# Proposal for a high brightness $\gamma$-ray source at the SXFEL postprint

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**Date:** 2023-06-18T00:00:00+00:00

## Abstract

High brightness $\gamma$-rays produced by laser Compton scattering (LCS) are ideal probes for the study of nucleon and nuclear structure. We propose such a $\gamma$-ray source using the backscattering of a laser from the bright electron beam produced by the linac of the Shanghai Soft X-ray Free-electron Laser (SXFEL) test facility at the Shanghai Institute of Applied Physics (SINAP). The performance is optimized through theoretical analysis and benchmarked with 4D Monte-Carlo simulations. The peak brightness of the source is expected to be larger than 2$×$1022 photons/(mm2 mrad2 s 0.1%BW) and photon energy ranges from 3.7 MeV to 38.9 MeV. Its performance, compared to Extreme Light Infrastructure-Nuclear Physics (ELI-NP), and the Shanghai Laser-Electron Gamma-ray Source (SLEGS), is given. The potential for basic and applied research is also briefly outlined.

## Full Text

## Preamble

### Proposal for a High Brightness $\gamma$-Ray Source at the SXFEL

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(Received April 4, 2015; accepted in revised form August 18, 2015; published online October 20, 2015)

High brightness $\gamma$-rays produced by laser Compton scattering (LCS) are ideal probes for the study of nucleon and nuclear structure. We propose such a $\gamma$-

ray source using the backscattering of a laser from the bright electron beam produced by the linac of the Shanghai Soft X-ray Free-electron Laser (SXFEL) test facility at the Shanghai Institute of Applied Physics (SINAP). The performance is optimized through theoretical analysis and benchmarked with 4D Monte-Carlo simulations. The peak brightness of the source is expected to be larger than $2 \times 10^{22}$ photons/(mm$^2$ mrad$^2$ s 0.1%BW) and photon energy ranges from 3.7 MeV to 38.9 MeV. Its performance, compared to Extreme Light Infrastructure-Nuclear Physics (ELI-NP), and the Shanghai Laser-Electron Gamma-ray Source (SLEGS), is given. The potential for basic and applied research is also briefly outlined.

**Keywords:** High brightness $\gamma$-ray source, Laser Compton scattering (LCS), Soft X-ray Free-electron Laser (SXFEL)

## Introduction

Over the past decades, remarkable advancements in high-intensity lasers and high-brightness electron beams have enabled laser Compton scattering (LCS) light sources—where relativistic electron beams scatter laser photons to produce quasi-monochromatic X-rays or $\gamma$-rays—to find broad applications across multiple fields. At photon energies below 100 keV, while storage ring light sources and X-ray free-electron lasers can produce higher brightness radiation, LCS sources offer attractive complementary capabilities at a fraction of the cost and size, making them particularly suitable for medical applications. At $\gamma$-ray photon energies, LCS sources will produce the highest brightness, enabling diverse applications including nuclear physics, nuclear astrophysics, polarized positron beams, polarized neutron beams, production of medical radioisotopes, nondestructive detection of radioactive isotopes, and assay of nuclear materials.

Although the Compton effect was discovered in the early 1920s by A. H. Compton in his Nobel-Prize-winning work, it was not until the 1960s that methods for generating very high-energy $\gamma$-rays via the LCS process in charged particle accelerators were independently proposed by Milburn and by Arutyunyan and Tumanyan. While numerous successful demonstrations of the LCS concept have been made through the years, the $\gamma$-ray yield remained quite low. In 1978, the first $\gamma$-ray LCS facility—the Ladon project—began operation in Frascati, followed by several new facilities including LEGS@NSLS and HI$\gamma$S@DFELL in the US, GRAAL@ESRF in France, ROKK in Russia, and LEPS@SPring-8 in Japan. Among these, Ladon, LEGS, and GRAAL were decommissioned in 1993, 2006, and 2008, respectively, while HI$\gamma$S and LEPS remain active for studies of low-energy nuclear structures, nuclear astrophysics, and hadron physics. Growing interest continues in building new $\gamma$-ray facilities at storage ring light sources, with projects at TERAS, SAGA, UVSOR-II, LEPS2, and NewSUBARU in Japan. The HI$\gamma$S team has also proposed the HI$\gamma$S2 project to further increase photon flux, and newly built third-generation light source facilities worldwide are pursuing integration of $\gamma$-ray sources, including PLS in Korea, ALBA in Spain, CLS in Canada, MAX-IV in Sweden, DA$\Phi$NE at LNF-INFN in Italy, and SSRF in China.

