

# LONGITUDINAL BUNCH PROFILE RECONSTRUCTION USING BROADBAND COHERENT RADIATION AT FLASH

E. Hass, University of Hamburg, Germany  
 C. Behrens, Ch. Gerth, B. Schmidt, M. Yan, DESY Hamburg, Germany  
 S. Wesch, HZB Berlin, Germany

## Abstract

The required high peak current in free-electron lasers is realized by longitudinal compression of the electron bunches to sub-picosecond length. Measurement of the absolute spectral intensity of coherent radiation emitted by an electron bunch allows monitoring and reconstruction of the longitudinal bunch profile. To measure coherent radiation in the terahertz and infrared range, a in-vacuum coherent radiation intensity spectrometer was developed for the free-electron laser in Hamburg (FLASH). The spectrometer is equipped with five consecutive dispersion gratings and 120 parallel readout channels: It can be operated either in short (5 - 44  $\mu\text{m}$ ) or in long wavelength mode (45 - 430  $\mu\text{m}$ ). Fast parallel readout permits the monitoring of coherent radiation from single electron bunches. Large wavelength coverage and superb absolute calibration of the device allows reconstruction of the longitudinal bunch profile from measured coherent radiation spectr using a Kramers-Kronig based phase retrieval technique. The device is used as a bunch length monitor and tuning tool during routine operation at FLASH. Comparative measurements with radio-frequency transverse deflecting structure show excellent agreement of both methods.

## INTRODUCTION

In order to measure the length of the electron bunches with femto second duration in a high-gain free-electron laser, a coherent intensity spectrometer with four stages (CRISP4) was developed at FLASH [1].

The emission process of an extended charge distribution can be described by a linear superposition of the electric fields of the  $N$  individual particles. The wavelength dependent energy density spectrum into a solid angle interval is given by

$$\frac{d^2U}{d\omega d\Omega} = \left( \frac{d^2U}{d\omega d\Omega} \right)_1 (N + N(N-1) |F(\omega, \Omega)|^2) \quad (1)$$

with  $F(\omega, \Omega)$  the (complex) bunch form factor and  $\left( \frac{d^2U}{d\omega d\Omega} \right)_1$  the spectrum of a single charge. Coherent radiation dominates for  $|F(\omega, \Omega)|^2 \gg 1/N$ .  $F(\omega, \Omega)$  is given by the Fourier transform of the normalized three dimensional particle density distribution  $S_{3D}$  as

$$F(\omega, \Omega) = \int S_{3D}(\vec{r}) e^{-i\vec{k}\cdot\vec{r}} d\vec{r}, \quad (2)$$

where  $\vec{k}$  is the wave vector pointing in the direction of the observer ( $|\vec{k}| = \omega/c$ ) and  $\vec{r}$  the position vectors of the individual charges. In case of uncorrelated longitudinal and

transverse charge distributions, the form factor can be factorized as

$$F(\omega, \Omega) = F_L(\omega, \Omega) F_T(\omega, \Omega). \quad (3)$$

For highly relativistic bunches ( $\gamma \gg 1$ ), the coherent radiation is confined in a narrow cone in forward direction. Restriction of the observation direction to small angles strongly suppresses the influence of the transverse bunch structure on the form factor. In this case, the frequency dependence of the form factor is predominantly determined by the longitudinal structure of the bunch

$$F(\omega, \Omega) \propto F_L(\omega) = \int S(t) e^{-i\omega t} dt. \quad (4)$$

A measurement of the coherent radiation spectrum yields the absolute magnitude of the form factor as a function of wavelength but the phase remains unknown. Hence the determination of the longitudinal charge distribution by inverse Fourier transformation is not directly possible. Phase information can be obtained with the help of the Kramers-Kronig relation [2] if a sufficient wavelength range is covered.

