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SIMULATION STUDY OF AN ACCELERATOR-BASED THz FEL FOR PUMP-PROBE EXPERIMENTS AT THE EUROPEAN XFEL*

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Abstract

The European XFEL considers to perform THz-pump and X-ray-probe experiments. A promising concept to provide the THz pulses with satisfactory properties for the experiments is to generate them using a linear accelerator-based free-electron laser (FEL). A simulation study of a THz FEL facility capable of generating powerful tunable coherent THz radiation that covers the wavelength range of 25 µm to 100 µm was performed. An accelerator beamline layout based on the Photo Injector Test Facility at DESY in Zeuthen (PITZ) and an APPLE-II undulator with a period length of 40 mm were used in the simulation study. Results of the study are presented and discussed in this paper.

INTRODUCTION

The European XFEL has planned to perform THz pump–X-ray probe experiments at the full bunch repetition rate for users. A promising concept to provide the THz pulses with a pulse repetition rate identical to that of the X-ray pulses is to generate them using a linear accelerator-based THz source [1, 2]. The Photo Injector Test Facility at DESY in Zeuthen (PITZ) is an ideal machine as a prototype for developments of the THz source [3].

Research and development (R&D) of the prototype linear accelerator-based THz source are ongoing at PITZ. The R&D has been conducted in two parts. The first part is a proof-of-principle experiment to generate THz Self-Amplified Spontaneous Emission (SASE) FEL using an LCLS-I undulator (on loan from SLAC) driven by an electron bunch from the PITZ accelerator [4–6]. The second part is a conceptual design study of an ideal accelerator-based THz source facility that can be established at the European XFEL site and used for the pump-probe experiments.

Recently, the installation of the first THz beamline setup at PITZ was finished [7] and the first commissioning of the proof-of-principle experiment has been performed with a bunch charge of up to 3 nC. Measurements of the THz generation have been taken using pyrodetectors and the statistics properties analysis reflects the expected SASE performance [8, 9].

As the proof-of-principle experiments are ongoing at the PITZ facility, we also have worked on a conceptual design of the ideal THz source that can produce intense, tunable, and narrow-band THz radiation using a SASE FEL, a seeded FEL, and superradiant undulator radiation (SUR). A basic concept layout of the ideal THz source for simulation studies is shown in Fig. 1. The layout consists of an RF electron gun, two identical RF linacs, a bunch compressor, and a THz FEL undulator. Models and locations of the RF gun and the first linac in the layout are identical to those at the PITZ facility, with an additional linac downstream from the first one. Descriptions of the gun and the linac are presented in [10]. Description and preliminary simulation studies of the bunch compressor are presented in [11]. The THz FEL undulator used in this study is an APPLE-II type undulator in a circular polarization mode with a period length of 40 mm [12].

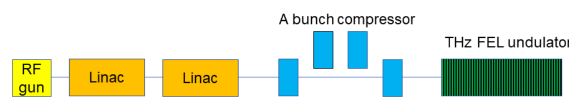

Figure 1: The basic concept layout of the ideal THz source.

In this paper, we focus on simulations of the SASE FEL. We also perform an example simulation of the seeding FEL for comparison with the SASE. We left SUR simulation for future study. First, we performed beam dynamics simulations using The ASTRA program package [13]. Next, we conducted FEL process simulations using the Genesis 1.3 code [14]. Then, we performed an example simulation of the seeded FEL with a center wavelength of 100 µm to demonstrate an improvement of THz pulse properties compared to the SASE case. Finally, a conclusion and outlook are given.

BEAM DYNAMICS SIMULATIONS

Beam dynamics simulations using the ASTRA program package were performed in order to deliver an uncompressed 4 nC electron beam from the cathode to the undulator entrance. Space-charge calculations were included in the simulations. The beam transport line layout used in these simulations follows the schematic diagram in Fig. 1. Some important machine and beam parameters used in the simulations are listed in Table 1.

The main solenoid current at the gun was optimized for minimum beam emittance values at the undulator entrance, 18 m downstream from the cathode. The accelerating gradient of the second linac was scanned from 0 to 18 MeV/m to achieve various beam momenta. Figure 2 shows simulated normalized transverse emittance at the undulator entrance as a function of the main solenoid current and the beam momentum. The emittance for each beam momentum is minimized in a main solenoid current range of 360 A to 365 A. We selected the beam with minimum emittance for each beam momentum and used it for FEL simulations in the next step.

