Bright broadband X-ray sources driven by high-power lasers at ELI Beamlines: For fundamental physics research and applications

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ABSTRACT

The development of compact X-ray sources is a key application of laser-plasma-based electron acceleration, producing femtosecond X-ray pulses that are bright, collimated, and partially coherent. These sources can deliver photon fluxes exceeding 10^{11} photons per shot, with further enhancement possible using high-repetition-rate, high-power lasers, offering complementary capabilities to large-scale facilities like synchrotrons and XFELs. Although their potential in the material and biological sciences is still emerging, it underscores the need for user-oriented X-ray beamlines. We update the results from the recently commissioned ELI Gammatron Beamline, to support fundamental physics research and advanced applications.

Keywords: Extreme Light Infrastructure, ELI beamlines, Laser Plasma Accelerator, Betatron Radiation, X-ray sources, Phase Contrast Imaging

1. INTRODUCTION

While conventional X-ray sources such as tubes and synchrotrons offer high spatial resolution, they fall short in accessing the ultrafast temporal dynamics of atomic and molecular motion. Large-scale facilities like synchrotrons and X-ray free-electron lasers (XFELs) provide ultrashort, high-brightness X-ray pulses capable of capturing real-time structural changes. However, the limited availability and high operational costs of these facilities create barriers for widespread access.

Compact, laser-driven X-ray sources based on laser wakefield acceleration (LWFA)[1] have emerged as promising alternatives.[2–4] In these systems, femtosecond laser pulses drive plasma waves that accelerate electrons to relativistic energies over centimeter-scale distances. These accelerated electrons can generate X-rays through Betatron radiation or Thomson/Inverse Compton scattering (TS/ICS). Betatron sources emit broadband, ultrashort[5] partially coherent and polarisation tunable[6] X-rays through the transverse oscillations of electrons in plasma, while TS/ICS sources produce high-energy X-rays and γ-rays by scattering a laser pulse off a relativistic electron beam. Despite these advantages, such sources are often limited by low photon flux and relatively poor laser-to-X-ray conversion efficiency. To address these limitations, several strategies have been proposed, focusing on improving the coupling between the laser and the plasma medium. These include tailoring the density of the plasma medium[7] and tailoring or combining multiple laser pulses to better support electron acceleration and radiation processes.[8] Recent experiments using laser systems with sub-petawatt power—along with optimized laser and target conditions—have demonstrated the capability to generate over 10^{11} X-ray photons per pulse.[9]

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This output can be further enhanced with petawatt-class lasers.

The ELI Beamlines facility in the Czech Republic, one of the pillars of the Extreme Light Infrastructure (ELI) initiative, has been established to advance such high-intensity laser technologies and their applications. The ELI Beamlines aim to deliver ultra-short particle and X-ray beams for global users in fundamental and applied research, while advancing laser-plasma accelerator technologies to support cutting-edge experiments with broad scientific and societal impact.
Here, we report the recently commissioned ELI Gammatron Beamline[10] —a user-oriented platform for generating ultrashort, energy-tunable, collimated hard X-rays based on laser plasma acclerator (LPA). The Gammatron beamline aim to delivers broadband X-ray pulses ranging from a few keV to hundreds of keV, with photon fluxes beyond 10^{11} photons per pulse. Designed to support a wide range of ultrafast experiments, the beamline enables cutting-edge research in condensed matter physics, plasma diagnostics, high-energy-density science, and other application-driven fields—bridging the gap between laboratory-scale sources and large-scale X-ray facilities.

