ELECTRON BEAM PHASE SPACE TOMOGRAPHY AT THE EUROPEAN XFEL INJECTOR

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Abstract

The FEL process is determined by the 6D phase space distribution of relativistic electron bunches. Experimental reconstructions of these distributions are therefore a step forward to understand the beam dynamics and to optimize FEL operation. The reconstructions of the transverse phase spaces can be achieved with tomographic methods. In the injector of the European XFEL, measurements for the reconstruction of the phase spaces were carried out using phase advance scans with multiple quadrupoles. The beam sizes were kept optimized at the measurement screen. A transversely deflecting cavity (TDS) was used to streak the beam vertically. That allows to do longitudinally slice resolved measurements of the horizontal phase space. The horizontal streak required for the slice measurements in the vertical plane was achieved with a correlated linear energy spread and dispersion. In this paper, we present measurement results showing longitudinal slice resolved reconstructions of the transverse phase spaces taken in the European XFEL injector.

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 is of use to accomplish this task.

In this paper, we present first reconstructions of the electron beam's transverse phase spaces from data obtained with quad scans in the European XFEL injector. The beamline layout and preparatory calculations can be found in [2].

MEASUREMENTS

Tomography techniques [3, 4] allow 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 were reconstructed. The optimum phase advance coverage in the measurement plane is $\Delta\phi_{i,\,\mathrm{ref}\to\mathrm{screen}} \in [0\,\mathrm{deg}, 180\,\mathrm{deg}] + \phi_0$ [2].

Horizontal Plane

Five quadrupole magnets were used to scan the horizontal phase advance between the optics reference position upstream the TDS and the measurement screen. The scan range was only $\Delta\phi_{x,\mathrm{ref}\to\mathrm{screen}} \in [30\,\mathrm{deg}, 170\,\mathrm{deg}]$, due to magnet current limitations. The vertical phase advance was kept constant in the same section such that the vertical streak from the TDS was optimized. A vertical beta function of $\beta_y = 2\,\mathrm{m}$ at the screen ensures that the fully streaked bunch fits on the screen with sufficient longitudinal resolution. The horizontal beta function β_x was about 20 m for all scan steps to ensure a sufficient transverse measurement resolution [2].

Vertical Plane

The streak of the bunches in horizontal plane necessary to measure longitudinally slice resolved vertical emittances could be achieved with a correlated linear energy chirp while the data was then taken on a screen in the dispersive arm of the spectrometer. Linear energy correlation was confirmed before the measurement using the TDS and the measurement screen. The required beta functions on the screen were like those for the measurement in horizontal case but with exchanged planes. The dispersion at the screen $\eta_{\mathrm{x,screen}} = 1\,\mathrm{m}$ was kept constant. Five quadrupole magnets were required to scan the vertical phase advance in a range of $\Delta\phi_{y,\mathrm{ref}\to\mathrm{screen}} \in [70\,\mathrm{deg}, 240\,\mathrm{deg}]$ fulfilling all named boundary conditions.

IMAGE ANALYSIS AND TRANSVERSE PHASE SPACE RECONSTRUCTIONS

Image analysis including FFT filtering and adaptive-mask-of-interest [7] to supress noise not related to the beam was perfomed. The bunches were sliced taking into consideration the correct assignment of the single bunch slices of all pictures. The charge profiles for each single picture and slice was extracted individually. A mean profile of the individual slices were then, after a smoothing using Savitzky-Golay filtering, used to reconstruct the phase spaces applying a maximum-entropy tomographic reconstruction [2, 3, 6] algorithm. A final Gaussian smoothing reduces artifacts from the tomographic reconstruction process.

RESULTS

Figure 1 and 2 show the reconstructed phase spaces for all slices with indices -8 to 9 (out of -11 to 11), showing the slices from bunch tail to head, in horizontal and vertical plane. It is apparent that the alignment of the horizontal phase ellipse shown in Fig. 1 rotates along the bunch. The expected mismatch for bunch head and tail can also be studied in Fig. 3. The emittances in horizontal plane along the