## TEMPORAL PROFILE RECONSTRUCTION

As shown in Eq. (1) to (4), the longitudinal charge distribution is related to the spectral density of the coherent radiation through the longitudinal form factor  $F_L(\omega)$ . For very low frequencies, corresponding to wavelengths much longer than the bunch length, all electrons radiate coherently. The form factor is a real number and approaches unity for  $\omega \rightarrow 0$ . For wavelengths comparable and shorter than the bunch length, the longitudinal form factor is a complex number

$$F_L(\omega) = |F_L(\omega)| e^{i\phi(\omega)} \quad (5)$$

with  $|F_L(\omega)| < 1$ . If both,  $|F_L(\omega)|$  and  $\phi(\omega)$  were known, the longitudinal charge profile  $S(t)$  could be reconstructed by inverse Fourier transform. From spectroscopic measurements, only  $|F_L(\omega)|$  can be derived while the phase remains unknown.

Generally it is not possible to reconstruct the phase from the modulus of a 1-dim complex function in an unique way even if this function is causal [3]. Nevertheless, it is possible to compute the minimal phase using the Kramers-Kronig relation which connects the real and imaginary parts of the Fourier transform of a causal function. The

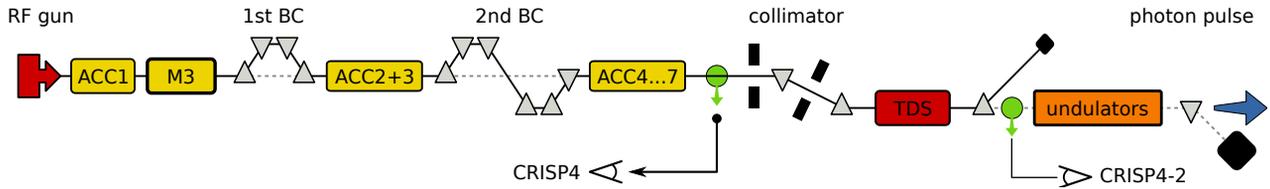


Figure 1: Schematic overview of FLASH: Radio-frequency (RF) gun, superconducting acceleration modules (ACC), third-harmonic module (M3), two magnetic bunch compressors (BC), transverse deflecting structure (TDS) and coherent radiation intensity spectrometer with four stages (CRISP4).

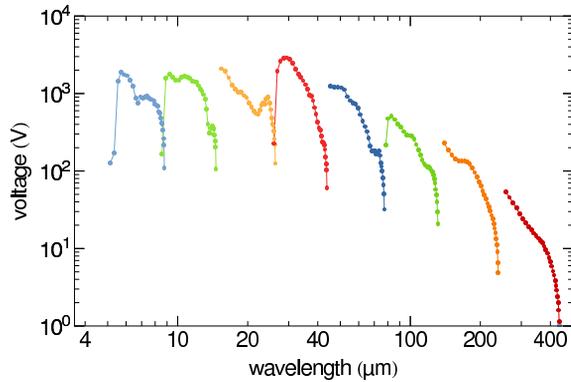


Figure 2: Spectrometer response function for both grating sets at ADC level for  $F_L = 1$ , a transverse Gaussian profile with  $200\ \mu\text{m}$  (RMS) and a bunch charge  $Q$  of  $1\ \text{nC}$ . Taken from [1].

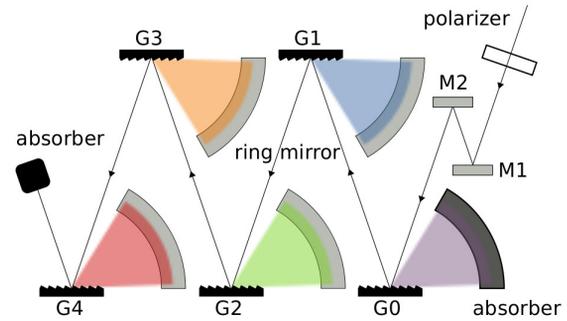


Figure 3: Spectrometer layout with five consecutive gratings: The gratings G1 - G4 consecutively disperse shorter wavelengths in backward direction onto focusing 90 deg ring mirrors and reflect longer ones to the next grating. A filter grating G0 suppresses higher order effects.

