CALCULATION FOR A COMPACT LASER PLASMA UNDULATOR BEAMLINE BASED ON THE EXPERIMENTAL BEAM PARAMETERS AT NCU

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Abstract

Laser-wake field accelerators (LWFAs) are potential candidates to produce intense relativistic electron beams to drive compact free electron lasers (FELs) in VUV and X-ray regions. Electron beams generated by LWFAs are characterized by their low transverse emittance, small beam sizes, and short bunch lengths. However, they also have significant beam divergence and large energy spread. In High-Field Physics and Ultrafast Technology Laboratory at National Central University (NCU), an LWFA is being developed to produce a 250 MeV high brightness electron beam by their 100-TW laser system. A seeded FEL is under design to generate high peak power coherent extreme ultraviolet (EUV) radiation. The initial phase of the project is to develop a beam energy modulator through the interaction of the LFWA produced electron beam with the 266-nm seed laser in a 12-period planar undulator of 35-mm period length. In this work, we perform a detailed simulation of the LWFA FEL from experimental data of the NCU LWFA beam. A 6D phase space analysis of multi-particle dynamics using IMPACT code is carried out to examine the effects of beam energy spread on beam focusing and bunch length evolution along the beam transport line. The electron beam is then transferred to GENESIS and PUFFIN for simulation of the laser-beam interaction in the undulator.

INTRODUCTION

Free electron lasers (FELs) are capable to generate high brightness, tuneable and ultra-short pulses with wavelengths ranging from THz to hard x-ray. As an accelerator-based light source, the emission of coherent radiation from a FEL is based on the subtle interaction of laser and electron beam in an undulator magnetic field under resonant condition. Furthermore, the output performance of a high gain FEL relies heavily on the quality of the drive beam. In conventional FEL systems, high brightness electron beam is generated from linear accelerators that based on high power microwave technologies. In recent years, LWFAs draw much attention in the community for their capability to provide high quality electron beam from the extremely high accelerating gradient (i.e., GV/m) plasma wave. Several projects such as the COXINEL project at SOLEIL and the compact EUV SASE project at Shanghai Institute of Optics and Fine Mechanics (SIOM) [1-2] are dedicated on the development of FELs that based on LWFA technology. Electron beams generated by LWFAs are characterized by their low transverse emittance, µm beam sizes, and fs bunch lengths. However, they also have relatively large beam divergence and energy spread that may have significant impact on beam transportation from the beam source to the FEL located downstream.

In NCU, a 100-TW Ti-sapphire laser system has been used to generate a 250 MeV electron beam from a LWFA. An LWFA beamline is being developed for generation of a high brightness, ultra-short electron beam. In this study, we perform a detailed simulation of an electron transport line using IMPACT [3]. A sensitivity test is also carried out to evaluate the influence of beam parameter fluctuations observed in their experiments. We also use a SVEA FEL code GENESIS [4] and a PIC-based, broadband FEL code PUFFIN [5] to simulate laser-beam interaction in the proposed NCU LWFA FEL to verify the effectiveness of beam quality at FEL entrance.

THE PROPOSED NCU LWFA FEL

The schematic layout of the proposed NCU LWFA FEL facility is shown in Fig.1. The beam transport line consists of a very high gradient quadrupole doublet installed close to the gas jet of LWFA and a quadrupole triplet in front of the undulator entrance for beam size control. As the first phase of this project, the electron beam is transferred from the LWFA to the U35 undulator for beam energy modulation in the undulator using a 266-nm laser. Currently, an electron beam of maximum kinetic energy up to 250 MeV tightly bunched beam with 20 pC bunch charge are available from the LWFA system. In the next phase, a fourth harmonic HGHG FEL for generation of EUV radiation with wavelength at 66.5 nm from a 20 mm period length planar undulator. PUFFIN will be used to simulate laser-beam interaction in the U35 beam energy modulator and in the U20 radiator as well.

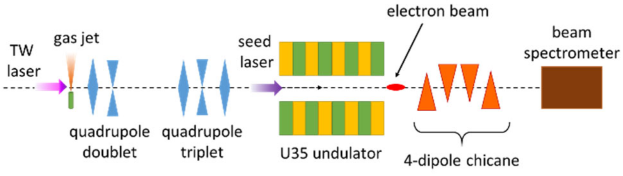

Figure 1: Schematics of the NCU LWFA FEL (Phase 1).

As a quick evaluation, the design of beam transport line has been done by MAD to get basic lattice parameters for a prescribed beam at the entrance of the undulator U35. Figure 2 depicts the horizontal and verticle beta functions of the beamline. The electron beam of high divergence generated by LWFA can be focused well throughout in the compact beamline that composed of five quadrupoles. However, MAD provides only results for monoenergitic beam. Thus, to study the effect of energy spread, multi-particle tracking of an energy spread beam is required.

