LONGITUDINAL BEAM DIAGNOSTICS APPLICATION OF SYNCHROTRON RADIATION AT FLASH

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For the operation of the FLASH free electron laser at DESY, Hamburg, tools to measure the longitudinal charge distribution and especially its stability over time are important for efficient machine running. Several techniques using both coherent far-infrared and incoherent visible synchrotron radiation from the FLASH bunch compressor chicanes are summarized and compared in this paper.

MEASUREMENT WITH SYNCHROTRON RADIATION AT THE FIRST BUNCH COMPRESSOR

The TOSYLAB[1] beam line at FLASH transports the full spectrum of synchrotron radiation (except for a gap due to a crystalline quartz window) from the end of the first bunch compressor to a laboratory outside of the accelerator tunnel [1], where several different analysis techniques have been compared.

Analysis of Coherent Radiation

To asses the longitudinal charge distribution from the far-infrared radiation spectrum, the relations for coherent radiation are employed. A bunch of N electrons radiates a spectrum according to

$$\frac{\mathrm{d}U}{\mathrm{d}\lambda} = \left(\frac{\mathrm{d}U}{\mathrm{d}\lambda}\right)_1 \left(N + N(N-1)\,|F(\lambda)|^2\right), \qquad (1)$$

where $(\mathrm{d}U/\mathrm{d}\lambda)_1$ is the single-electron spectrum and the longitudinal bunch form factor is

$$F(\lambda) = \int_{-\infty}^{\infty} S(z) \exp\left(\frac{-2\pi \mathrm{i}}{\lambda} z\right) \mathrm{d}z. \qquad (2)$$

$S(z)$ is the normalized longitudinal charge distribution. Transverse effects are ignored in this formulation (for some results on this issue, see [2]).

These relations allow within certain limitations a reconstruction of the charge distribution from the emitted radiation spectrum via phase retrieval techniques[3, 4]. The method has been employed at FLASH using a Martin-Puplett interferometer [5] and compared to a direct time-domain measurement with a streak camera, see Fig. 1. Within the streak camera resolution of about 500 ps, there is good agreement.

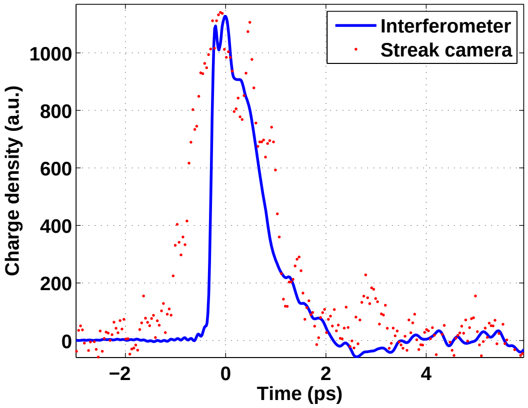

Figure 1: Charge distribution of electron bunches measured using an analysis of coherent far-infrared synchrotron radiation and and with a streak camera using the visible, incoherent radiation.

Streak Camera with Incoherent Visible Radiation

The previous measurement has been performed at so-called maximum compression of the first bunch compressor. The compression of the electron bunches is adjusted by the off-crest phase of the accelerating module in front of the compressor. The ensuing energy chirp results in bunch length changes from path length variation due to the R_{56} of the magnetic chicane. With little compression, the far-infrared radiation intensity is too small to apply coherent radiation techniques. With a streak camera, a measurement of the bunch length versus this off-crest phase is however possible over the full range, being limited only by its resolution. Such a measurement is shown in Fig. 2.

Incoming Bunch Length from Compression Scan

One way to reference the a priori arbitrary module phases at FLASH is a so-called compression scan. A detector measuring the total (wavelength-integrated) far-infrared intensity is used to measure the signal of, for example, synchrotron radiation[2] as a function of the phase of the accelerating module. The shorter the bunch gets, the higher the total emitted intensity. The shape of the resulting curve depends on the incoming charge distribution in front of the bunch compressor.

Such a measurement is shown in Fig. 3, together with the result from a calculation taking into account the R_{56} of the

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[2] The same works also with transition radiation.

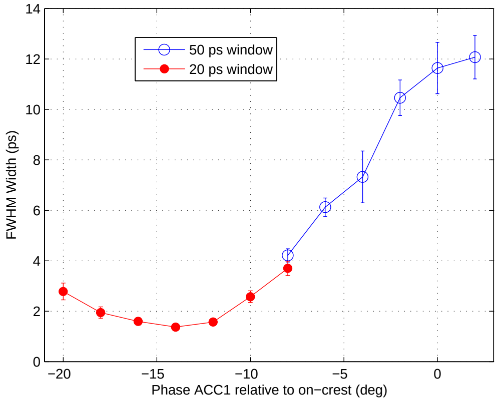

Figure 2: Bunch length measured with a streak camera as function of the acceleration phase that controls the bunch compression.

