

# ENERGY-TIME CORRELATION MEASUREMENTS USING A VERTICALLY DEFLECTING RF-STRUCTURE

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## Abstract

To initiate Self-Amplification of Spontaneous Emission (SASE) in single-pass Free Electron Lasers (FEL), electron bunches with high peak current and small slice emittance and energy spread are necessary. High peak currents can be generated by bunch-shortening in magnetic chicanes induced by a nearly linear energy-time gradient. The residual uncorrelated time-sliced energy width after compression is a crucial parameter for the lasing process. The final energy-time correlation provides information about the compression process and collective effects such as coherent synchrotron radiation (CSR) and longitudinal space charge (LSC) forces. A powerful method for measuring these quantities is to “streak” bunches transversally with an rf structure and thus to map the time delay within single bunches to the vertical axis of a downstream screen. Significant dispersion at the screen in the transverse direction perpendicular to the streak direction allows to directly image the longitudinal phase space distribution in a single shot. We successfully measured the longitudinal density profile, energy-time correlation and slice energy spread in high current regions for different bunch compression schemes using the vertically deflecting rf structure LOLA at FLASH. Clear indications for CSR and LSC effects have been found.

## INTRODUCTION

At the Free-electron LASer in Hamburg (FLASH), two magnetic chicanes BC2 and BC3 are used for longitudinal bunch compression induced by “off-crest” acceleration in the upstream accelerating module ACC1 (cf. Fig. 2). The compression process appears as a shearing of the particle distribution in longitudinal phase space. Distortions like CSR and LSC effects show up as deviations from the ideal shape and in particular increase the energy width within short time slices (“slice energy spread”). Transversely deflecting rf waveguides such as LOLA [1, 2, 3] allow to directly image the longitudinal phase space distribution. Thus distortions may be quantified, the compression process controlled and the slice energy spread determined.

During the passage of LOLA, 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. Downstream of LOLA the transverse bunch distribution is imaged with an OTR screen, whose vertical coordinates are related to

time coordinates via the vertical streak. For short enough bunches there is a linear relation between a vertical distance on the screen and a time interval. In case that additionally horizontal dispersion is generated at the location of the screen, the horizontal position of particles intercepting the screen depends on their energy. In this way the longitudinal phase space distribution can be directly imaged, as is illustrated in Fig. 1.

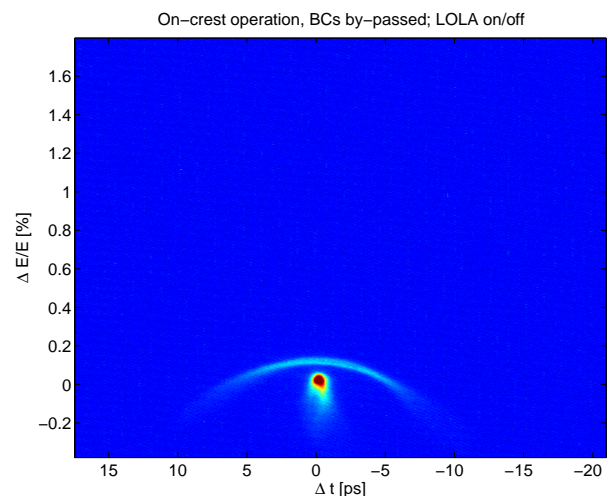


Figure 1: OTR image showing two bunches: the upper one streaked and the lower one not streaked with LOLA. The vertical position depends on the energy, the horizontal position on the arrival time at LOLA. The two bunches were separated by a kicker magnet. The original OTR image has been rotated by 90°.

