LONGITUDINAL PHASE SPACE BENCHMARKING FOR PITZ BUNCH COMPRESSOR

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Abstract

The longitudinal phase space characteristics of space-charge dominated electron beams are keys to achieving bunch compression for the accelerator-based THz source at the Photo Injector Test facility at DESY in Zeuthen (PITZ). Such a THz source is proposed as a prototype for an accelerator-based THz source for pump-probe experiments at the European XFEL. A start-to-end simulation has suggested the settings of the phase of booster linear accelerator manipulating longitudinal beam characteristics to optimize the performance of the THz FEL. Although beam diagnostics after compression at PITZ are limited, the longitudinal beam characteristics as a function of the booster phase have been measured and compared with the corresponding simulations. The benchmark involves measurements of longitudinal phase space distribution for bunch charges up to 2 nC. The measurement technique assigned uses 50-μm slits to achieve higher momentum and time resolution (1.8 keV/c and 0.5 ps, respectively).

INTRODUCTION

The Photo Injector Test Facility at DESY in Zeuthen (PITZ) is established for the commissioning and testing of electron sources with various diagnostic systems from measurement of beam charge, beam momentum to transverse and longitudinal phase space characterization [1]. At PITZ, an accelerator-based THz source prototype for pump-probe experiments at the European XFEL is under development to achieve a THz Self-amplified spontaneous emission (SASE) free electron laser (FEL) [2]. A bunch compressor using a magnetic chicane has been considered as an additional part of the prototype to provide an alternative option using ~17 MeV/c electron beams with bunch charge under 2.5 nC and an average bunch current near 200 A [3, 4]. Moreover, it has been foreseen for other applications at PITZ such as seeded FEL, superradiant radiation, etc.

The chicane consists of four rectangular dipole magnets identical in strength and dimensions. In order to fit in the available space of the original PITZ beamline components, this chicane has a vertical bending plane with an angle of 19 degrees, and its estimated R_{56} is 0.215 m. Furthermore, the performance of the PITZ bunch compression affected by coherent synchrotron radiation (CSR) effects is studied via start-to-end beam dynamics simulation combining the use of programs ASTRA [5], OCELOT [6], and IMPACT-t [7]. In [4], simulation results of fully-compressed electron bunch with different corresponding booster phases ϕ_2 for an initial Gaussian laser pulse with a pulse length of 8 ps in full width at half maximum (FWHM) are discussed. The booster phase becomes a beam-momentum-chirp tuning knob to optimize the performance of the SASE FEL and the other applications.

A challenge arises as the bunch compressor is installed downstream of a longitudinal bunch profile measurement station [8]. In other words, experimental results of the bunch profile after compression are not able to be measured. Thus, a measurement plan has been initiated to benchmark the simulation results. In the plan's first step, the beam momentum chirps dp/dt (with different booster phases) prior to the chicane are measured to benchmark ASTRA simulations. In the second step, a coherent transition radiation (CTR) measurement station will be installed between the chicane and LCLS-I undulator [2, 8]. The CTR measurement is expected to indicate the fully-compressed-bunch booster phases for the beam with bunch charge up to few hundred pC.

This paper discusses the first step of the measurement plan, which implies a characterization of the beam longitudinal phase space (LPS) distribution.

LONGITUDINAL PHASE SPACE MEASUREMENT

An LPS measurement setup at PITZ consists of a transverse deflecting system (TDS) and a dipole spectrometer (HEDA2), respectively (see details in [9, 10]). Note that the TDS is located between the CDS booster cavity and the chicane; see LPS measurement scheme at PITZ in Fig. 1, and longitudinal positions of the TDS, the HEDA2, and the chicane in Table 1.

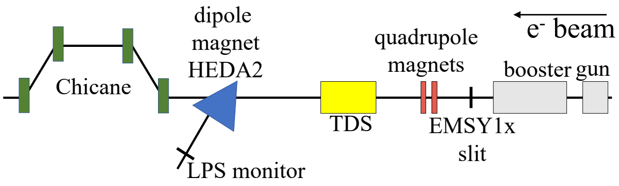

Figure 1: Longitudinal phase space measurement scheme at PITZ.

