SINGLE-BUNCH LONGITUDINAL PHASE SPACE DIAGNOSTICS IN MULTI-BUNCH MODE AT THE EUROPEAN XFEL

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Abstract

Dedicated longitudinal electron beam diagnostics is highly demanded for the control and optimization of modern X-ray free-electron lasers (XFEL). At the European XFEL (E-XFEL), 3 transverse deflecting structures (TDS) will be installed at different locations of the accelerator for measurements of slice emittance and longitudinal profile. Operation of a TDS in combined use with an energy spectrometer, e.g. a dispersive section after a single dipole magnet, allows additionally for longitudinal phase space measurements. However, utilization of a dipole magnet is not compatible with single-bunch measurements in multi-bunch operation mode, which will be the standard operation mode of the E-XFEL. In this paper, we propose a longitudinal phase space diagnostic beamline consisting of a TDS, fast kicker and septum magnet for the E-XFEL. The layout of the accelerator lattice with optimized optics for longitudinal phase space measurements and numerical simulation studying the performance of the beamline will be presented.

INTRODUCTION

Generation of short electron bunches with high peak currents, which are required for the FEL lasing process, is commonly achieved in several longitudinal bunch compression stages in a combination of off-crest acceleration and magnetic chicanes. Hence, the control and monitoring of the longitudinal phase space is important in an FEL and can be realized by utilizing a transverse deflecting structure (TDS) in combination with an energy spectrometer. As a user facility, the E-XFEL puts high demands on diagnostic methods which are non-disruptive to the FEL operation. Therefore, single-bunch resolved longitudinal phase space diagnostics in multi-bunch mode is desired. For the energy spectrometer located in the diagnostic section after the second bunch compressor BC1, a septum magnet is proposed to replace the commonly used dipole magnet, for monitoring the longitudinal phase space before final compression. In this paper, we present the accelerator lattice of the diagnostic beamline and results of numerical simulations for the study of the performance of the beamline.

CONCEPTUAL BEAMLINE LAYOUT

Longitudinal phase space measurements can be realized by a combined use of a TDS and energy spectrometer, which transform the longitudinal phase space into a transverse distribution that can be measured with an imaging screen. The time-resolved energy distribution can be reconstructed, and the achievable rms time and energy resolutions are given by [1]

$$\sigma_t = \frac{\sigma_{x_0}}{S},\ S = \frac{eV_0k}{pc}\sqrt{\beta_{x,\mathrm{TDS}}\,\beta_{x,\mathrm{Screen}}}\cdot\sin(\Delta\mu_x) \quad (1)$$

$$\sigma_\delta = \frac{\sigma_{y_0}}{D_y} \quad (2)$$

with TDS shear parameter S and vertical dispersion D_y.

In the diagnostic section downstream of the second bunch compressor chicane BC1 at the E-XFEL, a horizontally deflecting TDS will be installed. The TDS is operated at a frequency of 3 GHz and will be capable of streaking a single bunch out of a bunch train [2]. Two fast kickers and a septum magnet allow the extraction of this streaked bunch into an energy spectrometer without disruption of the rest of the bunch train. A Lambertson-type septum is chosen to bend the beam vertically by 12° at the design energy of 700 MeV. The good field region of the septum requires the beam having a horizontal offset of $x = 20$ mm at the entrance of the septum, which is achieved by the two pulsed horizontal kickers. Downstream of the septum, all components are aligned at a horizontal offset of 20 mm.

The layout of the diagnostic beamline and the accelerator optics are presented in Fig. 1. In order to achieve sufficient time and energy resolution, many conditions have to be considered during optimization of the accelerator optics. To increase the effective TDS shear parameter S given in Eq. 1, the horizontal beta functions and dispersion have been set to $\beta_{x,\mathrm{TDS}} = 30$ m, $\beta_{x,\mathrm{Screen}} = 4.2$ m and $\Delta\mu_{x,\mathrm{TDS}\to\mathrm{Screen}} = 225°$. The horizontal kickers generate extra dispersion in the horizontal plane. With a value of $D_x = 1.8$ mm at the imaging screen, the effect of the kickers has only negligible contribution to the intrinsic horizontal beam size defined as $\sigma_{x_0} = \sqrt{\beta_s \cdot \epsilon_x + D_x^2 \cdot \delta^2}$. The vertical dispersion and vertical beta function at the imaging screen amount to $D_y = 1.29$ m and $\beta_{y,x} = 3.0$ m respectively, which provide a good energy resolution (cf. Eq. 2). In addition, the phase advance of $\Delta\mu_{x,\mathrm{TDS}\to\mathrm{Septum}} = 175°$ from the TDS to the septum reduces the shear parameter S (Eq. 1) to about zero, thus minimizing the horizontal beam size of the streaked bunch in the septum. At maximum TDS deflecting voltage of 15 MV (at klystron power of 24 MW) and nominal normalized emittance of $\epsilon_N = 1\ \mu$m), a time resolution of 16 fs and an energy resolution of $6.3 \cdot 10^{-5}$ can be achieved for the presented beam optics.

