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NUMERICAL STUDY OF BEAM DYNAMICS IN PITZ BUNCH COMPRESSOR*

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Abstract

A magnetic bunch compressor has been recently designed for an accelerator-based THz source which is under development at the Photo Injector Test facility at DESY in Zeuthen (PITZ). The THz source is assumed to be a prototype for an accelerator-based THz source for pump-probe experiments at the European XFEL. As an electron bunch is compressed to achieve higher bunch currents for the THz source, we investigate the beam dynamics in the bunch compressor by numerical simulations. A start-to-end simulation optimizer has been developed by combining the use of ASTRA, IMPACT-T, and OCELOT to support the design of the THz source prototype. Coherent synchrotron radiation effects degrade the compression performance for our study cases with bunch charges up to 4 nC and beam energy of 17 MeV at a bending angle of 19 degrees. Simulation and preliminary beam characteristic results will be presented in this paper.

INTRODUCTION

An accelerator-based THz source prototype for pump-probe experiments at the European XFEL is being developed and constructed at the Photo Injector Test Facility at DESY in Zeuthen (PITZ). A challenge with highly space-charge-dominated electron beams arises for achieving a THz Self-amplified spontaneous emission (SASE) free electron laser (FEL), which ideally requires a flattop-like electron bunch with full width at half maximum (FWHM) length longer than 5 ps and average bunch current of 200-400 A for 2-4 nC beams [1, 2].

A bunch compressor using a magnetic chicane has been foreseen and assigned as a part of the prototype for various applications additional to the SASE FEL [3]. Firstly a seeded FEL is proposed and requires the bunch compressor to support a tuning of photocathode laser pulse modulation. A technique with gratings or a double slit placed at the center of chicane is also considered as another option to generate a modulation or a split bunch for our future seeded FEL. Moreover, a superadiant option is considered and requires full compression for a minimum bunch length expected to be lower than 1 ps FWHM long with a charge lower than 400 pC. Optionally a future application of the high brightness beams at PITZ for R&D on the so-called FLASH radiation therapy will also benefit from the bunch compressor as it allows to vary the bunch length by about 2 orders of magnitude (compression and stretching).

The chicane consists of four dipole magnets with an 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 (Fig. 1). Note that [3] states an original design consisting of a chicane with the bending angle of 17 degrees. We use old magnets (steerers from HERA accelerator) with newly designed pole shoes. The pole shoes are joined to the shims optimized by the program CST Studio 2018 to flatten the magnetic field profile of the magnet along a bending axis. Thus electrons at the same longitudinal position experience magnetic fields from the dipole magnets with $< 0.1\%$ difference. As the effective length of each dipole of 0.327 m is estimated, R_{56} of this chicane becomes 0.215 m.

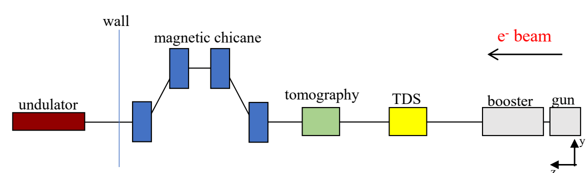

Figure 1: Bunch compressor in PITZ beamline.

We study the performance of the bunch compressor by beam dynamics simulations. A start-to-end simulation optimizer has been developed by combining the use of programs ASTRA [4], IMPACT-T [5], and OCELOT [6] to support our test experiments on the THz source prototype. In this paper, we report simulation results used to find conditions for the various applications such as average bunch current, energy chirp, and bunch length for requested charges. We consider RF-gun and booster phases as key tuning knobs to achieve the required beam parameters as well as focusing quadrupole magnets to transport the beam throughout the magnetic chicane. However, a coherent synchrotron radiation (CSR) effect challenges our study case involving high space charge up to 4 nC, low beam energy of ~17 MeV, and a large bending angle of 19 degrees. We also discuss the CSR effect influence on the performance of the bunch compression.

START-TO-END SIMULATION

A tool for start-to-end simulations has been developed for beam dynamics throughout the bunch compressor from

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RF-gun and booster contributing a longitudinal phase space (LPS) distribution for the compression. Combining the use of programs ASTRA, IMPACT-T, and OCELOT, the simulation starts as an electron beam travels from a cathode (z = 0 m) and ends at 0.61 m after the ending edge of the final chicane dipole magnet (z = 23.17 m). The beam is also being accelerated to the momentum of 6.7 and 17 MeV/c by the RF-gun and booster, respectively (simulated via program with ASTRA code) and then compressed by the chicane (via program using IMPACT-T), while focused by a solenoid for minimized transverse emittance (ASTRA) and by quadrupole magnets for beam transport (OCELOT).

