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'LWFA-DRIVEN' FREE ELECTRON LASER FOR ELI-BEAMLINES

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Abstract

Free-electron lasers (FEL) are unique light source for different applications on the femto-second scale, including for instance studying of the most basic reaction mechanisms in chemistry, structural biology and condense physics. Laser wake field acceleration (LWFA) mechanism allows to produce extremely short electron bunches of a few-fs length with the energy up to a few GeV providing peak current of many kA in extremely compact geometries. This novel acceleration method therefore opens a new way to develop compact "laser-based" FEL. ELI-beamlines (ELI-BL) is an international user facility for fundamental and applied research using ultra-intense lasers and ultra-short high-energy electron beams. In frame of this report we present conceptual solutions for an electron beam transport of a compact "LFWA" based soft X-ray FEL, which can deliver a photon peak brightness up to 10^{31} photons/sec/mm^2/mrad^2/0.1%BW. A combination of this achievement with novel laser technologies will open a new perspective for the development of extremely compact FELs with few or even sub-femtosecond photon bunches for a very wide user community.

INTRODUCTION

A few years ago, a new type of large-scale laser infrastructure specifically designed to provide high peak power and focused intensity ultrashort pulses was heralded by the European Community: the Extreme Light Infrastructure (ELI) [1]. ELI will be the world's first international laser research infrastructure. ELI is implemented as a distributed research infrastructure based on 3 specialized and complementary facilities located in the Czech Republic, Hungary and Romania. ELI-beamlines (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. Using laser systems in ELI-BL 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 dense plasma (in a gas-jet, gas-cell or capillary discharge targets). The ponderomotive force pushes the plasma electrons out of the laser beam path, separating them from the ions. 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 accelerator 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 have been obtained experimentally [3]. However, a controllable high-quality electron beam with desirable properties such as energy spread, low emittance, small transverse divergence and large beam charge are not demonstrated using a single-stage LWFA setup up to now. Remarkable experimental achievement has been reached recently using a cascaded acceleration [4] of electrons by decoupling the injection and acceleration. Through manipulating electron injection, quasi-phase-stable acceleration, electron seeding in different periods of the wake-field, as well as controlling the energy chirp, the high-quality electron beams have been obtained. The electron beams with energies in the range of 200÷600MeV, with the RMS energy spread of 0.4÷1.2%, the RMS transverse beam divergence of 0.2mrad with the bunch charge of 10÷80pC have been demonstrated experimentally for this new cascaded acceleration scheme [5].

Using recent experimental achievements one can define the parameters of the LWFA electron beam at the exit of the plasma channel as following: the electron beam energy in the range from 300MeV to 1000MeV; the RMS transverse beam size in the horizontal and vertical plane is 1μm or less; the RMS transverse beam divergence in the horizontal and vertical planes is 0.5mrad or less; the RMS bunch length is about 1μm; the RMS relative (total) energy spread is less than 1%; the normalized RMS transverse beam emittance in the horizontal and vertical planes is 0.2π mm.mrad; the bunch charge is about 20÷50pC. In frame of this report we discuss a conceptual solution for a dedicated electron beamline to transport high-energy electrons from a plasma target up to an undulator for a 'demonstration' FEL experiment with a possible expansion of such beamline to use it for a 'laser-driven' FEL, which is under discussion now in the ELI-BL Center.

Uniqueness of the 'laser-driven' FEL is based on the laser properties. The laser pulse of a few tens of fs allows to produce extremely short electron bunch with the bunch duration of a few fs. Such short electron bunch passing through an undulator magnetic field can produce a 'single-spike' coherent photon radiation, if FEL resonance conditions are satisfied. In principle, the 'laser-driven' FEL can operate with high repetition rate (up to 100Hz), which is limited by the current 'state-of-art' of the laser technology.