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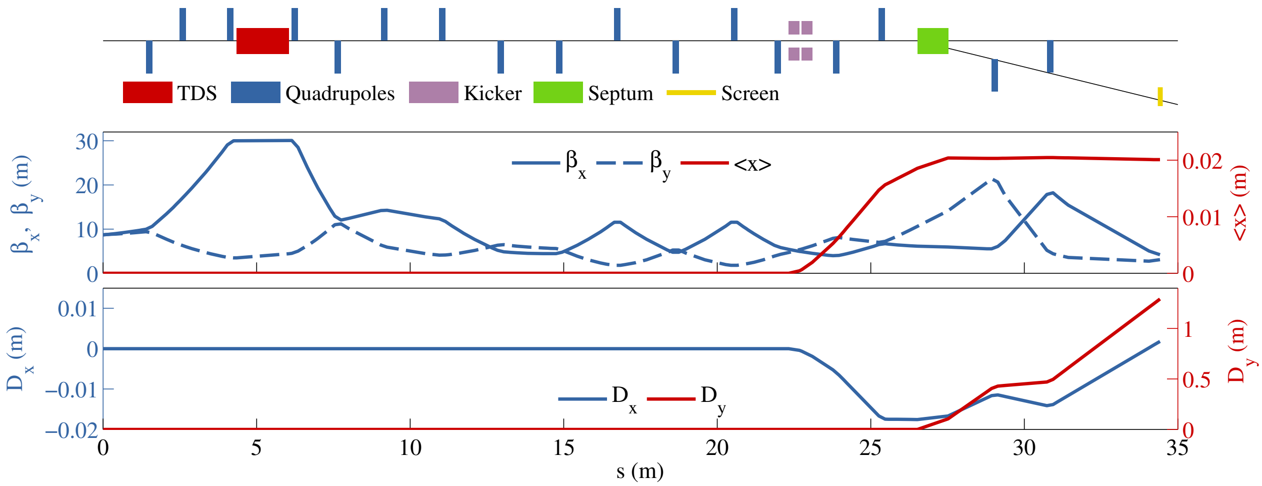

Figure 1: Top: Symbolic layout of the proposed online longitudinal phase space diagnostic beamline for the E-XFEL. The beamline starts at the exit of the second bunch compression chicane BC1 and ends at the imaging screen in the energy spectrometer arm. The deflection angle of the septum is 12° in the vertical plane. Bottom: Accelerator optics along the beamline with horizontal and vertical beta functions $\beta_{x,y}$, horizontal and vertical dispersions $D_{x,y}$ and horizontal offset of the beam centroid $\langle x \rangle$. The horizontal phase advances from the TDS to the septum and screen are $\Delta\mu_{x,\text{TDS}\rightarrow\text{Septum}} = 175°$ and $\Delta\mu_{x,\text{TDS}\rightarrow\text{Screen}} = 225°$, respectively.

NUMERICAL SIMULATION

The performance of the proposed diagnostic beamline (septum-beamline) was investigated in numerical simulations using the particle tracking code `elegant` [3]. In order to study the influence of the fast kickers and septum magnet, additional simulations were performed for a beamline, which is identical to the proposed one except omitting the kickers and substituting the septum with a dipole magnet (dipole-beamline). A Gaussian bunch and start-to-end (S2E) simulation bunch have been tracked through both beamlines and the results are compared with each other.

Gaussian Bunch

To study the general performance of the septum-beamline, a Gaussian bunch with the nominal beam parameters for the E-XFEL was tracked from the exit of the second bunch compression chicane BC1 through the TDS to the location of the imaging screen. The measured image is represented by the transverse particle distribution. For the reconstruction of the longitudinal phase space, the shear parameter S and dispersion D, which are needed to calibrate the time and energy coordinates, respectively, have been determined. Measurement of the time resolution is simulated in a setting with the TDS switched off. The energy resolution cannot be measured directly, but can be estimated using Eq. 2 with the twiss parameters of the design accelerator optics.

Table 1 lists the main parameters used for particle tracking. The simulations yield a shear parameter of $S \approx 5$, dispersion of $D = 1.29$ m, time resolution of $\sigma_t = 37$ fs and energy resolution of $\sigma_\delta = 6.3 \cdot 10^{-5}$. Figure 2 shows the results of simulations for the septum-beamline and dipole-beamline, compared with the input distribution. It is worth noticing that no distinct deviation is observed between the septum- and dipole-beamline. The use of a fast kicker does not influence the performance of the diagnostic section as expected. The reconstructed current profiles show a good agreement with the original. In the right plot of Fig. 2, a linear dependence of the mean slice energy on the longitudinal position (energy chirp) is resulted in the simulation, while no energy chirp exists in the input distribution. The difference of $< 2 \cdot 10^{-5}$ to the nominal energy is induced by the longitudinal electric field at off-axis positions inside the TDS [4, 5].

