ELECTRON BEAM DIAGNOSTICS WITH TRANSVERSE DEFLECTING STRUCTURES AT THE EUROPEAN X-RAY FREE ELECTRON LASER

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Abstract

The operation of the European X-Ray Free Electron Laser (XFEL) puts stringent demands on the peak current, transverse slice emittance and slice energy spread of the driving electron beam. For monitoring and stabilizing these parameters, dedicated diagnostic beamlines each including a horizontally operated transverse deflecting structure (TDS) are planned to be installed. Observation screens downstream of the TDS allow for measurements of the vertical slice emittance and the single-bunch current profile. By dispersing the beam vertically with a dipole magnet the energy distribution along a bunch can be measured with high accuracy and single-bunch resolution. In this paper we present a proposal for the layout of a diagnostic section. The focus is on the optics for slice emittance measurements. The accuracy and time resolution of current profile and slice emittance measurements is discussed on the basis of numerical simulations.

INTRODUCTION

The FEL amplification process in X-Ray Free Electron lasers is extremely sensitive to variations of the peak current, transverse emittance and energy spread of the driving electron beam. Measurement and control of these beam parameters is thus essential for operating such a facility. The amplification process takes place locally within longitudinal bunch slices with a duration in the order of femtoseconds so that time-resolved properties rather than time-averaged properties are crucial. As a consequence, there is a need for measurement techniques with a time-resolution on the femtosecond scale.

The time-domain technique which currently achieves the highest time resolution is based on transverse deflecting microwave structures [1, 2, 3, 4]. Within a transverse deflecting structure (TDS), a high-frequency electromagnetic field deflects the electrons of a passing bunch transversely as a function of time so that the time structure is converted into a transverse structure which can be measured on downstream observation screens.

At the European XFEL [5], diagnostic sections (DS) including a TDS are planned at three positions (Fig. 1): directly downstream of the electron gun and downstream of each of the two vertical bunch compressor chicanes (BC) used for shortening the electron bunches. In this paper, a proposal for the layout of the DS downstream of the first bunch compressor is presented, the focus being on measurements of the slice emittance. The layout can be easily adapted to the beam properties encountered in the other two diagnostic sections.

CONCEPTUAL DESIGN OF A TDS DIAGNOSTIC SECTION

A main objective of the diagnostic sections downstream of the bunch compressor chicanes is the measurement of the projected transverse emittance. Several observation screens based on optical transition radiation (OTR) will be used for this purpose (multi-screen method). Quadrupole magnets upstream of the bunch compressor BC1 will be used for matching the beam to a design optics. A TDS will be installed to “streak” single bunches horizontally. Measurements of the streaked bunches on the OTR screens then allow for a determination of the current profile and the vertical slice emittance. It is planned to use off-axis OTR screens in combination with fast vertical kicker magnets which allow current profile and slice emittance measurements without disturbing FEL operation. Downstream of this section for emittance measurements, a vertically deflecting bending magnet is foreseen to serve as an energy spectrometer. Since the TDS operates in $x-$direction and the dipole magnet in $y-$direction, a measurement of the time-resolved energy distribution of single bunches will be possible using an OTR station within the dispersive arm.

The TDS will be operated at a frequency of $f = 3$ GHz. It will have a length of $L = 1.6$ m and a filling time of about 320 ns so that it can be operated in a non-disruptive “pulse-picking” mode at 5 MHz bunch repetition rate. A klystron with an output power of 45 MW will provide a transverse deflecting voltage of up to 18 MV.

The resulting time resolution at a downstream observations point is limited due to the non-vanishing vertical beam emittance and depends on the accelerator optics and beam properties. Given a design horizontal beta function $\beta_x(s)$, a horizontal betatron phase $\phi_x(s)$ and a perfectly matched beam with energy E and normalized vertical rms emittance ϵ_y, the rms time resolution at the observation point s_2 is given by

$$\sigma_t = \frac{\sqrt{\epsilon_y/\gamma} \cdot E}{2\pi f e V_0 \sqrt{\beta_x(s_1)} \cdot \sin(\Delta\phi_x)}, \tag{1}$$

with s_1 the position of the center of the TDS, e the elementary charge, γ the Lorentz factor and $\Delta\phi_x = \phi_x(s_2) - \phi_x(s_1)$ [2, 4]. Using $\epsilon_y = 1$ μm, $E = 500$ MeV, $\beta_x(s_1) = 20$ m and $V_0 = 18$ MV one obtains a resolution of $\sigma_t = 10$ [fs]/sin $(\Delta\phi_x)$. The rms bunch duration downstream of BC1 amounts to about 300 fs.