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FEL: UNDULATOR AND RADIATION PARAMETERS

In order to provide effective coupling between electrons and photons the 'peak' undulator deflection parameter (K) should be in the range of (1÷3). The K-value depends on the 'on-axis' magnetic field of the undulator (B_0) and the undulator period (λ_u): $K=eB_0/(m_eck_u)$, $k_u=2\pi/\lambda_u$. The gain length of the radiation power scales as $L_{g,1D}\sim(\lambda_u K^{-2})^{1/3}$. Bigger value of the deflection parameter leads to smaller power gain-length for the same undulator period. Nevertheless, the peak angular deflection (θ) of the electrons in the undulator magnetic field is proportional to the K-value ($\theta_e=(K/\gamma)$), where γ is the relative electron energy. If K>>1 the electron trajectories will not overlap leading to an incoherent radiation. 'Cryogenic' permanent magnet undulators (CPMU) allow to increase the magnetic field and the K-value without significant reduction of the undulator gap. In comparison with a 'room-temperature' PMU the 'cryogenic' undulator has better magnetic and vacuum performance. In addition, CPMU has also better radiation damage resistance, which allows considering CPMU as a promising candidate for a compact FEL. In frame of this report to estimate the photon properties we use the 'cryogenic' planar undulator designed on praseodymium-based magnets and vanadium permendur poles. The undulator has been developed by the Helmholtz-Zentrum Berlin [6] in the collaboration with University of Hamburg. High remanent magnetic field of the undulator with a period length of λ_u=15mm allows to obtain the on-axis deflection parameter (K) in the range of 1.3÷2.4 in the case of changeable gap size of 6÷3mm, respectively. The total length of the undulator is 2m. Goal of the 'demo' FEL experiment is to demonstrate the FEL regime for low-energies photons and reach the power saturation at the end of an undulator.

In Table 1(A) main parameters of photon beam are summarized for the 'demonstration' FEL setup. The energy of the electron beam is 350MeV. The estimations have been performed taking into account possible degradation of the high-gain FEL performance, caused by effects of energy spread of the electron beam, finite emittance and betatron oscillations of the electron beam, as well as diffraction and optical guiding of the FEL field [7]. The estimated 3D-saturation length is 2.1m. The radiation wave-length is 41nm, the photon energy is 30eV and the radiation bandwidth is 0.72%. The total photon flux is 1.23×10^{13} photons/pulse and the photon peak brilliance is 4.4×10^{29} photons/sec/mm^2/mrad^2/0.1%BW. Successful realization of the 'demo' FEL experiment will open a way to the 'full-scale' 'laser-driven' FEL.

The main parameters of the 'water-window' photon beam for the case of 1000MeV electron beam are summarized in Table 1(B). The 3D-saturation length is estimated as 8.5m, which make the whole setup quite compact. The radiation wave-length is 5nm, the photon energy is 241eV and the radiation bandwidth is 0.2%. The total photon flux is 1.5×10^{12} photons/pulse and the photon peak brilliance is 7.05×10^{30} photons/sec/mm^2/mrad^2/0.1%BW.

In order to demonstrate experimentally the amplification and the saturation of the photon radiation in the compact 'laser-driven' FEL, it is necessary to satisfy the FEL conditions [8] at the entrance of the undulator: (1) the RMS energy spread of the electron beam should be less than a half of the 'Pierce' parameter; (2) the normalized RMS emittance of the electron beam should be less than the coherent normalized emittance. From the list of the 'LWFA-driven' electron beam parameters, discussed above, it is clear that significant energy spread of the 'laser-driven' electrons does not meet the FEL conditions. Moreover, it is necessary to avoid significant growth of the normalized RMS emittance of the electron beam in the dedicated beamline from the 'laser-driven' source up to the undulator to be able to use is for the FEL experiment.

