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PLASMA ACCELERATOR BASED FREE ELECTRON LASER PROGRAM AT ELI-ERIC (ELI-BEAMLINES)*

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Abstract

The plasma accelerator-based Free Electron Laser research program at ELI-ERIC (ELI-Beamlines, Czech Republic) intends to utilize unique qualities of plasma accelerators to build FELs with remarkable brightness, coherence and pulse length. The program is based on the novel high-power high-repetition-rate laser system, which is under preparation at ELI-Beamlines. The program entails expanding the LUIS experimental setup to test and validate the performance of the laser-plasma accelerator based extreme ultra-violet (EUV) FEL, integrating high-power laser, plasma source and electron beam transport line with relevant diagnostics to create a comprehensive test bed for the development of the EuPRAXIA LPA-based FEL. The plasma accelerator based FEL development program at ELI-Beamlines represents an innovative effort to expand the capabilities of FEL technology and open new possibilities for scientific research and industrial applications. In this report, we will examine the progress of key technologies at ELI-ERIC (ELI-Beamlines) and the primary challenges facing this Program.

INTRODUCTION

Recent advances in laser technology [1], improved acceleration gain, and upgrades in electron beam quality have paved the way for the development of an extremely compact high-energy electron beam accelerator that utilizes laser-plasma interaction. The ongoing progress in Laser Wakefield Acceleration (LWFA) methods positions it as a highly appealing option for innovative, compact undulator radiation sources. Several research groups have successfully acquired electron beam characteristics through laser-plasma interaction in the compact laser-plasma accelerator (LPA), showcasing the generation of incoherent photon radiation in a compact undulator. This significant advancement has been documented in multiple research papers [2]. Nowadays, the main focus is on improving the LPA-based electron beam quality to utilize it for generating coherent undulator photon radiation through the Self-Amplified Spontaneous Emission (SASE) regime of a Free Electron Laser (FEL) [3]. The innovative LPA-based source of incoherent and coherent photon radiation has garnered attention for applications in medicine [4] and industry [5].

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A compact LPA-based undulator radiation source is presently under preparation at ELI-ERIC in the Czech Republic within the LUIS research program. Once commissioned, it will provide the user community with a high repetition rate of incoherent soft X-ray radiation for high-temporal-resolution pump-probe experiments, as well as XANES spectroscopy and high-resolution microscopy.

The main objective of this project is to enhance the quality of the LPA-driven electron beam to go from incoherent to coherent operation in the extreme ultraviolet spectrum. This will enable the creation of a compact LPA-driven FEL customized for users, utilizing a ”200 TW-class” laser system with a repetition rate of up to 100 Hz. The setup will serve to test main technologies required to realize the LPA-based ”soft” X-ray FEL, which is one of the objective of the EuPRAXIA Project [6].

KEY COMPONENTS OF A LPA-BASED COMPACT FEL SETUP

Below we provide an overview of the current status of the development of the key components of LUIS technology at the ELI-Beamlines Facility, which will be prepared during realization of the research program.

Laser Development

The new LUIS-dedicated high-repetition high-power laser system, currently under development at ELI-ERIC (referred to as the ”L2-DUHA” laser) [7], is based on OPCPA technology. Once commissioned, it will generate two pulses. The primary laser pulse will reach energy levels up to 4 J (with a pulse duration of 25 fs and a wavelength of 820 nm). Additionally, the same laser will produce an auxiliary laser pulse with energy in the range of a few mJ, a pulse duration of 30 fs, and a wavelength around 2.2 μm. The primary laser pulse will be used for electron beam acceleration, while the auxiliary laser pulse will serve the purpose of pump-probe experiments. The auxiliary laser beam can be used also to generate a seeding FEL signal, which will be fully synchronized with the electron beam at the undulator entrance.

The primary objective of the DUHA-laser development is to achieve high-repetition rate operation, starting at 20 Hz and increasing to 100 Hz after an upgrade of the cooling system. Based on the laser-plasma acceleration modeling [8], this laser system can accelerate the electron bunch to an energy of approximately 1000 MeV with a bunch charge of at least 50 pC. Based on the current schedule of the ELI-Beamlines facility operation, the L2-DUHA laser system

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is set to deliver its first light to the LUIS target chamber in early 2025.