With the introduction of photocathode radio-frequency (RF) electron guns, linac electron beam quality has improved dramatically over the last decades. As noted in previous work, linac-based LCS light sources hold great promise for compact X-ray generation. Current global efforts for developing such sources include ATF at BNL and PLEIADES at LLNL in the US, PHOENIX at HZDR in Germany, AIST at ETL, LUCX and STF at KEK in Japan, and TTX at Tsinghua University in China. For $\gamma$-ray energies, colliding lasers with high-quality electron beams from linacs offers opportunities to generate $\gamma$-rays with exceptionally narrow spectral width ($< 0.1\%$) for photo-nuclear experiments, particularly nuclear resonance fluorescence studies. LLNL made an important breakthrough by producing a mono-energetic MeV-level $\gamma$-ray source, enabling entirely new isotope-specific applications important to material science, medicine, industry, and engineering, thus opening a new era of nuclear photonics. Building on this success, X-band techniques based on the MEGa-ray project at LLNL are under development, followed by the Extreme Light Infrastructure-Nuclear Physics (ELI-NP) project—a major facility in Europe' s Nuclear Physics Long Range Plan. ELI-NP, now under construction in Bucharest-Magurele, Romania, will be one of three ELI pillars and will consist of a very high-intensity laser beam and a very intense ($10^{13}$ $\gamma$/s), brilliant $\gamma$ beam with 0.1% bandwidth and photon energies up to 19 MeV, creating a new European laboratory covering frontier fundamental physics, new nuclear physics and astrophysics, and diverse applications.

In this paper, we propose a high-brightness, narrow-bandwidth $\gamma$-ray source using the LCS mechanism based on the SXFEL linac with electron beam energies ranging from 400 to 1300 MeV. As shown in [Figure 1: see original paper], the $\gamma$-ray source will be located at the second branch, and the colliding laser will share the same laser hutch as the seed laser of SXFEL.

We chose head-on interaction geometry to maximize overlap between the electron and laser beams. This source can produce photon energies ranging from 3.7 MeV to 38.9 MeV through Doppler up-shifting of 800 nm Ti:Sapphire laser beams by a factor of $4\gamma^2$E_L/(1 + $4\gamma^2$E_L/E_e). To obtain a narrow-bandwidth photon beam, we must study various factors that may impact the $\gamma$-ray spectrum. For realistic laser-electron interactions, both beams have intrinsic divergences and energy spreads at the interaction point. These non-ideal factors determine the bandwidth of the scattered photon beam. The relative energy spread of scattered photons generated by electron beam energy spread is straightforward: ΔE_$\gamma$/E_$\gamma$ = 2ΔE_e/E_e. The contribution from the natural laser bandwidth is ΔE_$\gamma$/E_$\gamma$ = ΔE_$\lambda$/E_$\lambda$. The effect of electron beam intrinsic divergence scales as ΔE_$\gamma$/E_$\gamma$ = [ _n/r_e]$^2$, where _n and r_e are the normalized emittance and beam radius of the electron beam, respectively. Nonlinear effects associated with laser intensity also cause spectral broadening due to inhomogeneous ponderomotive forces during the laser pulse, which change the electron' s longitudinal velocity and lead to variable redshift during scattering. As noted in previous work, even in the so-called non-relativistic regime, nonlinear effects may become significant if pulses become relatively long, yielding important spectral broadening.

In summary, for analytical optimization of the $\gamma$-ray source performance, the main goal is to maximize on-axis spectral brightness while reducing bandwidth and related parameters, including electron beam size and emittance, and laser beam size and pulse duration. Hereafter, we assume the laser pulse energy is limited to 100 mJ. The performance optimization is based on theoretical work by Hartemann et al. and Petrillo et al., as well as the MC simulation code developed by Luo.

## B. Performance Optimization: Linear and Nonlinear Regime

It has been found that in the linear regime, the peak on-axis brightness is given by:

$$\hat{B}_x = 4\times10^{-15}\left(\frac{N_e N_\lambda r_0^2}{\Delta\tau}\right)\left(\frac{\gamma_0^2}{w_0^2}\right)\left[\frac{\chi-1}{2\chi\Delta u^2}\right]\cdot\exp\left\{\frac{[\Phi(1/\eta)-1]-\mu e^{1/\mu^2}[\Phi(1/\mu)-1]}{\mu^2-\eta^2}\right\}\times\Bigg\{1-\Phi\Bigg[\frac{\chi-1}{\sqrt{\delta\omega^2+\delta\gamma^2}}$$