Table 1: Main Parameters of (A) 'Demo' FEL and (B) 'Water -Window' FEL

		A	B
Electron beam in Undulator			
Beam energy	MeV	350	1000
Bunch charge	pC	20	20
RMS bunch duration	fs	2	2
Peak current	kA	4	4
Matched beam size	μm	~ 30	~ 30
Normalized emittance	π mm.mrad	0.3	0.3
'Slice' energy spread	%	0.2	0.2
Photon coherent radiation in Undulator at saturation			
Photon energy, E_{ph1}	eV	30.1	246
Radiation wavelength	nm	41	5
Pierce parameter, ρ	$\times10^{-2}$	0.85	0.29
Coherent normalized RMS emittance, $\varepsilon_{n,coh}$	π mm.mrad	2.24	0.785
Cooperation length (3D), L_{coop}	μm	0.30	0.15
Gain length (3D), $L_{g,3D}$	m	0.107	0.45
Saturation length (3D)	m	~ 2.1	~ 8.5
Total photon flux	$\times10^{13}$ #	1.23	0.5
Radiation bandwidth	%	0.72	0.2
Photon flux per 0.1%bw	$\times10^{12}$ #	1.6	0.74
Photon brilliance	$\times10^{30}$ #	0.44	7.05
Photon pulse power	GW	10.8	5.2
Photon pulse energy	μJ	60	30

 # corresponding units are shown in the text

FEL Saturation Length

The FEL parameters, presented in Table 1 (A,B), depend strongly on the set of the electron beam parameters. Changing the 3D saturation length for different normalized RMS emittance and RMS energy spread has been analysed for the case of the 350MeV electron beam (Fig. 1). Main parameters of such electron beam are mentioned in Table 1(A). From the obtained result one can conclude that to keep the saturation length of 2m it is necessary to have the RMS normalized emittance of 0.2π mm.mrad and the RMS relative energy spread less than 0.4%. Such challenging electron beam parameters can be obtained only in a sense of the 'slice' parameters, which

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is a fraction of the bunch in the longitudinal directions with the length less than the cooperation length [7,8,16].

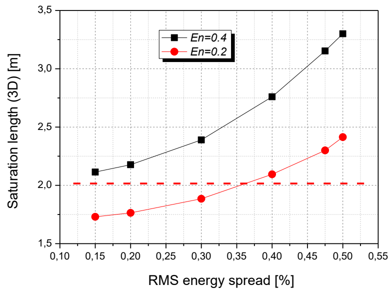

Figure 1: Estimation of the saturation length [7] for the 350MeV electron beam as a function of the RMS energy spread for different transverse normalized RMS emittance.

CONCEPTUAL SOLUTIONS FOR 'LFWA-BASED' FEL BEAMLINE

A dedicated electron beamline for both 'demo' FEL and 'water-window' FEL experiments has to provide: (1) capture of the electrons from the 'LWFA-source'; (2) effective transport of the electron beam with reasonable flexibility and (3) matching of the electron beam to the undulator. The beamline has been designed using the following 'basic' initial parameters of the electron beam: the normalized RMS emittance is equal to 0.2 π mm.marad; the transverse RMS beam size is 1µm; the transverse RMS beam divergence is 0.5mrad; the RMS relative energy spread is 1%. As it is shown below, the initial energy spread has to be reduced down to 0.5% in order to use the 'decompression' scheme without significant increasing the bunch charge, which allows to control the 'slice' parameters of the electron beam at the entrance of the undulator.

The 'capture' block of the electron beamline has to designed to minimize the intrinsic growth of the normalized emittance and to create a 'collimated' or 'focused' electron beam. Such beam should be able to propagate through a long drift space (about 3m) required to separate the laser beam and the electron beam using out-coupling optics. In addition, a set of steering magnets and beam-position monitors should be placed in this drift space to control the electron beam propagation at the beginning of the beamline. The 'capture' block of the beamline should be based on the triplet of the quadrupole magnets and placed at the minimum distance from the 'LWFA-source'. The triplet solution allows to provide a focusing of the electron beam in both transverse plane planes at the same time.

The Halbach-type [9] permanent quadrupole magnets (PQM) based on $Nd_2Fe_{14}B$ material with high gradient of the magnetic field (up to 450T/m, [10]) are chosen for the first focusing block of the beamline. The design of the 'target' vacuum chamber should allow to place the first quadrupole magnet at the distance of 4÷6cm from the source. The aperture of the permanent quadrupole magnets has to be big enough to guarantee the laser beam propagation without hitting the magnet material. For the developed setup of the 'capture' triplet the last quadrupole magnet is the normal electro-magnet with a moderate field gradient, because the required inner radius would be inconveniently large for a permanent quadrupole magnet. In order to adapt the 'capture' block for different electron energy, it is necessary to control the position of the permanent quadrupole magnets along the beamline.