In this study, the simulation includes the effect of space charge and coherent synchrotron radiation (CSR). The space charge effect is built within the programs ASTRA, IMPACT-T, and OCELOT as a minimum number of grid cells $N_x \times N_y \times N_z$ of $16 \times 16 \times 16$ is set. Moreover, the programs IMPACT-T and OCELOT include the CSR effect for the beam traveling throughout the chicane. Note that the space charge effect is only manually turned off at the chicane for the program OCELOT, when calculating matching conditions including quadrupole magnets.

In the first step of the start-to-end optimizer, the current of the gun solenoid and the laser beam size at the cathode position (beam shaping aperture: BSA) are fast scanned (low number of macroparticles ~ 10^4) for a minimum beam transverse emittance as the beam simulated by ASTRA travels to a reference screen (z = 8.92 m).

In the second step, the optimized solenoid current and the BSA are set to resimulate the beam at the reference screen using ASTRA. The purpose of this step is to investigate the possibility to minimize beam uncorrelated energy spread or linearize the beam longitudinal distribution, thereby minimizing the bunch length at full compression. Thus, the RF-gun phase is optimized for the uncorrelated energy spread and contributes the energy chirp for compression. Then all optimized parameters from steps 1 and 2 are set to resimulate the beam using ASTRA with a number of macroparticles of 5×10^5.

The third step is a beam transport from the reference screen to the entrance of the chicane due to the beam transverse divergence, space charge, and dispersion of the 19-degree dipole. Strengths of quadrupole magnets are matched to only lower the transverse beam size to avoid beam loss inside the chicane by OCELOT.

In the final step, the booster phase is scanned for final energy chirp contribution (additional to the optimized RF-gun phase). The beam is then simulated for the compression in the chicane by IMPACT-T and OCELOT. Therefore, a beam distribution from using each RF-gun and booster phases is analyzed for the various goals and applications.

SIMULATION RESULTS

Photocathode laser systems at PITZ are capable to generate pulses with flat-top and Gaussian temporal pulse profiles with FWHM pulse length between 1 and 12 ps. In this paper, we explore only the case of Gaussian pulses and investigate the possiblity of full compression aiming the minimum bunch length.

Results of the fast scan in the first step are shown in Fig. 2 for cases using a Gaussian laser pulse profile. The current of the solenoid and BSA for each bunch charge resulting in the minimum transverse emittance are analyzed and used for the next steps. With analogy to the space charge effect, current of the solenoid and BSA are higher for higher bunch charges.

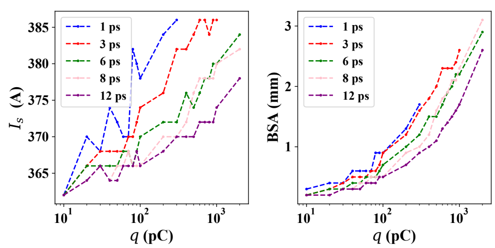

Figure 2: Optimum gun solenoid current (left) and BSA diameter (right) for each bunch charge for Gaussian laser pulses with different lengths (see legend).

Second step results shows that the gun phase is less significant to our optimization than the booster phase. For the case of 6 ps photocathode laser pulses and 2 nC bunch charge, average uncorrelated energy spread can be reduced by only < 13%. As a result, optimization with the gun phase becomes optional. Therefore, the gun phase will be kept constant for further steps at the zero offset from the maximum momentum gain phase.

After the third and final steps, the results of the compressed beam can be achieved. For example, the simulation results show that beams with an FWHM bunch length of 3 ps and average bunch current of 650 A could be achieved by full compression of 2 nC beams generated from laser pulses of 8 ps FWHM. In the case of longer laser pulse, transverse emittance growth in the bending axis plane is smaller while the CSR effects mainly introduce large emittance growth. Results of the optimized compression – rms electron bunch length, average bunch current and vertical emittance for varios photocathode laser pulse FWHM durations are shown in Figs. 3 and 4. Note that the bunch current is averaged over the temporal range ±3 times profile standard deviation around the mean bunch position.

In order to apply the simulation results to a practical use, bunch length and average bunch current of the LPS for different booster phases are estimated, shown in Fig. 5 for the case of initial FWHM laser pulse length of 8 ps. Moreover, OCELOT and IMPACT-T results are benchmarked and depicted in Fig. 6. The legend OCELOT indicates the use of ASTRA (emission and acceleration) and OCELOT (matching and compression with the CSR effect), while the legend IMPACT-T designates the use of all three programs described in the previous section. According to Fig. 6, the next section we are interested in a compression booster phase range between -15 and -40 degrees.

