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SIMULATION STUDY OF A BUNCH COMPRESSOR FOR AN ACCELERATOR-BASED THz SOURCE AT THE EUROPEAN XFEL

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Abstract

The European XFEL has planned to perform pump-probe experiments using its X-ray pulses and THz pulses. 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 an accelerator-based THz source. The THz source requires a bunch compressor in order to manipulate the longitudinal phase space of the electron bunch to match with various options of THz radiation generation. This paper presents and discusses simulation study of the bunch compressor for the THz source.

INTRODUCTION

Research and development (R&D) of an accelerator-based THz source prototype for pump-probe experiments at the European XFEL are ongoing at the Photo Injector Test Facility at DESY in Zeuthen (PITZ). The R&D have been conducted in two parts. The first part is a proof-of-principle experiment to generate THz SASE FEL radiation by using an LCLS-I undulator driven by an electron bunch from the PITZ accelerator [1, 2]. The second part is conceptual design studies of an ideal accelerator-based THz source facility that can be established at the European XFEL site and used for the pump-probe experiments.

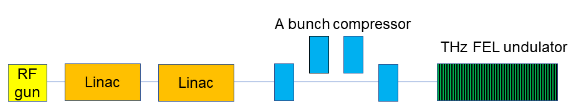

Figure 1: The basic concept layout of the ideal THz source.

A basic concept layout of the ideal THz source is shown in Figure 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. The accelerators can produce an electron beam with an average beam momentum of up to 35 MeV/c, a bunch charge of up to 5 nC, and similar beam emittance values that are achievable at the PITZ facility [3, 4].

The ideal THz source has been designed to produce intense, tunable, and narrow-band THz radiation by means of a SASE FEL, a seeded FEL, and superradiant undulator radiation (SUR) as the proof-of-principle experiments are ongoing at the PITZ facility. The different means of THz radiation generation require different temporal shapes of the electron bunch. For example, a several-ps long electron bunch is required for the SASE FEL, a temporal-modulated bunch is necessary for the seeded FEL, and a sub-ps long bunch is essential for the SUR. Therefore, a bunch compressor between the second linac and the THz undulator is needed to manipulate the longitudinal phase space of the beam in order to achieve the required temporal shapes.

In this paper, we present simulation study of a bunch compressor that can provide an electron bunch with a sub-ps bunch length, which is required for the SUR, at its full compression. This bunch compressor can be used for the other required bunch shapes, a several-ps long electron bunch and a temporal-modulated bunch, which will be studied in future work. First, the beam requirements of the SUR are presented in the next section. Then, specifications of the bunch compressor which is based on BC0 of the European XFEL [5] are presented. After that, details of beam dynamics simulations for bunch compression of a 100 pC electron bunch with different beam momenta are presented and discussed. The OCELOT [6] was used for the simulations. Finally, a summary and outlook of this work are given.

BEAM REQUIREMENTS

SUR requires an electron bunch with a bunch length equal to or shorter than the fundamental wavelength of the undulator radiation, so the radiation is emitted coherently [7]. Specifications of an undulator for the SUR are assumed to be identical to those in [4]. The undulator is a helical undulator with a period length of 40 mm. The undulator parameter (K) is variable in a range of 0.26 to 1.90. Figure 2 shows the calculated fundamental wavelengths with $K = 0.26$ and $K = 1.90$ of the undulator radiation as a function of the electron beam momentum. The vertical range of 20 µm to 100 µm is the required range of the FEL wavelength in [4]. By considering the fundamental wavelength of 100 µm from the plots in Fig. 2, the rms bunch length up to 0.333 ps (100 µm/c) within a momentum range of 7.84 to 15.76 MeV/c is required for the SUR. This requirement will be used as a benchmark for beam dynamics simulations.

BUNCH COMPRESSOR FEATURES

The lattice configuration of the bunch compressor is shown in Figure 3. The configuration consists of two sets of quadrupole doublet and a magnetic chicane. The doublet Q1 & Q2 is used for matching the beam into the bunch compressor, while the doublet Q3 & Q4 is used for downstream transport and matching. Parameters of the chicane are based on the bunch compressor BC0 at the European XFEL [5], which are summarized in Table 1.