The focusing properties of the quadrupole magnets depend on the energy and the energy spread of the electron beam passing through the magnets, leading to the chromatic aberrations and the emittance growth. There are a few approaches to minimize the chromatic effects without any elements with high-order ('sextupole') nonlinearity of the magnetic field, which can be used in principal for the 'LWFA-based' electron beamline: an 'apochromatic' beamline [11,12] and 'chromatic' matching [13]. In the case of the 'apochromatic' focusing the chromatic changing of the Twiss parameters can be corrected without the use of sextupole magnets. Recently a general method for designing drift-quadrupole beamlines with 'apochromatic' correction has been developed [12]. By using dedicated families of the quadrupole magnets it is possible to eliminate the energy dependence of the focusing to arbitrary order. Usage of such correction approach for the 'LWFA-based' electron beam-line requires additional quadrupole magnets making the electron beam-line quite long. Another disadvantage of this approach: it will not work in the case of a few undulators, because the 'apochromatic' condition can be met at a particular place of the beamline only.

There is another scheme to minimaize the effect of the chromatic aberrations [13], based on a second-order transverse beam manipulation turning large inherent transverse chromatic emittances of the LWFA beams into direct FEL gain advantage. To realize such approach it is necessary to control the high-order matrix elements of the chromatic perturbation. For practical usage it is necessary to consider more robust techniques, which are well-established in conventional accelerators.

For the energy selection one can use a traditional solution, based on the dispersive properties of dipole magnets. Or instead, apply the chromatic energy selection, which combines the advantages of focusing with energy selection in a single device, making the 'chromatic' filter with compact setup [14,15]. Both schemes should use a collimator to stop electrons with large deviation from the nominal beam energy.

In the case of the LWFA acceleration, the electron beam has a remarkably short bunch length (σ_z~1µm) and significantly large relative energy spread ($\sigma_{\Delta p/p}$ ~1%). During the electron beam propagation through the beamline the bunch length increases (velocity de-bunching), but not enough to change the 'slice' parameters of the beam to be able to satisfy the FEL conditions.

By using a dispersive section ('decompressor') in the beamline the electron bunch can be stretched longitudinally and effectively sorted by energy [16], resulting in a

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reduction of the local energy spread at the cost of a reduced peak current and an energy chirp. By changing the strength of the 'decompressor' bending magnets it is possible to control the 'slice' parameters of the 'laser-driven' electron beam.

Our conceptual electron beamline contains both schemes: (1) the 'chromatic' filter, based on the energy dependent focusing strength of the quadrupole magnets and (2) the 'decompressor', based on the 'C-shape' chicane with four dipole magnets. This solution of the dedicated electron beam line to transport the electron beam to the undulator for the 'demo-FEL' experiment is presented in Fig. 2. The 'basic' initial parameters of the 350MeV electron beam are the following: the RMS normalized emittance is 0.2 π mm.mrad; the RMS transverse beam size is 1.1µm; the RMS transverse beam divergence is 0.55mrad; the RMS relative energy spread is 1.1% and the RMS bunch length is 0.8µm.

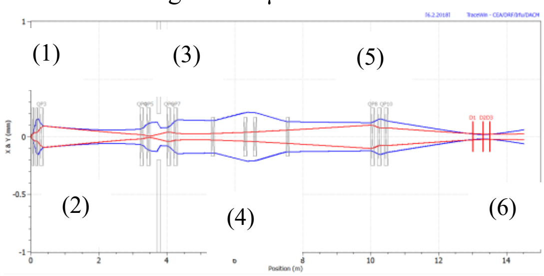

Figure 2: The horizontal and vertical beam envelope ($\sigma_{x,y}$) of the 'laser-driven' 350MeV electron beam for the 'demo' FEL experiment: (1) the 'capture' triplet block, based on PQMs; (2) the 'out-coupling' drift space; (3) the ' chromatic' filter with collimator; (4) the 'decompression' C-type chicane; (5) the 'matching' quadrupole triplet; (6) the undulator unit.