2. ELI GAMMATRON BEAMLINE: A HIGH-REPETITION, HARD X-RAY SOURCE FOR MULTIDISCIPLINARY APPLICATIONS

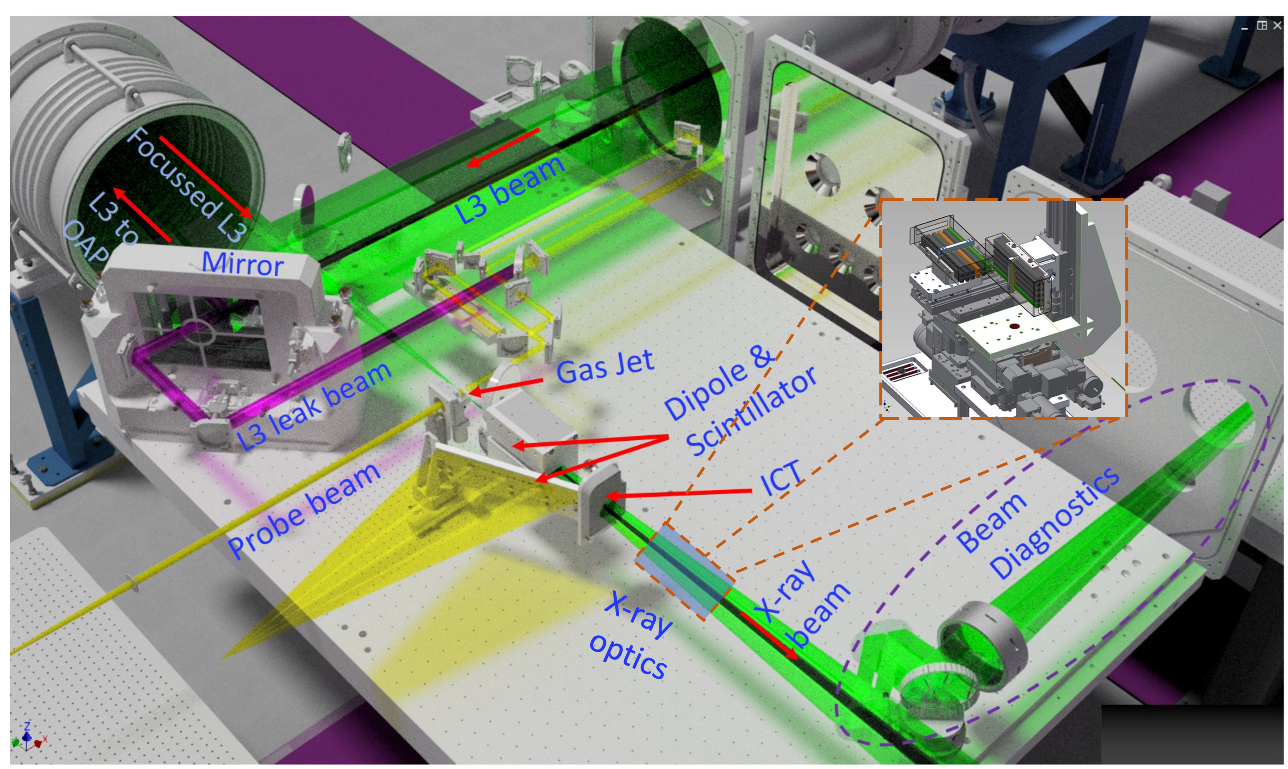

Figure 1: Schematic view of the Gammatron beamline and associated diagnostics inside the interaction chamber.

The ELI Gammatron beamline, located in Experimental Hall E2 at ELI Beamlines, is a state-of-the-art, user-oriented facility designed for the generation of hard X-ray radiation via LWFA. As a versatile and multidisciplinary platform, it enables a broad range of experiments requiring ultra-short, tunable, and highly collimated hard X-ray pulses. Currently the beamline operates in the Betatron scheme, wherein relativistic electrons oscillate transversely within a plasma bubble, emitting intense broadband X-rays. The core experimental setup—including the interaction chamber and integrated diagnostics—is depicted in Fig. 1.

The Gammatron is powered by the ELI beamlines L3 HAPLS laser,[11] diode-pumped Ti:sapphire petawatt-class laser system, delivering pulses of 10 J energy, 30 fs duration, and 800 nm central wavelength, operating at a repetition rate of 3.3 Hz. The beam is transported from the compressor chamber to the interaction chamber using seven high-damage-threshold,[12] multi-layer dielectric mirrors, ensuring high beam quality and minimal energy loss. An off-axis parabolic (OAP) mirror with a 4000 mm focal length, corresponding to an F-number of approximately 19, is used to focus the laser beam onto a gas target, initiating LWFA and enabling the generation of Betatron X-rays.