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Table 1: Machine and Beam Parameters for the Simulation Studies.

Parameters	Values
Laser distribution	Flattop
FWHM laser pulse duration [ps]	20
Gun gradient [MV/m]	60
Gun phase [°]	0 w.r.t. MMMG
Linac gradients [MV/m]	10 and 0–18
Linac phase [°]	0 w.r.t. MMMG
Bunch charge [nC]	4
Undulator period length [cm]	4
Number of undulator periods	125
Total length of undulator [m]	5
Undulator parameter	1.85

MMMG stands for maximum mean momentum gain.

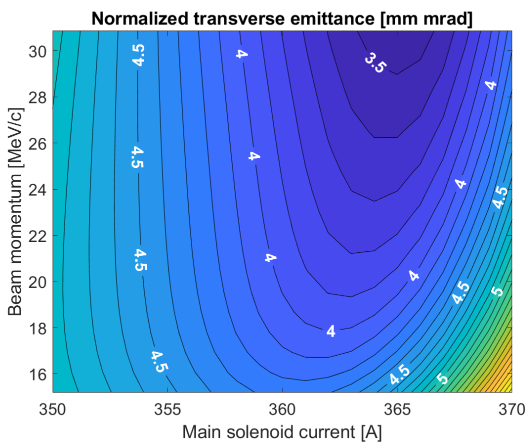

Figure 2: Normalized transverse emittance at the undulator entrance as a function of the main solenoid current and the beam momentum.

Figure 3 shows the average slice momentum spread of the optimized beam as a function of the beam momentum. The average slice momentum spread gradually reduces with the beam momentum starting from 8.07 keV/c at 15 MeV/c to 7.52 keV/c at 31 MeV/c. A plot of the peak current of the optimized beam as a function of the beam momentum is shown in Fig. 4. The trend of the peak current is increasing slightly with the beam momentum from about150 A to 152 A. Values of the peak current and the slice momentum spread are comparable to those from start-to-end simulations in [12].

FEL SIMULATIONS

Simulations of the FEL radiation were performed using the Genesis 1.3 code. The calculations in time-dependent mode including space-charge effects were used in the simulations. The undulator was set to be a helical undulator and its parameters are listed in Table 1. The optimized beams with different beam momenta were used as the input beams. We assumed a good beam-matching condition. The transverse rms sizes of each beam were assumed to be 0.5 mm and the values of the Twiss parameter α were assumed to be 0.1 at the undulator entrance. Beam matching for these values were demonstrated from the start-to-end simulations in [12].

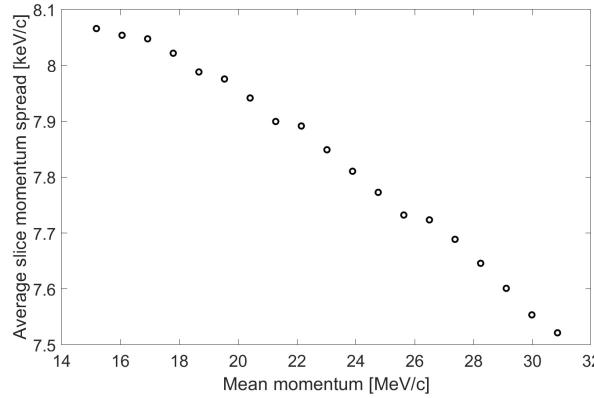

Figure 3: Average slice momentum spread of the optimized beam with different beam momenta.

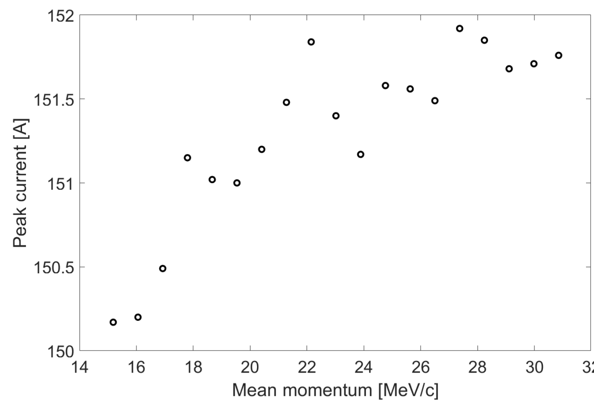

Figure 4: Peak current of the optimized beam with different beam momenta.