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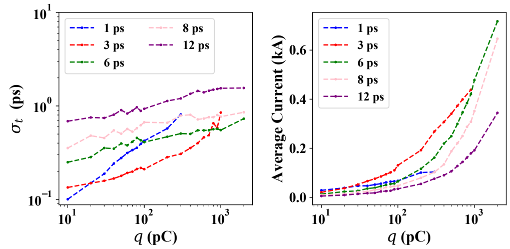

Figure 3: Results of the compression optimization: root-mean-squared bunch length (left) and average bunch current (right) for different initial FWHM laser pulse lengths.

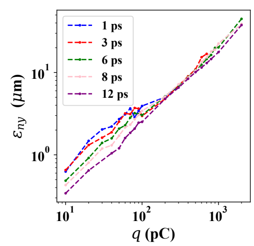

Figure 4: Simulation results of fully-compressed normalized transverse emittance in the bending axis for different initial FWHM laser pulse lengths.

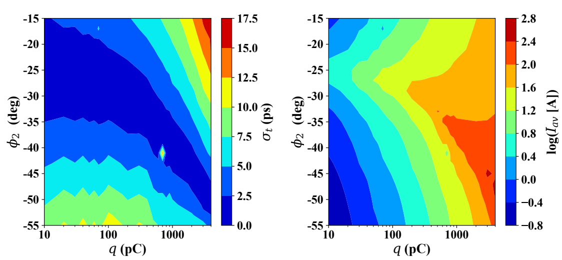

Figure 5: Density plot of bunch length (left) and average bunch current (right) vs booster phase and bunch charge for the initial FWHM (Gaussian) laser pulse length of 8 ps.

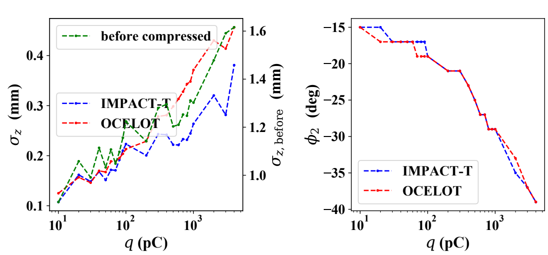

Figure 6: Simulation results of fully-compressed root-mean-squared bunch length (left) and corresponding booster phase (right) for different initial FWHM laser pulse lengths.

As above a result of all optimization steps suggest, a beam current profile shown in Fig. 7 satisfies our goal for THz SASE FELs. While the beam is compressed and the beam current is increased, space charge and CSR effects limit the chicane performance and distort the current profile.

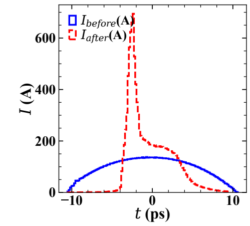

Figure 7: Undercompressed 2-nC beam current profile with booster phase of -39 degrees in red curve. The bunch profile before compression is shown with blue curve.

PRELIMINARY ELECTRON BEAM EXPERIMENTAL CHARACTERIZATION

An experiment at PITZ has been initiated to determine the beam chirp and LPS non-linearity by measuring LPS distributions [7]. To reduce the space charge effect contributing to the chirp measurement, we measure the LPS distribution of 10-pC beam for different booster phases. Fig. 8 shows that measured momentum chirp dp/dt is only different less than 9% from the simulation result at booster phase of -15, -20, and -25 degrees as in the compression range.

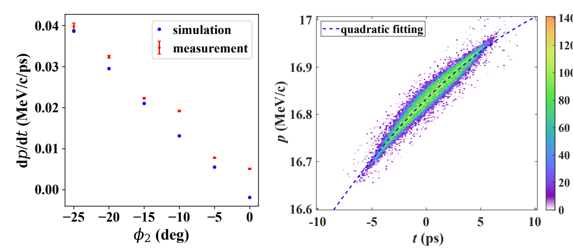

Figure 8: Left: Plot of momentum chirp dp/dt of 10-pC beam as a function of booster phase ϕ_2 for initial 8-ps Gaussian laser pulses. Blue dots represent ASTRA simulation results, while red dots donate measurement results at PITZ with rms momentum and time resolution of 6 keV/c and 1.3 ps, respectively. Right: Measured LPS distribution of 10-pC beam at booster phase ϕ_2 of -15 deg, where the color bar is a signal count and one count is equivalent to ~ 700 electrons.

FUTURE PLANS

The flattop laser temporal profile of the photocathode laser pulse will be simulated to compare with the presented Gaussian. The chicane will be installed in 2021 and commissioned for correcting the beam trajectory throughout the chicane and optimizing booster phase using a coherent transition radiation station.

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