According to Table 1, the distance between the TDS and HEDA2 is approximately 7 m. Thus, it is considered that the space charge effects cause a significant change in the LPS of the beam, thereby modifying the momentum chirp. This

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Table 1: Longitudinal Start Positions z_s and End Positions z_e of Elements Involving in the Longitudinal Phase Space Measurement at PITZ, where the Cathode Position is $z_s = z_e = 0$

	z_s (m)	z_e (m)
EMSY1	5.177	5.377
TDS	10.642	11.3288
HEDA2	17.140	18.016
chicane	18.500	22.560

benchmarking experiment is based on an assumption that the space charge effects do not significantly change the momentum chirp along the beam transport between the TDS and HEDA2. Table 2 shows the momentum chirps simulated by ASTRA at $z = 8.92$ m (prior to the TDS) and tracked further with an additional drift length of 8.93 m for different bunch charges and booster phases. Moreover, the booster phases that result in the momentum chirp near 0.022 MeV/c/ps are selected for the comparison. Note that the beam momentum chirp $\mathrm{d}p/\mathrm{d}t$ is defined as a linear term (coefficient) in the quadratic regression of the LPS distribution.

Table 2: Momentum Chirp $\mathrm{d}p/\mathrm{d}t$ Simulated by ASTRA at $z = 8.92$ m and Tracked Further with an Additional Drift Length of 8.93 m ($z = 17.85$ m) for Different Bunch Charges q and Booster Phases ϕ_2, where and an Initial Gaussian Laser Pulse Length is Fixed to 8 ps FWHM

		$\mathrm{d}p/\mathrm{d}t$ (MeV/c/ps)	
q (pC)	ϕ_2 (deg.)	$z = 8.92$ m	$z = 17.85$ m
10	-15	0.0210	0.0214
30	-17	0.0224	0.0225
50	-17	0.0214	0.0211
2000	-31	0.0233	0.0170

In the experiments, images of the LPS distribution on a LYSO screen are recorded and analyzed by a MATLAB program. The image processing algorithm firstly eliminates the image background (dark current, electronic noise, scattering light, etc). Here it preliminarily computes a trial quadratic regression curve. Then it removes image noises beyond 3.5 standard deviations (in momentum axis) along the trial quadratic regression curve of the remaining image data for three iterations. Finally, it estimates the beam momentum chirp $\mathrm{d}p/\mathrm{d}t$.

MEASUREMENT RESULTS

Preliminarily we simplify the measurement by using 17-MeV/c beams with a bunch charge of 10 pC and an initial Gaussian laser pulse length of 8 ps FWHM. This reduces the space charge effect contributing to the measurement and results in root-mean-square (rms) momentum and time resolution up to 6 keV/c and 1.3 ps, respectively. In this LPS measurement, the momentum resolution is defined as

$$\delta p = \sigma_x / D, \tag{1}$$

where D is the dispersion of HEDA2, and σ_x is a horizontal beam size on the reference screen HIGH2.SCR2 at PITZ [9]. In [4], the measured momentum chirp $\mathrm{d}p/\mathrm{d}t$ agrees to simulation results with a discrepancy of less than 9%. Thus, the measurements of relatively higher bunch charges which is sufficient for the superradiant radiation (50 pC) [11] and the SASE FEL (2 nC) [4], respectively, have been studied in detail.

For the superradiant radiation at PITZ, we consider a bunch charge up to 100 pC [11]. By selecting 50 pC for the LPS measurement, the initial Gaussian laser pulse length of 3 ps FWHM is suggested by the simulation results shown in [4]. Thus, the space charge effect is expected to appear in the measurement by influencing beam transport and focusing, which can degrade momentum and time resolutions. Figure 2 (left) shows that measured momentum chirps $\mathrm{d}p/\mathrm{d}t$ of the 50 pC beam resemble the simulation results. However, the difference is up to 27%, and rms momentum and time resolution are up to 11 keV/c and 0.6 ps, respectively. Since the bunch length is shorter than the previous one, the momentum resolution is sacrificed for the time one by tuning beam focusing strength. In this case, the vertical beam size is slightly decreased by tuning the quadrupole magnets upstream of the TDS to improve the time resolution. Therefore, the horizontal beam size is increased, and that slightly degrades the momentum resolution. These estimated resolutions indicate the limitation of the original LPS measurement method. Moreover, Fig. 2 (right) shows measured the LPS distribution of 50 pC beam at booster phase ϕ_2 of -15 deg that is analyzed by the MATLAB program (explained in the previous section).

