BUNCH LENGTH MEASUREMENTS USING A MARTIN-PUPLETT INTERFEROMETER AT THE VUV-FEL

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Abstract

The longitudinal charge distribution of short electron bunches can be characterized by a measurement of their coherent far-infrared radiation spectrum. This paper summarizes recent results obtained at the DESY VUV-FEL linear accelerator by observation of synchrotron radiation with a Martin-Puplett interferometer. The bunch shapes reconstructed with this method show a strong asymmetry with a full width at half maximum of about 1 ps.

INTRODUCTION

The linac-driven Vacuum-Ultraviolet Free Electron Laser (VUV-FEL) at DESY, Hamburg produces short pulses of intense soft X-ray radiation. Because the high gain FEL process depends strongly on a high peak current of the electron bunches, it is necessary to measure and control the bunch length. As a technique for bunch length measurements with sub-picosecond resolution, we analyze coherent synchrotron radiation (CSR) with a Martin-Puplett interferometer. Once the spectrum of the coherent radiation is determined, the form factor and the longitudinal charge profile of the bunch can be reconstructed.

EXPERIMENTAL SETUP

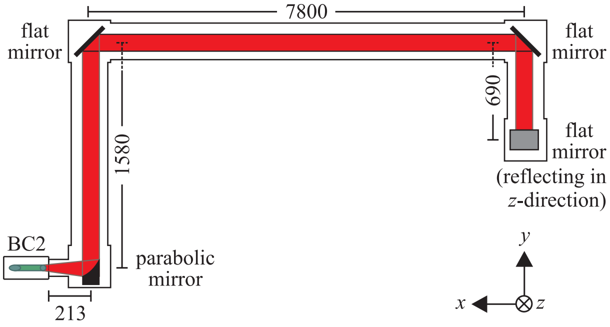

Figure 1: Setup of the CSR transfer line at bunch compressor BC2 (measures in mm)

The CSR beam is extracted from the last dipole magnet of a bunch compressor through a 4.8 mm thick vacuum window. To obtain good transmission properties up to 3.6 THz, a z-cut quartz single crystal has been chosen as the window material. By a series of mirrors, the radiation bundle is parallelized and reflected into a laboratory outside of the accelerator tunnel (Fig. 1). The transfer line can be flushed with dry nitrogen to reduce absorption by water vapor. However, due to the large enclosed volume, it currently takes more than one day to achieve sufficient suppression of the absorption effects. Therefore, preparations are underway to evacuate the beam line.

The Martin-Puplett interferometer[1] (Fig. 2) is a polarizing version of the well-known Michelson version. Grids of gold-coated tungsten wires (thickness 15 μm, distance 45 μm) are used as polarizers, permitting operation of the instrument up to freqencies of at least 3 THz. The far-infrared radiation intensity is measured with two pyroelectric DTGS detectors. Further details on the experimental setup and on the measurements can be found in [1].

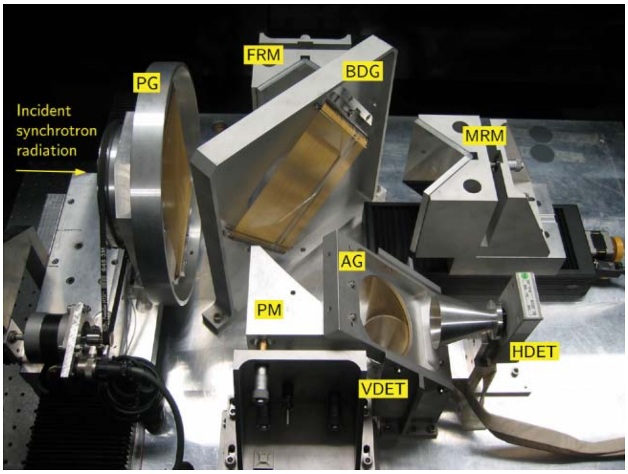

Figure 2: Setup of the interferometer. PG / BDG / AG – polarizer / beam divider / analyzer grid, FRM / MRM – fixed / moveable roof mirror, PM – parabolic mirror, VDET / HDET – detector for vertical / horizontal polarization.