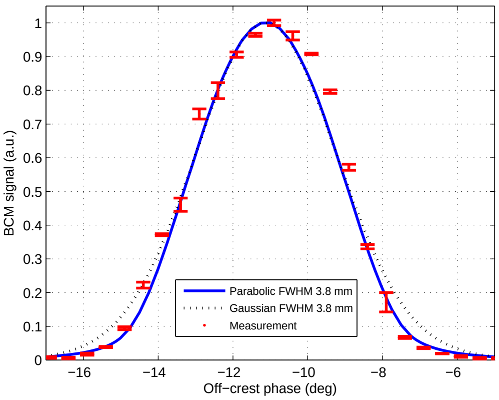

Figure 3: Compression scan and result of a simulation assuming two different initial charge distributions.

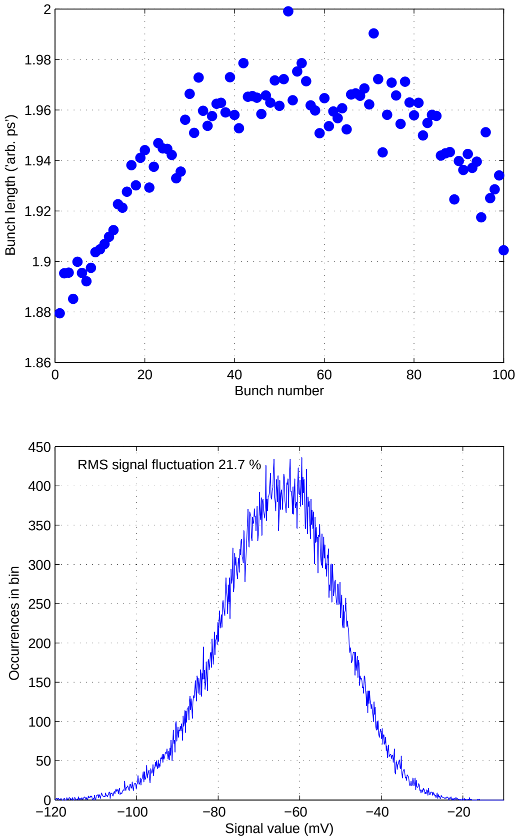

Figure 4: Bunch length deduced from analysis of intensity fluctuations (top) and histogram of signal intensities of the first bunch (below).

bunch compressor and the energy chirp from the module. The resulting bunch shape after the compressor is calculated considering linear beam optics, and then the form factor is deduced. The detailed frequency dependence of the single-electron spectrum in (1) does not influence the result significantly, therefore a flat spectrum is taken for simplicity. Assuming a parabolic shape, as expected from beam simulations, a good fit to the measured data is obtained for an incoming bunch length with FWHM 3.8 mm or 12.7 ps. This is in relatively good agreement with the streak camera result for 0° off-crest phase.

Analysis of Intensity Fluctuations

Information on the bunch length is also encoded in the statistical fluctuation of the incoherent synchrotron radiation intensity [6]. In [7], a simple analysis method employing only a narrow-band filter and an intensity detector has been proposed. This method has been implemented at the same beam line used for the measurements above. A result obtained during SASE operation of FLASH is shown in Fig. 4. The jitter within the curve gives an estimate of the resolution of the method. It must be noted that the absolute values are calculated with the assumption of a Gaussian charge distribution and a Gaussian filter curve. The bunches at FLASH when compressed are asymmetric, therefore the absolute bunch length values have to be regarded with caution. The shape of the distribution, however, agrees well with structures seen on the compression monitors. The accelerating phase for this measurement was 6° from on-crest. From Fig. 2, the rms bunch length is about 2.5 ps, in reasonable agreement considering the assumption of Gaussian bunch.

The bunch length σ is deduced from the measured intensities using the relation [7]

$$\sigma = \frac{1}{2\sigma_{\text{filter}}}\sqrt{\frac{< W >^4}{\sigma_W^4} - 1},$$

where σ_{filter} is the filter bandwidth. The individual measured intensity values W, baseline subtracted, have to be corrected for charge fluctuations (influencing the intensity proportional since only incoherent radiation is considered). The resolution of the baseline and charge measurement has to be accounted for to get the true fluctuation of the synchrotron radiation intensity σ_W.