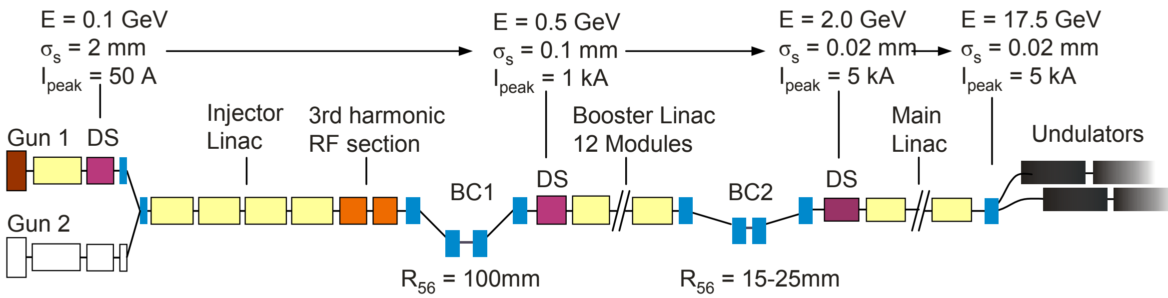


Figure 1: Accelerator layout of the European XFEL [6] (BC: bunch compressor; DS: diagnostic section, σ_S: rms bunch length, I_{peak}: peak current).

MULTI-SCREEN SLICE EMITTANCE MEASUREMENTS

The vertical rms emittance can be determined from measurements of the rms beam size at at least three different positions [7]. It is crucial for such a measurement how unavoidable measurement errors of the beam sizes affect the precision of the emittance. Given a number n of OTR stations and a design optics, then optimum precision will be obtained when the difference in vertical betatron phase advance ϕ_y between subsequent OTR stations amounts to $180°/n$ [7, 8]. More importantly, such an arrangement is the most reliable one in the sense that it allows a good precision also in case the beam is not perfectly matched to the design optics [4]. Typical diagnostic sections for emittance measurements as used e.g. at the soft X-ray free-electron laser FLASH therefore consist of three cells of a FODO-lattice with a phase advance per cell ϕ_{cell} of 45° and four OTR stations with one FODO cell between subsequent stations (45°-arrangement).

For slice emittance measurements using a TDS, both the precision of the emittance and the time resolution are crucial. According to Eq. (1), the time resolution at an observation point s_2 scales with $(\sin(\Delta\phi_x(s_2)))^{-1}$. Thus, a good time resolution at each observation point of a multi-screen emittance measurement and a high precision of the emittance can only be achieved simultaneously when there is a significant difference between the betatron phase advance in $x-$ and $y-$direction between the observation points. This is not the case in an 45°-arrangement as introduced above. As a consequence, there is always an observation point with a time resolution of only $\sigma_t \geq 2.6 \cdot \sigma_t^0$ with σ_t^0 denoting the optimum resolution obtained when $\sin(\Delta\phi_x) = 1$.

Improvements of the time resolution can be achieved by utilizing the asymmetry in phase advance in $x-$ and $y-$direction over a half cell of a FODO lattice, which becomes significant at a larger phase advance per cell ϕ_{cell}. It turns out that a phase advance $\phi_{cell} = 76°$ is particularly well suited. Moreover, asymmetric FODO lattices are attractive since they provide an easily controllable asymmetry in betatron phase advance in $x-$ and $y-$direction. Two possible optics solutions for slice emittance measurements utilizing these observations are proposed for the European XFEL and discussed in the following section.

Optics

The arrangement which is proposed for slice emittance measurements in the European XFEL includes six OTR stations. The magnet lattice allows for the realization three different optics (options 1-3) shown in Fig. 2. Option 1 is a standard 45° arrangement for measurements of the projected emittance in $x-$ and $y-$direction and mainly supposed for machine commissioning. The mean horizontal beta function in the TDS amounts to 20 m. The station OTR-2 is located at $\Delta\phi_x = 79°$ ($\Delta\phi_x$: difference in horizontal betatron phase between the center of the TDS and the observation point) and allows for a time resolution of $\sigma_t = 11$ fs. The time resolution for slice emittance measurements is poor since OTR-6 is located at $\Delta\phi_x = 169°$ resulting in $\sigma_t = 55$ fs.