## EXPERIMENTAL SETUP

A schematic of FLASH and the part used for the measurements are shown in Fig. 2. LOLA is located downstream of the accelerating modules and the two bunch compressors. The on-axis screen used for this measurement is located in a dispersive section called “dogleg”. To calibrate the energy scale on the horizontal axis of the screen, the dispersion generated by the upstream dipole has been measured and found to be about 300 mm. The time scale on the vertical axis has been calibrated by measuring the beam position for different phases of LOLA. In order to improve the resolution of the measurements, the optics was adjusted to get small beta functions of less than 3 m in both planes and large horizontal dispersion and streak at

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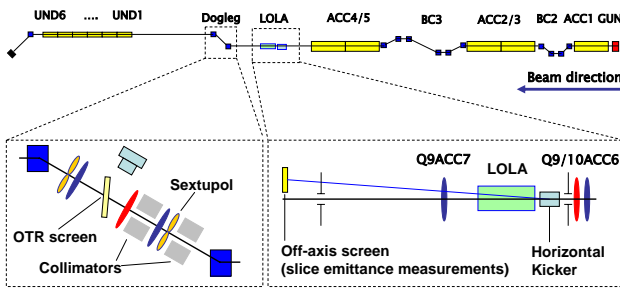


Figure 2: Sketch of the FLASH linac and the section used for the experiment.

the OTR screen. The collimators located between LOLA and the screen were set to the maximum diameter to have full transmission of the streaked bunches, and a sextupole was switched off to avoid chromatic distortions. The linac was operated at a beam energy of 650 MeV and a bunch charge of 1 nC.

## RESULTS

The first measurement has been performed with by-passed bunch compressors. The acceleration phases in modules ACC1 and ACC2/3 were adjusted to obtain minimum energy spread. The measured energy-time correlation is shown in Fig. 3. It shows clearly the rf-curvature imprinted on the bunch, which is symmetrically distributed around the crest as expected for minimal energy width. The rms bunch length is  $4.8 \pm 0.1$  ps and the rms energy width  $0.090 \pm 0.003\%$ . For comparison, the measured rms duration of the cathode laser is  $4.4 \pm 0.1$  ps [4].

In principle, also the energy spread of single slices may be measured. However, assuming the design beta function at the screen of 3 m and a normalized horizontal  $1\sigma$ -slice emittance of at least 1 mm mrad, the measured slice width of about  $50 \mu\text{m}$  in the bunch centre is just the resolution limit. From simulations we expect a slice energy spread of less than 10 keV, which corresponds to a width of only  $4 \mu\text{m}$  at the screen for the given dispersion.

The energy-time correlation for the same acceleration phases but with a deflection of  $5.4^\circ$  in BC3 is shown in Fig. 3. Due to the rf-curvature the bunch is compressed in the front part leading to a smaller rms bunch length of 3.8 ps and an asymmetric density profile.

The evolution of the longitudinal phase space distribution during a scan of the ACC2/3-phase and compression in BC3 can be seen in Fig. 4. The scan starts at  $-26^\circ$  from minimum energy spread, just before over-compression, and ends at  $-32^\circ$ , which is close to maximum compression. The bunch length is reduced down to  $325 \pm 17$  fs at  $-31^\circ$  (Table 1). Strong compression in the front part blows up the slice energy spread so it can be measured. The maximum value of  $0.55 \pm 0.03\%$  or about 3.6 MeV is reached at  $-32^\circ$ . A closer look at the phase space distribution reveals deviations from the pure rf-curvature caused by CSR

and LSC forces (Fig. 5). It remains to be studied by simulations which is the dominant effect here. The width of the head may be a measure for the peak current in case it is dominated by LSC.

## ERROR CONSIDERATIONS

The resolution of the presented measurements is mainly determined by the bunch size due to betatron oscillations. In the case of on-crest acceleration, the horizontal slice width was about  $50 \mu\text{m}$  in the bunch centre and up to  $130 \mu\text{m}$  at both ends. The resolution limit for the slice energy spread measurements corresponding to  $130 \mu\text{m}$  is below 300 keV, which is clearly smaller than the measured slice energy spread in the front region. The rms error of the beam energy is assumed to be roughly 2%. The calibration constants have a statistical errors below 2% in all cases.