where $N_e = q/e$ is the number of electrons in the bunch, $\Delta\tau$ is the bunch duration, $\varepsilon$ is the normalized emittance, $\gamma_0$ is beam energy, and $\delta\gamma$ is the energy spread. $N_\lambda = W/(\hbar\omega_0)$ is the total number of photons in the laser pulses, $w_0$ is the $1/e$ focal radius, $r_0 = 2.82 \times 10^{-15}$ m is the classical electron radius, and $\Phi(x) = (2/\sqrt{\pi})\int_0^x e^{-t^2}dt$ is the error function. $\mu = c\Delta t/2z_0$ is the normalized inverse Rayleigh length and $\eta = \varepsilon/(\gamma_0 r_b^2)$ is the normalized inverse beta function, where $r_b$ is the radius at the focus of the electron beam, $\Delta t$ is the laser pulse duration, and $z_0 = \pi w_0^2/\lambda_0$ is the Rayleigh length. $\chi = \omega_x/4\gamma_0^2\omega_0$ is the normalized upshifted frequency and $\delta\omega = \Delta\omega/\omega_0$ is the relative spectral width of the laser pulse.

In the nonlinear regime, when spectral broadening induced by the inhomogeneous laser ponderomotive force during interaction is considered, the brightness becomes:

$$\hat{B}_x = 4\times10^{-15}\left(\frac{N_e N_\lambda r_0^2}{\Delta\tau}\right)\left(\frac{\gamma_0^2}{w_0^2}\right)\int_{-\infty}^{\infty}\frac{e^{-\bar{z}^2}}{(1+\eta^2\bar{z}^2)(1+\mu^2\bar{z}^2)}\left[\frac{\chi\rho(\bar{z})-1}{2\chi\rho(\bar{z})\Delta u^2}\right]\left\{1-\Phi\left[\frac{\chi\rho(\bar{z})-1}{\sqrt{\delta\omega^2+\delta\gamma^2\chi^2\rho^2(\bar{z})}}\right]\right\}\Bigg[$$

where $\rho(\bar{z}) = 1 + A_0^2 e^{-\bar{z}^{2/2(1}+\mu^2\bar{z}^{2)}}$, with $A_0$ being the maximum laser normalized vector potential.

A large electron beam size causes significant spectral broadening, as shown in [Figure 2: see original paper]. Therefore, 20 μm is chosen as the working value for the e-beam size. At a given beam emittance, while a tight focal size causes significant spectrum broadening, loosening the spot size can produce a narrower spectrum but decreases overall spectral brightness due to reduced electron density. Consequently, an optimum beam size exists for maximum $\gamma$-ray beam brightness. With normalized emittance of 1.5 mm • mrad (see ), Figure 2 shows peak spectral brightness for four different electron beam focal radii: 5, 15, 20, and 25 µm. The spectral broadening due to large divergence for small beam sizes is clearly evident. Figure 3 shows peak spectral brightness as a function of electron beam focal radius with and without nonlinear spectral broadening effects. The brightness variation with electron beam size is not very sensitive, as it depends on the combined effects of divergence-induced spectral broadening and the laser-electron beam overlap integral. To achieve narrower bandwidth, we prefer a relatively large electron beam size.

As the scaling laws suggest, peak spectral brightness of LCS sources is proportional to electron beam brightness. For a fixed beam size, large emittance means large divergence, and divergence-induced spectrum broadening decreases peak brightness rapidly. Moreover, reducing beam emittance to around 0.5 mm • mrad would increase peak brightness by a factor of approximately 3.

In the case of Fourier-transform-limited laser pulses, the relation between pulse duration $\Delta t$ and spectral bandwidth $\Delta\omega$ satisfies $\Delta\omega\Delta t = 2$. For large laser pulse durations, the laser bandwidth is narrow and the normalized vector potential is small, allowing minimal linear and nonlinear spectral broadening. However, the overlap integral becomes small as normalized parameters $\eta$ and $\mu$ become large. Conversely, for ultrashort laser pulses, fractional laser bandwidth contributes strongly to spectral bandwidth, and nonlinear effects become important, further degrading brightness. Peak spectral on-axis brightness as a function of normalized Doppler-shifted frequency $\chi$ and laser pulse duration $\Delta t$ is shown in Figure 4 (nonlinear effects ignored) and Figure 5 (nonlinear effects included). When nonlinear effects are neglected, a relatively large range of laser pulse durations yields high-brightness operation, limited by laser bandwidth for short pulses and diffraction for long pulses. Accounting for nonlinear effects reveals much tighter constraints on drive laser pulse duration, as shown in [Figure 5: see original paper], where ponderomotive force strength is also indicated: the optimum lies in the range of 3–7 ps, with 5 ps being a good working point.

