LASER-DRIVEN COMPACT FREE ELECTRON LASER DEVELOPMENT AT ELI-BEAMLINES

A. Molodozhentsev*, G. Korn, K. Kruchinin, J. Hawke, D. Kocon, T. Green, M. Kaur
ELI-BL, Institute of Physics of CAS, Prague, Czech Republic
A. R. Maier, University of Hamburg and CFEL, Hamburg, Germany

Abstract

ELI-Beamlines Centre, located near Prague (Czech Republic) is an international user facility for fundamental and applied research using ultra-intense lasers and ultra-short high-energy electron beams. Using the optical parametric chirped-pulse amplification (OPCPA) technique, the ELI-Beamlines laser system will provide the laser pulse energy up to 10 Joules with the repetition rate up to 25 Hz. Combination of new laser development with constant improvement of the LWFA electron beam parameters has great potential in future development of a next generation of the compact high repetition rate Free Electron Laser, which is extremely demanded by the X-ray community.

The LWFA-driven FEL project, called 'LUIS', is currently under preparation at ELI-Beamlines in collaboration with University of Hamburg. The goal of the project is improvement of the electron beam parameters in order to demonstrate the amplification and saturation of the SASE-FEL photon power in a single unit of a FEL undulator.

An overview of the LUIS project including design features and a description of all instrumentations used to characterize the laser, plasma, electron beam, photon generation is presented in frame of this report.

INTRODUCTION

Extreme Light Infrastructure (ELI) [1] was heralded by the European Community to develop in Europe a new type of large-scale laser infrastructure specifically designed to provide high peak power and focused intensity ultrashort pulses. ELI should be the world's first international laser research infrastructure implemented as a distributed research infrastructure based on 3 specialized and complementary facilities located in the Czech Republic, Hungary and Romania. ELI-Beamlines (located in Dolni Brezany, near Prague, the Czech Republic) will be the high-energy beam facility responsible for development and use of ultra-short pulses of high-energy particles and radiation stemming from the ultra-relativistic interaction. In particular, using laser systems in ELI-Beamlines it will be possible to accelerate electrons up to a few GeV.

The principle of the 'laser-wake-field-acceleration' (LWFA) [2] is based on an ultra-high longitudinal electric gradient, created by the high-intensity laser pulse focused in underdense plasma (in a gas-jet, gas-cell or capillary discharge targets). A travelling longitudinal electric field can reach several hundreds of GV/m, which is much larger than the accelerating field achievable in conventional accelerators, making LWFA extremely attractive as a compact ac-

celerator to provide high-energy beams for different applications. During last decades, a remarkable progress has been made in the field of electron acceleration based on the LWFA concept. Electron beams with peak energies of multi-GeV in a short plasma channel (a few cm) have been obtained experimentally [3].

Using these achievements [4] one can define the parameters of the LWFA electron beam at the exit of the plasma channel as following: the electron beam energy is in the range of $300 \div 1000$ MeV; the RMS transverse beam size in the horizontal and vertical plane is less than $1 \mu m$; the RMS transverse beam divergence in the horizontal and vertical planes is less than 1 mrad; the RMS bunch length is about $1 \mu m$; the RMS relative (total) energy spread is less than 1 %; the normalized RMS transverse beam emittance in the horizontal and vertical planes is 0.2 π mm.mrad and the bunch charge is about 50 pC.

The novel acceleration methods open a new way to develop a compact "laser-based" SASE [5] free electron laser (FEL) with the 'fsec' photon pulse length. We present the laser-driven 'demo'-FEL setup, which is under development at ELI-Beamlines. After commissioning this setup will deliver to users a photon peak brightness up to 10^{30} photons/pulse/mm^2/mrad^2/0.1%BW using a single undulator. The 'laser-driven' FEL at ELI-Beamlines can operate with high repetition rate (up to 50Hz), which is limited by the current 'state-of-art' of the laser technology. Successful realization of the 'demo'-FEL research program at ELI-Beamlines will open a new perspective in development of compact soft and hard X-ray FELs with few or even sub-femtosecond photon bunches for a very wide user community.

LASER-DRIVEN 'DEMO'-FEL

The goal of the 'demo'-FEL setup at ELI-Beamlines is experimental demonstration of the laser-driven FEL in a single unit FEL undulator. For this purpose, a commercial-available 'in-vacuum' planar undulator, based on the hybrid permanent magnets [6], can be used. Such undulator has the undulator period of 15 mm with the variable gap $(3 \div 6$ mm).. The undulator parameter (K_0) is in the range of $0.8 \div 1.6$ depending on the gap size. In order to simplify the 'matching' condition the total length of such undulator should be 2.5 m. The average beta-function is 1.6 m. The saturation length $(L_{sat} \sim 20 L_{g,3D})$, estimated by using the Xie parametrization of the gain length [7] and checked by using the fitting formula for free-electron lasers with strong space charge effects [8], does not exceed such undulator length for the electron beam summarized in Table 1.

