MEASUREMENT OF THE SLICE ENERGY SPREAD INDUCED BY A TRANSVERSE DEFLECTING RF STRUCTURE AT FLASH

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Abstract

Operation of a high-gain free-electron laser requires a high-brightness electron beam with high peak current and small slice energy spread. The slice energy spread can be measured with high longitudinal resolution by using a transverse deflecting RF structure in combination with a viewing screen in a dispersive section. However, off-axis accelerating fields induce a correlated energy spread that depends inversely proportional on the longitudinal resolution. As a consequence, short bunches, which intrinsically require a high longitudinal resolution in order to be diagnosed, suffer from a large induced energy spread which limits the energy resolution. In order to be able to measure the impact of the transverse deflecting RF structure on the slice energy spread without distortions by space charge or coherent synchrotron radiation effects, we tailored short electron bunches with low peak currents by clipping low energy electrons with a collimator located in the first bunch compressor at FLASH. In this paper, we present first systematic measurements of the correlated energy spread induced by a transverse deflecting RF structure. The results are compared with analytical calculations.

INTRODUCTION

The successful operation of present X-ray free-electron laser (FEL) user facilities such as the Linac Coherent Light Source (LCLS) at SLAC or the Free-Electron Laser in Hamburg (FLASH) at DESY, and future facilities such as the European XFEL in Hamburg lead to increasing demands on the flexibility and tunability of FEL photon pulse length and shape which critically depend on the electron bunches driving the FEL. For the manipulation and control of the photon pulses via control of the electron bunches, the diagnosis of the longitudinal phase space with high temporal resolution, which can be achieved by transverse deflecting RF structures (TDS) in combination with magnetic energy spectrometers, provides useful information. However, the interpretation from this kind of diagnostics is subject to limitations due to additional energy spread that is induced by the transverse deflecting RF structures itself [1, 2, 3], which clearly has to be taken into account. It can be shown that this TDS-induced energy spread is inversely proportional to the achievable longitudinal resolution [2], i.e. the effect becomes significant for ultra-short bunch operation, where high temporal resolutions are intrinsically necessary to get sufficient information.

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THEORETICAL BACKGROUND

The working principle of transverse deflecting RF structures has its origin in the Panofsky-Wenzel theorem [4], which makes a general statement of the transverse momentum gained by fast particles moving through RF fields. The theorem states that transverse deflection is only possible if a transverse gradient of the longitudinal electric field is present. This leads to additional energy spread as shown in [1, 2, 3]. When the TDS is considered to have a length of L, and deflection plane in the vertical y, the analytical treatment of the TDS-induced energy gain results in the following expressions:

$$\delta = \frac{eV_0 k}{pc} \cdot \frac{1}{L} \int_0^L y(s) \cdot ds\,, \tag{1}$$

with the equivalent transverse deflecting voltage V_0, the RF wavenumber k, the beam momentum p, and the speed of light c. In the case of a short TDS, the vertical coordinate can be considered to be constant, and the TDS-induced energy spread with kick parameter K becomes

$$\sigma_\delta = \frac{eV_0 k}{pc} \cdot \sigma_y = K \cdot \sigma_y\,, \tag{2}$$

otherwise the effect of an angular spread in the electron beam and especially the deflection within the structure cannot be neglected. In order to discuss all the effects, it is practicable to introduce the phase space vector $(y, y', z, \delta)^{\mathrm{T}}$, which describes the 4d-phase space motion of the beam particles, and the symplectic matrix T of the transverse deflecting RF structure with length L (see [5])

$$T = \begin{pmatrix} 1 & L & KL/2 & 0 \\ 0 & 1 & K & 0 \\ 0 & 0 & 1 & 0 \\ K & KL/2 & K^2L/6 & 1 \end{pmatrix}. \tag{3}$$

The matrix for a short TDS is given by the limit of $L = 0$ and results in a single element $T_{41} = K$ for the energy gain with the corresponding simple expression for the induced energy spread in Eq. (2). For a TDS with finite length, there are further elements, and in particular $T_{43} = K^2L/6$ leads to an induced linear energy chirp

$$\frac{d}{dz}\delta = \frac{1}{6}K^2L\,. \tag{4}$$

It can be shown (see [2]) that the TDS-induced energy spread and linear energy chirp can be expressed as functions of the longitudinal resolution $\sigma_{z,R}$, and the expressions in Eqs. (2) and (4) can be written as

$$\sigma_\delta = \frac{\epsilon_y}{\sin(\Delta\Phi_y)} \cdot \sigma_{z,R}^{-1} \quad \text{and} \tag{5}$$

$$\frac{d}{dz}\delta = \frac{1}{6}\frac{\epsilon_y}{\sin^2(\Delta\Phi_y)}\frac{L}{\beta_0} \cdot \sigma_{z,R}^{-2} \ , \tag{6}$$

with the geometrical emittance ϵ_y, the phase advance $\Delta\Phi_y$, and the betatron function β_0 at the position of the TDS.