2.1 Gas target

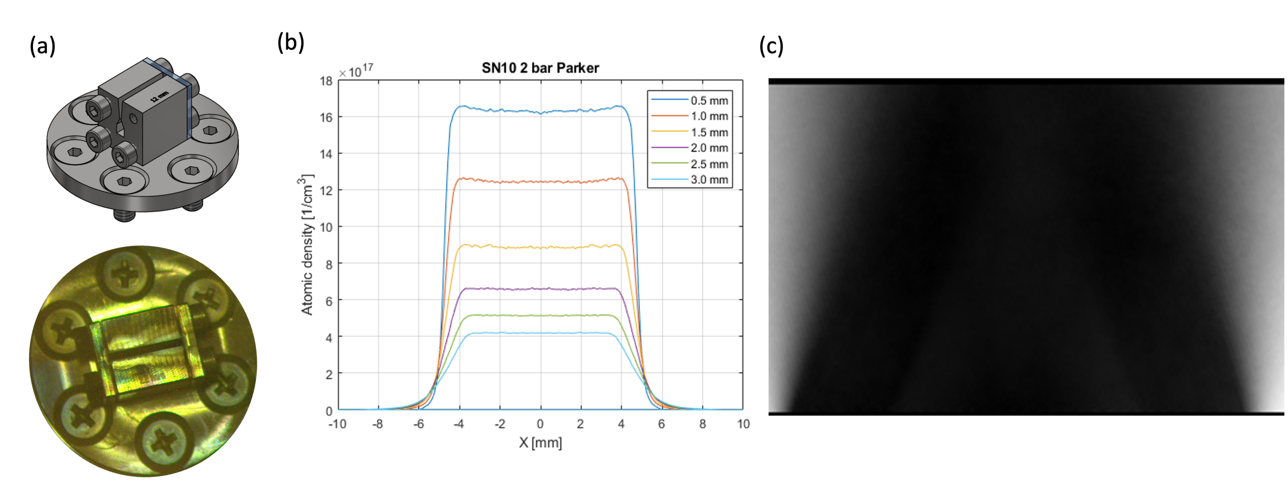

Figure 2: Supersonic slit nozzle with a dimension of 12 mm x 1.2 mm. (a) Schematic view, and picture after the experiment at the Gammatron beamline. (b) fluid simulation of the Nozzle showing flat-top density profile. (c) phase map of the Nozzle at 20 bar Helium gas measured at our interferometer.

Targets for generating relativistic electron bunches and subsequent X-ray emission consist of either a supersonic gas jet or a gas cell, with flexible gas choices such as helium (He), nitrogen (N_2), He–N_2 mixtures, or even a dry air,[13] depending on the desired electron beam and X-ray characteristics. We have developed a variety of gas targets with different shapes and lengths ranging from a few hundred microns to several centimeters. These targets were characterized using a custom-built interferometric probe system that employs multiple passes of the probe beam with relay imaging to enhance phase sensitivity.[14–17] This enhanced sensitivity enabled tomographic reconstruction of complex, non-rotationally symmetric gas density distributions. For the commissioning experiment, we have used an in-house developed slit nozzle with dimensions of 1.2 mm by 12 mm as shown in Fig. 2. The Nozzle provides a flat-top density profile with a uniform gas density Fig. 2b, this can be further validated with interferometric measurement. The phase map of the Nozzle at 20 bar He measured at our interferometer showing uniform flow reported in Fig. 2c.

