence and backscattering operation modes. 2. First “slanting incidence”mode facility with large-angle adjustment capability. 3. Best energy scanning precision, flux density, and flux stability.

SLEGS construction has promoted cross-fusion of accelerator and laser technologies, expanding their application fields. This enables precise experimental measurement of storage ring electron beam energy spread and other key parameters, real-time monitoring of storage ring vacuum, orbit, and other operational parameters, and precise experimental measurement of high-power focused laser spot size and profile, providing reference for ultra-long-distance laser transmission stability control.

Future Plans for SLEGS and Photonuclear Physics Research: 1. Conduct batch photoneutron cross-section measurements (GDR energy region) and resonance fluorescence measurements to enrich photonuclear databases with direct Chinese measurements. 2. Develop gamma irradiation effects, gamma detector calibration, gamma positron production, gamma activation, and gamma transmutation application platforms for technology development and national needs. 3. Conduct key technology research for next-generation laser Compton scattering gamma sources, planning construction of internationally leading laser electron gamma sources at the Soft X-ray Free Electron Laser (SXFEL) and Hard X-ray Free Electron Laser (SHINE) facilities.

References

[01] ARUTYUNYAN F R, TUMANYAN V A. Phys Lett, 1963, 4: 176.
[02] MATONE G, PICOZZA P, PROSPERI D, et al. Lecture Notes in Physics, 1977, 62: 149.
[03] SANDORFI A M, LEVINE M J, THORN C E, et al. IEEE T Nucl Sci, 1984, 30: 3083.
[04] OHGAKI H, TOYOKAWA H, KUDO K et al. Nucl Instr and Meth A, 2000, 455: 54.
[05] WELLER H R AND AHMED M W. Mod. Phys Lett. A, 2003, 18: 1569.
[06] GIBSON D J, ANDERSON S G, BARTY C P J, et al. Phys Plasmas, 2004, 11: 2857.
[07] GIBSON D J, ALBERT F, ANDERSON S G, et al. Phys Rev ST Accel Beams, 2010, 13: 070703.
[08] NAKANO T, EJIRIA H, FUJIWARA M ,et al. Nucl Phys A, 1998, 629: 559c.
[09] KANEYASU T, TAKABAYASHI Y, IWASAK Y, KODA Y, et al. Nucl Instr and Meth A, 2011, 659: 30.
[10] ALBERT F, ANDERSON S G, GIBSON D J, et al. Phys Rev ST Accel Beams, 2011, 14: 050703.
[11] AMANO S, HORIKAWA K, ISHIHARA K, et al. Nucl Instr and Meth A, 2009, 602: 337.
[12] TAIN J L, LALLENA A M, EBRAHIM M, et al. Proposal for the Construction of a Gamma-Ray Beam Line at the Spanish Synchrotron ALBA, December, 2004.
[13] WURTZ W A. Considerations for the Construction of a Gamma ray Beam Line at the Canadian Light Source. Canadian Light Source, Apr 22, 2010.
[14] AHNA J K, KIM E S. Nucl Instr and Meth A, 2004, 528: 600.
[15] HABS D, TAJIMA T, ZAMFIR V. Nuclear Physics News, 2011, 21: 23. and ELI-NP White Book, http://www.eli-np.ro/documents/ELI-NP-WhiteBook.pdf
[16] WANG Hongwei, FAN Gongtao, LIU Longxiang, et al. Nuclear Physics

Review, 2020, 37(1):53-63(in Chinese). doi: 10.11804/NuclPhysRev.37.2019043
[17] WANG H W, FAN G T, LIU L X, et al. NUCL SCI TECH (2022) 33:87, https://doi.org/10.1007/s41365-022-01076-0
[18] DU Yingchao, HUANG Wenhui, YAN Lixin, et al. High Power Laser and Particle Beams, 2009, 21(2): 265. (in Chinese)
[19] Du Yingchao, Chen Han, Zhang Hongze, et al. High Power Laser and Particle Beams, 2022, 34: 104010. doi: 10.11884/HPLPB202234.220132(in Chinese)
[20] AN Guangpeng, CHI Yunlong, DANG Yongle, et al. Matter and Radiation at Extremes 3(4), 2018: 219. doi.org/10.1016/j.mre.2018.01.005
[21] Guangyi Tang, Shanhong Chen, Yuan Chen et al. Rev Sci Instr,1 March 2020; 91 (3):033109. doi.org/10.1063/1.5132975
[22] Si M, Chen S, Huang Y, et al. Eur Phys J D 76, 63 (2022). doi.org/10.1140/epjd/s10053-022-00389-4
[23] Takahashi T., An G, Chen Y, et al. Eur Phys J C 78, 893 (2018). https://doi.org/10.1140/epjc/s10052-018-6364-1
[24] U S Department of Energy, Oct 27, 2008，Next-Generation Photon Sources for Grand Challenges in Science and Energy. United States, 2009. Web. doi:10.2172/964403.
[25] Graves W S, Bessuille J, Brown P, et al. Phys. Rev. ST Accel. Beams 17, 120701 (2014), doi.org/10.1103/PhysRevSTAB.17.120701
[26] Weller Henry R, Ahmed, Mohammad W, Gao Haiyan, et al. Progress in Particle and Nuclear Physics 62 (2009) 257 -303, doi.org/10.1016/j.ppnp.2008.07.001
[27] Tanaka K A, SpohrK. M, Balabanski D L, et al. Matter and Radiation at Extremes 5, 024402 (2020), doi.org/10.1063/1.5093535
[28] Kawano T, Cho Y S, Dimitriou P, et al. January 2020, Pages 109-162, doi.org/10.1016/j.nds.2019.12.002
[29]GE Zhigang, XU Ruirui, WU Haicheng, et al. EPJ Web of Conferences 239, 09001 (2020), doi.org/10.1051/epjconf/202023909001
[30] WANG Hong-Wei, FAN Gong-Tao, LIU Long-Xiang, et al. Nucl Sci Tech (2022) 33:87, doi.org/10.1007/s41365-022-01076-0
[31] XU H H, FAN G T, WANG H W, et al. Nucl Instr Meth Phys A 1033, 166742 (2022), doi.org/10.1016/j.nima.2022.166742
[32] HAO Z R, FAN G T, WANG H W, et al. Collimator system of SLEGS beamline at SSRF. Nucl Instr Meth A 1013, 165638 (2021), doi.org/10.1016/j.nima.2021.165638
[33] HAO Z R, FAN G T, WANG H W, et al. A new annular collimator system of SLEGS beamline at SSRF. Nucl Instr Meth B 519, 9–14 (2022), doi.org/10.1016/j.nimb.2022.02.010
[34]KUANG Pan, SONG Longlong, CHEN Kaijie, et al. Nuclear Physics Review, 2023, 40(1):58-65. doi: 10.11804/NuclPhysRev.40.2022040(in Chinese)
[35] HAO Z R, FAN G T, LIU L X, et al. Nuclear Techniques 43, 57–65 (2020). doi.org/10.11889/j.0253-3219.2020.hjs.43.110501(in Chinese)
[36]CHEN Kai-Jie, LIU Long-Xiang, HAO Zi-Rui, et al. Nucl Sci and Tech (2023) 34:47, doi.org/10.1007/s41365-023-01194-3
[37] LIU Longxiang, WANG Hongwei, HAN Jianlong, et al. Automatic Data

Acquisition System, Patent No.: ZL-2016-1-008934.7, authorized March 20, 2020

Note: Figure translations are in progress. See original paper for figures.