method has been adopted for the phase reconstruction of the complex bunch form factor by Lai and Sievers [4] where it has been shown that  $F_L(\omega)$  can be analytically continued into the upper half complex plane, and the minimal phase can be computed from the modulus of  $F_L$  by means of the following integral

$$\phi_{\min}(\omega_0) = -\frac{2\omega_0}{\pi} \int_0^\infty \frac{\ln(|F_L(\omega)|) - \ln(|F_L(\omega_0)|)}{\omega^2 - \omega_0^2} d\omega. \quad (6)$$

If the modulus of the form factor is experimentally known over a sufficiently large wavelength range, covering the main features of the bunch structure, Eq. (6) allows to determine the minimal phase and thus reconstruct a possible complex form factor using Eq. (5). Then the longitudinal charge distribution is calculated by a subsequent Fourier transformation.

The reconstructed bunch shape is not unique and has to be treated as one possible bunch shape. The reconstructed bunch shape is the shape with the least complex substructure compatible with the measured coherent radiation spectrum. In spite of these shortcomings, the phase reconstruction method yields very valuable information and allows to a wide extend a reliable reconstruction of the bunch shape as will be demonstrated in the next sections.

## EXPERIMENTAL SETUP

The CRISP4 is part of the longitudinal diagnostics at FLASH (Figure 1). Two spectrometers, located just behind the last accelerator structure and in front of the undulator magnets, are available for measurements. At both locations an arbitrary bunch can be kicked out of the bunch train with a fast kicker magnet to an off axis transition radiation screen. The produced coherent transition radiation is then transported to the spectrometer through evacuated beam pipes. For comparison measurements in time domain, a transverse deflecting structure (TDS) located just in front of the undulator magnets is used [5, 6].

To disperse polychromatic coherent radiation into its spectral components, reflective gratings are used in our setup. The spectrometers are equipped with five consecutive gratings, G0 to G4 (Figure 3), in a specific geometry [7]. The spectral intensity is recorded simultaneously in 120 wavelength bins. Two remotely adjustable grating sets are available to cover the mid-infrared ( $5\text{-}44\ \mu\text{m}$ ) and the far-infrared ( $45\text{-}450\ \mu\text{m}$ ) range.

Determination of the absolute value of the form factor requires a very detailed understanding of the whole measurement setup starting from the characteristic of the radiation process itself to the absolute spectral sensitivity of the detectors. Emission characteristic of the source and transport of the radiation to the detectors are calculated using

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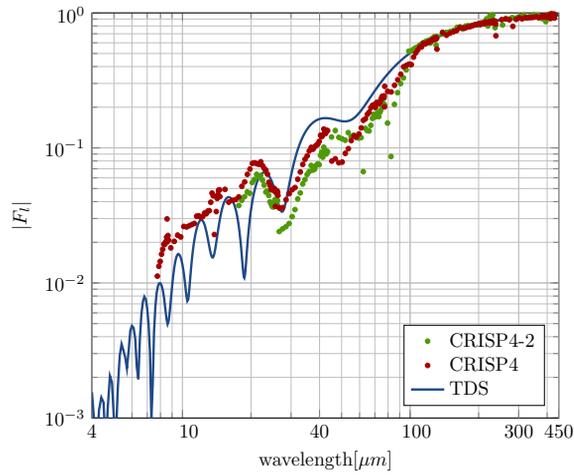


Figure 4: Form factor calculated from the temporal profile measured with the TDS and measured with the CRISP4 for the same compression setting. Corresponding temporal profiles are shown in Figure 5(a).

dedicated simulation code named THzTransport [8]. The absolute calibration of the pyroelectric detectors for the low wavelength range 5-110  $\mu\text{m}$  was done at the Free Electron Lasers for Infrared eXperiments (FELIX) [9]. For calibration of the spectrometer in the long wavelength range 110-450  $\mu\text{m}$ , a theoretical model and complementary measurements with the TDS were used. The final wavelength depended response  $R(\lambda)$  of the spectrometer for an infinite short bunch and a charge of 1nC is shown in Figure 2.