BEAM PREPARATION

At FLASH, longitudinal phase space measurements can be performed by using a TDS in combination with a dispersive section downstream of all accelerating modules (see Refs. [6, 7] for more details). The LOLA-type TDS has a length of $L = 3.826$ m, and can be operated with deflecting voltages of up to $V_0 = 20$ MV at which the observation of a TDS-induced energy spread and linear energy chirp becomes possible. In order to be able to resolve these effects, it is desirable to use electron bunches with a linear energy chirp and a slice energy spread that is much smaller than the TDS-induced energy spread. This can be achieved with uncompressed bunches. However, at sufficiently high deflecting voltages, uncompressed bunches typically extend the observation screen by far which renders a measurement of the TDS-induced linear energy chirp impossible. On the other hand, compressed bunches have an increased energy spread due to the required energy chirp for magnetic bunch compression or are subject to non-linear effects, i.e. space charge or coherent synchrotron radiation effects, due to high peak currents.

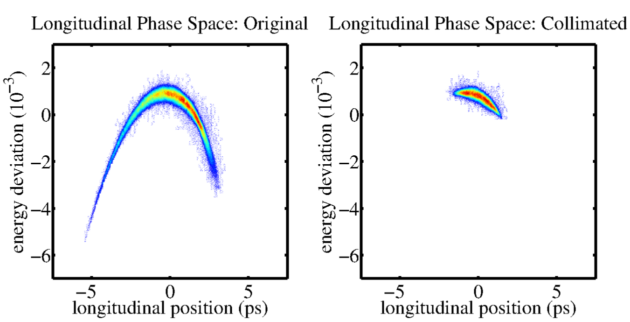

Figure 1: Bunch tailoring for verification of TDS-induced energy spread and linear chirp. Left: Measured longitudinal phase space for on-crest acceleration. Right: Same accelerator settings as in left plot but with low energy electrons clipped with a movable collimator in the first bunch compressor.

For the measurement of the TDS-induced energy spread we tailored short electron bunches with low peak currents by clipping the low energy tails of on-crest accelerated bunches with the help of a collimator in the first bunch compressor. All accelerating modules operating at the fundamental RF of 1.3 GHz were set to their on-crest phases, whereas the third-harmonic accelerating module for phase space linearization was switched off. The corresponding longitudinal phase space measurement is shown in the left plot of Fig. 1. A collimator, which is located in the straight section between the second and third dipole of the first bunch compressor and can be moved into the beamline from the low energy side, was then used to clip as much as possible from the low energy tails without influencing the central part of the bunch (right plot of Fig. 1).

MEASUREMENTS

The data analysis procedure that has been applied for the experimental verification of the TDS-induced energy spread and linear chirp as derived in Eqs. (5) and (6) is illustrated in Fig. 2. The longitudinal phase space of the tailored bunches was divided into three different slices around the centroid. The slice width was chosen to be equal to the achieved longitudinal resolution $\sigma_{z,R}$. For the induced linear energy chirp, the linear slope between the mean energy at longitudinal positions of $\pm 1.5\sigma_z$ was determined.

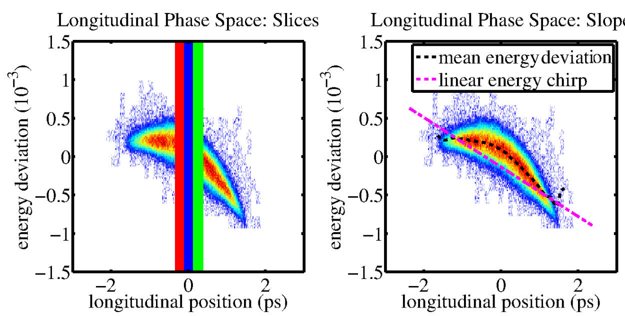

Figure 2: Data evaluation procedure for verification of the TDS-induced energy spread and linear chirp. Left: Three slices (colored) around the centroid with slice widths equal to the resolution. Right: Linear energy chirp between the mean energy at longitudinal positions of $\pm 1.5\sigma_z$.

The TDS-induced energy spread and linear chirp has been measured for various deflecting voltages V_0 of the TDS which translates into different longitudinal resolutions according to Eq. (8) given in Ref. [2]. The effect of increased deflecting voltage V_0, i.e. improved longitudinal resolution, on the energy spread and chirp is demonstrated in Fig. 3. The longitudinal resolution increases from plot (1) to (4), and the effect of the TDS is clearly visible; the slice energy spread increases, and the linear energy chirp changes and even flips the sign.

