EUPRAXIA AT ELI ERIC: DEVELOPMENT OF A COMPACT LPA FEL AND PLASMA SOURCES FOR ULTRAFAST SCIENCE

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Abstract

The ELI Beamlines Centre (part of the European Light Infrastructure), located near Prague in the Czech Republic, has been selected as the second pillar of the EuPRAXIA distributed user facility. It utilises a novel laser–plasma accelerator (LPA) to generate a high-quality electron beam for a range of applications. A key initiative is to develop an LPA-driven free-electron laser (FEL) spanning the soft X-ray water-window range, as the main objective of EuPRAXIA Phase 1. A two-phase development strategy is adopted, with an EUV-FEL prototype at around 400 MeV electron beam energy serving as the first step to validate the full system chain before the Phase 1 upgrade to 1 GeV. The soft X-ray LPA-based FEL will use 1 GeV electrons at 100 Hz, supporting research in biology, ultrafast chemistry, and nanoscale materials. The project leverages unique features of LPA-based FELs compared with LINAC-based facilities: naturally few-femtosecond electron bunches, high peak currents without compression, inherent sub-femtosecond synchronisation with the drive laser, and a significantly smaller accelerator footprint. These features enable experimental regimes that are challenging for existing large-scale FELs, particularly in ultrafast pump–probe and attoscience applications. Complementary developments at ELI Beamlines within the EuPRAXIA project include a betatron X-ray source and a low-energy positron source, broadening user access to advanced plasma-driven radiation and particle beams.

INTRODUCTION

Modern X-ray FELs are well-established, user-oriented facilities with broad applications across biology, chemistry, and imaging. Conventional radio-frequency linear accelerator (LINAC)-based FEL facilities, such as the European XFEL and the Linac Coherent Light Source (LCLS), deliver world-leading performance in photon flux, coherence, and pulse energy. However, these facilities impose major constraints on footprint (kilometre-scale), construction cost, operational cost, and user accessibility. The performance of compact designs such as SwissFEL [1], which achieved low emittance and a smaller footprint, demonstrates that more affordable FEL facilities can broaden access to ultrafast science. Reducing size and cost would fundamentally change the current paradigm of limited access to XFEL science, enabling university-scale installations [2]. Laser–plasma acceleration (LPA) technology offers a revolutionary route to compact free-electron lasers (FELs) by utilising the extremely high electric fields produced when a powerful laser pulse propagates through an underdense plasma. LPA can sustain acceleration gradients exceeding 100 GV/m, enabling electrons to reach GeV energies within a few centimetres [3]. Moreover, the electron beams generated by LPA can achieve six-dimensional brightness comparable to that of traditional LINAC-based sources [4]. Beyond their compactness, LPA beams offer inherent advantages for FEL applications: the acceleration process naturally produces electron bunches lasting a few femtoseconds with high peak currents. These bunches are intrinsically synchronised with the drive laser on a sub-femtosecond timescale, enabling pump–probe experiments with unmatched timing accuracy. Recently, several teams worldwide have demonstrated proof-of-principle free-electron lasing at different wavelengths [5-8], confirming that LPA technology has matured to the point where compact, plasma-based FELs are both scientifically and technically feasible. EuPRAXIA (European Plasma Research Accelerator with eXcellence In Applications) is the pan-European initiative to translate plasma-accelerator science into a user-facility platform and to build the first international plasma-accelerator-based research infrastructure. Its inclusion in the European Strategy Forum on Research Infrastructures (ESFRI) roadmap reflects broad recognition of the transformative potential of plasma-based accelerators for photon science, high-energy physics, and medical applications. EuPRAXIA's conceptual design [9] incorporates both laser-wakefield acceleration (LWFA) and particle-beam-driven plasma wakefield acceleration (PWFA). As an ESFRI project, EuPRAXIA aims to have two facilities operational by 2031, located at INFN-LFN (Frascati, Italy) and ELI Beamlines (Czech Republic), each hosting dedicated user zones for FEL pilots and complementary applications in materials science, structural biology, and high-field physics.