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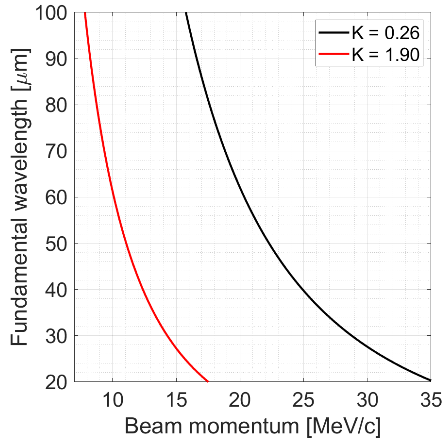

Figure 2: The calculated fundamental wavelengths of the undulator radiation with $K = 0.26$ and $K = 1.90$ as a function of the electron beam momentum.

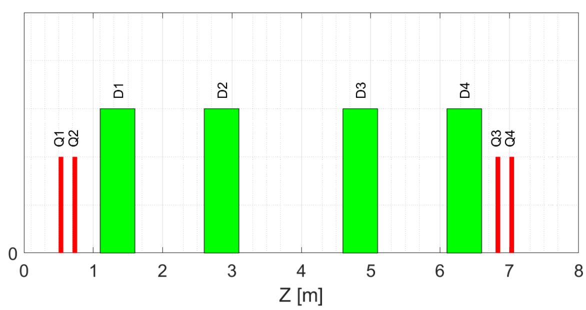

Figure 3: The lattice configuration of the bunch compressor.

Table 1: Parameters of the Chicane

Effective length of each dipole	0.5 m
Length between D2 and D4	1.5 m
Total length	5 m
Bending angle	5.67° - 8.19°
R_{56}	−26 to −80 mm

Compression of the rms bunch length is maximized in linear approximation when $h = -1/R_{56}$, where h is the energy chirp of the electron bunch at the entrance of the bunch compressor [8]. In this work, we fixed the bending angle at 8.19° which is corresponding to the R_{56} of 78.56 m. This R_{56} is calculated with an relativistic assumption, so R_{56} contribution from drift lengths ($R_{56,\Delta s} = \Delta s/\gamma^2$, where Δs is a drift length and γ is the Lorentz factor of the electron beam), is negligible. However, in our case, the beam momentum of up to 35 MeV is not fully relativistic and therefore $R_{56,\Delta s}$ contributes significantly to the total R_{56} of the bunch compressor. For example, the momentum range of 7 to 35 MeV corresponds to the total R_{56} range of −120 to −81 m when contributions of $R_{56,\Delta s}$ are considered.

BEAM DYNAMICS SIMULATIONS

Beam dynamics simulations with the lattice configuration in Fig. 3 were performed in order to evaluate the bunch compression efficiency of the bunch compressor. The Generator tool of ASTRA [9] was used for generating initial electron bunches at the beginning position ($Z = 0$). Parameters of the initial bunches are listed in Table 2. Each initial bunch has a different beam momentum, which is varied from 7 to 35 MeV/c with a step of 1 MeV/c. In order to maximize bunch compression, the energy chirp of each bunch is adjusted to match the R_{56} that changed with the beam momentum as explained in the previous section.

Table 2: Parameters of the Initial Electron Bunches at $Z = 0$

Bunch charge	100 pC
σ_z	5.85 ps
$\varepsilon_{n,x}, \varepsilon_{n,y}$	1 μm
β_x, β_y	10 m
beam momentum	7 to 35 MeV/c
energy spread	0.05 %
energy chirp	8.3 to 12.36 m^{-1}

Each initial bunch was tracked through the bunch compressor from $Z = 0$ to $Z = 7.6$ m by using Ocelot. Each tracking was performed for two cases: one with the space-charge (SC) method and another one with the coherent-synchrotron-radiation (CSR) method. The focusing strengths of Q1 to Q4 were optimized by using a matching tool of Ocelot. The matching constraints are that the dispersion is zero at the final location and that the beta functions of the final bunch are the same as those of the initial bunch.

