Research on Positron Beams Based on the Shanghai Laser Electron Gamma Source

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Abstract

This study investigates two positron beam generation methods based on the Shanghai Laser Electron Gamma Source (SLEGS). Using the Monte Carlo program Geant4, we simulated positron target selection, deflection magnet and focusing system configurations, background interference and suppression for both single-target magnetic field separation and multi-target lateral extraction modes. Based on the simulation analysis, we optimized the positron beam generation parameters to obtain high-quality MeV-level positron beams at SLEGS and construct a positron beam application platform, extending SLEGS research to positron beam annihilation experiments and other application fields. Under conditions of SLEGS gamma-ray energy continuously tunable from 0.66-21.7MeV and gamma beam intensity of ~107 photons/s, the single-target magnetic field separation mode yielded positron beams with energy range of 1.0- 12.9 MeV and flux density of 102- 103 e+/s/cm2. The optimized solenoid multi-target lateral extraction mode provides the positron beam with better flux and energy resolution, and can effectively avoid the influence of gamma background, finally obtaining positron energy range of 1.0 MeV- 9.1 MeV and flux density of ∼103 - 105e+/s/cm2. Experimentally measured SLEGS positron annihilation yield and gamma-ray angular distribution, the LaBr3(Ce) detector measured full-space positron annihilation gamma rays of approximately 2.5\$$\times 108 photons, whilethesimulationcalculationcollected 2.47\times 108 photonsof 511 keV raysin 4$ \$ solid angle, consistent with simulation results within error range, verifying the reliability of the simulation analysis. The paper also presents the detector and electronics layout for SLEGS positron annihilation lifetime spectrum measurement, as well as preliminary experimental research. Future considerations include extracting more accurate start time signals from storage ring accelerators, short-pulse lasers, and other methods to obtain precise positron

annihilation lifetime spectra.

Full Text

Positron Beam Production Study at Shanghai Laser Electron Gamma Source

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Abstract

Positron beams have extensive applications, most notably as probes for nondestructive testing (NDT) to study submicroscopic defects such as dislocations and vacancies. Positron annihilation techniques provide insights into the kinetic energy and density distributions of materials. Pair production from gamma-matter interactions represents one of the most effective methods for generating positron beams. This study investigates two positron production methods based on the Shanghai Laser Electron Gamma Source (SLEGS) at the Shanghai Synchrotron Radiation Facility (SSRF). Using Monte Carlo simulations with Geant4, we optimized target selection, deflection magnet and focusing system configurations, and background interference suppression for both single-target magnetic separation and multi-target lateral extraction modes. Based on these simulations, we optimized positron beam generation parameters to obtain high-quality MeV-energy positron beams and establish a positron beam application platform, extending SLEGS research to positron annihilation spectroscopy and related applications.

With SLEGS gamma-ray energy continuously tunable from 0.66–21.7 MeV and beam intensity of ~10^7 photons/s, the single-target magnetic separation mode yields positron beams with energies ranging from 1.0–12.9 MeV and flux densities of 10^2–10^3 $e^+/s/cm^2$. The optimized solenoid-based multi-target lateral extraction mode provides superior beam intensity and energy resolution while effectively eliminating gamma background contamination, producing positron beams with energies from 1.0–9.1 MeV and flux densities of ~10^3–10^5 e^+/s/cm^2. Experimental measurements of SLEGS positron annihilation yield and gamma-ray angular distribution using $LaBr_3$(Ce) detectors revealed approximately 2.5$×10^{8}$ annihilation photons in 4π space, in excellent agreement with the simulated value of 2.47$×10^{8}$ photons obtained from 4π solid angle collection. SLEGS positron annihilation lifetime-momentum correlation measurements indicate that accurate determination of positron start time remains challenging under current conditions. Future improvements will consider extracting timing signals from the storage ring RF system or using short-pulse laser triggering to obtain more precise start time signals, enabling reliable positron annihilation lifetime-momentum correlation spectroscopy.