The quantitative results for the slice energy spread, evaluated for 50 images for each data point, are summarized in Fig. 4. The slice energy spread for three different slices around the centroid is shown as a function of the longitudinal resolution. The magenta curve represents the results of the analytical expression of Eq. (5) with realistic assumptions for the vertical emittance, phase advance from the TDS to the viewing screen, and energy spread offset due to finite energy resolution.

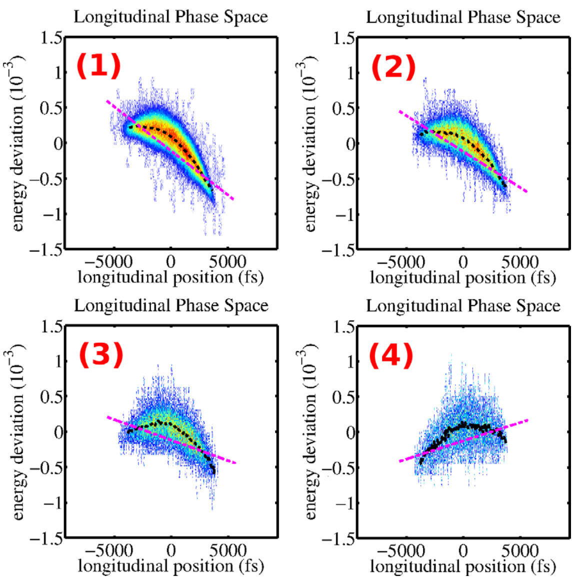

Figure 3: Longitudinal phase space measurements for different deflecting voltages V_0 of the TDS. The achieved longitudinal resolution increases from plot (1) to (4).

Figure 5 shows the corresponding results for the measured TDS-induced linear energy chirp as a function of the longitudinal resolution. The initial energy chirp, i.e. the chirp for the lowest deflecting voltage V_0, was used as reference and subtracted from each measurement. The magenta curve shows the result of the analytical expression of Eq. (6) with realistic assumptions for the vertical emittance and accelerator optics.

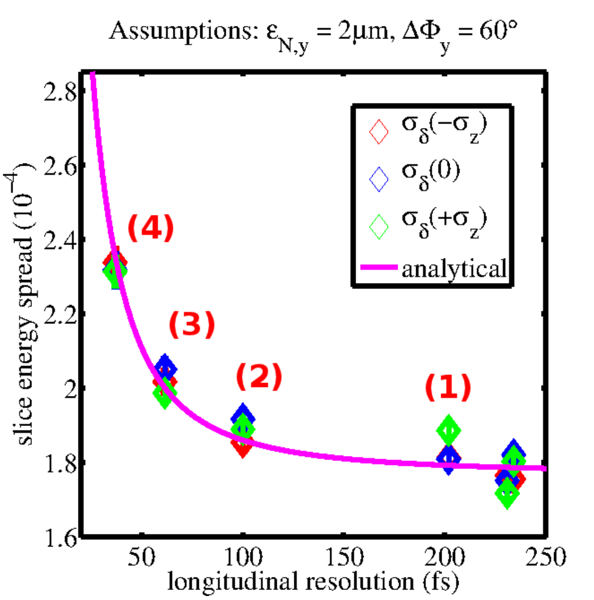

Figure 4: Measured slice energy spread (colored diamonds) for the three different slices around the centroid as function of longitudinal resolution together with the result of the analytical expression (magenta line) in Eq. (5).

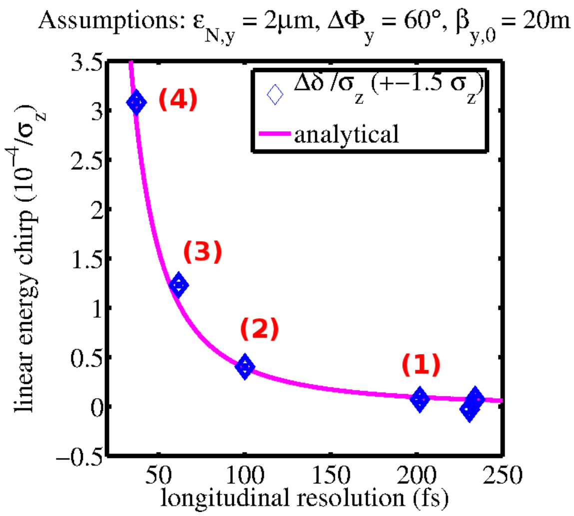

Figure 5: Measured linear energy chirp (diamonds) induced by the TDS as function of the longitudinal resolution together with the result of the analytical expression (magenta line) in Eq. (6).

CONCLUSIONS

We have presented the experimental verification of the limitation on longitudinal phase space measurements using a TDS. The TDS-induced energy spread and linear energy chirp has been measured as a function of the longitudinal resolutions, and the data are in good agreement with the results of analytical expressions (Eqs. (5) and (6)). The effect of longitudinal accelerating fields in the TDS have to be taken into account for the interpretation of high-resolution measurements of the longitudinal phase space.

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