Since the undulator parameter was fixed at 1.85 in this work, the center wavelength depends on the beam momentum. Figure 5 shows FEL pulse energy at the undulator exit as a function of the center wavelength. The pulse energy of 1.1 mJ was obtained at the center wavelength of 24 µm and the maximum pulse energy of 1.8 mJ was obtained at 100 µm. In summary, we got the pulse energy of > 1 mJ for all the center wavelengths.

In addition to high intensity, the ideal THz source should deliver stable THz pulses with low shot-to-shot pulse energy fluctuation and low arrival time jitter. However, SASE FELs demonstrate significant shot-to-shot fluctuation due to the stochastic nature of the SASE process. To achieve more stable shot-to-shot performance, several seeding methods can be used [15]. We performed an example seeded FEL simulation for the center wavelength of 100 µm. A pre-bunched electron beam was used by setting the bunching value in the simulation code to be 0.01. The beam current modulation for this bunching value can be seen in [15]. The gain curves

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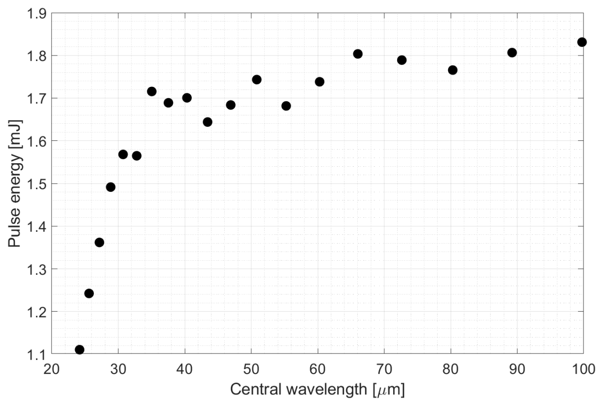

Figure 5: FEL pulse energy at the undulator exit as a function of the center wavelength.

obtained from SASE and seeded FEL simulations are shown in Fig. 6. The results for each method are based on 100 shots statistics with different seed numbers given to the particle generator in the simulation code. The main parameters of THz pulses obtained from both methods are summarized in Table 2. The results show that the seeding method can improve the pulse energy fluctuation, arrival time jitter and center wavelength jitter significantly compared to those from the SASE.

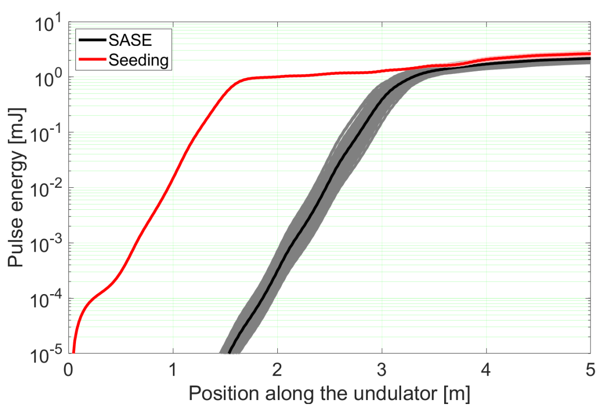

Figure 6: Comparison of the gain curves obtained from SASE and seeded FEL simulations for the center wavelength of 100 µm.

Table 2: Main Parameters of THz Pulses at the Undulator Exit Obtained from SASE and Seeding FELs.

Parameters	**SASE**	**Seeding**
Pulse energy [mJ]	1.85	2.67
Pulse energy fluctuation [%]	6.13	0.08
Arrival time jitter [ps]	0.47	0.01
Center wavelength [µm]	117	114
Center wavelength jitter [µm]	2.28	0.02

CONCLUSION AND OUTLOOK

Simulations of the THz FEL were performed. The results show that a SASE FEL pulse energy of at least 1 µJ is achievable for the center wavelengths of 25 to 100 µm. The preliminary seeding FEL simulation shows that the seeding method can improve the stability of the THz pulse significantly compared to that from the SASE.

We plan to perform more simulations including more realistic start-to-end simulations with quadrupole magnets, FEL simulations from the APPLE-II type undulator in linear polarization modes, and detailed seeded FEL simulations. Possible impact of the narrow vacuum chamber of the undulator (wakefield of electron bunch and waveguide effect of the FEL process) also has to be investigated.

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