This paper presents the current development status of EuPRAXIA at ELI ERIC, focusing on the compact LPA-driven FEL and complementary plasma-based secondary sources for ultrafast science.

ELI ERIC AND EUPRAXIA

ELI Beamlines (the ELI ERIC user-oriented facility in the Czech Republic) will host the LWFA-focused second pillar of the EuPRAXIA distributed European infrastructure. Its world-leading laser capabilities [10] and established experimental infrastructure for laser-plasma interactions and secondary-source generation underpin this role. Multiple beamlines based on high-harmonic generation (HHG), betatron radiation, and plasma-generated X-ray sources are currently operational at ELI Beamlines, supporting ultrafast XUV and X-ray user experiments [11]. This infrastructure and operational experience enable ELI Beamlines to rapidly integrate LPA-based electron beams and FEL testbeds into its user program.

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The core of the EuPRAXIA photon science user program at ELI Beamlines is the LPA-based compact FEL [12]. Its design integrates a high-power laser, a plasma accelerator, an electron beamline, an undulator, and a photon beamline, covering EUV to soft X-ray wavelengths through separate setups. This compact LPA-based FEL aims to deliver coherent photon beams for user experiments — including resonant X-ray spectroscopy, coherent diffractive imaging, and ultrafast photon science — while serving as a technology demonstrator for plasma-accelerator-based FELs.

LPA-BASED COMPACT FEL AT ELI ERIC

At ELI Beamlines (ELI ERIC), we are considering a two-step development approach for the LPA-based FEL programme: an EUV prototype followed by a soft X-ray user line. This approach offers a pragmatic path to water-window LPA-based FEL capability [12], manages technical risk, and enables early scientific impact, with a clear transition from EUV to soft X-ray operation, which requires upgrading the LPA energy from 400 MeV to 1000 MeV. The EUV prototype can deliver scientifically valuable output in the 20–50 nm range (25–60 eV), relevant to materials science, surface chemistry, and atomic/molecular physics. Early user experiments build the scientific case and user community for the subsequent water-window facility, while also providing operational experience with LPA-driven FEL user operations. Modelling the SASE FEL process for both EUV and water-window cases allows us to set the following LPA-based FEL parameters for users. In the EUV case, the pulse energy of the photon radiation at saturation will be around 50 μJ for the reference fundamental-harmonic resonance wavelength of 43 nm (corresponding to a resonance energy of 29 eV). The total number of photons per pulse should be at least 10^{13}. The expected radiation peak brightness is 10^{29} photons/pulse/mm^2/mrad^2/0.1%bw. The radiation bandwidth is less than 0.015. In the case of the soft X-ray LPA-based FEL, the pulse energy of the photon radiation at saturation will be around 8 μJ for the reference fundamental-harmonic resonance wavelength of 3.4 nm (resonance energy of 368 eV). The total number of photons per pulse should be at least 1.4×10^{11}, with a radiation bandwidth of less than 0.005. The expected radiation peak brightness is 7×10^{29} photons/pulse/mm^2/mrad^2/0.1%bw. The photon beam pulse duration is just a few fsec without usage of any compression schemes in the electron beamline.

Laser System

ELI Beamlines' two-step strategy to advance the LPA-based FEL program from the EUV to soft X-ray is also based on the L2-DUHA laser development project. The L2 laser system is currently being prepared, with commissioning planned for the second half of 2026. During its commissioning, it will operate at a pulse energy of 3 J, with a pulse duration over 25 fs and a repetition rate of 20 Hz. These parameters are sufficient to generate a stable electron beam with energies below 500 MeV, offering beam quality suitable for the EUV LPA-based FEL [5, 7]. Later, the L2 laser will be upgraded to produce 5 J pulses with a repetition rate of up to 100 Hz. This higher pulse energy will enable acceleration of electron bunches to 1000 MeV, facilitating the development of the LPA-driven soft X-ray FEL [12].

