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START-TO-END SIMULATIONS FOR BUNCH COMPRESSOR AND THz SASE FEL AT PITZ*

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Abstract

The magnetic bunch compressor was designed as part of a THz accelerator source being developed at the Photo Injector Test facility at DESY in Zeuthen (PITZ) as a prototype for pump-probe experiments at the European XFEL. As an electron bunch is compressed to achieve higher bunch currents for the THz source, the beam dynamics in the bunch compressor was studied by numerical simulations. A start-to-end simulation optimizer including coherent synchrotron radiation (CSR) effects has been developed by combining the use of ASTRA, OCELOT, and GENESIS to support the design of the THz source prototype. In this paper, we present simulation results to explore the possibility of improving the performance of the THz FEL at PITZ by using the developed bunch compressor.

INTRODUCTION

An accelerator-based THz source prototype for pump-probe experiments at the European XFEL is in the final stage of installation at the Photo Injector Test Facility at DESY in Zeuthen (PITZ). The electron beam from the RF gun is further accelerated to a beam momentum of ~17 MeV/c by the CDS booster cavity. In order to achieve a THz Self-amplified spontaneous emission (SASE) free electron laser (FEL) with pulse energy in the mJ-range, highly space-charge-dominated electron beams such as 4 nC beams with a bunch current of about 160-200 A are set as a nominal setting [1–3] with a challenge in beam transport and matching to the undulator. Alternatively, relatively-lower-charge beams such as 1.5-2.5 nC beams with an average bunch current near 200 A are considered as an option when using a bunch compressor [4]. In this option, the lower-charge beams may also provide experimental benefits such as less challenges in beam transport and matching, etc.

The bunch compressor using a magnetic chicane has been foreseen and assigned as a part of the prototype for various applications such as the SASE FEL, seeded FEL, superradiant radiation, etc [4, 5]. The chicane consists of four rectangular dipole magnets with identical strength and length. Due to limited available space in the PITZ tunnel, this chicane has a vertical bending plane with an angle of 19 degrees in order to make a vertical clearance above the original PITZ beamline components. These dipole magnets are obsoleted from the HERA beamline [6]. While the magnetic field of the dipole magnet is yet to be measured, the effective length of each dipole of 0.327 m is estimated from the magnetic field simulation via the program CST Studio Suite [7]. Therefore, R_{56} of this chicane is 0.215 m.

We study the bunch compressor option at PITZ by simulating the beam dynamics and SASE FEL. A start-to-end simulation optimizer has been developed by combining the use of the programs ASTRA [8], OCELOT [9], and GENESIS 1.3 [10] to support our test experiments on the THz source prototype. Note that coherent synchrotron radiation (CSR) effects influencing the performance of the bunch compression was discussed in [4]. In this paper, we report simulation results such as optimized FEL pulse energy with booster phases as a beam-energy-chirp tuning knob, while discussing possible beam transports using available quadrupole magnets.

START-TO-END BEAM DYNAMIC SIMULATION

The start-to-end beam dynamic simulation [4] was previously developed with a combination of the programs ASTRA [8], OCELOT [9], and IMPACT-t [11]. ASTRA is firstly used to track the electron from the cathode to the booster, and then OCELOT and IMPACT-t are set up to investigate the bunch compression performance including CSR effects. While the CSR simulation with OCELOT is benchmarked with IMPACT-t, IMPACT-t is replaced by OCELOT for faster optimization in the investigation of beam transport and FEL performance. The FEL performance parameters such as saturation length and pulse energy are estimated by both the program GENESIS and a semi-analytical calculation of M. Xie's solutions in the framework of the one-dimensional model [12, 13] implemented to OCELOT evaluation functions. In this semi-analytical calculation, when the electron bunch is much longer than the FEL cooperation length (~400 μm), the electron bunch is sliced and the SASE power growth of each slice is estimated.

SIMULATION OF BEAM TRANSPORT AND MATCHING IN CHICANE

Since several quadrupole magnets prior to the chicane at PITZ are installed [14], it is possible to transport the beam with constraints. In this study, the first constraint is described by a following mathematical condition at the middle z-position of the chicane with the Courant–Snyder (CS) parameters,

$$\alpha_x = \alpha_y = 0. \tag{1}$$

This condition is applied to all cases in a scan of bunch charge and booster phase. Note that other constraints can also be

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considered in a future study to support beam transport to the undulator.

