MEASUREMENT OF SLICE-EMITTANCE USING TRANSVERSE DEFLECTING STRUCTURE

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Abstract

Among the very critical parameters for the operation of the VUV-FEL at DESY are slice emittance and slice Twiss parameters of the current peak in the electron bunch. Conventional tools for measuring the beam size are sensitive to projected properties of the bunch only and hence suffer from mixing of different parts of the bunch. A combination of streaking with a transverse deflecting rf structure and a quadrupole scan allows to measure slice parameters. Indeed the experiment reveals slice Twiss parameters changing gradually along the bunch and a significant increase in slice emittance in the head of the bunch.

INTRODUCTION

Radiation generated by Free Electron Lasers based on the SASE phenomenon may be emitted only from a small fraction of an accelerated particle bunch. Emittance and charge of the total bunch are therefore not necessarily relevant parameters for the lasing process.

At the VUV-FEL at DESY, where first lasing at 32 nm has been achieved at the beginning of this year [1][2], experiments and simulations show that the bunches have the highest particle density in a spike at the front of the bunch we call the head [4]. The head is assumed to be the source for FEL radiation. For this reason it would be desirable to know the transverse emittance of thin slices of the bunch, especially in the front part. The development of the transverse slice emittance along the bunch would be an important information to understand the machine.

However, the standard methods for transverse emittance measurements are based on the measurement of projected particle distributions which do not allow to consider longitudinal fractions of the bunch separately. These methods may be supplemented by a transverse deflecting cavity, which deflects the particles in e.g. vertical direction depending on their longitudinal position [3]. The measured transverse projections then allow to distinguish longitudinal parts of the bunch and to reconstruct their transverse properties.

SETUP OF THE EXPERIMENT

The presented experiment is the first one at the VUV-FEL aiming at the measurement of slice properties using a transverse deflecting cavity. The measurement has been performed at the end of the VUV-FEL accelerator at an energy of 445 MeV. The properties of the longitudinal density profiles originate from two upstream magnetic bunch compressors "BC2" and "BC3" located at the 127 MeV and 380 MeV point of the accelerator, respectively. The particle distributions after compression sensitively depend on their energy distribution and therefore on the acceleration phase in module ACC1. The phase was set to $-6.5°$, about $-4.5°$ from maximum compression. FEL-operation typically takes place between $-6.5°$ and $-8°$. All other modules work on-crest. Using these settings, the longitudinal charge distribution is less distorted so the measurement as well as the evaluation is simplified.

The crucial part of the beamline is sketched in figure 1. The bunches pass a vertically deflecting cavity at zero crossing of the rf phase. This results in changes of the vertical particle momenta which depend linearly on the longitudinal position within the bunch and vanish at the center [3]. The rf power of the cavity is chosen so the main part of each bunch still hits the screen, and is therefore not set to the maximum value. A kicker is installed which deflects single bunches horizontally onto an off-axis OTR monitor. A constant tranfer function from the cavity to the screen guarantees that the vertical offsets of the particles at the screen depend only on the kick applied in the cavity and thus on their longitudinal position in the bunch. The device can be calibrated by varying the cavity phase while monitoring the vertical movement of the beam at the screen.

In order to obtain emittance and Twiss parameters of the total bunch as well as of single slices, a quadrupole scan

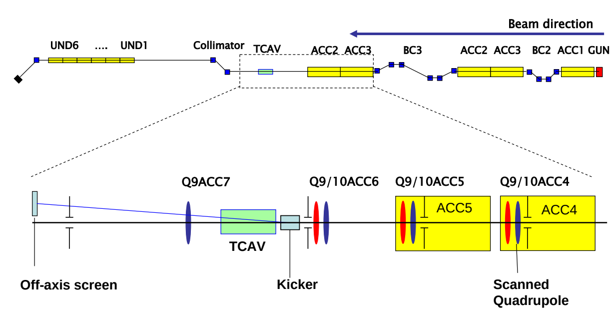

Figure 1: Sketch of the VUV-FEL beam line and the part used for the experiment. The beam passes a transverse deflecting cavity (TCAV) streaking it vertically and gets horizontally deflected by a kicker onto an off-axis OTR monitor. The Quadrupole Q9ACC4 is used for scanning.

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has been performed using the Quadrupole Q9ACC4 shown in figure 1. For each quadrupole current, ten bunch images have been taken to determine the average horizontal widths. To remove camera artefacts, an average background has been subtracted from the beam images. The transfer functions from the scanned quadrupole to the screen have been measured using steerers and beam position monitors to exclude large systematic errors.

