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CONCEPTUAL DESIGN OF THE LASER-PLASMA ACCELERATOR BASED SOFT X-RAY FREE ELECTRON LASER*

A. Molodozhentsev†, T. Green, B. Rus, A. Whitehead, S. Maity, P. Sasorov, A. Jancarek,
M. Albrecht, M. Miceski, S. Niekrasz, P. Zimmermann
ELI-ERIC (ELI-Beamlines), Donli Brezany, Czech Republic

Abstract

Conceptual design of the laser-plasma based soft X-ray Free Electron Laser, which is under preparation at ELI-Beamlines, involves integration of a novel high-power high-repetition-rate laser, plasma source, a compact LPA-based electron beam accelerator, dedicated electron beam line with relevant diagnostics, undulator beam line, photon beam line with required diagnostics and photon beam distribution systems to deliver the photon beam to a few user stations. The proposed concept of the whole setup is optimized to produce high-quality, coherent X-ray pulses with femtosecond duration in the 'water-window' range of the wavelength of the fundamental photon radiation, which will be used by the photon user community for expiring research in the field of biology to study biological structures and processes at the cellular and molecular level at high resolution. In this report, we outline the conceptual design of the full setup to be integrated into the existing infrastructure of the ELI-Beamlines Facility. We also address the main challenges and the Project's role in the EuPRAXIA collaborative activity.

INTRODUCTION

While undulator radiation is widely used in synchrotron radiation sources to generate high-brilliance ultraviolet and X-ray beams, a boost in intensity by many orders of magnitude is achieved in Free Electron Lasers (FELs) due to the interaction of the electrons with the radiation field generated in the undulator. Compared to storage-ring based synchrotron radiation sources, LINAC-based SASE FELs are capable of providing typically eight orders of magnitude higher peak brilliance with pulse lengths of about 50–100 fsec and almost full transverse coherence. LINAC-based FELs are now poised to take centre stage as the premier source of tunable, intense, coherent photons of either ultra-short time resolution or ultra-fine spectral resolution, from the far infrared to the hard X-ray regime.

Desired characteristics of next generation X-ray light sources include full transverse and temporal coherence, pulse durations extending to femtoseconds and possibly attoseconds, high peak and average flux, rapid tunability of photon energy, and full polarization control. Nowadays, laser-plasma-based compact accelerators (LPA) can generate high-energy high-quality electron bunches [1] with the duration of a few femtoseconds, which already used for the lasing of the photon radiation in undulators [2].

The ongoing activity at ELI-ERIC (ELI-Beamlines) involves expanding the LUIS experimental setup to evaluate and authenticate the efficiency of the laser-plasma accelerator-driven extreme ultra-violet (EUV) FEL [3]. The plasma accelerator-driven FEL program at ELI-Beamlines signifies a pioneering endeavor to broaden the scope of FEL technology and unlock novel avenues for scientific exploration. This entails merging a high-power high-repetition-rate laser, plasma source, and electron beam transport line with diagnostics integrated into the setup to establish a comprehensive testing environment for the advancement of the LPA-based soft X-ray FEL, which is the one of the objective of EuPRAXIA Consortium [4]. This report outlines a conceptual design of the soft X-ray (water-window) LPA-based FEL complex, which can seamlessly integrate into the current infrastructure of the ELI-Beamlines facility, augmenting its attractiveness for synchrotron-light users.

MAIN PARAMETERS OF KEY COMPONENTS

To minimize the facility layout, it is crucial to address design constraints and determine key parameters of the LPA-based compact FEL setup. The primary goal is to attain a particular wavelength for coherent undulator radiation, ideally falling within in the range of 3–5 nm (the photon energy around 270 eV). In the case of the LPA-based FEL, the length of the undulator line, combined with the photon beamline to the user stations, will determine the total space required for the setup and significantly impact the construction cost [4].

Undulator Technology

There are two basic approaches which it is necessary to consider to choose a proper undulator technology for a future LPA-based FEL: super-conducting undulator (SCU) and permanent magnet undulator (PMU). Both technologies are well developed in EU. The following benefits of SCU [5] over PMUs should be emphasized: SCU enables the construction of a more compact FEL undulator line; SCU provides improved tunability of the photon beam by achieving high peak field with the same geometry as PMU (specifically, the undulator period and undulator gap size). As a result, the proposed upgrade of existing LINAC-based FEL facil-

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† Alexander.Molodozhentsev@eli-beams.eu

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ities is based on the SCU technology [5] with a period of 15 mm, and a vacuum gap of 6 mm, providing the undulator K-parameters of 1.6.