THE RECONSTRUCTION PROCESS

Measuring principle

The direct result of an interferometer scan is a series of data points of the two detector signal amplitudes U_h, U_v versus the time shift between the two partial beams in the instrument. While the interference signal is anticorrelated in the detectors, fluctuations and drifts in the incident radiation intensity affect both signals likewise. Therefore, the normalized *difference interferogram* $\delta = (U_\mathrm{h} - U_\mathrm{v}) / (U_\mathrm{h} + U_\mathrm{v})$ shows a much better signal-to-noise ratio than the single interferograms (Fig. 3 and 4).

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[1] Components manufactured at RWTH Aachen

The power spectrum $I(\omega)$ is obtained by a Fourier transform of the difference interferogram. It is corrected by applying transfer functions for various optical elements of the radiation transfer line. Well understood transfer functions cover the absorption by residual water vapor and the transmission behavior of the quartz window, while important contributions like diffraction losses and detector sensitivity are still under investigation (cf. [4]).

As the 8 mm high vacuum chamber of the bunch compressor imposes an electromagnetic cutoff, frequencies below 275 GHz are almost completely suppressed in the measured spectra. An appropriate asymptotic curve is fitted to the data to replace the missing intensity information.

Form factor analysis

The radiation emitted by a relativistic bunch of electrons is usually incoherent because the particles radiate under random phases. However, at wavelengths longer than the bunch itself, the emission is coherent. If $I_1(\omega)$ is the spectral intensity distribution for a single electron, a bunch of N particles shows the spectrum

$$I(\omega) = I_1(\omega)\left(N + N(N-1)\,|F(\omega)|^2\right)\,, \qquad (1)$$

with $F(\omega)$ denoting the form factor of the bunch. In the case of tangential observation, $F(\omega)$ can be expressed as the one-dimensional Fourier transform of the normalized longitudinal charge density $\rho(t_z)$:

$$F(\omega) = \int \rho(t_z)\exp(-\mathrm{i}\omega t_z)\,\mathrm{d}t_z$$

From a measurement of the spectrum, (1) allows to determine the modulus of the form factor.[2] To recover the missing phase information of the generally complex-valued $F(\omega)$, we use a *Kramers-Kronig relation* as proposed in [2]:

$$\eta(\omega) = \frac{2\omega}{\pi}\int_0^\infty \frac{\ln(|F(\omega')|\,/\,|F(\omega)|)}{\omega^2-\omega'^2}\,\mathrm{d}\omega'$$

It has been verified that this *minimal phase* is a good approximation of the actual phase of the complex form factor for typical bunch shapes (cf. [3]).

Finally, an inverse fourier transform of the form factor gives access to the longitudinal charge distribution of the electron bunch.

Resolution

The limits of the bunch length reconstruction are defined by the spectral range accessible to the measurement. In our case, the low-frequency cutoff limits the maximum length of reconstructible bunch features to about

$$l_{\mathrm{max}} = \frac{1}{2}(275\ \mathrm{GHz})^{-1} \approx 1.8\ \mathrm{ps}\ (550\ \mu\mathrm{m}).$$

Towards high frequencies, the absorption edge of the quartz window at 3.6 THz is a hard limit. Therefore, no structures smaller than

$$l_{\mathrm{min}} = \frac{1}{2}(3.6\ \mathrm{THz})^{-1} \approx 140\ \mathrm{fs}\ (42\ \mu\mathrm{m})$$

can be resolved.

MEASUREMENT RESULTS

Scan during SASE FEL operation

Figures 3 and 4 show the results of a selected interferometer scan[3] during operation of the SASE FEL. As the scan took more than 20 minutes to complete, even comparatively slow drifts of machine parameters are visible in the total CSR intensity. The width of the difference interferogram, 0.51 ps (fwhm), is already a coarse indicator for the bunch length.