RESULTS

Figure 2 shows the image of a vertically streaked bunch on the OTR monitor. The dense head of the bunch (top) and the long trailing tail are clearly visible. A zoom into the head reveals a substructure characterized by horizontal offsets of the slice centroids. The tail appears to be nearly homogenous.

The conversion factor from vertical position on the monitor to time is 16.6 fs / pixel, the pixel width being 27 μm. Using this conversion, the longitudinal charge density profiles can be obtained (figure 5). The spike at the front of the bunch contains roughly $0.23\,\%$ of the total bunch charge of $1\,$nC and has a width of $132.8 \pm 8.3\,$fs. These values are both resolution limited, the resolution being determined by the vertical slice sizes. The images used for this evaluation have been taken with identical quadrupole settings and show the smallest spike width. Nevertheless, the given values are upper limits for the true ones.

Figure 3 shows the measured horizontal rms sizes of the total bunch during the quadrupole scan. Using the transfer matrices from the scanned quadrupole to the screen, bunch emittance and bunch Twiss parameters have been reconstructed by a least square fit method [5]. We have obtained a normalized horizontal emittance of $8.04 \pm 2.81\mu$m (systematic error, see section "Error analysis"), and initial horizontal Twiss parameters $\beta_x = 75.44 \pm 1.24 \pm 1.98\,$m and $\alpha_x = -4.76 \pm 0.08 \pm 0.65$ (statistical and systematic errors, respectively).

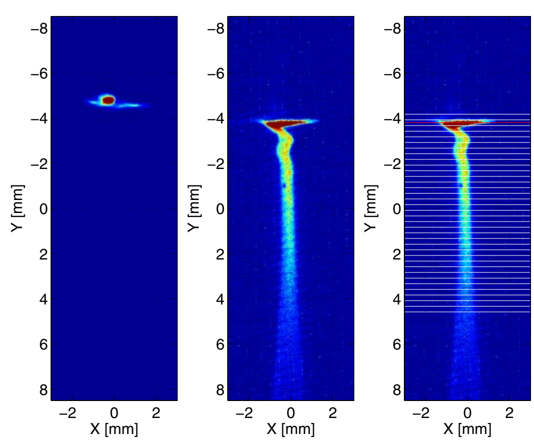

Figure 2: The monitor image on the left hand side shows a bunch without streak, the one in the middle a vertically streaked bunch. The head of the bunch is at the top. In the picture on the right the edges of the horizontal slices are drawn in. The reference point for slicing is the peak value in the vertical density profile (red line).

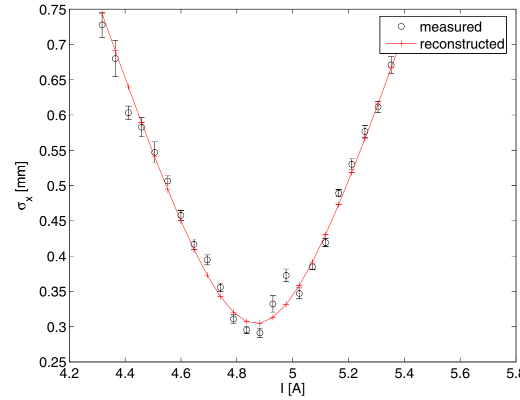

Figure 3: Measured and reconstructed horizontal bunch sizes for different quadrupole currents.

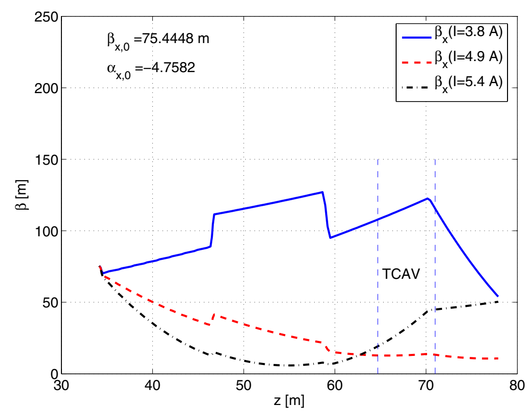

Figure 4: Reconstructed beta function of the total bunch for different quadrupole currents

In order to determine slice parameters, the images of the streaked bunches have been subdivided into horizontal slices of $0.25\,$mm or $154\,$fs width each (figure 2). The peak value in the vertical profile has been used as reference in each image to correct for cavity phase jitter. From the horizontal rms sizes of these slices, slice emittance and slice Twiss parameters upstream of the scanned quadrupole can be reconstructed just as for the entire bunch.

