ELECTRON BEAM PHASE SPACE TOMOGRAPHIE AT THE EUROPEAN XFEL INJECTOR

M. Scholz*, B. Beutner, DESY, Hamburg, Germany

Abstract

Transverse emittances as well as the energy spread and the peak current of the electron bunches are important parameters for high-gain free electron lasers such as the European XFEL. Investigations of the 6D phase space characterization would give important indications to optimize the beam quality for SASE operation. The injector of the European XFEL includes, inter alia, a laser heater, a transverse deflecting cavity (TDS), a spectrometer, a diagnostic section with four screens as well as several quadrupole magnets. In this paper, we will discuss the possibilities to characterize the 6D phase space of the electron beam in the injector of the European XFEL.

INTRODUCTION

Crucial electron beam parameters like the minimum slice and projected emittances as well as the minimum energy spread are defined by the injector system. SASE FELs like the European XFEL [1] depend strongly on the emittance and the energy spread, thus it is significant to investigate and optimize these parameters. A reconstruction of the two transverse phase spaces, preferably time resolved, and of the longitudinal phase space will be of use to accomplish this task.

A separate beam dump at the end of the European XFEL injector and a concrete shielding wall between the injector and the subsequent machine components allow to start the injector commissioning while the linac is still under construction.

In this paper we study the possibilities to use the XFEL injector components for measurements that are required to reconstruct the transverse and longitudinal phase spaces of the electron beam.

EUROPEAN XFEL INJECTOR

A schematic layout of the European XFEL injector is presented in the upper part of Fig. 1. Two superconducting accelerating modules are installed in the linac, a 1.3 GHz module and a third harmonic module to linearize the longitudinal phase space of the particle distributions. The beam energy downstream these modules is 130 MeV.

A subsequent diagnostic section including a transverse deflecting cavity as well as four screens [2] and a spectrometer allow to study the electron beam quality. The TDS installed in the XFEL injector is a 16 cell traveling wave S-band RF waveguide structure operating with a frequency of 2.997 GHz [3]. The streak is applied in the vertical plane. A following periodic FODO section is designed such that the betatron phase advances between the TDS and the screens are optimized for emittance and bunch length measurements. Figure 1 shows the default beta functions in the XFEL injector from the electron gun to the injector dump.

Four fast kickers can deflect single bunches out of a long bunch train such that one bunch can be observed on each screen. That makes it possible to measure electron beam optics and emittances online during SASE operation. The screens can also be moved into the electron beam so that the measurements can take place without kickers.

The default beam optics in the injector was not designed to measure the slice emittances with quadrupole scans as required for the reconstruction of the transverse phase spaces. Several special beam optics that fulfill the requirements and that can be realized with the available beam optics elements had to be developed.

TOMOGRAPHY

The tomography technique [4] allows to reconstruct an inner structure using cross sections of the volume taken from different viewing angles. The reconstruction of an electron beam's transverse phase space can be obtained with several projections of the particle distribution while the beam rotates in the respective phase space [5]. The latter can be achieved with a scan of the betatron phase ϕ_x respectively ϕ_y using quadrupole magnets between an optics reference point and a screen where the measurements take place. The optics reference point is the position where the Twiss functions and the emittance will be reconstructed. The range of the phase scan $\Delta\phi_{i,\,\mathrm{ref}\to\mathrm{screen}}$ has to be about 180 deg [6]. The number of required projections depends on the reconstruction algorithm. More projections will lead to a better reconstruction result. We decided to apply the maximum entropy (MENT) algorithm [7] that requires a comparatively small number of measurement steps. However, a fixed electron beam optics and a measurement with the four screens in the diagnostic section is not sufficient. The four steps that can be achieved with these screens are not enough for the tomographic reconstruction. For this reason, a phase scan with quadrupoles, in steps of 10 degree phase advance, will be used. The beam will be observed on the last screen upstream the spectrometer magnet.

