STATE-OF-THE-ART LASER-DRIVEN ELECTRON ACCELERATORS AND APPLICATIONS AT ELI–ERIC

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Abstract

Laser wakefield acceleration (LWFA) enables gradients up to 1 GV/cm in plasma and the generation of femtosecond electron beams. At the Extreme Light Infrastructure ERIC (ELI ERIC), 4 dedicated laser electron accelerators have been commissioned and are available for access via User calls. The high-repetition-rate ALFA and eSYLOS accelerators deliver ultra-relativistic electron beams at the highest energy worldwide (tens of MeV) at 1 kHz. Such beams are used for radiobiology experiments and for the generation of tertiary particle sources (positrons, x-rays, and neutrons). The high-energy ELBA and ePW accelerators deliver multi-GeV at Hz repetition rate. Primary use of these beams is QED, radiobiology and radiotherapy investigations and muon production.

INTRODUCTION

Laser wakefield acceleration (LWFA), first proposed by Tajima and Dawson in 1979 [1], exploits the ponderomotive force of an intense ultrashort laser pulse propagating through a plasma to drive large-amplitude plasma waves (wakefields) capable of sustaining accelerating gradients exceeding 100 GV/m — three to four orders of magnitude beyond those achievable in conventional radio-frequency (RF) accelerators. Nowadays, LWFA technology allows acceleration to multi-GeV energies in sub-meter scale plasma [2-4], and several facilities worldwide now offer LWFA-based electron beams to user communities [5].

The Extreme Light Infrastructure ERIC [6] is a pan-European research infrastructure hosting, among others, two world-leading laser facilities: ELI Beamlines in the Czech Republic and ELI ALPS in Hungary. A distinguishing feature of ELI ERIC is the co-location of synchronized multiple high-power laser systems spanning the full parameter space relevant to LWFA — from kHz few-cycle TW systems (tens of mJ on target) ideal for high-average-power applications, to PW-class multi-Hz systems (tens of J on target) enabling GeV-scale acceleration.

The four commissioned beamlines — ALFA [7] and ELBA [8] at ELI Beamlines, and eSYLOS [9] and ePW [10] at ELI ALPS — form a unique complementary set of platforms built around different laser drivers, targeting various scientific priorities and covering a parameter space that is difficult to reproduce within a single laboratory. All beamlines follow a typical LWFA setup. A high-power laser is steered on an off-axis parabola (OAP), which focuses the laser on a gas target, creating non-linear plasma waves, which accelerate electrons to relativistic energies. The beamlines have proper radiation protection solutions and offer motorization of the necessary hardware to allow remote-controlled experiments. The present paper provides an overview of these four beamlines, by summarizing their laser drivers and the beam parameters.

HIGH REPETITION BEAMLINES

The high repetition beamlines at the facilities are driven by their respective OPCPA laser systems with up to 1 kHz repetition rate, achieving relativistic intensities (> 10^{18} W/cm^2) and long, stable operation runs (> 4 hours).

ALFA is driven by the ELI Beamlines L1-Allegra laser, operating at 40 mJ, 15 fs (FWHM), 1 kHz. The beamline offers a compact focus geometry and an all-reflective dielectric optics setup that eliminates thermal instabilities.

The ALFA accelerator (shown in Fig. 1(a)) delivers ultra-short (few fs) electron beams at a tunable frequency (up to 1 kHz) with energies up to 50 MeV [11]. To allow stable operation over hours of kHz LWFA beams, a differential pumping system [12] is used to allow continuous flow of Nitrogen and Helium from the gas-jets [13]. The electron beams are characterized with a calibrated spectrometer [14]. In the ALFA beamline is possible to irradiate cm-size samples in-air with an average dose rate up to 30 Gy/min and a sub-mrad target alignment precision [15]. This allowed the first pre-clinical irradiations of in-vivo zebrafish embryos to study the potential sparing effect of laser-driven ultrashort radiation while maintaining anticancer efficacy.

eSYLOS beamline (shown in Fig. 1(b)) at ELI-ALPS is driven by the SYLOS3 (120 mJ, 8 fs, 1 kHz) or SEA (30 mJ, 13 fs, 10 Hz) lasers. Thanks to the reliability of the SYLOS driving lasers, this beamline offers high day-to-day throughput and User availability, in stable and repeatable operation modes with a large, configurable acceleration chamber to adapt the beamline to various experiments. The beamline allows further optimization of acceleration via in-situ gas mixing, with electron cutoff energies reaching and exceeding 100 MeV and electron charges of 50 pC.

The beamline also can provide ultrashort electron beams to the dosimetry (IFIR) and x-ray (XSYLOS) end stations. The main application areas of eSYLOS are radiobiological irradiation, soft x-ray pump-probe experiments and the study of tertiary sources (positrons, photoneutrons, THz). In practice, this creates a flexible platform for radiation-biology studies, reaching the VHEE regime, detector development and experiments that exploit the natural synchronization of laser, electron and secondary X-ray signals.

