INVESTIGATIONS OF THE LONGITUDINAL ELECTRON BUNCH STRUCTURE AT THE FLASH LINAC WITH A TRANSVERSE DEFLECTING RF-STRUCTURE

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Abstract

In the single-pass Free-Electron Laser FLASH, Self-Amplification of Spontaneous Emission (SASE) occurs in a small fraction of an electron bunch with a length in the order of micrometers. As a consequence, there is a need for bunch diagnostics with a time resolution in the femtosecond regime for understanding and improving the machine performance. At FLASH, a vertically deflecting structure (LOLA) is used to measure the longitudinal charge density profile and phase space distribution of single bunches with high time resolution. The horizontal slice emittance can be determined by additionally using quadrupole scan techiques. In this paper, we present results of measurements under conditions close to SASE operation at 13.7 nm. We reached a RMS resolution of 20 fs for the longitudinal profile measurements, and resolved the longitudinal phase space distribution and slice emittance with 50 fs and 60 fs, respectively. Strong indications for a substructure within the horizontal phase space distribution of the peak current region have been found.

INTRODUCTION

At the Free electron LASer in Hamburg (FLASH), electron bunches with peak currents of 1-3 kA are produced by longitudinal bunch compression in two magnetic chicanes. This results in a narrow high current region at the front of the bunch (“spike”) with a width of less than 100 fs (FWHM) and a long trailing tail. The SASE process may be initiated within the spike, if transverse slice emittance and slice energy width are sufficiently small. However, these parameters are significantly degraded by coherent synchrotron radiation (CSR) effects in the dipoles of the magnetic chicanes, and by space charge forces along the linac. The SASE signal with a duration in the order of 10 fs suggests that only a fraction of the charge in the spike contributes to the lasing process. To resolve the longitudinal structure, bunch diagnostics with an appropriate time resolution is necessary.

The most powerful and multifunctional tools for this purpose are currently transverse deflecting rf-structures called LOLA [1, 2, 3]. LOLA structures operate in a hybrid mode (a superposition of a TM_{110} and a TE_{110} mode), which propagates with a phase velocity equal to the speed of light. A passing relativistic electron is subject to a deflecting force in vertical direction, which is independent of the transverse position of the electron within the structure and constant in time. The force sensitively depends on the phase of the fields at the arrival time due to a high frequency time variation at 2.856 GHz. Injection of a bunch at zero crossing of the deflecting force results in a shearing or “streaking” of the bunch without centroid deflection. As a consequence, the vertical positions of the bunch electrons downstream of the structure are linearly correlated with their longitudinal coordinates. Standard OTR screens then allow for measurements of the particle distribution in the longitudinal-horizontal plane. Alongside the measurement of the longitudinal charge density profile, this technique permits to determine the horizontal slice emittance by scanning quadrupoles upstream of LOLA [4]. Furthermore, the longitudinal phase space distribution can be obtained in a single shot measurement at locations with significant horizontal dispersion. An estimate for the time resolution is given by the vertical size of the bunches at the screen location without streak, i.e. with LOLA being switched off. Parameters of the LOLA structure are listed in Table 1 [3].

Table 1: Properties of LOLA [3]

Length	3.64 m
Frequency	2.856 GHz
Max. operating power	25 MW
Deflecting voltage at 20 MW	26 MV
Filling time	0.645 μs
Aperture	44.88 mm

EXPERIMENTAL SETUP

A schematic of the FLASH linac and the sections used for the measurements is shown in Fig. 1. Electron bunches are generated in an rf photocathode (gun) and accelerated in five superconducting modules ACC1 to ACC5. The bunches are longitudinally compressed in two magnetic chicanes BC2 and BC3 at energies of typically 127 MeV and 360 MeV, respectively. A dispersive section (dogleg) is used to collimate the beam before it enters the undulator section. For the presented measurements, the linac was operated with a bunch charge of 0.5 nC and a final energy of 677 MeV to produce a SASE signal at 13.7 nm wavelength. We obtained an average radiation energy of 5 μJ per electron bunch. The phase of module ACC1 was set to -7.6° from minimum energy width operation, which is 4.4° above the phase for maximum peak current (-12°). The

