ELI ELECTRON BEAM LINE FOR LASER-PLASMA-DRIVEN UNDULATOR X-RAY SOURCE

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Abstract

ELI LUX experiment (as a part of the experimental program of the ELI-Beamlines Project[1] [1]) is based on electron beam with the energy tuneable in the range from 400MeV up to 1200MeV, accelerated by the laser plasma wakefield. ELI LUX aims to deliver for users the X-ray beams with radiation length (0.4-4.5) nm and the peak brilliance up to 10^{20} photons/(s.mrad^2.mm^2.0.1% B.W.), which makes this source comparable with modern synchrotron sources. In order to provide small transverse size of the electron beam and small transverse beam divergence in the undulator, permanent quadrupole magnets with high gradient of the magnetic field up to 520 T/m are used in the electron beam line. In frame of this report we present main features of the designed electron beam line. Effects of the chromatic and spherical aberrations are taken into consideration. The electron beam dynamic is studied by using pre-simulated 3D field maps of the permanent quadrupole magnets. Effects of the space charge of the electron beam, beam collimation, injection and alignment errors and realistic field errors are discussed. Finally parameters of the photon beam, generated in compact undulator, are presented in this report.

INTRODUCTION

ELI beamlines Project, leaded by Institute of Physics of Academy of Science of the Czech Republic, aims to create a laser-based user-facility for wide experimental program. At the first stage of this Project, the ultra-short electron bunch with the energy range of few hundreds MeV to few GeV and high repetition rate (5-10 Hz) will be delivered for different experiments using the "peta-watt' class laser system [1].

A high-efficient undulator and dedicated electron beam line, as well as a stable laser plasma-wave accelerator, are important elements for this state-of-are synchrotron source. The parameters of the photon beam, delivered to users from this compact source, have to be compatible with the standard photon beams, generated by electron beams in large-scale synchrotron accelerators. The X-ray radiation in the water window (290÷530 eV) and the lighter elements K-edge (530÷2500 eV) ranges with the wave length from 0.4 nm up to 4.5 nm are very demanding for bio-medical applications due to its unique spectral characteristics. To deliver the x-ray beam, generated in such undulator source with the undulator period of 5 mm (Ku=0.3, Bu=0.6 T), the electron beam should have the energy in the range from 400 MeV up to 1200 MeV with the RMS beam size less than 100 µm.

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Electron Beam Line

Main concept of the dedicated beamline is based on two main assumptions. The beamline should contain permanent quadrupole magnets only with the maximum field gradients up to 520 T/m. The position of the quadrupole magnets should be adjustable to provide the required parameters of the electron beam in the energy range from 400 MeV up to 1200 MeV. The strong permanent quadrupole magnets allow to capture and collimate the electron beam just near the source. In this case one can minimize emittance growth, caused by large energy spread of the electrons from the LWFA source, and avoid significant increasing the transverse beam size of the electron beam at the beginning of the beamline.

The electron beamline design, presented in this report, is based on the following initial parameters of the electron beam from the LWFA source. The normalized transverse beam emittance is 0.2π mm.mrad and the transverse beam size is 1µm. The RMS bunch length is 1µm. The most challenging parameters of the electron beam from the laser source, used for the beamline design, are the RMS transverse beam divergence of 1mrad and the RMS energy spread of 1%. The maximum charge of the electron beam expected in this experiment is 10pC assuming the propagation efficiency of 50% through the electron beamline. Basic beamline design has been made by MADX [2] and GPT [3] codes. Variation of the RMS beam size in the horizontal and vertical planes along the electron beamline for the case of the 400MeV electron beam is presented in Fig. 1, including the effect of the horizontal collimators, placed at the beam-waist position.

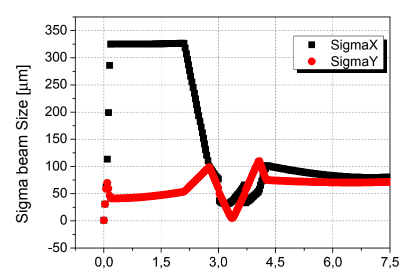

Figure 1: RMS beam size in the horizontal and vertical planes of the 400 MeV electron beam with $\sigma_{\Delta p/p}$=1% and the RMS beam divergence of 1 mrad.

