MEASUREMENT AND ANALYSIS OF CSR EFFECTS AT FLASH

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Abstract

The vacuum-ultra-violet free electron laser in Hamburg (FLASH) is a linac driven FEL. High peak currents are produced using magnetic bunch compression chicanes. Such peak currents are required for the SASE process in the undulators. In these magnetic chicanes, the energy distribution along an electron bunch is changed by effects of Coherent Synchrotron Radiation (CSR). Energy changes in dispersive bunch compressor chicanes lead to transverse displacements. These CSR induced displacements are measured using a transverse deflecting RF-structure. Recent experiments and simulations concerning the charge dependence of such transverse displacements are presented and analysed.

INTRODUCTION

Electron bunches in magnetic bunch compressor chicanes are subject to CSR self-forces. CSR induced energy changes along the bunch give rise to different trajectories for different longitudinal slices. Measurements of such effects were done at FLASH in 2006 [1][6]. We present results of CSR induced centroid shift measurements, in the first chicane, as a function of bunch charge.

For an undisturbed measurement of CSR effects, space charge fields are reduced by over-compressing the bunch. The longitudinal energy correlation (chirp) introduced in the accelerating module upstream of the first bunch compressor chicane is chosen to reach minimum bunch length and a peak current of about 1.2 kA toward the end of the second magnet in the chicane. Due to over-compression, the bunch will exit the chicane with a length comparable to its incoming length of about 2 mm RMS, corresponding to about 50 A peak current (see Fig. 1). The integrated effect of space-charge from the exit of the chicane to the observation point ≈ 60 m downstream is then small compared to the CSR effects.

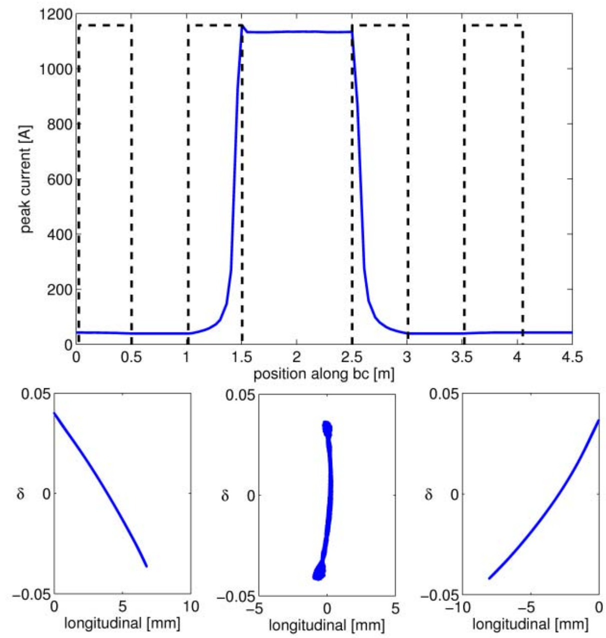

Figure 1: Top: Beam current along the bunch compressor chicane in over-compression mode. Dipoles are indicated as dashed boxes. Bottom: longitudinal phase space at the entrance, the middle, and the end of the bunch compressor.

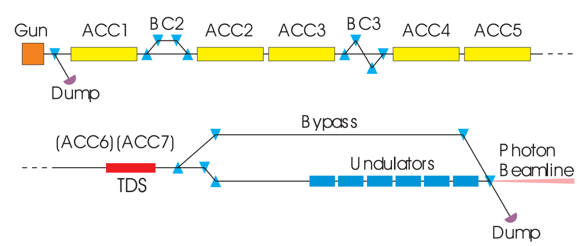

Figure 2: Sketch of FLASH. The blue triangles indicate dipole magnets, the yellow boxes symbolise TESLA accelerator modules.

MEASUREMENTS

A layout of FLASH is given in Fig. 2. We vary the phase offset of acceleration module ACC1 and keep the beam on crest in the modules ACC2/3 and ACC4/5. The expected CSR effects are created in BC2. Downstream, the transverse deflecting RF-structure (TDS) is used to analyse the longitudinal-horizontal beam profile. The experimental setup is as in [1][6].

