FAST BUNCH PROFILE MONITORING WITH THz SPECTROSCOPY OF COHERENT RADIATION AT FLASH

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Abstract

We developed a fast bunch profile monitor based on wavelength-resolved THz detection. An in-vacuum spectrometer with four dispersive gratings and parallel readout of 120 individual wavelength bins provides detailed shot-to-shot information on the bunch shape. The device can be operated in short ($5-44\,\mu$m) and long range ($45-435\,\mu$m) mode to cover the entire longitudinal phase space for compressed bunches of the FLASH linac. Due to the large wavelength range, the electron bunch time profile can be reconstructed reliably in detail using Kramers-Kronig algorithm for the phase retrieval. Performance of the instrument and results compared to direct time domain measurements will be presented for electron bunches down to a few 10th femtoseconds length.

BUNCH PROFILE DETERMINATION

Frequency-domain techniques provide a complementary access to determine bunch structures in the femtosecond regime to the complex and expensive transverse RF streaking time-domain techniques (e.g., Refs. [1, 2]). The profile information is encoded into the spectral intensity of the coherent radiation emitted by a bunch with N electrons

$$\frac{dU_{\mathrm{coh}}}{d\lambda} \approx \frac{dU_1}{d\lambda}\, N^2\, |F_l(\lambda)|^2\ , \qquad (1)$$

where $dU_1/d\lambda$ is the spectral intensity radiated by a single electron and F_l is the complex longitudinal form factor of the bunch, which is the Fourier transform of the normalized line charge density ρ_l:

$$\begin{aligned} F_l(\lambda) &= |F_l(\lambda)|\, \exp\bigl(i\Phi(\lambda)\bigr) \\ &= \int_{-\infty}^{\infty} \rho_l(z)\, \exp\left(-i\, 2\pi z/\lambda\right)\, dz\ . \end{aligned} \qquad (2)$$

A measurement of the coherent radiation spectrum yields the absolute magnitude of the form factor F_l as a function of wavelength Eq. (1) but the phase Φ remains unknown, Eq. (2). Hence the determination of the longitudinal charge distribution by inverse Fourier transformation is not directly possible. The phase information can be obtained with the help of the Kramers-Kronig relation [3]:

$$\Phi_{\mathrm{kk}}(\lambda) = -\frac{2\lambda}{\pi} \int_0^{\infty} \frac{\ln|F_l(\lambda')| - \ln|F_l(\lambda)|}{\lambda'^2 - \lambda^2}\, d\lambda'\ . \qquad (3)$$

It should be kept in mind that a correct phase retrieval from the measured modulus of the form factor is generally not feasible, any reconstruction is neither unique nor bias free. Nevertheless is the retrieved Kramers-Kronig phase Φ_{kk} a useful approximation, the reconstructed bunch shape

$$\rho_l(z) = -2 \int_0^{\infty} \frac{|F_l(\lambda')|}{\lambda'^2}\, \cos\!\left(\frac{2\pi z}{\lambda'} - \Phi_{\mathrm{kk}}(\lambda')\right) d\lambda' \qquad (4)$$

based on it represents the "most compact" current profile compatible with the measured form factor modulus. Since Eqs. (3) and (4) require integration over the full wavelength range, reliable broadband spectral information is mandatory to reach the intrinsic limitations of the algorithm.

EXPERIMENTAL SETUP

We have developed a novel broad-band spectrometer with single-shot capability based on [4]. In the following it is denominated as "coherent radiation intensity spectrometer with 4 stages" (CRISP4). It is part of the instrumentation for longitudinal diagnostics at FLASH [5] as shown in Fig. 1 and is located between the last accelerating module ACC7 and the energy collimator. A fast kicker magnet sends individual bunches from the bunch trains to an off-axis screen. The produced coherent transition radiation (CTR) is coupled out of the accelerator vacuum through a CVC diamond window and guided by an evacuated beam pipe [6] to the spectrometer located in an external laboratory. A transverse deflecting structure (TDS) together with a spectrometer dipole is used to map the longitudinal phase space of individual bunches [7] and was used for benchmarking the spectrometer performance.

With two sets of gratings, which can be interchanged by remote control, either the far-infrared wavelength range from 45 to $430\,\mu$m or the mid-infrared range from 5 to $44\,\mu$m is covered with CRISP4. The spectral intensity is recorded simultaneously in 120 wavelength bins. The key principle of our spectrometer is the use of blazed reflective gratings acting as pre-filters and dispersive elements simultaneously. In the chosen geometry, the gratings disperse radiation in a certain wavelength range into first order with an efficiency above 0.9 while longer wavelengths are reflected in zero order (as from a mirror) with equally high efficiency. Shorter wavelengths have to be filtered out by previous grating stages avoiding higher order effects. This principle leads to the design shown in Fig. 2 with five consecutive gratings from which four are equipped with 30 channel pyroelectric sensors for parallel readout using fast amplifiers and fast analog-to-digital converters (ADCs). A detailed description can be found in [8].