In the example shown, a filter with centre wavelength 670 nm and a FWHM of 3 nm was used. The rms fluctuation of the intensity of 22% is much larger than the uncertainties of the charge measurement (0.5%) and the base line determination (1%). The stability of the high voltage power supply[3] for the photomultiplier[4] is better than 50 mV, results in a fluctuation, through the gain curve of the photomultiplier, of below 4×10^{-4} and can be neglected.

The measurement was made over 100000 shots of the machine, taking almost six hours at the repetition rate of 5 Hz. The measurement time for a given resolution can be reduced further to some degree by using a narrower filter, increasing thereby the fluctuations, but clearly this technique is not an online measurement tool. However, it allows monitoring the length of all bunches with a relatively simple set-up, and also works on-crest.

Reducing the filter bandwidth comes at the cost of less light intensity, and ultimately the photon counting statistics will overlay the emission statistics and bury the length information. For the measurement presented, about 5000 electrons are emitted by the cathode of the photomultiplier, contributing therefore on the percent level to the fluctuation.

MEASUREMENT WITH SYNCHROTRON RADIATION AT THE SECOND BUNCH COMPRESSOR

An additional exit port at the last bending magnet of the second bunch compressor (BC3) allows to monitor the synchrotron radiation directly after the second compression stage. Extending the scope of the CSR ports discussed so far, this port is equipped with a synthetic diamond window instead of cristalline quartz. It does not constrain the spectral range and allows to measure synchrotron radiation from the visible down to the far infrared regime. From spectroscopic measurements of cohererent transition radiation [8] it is known that the leading compression spike of the charge distribution radiates predominantely in the regime between 15 µm and 40 µm, a wavelength regime which is not transmitted by quartz windows. The CSR intensity observed at the new BC3 port is therefore expected to be much more sensitive to the details of the compression process. A first confirmation of this is shown in Fig. 5. The CSR intensity observed at a ”conventional” CSR port (top figure, ECOLL-CSR, equipped with quartz window) follows linearly the intensity of a diffraction radiator for bunch charges between 0.4 nC and 1 nC and both increase monotonically with charge. These devices are predominantely sensitive for wavelength above 100 µm and are perfect to monitor the overall compression of the bunch. In contrast to this, the intensity at the BC3-CSR port (bottom figure) exhibits a much more complex charge dependence since the compression and the charge density of the leading spike is very sensitive to collective phenomena dominating the behaviour for larger bunch charges. It is planned to equip this port with a spectrally resolving detector for compression monitoring and as input for the intra bunch train feedback system.

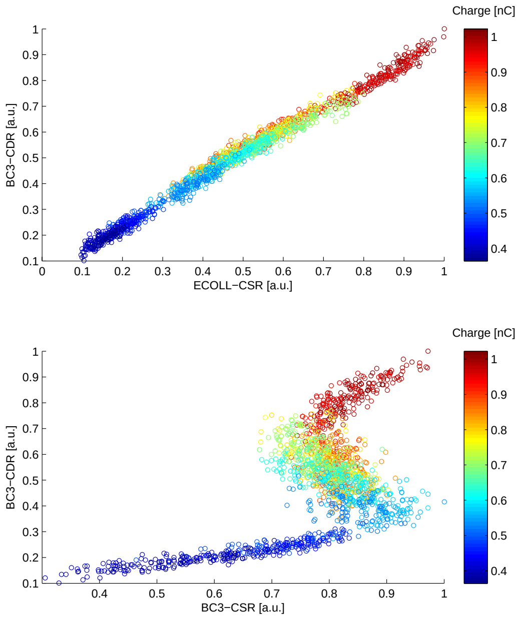

Figure 5: Correlation of signals from different compression monitors as function of the bunch charge.

REFERENCES

[1] O. Grimm et al., Proceedings of EPAC 2004, Lucerne, 5-9 July 2004, p. 2586

[2] O. Grimm et al., this conference (TUPC030)

[3] R. Lai, A.J. Sievers, Nucl. Instr. Meth. A397(1997) 221

[4] O. Grimm, P. Schmüser, TESLA-FEL 2006-03 (2006)

[5] L. Fröhlich, DESY-THESIS 2005-011 (April 2005)

[6] J. Krzywinski et al., TESLA-FEL 1997-03 (1997)

[7] F. Sannibale et al., Proceedings of PAC 2007, Albuquerque, 25-29 June 2007, p. 2661

[8] C. Behrens et al., this conference (MOPC029)

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[3] iseg NHQ 206L

[4] Valvo XP2008/UB/10