Starting from a stable SASE working point, we achieved good transmission of the beam in the over-compression range ($\varphi_{ACC1} = 23^\circ - 26^\circ$), while keeping the beam energy constant by adjusting the RF-amplitude.

To optimise the resolution of the measurements, a special beam optics between BC2, the transverse deflecting cavity and the screen is used.

To ensure a proper optics set-up, the emittance and Twiss parameters of the beam were measured in the diagnostic section downstream the first bunch compressor [7]. The measured Twiss parameters are used to determine corrections to the five quadrupoles upstream of this diagnostic section, after BC2, to achieve a matched beam optics in the diagnostic section FODO lattice.

Due to space charge effects in the injector, the beam optics depends on the bunch charge. To ensure a good transmission up to the transverse deflecting cavity, the matching in the DBC2 section was redone for every bunch charge.

IMAGE ANALYSIS

The measured longitudinal-horizontal beam profiles are analysed to obtain information about the general beam dynamics and CSR effects in BC2. We observe a horizontal deformation of the beam profile (see Fig. 3).

In the first step of the analysis, we determine the maximal horizontal displacement of the centroid curve along the bunch and use it as a measure for the strength of the CSR interactions. This maximal centroid displacement is related to the maximal energy loss per longitudinal bunch slice due to CSR in BC2.

Each picture is divided into slices along the longitudinal axis. Only the central part of the picture is analysed. The head and tail sections are omitted because of the noise in these low charge regions.

The horizontal charge profiles of these slices are calculated. Within these horizontal charge profiles the centre position has to be determined. The maximum or the centre of mass can be used for such a definition. The centre of mass within such a slice is strongly influenced by noise in the empty regions of the picture, drawing this value to the geometrical centre of the slice. The maximum of a profile does not underestimate the centroid shifts but is unstable due to noise in the charge profiles. A Gaussian fit to the charge profile is also not completely appropriate to our situation. The horizontal charge profiles are not Gaussian but asymmetric in the regions of the picture with strong centroid shifts which lead to an underestimation of the centre.

A double Gaussian

$$f(x) = a_1 e^{-\left(\frac{x-a_2}{2a_3}\right)^2} + a_4 + a_5 e^{-\left(\frac{x-a_6}{2a_7}\right)^2} \qquad (1)$$

is used to fit the data. As initial values for the fit of a_2 and a_6 we use the maximum and the mean of the transverse charge profile. a_2 is then a good choice for the centre position. It is close to the maximum but more stable than the position of the maximum value.

The centre position of each slice together with the mean of its longitudinal position defines the centroid curve. The centroid curves corresponding to different fit methods are shown in Fig. 3.

In general, the bunch does not line up exactly parallel to the screen axis (see next section). The linear correlation of the different centroid curves, as indicated by the green line in Fig. 3, is subtracted.

After subtraction of the tilt the horizontal peak to peak shifts of the centroid curves are calculated. A summary of these data is shown in Fig. 4.

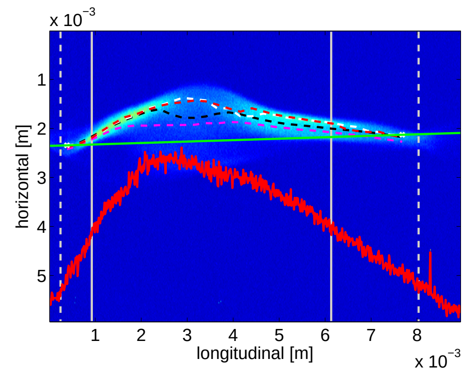

Figure 3: An example of a TDS measurement with bunch charge $q = 0.65$ nC. Longitudinal charge profile (red line), FWHM lines (white solid) and the lines corresponding to "full width of 1/6 maximum" (white dashed) are shown, indicating the omitted head and tail parts of the bunch. Different centroid curves (black - Gaussian fit; white - maximum value; magenta - mean value; red - double Gaussian fit) are plotted as dashed lines. The green line represent an overall linear slope determined from the edge points of the centroid curves. Bunch head is to the left.