Laser beam size also impacts the laser normalized vector potential. Larger laser beam size results in smaller normalized vector potential, reducing nonlinear-induced spectral broadening. However, larger laser beam size also decreases laser photon density, resulting in smaller photon flux and spectral brightness. Meanwhile, the Rayleigh length should be longer than the pulse duration, and small sizes introduce large divergence. Figure 6 shows peak spectral brightness as a function of laser beam focal radius, with a laser spot size of 15 µm chosen as the working point.

### C. Comparison with ELI-NP and SLEGS

The SLEGS project is a LCS $\gamma$-ray source proposed for the SSRF storage ring, to be built at one of the long straight sections. It has two operational modes: intermediate energy mode with backscattering geometry, and low energy mode with side-scattering geometry. In low energy mode, the interaction angle between the electron beam and $CO_2$ incident laser can be changed continuously with a rotating platform, producing $\gamma$-ray photons with energies ranging from 0.4 to 20 MeV. The main parameters of SLEGS low energy mode are listed in . Similarly, optimized performance is shown in [Figure 8: see original paper].

Performance comparison with ELI-NP and SLEGS is summarized in . Despite lower repetition rate and single-bunch operation mode with approximately three orders of magnitude lower spectral density, the flux per shot and peak brightness are comparable to ELI-NP, and are two orders of magnitude and eleven orders of magnitude higher than SLEGS, respectively.

### D. Potential Scientific Opportunities

As aforementioned, the proposed $\gamma$-ray source at SXFEL will be useful in diverse fields from nuclear structure physics to nuclear isomers, nuclear astrophysics, and nuclear data, as well as space radiation effects research for aerospace electronic components and accurate calibration of gamma detectors for aerospace applications. Moreover, combining high-brightness X-rays and $\gamma$-rays in a single facility enables numerous opportunities for fundamental physics studies. For over 30 years, photon colliders have been considered natural additions to electron-positron collider projects in the high-energy physics community. Recent interest has renewed in building a photon collider as a Higgs factory since the 2012 Higgs boson discovery. A new class of photon collider has been proposed where a $\gamma$-ray beam is fired into the high-temperature radiation field of a laser-heated hohlraum. The SXFEL case fits this concept well and provides more precise tools for studying the Breit-Wheeler pair production process, a striking prediction of quantum electrodynamics.

The possibility of creating a nuclear gamma-ray laser (NGL) has attracted attention for half a century. However, convincing experimental data remains absent. The key conflict inherent in NGL concepts is the antagonism between accumulating sufficient excited nuclei and narrowing the emission line to its natural radiative width. For the combined high-brightness, narrow-bandwidth $X/\gamma$ sources at SXFEL, testing the X-ray pumped NGL concept becomes possible.

## IV. Conclusion

This paper presents the design of a narrow-bandwidth, high peak brightness LCS $\gamma$-ray source based on the SXFEL linac. Its peak brightness will exceed $2 \times 10^{22}$ photons/($mm^2$ $mrad^2$ s 0.1%BW) with photon energies ranging from 3.7 MeV to 38.9 MeV, enabling broad nuclear physics studies and advanced nuclear photonics applications. The photon flux will be at least two orders of magnitude higher, and peak brightness eleven orders of magnitude higher, than the SLEGS project. Its performance is also comparable to the most advanced $\gamma$-ray source, ELI-NP. By combining bright $\gamma$-rays with bright X-rays, a new type of photon collider for fundamental QED physics studies can be envisioned, and exploration of a new approach to $\gamma$-ray lasers can be pursued.

It is worth noting that current design studies are preliminary, with considerable room for further improvement. Potential enhancements include reducing electron beam emittance, adopting multi-bunch operation, integrating laser cavities, and using plasma channels, which may increase photon flux by orders of magnitude. Spectral broadening effects can be compensated by chirped electron beams and/or suitable frequency modulation of incident laser pulses. Simultaneous operation of the X-ray FEL and $\gamma$-ray source will present technically challenging demands on X/$\gamma$-ray optics for the aforementioned experiments, which will be topics of future studies.

## Acknowledgments

We appreciate stimulating discussions with Prof. Yu-Gang Ma, De-Qing Fang, Hong-Wei Wang, Gong-Tao Fan, and Yong-Jiang Li of the Shanghai Institute of Applied Physics, Chinese Academy of Sciences.

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