All beam optics calculations were carried out using the optimization and tracking code elegant [8].

Horizontal Phase Space

The injector TDS enables horizontal slice emittance measurements. This makes it possible to reconstruct the horizontal phase space of single bunch slices. The use of the TDS entails additional constrains on beam optics. The vertical

* matthias.scholz@desy.de

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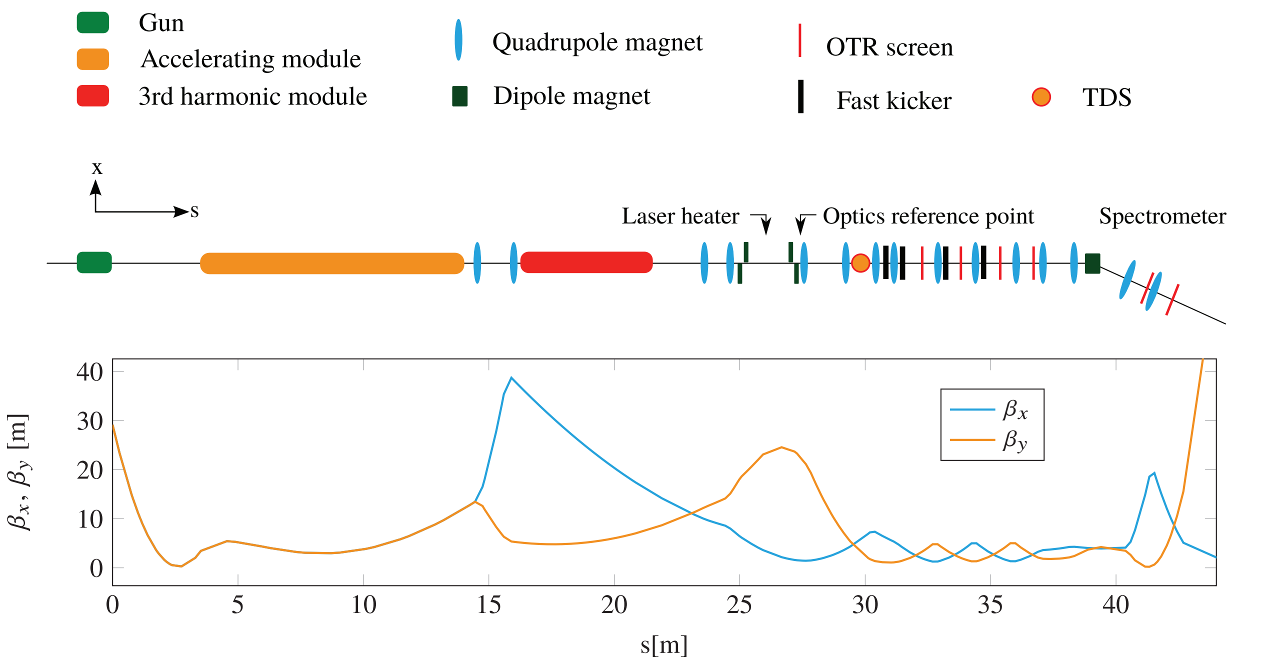

Figure 1: The default beta functions in the XFEL injector starting at the photo cathode and ending in the injector dump. Above the plot one can find a schematic layout of the XFEL injector.

offset of a particle at the screen, y_{screen}, deflected by the TDS, at the observation screen can be described as follows [3]:

$$y_{\text{screen}} = y_0 \pm \sqrt{\beta_y(s_{\text{screen}})\beta_y(s_{\text{TDS}})}\sin\left(\phi_{\text{y, TDS}\rightarrow\text{screen}}\right) K z,$$

with the initial offset y_0, the vertical beta function β_y at the position of the TDS as well as at the position of the screen. $\phi_{\text{y, TDS}\rightarrow\text{screen}}$ describes the vertical betatron phase advance between the TDS and the screen. K can be calculated as follows: $K = (eV_0k)/(pc)$ with e, the elementary charge, k, the wave number of the structure, p, the momentum of the electrons and c, the velocity of light. The longitudinal position of the particle in the bunch is described with z.