For the correct evaluation of the data, image analysis is crucial since there is always noise in the images mainly caused by dark current. The noise may largely influence measured rms values, especially if single slices are evaluated. In case of complex bunch shapes on the screen as

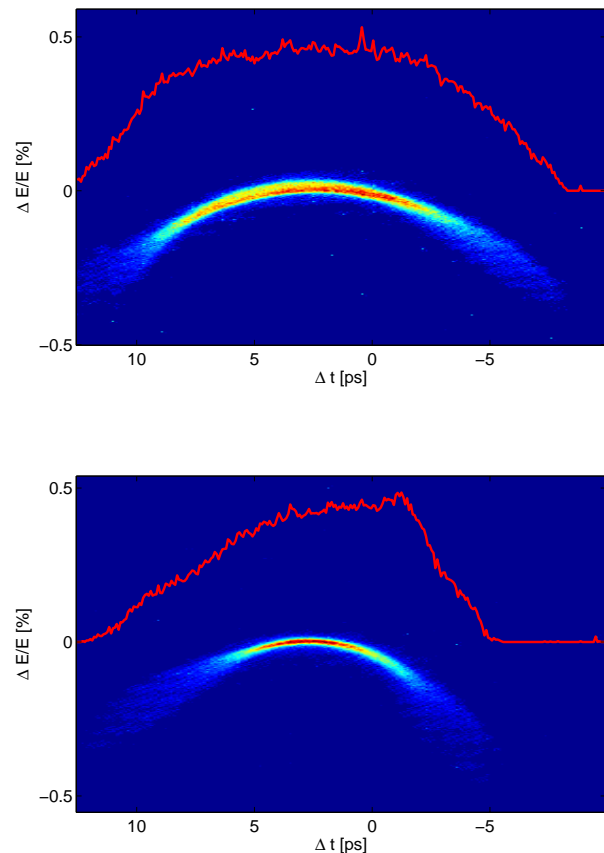


Figure 3: Measured energy-time correlation for on-crest acceleration with by-passed bunch compressors (top) and a deflection of  $5.4^\circ$  in BC3 (bottom). The solid lines give the normalized density profiles. The front of the bunch is on the right.

in these measurements, finding the bunch region without cutting parts of the bunch is complicated. The analysis program used for the data shown here has been tested and no systematic deviations have been found.

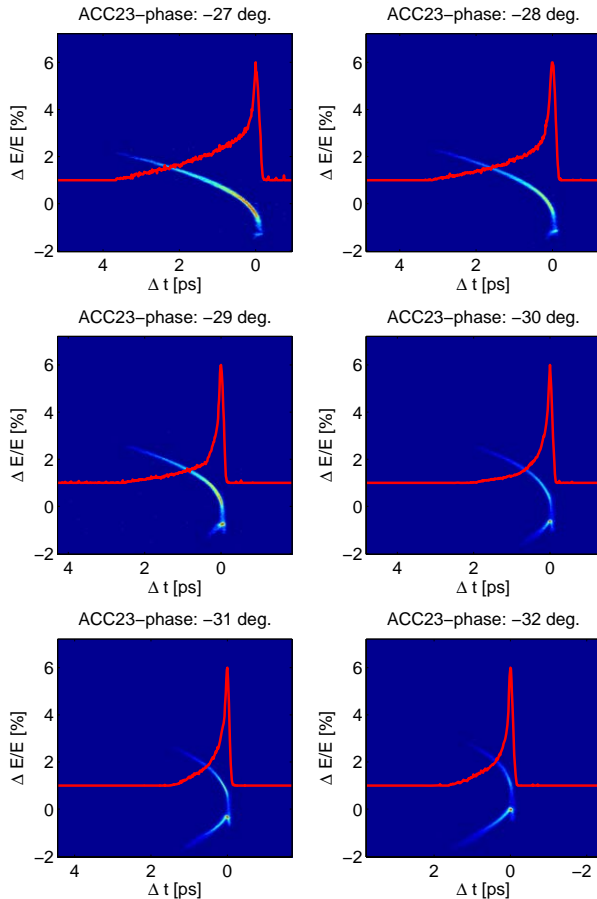


Figure 4: Energy-time correlations for off-crest acceleration in module ACC2/3 between  $-27^\circ$  and  $-32^\circ$  and compression in BC3 ( $5.4^\circ$  deflection). The red lines represent the longitudinal density profiles.