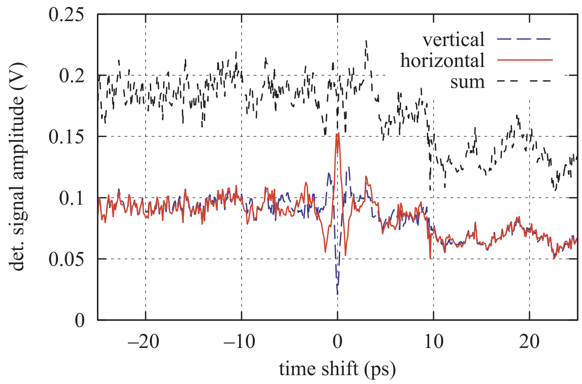

Figure 3: Raw interferograms. Drifts and fluctuations of the CSR intensity are visible.

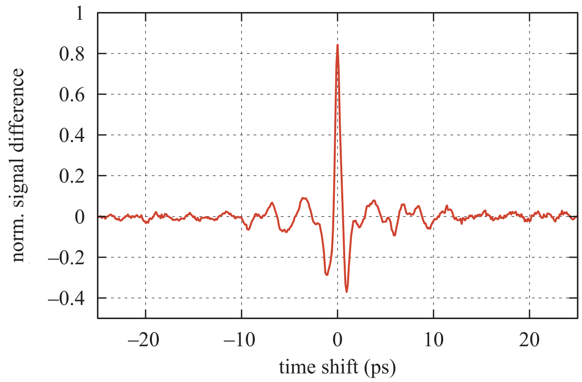

Figure 4: Difference interferogram. The distortions are well suppressed.

The corresponding spectrum (Fig. 5) shows that the measured coherent radiation power has almost no contribution above 2 THz. Even after correction with the known transfer

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[2] This step requires a good knowledge of the single-particle spectrum $I_0(\omega)$. The subject is under continuous study with particle-tracking simulations.

[3] Machine parameters: beam energy 125 MeV, acceleration phase $-5°$, bunch charge 1.2 nC

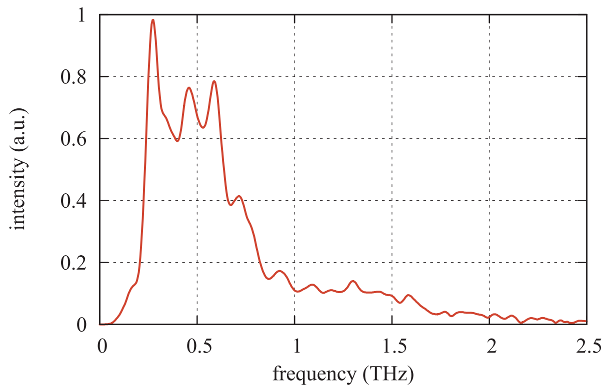

Figure 5: Power spectrum of the observed radiation after correction with the transfer functions.

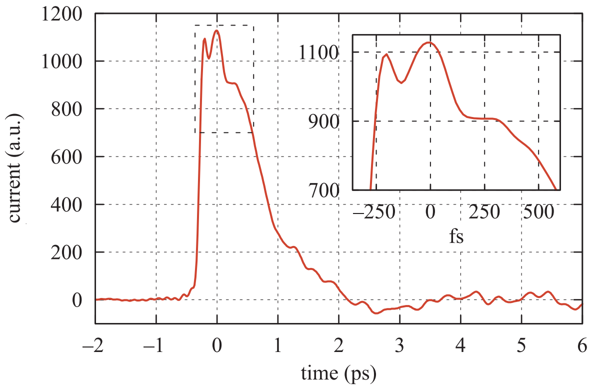

Figure 6: Reconstructed bunch shape. The width is 0.98 ps (fwhm) or 0.50 ps (rms).

functions, the spectrum reveals some unexplained oscillations, which might be an indication for as yet unconsidered effects, e.g. in the detector sensitivity.

The reconstructed bunch shape (Fig. 6) is clearly asymmetric, with a width of 0.98 ps (fwhm) or 0.50 ps (rms[4]). The small structures on top of the bunch have an extent below or very near the resolution limit and should therefore be considered as artifacts.