The longitudinal form factor modulus is computed according to

$$|F_L(\lambda)| = \sqrt{\frac{S_{\text{SP4}}(\lambda)}{Q^2 R(\lambda)}} \quad (7)$$

with  $Q$  the charge of the bunch and  $S_{\text{SP4}}$  the ADC signal from the detectors.

Further technical information can be found in [1].

## MEASUREMENTS

Due to the fact that for the transition radiation spectrometers individual electron bunches are kicked to off-axis TR screens, it is not possible to measure the spectra with both spectrometers from the same bunch. This is true as well for the direct TDS time domain measurement. It has been verified that the fluctuations of the bunch shape for adjacent bunches from the same bunch train are small, making a direct comparison of the bunch profile measured with all three devices meaningful.

A first comparison can be done on the level of the form factors to avoid the problem of phase reconstruction. Figure 4 shows the directly measured form factors from both spectrometers in comparison with the form factor derived from the TDS profile by Fourier transformation.

All three form factors agree very well both in absolute magnitude and wavelength dependence. Down to wave-

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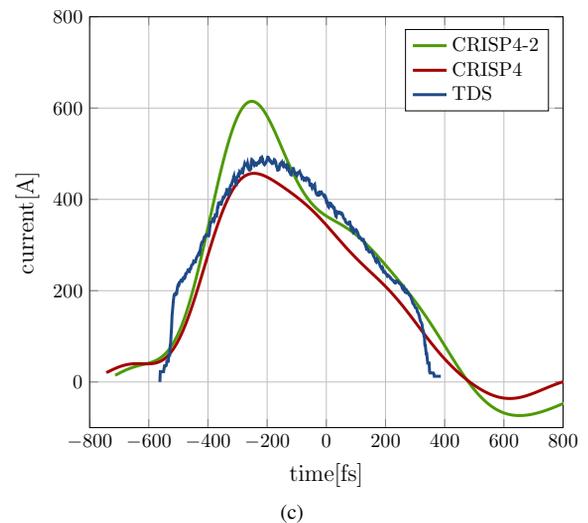
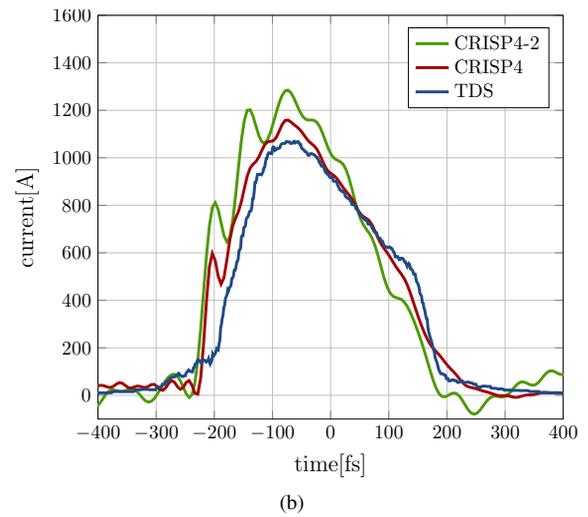
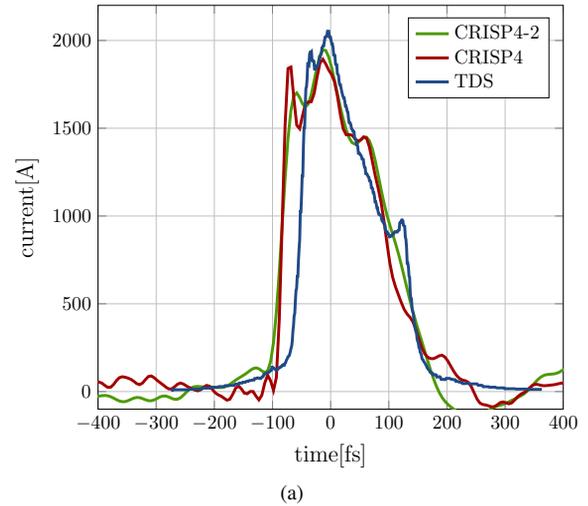