Keywords: positron beam, Shanghai Laser Electron Gamma Source, Monte Carlo, non-destructive testing, Geant4

1 Simulation of Positron Beam Production at SLEGS

The beam intensity, energy spectrum, and signal-to-noise ratio of positron beams generated by gamma-ray injection into solid targets critically determine their suitability as positron sources. We employed the Geant4 Monte Carlo toolkit to simulate positron beam generation at SLEGS, analyzing key parameters affecting positron production from inverse Compton scattering gamma rays injected into solid targets, including target material, target thickness, magnetic field strength, field uniformity region, and post-target drift distance. These interdependent parameters were systematically optimized through simulation to identify optimal configurations for producing high-quality positron beams at specific gamma energies. By performing optimization simulations across multiple SLEGS energy points, we obtained a continuously energy-tunable positron beam and conducted detailed analyses of its intensity, energy spectrum, and signal-to-noise ratio.

1.1 Single-Target Magnetic Separation Simulation

When gamma rays interact with solid targets, Compton scattering, photoelectric effect, and pair production occur, with their relative contributions depending on the target atomic number and incident gamma energy. By selecting appropriate gamma energies and target materials, pair production can be made dominant. The resulting secondary particles—including electrons, positrons, scattered gamma rays, and unreacted gamma photons—are emitted within a forward cone, necessitating positron separation to establish a usable source. A dipole magnet placed downstream of the target deflects and collects positrons, with simulations optimizing magnetic field strength and field uniformity region. A free drift region after the magnet allows positrons to continue moving away from the high-background region upon exiting the magnetic field. Figure 1 illustrates the schematic of SLEGS gamma injection into a solid target for positron beam generation, with parameters optimized to maximize beam intensity and achieve optimal deflection and separation.

To validate our simulation against published results, we initially used gamma-ray parameters from NewSUBARU's 17 MeV experiment with lead targets. The simulated positron yields showed good agreement with experimental data, confirming the reliability of our simulation framework. We then adopted actual SLEGS gamma parameters for systematic optimization of positron production targets (material and thickness), deflection magnets (field strength and uniformity region), and post-target drift distances. Table 2 presents the optimized positron beam parameters for various SLEGS gamma energies. As gamma energy increases, the central positron beam energy increases correspondingly. With incident gamma energies ranging from 3.0–21.0 MeV at 10^{7} photons/s intensity, the positron beam central energy varies from 1.0 MeV to 12.9 MeV, with flux densities of 3.7$\$\times10^{\{2\}–7.0\times10}\{3\}\$$ e^{+}/s/cm^{2}. A square collimator with 15 mm aperture at the magnet edge confines the positron beam spot, yielding an energy resolution of approximately 40% (FWHM).

1.2 Multi-Target Lateral Extraction Simulation

The single-target magnetic separation approach exhibits several limitations: (1) low utilization efficiency of gamma rays in thin targets, with most photons passing through without interaction, while increasing target thickness reduces positron energy; (2) low beam intensity in the low-energy region due to reduced pair production cross-section; and (3) strong scattered gamma background that, despite deflection and drift separation, still compromises beam quality. Following the ELI-NP design concept, we replaced the single thick target with multiple thin targets. This configuration maintains gamma utilization efficiency along the beam axis while allowing positrons to exit through target gaps, avoiding energy degradation from thick targets. In the low-energy region where pair production cross-sections are inherently low, the multi-target approach significantly enhances positron yield.

Lateral positron collection from target gaps requires a deflection magnet to steer positrons vertically. Since scattered gamma photons exhibit strong forward collimation with minimal vertical distribution, optimizing the vertical collection distance effectively eliminates gamma background contamination. However, the large extraction area necessitates beam spot reduction, which we achieve using a solenoid focusing system in the simulation. Figure 2 (left) shows the Geant4 simulation geometry including SLEGS gamma rays, multi-target positron production, deflection magnet, and solenoid focusing system.