Plasma Sources for High-Quality Electron Beam

The EUV FEL program (Phase-0) at ELI Beamlines targets the EUV photon range at a 20 Hz repetition rate using a single-stage laser-plasma accelerator [5, 7]. Achieving FEL saturation in a compact 4 m undulator requires stringent electron beam quality: slice energy spread < 0.5%, projected energy spread < 0.5%, normalised emittance < 0.20 mm·mrad (H/V), and peak current > 3.5 kA at 400 MeV. To deliver such a beam, the plasma source R&D program focuses on optimising injection control, phase-space manipulation, beam-loading dynamics, and plasma density tapering to meet these specifications while maintaining stable operation. Recent experimental and simulation research for high-quality electron beams with energies around 500 MeV indicates that plasma densities between (2–5) × 10^{18} cm^{-3} offer an optimal compromise [5, 7]. This balance enhances the accelerating gradient (~100 GV/m), dephasing length (~a centimetre), and wakefield stability [3]. Gas-jet targets with integrated four-region density profiles are used to achieve the FEL-required electron-beam quality: an up-ramp at the plasma entrance, a controlled shock down-ramp (50–100 μm), a plateau, and a tapered density at the exit. The shock down-ramp length is a crucial control parameter that influences both the injection threshold and beam-loading strength. It was demonstrated experimentally that shock-front injection, combined with laser self-evolution effects, actively leverages beam loading to optimise the final phase-space distribution, allowing the acceleration of an electron bunch with controllable energy spread, charge, and transverse emittance. Optimisation of the plasma density at the exit of the plasma source is required to minimise the transverse divergence of the electron beam. This parameter of the LPA-based electron beam, in combination with the energy spread, plays a crucial role in avoiding significant dilution of the transverse normalized emittance [13]. Open R&D challenges specific to Phase-1 include: development of robust gas-jet and gas-cell waveguide/capillary technologies for cm-scale plasma channels; demonstration of acceleration stability and reproducibility at 100 Hz; preservation of sub-0.5 mm·mrad emittance during long-channel acceleration and plasma-to-vacuum extraction; and thermal management of high-repetition-rate gas-targets under 5 J laser-pulse loading.

In addition to the LPA schemes mentioned above, hybrid LWFA+PWFA staging [14] and ReMPI injection [15] offer pathways to meet the stringent Phase-1 FEL beam requirements. The hybrid scheme is supported by experimental demonstrations of stable GeV-class beams with improved quality compared with single-stage LWFA, though emittance preservation and staging efficiency remain active R&D challenges. The ReMPI scheme promises exceptional beam quality in simulations—with normalised emittances well below 0.35 mm·mrad and slice energy spreads at the 10^{-3} level — with a bunch charge of 10 pC and a bunch duration of 350 as, but requires experimental validation of the resonant multi-pulse driver and synchronisation of the ionisation pulse. Continued optimisation and experimental campaigns will determine which approach best balances beam quality, stability, and operational complexity for the EuPRAXIA-ELI Phase-1 soft X-ray FEL.