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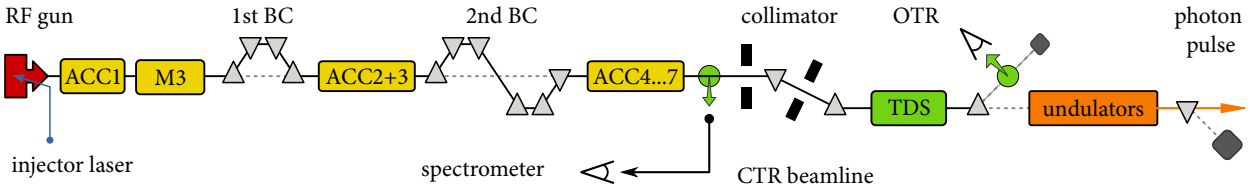

Figure 1: Schematic overview of FLASH: Radio-frequency (RF) gun, superconducting acceleration modules (ACC), third-harmonic module (M3) and two magnetic bunch compressors (BC). The transition radiation screen and the spectrometer are installed behind ACC7. The transverse deflecting structure (TDS) is located in front of the undulator.

One of the key challenges on the road to reliable bunch profile reconstruction through coherent radiation spectroscopy is the absolute calibration of the spectrometer in terms of its spectral sensitivity. Accurate determination of the form factor requires very detailed understanding of the entire chain from the radiation process itself to the wavelength dependent sensitivity of the detectors. For the long wavelengths used here, diffraction is of strong influence and dominates the radiation transport to the spectrometer and inside it. The diffractive power of the gratings proved to be a non-trivial issue. The final result, the wavelength dependent response R of the spectrometer (Fig. 3) of a infinite short electron bunch is a product of many carefully determined factors [8].

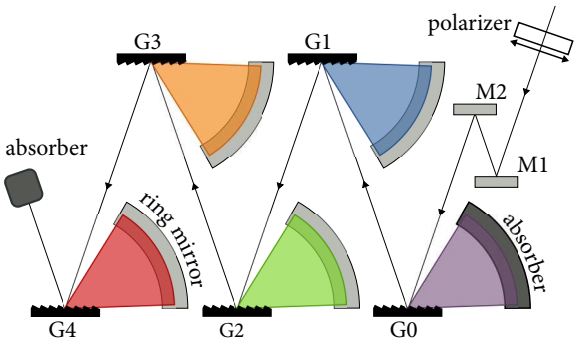

Figure 2: Spectrometer layout with cascaded stages: A defined polarization is fed by alignment mirrors through five consecutive grating stages. The gratings G1 - G4 consecutively disperse shorter wavelengths in backward direction onto focusing 90° ring mirrors and reflected longer ones to the next grating. A filter grating G0 suppresses higher order effects.

The longitudinal form factor modulus is finally computed by the charge and response normalized ADC signal S_{ADC} according to

$$|F_l(\lambda)| = \sqrt{\frac{S_{\mathrm{ADC}}(\lambda)}{R(\lambda)\,Q^2}}\,. \tag{5}$$

MEASUREMENTS

In Fig. 4, the form factor as measured with CRISP4 is compared to the form factor calculated from a current

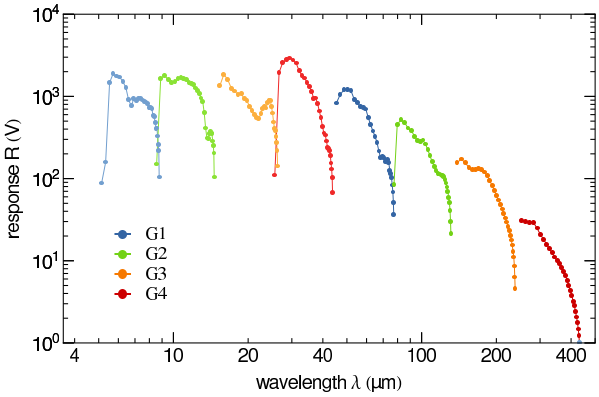

Figure 3: Spectrometer response R for both grating sets at ADC level for $F_l = 1$, a transverse Gaussian profile with 200 µm (RMS) and a bunch charge Q of 1 nC.

profile measured with the TDS simultaneously. A "two-point" tomographic reconstruction [9, 10] using different streaking polarities has been used for the TDS profiling to avoid problems due to intrinsic longitudinal-transversal correlations inside the bunches. After that, the directly measured and calculated form factors agree perfectly well for long wavelengths showing the same distinctive minima, which is characteristic for a close to rectangular bunch profile. The directly measured form factor shows significantly more short wavelength content, not unexpected due to the finite resolution of the TDS measurement.

