SLICE EMITTANCE MEASUREMENTS AT FLASH

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Abstract

The SASE process in Free Electron Lasers mainly depends on time-sliced parameters of beam current, energy spread and transverse emittance. At FLASH at DESY, electron bunches are compressed longitudinally in two magnetic chicanes to achieve high peak currents. The compression causes considerable variations in slice emittance along the bunches. The vertically deflecting rf structure LOLA, which is in operation at FLASH since early 2005, allows to resolve longitudinal variations in horizontal slice width for single bunches. The horizontal slice emittance can be determined by additionally varying the strengths of the quadrupoles upstream of LOLA. Results for slice emittance and longitudinal density profile using different compression schemes are presented. Significant differences between the slice emittance profiles and especially between projected and slice emittance have been found.

INTRODUCTION

In single-pass Free-Electron Lasers (FELs), Self-Amplification of Spontaneous Emission (SASE) typically occurs only in a small part of an electron bunch which is characterized by high charge density, small transverse emittance and small energy spread. These properties may strongly vary along a bunch due to collective effects such as coherent synchrotron radiation (CSR) and space charge forces (SCF) which are largely caused by the longitudinal compression process. Hence, there is a need for time-correlation measurements on the bunch length scale. A powerful method therefor is to "streak" single bunches transversally with a travelling wave rf deflecting structure and to image the particle distribution in the transverse plane downstream of the structure using an OTR screen [1, 2]. On these images, the coordinates in the direction of the streak effectively correspond to time coordinates and thus time-correlated properties may be analysed, e.g. the longitudinal density profile, energy-time correlation, time-correlation of slice energy spread [3], and time-correlation of slice emittance in the other transverse direction. Slice emittance may be reconstructed by measuring the rms width of time slices on OTR images taken at appropriate locations, or, as done here, for different settings of the quadupoles upstream of the rf structure.

The presented measurements have been performed at FLASH at DESY using the vertically deflecting rf structure LOLA [4]. Within LOLA, passing particles traverse an rf voltage in the vertical direction. Due to a high frequency time variation of the fields, bunches injected at zero crossing of this voltage are vertically streaked. For short enough bunches there is a linear relation between a vertical distance on the screen and a time interval, so only a calibration constant is needed to establish a time scale on the vertical screen axis.

In addition to the purpose of beam diagnostics at FLASH, experience with LOLA is also helpful with regard to future projects, e.g. the European XFEL, where it is intended to use rf deflecting structures as standard tools for on-line beam diagnostics.

SETUP OF THE EXPERIMENT

A schematic of the FLASH linac and the part used for slice emittance measurements is shown in Fig. 1. LOLA is located downstream of five accelerating modules ACC1 to ACC5 and two bunch compressors BC2 and BC3. An off-axis screen downstream of LOLA is used in combination with a horizontal kicker upstream of LOLA to measure the transverse particle distribution. This configuration renders the possibility of parasitic measurements by kicking single bunches out of a bunch train. The time scale on the vertical screen axis can be calibrated by measuring the vertical position of a distinctive part of a bunch, e.g. the density peak, while scanning the phase of LOLA.

The longitudinal resolution is determined by the ratio of the divergence induced by LOLA and the inherent beam divergence at LOLA. The optics was therefore adjusted to obtain a large vertical beta function of approximately 40 m at LOLA . The beta function at the OTR screen was adapted to the screen size in vertical direction and to the screen resolution in horizontal direction. In order to keep the streak at

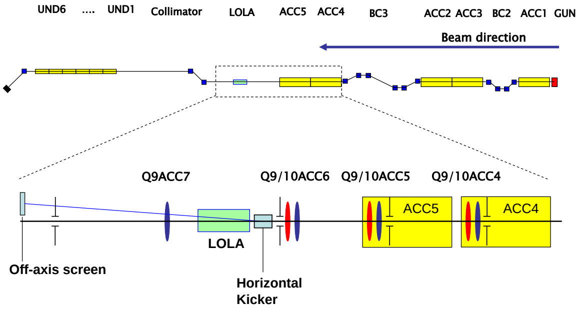

Figure 1: Sketch of the FLASH linac and the part used for the experiment.

