ISBN: 978-3-95450-224-0 ISSN: 2673-7035 doi:10.18429/JACoW-FLS2023-TH2C2

DEVELOPMENT OF LASER-DRIVEN PLASMA ACCELERATOR BASED UNDULATOR RADIATION SOURCE AT ELI-BEAMLINES

A. Molodozhentsev†, J. T. Green, A. Mondal, S. Maity, S. Niekrasz, E. Vishnyakov, A. Jancarek, P. Zimmermann
Extreme Light Infrastructure ERIC, ELI-Beamlines, Dolni Brezany, Czech Republic

Abstract

A compact undulator radiation source based on a laser-driven plasma accelerator (LPA) is currently being commissioned at ELI-Beamlines (ELI-ERIC, Czech Republic). An intermediate goal of this activity is to deliver a stable and repeatable incoherent photon beam with a wavelength of about 4 nm to a user station. As a result of this development, the electron beam parameters will be improved, with the aim of producing a coherent photon beam, utilising a dedicated FEL undulator. An overview of the current status of the project (LUIS) is presented in this report, including the high-power high-repetition rate laser, the compact electron beam accelerator based on the laser-plasma interaction, and the electron and photon beamlines with relevant diagnostics. The challenges and future developments of the LUIS project, aimed at LPA-based EUV-FEL, will also be discussed.

INTRODUCTION

The scientific success and tremendous demand from the photon beam user community stimulate intensive research to find competitive approaches which would lead to a significant size and cost reduction of the instruments for both incoherent and coherent photon beams.

Constantly developing Laser Wakefield Acceleration (LWFA) techniques make it a very attractive candidate for novel, compact undulator radiation sources, especially in the light of recent progress in the laser technology [1], acceleration gain [2] and breakthroughs in electron beam quality improvement [3]. With the electron beam properties, obtained experimentally by different teams as the result of the laser-plasma interaction in the compact laser-plasma accelerator (LPA), a generation of the incoherent photon radiation in a compact undulator has already been demonstrated [4-6].

Nowadays main effort is concentrated on the improvement of the LPA-based electron beam quality to be able to use such a beam to generate a coherent undulator photon radiation utilizing the so-called Self-Amplified Spontaneous Emission (SASE) regime [7] of a Free Electron Laser (FEL). The novel LPA-based source of incoherent and coherent photon radiation has attracted interest for applications in medicine [8] and industry [9].

A compact LPA-based undulator radiation source (LUIS) is currently under development at ELI-ERIC in the Czech Republic. After the commissioning, it will bring to the user community a high repetition rate (50-100 Hz) of soft X-ray radiation aiming for high-temporal-resolution pump-probe experiments, combined with XANES spectroscopy and high-resolution microscopy.

The main goal of this development is to improve the quality of the LPA-based electron beam to make this beam usable for not only for the incoherent regime but also for the coherent one in the extreme ultra-violet range of the radiation wavelength (for the fundamental harmonic). It will open the way to prepare the user-oriented compact LPA-based FEL, based on the 100 TW-class laser system with a repetition rate up to 100 Hz.

DEVELOPMENT AT ELI-BEAMLINES (ELI-ERIC)

The Extreme Light Infrastructure (ELI-ERIC) is the world's largest and most advanced high-power laser infrastructure and a global technology and innovation leader in high-power, high-intensity and short-pulsed laser systems. ELI-beamlines, as a part of ELI-ERIC, locates near Prague (Czech Republic). ELI-beamlines is a unique infrastructure in the field of photonic-based user-oriented research and the first large-scale facility in this worldwide domain. The specific nature of the ELI-beamlines user facility is its multi-disciplinary features, which open extremely wide opportunities for the user community to develop new secondary radiation and particle sources, creating new paths of applied and fundamental research, pushing the boundaries of science and technology.