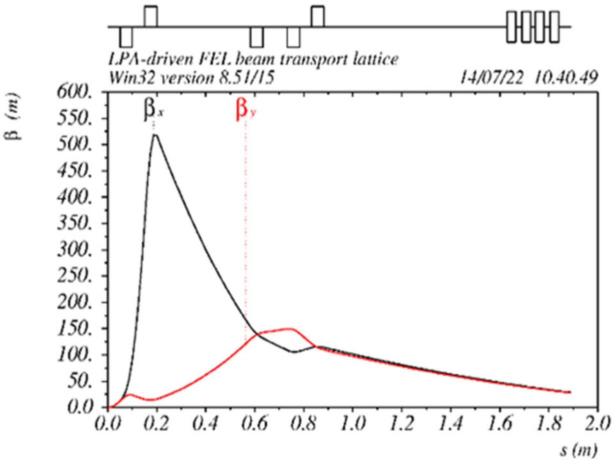

Figure 2: Beam transport lattice simulation using MAD code.

BEAM TRANSPORT SIMULATION

Following a monoenergetic evaluation, we use IMPACT to perform particle tracking, which includes both 3D space charge and coherent synchrotron radiation (CSR) effects. The electron parameters are based on experimental observations that help to build a more accurate model of electron beam for the study of beam transport. The electron parameters used in the simulation are shown in Table 1.

Table 1: Measured Beam Parameters from LWFA

LWFA Beam Parameters	**Value**
Beam energy [MeV]	250
Bunch charge [pC]	20
Bunch duration [fsec]	5
Normalized emittance [µm]	0.5
Initial beam size [µm]	0.72
Initial beam divergence [mrad]	0.7
Energy spread [%]	2

Objective optimization

To optimize the beam optics, the MATLAB surrogate optimization algorithm has been used. By setting a function of Twiss parameters (denoted as α, β and γ) from IMPACT as object value, the algorithm scans randomly the quadrupole strengths and gets a coarse fitting curve. Then, a detailed scan is applied to the neighbourhood of the fitted curve minimum. The algorithm repeats this process in this region until the global minimum of the object value is obtained. By changing the optimization object value, we are able to fine-tune the lattice parameters to meet our specific requirements. Figure 3 shows the optimization process by setting $\alpha^2\beta$ as our object value and its minimum has been found.

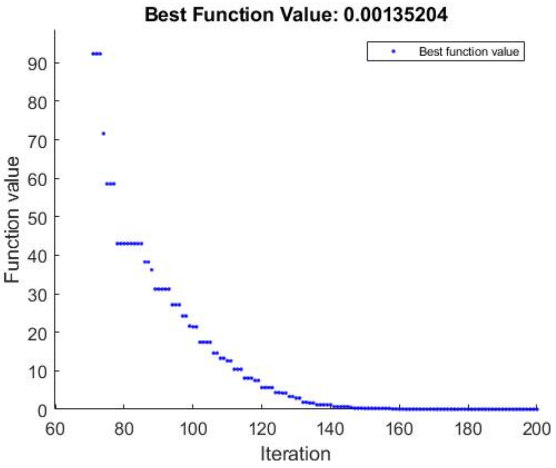

Figure 3: Objective optimization process.

Beam transport lattice simulation

In order to focus quickly the LWFA electron beam that have relatively large divergence, a very high gradient quadrupole doublet with maximum field gradients of 325 T/m is used. Another three quadrupoles are used to focus the beam to the undulator properly. In the IMPACT simulation, space charge, CSR, and fringe field effects has been considered such that we can ensure that the electron beam transport from the LWFA to U35 undulator has been optimized for best performance. A highly collimated beam at the entrance of the undulator with a transverse beam size of 300µm can be achieved (Fig.4).

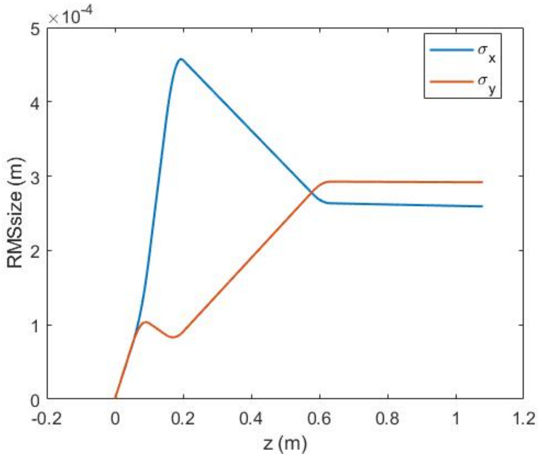

Figure 4: Beam size evolution along beamline.

SENSITIVITY TEST

Figure 5 depicts shows the linear dependence of beam size at undulator entrance on initial beam divergence of LWFA. This suggests that the initial beam divergence does not have much effect on the quadrupoles focusing properties. Figure 6 shows a quadratic dependence of final beam size on beam energy spread. The initial beam energy spread is considered to be a sensitive parameter to beam focusing. Fortunately, beam electron energy spread in the current experiment configuration can be lower if higher electron energy can be achieved.