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Figure 1: The kHz LWFA beamlines available at ELI ERIC: (a) The ELI-Beamlines ALFA based on L1-Allegra laser and (b) the ELI-ALPS eSYLOS based on SYLOS lasers.

HIGH ENERGY BEAMLINES

ELBA is driven by the ELI Beamlines L3 HAPLS laser, operating at 430 TW, 30 fs on target, with a repetition rate ranging from shot-on-demand up to 3.3 Hz.

ELBA (shown in Fig. 2(a)) is an all-optical laser-electron collider to enable strong-field QED research. The laser driver is split into two synchronized pulses in the interaction chamber. One pulse is used to produce electron beams with energy up to 3 GeV, 10 pC charge and 1 mrad beam divergence [16]. The second pulse is focused onto the electron beam approaching a target intensity of 10^{21} W/cm^2.

The interaction of GeV electron beams with the 2 m-thick concrete beam dump allows the generation of muons which are available to users.

The ePW beamline is the high-energy counterpart at ELI ALPS, with its 1st User experiment during Q2 2026. ePW is a GeV-class LWFA platform (shown in Fig. 2(b)) aimed at producing energetic electron beams and hard Betatron X-rays, up to 10 Hz. It is driven by the HF PW laser (currently running at 12 J, 20 fs, 2.5 Hz).

The ePW's unique feature is the interchangeable dual focusing geometry (f/55 and f/15), allowing different intensities to be reached on target, with minimal turn-over time. Broadband hard (> 30 keV) X-ray generation (Betatron radiation) and studies relevant to phase-contrast imaging (micro-CT) and VHEE radiotherapy-related research can be easily and swiftly explored [17-18]. This makes ePW especially important for projects where compactness, femtosecond synchronization and high peak dose or peak brightness matter more than the narrow-band structure typical of conventional accelerator sources.

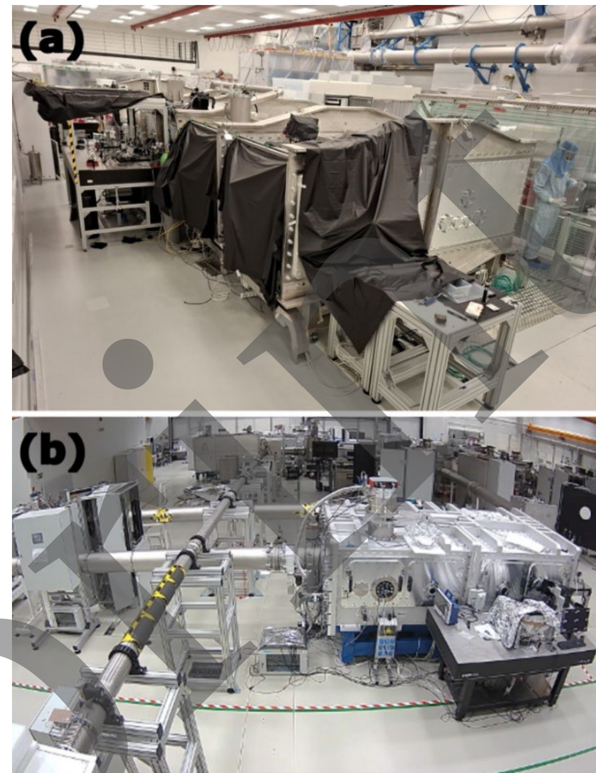

Figure 2: High-energy LWFA beamlines available at ELI ERIC: (a) The ELI Beamlines ELBA based on L3-HAPLS laser and (b) the ePW beamline at ELI-ALPS.

Table 1: Overview of user proposals per instrument, over the first 3 years of operation.

Beamline	Submitted	Awarded	%
L1-ALFA	33	15	45
L3-ELBA	36	12	33
eSYKLOS	26	11	42
ePW	5	3	60
Total	100	41	41

Table 2: Overview of user proposals per scientific area, over the first 3 years of operation.

Area	Submitted	Awarded	%
Plasma Physics	26	9	35
Acceleration	37	15	41
Irradiaftion	37	17	46
Total	100	41	41

CONCLUSION

ELI ERIC operates four laser wakefield electron accelerator beamlines spanning an unprecedented range of electron beam parameters and scientific applications.

The ALFA and eSYLOS beamlines, driven by kHz TW laser systems, are the state-of-the-art high repletion-rate application-facing frontier of LWFA, where reproducibility, statistics and high flux (high dose rates) are central.

The ELBA and ePW beamlines, driven by PW-class multi-Hz lasers, extend the portfolio into GeV regime range; enabling cutting-edge experiments in QED [19], laser–electron collisions, radiobiology and radiotherapy investigations [20] and muon production [21].

The beamlines are offered twice a year through the ELI ERIC User Call. In the first 3 years of operation, the four beamlines have received a total of 100 user proposals with an average acceptance rate of 41%. These are divided in 3 scientific area: plasma physics, wakefield acceleration, and irradiation of samples.

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