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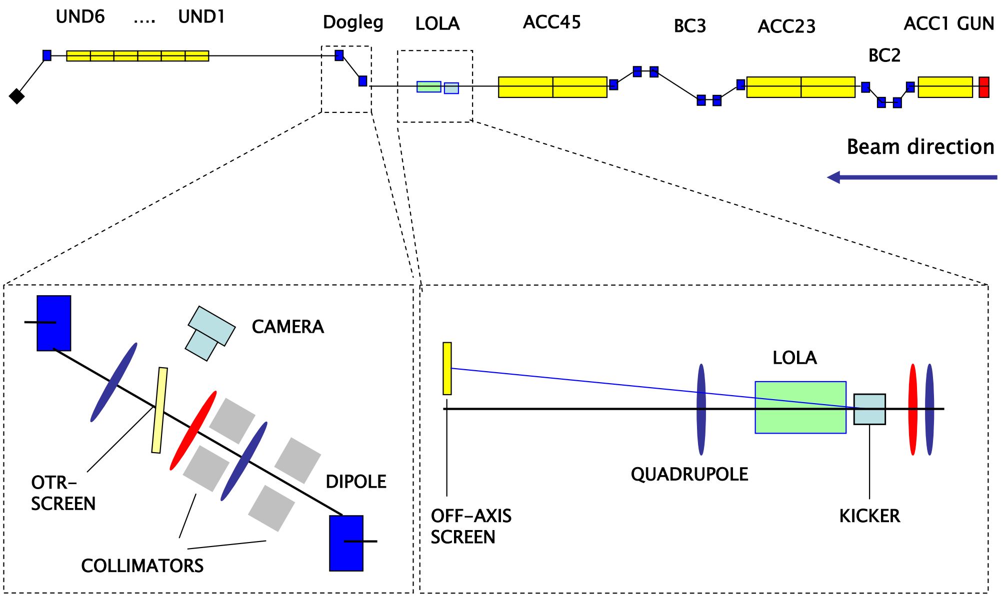

Figure 1: Schematic of the FLASH beamline and a zoom into the regions used for the measurements. Longitudinal profile and slice emittance have been measured on an off-axis screen (bottom right), the distribution in longitudinal phase space with a screen in the dogleg section (bottom left).

phases of modules ACC23 and ACC45 were set to -25° and 0°, respectively.

LOLA is located at the end of the linac. An off-axis screen with a hight of 17 mm has been used in combination with a horizontal kicker preceding LOLA to measure the longitudinal profiles. The time scale on the vertical axis of the screen has been calibrated by measuring the vertical bunch position while varying the phase of LOLA around zero crossing. The calibration constant or “streak strength” was 4.9 mm/ps in case of the density profile measurement. The input power of LOLA has been adjusted to observe entire bunches on the screen, including the long tails. In this way additional quantities may be infered, e.g. the charge portion within the spike, whereas the time resolution is slightly degraded. The horizontal slice emittance has been measured by varying quadrupoles upstream of LOLA. Several quadrupoles had to be scanned simultaneously in order to minimize the changes in time resolution (vertical beam size with LOLA switched off) while the phase advance in horizontal direction was varied.

An OTR screen in the horizontally dispersive dogleg section has been used for measuring the longitudinal phase space distribution. The dispersion generated by the upstream dipole has been determined to be 233 mm by measuring the horizontal beam position on the screen for different dipole currents.

Before the measurements, the optics downstream of BC3 had been modified in order to improve the resolution of the measurements. However, we expect only a negligible modification of the longitudinal bunch properties and the horizontal emittance. In case of longitudinal phase space measurements, also the optics upstream of BC3 had to be modified slightly, which may have altered CSR effects in the dipoles of BC3.

RESULTS

LONGITUDINAL PROFILE

Fig. 2 shows the measured longitudinal charge density profile of a single bunch. It consists of a sharp leading spike and a long tail. The width of the spike is $\sim$70 fs (FWHM). The time resolution is $\sim$50 fs FWHM and $\sim$20 fs RMS. The properties of the spike change slightly from bunch to bunch most likely due to phase and / or amplitude fluctuations of the first acccelerating module. An analysis for 100 successive bunches reveals a nearly gaussian-shaped distribution of the spike width with a mean of 74 fs and a sigma of 9 fs. The same applies to the charge in the spike defined by the coloured area in Fig. 2 and the corresponding current, which are 0.13 ± 0.01 nC (25 ± 1 % of the total bunch charge) and 1.7 ± 0.1 kA.