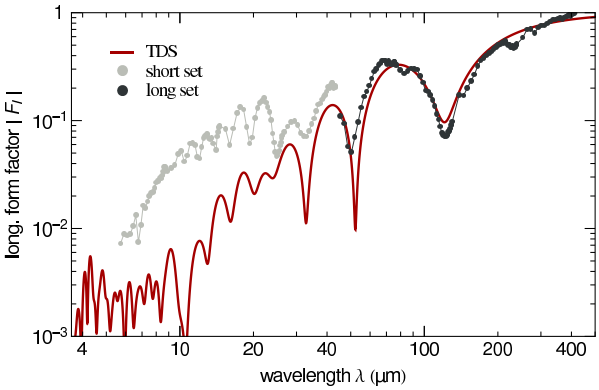

Figure 4: Measured (dots) and calculated (solid line) longitudinal form factor $|F_l|$ for the electron bunch profile shown in Fig. 5.

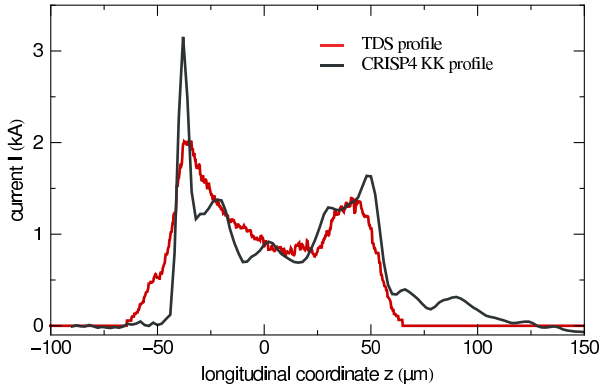

Figure 5: Longitudinal electron bunch current profiles $I(z) = c\,Q\,\rho_l(z)$ measured with TDS and reconstructed with CRISP4 (see Fig. 4) according to Eqs. (3) and (4). c names the vacuum speed of light.

As described above, we used the Kramers-Kronig algorithm to retrieve the "minimal phase" from the measured form factor and to thus reconstruct the bunch profile from the spectrum. The comparison with the TDS measured profile is shown in Fig. 5. The two profiles agree quite well in total length, absolute current and overall shape. The CRISP4 profile exhibits a more pronounced leading spike containing the more pronounced short wavelength content and a slightly longer tail. It should be kept in mind that the two measurements are not at the same location at the accelerator but separated by about 60 m and perfect agreement is not even expected.

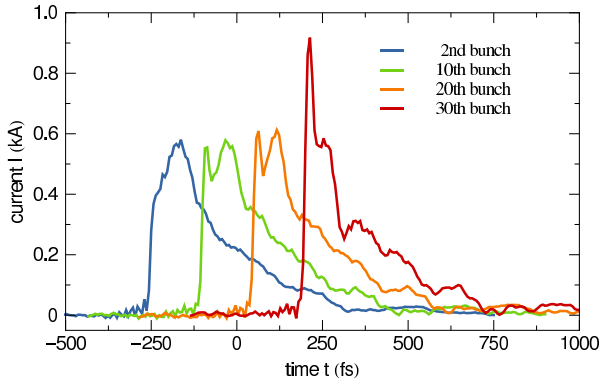

Figure 6: Reconstructed electron bunch current profiles for different bunch positions along the pulse train.

The CRISP4 is now routinely used during machine operation to monitor the bunch profile. Basically the spectrum can be taken in a single shot, but for both wavelengths ranges the changing between the grating sets within 30 seconds is the limiting factor. As an example, we show in Fig. 6 the reconstructed profiles for a sequence of bunches along the bunch train clearly demonstrating that profile and peak current are not constant in this case. Such a behavior normally leads to pronounced dependence of the SASE intensity on the bunch number. Fig. 7 finally shows the form factor and reconstructed profile of a very highly compressed bunch of low charge of 120 pC with a leading spike of less than 10 fs (RMS). Operation of the spectrometer down to 60 pC has been demonstrated.

SUMMARY

We have developed a broadband spectrometer for coherent radiation from electron bunches and successfully commissioned it as an online routine tool for the operation of FLASH. The device is complementary to the conventional TDS method with the unique capability for a fast multi-bunch monitoring within few seconds. The ability to measure absolute form factors over a wide wavelength range and to reliably reconstruct bunch profiles using phase retrieval has been demonstrated.

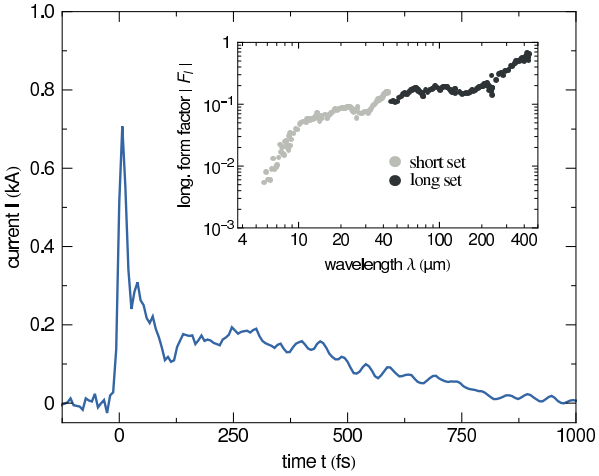

Figure 7: Reconstructed current profile related to the measured form factor (inset) for a electron bunch with 120 pC. Width of the current spike determines to 22 fs (FWHM).

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