Figure 6 shows that the resulting normalized slice emittance takes nearly constant values of roughly 4.0 μm in the tail of the bunch and rises strongly up to 11 μm in the head. The slice having the peak current has an emittance of roughly $7.5\,\mu$m. The number of particles in the slice at the very front of the bunch which has the largest emittance value is clearly smaller than in most other slices and depends strongly on the vertical beta function of the head.

Restriction to the 90% - core of the horizontal profiles yields normalized emittances ranging from 1.5 μm in the tail up to 6.3 μm in the head. The 90% - value for the slice having the peak current is 4.1 μm, the one of the total bunch

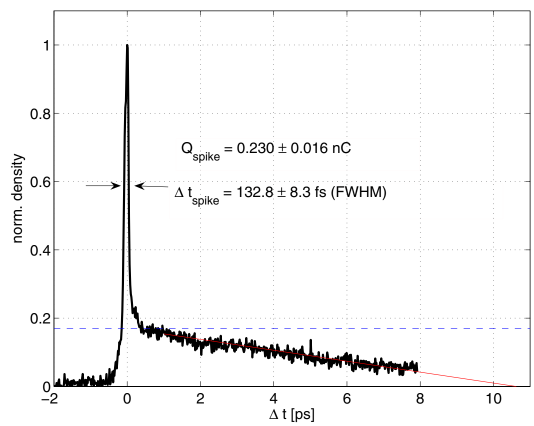

Figure 5: Measured longitudinal density profile. The charge density is normalized to its peak value. The region with densities larger than the threshold given by the dashed blue line defines the spike. The red line is a simple approximation for the part of the bunch that didn't hit the monitor.

$4.0\,\mu$m. All given values of course depend to a certain extent on the choice for the slice boundaries, especially in the front region.

The observed increase in slice emittance in the bunch head may have two different causes. The first one is a true increase in slice emittance. Slice emittance growth in the peak current region may originate from stronger nonlinear forces, especially due to space charge and coherent synchrotron radiation. There may also be a larger residual slice energy spread which effects the distribution of the transverse momenta at the horizontal kicker and thus the slice emittance. But since the slice energy spread is expected to be clearly smaller than 1% even for slices in the head [4], this is probably not a strong effect.

The second possible cause is an increase solely in projected emittance, since the slice width is finite. The observed slice centroid shifts in the head (figure 2) suggest that this effect largely contributes to the measured slice emittance in the front region.

The mismatch parameter B [5] of the slice Twiss parameters with respect to the Twiss parameters of the total bunch varies slightly in the range from B=1 to B=1.5 (figure 6). At the same time the mismatch phase Θ_x [6] gradually decreases along the bunch from $150°$ in the head down to $0°$. This indicates that the transfer functions for the single slices along the accelerator are different from each other, most likely because of chromaticity.

ERROR ANALYSIS

Monte Carlo simulations have been performed in order to determine systematic errors caused by deviations of the integrated quadrupole gradients and the energy. We assumed a homogenous distribution of the integrated quadrupole gradients between $\pm 3\%$ of the measured value, and a gaussian energy distribution with 2% standard devia-

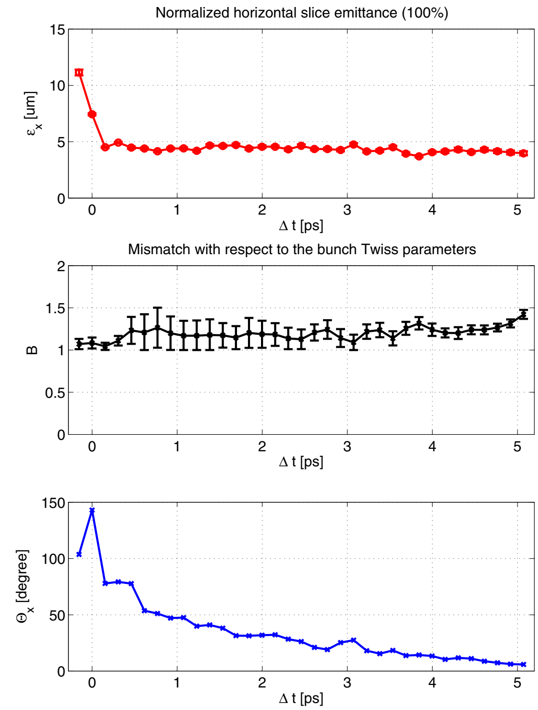

Figure 6: Horizontal slice emittance ϵ_x, mismatch parameter B and mismatch phase Θ_x along the bunch. $\Delta t = 0$ refers to the peak density in the vertical profile. Mismatch parameter and phase are calculated with respect to the Twiss parameters of the total bunch. The error bars refer to statistical errors only.

tion.