In this case, to get a radiation wave length of 4–5 nm, the electron beam energy should be around 1000 MeV, which is the first goal of the EuPRAXIA Project [4]. At the beginning of the conceptual design a SASE-FEL analysis using 1D and 3D models [6] was conducted, assuming a Gaussian distribution of electrons in the bunch. The key constraints on the LPA-based electron beam and corresponding coherent photon radiation parameters have been determined. The findings suggest that to maintain a (3D) saturation length of approximately 25 m in the case of the electron beam energy of 1000 MeV the electron bunch in the undulator should have the following parameters: the bunch charge of around 35 pC with the RMS bunch duration of 3 fsec (the corresponding peak current is 2.5 kA); the RMS "slice" normalized transverse emittance of 0.4 π mm-mrad; the RMS "slice" relative energy spread of roughly 0.3 %; the RMS average transverse size along the undulator of about 35 μm. Similar parameters of the electron beam, obtained using the laser-wakefield-acceleration approach have been experimentally demonstrated in a compact (1–2 cm) laser-plasma interaction zone using a moderate power level (around 100 TW in the focus) of the compressed laser pulse with the pulse duration of 30 fsec [1].

Laser-Plasma Accelerator

Basic parameters for the laser system and the compact laser-plasma accelerator are estimated using the LPA-scaling approach [7]. This approach helps in determining the main parameters of the laser and the compact laser-plasma accelerator. The current experimental results also show the range of LPA-parameters necessary to achieve a high-quality electron bunch with an energy of around 1000 MeV.

The laser system to be used at ELI-Beamlines for the LPA-based FEL development, known as the L2-DUHA laser system [8], has the following specifications: pulse energy of 3 Joules, pulse duration of 25 fsec, laser wavelength of 820 nm, and repetition rate of 50–100 Hz. Additionally, this laser system will produce a fully synchronized auxiliary "infra-red" pulse with a pulse energy of a few mJ, which can be used to provide the seeding signal.

To get a 1000 MeV electron beam, a 100–120 TW laser pulse power focused with a 30 μm laser spot radius is essential. This results in a laser intensity around (3–5)×10^{18} W/cm^2 at the focus, with a normalized vector (a_0) of approximately 1.5–1.8. The required plasma density (n_0) should range between (1–3)×10^{18} cm^{-3}. The estimated acceleration length, constrained by the dephasing effect, is not less than 50 mm. More specific parameters of the laser-plasma accelerator will be determined following an optimization of the laser-plasma interaction to generate the necessary high-quality electron beam.

The novel LPA-based accelerator, integrated into the infrastructure of the ELI-Beamlines facility, is under development. The commissioning of the compact accelerator is set to begin in the first half of 2025, with the goal of accelerating high-quality 1000 MeV electron beams at a repetition rate of up to 100 Hz.

Based on the published experimental results, obtained recently [1], we are aiming to obtain the following parameters of the 1 GeV electron beam at the exit of the plasma: the RMS normalized (projected) emittance of 0.35 π mm-mrad; the RMS relative (projected) energy spread of 0.3 %; the RMS transverse beam size of a few μm; the RMS transverse beam divergence of 0.3 mrad; the bunch charge of around 30 pC and the RMS bunch duration of 3 fsec. To achieve the demanding parameters of the LPA-based electron beam, optimizing the self-injection and acceleration mechanisms in the plasma is essential [9, 10].

Electron and Undulator Beamlines

The conceptual design of a dedicated electron beamline to transport the electron bunch from the compact accelerator to the undulator section has been completed. This beam transport system must carry out the following tasks: capturing the electron beam from the plasma exit of the laser-plasma accelerator, manipulating the electron bunch in the transverse and longitudinal planes, and matching the electron beam with the undulator section. At the moment, the conceptual solution is based on a combination of the permanent quadrupole magnets (used in the capture block of the beamline) and electro-quadrupole magnets (used in the "halo" cleaning section and in the "matching" section) [11]. To control the "slice" parameters of the electron bunch (specifically the "slice" energy spread to fulfill the SASE-FEL requirements), the magnetic chicane, consisting of 4 dipole magnets, needs to be incorporated into the electron beam transport [12] .

The electron beamline has enough space to install required diagnostics to control the electron beam along the beam transport, including the correction of the beam position, measuring the electron beam emittance and the bunch charge. Near the undulator section it is necessary to measure the longitudinal parameters of the bunch, controlling the energy spread, the normalized emittance and the peak current. We plan to implement transverse deflecting structure technique, based on the THz-based deflector [13], utilizing the L2-auxiliary laser pulse synchronized with the main L2-laser pulse used for electron acceleration.