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the screen constant and to fulfill the aforementioned boundary conditions while scanning the horizontal phase advance over a range of roughly $180°$, the six quadrupoles Q9ACC4 to Q10ACC6 upstream of LOLA had to be changed simultaneously. The beam was matched to this optics downstream of BC3 by carrying out a quadrupole scan.

We have measured 1σ-slice emittances for different compression schemes, i.e. different acceleration phases in modules ACC1-3 and different settings of the bunch compressors. An overview on the settings is given in Table 1. The bunch charge was set to 1 nC for all measurements.

RESULTS

The results of the measurements are presented in Fig. 2. For the first measurement (Fig. 2(a)) the acceleration phases in modules ACC1 and ACC2/3 had been adjusted to obtain minimum energy width. The longitudinal profile given by the dashed line is not gaussian shaped in this case, since there is compression at the front end of the bunches in the bunch compressors due to the rf curvature. The rms length of the total bunch is 3.7 ± 0.1 ps. The slice emittance varies around 5 mm mrad and rises at both ends. The increasing values towards the ends may be explained by the solenoid of the gun, which is adjusted to compensate space charge forces in the bunch centre and therefore overfocuses the low current regions.

A projected emittance of 4.3 mm mrad was measured upstream of ACC2/3 using the multi-screen method. Since for this setting no emittance dilution should occur, the absolute values of the slice emittance are slightly larger than expected. This may be explained by systematic errors due to quadrupole gradient errors and energy errors, which are about 30% for pessimistic assumptions, as discussed in detail in the following section.

The projected emittance, shown as a solid line in Fig. 2, is roughly a factor of 2 larger than the average slice emittance. This mismatch is caused by a time-correlated horizontal slice centroid shift, which appears as a nearly linear tilt of the bunch on the screen for certain quadrupole settings (Fig. 3). This tilt has been detected in all measurements. About the cause of this tilt can only be speculated at the moment. Possible explanations are wake fields and kicks due to field asymmetries within the accelerating cavities, especially at the couplers. Spurious dispersion can be excluded, since the slice centroid shift does not show the shape of the rf curvature. Moreover, the dispersion would have to be about a factor of 10 larger than it typically is to produce this tilt. Causes in the gun area may be excluded, too, since the projected emittance measured upstream of BC2 has been smaller by roughly a factor of 2. The tilt is also not artificially created by LOLA as can be seen from a measurement of the projected emittance with LOLA turned off delivering even a slightly larger value.

For compression solely in BC2 (Fig. 2(b)), a clear increase in slice emittance at the front of the bunch has been measured, which is most likely caused by CSR and SCF. The phase of ACC1 was set to $-14.1°$. The maximum peak current is obtained at $-9.5°$. The phase was chosen so the longitudinal bunch distribution does not vary strongly from bunch to bunch, which is the case at maximum compression. The result is similar as for a measurement performed in 2005 with deflection in both bunch compressors and an ACC1 phase of $-6.5°$ [2].

Table 1: Overview on the settings for the measurements a,b,c,d. α_{BC2} and α_{BC3} are the deflection angles in BC2 and BC3, respectively. ϕ_{ACC1} and $\phi_{ACC2/3}$ are the acceleration phases in the corresponding modules. The reference phase ($0°$) corresponds to minimum energy width.

	α_{BC2} [deg]	α_{BC3} [deg]	ϕ_{ACC1} [deg]	$\phi_{ACC2/3}$ [deg]	E [MeV]
a	18	3.8	0	0	630
b	18	0	-14.1	0	630
c	0	5.4	0	-26	650
d	18	3.8	-20	0	630