The proposed electron beamline has enough space for beam diagnostics after each 'key' element of the beamline to be able to: (1) measure and correct the beam-centre offset, caused by the quadrupole misalignments; (2) measure the transverse and longitudinal properties of the electron beam; (3) measure the bunch intensity and the propagation efficiency along the beamline. The collimator, placed in the 'chromatic' filter, allows to reduce growth of the normalized transverse emittance, caused by the 'chromatic' aberrations in the quadrupole magnets. For the initial RMS relative energy spread of 1% the propagation efficiency is 89% without any imperfections, if the collimator gap is 400µm. The normalized 'projected' RMS emittance in the horizontal and vertical phase-planes are 0.64 and 0.33 π mm.mrad, respectively. In the middle of the undulator (at the 'beam-waist' position) the RMS beam size in the horizontal and vertical planes are about 20µm. If the collimator in the 'chromatic' filter is opened, the corresponding RMS emittances are 1.30 and 0.35 π mm.mrad, respectively. The RMS beam sizes in the horizontal and vertical planes at the 'beam-waist' position are 31 µm and 22 µm, respectively.

If the 'capture' block of the quadrupole magnets is based on the electro-magnets with the maximum field gradient of 140T/m, the RMS normalized emittance in the 'out-coupling' drift space increases by about 50% and 170% in the horizontal and vertical planes, respectively.

The 350MeV electron beam properties have been analysed for different strength of the decompressor. The effective length of the dipole magnet of the chicane is 9cm. In this case, in order to provide the bending angle of 1degree the dipole magnetic field should be 0.255T. The corresponding R_{56} value is 5.6e-4 m.

The optimization of the electron beam line has been performed using TRACE3D [17] and TraceWin [18] codes.

'Slice' Parameters of the Electron Bunch

The main purpose of the decompression chicane in the electron beamline for the 'laser-driven' 'demo' FEL experiment is control the 'slice' parameters of the electron bunch to get the saturation of the photon radiation in the single undulator module with the length of 2m. By changing the bending angle of the chicane dipole magnets, the 'slice' energy spread and the 'slice' transverse emittance can be controlled. At the same time, the bunch length will be changed leading to variation of the peak current. The reduction of the peak current would lead to increasing the FEL saturation length. The parameters of the decompressor should be determined in a such a way to keep a reasonable (achievable) bunch charge and provide the 'slice' beam parameters, which meet the requirements: the 'slice' relative energy spread should be less than a half of the Pierce parameters ($\sigma_{\Delta p/p,S} < 0.4\%$); the 'slice' transverse normalized emittance should be less than 0.3 π mm.mrad. The bunch change should not be bigger than 50pC, providing the peak current of 4kA (Table 1).

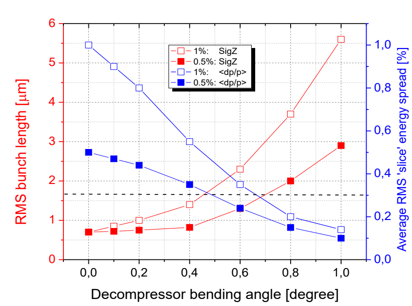

Figure 3: The RMS bunch length (red) and the average RMS 'slice' energy spread (blue) for different bending angle of the 'decompressor' dipole magnets for the case of the 350MeV electron beam, propagating through the electron beamline with different initial energy spread $\sigma_{\Delta p/p}$ of 1% (the 'open' mark) and 0.5% (the 'solid' mark).