Table 1: Main simulation parameters

Parameter	Value	Unit
Number of particles	$2 \cdot 10^5$	
Bunch charge	1	nC
Beam energy	700	MeV
Norm. emittance (x)	0.97	μm
Norm. emittance (y)	2.94	μm
TDS deflecting voltage	7	MV

Bunch from S2E Tracking

The simulation results with the Gaussian bunch have proved the general performance of the diagnostic beamline. Further simulations have been carried out to investigate the particular situation for the E-XFEL. A bunch distribution from the 3-dimensional S2E tracking [6] with the codes CSRtrack and ASTRA is taken at the exit of the BC1 chicane and tracked through the beamline with `elegant` [3].

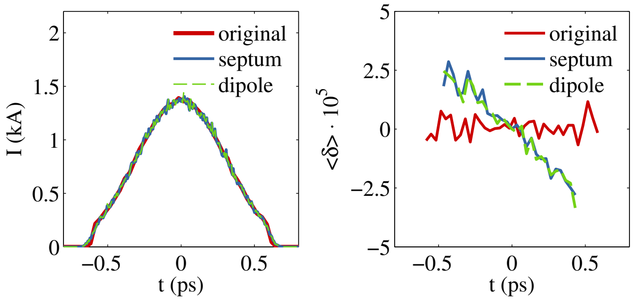

Figure 2: Simulation results with a Gaussian bunch: Comparison of the longitudinal beam parameters of the original distribution (red) with the reconstructed ones through the septum-beamline (blue) and dipole-beamline (green dotted). Left: Current profile. Right: Mean slice energy.

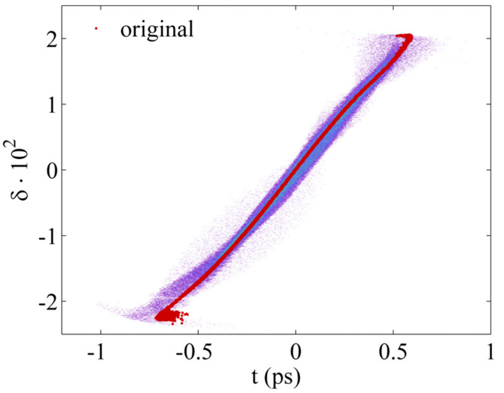

Figure 3: Density plot of the reconstructed longitudinal phase space compared with the original particle distribution (red dots).

The beam parameters and simulation parameters are the same as those used for the Gaussian bunch (Table 1).

Figure 3 compares the density plot of the reconstructed longitudinal phase space with the original particle distribution. The overall shape of the longitudinal phase space is well revealed in the reconstruction. Most significant deviations appear in the bunch head (negative time axis) and tail (positive time axis), where the electrons have a large energy offset of about 2% due to the strong energy chirp that is required for longitudinal bunch compression.

To exclude the effect of the kickers as the origin for the discrepancy, a simulation with the dipole-beamline is performed and compared to the result for the septum-beamline. The simulation results are shown in Fig. 4. As in the case for the Gaussian bunch, the septum-beamline shows the same performance as the dipole-beamline.

As can be seen in Fig. 4 right, the energy chirp of the original bunch is reconstructed by the simulations, with small energy deviations induced by the TDS as expected. The overall shape of the current profile and peak current show good agreements with the original ones (Fig. 4 left). The bunch length determined from the reconstructed current profile amounts to 312 fs and the one from the original 304 fs. The deviations in the head and tail of the current profiles can be explained by the large initial energy chirp inside the bunch. According to Eq. 1, the TDS shear parameter S depends inversely on the electron energy, i.e. electrons with energies smaller than the nominal value experience a larger shear strength S by the TDS compared to the calibrated one. In case of this simulation, where the energy offset due to the energy chirp is in the order of $\pm 2\%$, this effect becomes noticable. One perspective method to correct the influence of the initial energy chirp could be introducing an energy-dependent shear parameter $S(\delta)$ which scales with the measured energy offset.

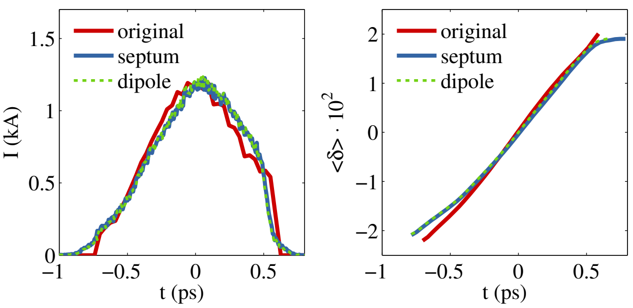

Figure 4: Simulation results with the bunch from S2E tracking: Comparison of the longitudinal beam parameters of original distribution (red) with the reconstructed ones from septum-beamline (blue) and dipole-beamline (green dotted). Left: Current profile. Right: Mean slice energy.

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