Bunch Length and Phase Stability Measurements at the TESLA Test Facility

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Electron bunch lengths and time jitters have been measured with sub-ps resolution at the TESLA Test Facility at DESY. Synchrotron radiation emitted from a dipole magnet reflects the longitudinal charge distribution of the electron bunch and can also be used as a timing reference of the radiation pulses produced by the free-electron laser. For sub-ps time resolution, dispersion effects of the spectrally broad-band synchrotron radiation have to be suppressed. The phase stability of the FEL pulses with respect to the radio-frequency master oscillator has been studied with a streak camera operating in synchroscan mode.

1. Introduction

Single-pass free-electron lasers (FEL) operating in self-amplified spontaneous emission (SASE) mode are promising sources for the generation of tunable, short-pulse, laser-like radiation in the VUV and X-ray region (Ref. [1] and references therein). The SASE process requires a high-quality electron beam and a long, precise undulator. Presently, only laser-driven radio-frequency (rf) electron guns in combination with bunch compression schemes can produce ultra-short bunches with high peak currents and small emittances. Much work has been devoted to the development of diagnostic techniques for electron bunches with sub-ps duration (for an overview see Refs. [2,3]). In this paper, we report on electron bunch length measurements at the TESLA Test Facility (TTF) with a high-resolution streak camera.

In order to exploit the short pulse length of the FEL radiation, an optical fs laser system will be synchronized to the TTF FEL for sub-ps two-colour pump-probe experiments [4]. A crucial issue is the synchronization of the optical laser to the FEL pulses [5–8] with an accuracy of approximately the pulse length (200 fs (rms)). To fulfil such a requirement, the time (or phase) stability of the FEL pulses must be on the same timescale. In this paper, we report on phase stability measurements of the electron bunches with respect to the rf of the linear accelerator that dives the FEL. Under SASE conditions, the phase jitter of the electron bunches is a fingerprint of the time jitter of the FEL pulses.

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2. Experimental set-up

A schematic overview of the main components of the TTF (phase 1) is depicted in Fig. 1. Electron bunches were generated from a Cs_2Te cathode located in an L-band (1.3 GHz) rf gun. The cathode was illuminated by frequency-quadrupled UV laser pulses (262 nm) of a mode-locked Nd:YLF laser. The laser has been synchronized to the rf and its measured (rms) pulse length in the UV is 7(1) ps [9]. The rf gun is followed by a super-conducting TESLA cavity which boosts the electron energy up to 16.5 MeV. Two super-conducting accelerating modules (ACC1 and ACC2) further accelerate the electron bunches up to 300 MeV. Two magnetic chicanes (BC1 and BC2) have been installed to compress the electron bunches: BC1 is located downstream from the booster cavity and BC2 between the two accelerating modules. For a detailed discription of the set-up refer to Ref. [1].

Synchrotron radiation (SR) emitted by the dipole magnet has been utilized to study the electron bunch length and the phase stability with respect to the rf master oscillator. The temporal distribution of the SR pulse, which mirrors the longitudinal charge dis-

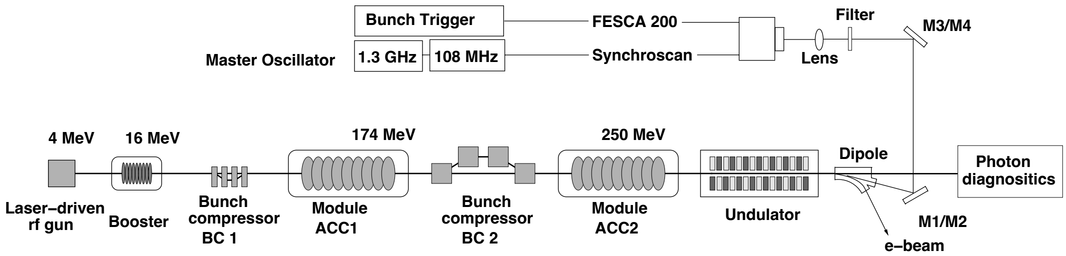

Figure 1. Schematic layout of the TTF (phase 1). The total length is about 100 m (not to scale).

tribution of the electron bunch, has been measured with a streak camera. The spectrally broad-band SR has been transported by four plane Al mirrors from the accelerator tunnel through 15 m of air to a diagnostic hutch and focused with an achromatic lens ($f = 0.2$ m) onto the entrance slit of the streak camera. The CCD image produced by the streak camera has been binned in order to get the temporal profile.