Laser-plasma Compact Accelerator

Typical parameters, as demonstrated by multiple groups recently, indicate that generating an electron beam with a few hundred MeV energy, a FWHM relative energy spread of a few The quality of the LPA electron beam is heavily influenced by the injection mechanism and its parametric dependencies. The self-truncated ionization-induced injection mechanism [9], along with beam loading [10] and energy chirp manipulation [11], is considered the most promising technique for controlled injection and acceleration processes in compact laser-plasma accelerators.

A systematic and comprehensive study was conducted using PIC simulations [8] to achieve high-quality electron beams resulting from laser-plasma interaction in a single gas cell. This study utilized a combination of self-truncated ionization-injection (using a mixture of nitrogen and hydrogen gases) and acceleration in pure hydrogen gas.

The effect of beam loading on the properties of accelerated electron beams at various stages of evolution has been analyzed and discussed. According to the obtained results, using the laser with 50 TW peak power and 30 μm (FWHM) spot size after the proper optimization, including the position of the focus, gas mixture and distance of the injection/acceleration area, one can obtain the electron bunch with the energy of 500–600 MeV with the relative (FWHM) energy spread is below 4 %, the normalized (RMS) beam emittance is ~ 1.5 π mm-mrad. The bunch charge is approximately 20–50 pC in this case.These findings are well suited for the needs of incoherent undulator physics and will be beneficial for the associated experimental efforts at the ELI Beamlines facility following the deployment of the compact LP-accelerator, utilizing the high-repetition rate L2-DUHA laser system. However, further optimization of the laser-plasma interaction in the gas-cell is necessary to meet the SASE-FEL criteria for the development of the LPA-based EUV-FEL. The commissioning of the LPA-based compact accelerator will be performed as soon as the laser beam is delivered to the experimental setup.

Electron Beam Transport

Free-electron lasing in the extreme-ultraviolet range of the photon wavelength was experimentally demonstrated recently utilizing the LPA-based setup [12]. The EUV-FEL setup at ELI-Beamlines aims to achieve power saturation of coherent photon radiation in a single undulator section with the length less than 4 m long. To reach this objective, the electron beam transport system must efficiently capture electrons from the compact LP-accelerator, transport the electron bunch while minimizing transverse emittance dilution, control the ”slice” parameters of the electron bunch, and match the electron beam to the undulator at the end of the beamline [13]. Moreover, the electron beam transport system should also accommodate relevant electron beam diagnostics.

A dedicated electron beam transport for the LPA-based EUV-FEL has been designed, assuming the electron bunch at the exit of the compact accelerator with the following parameters, demonstrated experimentally by different groups [14], [15]: the central energy of the bunch is around 350 MeV; the RMS relative energy spread is 0.5 % ; the bunch charge is in the range of 30-50 pC; the transverse normalized RMS emittance in both transverse phase-planes is 0.3 π mm-mrad; the transverse RMS divergence of the beam is 0.5 mrad; the RMS bunch duration is 3 fsec.

To maintain the transverse normalized emittance at a suitable level for the FEL regime, it is essential to minimize the distance between the compact LPA-based accelerator and the capture block. It can be achieved by utilizing a series of permanent quadrupole magnets or an active plasma lens [16]. Preparations are currently underway at ELI-Beamlines to integrate the active plasma lens technology with other components of the electron beamline.

Control of the ”slice” energy spread can be performed by utilizing a magnetic chicane [17] through a variation of the bending angle in the individual dipole magnet of the decompressor. To maintain the peak current at the required level for the ”slice” (to prevent extending the saturation length in the case of the SASE-FEL regime), it is essential to increase the bunch charge for a larger bending angle. It is necessary to stress that in the case of large bending angle in the magnetic chicane the CSR effect [18] will lead to significant dilution of the transverse emittance of the electron bunch [19].

The last elements of the dedicated electron beam transport system are the ”matching” set of quadrupole magnets and the collimation section. These components are used to match the transverse parameters of the electron beam with the undulator and to remove the halo of the electron bunch caused by chromatic and collective effects [13].

Undulator for LPA-FEL

The basic design of the entire EUV LPA-based FEL setup is based on the parameters of the hybrid permanent magnet undulator similar to the ”Aramis” undulator line of SwissFEL [20]. The undulator period is 15 mm, providing the undulator coefficent of 1.1 for the gap size of 5 mm. The length of one undulator unit of ”Aramis” line is 4 m. The 1D-Pierce parameter for the initial electron beam parameters, specified above, for such undulator is 0.006, which leads to significant limitation of the ”slice” energy spread, which should be less than 0.3 % in such a case. Detailed analysis of the SASE-FEL regime allow to indentify the required ”slice” electron beam parameters, which should be obtained at the entrance of the undulator, in particular, the required RMS relative energy spread of the electron bunch, the peak current and the RMS transverse normalized emittance.