Table 1: Main Parameters of the 'Demo'-FEL

Electron beam in Undulator ($K_0=1.4$)		
Beam energy	MeV	350
Bunch charge	pC	30
RMS bunch duration	fs	3
Peak current	kA	4
Matched beam size	μm	25
Normalized emittance	π mm.mrad	0.24
'Slice' energy spread	%	0.3
Photon coherent radiation at saturation		
Radiation wavelength	nm	32
Pierce parameter, ρ	$\times 10^{-2}$	0.8
Coherent normalized RMS emittance, $\varepsilon_{n,coh}$	π mm.mrad	1.7
Cooperation length (3D), L_{coop}	μm	0.26
Gain length (3D), $L_{g,3D}$	m	0.12
Saturation length (3D)	m	2.4
Radiation bandwidth	%	0.65
Photon flux per 0.1%bw	$\times 10^{12\,\#}$	2.2
Photon brilliance	$\times 10^{30\,\#}$	1
Photon pulse power	GW	8.2
Photon pulse energy	μJ	63

 # corresponding units are shown in the text

LASER SYSTEM FOR THE LASER-DRIVEN FEL AT ELI-BEAMLINES

A high repetition rate '100TW'-class laser is currently under development at ELI-Beamlines, which will be used to produce a stable electron beam with required parameters for the laser driven compact 'demo'-FEL. The laser system is designed to produce the laser pulse with extraordinary energy and pointing stability. The laser system is based on a diode pumped solid state laser (DPSSL) with optical parametric chirped pulse amplification (OPCPA). The central wavelength of the laser is 820 nm and the pulse duration is less than 25 fs. The ultimate goal of the laser system is to reach the energy of 5 Joules for the 50 Hz operation. As the result of the first phase of the laser development the energy should be 2.5 Joules at 20 Hz. In addition, the laser system will be able to produce a synchronized, high repetition rate mid-IR auxiliary output. Because it is synchronized with the main output pulse, it can be used to generate X-ray pulses via the high harmonic generation (HHG) which will be synchronized with the driver laser of the electron acceleration. In the frame of the 'demo'-FEL development at ELI-Beamlines the 'seeded' FEL is planned.

Laser Diagnostics

The laser diagnostic will be integrated into the 'setup, which is under development at ELI-Beamlines in order to measure the laser properties before and after the laser-plasma interaction. It will allow to optimize the interaction process and guiding acceleration of electrons to get required parameters of the electron beam. The prototype of such setup has been developed and tested for the LUX setup at DESY in the frame of the collaboration between University of Hamburg and ELI-Beamlines [9].

GUIDED LWFA FOR 'DEMO'-FEL

We aim to use a plasma channel guide of the laser beam in order to produce the required electron beams with the energy of 300 ÷ 500 MeV by using the laser power of 50 TW ($\lambda_{Laser} \sim 820$ nm) [10,11]. The discharge capillary should be 20 mm or smaller. For the laser pulse duration of 25 fsec the corresponding laser energy is 2 Joules assuming 80% of the total laser energy in the spot. Such requirements on the laser parameters open the way for the high repetition rate laser operation (up to 50 Hz).

The on-axis plasma density in the preformed plasma channel should be around 1×10^{18} cm^{-3}. The laser intensity on the target is $\sim 1\times10^{18}$ W/cm^2. In order to optimize the plasma parameters for the capillary-discharge setup, the plasma characterization will be measured by using the Stark broadening of the H$_\alpha$, H$_\beta$ and H$_\gamma$ Balmer emission lines. The plasma discharge setup with the proper plasma diagnostics is under preparation at ELI-Beamlines. The continuous operation of the setup with the gas-filled capillary has been tested for the LUX setup in Hamburg with the laser repetition rate up to 5 Hz [9], producing stable electron beam with the energy of 450 MeV.