Option 2 comprises a symmetric FODO lattice with $\phi_{cell} = 76°$ between OTR-2 and OTR-6. It is suited for measurements of the projected emittance in $x-$ (OTR-2,3,4,5) and the projected and slice emittance in $y-$ direction (OTR-3,4,5,6). In order to investigate the precision of an emittance measurement using such an arrangement the emittance error resulting from a beam size error of 5 % was calculated using a least squares method and error propagation. Since the result depends sensitively on the assumed mismatch between the beam ellipse parameters and the design Twiss parameters, the emittance error was calculated as a function of the corresponding mismatch parameter M and the mismatch phase as defined in [9]. Figure 3(a) shows the dependence of the emittance error on the mismatch phase at a fixed mismatch parameter of $M = 3$ for an 45°-arrangement and the 76°-arrangement used in option 2. Both results are periodic in the mismatch phase with a periodicity of 180°. The maximum error is slightly smaller in case of the 45°-arrangement. Figure 3(b) shows the maximum emittance error within one period of the mismatch phase as a function of the mismatch parameter M. The result shows that the difference between both arrange-

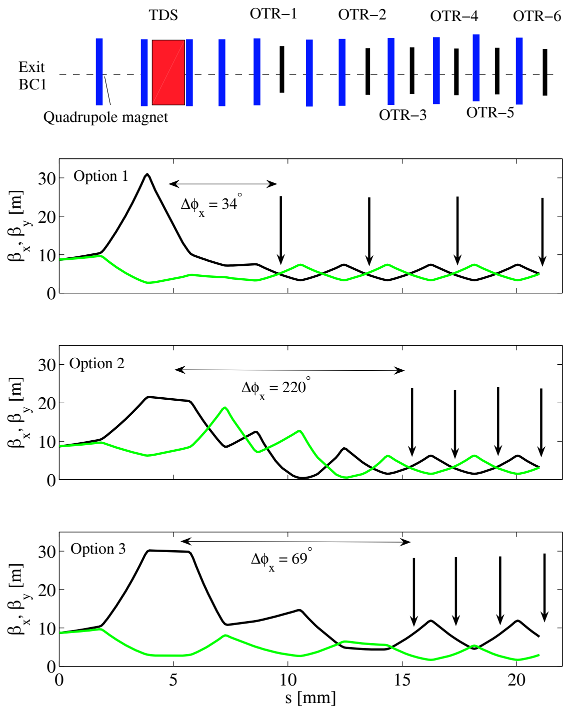


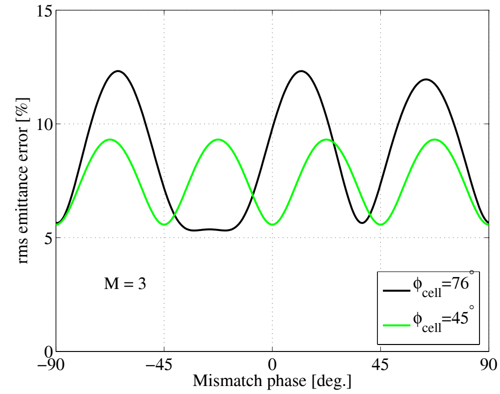
Figure 2: Arrangement of TDS, quadrupole magnets and OTR stations (top) and possible beta functions β_x (black) and β_y (green). Arrows indicate which OTR stations are suited for a measurement of the vertical emittance in each case.

ments is negligible at $M \approx 1$ and moderate up to significant a mismatch of $M = 5$.

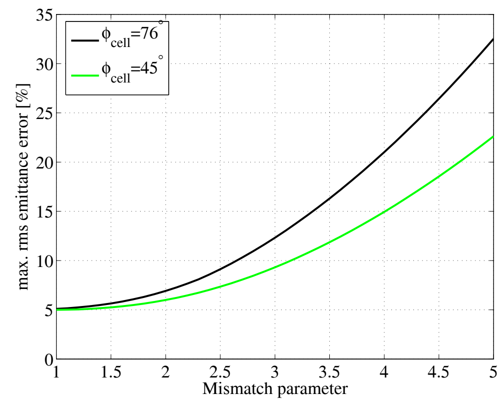
With a beta function $\beta_x = 20$ m in the TDS, the time resolution on the screens used for slice emittance measurements ranges between 16 fs at OTR-3 ($\Delta\phi_x = 220°$) and 11 fs at OTR-4 ($\Delta\phi_x = 271°$) and is thus significantly improved compared to option 1. As long as the beam is roughly matched to the design optics the 76°-arrangement is thus attractive since it combines a reasonable accuracy of the emittance with a good time resolution.