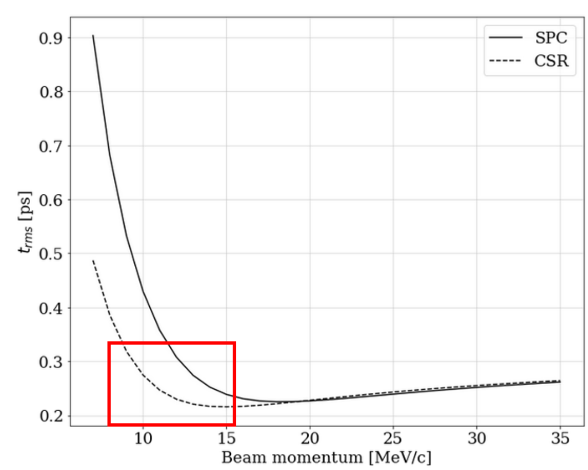

Figure 4: Simulated final RMS bunch lengths as a function of beam momentum. The red box represents the ranges that are suitable for generating SUR with a fundamental wavelength of 100 μm.

Figure 4 shows simulated final RMS bunch lengths (t_{rms}) as a function of beam momentum when tracking with the SC method and the CSR method. The graph shows that

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t_{rms} of the SC case is about 0.9 ps at the beam momentum of 7 MeV/c and then drops sharply to 0.22 ps at the beam momentum of 18 MeV/c. The curve of t_{rms} of the CSR case shows the same trend as that of the SC case but with much smaller t_{rms} for the beam momentum below 18 MeV/c. The area inside the red box in Fig. 4 represents the ranges that the compressed bunch is suitable for generating SUR with a fundamental wavelength of 100 µm. Since there are parts of the curves inside the box, the compressed bunches for generating the 100 µm SUR are achievable with this bunch compressor.

Examples of the compressed longitudinal phase space (LPS) of a 15 MeV/c bunch when tracking with the SC method and CSR method are shown in Figure 5. Each LPS has a strong curvature. However, the shape of the SC case looks more distorted and has modulation. This modulation can possibly be an effect of microbunching instability [10]. The bunch length of the SC and the CSR cases are 0.24 ps and 0.21 ps, respectively.

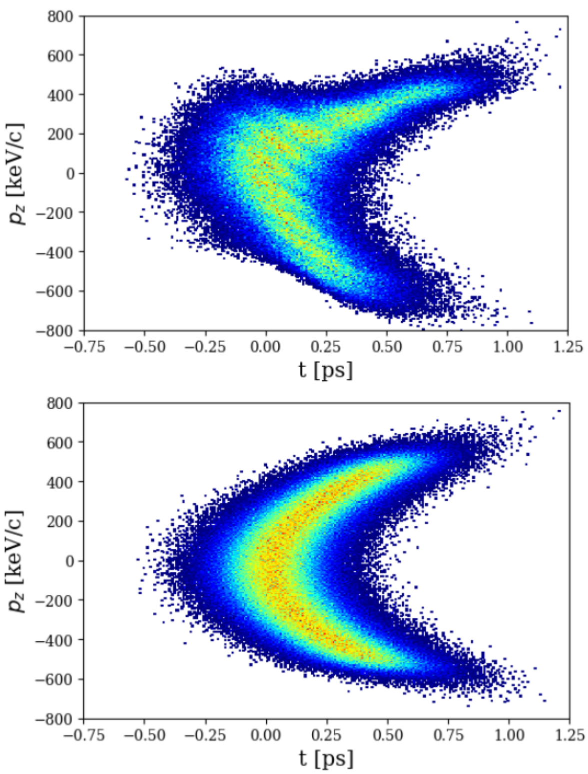

Figure 5: Longitudinal phase space of the compressed bunch when tracking with the SC method (top) and the CSR method (bottom). The average beam momentum for both cases are 15 MeV/c.

CONCLUSION

Beam dynamics simulations of electron bunch compression for the ideal THz source were performed. The design of the bunch compressor is based on the bunch compressor BC0 at the European XFEL. The results show rms bunch lengths below 0.33 ps within a momentum range of 7.84 to 15.76 MeV/c are achievable.

We will continue to optimize bunch compression in beam dynamics simulations and calculate the output SUR from the optimized bunches. Output SUR parameters that comparable to those of at HZDR [11] are expected. Finally, we will perform start-to-end simulations. All steps will be repeated for the SASE and the seeded FELs.

ACKNOWLEDGEMENTS

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