Electron Beamline

The dedicated electron beamline transports electron bunches generated by the laser-plasma accelerator (LPA) from the plasma exit to the undulator entrance, preserving slice emittance and reducing the projected energy spread to FEL-useful levels [5, 7, 8, 12]. The first focusing "capture" block employs a permanent-magnet quadrupole (PMQ) triplet placed immediately after the plasma exit to intercept the divergent beam before emittance blow-up [13]. The large projected energy spread (at the per cent level) induces strong chromatic aberration, leading to significant beam halo formation and a resulting increase in the transverse emittance of the LPA electron beam [12]. A suitable set of collimators should be used along the electron beamline to deliver the electron bunch with the required bunch charge and rms transverse emittance to the undulator section. As demonstrated experimentally [16], an active plasma lens can capture electrons, thereby preventing the growth of transverse emittance. To reduce the projected energy spread to a FEL-useful slice energy spread tailored to the distinct FEL physics, a bunch-decompression chicane was proposed to stretch the bunch longitudinally, converting correlated energy spread into bunch length and thereby reducing the slice energy spread at the cost of reduced peak current [17]. To align the electron beam properties with the undulator's focusing parameters, the matching section (3 or 4 electro-quadrupole magnets) should be placed before the undulator section [18]. A comprehensive diagnostic suite distributed along the beamline enables beam characterisation, alignment, and optimisation. Optical transition radiation (OTR) for single-shot measurements [19] and scintillating screens at multiple stations measure transverse beam profile, trajectory, and centroid position with micrometre spatial resolution [20]. Normalised emittance can be measured using single-shot "incoherent OTR" screen techniques at dedicated diagnostic stations before and after the chicane, as well as with an electron-beam spectrometer. Timing diagnostics preserve the sub-femtosecond intrinsic synchronisation between the LPA drive laser and the electron bunch, enabling pump-probe experiments with sub-10 fs temporal resolution. Beam-based alignment procedures using dipole correctors and beam position monitors iteratively minimise trajectory errors and dispersion leakage, which are critical to preserve emittance through the chromatic transport lattice. In addition, it is necessary to measure the slice parameters of the LPA-based electron bunches using a single-shot approach [21].

Undulator Line

The EuPRAXIA-ELI ERIC facility adopts hybrid permanent-magnet undulator (HPMU) technology for both Phase-0 (EUV) and Phase-1 (soft X-ray) FEL operations, leveraging the proven performance and field quality demonstrated by the Swiss-FEL program [22]. For Phase-0, the undulator line, with a total length of 4 m, should be integrated into the electron beamline. For Phase-1, the 20 m saturation length balances FEL performance (requiring high K and a short period for water-window resonance at 1 GeV) with facility infrastructure constraints and is achieved through careful optimisation of electron-beam parameters and undulator-field quality. SwissFEL-type undulators achieve the stringent field quality required for SASE FEL operation through magnetic measurements, shimming, and pole tuning during fabrication and commissioning [22]. The undulator line employs permanent-magnet phase shifters between segments to maintain longitudinal phase coherence across the operating gap range, with magnetic shielding to prevent crosstalk between adjacent devices, as well as a single quadrupole magnet to control the periodic variation of the beam's transverse size along the long multi-section undulator line. Trajectory correction should be implemented using dipole corrector magnets and beam position monitors (BPMs) located at the inter-segment breaks, with beam-based alignment (BBA) and automated tuning algorithms used during commissioning to minimise orbit offsets and residual phase errors.

Photon Beamline

The photon beamline system for the EuPRAXIA-ELI ERIC FEL is designed following the proven architecture of the FLASH facility at DESY [23], adapted to the specific requirements of laser-plasma accelerator (LPA) driven FEL operation in the EUV (Phase-0) and soft X-ray (Phase-1) regimes. The beamline layout follows the canonical FLASH arrangement: undulator exit → front-end (safety shutters, apertures/slits) → gas attenuator → grazing-incidence mirror train → monochromator branch or direct branch → Kirkpatrick-Baez (KB) refocusing optics → end-station [24]. This modular architecture provides flexibility for both monochromatic and direct (non-monochromated) beam delivery while preserving femtosecond pulse duration and enabling pulse-resolved diagnostics for user experiments [25]. Phase-0 will employ a plane-grating monochromator (PGM) for EUV wavelengths, while Phase-1 requires a time-delay-compensated double-grating monochromator design to preserve femtosecond pulse duration across the water-window range [25]. For Phase-0 commissioning (2028-2029), the facility will deploy one primary beamline serving the 30-40 nm EUV FEL output, with provision for a second diagnostic/commissioning branch to enable parallel beamline development and machine studies. Phase-1 operation (2031) will expand to two or three beamlines serving the water-window soft X-ray regime (3.5–5.5 nm, 220–350 eV), supporting simultaneous user experiments and advanced pump-probe applications. The beamline design prioritises mitigation of radiation damage through grazing-incidence optics, gas attenuators for pulse-energy control, and distributed diagnostics for measuring pulse energy, wavelength, wavefront, and arrival time [26].