Option 3 uses an asymmetric FODO lattice with a betatron phase advance per cell of 76° in $y-$ and 30° in $x-$direction. While the emittance accuracy is basically the same as in case of optics 2, the time resolution is further improved. The beta function of $\beta_x = 30$ m in the TDS results in a nearly constant time resolution of about 9 fs at the stations OTR-3 to OTR-6. Due to the small phase advance per cell in the horizontal direction, this option is not suited for measuring the projected emittance in horizontal direction.

Aside from its flexibility, a key advantage of the presented magnet lattice is its compactness. The minimization of the length of the diagnostic section is (besides cost issues) important for mitigating the influence of space charge forces which degrade the beam quality and also the accuracy of emittance measurements. Moreover, the compact design results in the same sign of the term $(\sin(\Delta\phi_x))$ in



(a)



(b)

Figure 3: Calculated emittance error resulting from beam size errors as a function of the mismatch between the beam ellipse parameters and the design optics. Beam size errors of 5 % (rms) are assumed. A standard 45°-arrangement (green) and option 2 (black) with a phase advance of $\phi_{cell} = 76°$ per cell (Fig. 2) are considered. See text for details.

Eq. (1) at all observation points used for slice emittance measurements which greatly facilitates an accurate data evaluation [4].

Numerical Simulations

Numerical simulations were performed to study the performance of the presented arrangements in the case of the particular beam properties encountered at the European XFEL. A particle distribution (input distribution) with $2 \cdot 10^5$ particles and a bunch charge of 1 nC taken from a start-to-end simulation including collective effects was used for this purpose. The particle distribution was tracked through the lattices (including the TDS) presented in the previous section using the code Elegant [10]. At the position of the screens, the particle distribution within a window of 12×15 mm centered on the beam axis (including entire streaked bunches) was transformed into digital images with a resolution of 1024×1580 pixel simulating a measurement with a CCD camera. These images were

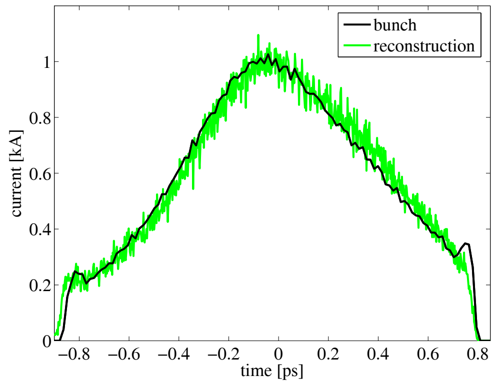


Figure 4: Current profile of the input distribution (black) and current profile reconstructed from a simulated CCD image (green).

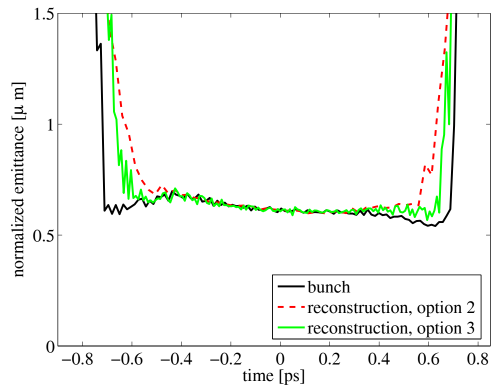


Figure 5: Simulation of a slice emittance measurement using the arrangements option 2 and 3 shown in Fig. 2. The reconstructed vertical slice emittance obtained with option 2 and option 3 is compared to the slice emittance of the input distribution.

used for reconstructing the slice emittance and the current profile.

Figure 4 shows a comparison between the current profile of the input distribution and the one reconstructed from an image using option 2 and the maximum input power of the TDS ($\sigma_t = 11$ fs). The comparison shows that the time resolution is fully sufficient to resolve the longitudinal bunch structure. The calculated rms bunch duration amounts to 0.38 ps in case of both profiles. The strong oscillations in the reconstructed current profile are due to numerical noise.

Figure 5 shows a comparison between the normalized vertical slice emittance of the input distribution and the one reconstructed from images using options 2 and 3. The slice emittance profiles agree well in the bunch center. At both edges, slight deviations occur due to rapid variations of the slice emittance and the limited time resolution. The resolution is worse at both edges compared to the bunch center since the horizontal slice emittance is significantly larger.

CONCLUSIONS

We have presented a magnet lattice for the European XFEL which allows the realization of different optics options for measurements of the vertical slice emittance using a TDS in combination with a multi-screen method. The arrangement allows the measurement of the slice emittance with a time resolution on the order of 10 fs. Numerical simulations revealed that the time resolution is sufficient to resolve the longitudinal bunch structure expected at the XFEL.

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