To guide the electron bunch through the series of the undulator sections (7 units of the SCU planar undulators with a 3.5 m length), one may employ the QF-U-QD-U focusing arrangement with a 7.5 cm quadupole magnet length between each undulator section, featuring a maximum magnetic field gradient of 15 T/m. The distance between each undulator section is around 50 cm to place the phase shifter in addition to the quadrupole magnet.

Saturation of the photon beam energy at the end of the undulator line is presented in Figure 1. The conceptual study of the SASE-FEL regime has been performed by using the SIMPLEX code [14]. The spectrum of the flux density of the radiation at the saturation contains just a few peak, representing the advantage of the LPA-based FEL in comparison

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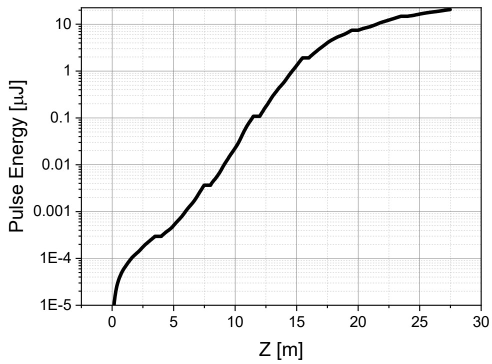

Figure 1: Photon pulse energy along the undulator sections for the LPA-based SASE-FEL with the photon energy of 278 eV.

with the LINAC-based FEL, which makes the novel compact FEL extremely demanding from the worldwide user community. Comprehensive start-to-end simulations are required to optimize the LPA-based FEL setup.

Main parameters of the main components of the LPA-based soft X-ray FEL are collected in the Table 1.

Photon Beamline and User Stations

The benefits of femtosecond laser-like properties of coherent photon radiation will unlock new scientific frontiers, as demonstrated in next-generation experiments previously out of reach with lower-flux or incoherent synchrotron radiation sources due to their longer photon pulse duration. Coherent soft X-ray radiation opens up new opportunities for imaging, such as high-resolution 'water window' microscopy of biological specimens (e.g. viruses, bacteria, living cells, etc.), full-field microscopy, and lensless imaging techniques like coherent diffraction imaging (CDI) and ptychography, as well as high-resolution tomography for 3D imaging. Coherent imaging holds significant promise for applications in the biological and life sciences, environmental studies, and in comprehending the fundamental processes involved in material treatment and chemical reactions. To make the LPA-based FEL more user-friendly and allow for sharing the photon beam, incorporating a multi-user station design for the photon beamline is essential.

With the ability to use both laser pulses and soft X-ray pulses as pump and probe sources, improvements in pump-probe imaging, spectroscopy, metrology, and studies on optical material damage will be accessible to users. There will be an option of using two types of laser pulses ($\lambda \sim 820$ nm, $\tau \sim 30$ fs, or $\lambda \sim 2.1$ µm, $\tau \sim 50$ fs) for the pump-and-probe experimental implementations. With flexible sample delivery systems and pump-probe techniques, user-oriented soft X-ray beamlines at this stage will enrich many experiments on physical, chemical and biological phenomena [15].

Table 1: Main Parameters

Laser		
Pulse energy (in focus)	Joule	2.5
Central wavelength	nm	820
Pulse duration	fsec	25
Laser intensity in focus	10^{18} W/cm^2	5
Laser spot (FWHM in focus)	µm	35
Repetition rate	Hz	100
LPA-Accelerator		
Plasma density	10^{18} cm^{-3}	1
Plasma length	mm	30
Normalized potential (a_0)		< 1.9
"Slice" electron beam		
Electron beam energy	MeV	1000
Peak current	kA	2.5
Normalized (RMS) emittance	mm.mrad	0.35
RMS relative energy spread	%	0.3
Photon radiation (K=1.6)		
Photon energy	eV	278
Radiation wavelength (h=1)	nm	4.5
Wavelength bandwidth	%	0.1
Total photon flux	10^{11} ph	1.0
Peak power at saturation	GW	0.5
Photon peak brilliance	10^{29}	3.0
Saturation length	m	27
Length without Photon Line	m	50

INFRASTRUCTURE AND POTENTIAL TIMETABLE

According to the conceptual design of the LPA-based soft X-ray FEL, the total setup length is around 80–90 m, from the laser-plasma interaction area to the photon user chambers. This can be integrated into the existing infrastructure of the ELI-ERIC (ELI-Beamlines) facility. The dedicated laser system, the L2-DUHA laser at ELI-Beamlines, is set to start operating in early 2025. Preparation of the LPA-based soft X-ray FEL, depending on financial support, can be completed by mid-2027 to send the first photon beam to the user-station in the first half of 2028. Organizing the collaborative activity of the EuPRAXIA Consortium is crucial to achieve this goal at ELI-Beamlines.

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