Laser Development at ELI-beamlines

New LUIS-dedicated high-repetition high-power laser system is under development at ELI-ERIC (L2-DUHA laser) [10], based on the OPCPA technology, will deliver two pulses: the main laser pulse with energy of up to 5 J, 25 fs pulse duration and the wavelength of 820 nm, as well as the auxiliary laser pulse with the energy of a few mJ, 30 fs pulse duration and the wavelength of around 2.2 μm. The main laser pulse will be focused in the prefilled gas-cell (or preformed plasma channel) to produce a high-quality high-energy electron bunch. The auxiliary laser pulse will be used for the pump-probe experiments.

At the moment the LUIS technology is integrated with the L3-HALPS laser. This laser system currently operated at a 3.3 Hz repetition rate and provides a pulse with a central wavelength of 820 nm, 30 fs pulse duration and a pulse energy of up to 13 J with a possible upgrade up to 30 J. In the case of the L3-LUIS operation, the maximum pulse energy of the cropped laser beam is limited by 1.5 J (before the L3 upgrade) or 3.5 J after upgrade.

† Alexander.Molodozhentsev@eli-beams.eu

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Both laser systems are suitable to accelerate the electron bunch with the parameters needed to generate the incoherent 'water-window' photon beam (the electron beam energy of 300-600 MeV and the bunch charge of the order of 50 pC).

Laser-Plasma Accelerator

Significant progress has been made to demonstrate to reach a few GeV energy of the electron beam using laser-plasma interaction [6], including machine learning [3] to produce stable and repeatable electron beams during the long-term continuous experimental activity.

Typical parameters, demonstrated recently by many groups, show that the electron beam with the energy of a few hundred MeV with the FWHM relative energy spread of 1-2% and the bunch charge of about 50 pC is achievable. However, the generation of high-quality electron beams still remains extremely challenging for a plasma-based accelerator.

The LPA electron beam quality depends strongly on the injection mechanism and its parametric dependence [11]. The self-truncated ionization-induced injection mechanism [12] in combination with the beam loading [13] and the energy chirp manipulation [14] is considered as the most promising technique for controlled injection and acceleration processes in the compact laser-plasma accelerator.

The LUIS setup at ELI-Beamlines is based on the LUX technologies, developed and tested at DESY in the collaboration between the University of Hamburg and ELI-Beamlines [4]. The compact laser-plasma accelerator, integrated into the LUIS Phase0 setup, is the gas-cell utilizing the 15 mm Sapphire capillary, which also can be used as the capillary with the preformed plasma for the laser guiding [15]. In the case of the gas-cell ('staged' LPA), the helium-nitrogen (90+10%) gas mixture will be utilized in the injection part of the gas-cell. In the acceleration part, pure helium gas with less pressure will be used. The results of the PIC-modelling will be published soon [16].

The performed LWFA PIC-simulations show [16] that the electron beam energy around 500-600 MeV can be obtained using the laser pulse energy of 1.5 J in the focus (laser intensity of 10^{19} W/cm^2) if the plasma density is around 1.6×10^{18} cm^{-3}. In this case, the FWHM relative energy spread is less than 5% and the FWHM transverse divergence is less than 1 mrad for the bunch charge of around 50 pC.

Such electron bunch can be used to generate the incoherent undulator radiation in the 'water-window' wavelength range, which is the intermediate goal of the LUIS development at ELI-Beamlines.

Incoherent Undulator Radiation Source

The incoherent LUIS setup at ELI-beamlines is based on the compact permanent-magnet undulator with the undulator period of 5 mm, the on-axis magnetic field of 0.6 T and the K-value of 0.28. The length of the undulator is 0.5 m. This unit will be placed at the end of a dedicated LUIS electron beam line. According to the LUIS commissioning plan, the electron beam line will be updated step-by-step aiming for the setup, which will integrate all required components [17] to: (1) capture the electron beam from the LPA source; (2) clean the halo of the electron beam, caused by the chromatic aberration effect; (3) control the 'slice' energy spread (needed for the coherent FEL regime) and focus the electron beam in the undulator. The electron beam line will be equipped with relevant diagnostics to measure the main parameters of the beam along the beamline [18].