Table 1: Rms length  $\sigma_t^{tot}$ , relative rms energy width  $\delta^{tot}$  of the total bunch and relative rms energy width  $\delta^{head}$  in the head of the bunch for different phases  $\phi_{ACC2/3}$  of module ACC2/3. Only statistical errors are given here.

$\phi_{ACC2/3}$ [deg]	$\sigma_t^{tot}$ [fs]	$\delta^{tot}$ [%]	$\delta^{head}$ [%]
-26	$948 \pm 76$	$0.78 \pm 0.05$	$0.24 \pm 0.06$
-27	$831 \pm 59$	$0.83 \pm 0.05$	$0.34 \pm 0.04$
-28	$693 \pm 51$	$0.94 \pm 0.03$	$0.41 \pm 0.04$
-29	$557 \pm 52$	$1.03 \pm 0.03$	$0.49 \pm 0.04$
-30	$420 \pm 48$	$1.07 \pm 0.02$	$0.50 \pm 0.02$
-31	$325 \pm 17$	$1.06 \pm 0.01$	$0.52 \pm 0.03$
-32	$358 \pm 26$	$1.04 \pm 0.01$	$0.55 \pm 0.03$

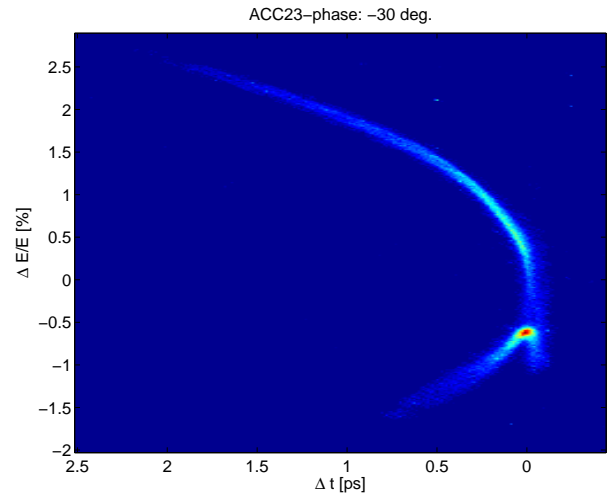


Figure 5: Measured energy-time correlation at  $-30^\circ$  ACC2/3-phase. In the front part of the bunch distortions are clearly visible. The spike towards smaller energies at the very front of the bunch consists of particles which have lost energy either because of CSR within BC3, or because of LSC. In case of LSC there would also be spike towards higher energies, but it may just not be resolved here.

## OUTLOOK

In order to understand the obtained results, we are currently modelling the beam dynamics using simulation codes as ASTRA and CSR-Track. Further measurements for different compression schemes, especially under SASE conditions, are scheduled for August 2006.

## ACKNOWLEDGEMENTS

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## REFERENCES

- [1] P. Emma *et al*, "A Transvers RF Deflecting Structure for Bunch Length and Phase Space Diagnostics", SLAC-PUB-8864, August 2000.
- [2] M. Röhrs *et al*, "Slice Emittance Measurements at FLASH", these proceedings.
- [3] O. Grimm *et al*, "Longitudinal Bunch Shape Diagnostics with Coherent Rrdiation and a Transverse Deflecting Cavity at TTF2", FEL Conference 2004, Trieste, August 2004.
- [4] S. Schreiber, "The Injector of the VUV-FEL at DESY", FEL Conference 2005, Stanford, August 2005