To reduce chromatic effects, a narrow band-pass filter has been employed [10]. Figure 2 demonstrates the broadening of the profiles which is mainly due to dispersion effects in the vacuum window of the dipole magnet and the focusing optics of the streak camera. The profiles have been recorded during FEL operation in the saturation regime for three different radiation bandwidths. The asymmetric profile is only resolved if a narrow band-pass filter is used. The width of the leading peak has been determined to be 0.6(1) ps (rms) if the filter $\lambda = 515 \pm 5$ nm (Fig. 2(c)) is used and 1.0(1) ps (rms) if the filter $\lambda = 500 \pm 40$ nm (Fig. 2(b)) is used. Without applying any filter, the leading peak smears out completely (Fig. 2(a)).

The FESCA-200 camera [11] employed for the bunch length measurements has a resolution of 0.22 ps (rms) at the second fastest streak speed of 50 ps/10.29 mm. A bunch signal with a jitter of about 50 ps served as a trigger for the streak.

A streak camera operating in synchroscan mode [12] was utilized for the study of the phase jitter of the FEL pulses. Instead of using a trigger signal, the streak repetition rate of the camera was synchronized to the sub-divided 108 MHz of the rf master oscillator of the accelerator. The rf signal was transported from the master oscillator located in the injector region to the synchroscan camera by a temperature stablilized, 100 m long cable.

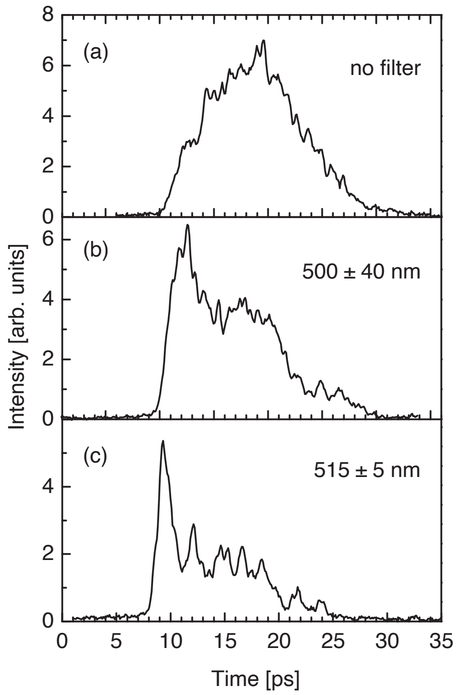

Figure 2. Temporal profiles of the synchrotron radiation pulses emitted by the dipole magnet. The profiles have been recorded for different bandwiths of the radiation. The profile in part (c) is an average of six single-shot profiles.

3. Bunch length measurements

Figure 3 compares the longitudinal bunch profiles measured for three different phase settings of module ACC1 with the results of numerical simulations. The experimental data represent the longitudinal charge distribution of single electron bunches. For these measurements, a filter with a bandwidth

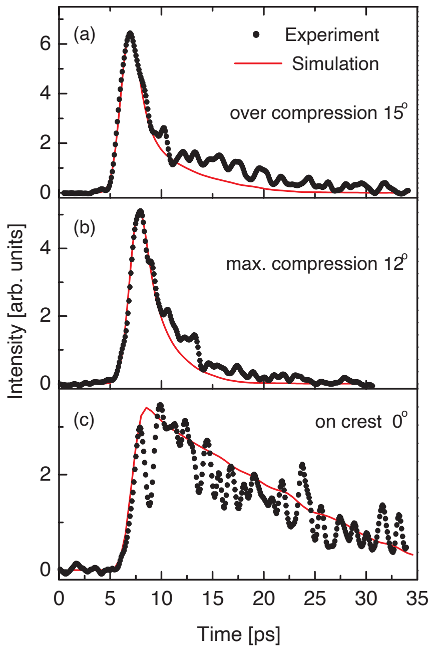

Figure 3. Profiles of the longitudinal charge density distribution of single electron bunches for different phase settings of the accelerating module ACC1. Dots: experiment; solid line: simulation.

$\Delta\lambda = \pm 40$ nm and a streak speed of 50 ps/10.29 mm have been used. Bunch compressor BC2 was operated at its nominal bending angle of 20° whereas BC1 was switched off during these measurements.

The beam dynamics was simulated with the set of computer tracking codes Astra [13] and Elegant [14]. The former programme includes a mesh-based space-charge algorithm and is used for the beam generation and transport at low energies. The latter programme is used to track through the accelerating module ACC1 and the bunch compressor BC2. It incorporates a simple model for bunch self-interaction induced via coherent synchrotron radiation (CSR) in the bunch compressor. The profiles generated by the simulations have been convolved with Gaussian profiles to account for the experimental resolution.