The strength of the focusing elements is optimized to transport the electron beam with the energy from 300 MeV to 600 MeV. If the charge of the electron beam, which is propagating along the undulator, is 30 pC the following parameters of the photon radiation will be obtained: the photon energy and corresponding photon wavelength in the range of 165 eV (7.5 nm)-658 eV (1.8 nm); the number of photons per pulse in the 0.1% bandwidth from 1.7×10^5 to 7.1×10^6; the peak brilliance at the peak current of the electron bunch from 4.8×10^{20} to 1.9×10^{21} photons/pulse/mrad^2/mm^2/0.1%bw, respectively. The expected RMS transverse size of the photon beam in the undulator is around 110 μm in both transverse planes with the RMS divergence of around 80 μrad.

In order to focus the photon beam in the sample location a focusing ellipsoidal mirror will be placed in a photon beam chamber with x6 demagnification in the aberration-corrected regime allowing a small focal spot of the photon radiation better than 20 μm with later reduction up to at least 5 μm [19]. The incoherent photon beam will be used for the user-oriented operation, using the following user-operation modes: (1) focused non-dispersed beam in combination with the pump-probe option; (2) defocused non-dispersed beam and (3) monochromatic photon beam.

Using the LWFA scaling laws [20] and existing experimental results [15] one can predict that by using the L2-DUHA laser system the electron beam energy of 1 GeV is achievable at the early stage of the L2-DUHA laser operation with the laser power of around 150 TW. The discharge plasma formation setup is under development at ELI-Beamlines, which can be used for the laser guiding and/or as an 'active' plasma lens [21] to focus the accelerated electron beam into an electron beam line, required to transport electrons from the compact laser-plasma accelerator up to the undulator line.

Coherent Undulator Radiation Source

The incoherent LUIS setup at ELI-Beamlines can be transferred to the coherent one if the electron beam quality at the undulator entrance fits the criteria for the SASE-FEL regime. We are aiming to use a hybrid-permanent-magnet-undulator (planar-HPMU) type [22] with the undulator period (λ_u) of 15 mm, the undulator parameter (K_u) of 1.0-1.5 (depending on the gap size) and the total length of 4 m. In the case of the electron beam energy of 350 MeV, the energy and the wavelength of the photon radiation (the fundamental harmonic) are 44.5 eV and 27.8 nm, respectively.

The free-electron lasing at 27 nm based on the laser-plasma accelerator was already demonstrated experimentally by the group from Shanghai Institute of Optics and

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Fine Mechanics [23] by using the LPA-based electron bunch, propagating through 3 separated sections of the undulator with the length of 1.5 m each.

Using the 3D-model of the SASE-FEL regime ([24], [25]) we defined the parameters of the electron bunch, required to reach the saturation of the power of the photon radiation in one undulator unit ($L_{sat,3D} \sim 4$m). To get it, the electron beam energy should be around 350 MeV with the 'slice' RMS energy spread of less than 0.3 %. In addition, the transverse normalized RMS emittance should not exceed 0.3 π mm.mrad and the peak current has to be a few kA. The slice energy spread we are planning to control by utilizing the 'decompression-chicane' scheme [26], integrated into the dedicated electron beam transport [27]. Another possible approach to control the slice energy spread proposed recently is based on the usage of extra components, integrated into the electron beam line, in particular the X-band cavity [28] or the active plasma dechirper [29].

The initial RMS parameters of the LPA-based 350 MeV electron beam, which we used for our analysis, are based on the experimental results published recently [23]: the 'projected' relative energy spread is 0.5 %, the normalized emittance is 0.2 π mm.mrad, the transverse divergence is 0.5 mrad, the bunch length is 1 μm and the bunch charge is 40 pC (the corresponding peak current is 5.3 kA). Such a high initial peak current is required to provide the 'slice' peak current of the bunch in the undulator after the decompression. For such challenging initial parameters of the LPA electron bunch, the intrinsic growth of the normalized emittance [30] is negligible (the relative normalized emittance growth is less than 1% even after 20 cm for the bunch charge up to 75 pC).