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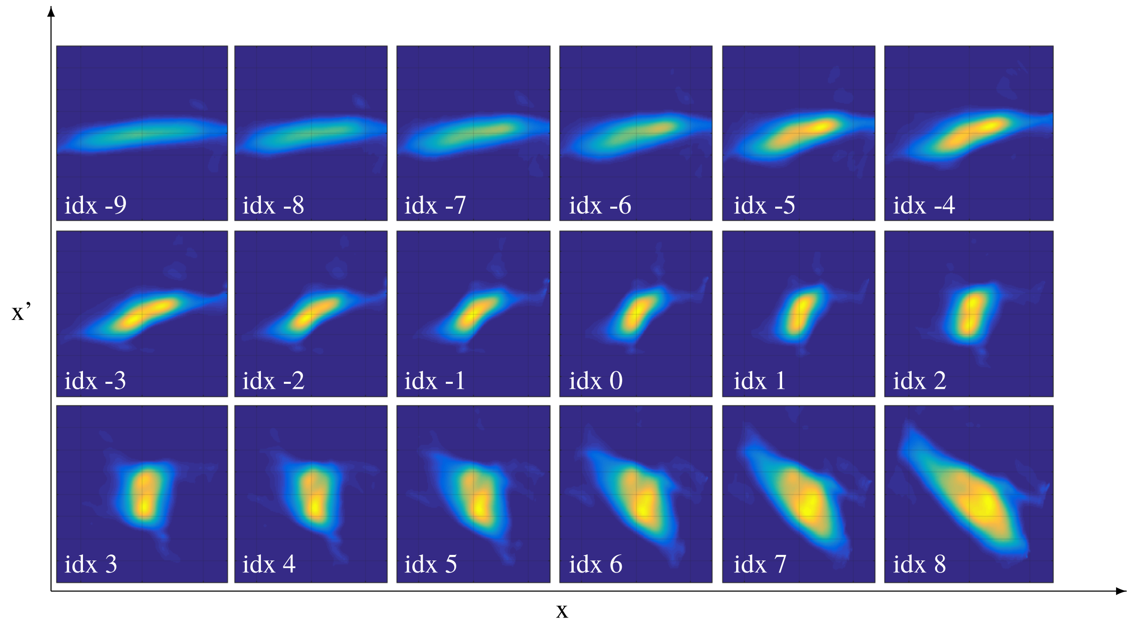

Figure 1: Reconstructions of the horizontal slice phase space distributions for the slices from index -9 (top left) to index 8 (bottom right).

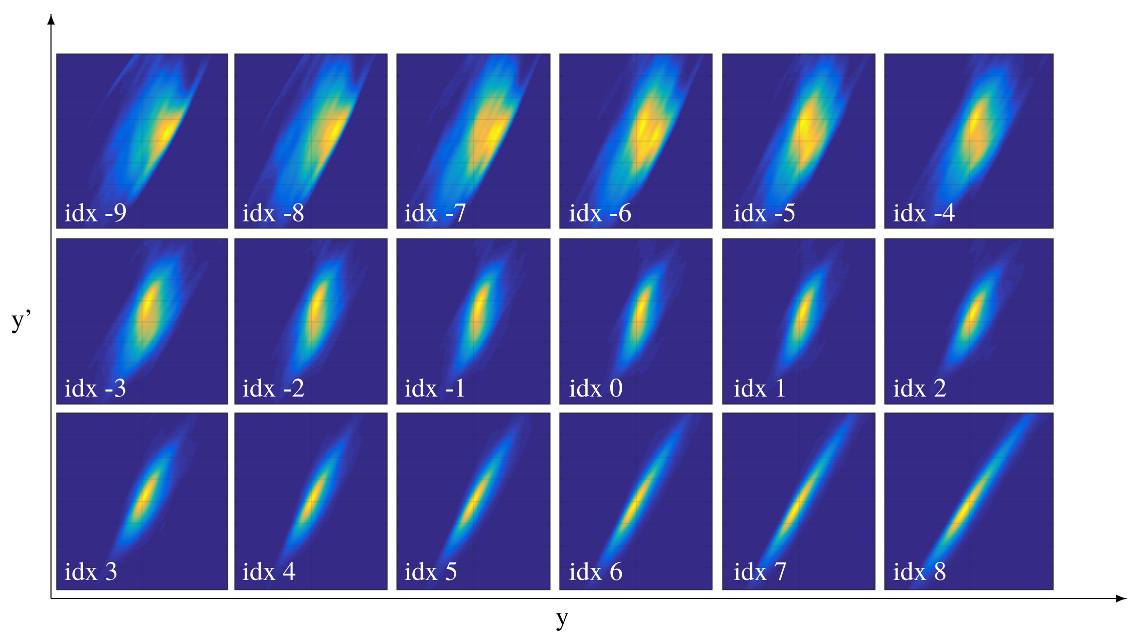

Figure 2: As in Fig. 1 but in the vertical plane.

bunch are below 1 mm mrad, as presented in Fig. 4, and thus within specs. The plots show the emittances calculated from slice sizes using Gauss fits as well as rms emittances calculated from the reconstructed phase spaces. The current profile is calculated from the intensity of single slices. The potential SASE gain of each slice idx is estimated as $g_{\mathrm{idx}} = \sqrt{c_{\mathrm{idx}}}/\varepsilon_{\mathrm{x,idx}}^{5/6}$ with the current c and the emittance ε_{x}. In the vertical plane, the mismatch along the bunch is smaller than in the horizontal plane as shown in Fig. 2 and Fig. 5. Figure 6 shows the vertical slice emittances along the bunch. As expected, the rms emittances calculated without additional charge cuts are larger compared to the emittances from Gauss fits.