To provide the required parameters of the electron beam for the undulator without any collimation systems the rms energy spread of the electron beam should not exceed 0.5%. The full gap sizes of the planar collimators are 200 µm and 360 µm for the horizontal and vertical planes, respectively. The horizontal collimator should

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have two blocks, placed around the beam waist, to cut electrons with large energy off-set. The propagation efficiency of the electron beam and the RMS beam size at the entrance of the undulator, obtained from the 6D tracking without injection end alignment errors for different RMS energy spread of the initial electron beam (the RMS beam divergence of 1mrad), are presented in Fig. 2.

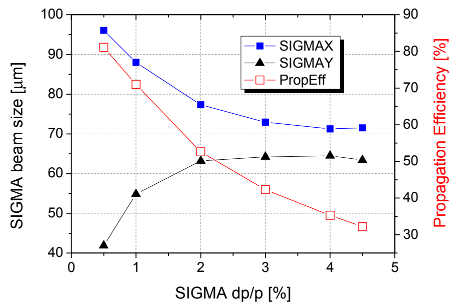

Figure 2: RMS beam size and propagation efficiency of the collimated electron beam at the entrance of the undulator as a function of the RMS energy spread of the initial beam ($\sigma_{x'}=\sigma_{y'}=1$ mrad).

To keep the propagation efficiency above 50% the initial RMS energy spread of the electron beam should not exceed 2% for the designed electron beamline. For such energy spread of the electrons the RMS beam size of the collimated beam at the undulator is less than 100 µm even for a big initial beam divergence (Fig. 3). For the initial beam divergence more than 3 mrad the propagation efficiency becomes less than 20%. Nevertheless, required electron beam intensity in the undulator can be obtained by increasing the initial beam intensity from the source.

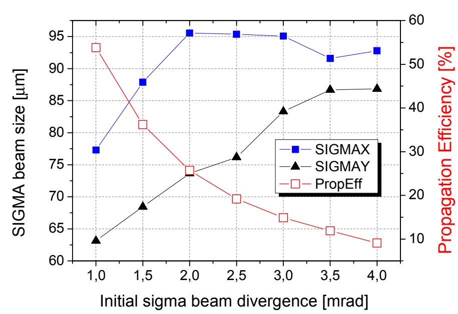

Figure 3: RMS beam size and propagation efficiency of the collimated electron beam at the entrance of the undulator as a function of the RMS beam divergence from the source ($\sigma_{\Delta p/p}$ = 2%).

Effect of the Space Charge

The RMS bunch length of the electron beam from the LWFA source is 1 µm. For the required bunch charge of 5pC the peak current of the electron bunch is about 1.6 kA. The space charge effects in the beamline are simulated for the 400 MeV beam by using the "point-to-point" method, implemented into the GPT code [3]. The simulated propagation efficiency for different energy spread of the electrons in the bunch (Fig. 2) is taken into account to provide required number of electrons for the undulator. Propagation of the electron beam through the beamline with the collimators has been simulated for the space charge dominated cases without wake field effects, changing the initial energy spread of the particles. The rms beam size in the transverse planes for different energy spread is presented in Fig. 4. The open marks show the rms beam size without the space charge effect. One can clear see increasing of the rms beam size in the undulator, caused by the collective effect. The propagation efficiency for each energy spread is about the same, as was presented above (Fig. 2).

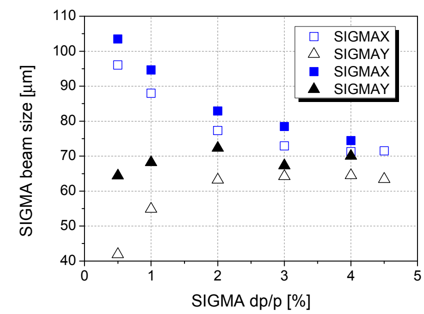

Figure 4: RMS beam size at the entrance of the undulator without (open marks) and with the space charge effect for the bunch charge of 5pC in the undulator (solid marks) for different energy spread (W_{kin}=400 MeV).

Injection and Alignment Errors

The laser pointing jitter at the focusing mirror, placed just before the capillary, leads to random variation of the initial electron beam center in the transverse planes. Such intrinsic initial error will reduce the propagation efficiency of the beam passing through the beam line with strong quadrupole magnets. As the result, the position of the electron beam center at the entrance of the undulator will change randomly. This effect has been included into the tracking of the 400 MeV electron beam in combination with the space charge effect and the collimations.