For the comprehensive analysis, it is necessary to use the pre-simulation 6D particle distribution, obtained as the result of the comprehensive 3D simulations of the laser-plasma interaction and the laser wakefield acceleration.

The second effect which will lead to the dilution of the transverse emittance in addition to the space charge effect is the chromatic aberrations in the first block of the focusing elements. Comparison of the emittance growth in 3 possible combinations of the focusing elements, which can be utilized to capture the electron beam from the LPA-source, in particular: (1) triplet of the electro-quadrupole magnets; (2) combination of 2 permanent quadrupole magnets and one electro-quadrupole magnet [17] and (3) active plasma lens [21], shows that only the active plasma lens or the permanent quadrupole magnets should be used as the first block of the dedicated electron beam line for the compact LPA-based FEL setup.

The 'slice' energy spread control by using the 'decompression' chicane requires increasing bunch charge from LPA-source to get the peak current needed to get saturation of power of coherent photon radiation in one undulator unit with a length of 4 m. Nevertheless, collective effects [31] in the 'decompression' chicane with a relatively small bending angle ($R_{56} < 0.5$ mm) do not change significantly the electron beam parameters for the considered case.

At the same time, in order to clean the electron beam from the halo, caused by mainly the chromatic aberration and space charge effect, it is necessary to use a collimator (transverse slits) placed near the undulator. It will improve the transverse quality of the electron bunch at the end of the dedicated beamline without reduction of the peak current leading to a reduction of the saturation length (see Fig.1).

After the proper analysis of the 'slice' parameters of the electron bunch at the end of the electron beamline, based on the active plasma lens as the first 'capture' element of the dedicated beam transport, the lasing and saturation in one undulator unit were verified using the SIMPLEX-code [32] in the case of the LPA-based EUV FEL. The saturation length as a function of the resulting 'slice' peak current is presented in Fig.1 for two cases: without collimator before the undulator ("red" line) and with collimator ("black" like).

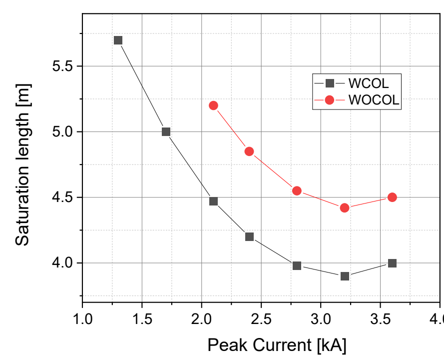

Figure 1: Dependence the saturation length on the peak current for the optimized decompressor parameters.

The saturation length is around 4m only in the case with the collimator if the "slice" peak current is around 3 kA. In order to get such a "slice" peak current the initial bunch charge should be around 60 pC. The bending angle of the dipole magnets in the decompression chicane should be around 0.9 degrees. The aperture of the collimator should be 0.8 mm. Comprehensive "Start-to-End" modelling is required to confirm the performance of the proposed setup.

CONCLUSION

Development of the incoherent undulator photon radiation source (LUIS), based on the compact high-repetition rate laser-plasma accelerator, is underway at ELI-Beamlines (ELI-ERIC). An upgrade of the LUIS technology to produce coherent EUV radiation using the SASE-FEL regime is in preparation aiming to achieve photon beam power saturation in the 4-m long undulator section. The main challenges of this project are the following: obtaining the required initial electron beam parameters from the modern LPA-based compact accelerator; maintaining the normalised emittance of the beam; controlling the 'slice' energy spread in combination with the beam charge; and matching and collimating the electron beam at the entrance of the undulator.

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