In order to obtain solutions of Eq. (1), the simplex algorithm [15] is combined with the use of OCELOT including the space charge and the CSR effects. First, OCELOT generates a Gaussian distribution at the selected position in front of the chicane – a reference screen position – with assumed CS parameters and beam emittance obtained from ASTRA simulation and tracks the beam to the middle z-position of the chicane in each iteration. The simplex algorithm is used to find the CS parameters that satisfy the condition defined by Eq. (1). Solutions of the simplex algorithm depend on initial guesses of CS parameters, since Eq. (1) does not define a unique beam transport.

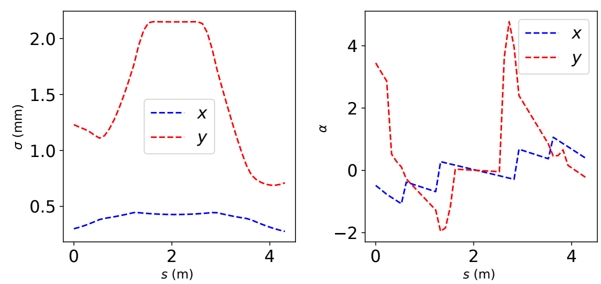

Figure 1: Evolution of root-mean-squared transverse beam size (left) and Courant–Snyder parameter α (right) of a 17 MeV/c beam with a bunch charge of 1.5 nC along a beam path s throughout the chicane ending at 0.453 m downstream to the final dipole magnet, where $s = 0$ indicates the location with a longitudinal distance of 0.238 m prior to the first dipole magnet.

The second constraint dictates the beam transport and matching after the chicane. Due to limited available space in the PITZ tunnel [14, 16], only one quadrupole magnet is installed at 0.45 m downstream to the chicane exit. To transport the beam with a distance of 3.8 m from the chicane exit to a quadrupole triplet, installed for matching the beam into the undulator, solutions with relatively low beam size and divergence in one of the transverse axes at the chicane exit is preferred. Thus, the horizontal root-mean-squared (rms) beam size σ_x at the chicane exit must be smaller than the vertical one σ_y.

Once such a solution is obtained, the simplex algorithm is again combined with OCELOT to instead tune strengths of several quadrupole magnets prior to the chicane in order to achieve the earlier-solved CS parameters. Here the beam distribution simulated by Astra is taken as input. Figure 1 shows the transport of a model beam of 1.5 nC along the chicane, where a beam waist ($\alpha_x, \alpha_y \sim 0$) is achieved in both horizontal and vertical planes in the middle z-position of the chicane. Meanwhile, the beam is small and converging in the horizontal plane but is large and diverging in the vertical plane. This guarantees the further transport of the beam using the single quadrupole that follows the chicane.

SASE FEL SIMULATIONS

In this section, we firstly discuss the semi-analytical calculation and its results for LCLS-I undulator parameters. The semi-analytical calculation is performed by solving the M. Xie's solutions with the compressed beam parameters [12, 13] in order to obtain an optimized CS parameter β_x giving maximum FEL pulse energy. Then the optimized β_x becomes a primary goal of tuning quadrupole magnet strengths prior to the undulator by the simplex algorithm with beam tracking to the undulator using OCELOT including the space charge effect. Furthermore, several constraints such as CS parameters $\alpha_x = \alpha_y = 0$, rms transverse beam size along the tracking $\sigma_x, \sigma_y < 4$ mm are implemented to the goal of the simplex algorithm.

In this study, we scan the bunch charge, booster phase, and the (ASTRA) initial Gaussian laser pulse length to find the maximum FEL pulse energy, see details of the parameters in [4]. Due to the space charge effect, β_x from the tracking with the calculated quadrupole magnet strengths is larger than the optimized β_x and FEL pulse energy in the case of 1.75 nC bunch charge drops from 950 to 276 μJ. Note that the initial laser pulse length is represented in full width at half maximum (FWHM).