The injection error (shift of the beam center from the optical axis of the electron beam line) is assumed as 4 µm, which corresponds to the laser pointing stability of 2 mrad and the distance from the focusing mirror and the capillary of 2 m. The properties of the electron beam, such as the beam propagation efficiency from the source up to the undulator, changing the position of the electron beam center and the sigma beam size at the undulator, can be controlled by changing the position the last quadrupole magnet in the beam line. The result of such optimization for the injection error of 4µm is presented in Fig. 5. The initial RMS energy spread of the electron beam is 1%. By optimizing the position of the quadrupole magnets one can improve the propagation efficiency up to 63%, keeping the shift of the beam center less than the sigma beam size in both transverse planes. Without injection error the propagation efficiency for the case of ΔZ_{56}=40 mm is 72% (σ_x = 60.6 µm, σ_y=40.3 µm).

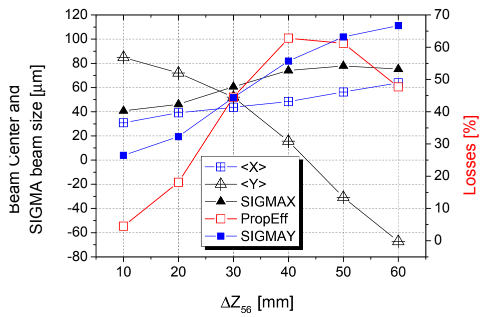

Figure 5: Electron beam propagation through the beam line with initial injection error of 4 µm for different position of the last permanent quadrupole magnet before the undulator.

Misalignment of the quadrupole magnets has been introduced into the simulations. The propagation efficiency and the electron beam parameters in the undulator depend strongly on the transverse shift of the center of the permanent quadrupole magnets from the central axis, which should not be more than 5 µm. It requires accurate field measurement of the quadrupole magnets and alignment control.

Scattering in Collimators

Collimation of the primary electron beam including the EM shower for different material of the collimators has been simulated by using G4beamline [4]. This study has been performed to minimize the background effect for photon detectors. The energy spectrum of the electron beam at the entrance of the undulator after the proper beam collimation remains almost the same for different material of the collimator (stainless steel 304 L or lead). In addition, the wake-field effect of the high intensity beam in the collimator should be analysed. First estimation does not show significant impact of this effect on the electron beam properties in the undulator.

Permanent Quadrupole Magnets

The quadrupole magnets (the "Halbach" type with 12 wedges, material: $Nd_2Fe_{14}B$) with the field gradient of 520T/m have been designed for the proposed electron beam line by using the CST Studio. The inner radius of the quadrupole magnets has to be big enough to allow the laser beam propagation before the laser and electron beam are separated. Effect of the magnetization error for each wedge in the case of the remnant field of 1.0236 T has been studied. The random error of the magnetic field for each wedge of 5% has been used for these simulations. Such error leads to increasing the integrated field gradient for the strongest quadrupole magnet up to 0.15% from the required value. The CST 3D field maps of the magnetic field for the permanent quadrupole magnets have been used to simulate the electron beam propagation through the realistic magnetic field. Small correction of the position of the permanent quadrupole magnets should be performed according to measured integrated field gradient. High order field components do not lead to significant increasing of the RMS beam size in the undulator.

Parameters of Photon Beam

The proton beam properties for the ELI-LUX experiment have been estimated assuming the planar undulator with the following parameters: the undulator length is 0.5m, the undulator period is 5mm, the normalized undulator parameter (K_u) is 0.28. The fundamental harmonic wavelength for the electron energy of 400 MeV is 4.149 nm. The photon energy of the fundamental harmonic for a single electron is 292.4 eV. The polar angle of the photon beam for the electron energy of 400 MeV is 92 µrad. The estimated peak brilliance of the photon beam is 1e20 for the phase-1 without focusing the photon beam. For the electron energy of 1200 MeV the fundamental harmonic wavelength is 0.46 nm, the photon energy of the fundamental harmonic is 2.63 keV, the polar angle of the photon beam is 30.7 µrad. The spread of the fundamental wavelength is 1%.

CONCLUSION

The initial beam parameters, used for this study, are the most challenging. Using the permanent quadrupole magnets it is possible to deliver the electron beam with 5pC/bunch to the undulator, keeping the RMS beam size less than 100 µm for both transverse planes with the propagation efficiency more than 50%. Successful development of such LPWA-based undulator X-ray source will open the way to the LPWA-based Free Electron Laser.

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