SECONDARY SOURCES FOR ULTRAFAST SCIENCE

Betatron Radiation Source

Betatron X-ray emission arises when relativistic electrons trapped in the laser-driven plasma wakefield (blowout regime) undergo transverse betatron oscillations within the plasma bubble and radiate broadband, synchrotron-like photons [27, 28]. The emitted spectrum is broadband and continuous, spanning from hundreds of eV to tens or hundreds of keV, depending on electron energy and plasma conditions. The current betatron radiation setup at ELI Beamlines is integrated with the L3 laser system [29]. The betatron source is intrinsically ultracompact: the emission region has a transverse size of ~ 0.5 – a few µm, and the X-ray pulse duration inherits the electron bunch duration of ~ a few fs to sub-100 fs [30]. The beam is forward-directed with mrad-scale divergence [27] and exhibits partial spatial coherence sufficient for propagation-based phase-contrast imaging [31]. In the case of the 1 GeV electron beam energy, hard X-rays (cut-off energy of ~50–100 keV) enable dense matter studies, time-resolved crystallography, and ultrafast radiography. The pulse duration of this X-ray source is femtoseconds, the source size is of the order of a micrometre or less, and the peak brightness is in the order of 10^{22} photons/s/mm^2/mrad^2/0.1%bw. The Betatron setup is fully commissioned at ELI Beamlines and is open to external users through open calls.

Positron Generation

The EuPRAXIA-ELI ERIC facility is developing a compact, high-repetition-rate positron source that exploits laser-wakefield acceleration (LWFA) of electrons to tens of MeV, followed by Bethe–Heitler (BH) pair production in a thin, high-Z solid converter [32]. This approach combines the ultrashort pulse structure and high peak brightness of laser-plasma sources with kHz-class repetition rates to deliver average positron fluxes and temporal resolutions unattainable with conventional radioactive or linac-based sources. Numerical simulations for mJ-class, kHz-capable laser scenarios predict on the order of 10^3 positrons per shot in a 50 keV energy bandwidth around MeV energies, translating to average fluxes exceeding 10^5 positrons per second at kHz repetition rates [32]. Ongoing work includes optimising converter thickness, material composition, and multi-layer approaches to maximise yield and beam quality [33], as well as designing dedicated beamlines to guide and select positron beam parameters for specific applications. As high-repetition-rate LWFA technology matures and average laser power increases, laser-driven positron sources are expected to achieve average fluxes and operational stability that are competitive with conventional facilities while retaining the advantages of ultrashort pulse duration, energy tunability, and a compact footprint. The primary application of the kHz positron source is Positron Annihilation Lifetime Spectroscopy (PALS), a non-invasive technique for detecting sub-nanometer defects in materials and characterizing defect type and size [34]. The kHz laser-driven positron source at EuPRAXIA-ELI ERIC represents a significant step toward compact, high-repetition-rate secondary sources for material science and fundamental physics.

CONCLUSION

The EuPRAXIA-ELI program leverages ELI Beamlines' established infrastructure, operational experience with laser-driven secondary sources, and world-leading laser capabilities to accelerate the transition from proof-of-principle demonstrations to reliable user operation. As the first ESFRI-recognised plasma-accelerator facility, EuPRAXIA-ELI ERIC will provide the global scientific community with unprecedented access to compact, femtosecond-synchronised photon and particle beams, enabling experimental regimes in attoscience, ultrafast chemistry, and structural biology that remain challenging for conventional large-scale facilities. The EUV LPA-based FEL setup at ELI Beamlines is expected to be commissioned in 2028-2029. The soft X-ray water-window LPA-based FEL setup should be commissioned by 2031. The betatron setup at ELI Beamlines, based on the L3 laser, is already open to users.

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