A large vertical beta function at the position of the TDS as well as $\Delta\phi_{\text{y, TDS}\rightarrow\text{screen}} = 90$ deg is suggested to optimize the streak effect. The formula presented above indicates also a large vertical beta function at the position of the screen. However, that would also lead to a larger unstreaked beam thus it will not increase the streak's resolution. It has to be considered that the requirements on the beta functions and on the phase advances are not independent.

Demands on the beam optics in the horizontal plane are: The betatron phase has to be scanned over 180 degree as discussed before. The horizontal beta function in the TDS should be small in order to minimize additional energy spread induced by off axis field components. At the position of the screen, β_x has to be large enough that the beam size is larger than the screen's resolution.

A set of 18 different beam optics setups for the horizontal slice emittance measurements were developed fulfilling the specifications as discussed before. The electron beam optics reference point was chosen between the laser heater and the TDS. For this reason, the beam optics stays unchanged in the linac as well as in the laser heater during the scans. In total 7 quadrupoles were used and the setups are presented in Figures 2, 3 and 4. All three plots are presented as functions of the horizontal phase advance between the optics reference point and the observation screen. The first one, Fig. 2, shows the horizontal and the vertical beta functions at the position of the TDS. As required, the horizontal beta function is small and β_y is around 10 m or larger.

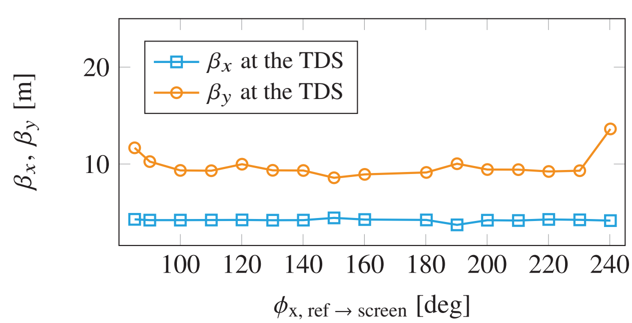

Figure 2: Beta functions at the position of the transverse deflecting cavity.

Figure 3 presents the beta functions at the observation screen. The horizontal function is, for all steps, around 30 m and the vertical beta function is for most of the steps below 0.5 m.

All quadrupole magnet's strengths for each measurement step are depicted in Fig. 4. The magnets are all within their maximum gradients and the unipolar quadrupoles in the FODO section were considered.

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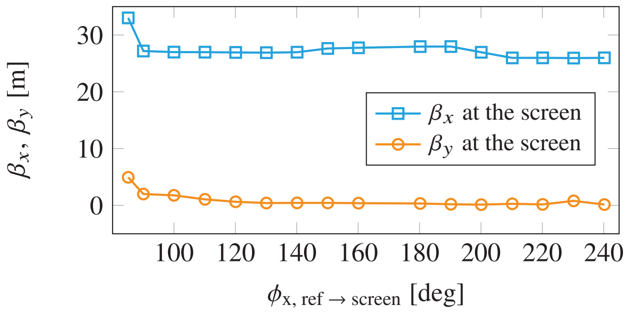

Figure 3: Horizontal and vertical beta functions at the screen for all steps of the horiztonal phase scan.

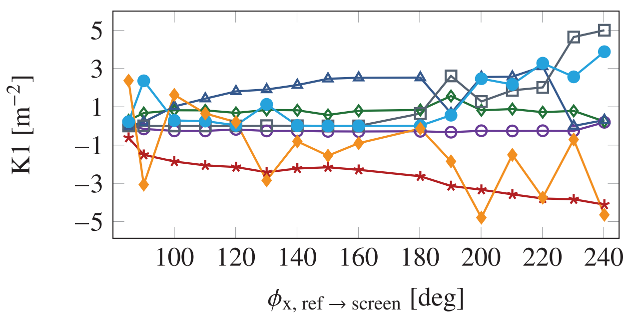

Figure 4: Normalized gradients of the quadrupoles used for the horizontal betatron phase scan.