SIMULATIONS

Tracking calculations were done to simulate longitudinal-horizontal beam projections at the TDS. Photo emission and beam transport through ACC1 was calculated with the space charge tracking code ASTRA [2]. After ACC1, wake fields are applied as a discrete effective kick [4]. The tracking code CSRTrack [3] is used to simulate CSR effects in BC2. Downstream of ACC1 linear transport theory is used. The actual currents of the quadrupoles were used to calculate the transport matrices. Transverse and longitudinal wake fields are added as perturbations [4]. From the resulting particle distributions at the TDS beam images are obtained by representing each particle with a 2D Gaussian.

The simulated images are analysed with the same methods as the measured ones. In Fig. 4 simulated maximal centroid shifts vs. bunch charge for different threshold intensities are compared with measured data.

To simulate the minimum intensity observable with the camera system, a lower threshold of charge density is used in the image calculation. An image intensity threshold is chosen as a charge density $\rho(T)$ for a given charge T. The intensity of each pixel is reduced by $\rho(T) = T/$(total number of pixels), while negative values are set to zero.

Considering the space charge effects on bunch length and uncorrelated energy spread, one can predict the behaviour of peak current, and thus the centroid shift, with increasing charge. The peak current is not increasing linearly with charge, it saturates beyond 1 nC and for higher total bunch charges, the peak current is decreasing.

Two effects play a role here. First the bunch length

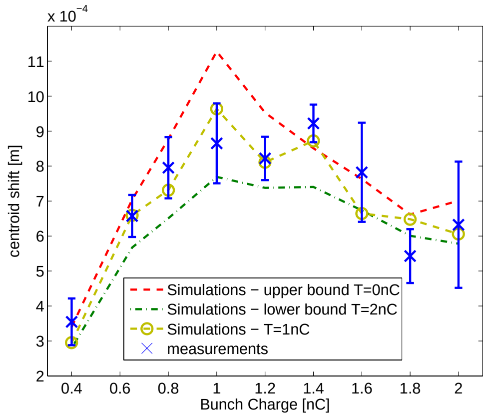

Figure 4: CSR induced centroid shifts as a function of bunch charge. The measured centroid shift is plotted and compared with the simulated obtained from the image analysis for three different image intensity cutoffs.

increases with higher bunch charge due to space charge forces in the RF-Gun, which reduces the charge density and thus the peak current. Second, the space charge interaction in the injector increases the uncorrelated slice energy spread towards higher bunch charges. Due to this increase of the energy spread the width of the charge spike after the chicane is increased. As a result the peak current is reduced even further. While the maximum centroid shift is an important property to identify the strength of the CSR effects, it is not sufficient for the analysis of the beam dynamics. Hence, in a second step of this analysis, the whole centroid curves are compared with simulated data.

The comparison of the measured and simulated centroid curves is summarised in Fig. 5. The measured curves are determined using the Gaussian method described earlier. Error bars are calculated as the standard deviation using the set of 20 pictures taken at each machine setting and a systematic error of the image analysis algorithm.

Different self-field effects act on the beam and cause additional distortions downstream of BC2. A model of transverse wake fields in the acceleration modules ACC2 and ACC3 is included to simulate the observed beam tilt. Together with the spurious dispersion [5] this has an important impact on the centroid curve tilt.

Cavity misalignment and cavity tilts inside an acceleration module yield similar transverse wake fields as a beam offset. On the other hand, the effect of the transverse wake fields and of horizontal dispersion is similar. Images from the TDS can not distinguish between transverse deformations caused by transverse wakes induced by an orbit offset and horizontal dispersion.

