

Ultrafast laser-driven X-ray sources at ELI Beamlines: From HHG and plasma X-ray to LPA-driven sources

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ELI Beamlines is advancing ultrafast X-ray science through a multi-pronged strategy that transforms driving laser pulses into brilliant beams of short-wavelength radiation. Our program is built on three complementary approaches—high-order harmonic generation (HHG) in gases, plasma X-ray sources, and laser-plasma accelerator (LPA)–based sources—each implemented on dedicated beamlines that integrate fundamental research with diverse applications.

The HHG Beamline¹ is driven by state-of-the-art optical parametric chirped-pulse amplification (OPCPA) technology, as demonstrated by the L1 laser at ELI Beamlines. Delivering 45 mJ, 15 fs pulses at 1 kHz, the system significantly enhances the extreme ultraviolet (XUV) photon yield, overcoming traditional limitations of low flux and spectral mismatches that have hindered nonlinear XUV studies. Furthermore, a synchronized auxiliary beam with electronically adjustable delay enables advanced XUV–XUV pump–probe experiments for exploring ultrafast atomic and molecular processes.

Complementing this, a newly commissioned kHz laser-driven copper plasma X-ray source² (PXS) expands our experimental capabilities. This source can be driven by either previously mentioned in-house developed near-infrared TW laser (L1) or a conventional Ti:Sapphire laser delivering 12 mJ, 45 fs pulses at 1 kHz. It reaches fluxes of up to 10^{12} K α photons/4 π /s, with the OPCPA driver offering enhanced performance through higher pulse energy, shorter pulse duration, and enhanced pulse contrast. The source is implemented in setups for ultrafast X-ray diffraction and X-ray absorption/emission spectroscopy.

In parallel, significant progress has been made in LPA-based X-ray source generation. Current LPA-based X-ray sources achieve photon fluxes exceeding 10^{11} photons per shot³, with ongoing research exploring novel techniques to further enhance their performance. The ELI Gammatron beamline⁴ driven by a PW-class laser (L3) produces a collimated, partially coherent broadband X-ray beam. An in-house designed broadband X-ray mirror⁵ further refines its performance, allowing for precise pump–probe experimental capability. Additionally, the Betatron X-ray source at the ELI plasma physics platform (P3) has been developed as a high-resolution backlighter for laser–matter interaction studies, including experiments in high-energy density physics and as a probe for advanced plasma physics experiments⁶.

Together, these initiatives demonstrate our commitment to pushing the frontiers of ultrafast X-ray science, providing versatile experimental platforms that address both fundamental research questions and applications in different fields of science and technology.

References

1. O. Hort et al., High-flux source of coherent XUV pulses for user applications, *Opt. Express* 27 (2019) 6.
2. Y. Pulnova et al., Compact laser-driven plasma X-ray source for time-resolved diffraction, spectroscopy, and imaging experiments at ELI Beamlines, *J. Synchrotron Rad.* 32 (2025).
3. S. Fourmaux et al., Laser-based synchrotron X-ray radiation experimental scaling, *Opt. Express* 28 (2020) 3.
4. U. Chaulagain et al., ELI Gammatron Beamline: A Dawn of Ultrafast Hard X-ray Science, *Photonics* 9 (2022) 11.
5. M. Raclavsky et al., Multi-Lane Mirror for Broadband Applications of Betatron X-ray Source, *Phot.* 8 (2021) 579.
6. N. Jourdain, et al., The L4n laser beamline of the P3-installation: Towards high-repetition rate high-energy density physics at ELI-Beamlines, *MRE* 6.1 (2021) 015401.