2.2 Preliminary results

During the commissioning phase, our major objective was to characterize the laser at the Gamamtron beamline and comission all the laser plasma and radiation diagnostics, and finally to generate a stable relativistic electron beam and a hard X-ray source via Betatron radiation. Laser pulses with energies up to 10 J, measured after the compressor, were employed using the available focusing geometry of the Gammatron beamline. This configuration delivered on-target intensities on the order of several times 10^{18} W/cm^2. The laser was focused at the entrance of a gas jet composed of a helium-nitrogen admixture (98% He, 2% N_2), selected to facilitate stable Betatron beam generation through ionization injection. A stable electron beam reaching energies close to 1 GeV was successfully generated at lower backing pressures. The electron beam properties were characterized using an electron spectrometer. A representative electron spectrum at a backing pressure of 10 bar is shown in Fig. 3a.

To enhance Betatron X-ray generation, we further optimized the gas backing pressure. Through systematic pressure scans, we observed the emergence of a bright, collimated Betatron X-ray beam with a full width

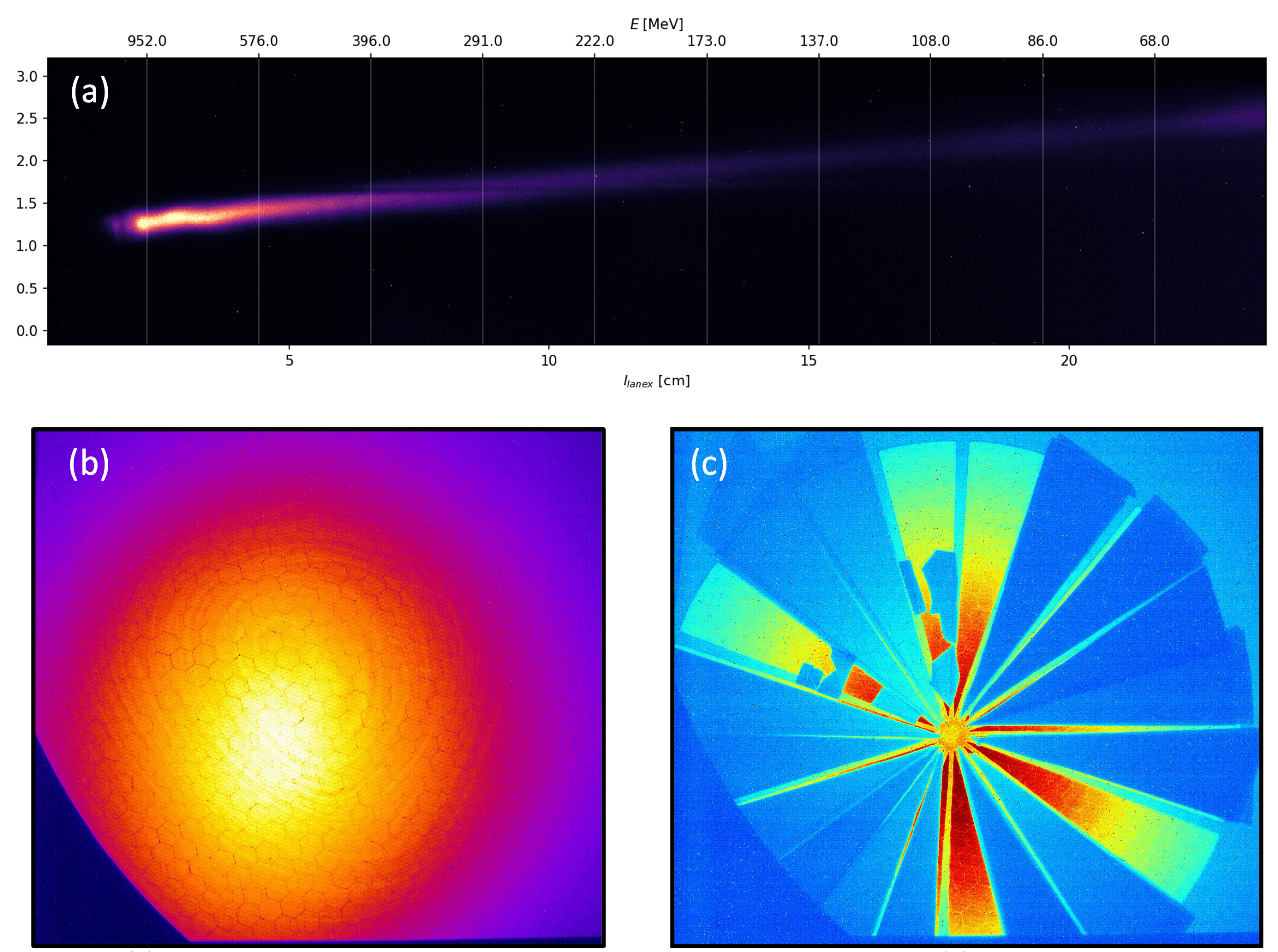

Figure 3: (a) Representative electron spectrum reaching energy close to GeV. (b) Footprint of the Betatron X-ray recorded by the X-ray CCD (indirect detection) at 190 cm from the source, The X-ray is collimated with a beam divergence of about 15 mrad (FWHM). (c) The X-ray beam on hard X-ray spectrometer based on the Ross-filter pairs covering energy range up to 90 keV.

at half maximum (FWHM) divergence of approximately 15 mrad. The spatial profile of the X-ray beam was monitored using either a direct detection X-ray CCD or a scintillating screen coupled to an imaging CCD. Spectral measurements were carried out with X-ray spectrometers equipped with filter wheels. For photon energies below 30 keV, spectra and photon fluxes were measured on a single shot basis using direct CCD detection. The spatial footprint of the X-ray beam on a CCD positioned 190 cm downstream of the source is shown in Fig. 3b. The corresponding spectral data captured with a hard X-ray spectrometer is presented in Fig. 3c. The preliminary analysis of the recorded X-ray spectrum shows the critical energy over 12 keV. We further evaluated the source's capability by performing in-line phase-contrast imaging of various samples. The brightness of the Betatron X-ray source proved sufficient to capture high-contrast images in a single laser shot. Comprehensive characterization of the electron and X-ray beams is currently underway, with detailed results to be published in an upcoming paper.