Table 3 presents the optimized positron beam parameters for various energies. The multi-target lateral extraction scheme dramatically improves beam intensity, particularly in the low-energy region where enhancements reach orders of magnitude. Figure 2 (right) shows the axial distributions of 1.2 MeV positrons and scattered gamma rays for solenoid field lengths of 30 mm and 100 mm. While solenoid length does not affect positron yield, it significantly reduces gamma background—a 100 mm solenoid suppresses scattered gamma background by one order of magnitude, with further improvements possible through additional length increases.

1.3 Thick-Target Positron Annihilation Simulation

An alternative research mode at LCS facilities involves direct injection of >1.022 MeV gamma beams into thick targets, where positrons produced along the beam path annihilate near defects in the target material. By measuring the time between gamma beam injection and arrival of 511 keV annihilation photons, Age-Momentum Correlation (AMOC) spectroscopy can probe atomic-scale defects and free-volume defects in polymers. Gamma-ray-induced AMOC (GiAMOC) offers several advantages over conventional AMOC: (1) defect analysis of centimeter-thick samples becomes possible since positrons are generated within the sample by penetrating gamma beams; (2) positrons annihilate both within the target and in surrounding materials, including detectors, complicating lifetime and Doppler broadening spectra analysis—requiring careful target thickness optimization; and (3) polarized gamma beams can produce highly polarized positrons for electron spin measurements. The typical GiAMOC experimental layout for LCS facilities is described in references [11,28]. At SLEGS, we will validate positron yield and angular distribution through this production and annihilation process.

2 Experimental Validation at SLEGS

We conducted experimental validation using SLEGS gamma beams injected into lead targets to produce positrons and their subsequent 511 keV annihilation photons. Multiple LaBr$_3$(Ce) detectors measured annihilation photon yield and angular distribution. Additional detectors including LaBr$_3$(Ce), CeBr$_3$, and BaF$_2$ were employed to study positron annihilation lifetime spectra through time and energy measurements.

2.1 Angular Distribution Measurement of Annihilation Photons

We performed test experiments measuring the angular distribution of positrons and their annihilation photons produced by SLEGS gamma rays. The Geant4 simulation modeled eight LaBr$_3$(Ce) detectors arranged at $\pi/4$ intervals covering 2π in the horizontal plane. As shown in Figure 3 (left), a 13 MeV, 7$×10^{4}$ photons/s gamma beam was injected into a 1 cm thick lead target. Detector dimensions and shielding materials matched experimental specifications. Using a thick lead target prevented positron escape, ensuring annihilation occurred within the target and produced 511 keV photon pairs. Counting 511 keV photons at different angles allowed reconstruction of positron yield. The experimental layout (top view) is shown in Figure 3 (right), using six LaBr$_3$(Ce) detectors from a nuclear resonance fluorescence spectrometer positioned horizontally relative to the target and beam axis, covering a solid angle of 0.028 with 40% efficiency.

Figure 4 presents the angular distribution simulation results, showing the symmetric relationship between angle and annihilation photon intensity, with enhanced vertical distribution. The simulation agrees well with experimental measurements. The six $LaBr_3$(Ce) detectors recorded 2.8$×10^{6}$ 511 keV counts, corresponding to approximately 2.5$×10^{8}$ annihilation photons in 4π space. The Geant4 simulation yielded 2.47$×10^{8}$ photons in 4π, consistent with experimental results within uncertainties.

2.2 Positron Annihilation Lifetime Spectrum Measurement

Positrons are unstable particles that thermalize through inelastic collisions with electrons, ions, and atoms within picoseconds, then diffuse until annihilation. The diffusion time (100–10,000 ps) constitutes the positron lifetime, which increases with defect size. Positron annihilation lifetime spectroscopy reveals material microstructure and has become an important NDT technique, with depth profiling achievable through energy variation. As a random process, lifetime determination requires statistical analysis of numerous annihilation events. The experimental setup for SLEGS positron annihilation lifetime-momentum correlation spectroscopy is shown in Figure 5.