Vertical dispersion leads to changes in the longitudinal profile observed at the screen after the TDS because the TDS streaks the longitudinal beam axis in vertical direction. Therefore, one can not distinguish between vertical dispersion at the TDS and errors in the longitudinal dispersion of the transport matrices or phase errors in ACC2-ACC5.

In this sense, the vertical dispersion and the horizontal beam position offset assumed in these simulations are effective parameters, which can not be directly be identified with the real properties of the beam orbit during the measurements.

Other studies on orbit errors and spurious dispersion give a reasonable upper limit estimate of these effects. Orbit errors up to 10 mm and spurious dispersion up to 200 mm have been measured in 2006 [5]. With assumptions of this order the simulated centroid curves can be matched to the measured ones (Fig. 5).

SUMMARY AND OUTLOOK

We did extensive studies on the beam dynamics of FLASH using both numerical simulations and experiments. In normal SASE operation the overall effects on the beam are complicated due to a commingling of different self-field effects, like space charge, CSR, and wake fields. Studies on CSR effects are done in an special over-compression mode. In this compression scheme CSR interactions are the dominant self-field effect.

A quantitative comparison of CSR simulations and measurements was done with a dedicated experiment. CSR induced energy loss throughout the bunch can be observed as a horizontal sag on the TDS screen. The measurement was performed for different bunch charges to compare parameter dependencies with those predicted by simulations. The magnitude of the effect is expected to be up to 130 keV, leading to a trajectory offset of up to 1 mm after the bunch compressor chicane. With proper settings of the optics between the chicane and the TDS (involving 4 more accelerating modules, the 2nd bunch compressor, diagnostic and matching sections) the sag in the longitudinal-horizontal beam profile is of the same order. The sag (i.e. the largest offset of the slices from the nominal position) is derived for different bunch charges. The sag gets smaller for large bunch charges because the bunch length and the uncorrelated energy spread at the entrance of the bunch compressor increases, resulting in a smaller maximal peak current inside the chicane.

A numerical model of the FLASH linac with the same conditions as the real machine was constructed. Despite the limited knowledge of all machine parameters, a good agreement between numerical results and experimental data was achieved. We demonstrated that the numerical tools as well as the beam diagnostics at FLASH are suitable for quantitative studies on CSR.

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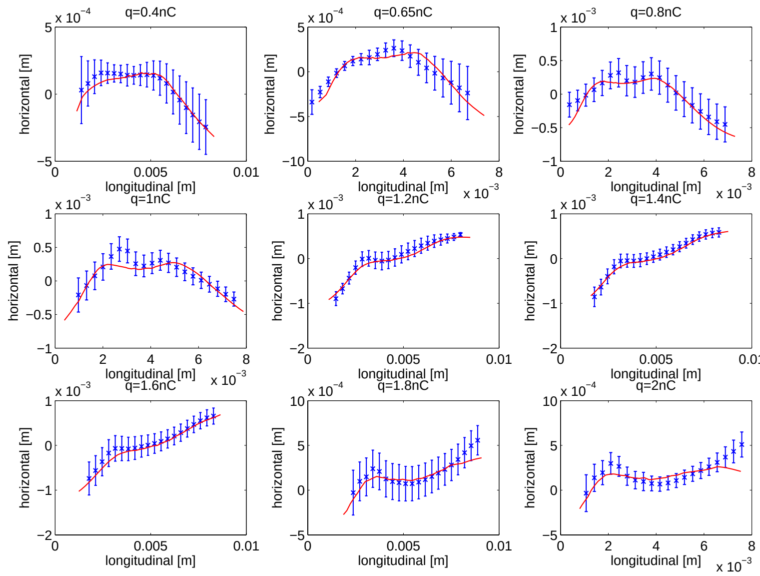

Figure 5: Comparison of centroid curves obtained from measurements (blue) and simulations (red). ACC1 phase offset is $\varphi = 24.9°$. The centroid curves obtained by the image analysis of measured profiles are shown. Bunch heads are to the left.

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