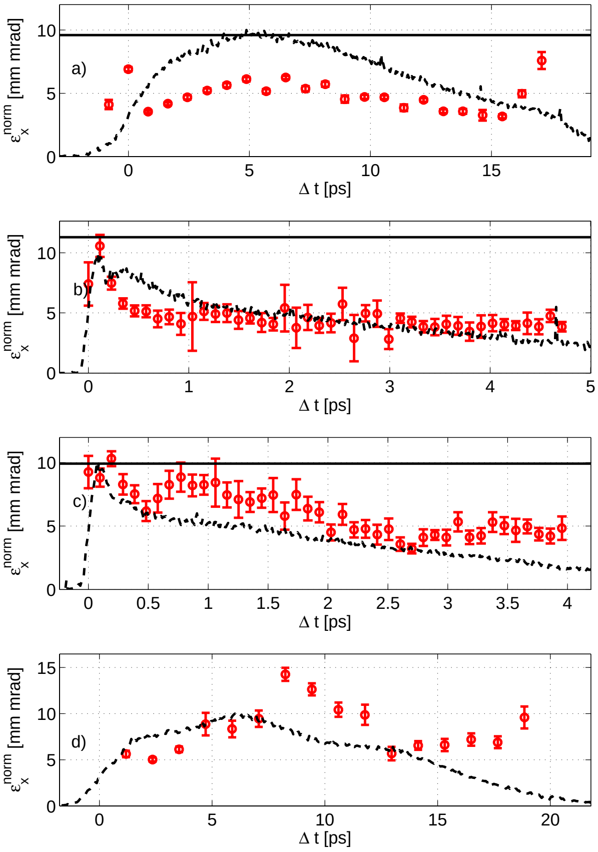

Figure 2: Measured slice emittances (red error bars) for the settings listed in Table 1. The dashed lines give the longitudinal density profiles normalized to the peak density times 10 mm mrad. The solid lines give the values of the projected emittance of the considered slices. The front of the bunches is on the left.

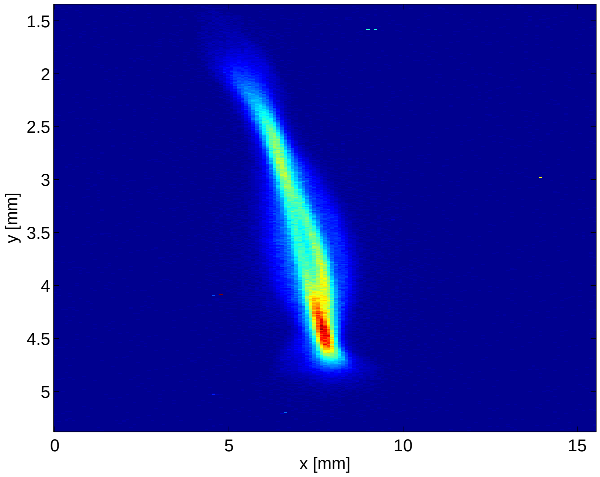

Figure 3: Image of a longitudinally tilted bunch. The tilt changes during the quadrupole scan.

The slice emittance in case of compression only in the S-chicane BC3 (Fig. 2(c)) shows similar values at the front, but also a clearly increased emittance in the centre of the bunch. The phase of modules ACC2/3 was set to -26°. The maximum compression in this case is at -31°. The increase in slice emittance in the bunch centre is unexpected, since there is not a high current region and also no over-compression. The large values seem to rise from a horizontal splitting of the bunches in two parts in this region for some quadrupole settings, which cannot be explained so far.

Finally, a measurement with deflection in both bunch compressors and strong over-compression induced by off-crest acceleration in module ACC1 at -20° has been done (Fig. 2(d)). The slice emittance strongly rises up to a factor of 3 in the bunch centre. This behaviour is assumably caused by CSR in the high current regions of the bunches in BC2, which are finally located in the bunch centre due to over-compression. Space charge effects are supposed to be small compared to CSR effects in this case, since the bunches are strongly compressed only for a short distance within BC2.

ERROR ANALYSIS

The main error source for the presented emittance values are assumed to be erroneous transfer matrices used for the emittance calculations. The transfer matrices may deviate due to gradient errors of the six quadrupoles involved, energy errors and unconsidered effects of the accelerating modules ACC4 and ACC5. It is important to note that these errors only affect the absolute emittance values, and not contribute to the errors of the ratios of emittance values calculated with the same set of transfer matrices. To estimate the error caused by quadrupole gradient and energy errors, a monte carlo simulation for 2% rms gradient errors and 2% rms energy error has been performed. The resulting emittance error for these rather pessimistic assumptions is about 30%. The transfer functions have been measured so large quadrupole errors can be excluded.

Another important error source is noise and background signals in the images, which may strongly effect the calculated rms widths. To minimize the effects, averaged background images have been subtracted from the bunch images, and a program has been used to isolate a narrow region of the screen containing the bunch.

OUTLOOK

We are currently working on simulations to reproduce the results. A matter of particular interest is to understand the time-correlated centroid shift which blows up the projected emittance. For August 2006, further slice emittance measurements especially for SASE conditions are scheduled.

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