ELECTRON BEAM TRANSPORT

The electron beam transport has to be developed to minimize growth of the RMS normalized transverse emittance, provide required energy spread of the electron beam and to have sufficient laser beam and electron beam diagnostics. Initial electron beam parameters from the LWFA source are quite different from typical parameters reachable in conventional linear accelerators. Significant relative energy spread and transverse divergence of the LFWA electron beam in combination with strong space charge effect require a dedicated design of the electron beam transport [12] to capture, transport and match the electron beam to the FEL undulator. It was shown that by using the permanent quadrupole magnets at the beginning of the beamline, the transverse normalized RMS emittance can be kept at the level, acceptable for the FEL lasing [13-16]. The control of the slice energy spread can be performed by using the magnetic chicane (so called 'decompressor', which can be the 'C-type' chicane) [17]. The performed study of the electron beam dynamics in the beam transport including the space charge and the magnetic chicane shows that the average slice energy spread of 0.25 % can be obtained, if the initial bunch charge is 40 pC and the bending angle in the decompression chicane is 0.4 degree. In this case after the chicane the particle distribution in the bunch becomes semi-uniform with the bunch length of 6 μm (the peak current is 2 kA).

Finally, using the matching triplet of the quadrupole magnets it is possible to provide required average size of the electron beam along the undulator $\sim$ 25 μm along the 2.5 m undulator. The total length of the proposed electron beam transport from the LWFA source till the exit from the undulator is 14 m. The electron and photon beams will be separated by using the dipole magnet of the electron beam spectrometer. Conceptual design of the photon beam

transport from the undulator up to the user chamber is in progress.

Electron Beam Diagnostics

Electron beam diagnostics are absolutely crucial for achievement the aim of the 'laser-driven' FEL development. Specific properties of the beam produced nowadays by LWFA, such as low charge, poor beam stability, large beam divergence and energy spread, require re-evaluation of the conventional diagnostic tools or development of completely new ones. The electron beam diagnostic for the 'laser-driven' FEL should be compact, stable, non-invasive allowing the measurements in a single-shot operational mode. For this purpose, a comprehensive set of diagnostic instruments has been designed at ELI-Beamlines [18].

LASER-DRIVEN 'DEMO'-FEL

The photon beam parameters for the 'demo'-FEL setup has been simulated for different cases: (1) without the 'decompression' chicane; (2) including the optimized 'decompression' chicane and (3) including the 'decompression' chicane and the external seeding. The aim of this study was establishing the SASE-FEL regime with amplification of the photon beam power along the undulator. The photon pulse energy along the undulator for all these cases is presented in Figure 1. The energy of the electron beam is 350 MeV and the undulator parameter is K_0=1.4. The simulations have been performed by using SIMPLEX [19] for different parameters of the electron beam, obtained from the multi-particle tracking through the whole beamline taking into account the space charge effects [20]. The other collective effects, such as the coherent synchrotron radiation (CSR) in the magnetic chicane, has been studied by using ELEGANT [21]. It was shown, that CSR will lead to significant degradation of the transverse RMS normalized emittance of the 350 MeV electron beam, if the bunch charge exceeds 50 pC and the bending angle of the chicane dipole magnets exceeds 1 degree. Any beam or beam-transport imperfections, which will lead to additional degradation of the electron beam quality, were not included into the analysis.

The saturation of the photon beam power starts if the bending angle of the chicane magnets is 0.4 degree (Figure 1: the 'black' line). The 'blue' line represents the case without the chicane. The external seeding reduces the saturation length for the same electron beam parameters (Figure 1: the 'red' line). In this case the seeding signal with the following parameters has been used: the seeding wave-length is 32 nm and the seeding power is 2 kW. The simulations indicate that without the external 'seeding' the saturation can be reached in the 2.5 m-long undulator. The external seeding allows to get the saturation even at 2.2 m.
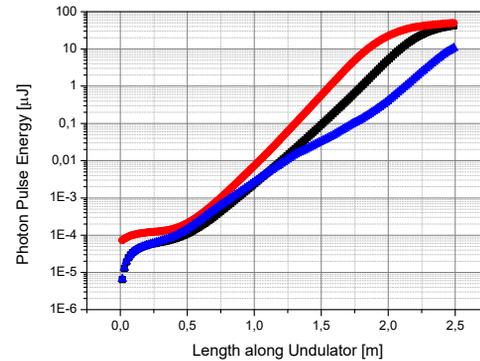

Figure 1: The saturation of the photon pulse energy in the case different 'demo'-FEL setups.

CONCLUSION

The laser-driven 'demo'-FEL program at ELI-Beamlines is based on combination of new laser development, novel LWFA acceleration approaches and development of the dedicated electron beam transport. Successful demonstration of the laser-driven FEL operation at ELI-Beamlines will open the way to compact laser-driven soft and hard X-ray FELs, which are extremely demanding by the X-ray community.

ACKNOWLEDGEMENTS

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