LONGITUDINAL PHASE SPACE

The particle distribution of a single bunch in longitudinal phase space, which is directly obtained from an OTR image of a streaked bunch in the dispersive dogleg section, is presented in Fig. 3 (top). It shows the expected overall

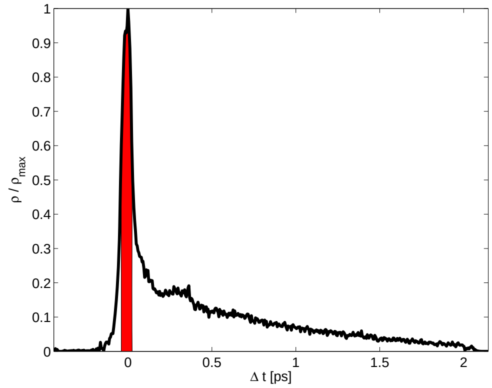

Figure 2: Normalized longitudinal charge density profile measured with LOLA. The width of the coloured region is equal to the width of the spike (FWHM). The specified charge fraction in the spike refers to this area.

correlation, which is characterized by a rapid energy variation at the head of the bunch leading to the observed sharp spike in the longitudinal profile, and an increasing energy along the tail due to off-crest acceleration. Within the high density region, there are deviations from the ideal shape in terms of spikes in time and energy direction. Tracking calculations with ASTRA [5] and CSR-Track [6] are in qualitative agreement with these results [7]. Some distinct distortion patterns are mostly related to longitudinal space charge (LSC) forces: On the way from BC3 to the screen, LSC causes an increase in energy width, which can clearly be seen in Fig. 3. The spike at the very front of the bunch in time direction is due to energy spread generated by LSC during the passage from BC2 to BC3, which is then sheared in longitudinal phase space in BC3.

The slice energy widths and the longitudinal density profile calculated from the measured phase space distribution are shown in the bottom plot in Fig. 3. The chosen slice widths is equal to the RMS resolution of 50 fs. The slice energy spread reaches a maximum value of $\sim$0.26 % or $\sim$1.8 MeV at the bunch head and decreases to $\sim$ 0.06 % ($\sim$406 keV) in the tail. Here, the values are limited by the residual transverse beam size without dispersion and provide an estimate for the energy resolution of the measurement.

The increase in energy width at the front is largely due to a non-gaussian energy distribution. Within this region, two local maxima of the energy profile can be observed (Fig. 4). This structure may arise from both, LSC and CSR, but we expect the LSC effects to be dominant. By dividing the phase space distribution between the two maxima as indicated by the dashed line in Fig. 4, the longitudinal density profile in the high current region can be considered seperately for the two regions, revealing a separation of the charge density maxima in time by $\sim$50 fs (see Fig. 4). It may be speculated that this is a true substructure of the spike in the longitudinal density profile, which could not be resolved here.

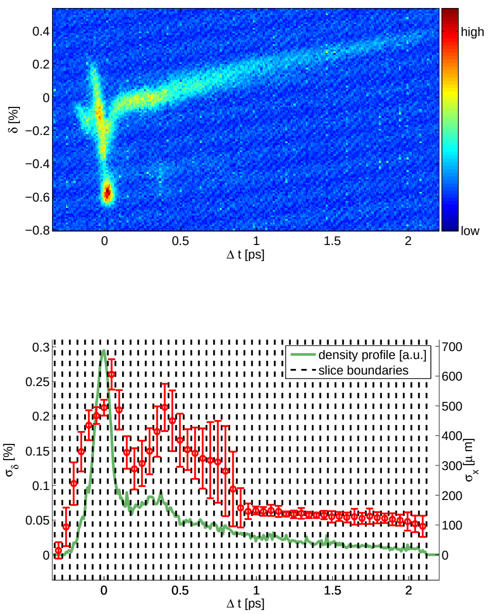

Figure 3: Longitudinal phase space distribution for a single bunch (top) and corresponding RMS slice energy width σ_δ (bottom). In the bottom image, the slice boundaries and the density profile are drawn in.

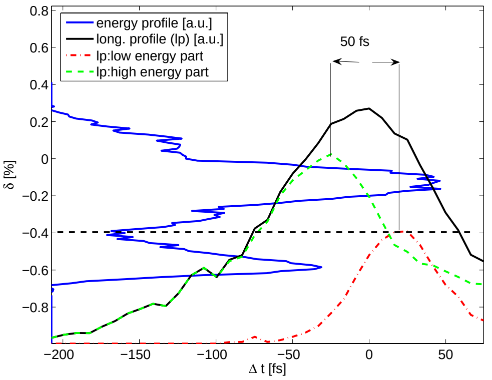

Figure 4: Projections of the longitudinal phase space distribution within the peak current region (Fig. 3) onto the time and energy axis. The longitudinal profile is splitted into two parts, as is indicated by the dashed horizontal line: The one for the low energy part and the one for the high energy part. The maximas of the profiles are seperated in time by $\sim$50 fs.