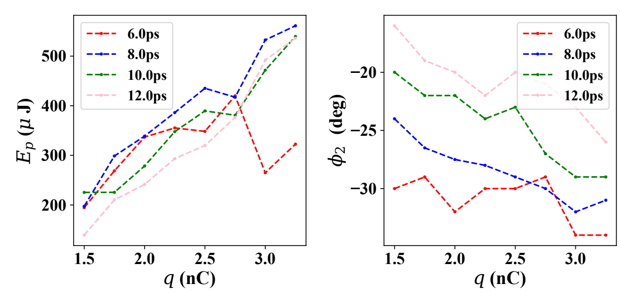

Figure 2: Optimized FEL pulse energy via the semi-analytical calculations and corresponding booster phase with respect to MMMG phase as a function of a bunch charge with initial laser pulse length of 6, 8, 10, and 12 ps (FWHM).

Figure 2 shows the results of the semi-analytical calculation with a resonant wavelength of 100 ± 2 μm, as the saturation length is under 4.6 m. They preliminarily indicate that the maximum FEL pulse energy is obtained from the initial laser pulse length of 8 ps in FWHM with optimized booster phases for each bunch charge. Note that all optimized booster phases correspond to under-compression in the chicane, see Fig. 6 in [4] showing the full compression phases. Therefore, we further investigate FEL simulations with GENESIS using the initial pulse length of 8 ps FWHM and the expected bunch charges in the same scan method.

GENESIS is also used to perform FEL simulations with a 3.4-meter-long LCLS-I undulator (currently installed at PITZ for proof-of-principle experiments). In the first step using GENESIS, a simulated transverse beam profile after the compression is represented by CS parameters. Thus, CS parameters are optimized (by scanning) for maximum FEL pulse energy simulated by GENESIS, while the original

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transverse emittance is maintained. For simplicity, the CS parameters $\beta_x = 2.605$, $\beta_y = 0.231$, $\alpha_x = 0.695$, $\alpha_y = 2.174$ are obtained from the scan using a 2.5 nC beam with booster phase ϕ_2 of -32 degree with respect to maximum mean momentum gain phase (MMMG phase) and are set for all study cases using bunch charge of 1.5-2.5 nC and booster phases between -24 and -32 degree.

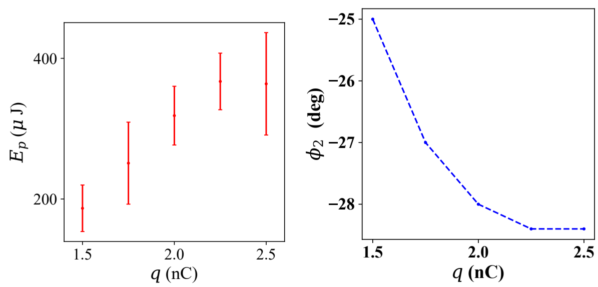

Figure 3: Optimized FEL pulse energy via GENESIS (left) and corresponding booster phase (right) as a function of bunch charge with initial laser pulse length of 8 ps (FWHM).

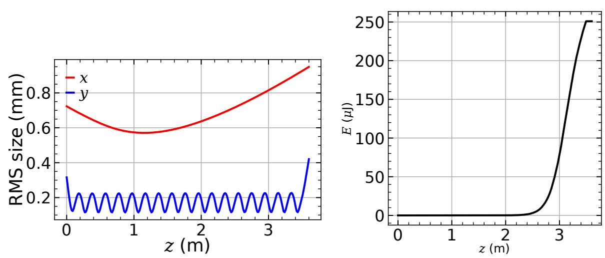

Figure 4: Evolution of the rms transverse beam size (left) and FEL pulse energy (right) of 17-MeV beam with a bunch charge of 1.75 nC along the longitudinal axis throughout LCLS-I undulator via GENESIS.

Figure 3 shows GENESIS results for the beam with initial laser pulse length of 8 ps FWHM. They show reasonable agreement with the earlier semi-analytical calculations, whereas the GENESIS simulation yields the relatively smaller FEL pulse energy. For instance, the FEL pulse energy of ~250 μJ is obtained for the 17-MeV beam, which is slightly lower than the semi-analytical result. As a result of the CS parameter scan, Fig. 4 shows that rms transverse beam size of the 17-MeV beam with a bunch charge of 1.75 nC is expected to be smaller than 1 mm, while the FEL pulse energy does not reach the saturation.

SUMMARY

A start-to-end beam dynamic simulation tool is developed by a combination of the several codes to optimize the PITZ bunch compressor option. A FEL pulse energy of ~250 μJ is obtained from a 1.75 nC beam (smaller than the nominal bunch charge) with optimized booster phases via GENESIS for the setup of the proof-of-principle experiments.

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