The maximum effective voltage of the TDS installed in the injector is $V_{0,\text{max}} = 1.84$ MeV [3]. With the above mentioned TDS frequency and a longitudinal position of a particle in the bunch of $z = 3$ mm (The bunches are not compressed in the injector), with an average vertical beta function at the transverse deflecting cavity of $\beta_y(s_{\text{TDS}}) = 10$ m and with an average vertical beta function at the screen of $\beta_y(s_{\text{screen}}) = 0.3$ m, the maximum offset of a particle with no initial vertical offset ($y_0 = 0$ m) is about $y_{\text{screen}} \approx 4.5$ mm, which is much larger than the expected size of the unstreaked beam:

$$\sigma_y = \sqrt{\beta_y(s_{\text{screen}}) * \epsilon} \approx 25\mu\text{m},$$

calculated with an emittance of $\epsilon = 0.5\,\mu$m ($\epsilon_{\text{phys}} = 2$ nm). The resolution of the screen is $10\,\mu$m [2]. Thus, the beam optics setups as presented are suitable to get a sufficiently streaked beam at the screen for horizontal slice emittance measurements, even when the maximum effective voltage of the TDS is not applied.

Vertical Phase Space

Since there is no TDS in the injector streaking in the horizontal plane it was necessary to find another way to do the vertical slice emittance measurements. When a linear chirp is applied on the electron bunches it is possible to streak them with the spectrometer magnet in a suitable way. The linearity of the energy chirp can be verified with a measurement of the longitudinal phase space, as it will be described below.

As for the horizontal slice emittance measurement, 18 quadrupole setups were developed that scan the vertical betatron phase over 180 degree while the dispersion at the observation screen downstream the spectrometer bending magnet is constant within small limits. The horizontal and vertical beta functions at the screen have to be such that the beam sizes are above the resolution limit of the screens [2].

The normalized gradients of the quadrupoles during the scan of the vertical betatron phase advance are depicted in Fig. 5. In total, 11 quadrupoles between the optics reference point and the screen were used. All quadrupoles stay within their maximum gradients and the unipolar magnets are considered.

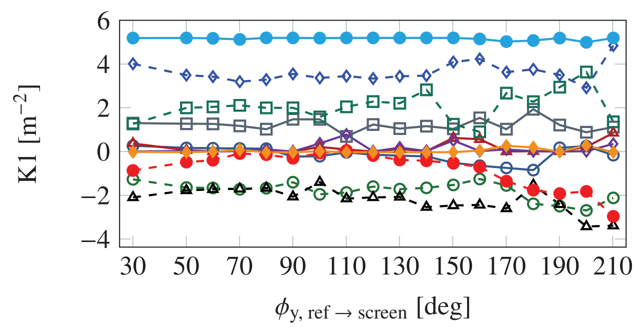

Figure 5: Normalized gradients of the quadrupoles used for the vertical betatron phase scan.

The dispersion at the screen during the scan of the vertical betatron phase advance is depicted in Fig. 6. Its around 0.6 m for all steps.

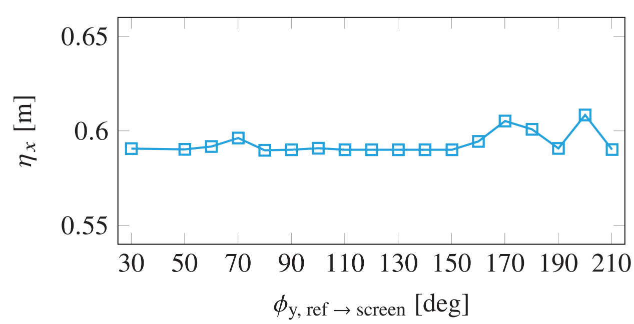

Figure 6: Dispersion at the screen downstream the spectrometer during the vertical betatron phase scan.