SLEGS gamma beams produce positrons in targets where they annihilate. Multiple detectors and two data acquisition systems were employed: a LeCroy HDO 6104A 1 GHz digital oscilloscope and a TechnoAP positron DAQ system comprising APV8002 waveform processing modules, APV8702 time measurement modules, APV3003 high-voltage modules, and APV4004 amplifier power supplies. Tested detectors included BaF_2-1, BaF_2-2 (40 mm × 25 mm, domestic), BaF_2-3, BaF_2-4 (50 mm × 20 mm, Scionix), $CeBr_3$-1 (50.8 mm × 76.2 mm), and $LaBr_3$(Ce)-3 (50.8 mm × 50.8 mm).

Positron annihilation lifetime measurements used SLEGS gamma beams injected into 1 cm thick natural copper and lead targets. Signals were processed by oscilloscope and dedicated timing modules. Prior to experiments, time resolution of BaF_2-1 and BaF_2-2 detectors with APV8702 modules was measured using a ^{60}Co source, yielding ~182 ps FWHM (Figure 6, left). Start signals were derived from gamma injection time, while stop signals came from 511 keV annihilation photons, with their time difference representing positron lifetime. We attempted to obtain start timing from laser pulse triggers and direct measurement of scattered gamma rays. However, SLEGS currently operates with 50 s long CO_2 laser pulses colliding with multiple electron bunches, producing gamma rays with 50 s temporal jitter that prevents accurate start time determination. Tests using BaF_2, $LaBr_3$(Ce), and $CeBr_3$ detectors for scattered gamma timing, along with external pulse generators and laser triggering, all suffered from large timing fluctuations, preventing ideal lifetime spectra. Figure 6 (right) shows preliminary results for a 1 cm thick lead target (C5T3 collimation, ~1 hour measurement), exhibiting an unexpected double-peak structure that persists in pure copper targets. This artifact is attributed to start time jitter. Future improvements will implement storage ring RF timing signals in the

DAQ system (currently being installed) and consider short-pulse laser operation to achieve precise timing similar to UVSOR BL1U, combined with HPGe detectors for 511 keV photon measurement to obtain reliable positron annihilation lifetime-momentum correlation spectra.

Conclusion

Our Geant4 simulations of SLEGS positron beam production optimized target and magnet parameters to increase beam intensity while eliminating scattered gamma background effects. The single-target magnetic deflection scheme, though simple to implement, suffers from strong gamma background and modest signal-to-noise ratio. Leveraging SLEGS's continuously tunable gamma energy, systematic simulations across multiple energy points yielded energy- and intensity-tunable positron beams: 1.0–12.9 MeV energy range with flux densities of ~10^2 $e^+/s/cm^2$ at low energies and ~10^3 $e^+/s/cm^2$ at high energies. The multi-target lateral extraction scheme, optimized with solenoid parameters, achieves high flux densities approaching 10^5 e^+/s while suppressing scattered gamma background by nearly two orders of magnitude compared to axial extraction. The resulting positron beam spans 1.0–9.1 MeV with flux densities of ~10^3–10^5 $e^+/s/cm^2$.

Validation experiments for thick-target gamma injection demonstrate excellent agreement between measured annihilation photon yields/angular distributions and simulations, confirming Geant4 reliability. Initial attempts at positron annihilation lifetime-momentum correlation spectroscopy revealed challenges in accurate start time determination due to SLEGS's unique oblique incidence design and quasi-continuous CO_2 laser pulse structure. Future work will implement storage ring RF timing signals and short-pulse laser operation to achieve precise timing for reliable lifetime-momentum correlation measurements. Beyond positron beam production and annihilation studies, SLEGS is also developing gamma imaging, activation analysis, and electron beam characterization techniques.

Author Contributions: All authors contributed to research design and methodology. Jin Sheng developed simulation codes, performed data analysis, and wrote the manuscript. Wang Hongwei and Fan Gongtao provided overall guidance, reviewed and revised the manuscript. Xu Hanghua, Zhou Weixin, Zhang Yue, Hao Zirui, Liu Longxiang, Yang Yuxuan, Chen Kaijie, Sun Qiankun, Wang Zhenwei, Xu Mengke, and Wang Xiangfei participated in SLEGS operation, experimental measurements, and manuscript discussion/revision.

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