The RMS bunch length (red) and the average RMS 'slice' energy spread (blue) for different bending angle of the decompressor dipole magnets are presented in Fig. 3 for the case of 350MeV electron beam, propagating through the electron beamline with different initial energy spread $\sigma_{\Delta p/p}$ of 1% ('open' mark) and 0.5% ('solid' mark).The

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'slice' energy spread should be less than 0.3% in order to reach the FEL saturation at the end of the 2m undulator for the 'demo' FEL setup (Table 1(A)). To reach such value of the 'slice' energy spread in the case of the initial RMS energy spread of 1%, the bending angle of the 'chicane' dipole magnets should be more than 0.7degree. As a result, the RMS bunch length after the decompressor becomes more than 3µm (Fig. 3). If the initial RMS energy spread of the 'laser-driven' electrons is 0.5%, the required 'slice' energy spread of 0.3% can be obtained for the bending angle of the dipole magnets of 0.6degree. In this case the RMS bunch length after the decompressor is about 1µm, which allows to reduce the bunch charge from 100pC to 40pC keeping the same 'peak' current of the bunch of 4kA (Fig. 4).

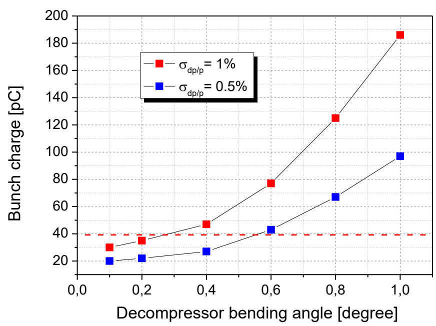

Figure 4: Require bunch charge to provide the peak current of 4kA for different bending angle of the decompressor dipole magnets in the case of different initial RMS energy spread $\sigma_{\Delta p/p}$=1% or 0.5%.

The 'slice' transverse emittance of the electron bunch after the decompressor is presented in Fig. 5 for the initial RMS energy spread of 0.5%. In the case of the bending angle of the decompressor dipole magnets of 0.6degree, the average 'slice' RMS emittances in the horizontal and vertical phase planes are 0.32 and 0.2 π mm.mrad, respectively.

The initial electron beam parameters for the 'demo' FEL experiment have to meet the following requirements in order to reach the radiation saturation at the end of the 2m 'cryogenic' undulator: the transverse RMS beam size is 1µm in both horizontal and vertical planes; the transverse RMS divergence of the electron beam is at least 0.5mrad and the RMS energy spread is not more than 0.5%. The bunch charge is less than 50pC.

The decompression of the electron bunch leads to the energy chirp, so that each 'slice' of the electron bunch will have the own 'central' energy. As the result, the radiation wavelength will be different from slice-to-slice. Nevertheless, for the 'demo' FEL the RMS variation of the radiation wavelength, caused by the energy chirp, will be less than the radiation bandwidth. For the high energy electrons, propagating through a long undulator, the effect of the coherent synchrotron radiation will also contribute into the energy chirp. Detailed study of such effects in combination with other collective effects is required.

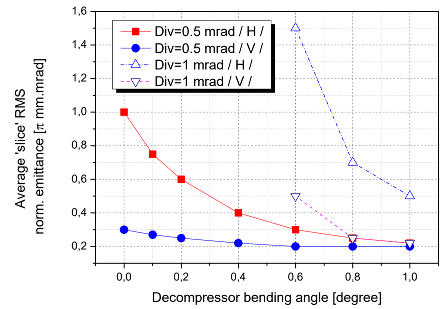

Figure 5: Average 'slice' RMS emittance in the horizontal and vertical phase plans as a function of the 'decompressor' bending angle for the initial RMS energy spread of the electron beam of 0.5% and for different initial divergence of the 'LWFA' electrons (0.5 mrad and 1 mrad).

FEL ANALYSIS

Using the obtained information about the electron beam properties after the decompressor chicane, it is possible to simulate the 'demo' FEL performance. Depending on the bending angle of the chicane dipole magnets three cases have been simulated using the SIMPLEX code [19] for the single module (total length of 2m) of the 'cryogenic' planar undulator, discussed above: (1) the bending angle of 0.2 degree; (2) 0.4 degree; (3) 0.6 degree. The 'slice' RMS energy spread after the decompressor is: (1) 0.44%; (2) 0.35%; (3) 0.24%, respectively. To keep the peak current of 4kA for each set of the chicane magnets the bunch charge for each case is: (1) 23pC; (2) 27pC; (3) 43pC, respectively. The simulated photon pulse energy along the undulator module is presented in Fig. 6 for each set of the parameters. The photon pulse energy at the exit of the undulator depends strongly on the electron beam parameters. The saturation of the photon energy has been reached for the case (3) only with the initial RMS energy spread of 0.5%. The obtained results show that a proper choice of the initial 'LWFA-driven' electron beam parameters and tuning of the decompressor allow to get the FEL amplification and the saturation in the case of 'short' undulator.