Figure 7 shows the horizontal and vertical beta functions at the observation screen. For most of the steps both parameters could be kept around 6 m.

A particle offset at the screen due to the dispersion can be calculated as follows:

$$x_\eta = \eta_x \delta,$$

with the horizontal dispersion η_x and the relative energy deviation of the particle $\delta = \Delta p/p_0$. Assuming an energy chirp of 0.5 % and a dispersion $\eta_x = 0.6$ m, this leads to a horizontal offset of $x_\eta \approx 3$ mm. The expected (unstreaked)

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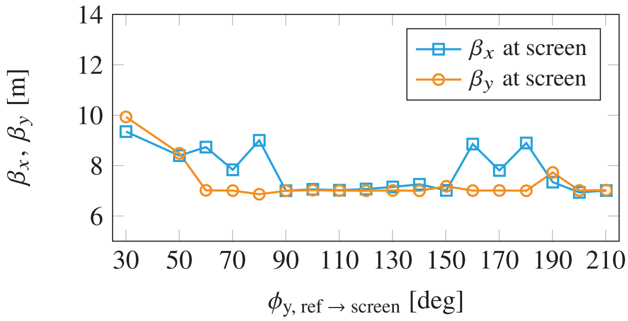

Figure 7: Beta functions at the screen downstream the spectrometer during the vertical betatron phase scan.

beam sizes at the screen are, under the assumption that the $\beta_x = \beta_y = 6\,\text{m}$:

$$\sigma_x = \sigma_y = \sqrt{\beta_y(s_{\text{screen}}) * \epsilon} \approx 20\mu\text{m}.$$

With that, the horiztontal streak is much larger than the unstreaked horizontal beam size and the vertical beam size is larger than the resolution of the screen.

Longitudinal Phase Space

The vertically streaking TDS and the horizontally deflecting spectrometer bending magnet allow, with small restrictions, to observe the longitudinal phase space on the screen in the dispersive section [5]. The additional energy spread added to the particle distributions by the longitudinal electromagnetic fields in the TDS has to be taken into account while evaluating the taken pictures. An optimized optics solution was developed providing a vertical betatron phase advance of $\phi_{\text{y, TDS} \to \text{screen}} = 90$ degree and suitable beta functions at the screen. The beta functions between the electron gun and the observation screen are depicted in Fig. 8.

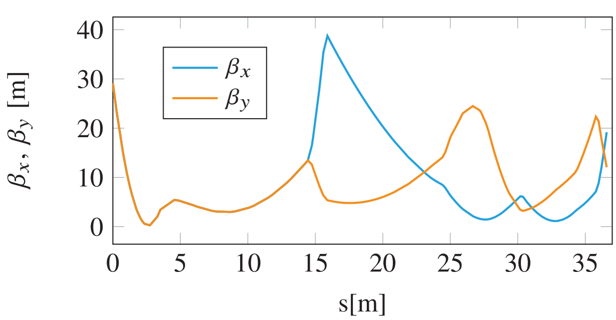

Figure 8: Beta functions in both planes as designed for the longitudinal phase space measurement on the screen downstream the spectrometer.

CONCLUSIONS

It was shown that the existing magnets, the transverse deflecting cavity and the screens installed in the European XFEL injector can be used for a horizontal and vertical slice emittance measurement. This makes it possible to reconstruct the transverse phase spaces of the bunch slices. In addition with the longitudinal phase space, which can be observed in the dispersive section of the injector, this gives an overview of significant beam parameters and allows optimizing the electron beam for SASE operation.

ACKNOWLEDGMENT

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