All profiles exhibit a distinct asymmetry. Figure 3(b) shows the profile at maximum compression which has experimentally been determined to be $12(1)^\circ$ off maximum acceleration (on crest). The profile comprises a narrow leading peak and a long tail. The width of the peak amounts to $0.9(1)$ ps. This corresponds to an electron bunch length of $\sigma_z = 0.27(3)$ mm. The longitudinal bunch profile presented in Fig. 3(c) has been recorded for a module ACC1 phase at on-crest acceleration (0°) whereas the profile in Fig. 3(a) is slightly overcompressed (15°). The rms bunch lengths of the entire profiles are in good agreement with the results of previous measurements [15] in which the asymmetric shape of the profiles could not be resolved due to a limited resolution at that time.

Since the bunch length is not negligible compared to the rf wavelength, off-crest acceleration for maximum bunch compression induces a curvature in the longitudinal phase space distribution (see Fig. 1 in Ref. [16]). This together with the small uncorrelated energy spread of less than $\approx$ 20 keV give rise to a spike in the longitudinal charge distribution. The longitudinal slices with extremely high peak currents (1–1.5 kA) lead to the SASE process producing ultrashort FEL pulses in the fs regime (≈ 100 fs) with GW peak powers [1,16].

4. Phase jitter measurements

Due to the dispersive sections (bunch compressors) in the accelerator, an energy variation of the electron beam results in a time jitter of the electron bunches and hence the FEL pulses. For instance, an energy variation of $\Delta E/E = 0.1\%$ would lead to a time jitter of the electron bunches with respect to the rf of $\Delta t = R_{56}/c \cdot \Delta E/E = 0.8$ ps behind bunch compressor BC2 with a longitudinal dispersion of $R_{56} = 227$ mm.

To study the time jitter between subsequent bunch trains with respect to the rf master oscillator, the accelerator was operated with single bunches at a 1 Hz repetition rate. A shot-to-shot variation of the centre position of the profiles directly reflects the time jitter with respect to the rf master oscillator. A histogram of the center positions of 100 subsequent pulses together with a Gaussian fit is shown in Fig. 4. The rms width of the Gaussian fit amounts to $0.7(1)$ ps. However, the latter value can only be regarded as an upper limit for time jitter, since it corresponds to the camera resolution.

A statistical energy jitter that results in a time jitter of about 1 ps could not be corrected for in a synchronization scheme. In this case it is necessary to mea-

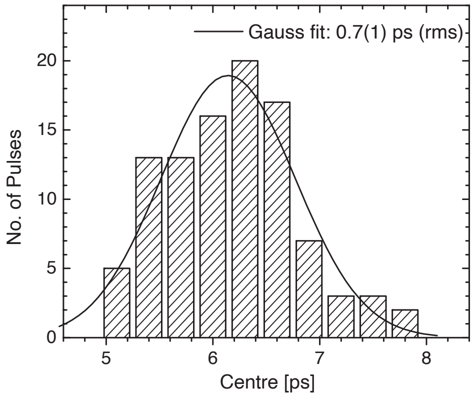

Figure 4. Histogram of the centre positions of 100 subsequent electron bunches. The width of the Gaussian fit amounts to 0.7(1) ps (rms).

sure the exact timing of the FEL and optical pulse (see Sec. 1) for each shot and to bin the data for different time delays. An upgrade of the present set-up will measure both the FEL and optical pulse on a single streak of a high-resolution FESCA-200 streak camera [5–8]. The time difference between the pulses will then provide the necessary information for implemanting a feedback correction for slow drifts.

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REFERENCES

1. V. Ayvazyan *et al.*, Eur. Phys. J. D **20** (2002) 149.
2. G.A. Krafft, Proc. DIPAC 97, Frascati, (1997) 48.
3. M. Geitz *et al.*, Nucl. Instr. and Meth. A **445** (2000) 343.
4. Project within the Fifth Framework Programme of the European Comission under contract No. HPRI-CT-1999-50009.
5. R.J. Stanley *et al.*, Opt. Commun. **115** (1995) 87.
6. M. Uesaka *et al.*, J. Nucl. Mat. **248** (1997) 380.
7. G.M.H. Knipples *et al.*, Opt. Lett. **23** (1998) 1754.
8. Y. Tanaka *et al.*, Nucl. Instr. and Meth. A **467-468** (2001) 1451.
9. S. Schreiber *et al.*, Proc. EPAC 2002, Paris, 1804.
10. M. Uesaka *et al.*, Nucl. Instr. and Meth. A **406** (1998) 371.
11. Hamamatsu CS6138 FESCA-2000.
12. Hamamatsu Synchroscan Camera.
13. K. Flöttmann, Astra user manual `www.desy.de/~mpyflo/Astra_dokumentation`
14. M. Borland, APS note LS-287, Argonne National Laboratory IL, USA.
15. K. Honkavaara *et al.*, Proc. PAC 2001, Chicago, 2341
16. V. Ayvazyan *et al.*, Phys. Rev. Lett. **88** (2002) 10482.