Various degrees of bunch compression

The main parameter for tuning the compression of the electron beam is the relative phase between the electromagnetic RF wave and the electron bunch. If this phase is zero, the bunch is accelerated "on crest", and no compression takes place in the magnetic chicane. At BC2, maximum compression is found at about -11°. In the intermediate range, the coherent radiation intensity emitted by the bunch is very sensitive to changes of the phase.

Figure 7 shows CSR spectra measured at various acceleration phases. The plot illustrates that no clear correlation between the shape of the spectral distribution and the compression setting can be established. While the total radiation intensity increases with higher bunch compression, this increase is not accompanied by a shift to the high frequency range as expected in the case of a shortening of the coherently radiating part of the bunch.

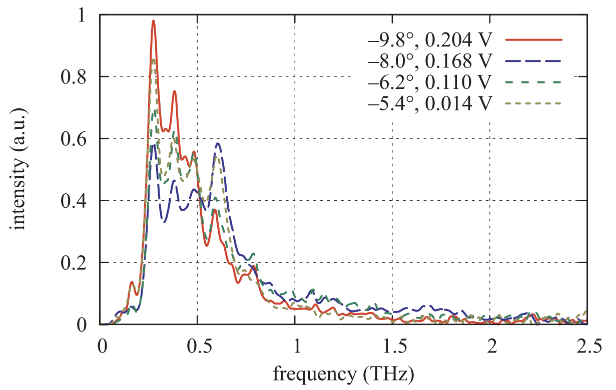

Figure 7: CSR spectra for various acceleration phases. The mean detector signal amplitudes are given.

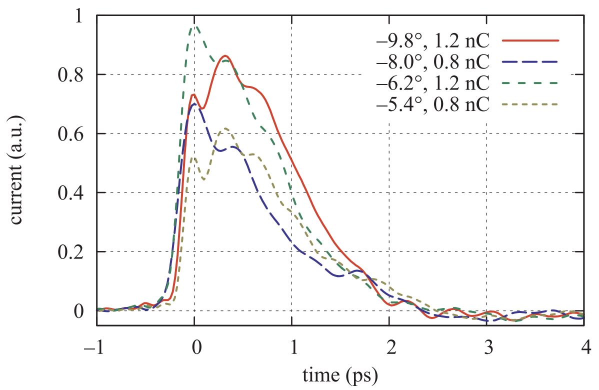

Figure 8: Reconstructed bunch shapes for various compression settings. The curves are scaled according to the respective bunch charge.

From this observation, it is not surprising that also the reconstructed bunch shapes show little dependence on the phase, as seen in Fig. 8. The corresponding bunch lengths are found in Tab. 1 together with the relevant machine parameters.

Table 1: Measurement parameters

Phase (°)	**Energy (MeV)**	**Charge (nC)**	**FWHM (ps)**
−9.8	125	1.16 ± 0.07	1.23
−8.0	127	0.80 ± 0.05	0.92
−6.2	125	1.16 ± 0.07	1.08
−5.4	127	0.81 ± 0.04	1.17

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[4] It should be noted that only points with a current above 5% of the maximum value are included in the calculation of the rms width to remove the influence of noise on the right side of the reconstructed bunch shape.

OUTLOOK

At present, a number of unknown quantities enter into the process of bunch shape reconstruction. To improve the accuracy of the method, especially two points need further investigation:

- The diffraction losses along the beam transfer line should be measured to obtain a reliable transfer function.
- The spectral responsivity of the detectors for far-infrared radiation needs to be determined. First steps in this direction have already been taken (cf. [4]).

At the moment, the low-frequency cutoff of the vacuum chamber constitutes a severe limitation of the achievable resolution. Experiments with different coherent radiation sources may help to widen the accessible spectral range.

REFERENCES

[1] L. Fröhlich, "Bunch length measurements using a Martin-Puplett interferometer at the VUV-FEL", DESY report DESY-THESIS-2005-011 / TESLA-FEL 2005-02, June 2005.

[2] R. Lai and A. J. Sievers, "Examination of the phase problem associated with the determination of the longitudinal shape of a charged particle bunch from its coherent far IR spectrum", Phys. Rev. E, vol. 50, pp. 3342–3344, 1994.

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