SLICE EMITTANCE

Figure (5) shows the measured horizontal 1σ slice emittance (normalized) along the bunch (bottom) with a resolution of 60 fs, and an OTR image of a bunch during the scan (top). Within the bunch tail the slice emittance ranges from 2 μrad to 3 μrad. There is a dramatic increase in slice emittance at the front of the bunch with a value of $\sim$16 μrad within the density spike, which is significantly larger than expected for SASE operation. Assuming an RMS energy

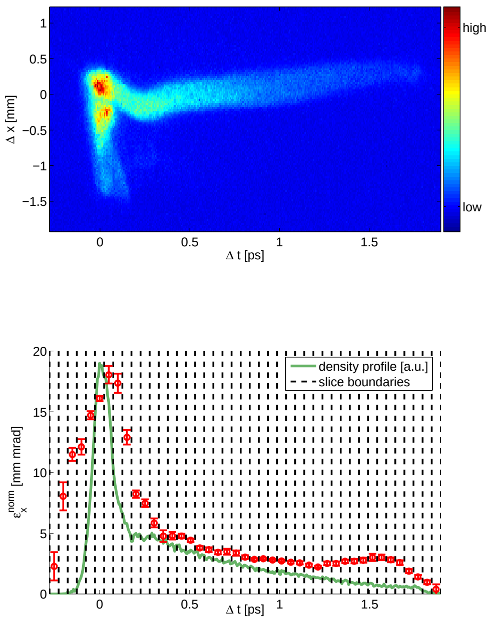

Figure 5: OTR image of a bunch during the quadrupole scan (top) and 1σ slice emittance along the bunch (bottom). In the bottom image, the slice boundaries and the density profile are drawn in.

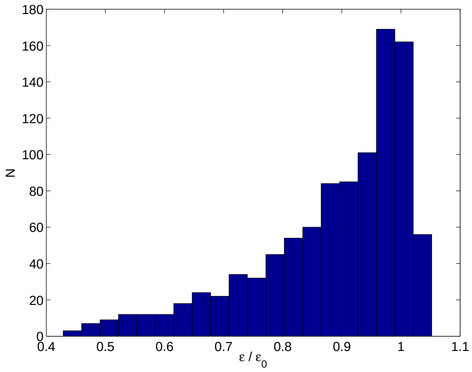

Figure 6: Result of a Monte Carlo simulation with 1000 seeds for the relative emittance error assuming 3 % peak to peak quadrupole gradient errors.

width of $\sim$0.2 % as measured in the spike, the emittance would have to be about $\sim$5 μrad to obtain the observed SASE power [8].

One contribution to this increase in slice emittance is due to a substructure in the horizontal profile of slices in the high current region. For certain quadrupole settings, two separate density maxima appear, as can be seen on the bunch image in Fig. 5. This suggests that there are two islands with high charge density in the horizontal phase space distribution, each for its own having a smaller emittance. Assuming that these density maxima correspond to the observed maxima in the energy profile of the head, the horizontal displacement of the two density maxima may be explained by dispersion in the order of 50 mm, which is a possible value at this location. The dispersion caused by the kicker amounts only to $\sim$10 mm and does therefore not explain this behaviour. In case CSR forces significantly contribute to the separation of the energy maxima, this would lead to a horizontal displacement as well. However, we have no proof yet that there is a connection between the observed structures in the energy profile and the horizontal profile.

Another contribution may come from a systematic error of the absolute emittance values. The accuracy is mainly determined by quadrupole gradient errors, since six quadrupoles have been used for the scan. Figure (6) shows the result of a Monte Carlo simulation for 3 % peak to peak errors of all quadrupole gradients (independently), which is a rather pessimistic assumption. The probability of having an error larger than 30 % is accordingly 15 %. The ratios of the given slice emittance values are not affected by gradient errors.

The shown results for the slice emittance suggest that a reasonable analysis of the emittance in the high current region can, at least for the time resolution given here, only be done by reconstructing the transverse phase space distribution. A main goal for the future is therefore to apply phase space tomography methods. Moreover, quantitative comparisons with simulations using ASTRA and CSR-Track will be done.

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