By controlling the ”slice” energy spread of the electron bunch using the magnetic chicane as the part of the electron beamline and by cutting the transverse halo of the electron beam after the matching section it is possible to reach the saturation of the photon radiation power at the length of

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3-4 m [16]. Comprehensive ”start-to-end” simulations are needed to define required for injection errors, field imperfections and misalignments of main components the the entire setup.

By utilizing the external seeding, based on the auxiliary laser pulse mentioned above, it is possible to reduce the saturation length and improve the coherence of the photon radiation [13]. In the case of the EUV-FEL regime, the seeded signal can be generated by using the ”high-harmonic-generator” technique [21], which is under developing at ELI-beamlines.

Main parameters for each key technology for the LPA-based EUV-FEL setup are summarized in Table 1. The total expected length from the laser-plasma interaction point incuding the undulator and the photon beam transport is around 25 m. After the undulator the electron beam will be sent to the electron beam spectrometer and pumped into the radiation protection block.

Table 1: Main Parameters

Laser		
Pulse energy (nominal)	Joule	3
Central wavelength	nm	820
Pulse duration	fsec	25
Repetition rate	Hz	50
LPA-Accelerator		
Plasma density	10^{18} cm^{-3}	2-5
Plasma length	mm	20
”Slice” electron beam		
Electron beam energy	MeV	350
Peak current	kA	3
Normalized (RMS) emittance	mm.mrad	0.4
RMS relative energy spread	%	0.25
Photon radiation (K=1.1)		
Photon energy	eV	48.4
Radiation wavelength (h=1)	nm	25.6
Wavelength bandwidth	%	0.24
Total photon flux	10^{13} ph	1.3
Peak power at saturation	GW	4.2
Photon peak brilliance (0.1%bw)	10^{29}	1.4
Saturation length	m	< 4

The start-to-end simulations of the electron beam dynamics with collective effects and the generation of the coherent photon radiation in the chosen undulator have been performed [13] by using the optimized set of the decompressor chicane. The SASE-FEL regime in the case of a single-unit undulator with the has been studied, using the SIMPLEX code [22], to confirm the saturation of the radiation power at the exit of the undulator including an external seeding to improve the longitudinal coherence of the generated photon pulse.

The saturation of the photon pulse energy can be reached after approximately 4.5 m if the initial projected RMS energy spread of the laser-driven electron beam is 0.5 % and the slice ”peak” current is 3 kA. If the initial projected RMS energy spread is increased to 1 % the saturation of the photon pulse energy along the same undulator can not be obtained. The effect of the halo of the electron beam, caused by the collective effects and the chromatic aberrations, is shown in Figure 1. Applying collimation reduces the ”slice” normalized emittance, leading to a saturation length below 4 m. In order to compensate for the finite propagation efficiency (which is around 85 % without any injection errors), it is necessary to increase the bunch charge of the initial electron beam.

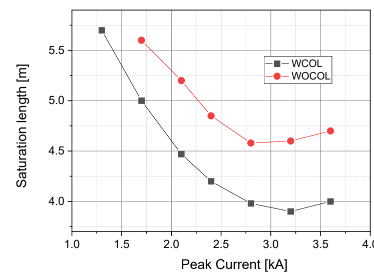

Figure 1: Saturation length as a function of the peak current for the optimized decompressor angle without (WOCOL) and with (WCOL) the collimation of the beam halo at the undulator entrance.

The successful execution of the LPA-based EUV-FEL Program at ELI-Beamlines will enable the utilization of this setup for the user-oriented program and progress towards the realization of the LPA-based ”soft” X-ray FEL project, a goal of the EuPRAXIA development program.

User-oriented Program

For the EUV-case the photon beam transport will be build to (1) characterize the photon radiation and (2) focus the photon beam into a user-oriented chamber. There are several experimental topics to explore the advantages of coherent and high-flux EUV radiation, which will be proposed to the user-community: coherent diffraction imaging; scanning microscopy; spectroscopy and metrology. With implementation of pump-probe techniques at the LUIS beamline, XANES spectroscopy gives a tool for tracking state-resolved carrier motion in quantum materials [23]. The EUV spectral range is also suitable for plasma absorption spectroscopy experiments [24] and for low-temperature laboratory astrophysics [25].

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