CONCLUSIONS

First tomographic reconstructions of the electron beam's transverse phase spaces in the European XFEL injector could be reconstructed and were presented in this paper. Applications of these methods in other sections of the European XFEL are straightforward. The presented methods allow now for more detailed studies and optimizations of the transverse beam dynamics.

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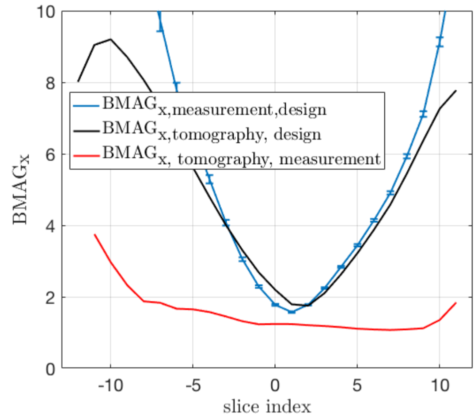

Figure 3: This plot shows different mismatch amplitudes along the bunch for the measurement/reconstruction of the horizontal plane. The first line shows the mismatch between the Twiss parameters calculated from beam sizes, the second line the mismatch calculated from the reconstructed phase space data. The third line shows the difference between the two calculations.

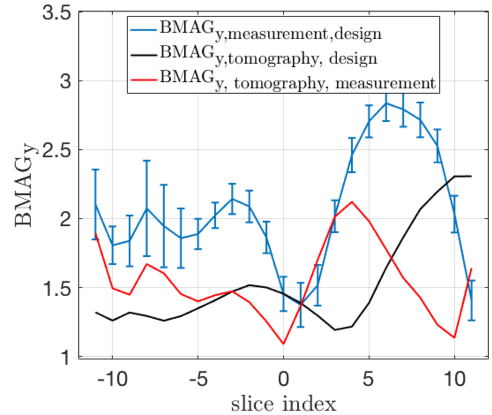

Figure 5: This plot shows different mismatch amplitudes along the bunch for the measurement/reconstruction of the vertical plane. The first line shows the mismatch between the twiss parameters calculated from beam sizes, the second line the mismatch calculated from the reconstructed phase space data. The third line shows the difference between the two calculations.

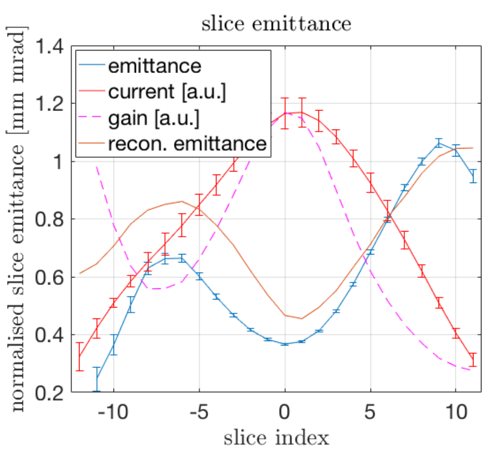

Figure 4: Horizontal slice emittance along the bunch calculated from slice sizes (Gaussian fit) and from the reconstructed phase spaces (rms). The current profile represents the charge per slice and the gain is calculated from the slice charge and the related emittance.

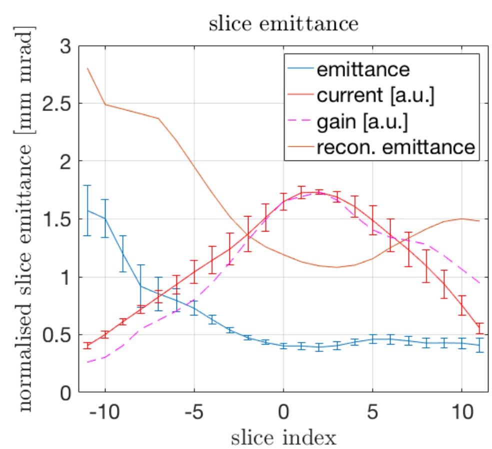

Figure 6: Vertical slice emittance along the bunch calculated from slice sizes (Gaussian fit) and from the reconstructed phase spaces (rms). The current profile represents the charge per slice and the gain is calculated from the slice charge and the related emittance.

ACKNOWLEDGMENT

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