The FEL regime has been simulated in the case of the 'water-window' radiation (Table 1(B)). The 'laser-driven' electron beam should have the energy of 1000MeV. The conceptual solutions for the electron beamline from the source up to the undulator entrance remain the same. The permanent quadrupole magnets in the capture focusing block have to be changed and the position of these quadrupole magnets should be optimized to provide focusing at the location of the out-coupling optics. The strength of the electro-quadrupole magnets can be scaled for the high-energy operation. The estimated 3D saturation length for this case is about 9m, so that it is necessary to consider a few segments of the undulator separated by a drift space.

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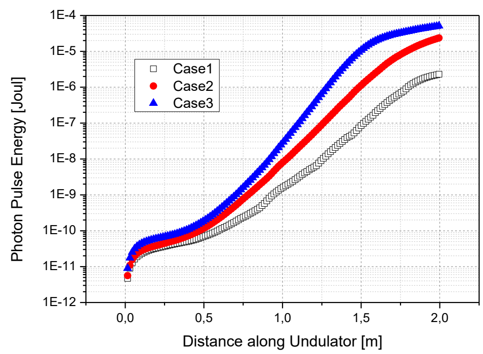

Figure 6: Photon pulse energy along the 'cryogenic' planar HPM undulator, discussed above, for different parameters of the electron bunch after the decompressor (see in the text).

This drift space should be long enough to accommodate additional focusing elements, electron beam diagnostics and 'phase-shift' magnetic structure. For the 'water-window' 'laser-driven' FEL we consider the 'cryogenic' HPM undulator with the segment length of 2.5m, separated by the drift space of 0.75m. The number of the undulator segments is 4. The electron beam parameters, used for the FEL simulations, are summarized in Table 1(B). The photon pulse energy along the undulator segments is presented in Fig. 7. After the 3rd segment of the undulator the saturation of the photon energy has been reached. The total length of the whole setup of the 'laser-driven' FEL including the dedicated electron beamline and 4 'cryogenic' undulator segments is about 25m, which can be integrated in to the existing ELI-BL experimental Hall.

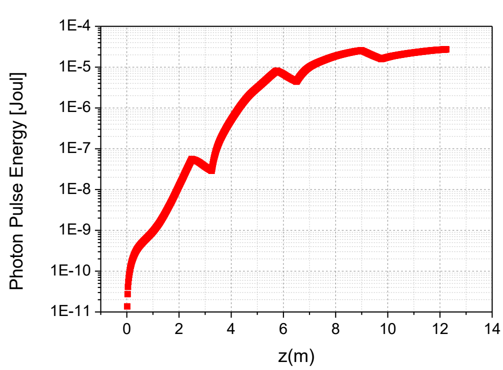

Figure 7: Photon pulse energy evolution along the segments of the 'cryogenic' undulator for the case of the 'laser-driven' electron beam with the energy of 1000MeV (Table 1(B)).

CONCLUSION

The conceptual solutions of the dedicated electron beamline from the 'LWFA-source' up to the undulator have been discussed. These solutions allow to: capture electron beam right after the laser-acceleration and transport the electron beam keeping the normalized RMS emittance under the control. The magnetic chicane, integrated into the electron beamline, provides the required 'slice' parameters of the electron beam for the undulator. The effects of different initial parameters of the 'laser-driven' electron beam have been discussed. The FEL performance has been analyzed for different decompressor strengths. The FEL performance for both 'demo' and 'water-window' FEL has been presented. It was shown that the saturation length can be reduced up to 2m and 9m, respectively. This study should be extended to include collective effects, which would lead to additional degradation of the electron beam properties.

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