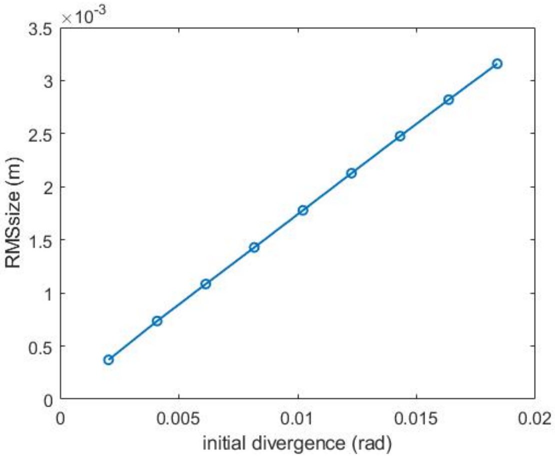

Figure 5: Final beam size as a function of initial divergence which is ranging from 2 mrad to 18 mrad.

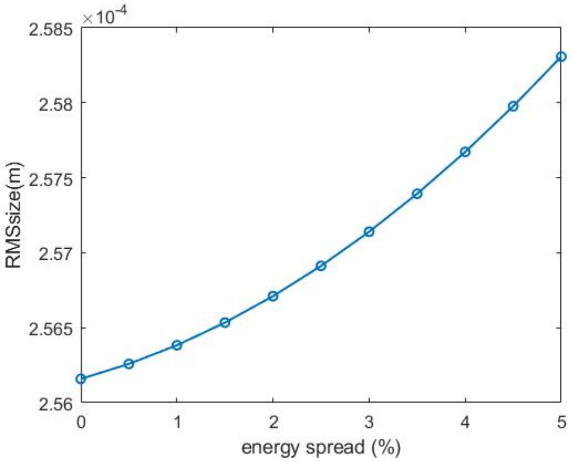

Figure 6: Final beam size as a function of energy spread which is ranging from 0 to 5 percent.

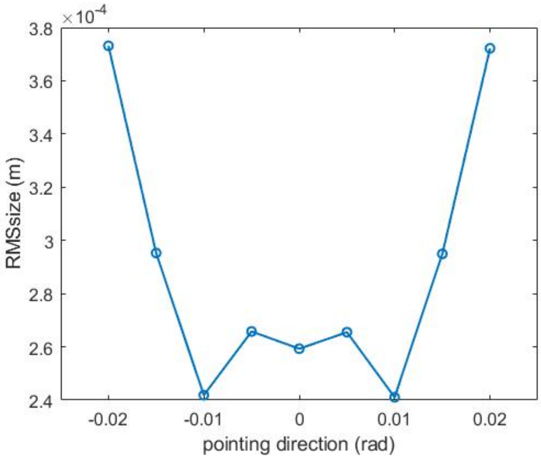

Figure 7: Final beam size as a function of initial pointing direction which is ranging from -20 mrad to 20 mrad.

Finally, as shown in Fig. 7, the pointing direction is the most sensitive parameter to final beam size. Moreover, the dependence of final beam centroid position on pointing direction is a serious problem. For a 10 mrad change in pointing direction, the displacement of beam centroid from its original value at undulator entrance can be as high as 4 mm. This is not an acceptable value because the high gradient quadrupoles usually have relatively small physical aperture. Thus, it is important task to minimize the fluctuation of beam pointing direction in LWFA.

ENERGY MODULATION

In the current design, the beam energy modulator is a 12-period undulator with period length of 35 mm. The *K* value is set at 1.62 for a seed laser of 266 nm wavelength. Figure 8 shows the electron distribution in longitudinal phase space at the end of the beam energy modulator. The transverse spot size of the seed laser is 1 mm with pulse duration of 50 fs, which should overlap with the 5 fs beams. The electron beam will then be sent to a small chicane for density modulation, which is an essential part of HGHG FEL.

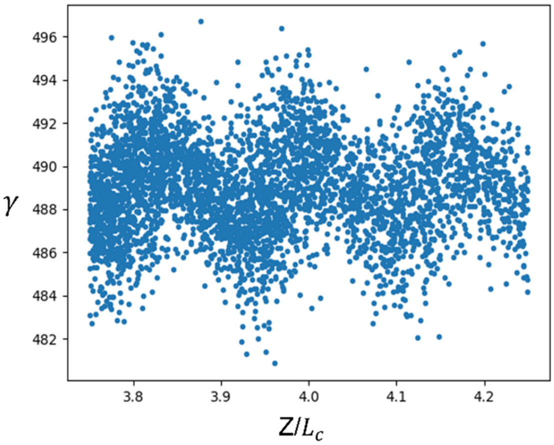

Figure 8: Electron beam phase space distribution at the end of the beam energy modulator U35.

CONCLUSION

A 6D simulation using IMPACT has been performed to study the beam dynamics in the beam transport system for an LWFA electron beam. With typical LWFA beam parameters, FEL power amplification might not be achieved unless a beam transport system that is not susceptible to large divergence and energy spread has been designed. The sensitivity test results suggest the impact of pointing direction on beam size and beam centroid position is serious. Laser beam interaction for such an ultra-short electron bunch is also simulated by an unaveraged FEL code PUFFIN. The resulting electron distribution shows that we can produce enough energy modulation by a 12-period U35 undulator. Further study on applying a dispersion section to transfer the energy modulation to density modulation in the beam for a fourth harmonics HGHG scheme will be done.

ACKNOWLEDGEMENTS

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