We have found that the systematic errors of the mismatch parameters, the mismatch phases and the slice emittance ratios are neglectable compared to their statistical errors.

In case of the absolute emittance values the systematic error is about 35% (figure 8). It is also the dominating error of the reconstructed Twiss parameters. These deviations are mainly caused by errors of the integrated quadrupole gradients. They are rather large since there are seven quadrupoles with partly high gradients in the beamline and beta values up to $130\,m$.

Chromaticity may effect the ratios of the slice emittance values and the mismatch parameters. A systematic correction of chromaticity requires a measurement of the energy distribution along the bunch, which unfortunately has not been done for this measurement. But assuming a residual correlated energy spread of less than 1% [4], the effect should be within the range of statistical errors.

The longitudinal resolution is mainly determined by the vertical size of the slices at the monitor. To estimate the vertical slice sizes, a scan of the same quadrupole has been performed without streaking the bunch. The measured vertical rms sizes of the total beam are presented in figure 7. The values range from $160\mu m$ to $340\,\mu$m. The chosen vertical slice width is within the range of these values. This suggests that the dominating part of the particles in each

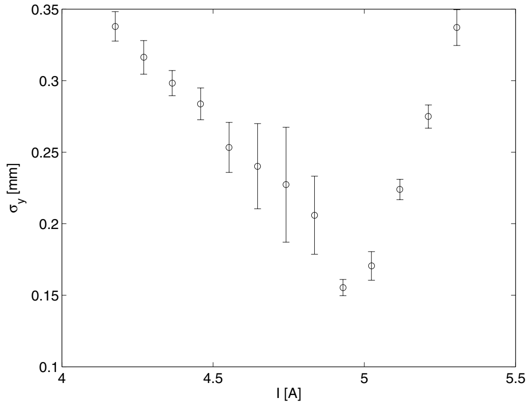

Figure 7: Measured vertical bunch sizes for different quadrupole currents.

vertical slice really is located in the assigned longitudinal slice. However, in case of strong variations of the longitudinal charge density, as e.g. in the region of the head of the bunch, this need not be the case.

OUTLOOK

It is planned to repeat the measurement with a different optics. Thereby the intention is to scan multiple quadrupoles simultaneously in such a way, that a constant and small vertical beta function at the screen is guaranteed. This would improve the resolution.

The error analysis has shown that quadrupole gradient errors have a strong effect on the measurement. The goal is to determine the integrated quadrupole gradients as well as the beam energy with an accuracy of about 1%. To reduce the influence of these errors on the results, an optics with minimal horizontal beta values at the quadrupoles is to be worked out.

A variation of the vertical streak of the bunches may allow to reconstruct the particle distribution in the (y, z) - plane by tomography. The particle distribution could then be used to calculate the vertical slice emittances. Moreover, a calculation of the overlap of the projections of the slices and a corresponding correction of the horizontal slice widths may be possible.

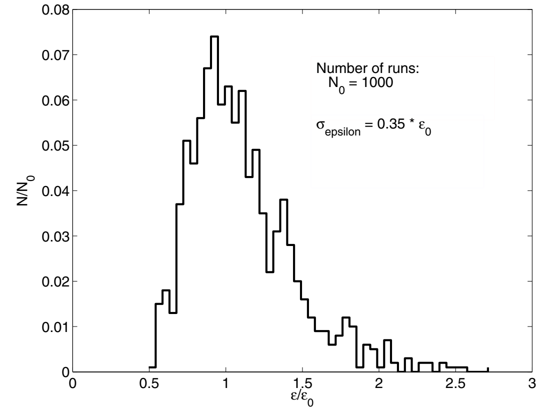

Figure 8: Result of a Monte Carlo simulation for the reconstruction of the emittance with random quadrupole strengths as specified in the text. The emittance values ϵ are normalized to the value ϵ_0 obtained for the default quadrupole stregths.

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