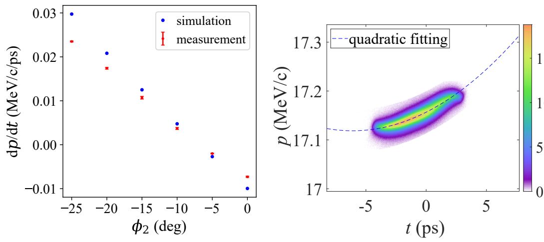

Figure 2: Left: Plot of momentum chirp $\mathrm{d}p/\mathrm{d}t$ of 50 pC beam as a function of booster phase ϕ_2 for 3 ps Gaussian laser pulses. Blue dots represent ASTRA simulation results at a distance of 8.92 m downstream of the cathode, while red dots give measurement results at PITZ with rms momentum and time resolution up to 11 keV/c and 0.6 ps, respectively. Right: Measured LPS distribution of 50 pC beam at booster phase ϕ_2 of -15 deg, where the color bar corresponds to a signal count and one count is equivalent to ~ 80 electrons.

For the SASE FEL at PITZ, we consider a bunch charge of 1.5-2.5 nC and the initial Gaussian laser pulse length of 8 ps FWHM. In this study, we select a bunch charge of 2 nC. Since this bunch charge results in a significant influence by space charge, the above-described method to measure LPS has to be modified.

The use of slits can be applied to LPS measurement for different purposes. For example, the measurement of 6D phase space and correlations shown in [12] uses a set of six movable slits to localize particles inside a small area of the 6D phase space. In our case at PITZ, 50-μm-slit at the emittance measurement station (EMSY1x) is used to reduce x-emittance influence in order to enhance the LPS resolution, while the slit is located to select a beamlet with the highest charge by our scanning program. Therefore, we define the highest-charge beamlet as a x-central beamlet. A simulation result via OCELOT predicts the resulting bunch charge is ~30 pC.

Figure 3 (left) shows measured momentum chirp of the x-central beamlet of the 2 nC beam as a function of booster phase. It can also be seen that measured momentum chirp $\mathrm{d}p/\mathrm{d}t$ deviates by less than 15% from the simulation result at booster phases of -20, -25, and -30 degrees which is the compression range. The rms momentum and time resolution are improved to 1.8 keV/c and 1.6 ps, respectively. Furthermore, Fig. 3 (right) shows measured LPS distribution of a 2 nC beamlet at booster phase ϕ_2 of -20 deg.

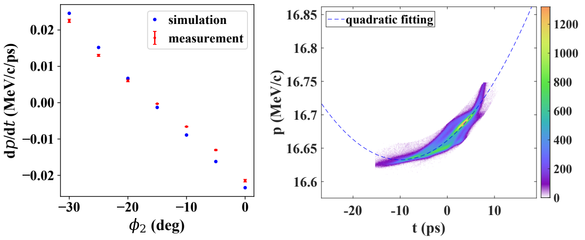

Figure 3: Left: Plot of momentum chirp $\mathrm{d}p/\mathrm{d}t$ of 2 nC x-central beamlet as a function of booster phase ϕ_2 for initial 8-ps Gaussian laser pulses. Blue dots represent ASTRA simulation results at the EMSY1 slit position, while red dots give measurement results at PITZ with rms momentum and time resolution up to 1.8 keV/c and 1.6 ps, respectively. Right: Measured LPS distribution of 2 nC beamlet at booster phase ϕ_2 of -20 deg, where the color bar corresponds to a signal count and one count is equivalent to ~ 106 electrons.

CONCLUSION

The momentum chirps of two selected cases for THz generation (superradiant radiation and SASE FEL) are measured and benchmarked with the simulation. The measurement for the 50 pC beam is limited by the momentum and time resolutions. The use of the slit allows us to observe only the x-central beamlet LPS of the 2 nC beam. Therefore, the measurement results show a possibility to tune the momentum chirps close to the ASTRA simulation results. Currently, the chicane is in the final stage of the installation and will be commissioned for optimized beam trajectory and minimized energy dispersion. Then the CTR will be measured as the next step in the measurement plan.

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