3. CONCLUSION

The recently commissioned Gammatron beamline delivers bright, ultrashort X-ray pulses across a broad photon energy spectrum. These X-ray pulses can be precisely synchronized with a pump pulse derived from the main laser, facilitating time-resolved pump-probe experiments with atomic-scale resolution. In addition to dynamic studies, the beamline supports advanced capabilities in X-ray imaging,[18,19] time-resolved diffraction, and spectroscopy,[20] serving a wide array of applications in physical and chemical sciences, energy research, biomedical technologies, and industrial diagnostics. A dedicated end-station, the Gammatron User Station (Gauss), has been developed to facilitate time-resolved measurements with femtosecond resolution, accommodating a wide array of experimental configurations. The Gauss station, yet to commission for time-resolved studies, is equipped with a custom Kirkpatrick–Baez (KB) X-ray optics system. This system comprises a multi-lane, multi-layer coated mirror configuration, capable of focusing X-rays up to 12 keV.[21]

In addition, a dedicated Betatron X-ray source is currently being commissioned at the ELI Beamlines Plasma Physics Platform (P3).[22] This advanced source is designed to serve as a key diagnostic tool for probing warm dense matter (WDM)[23,24] and high-energy density (HED) plasma relevant to interiors of planets and astrophysics.[25–27] Its micron source size and ultrafast temporal resolution make it particularly well suited for capturing dynamic phenomena in extreme plasma environments with high spatial and temporal precision. Besides, at ELI beamlines other available X-ray sources powered by kilohertz, terawatt-class lasers, such as the coherent extreme ultraviolet (XUV) radiation from the High Harmonic Generation (HHG) beamline,[28,29] as well as incoherent plasma-based K-alpha X-ray source which are offered for various user experiments.[30,31] With the successful commissioning of the Gammatron beamline, ELI beamlines now offer a comprehensive suite of laser-driven secondary radiation sources spanning from extreme ultraviolet (XUV) to hard X-rays and gamma rays. These capabilities empower a broad spectrum of research, from fundamental studies in physics to practical applications in biology, chemistry, and materials science.

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