Figure 5: Temporal profiles measured with the TDS and reconstructed with help of the Kramers-Kronig based phase retrieval technique from CRISP4 measurements for three different compression settings. Form factors of the profiles in Figure 5(a) are shown in Figure 4.

lengths of about 20  $\mu\text{m}$ , even the fine structure is reproduced by the complementary methods. It should be mentioned that none of the methods is truly single shot, despite the fact that data (spectra in case of CRISP4, camera images in case of the TDS) for single bunches can be measured. The spectrometers require two measurements with different grating sets to cover the full range of wavelength (2 orders of magnitude) while the TDS method always requires at least measurements for two opposite streak directions to overcome the possible problem of longitudinal-transverse correlations inside the bunch.

Figure 5 compares bunch profiles in the time domain for three different compression settings. The TDS profiles are reconstructed by two-point-tomography using opposite streak directions as mentioned above. The profiles reconstructed from the spectrometer data use the Kramers-Kronig phase (minimal phase) as described in the section above. Due to the coverage of two decades in wavelength, basically no extrapolation of the measured form factors is needed. At long wavelengths, the measured form factor is very close to one (the limit for infinite wavelength) while at short wavelengths it is so small that the contribution to the reconstructed phase is negligible.

A comparison of the reconstructed bunch shapes from both spectrometers shows excellent agreement, despite the fact that the two devices are located about 60 m apart along the accelerator. While CRISP4 is located outside the tunnel and connected to the coherent transition radiation (CTR) screen by a 20 m long beamline containing seven optical elements (off-axis mirrors) [8], CRISP4-2 is located downstream the accelerator inside the tunnel. Furthermore, different types of pyroelectric detectors are used in both instruments. The excellent agreement of the reconstructed bunch lengths and structures demonstrates the excellent calibration and understanding of the spectrometers. This is further emphasized by the independent TDS measurement, both in absolute value of the peak current and the length and structure of the bunch.

Looking into more detail, there are still systematic differences visible which clearly need further study. Negative currents for instance in the phase reconstructed profiles are due to the "minimal phase" problem and can potentially be avoided by applying additional boundary conditions to the phase retrieval algorithm.

## SUMMARY

The technology of bunch profile determination using coherent radiation spectroscopy has made a considerable step forward by using the multi-stage spectrometers developed at DESY. For the first time, we used two independent devices at different locations of the linac to cross check the reliability of the method and benchmarked the result with direct measurements in time domain. The spectrometers are rather easy to use versatile instruments to permanently monitor and adjust the bunch profile at FLASH. Similar spectrometers will be used at FLASH-2 and the European XFEL.

## REFERENCES

- [1] Stephan Wesch et al. "A multi-channel THz and infrared spectrometer for femtosecond electron bunch diagnostics by single-shot spectroscopy of coherent radiation". In: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 665.0 (2011), pp. 40 to 47. ISSN: 0168-9002.
- [2] Schneider G. Lai R. and Sievers A.J. "Handbook of Accelerator Physics and Technology". In: ed. by Eds. A.W. Chao and M. Tigner. World Scientific, 2006. Chap. "Measuring Longitudinal Distribution of Electron Bunches with Coherent Radiation."
- [3] Edwin J. Akutowicz. "On the determination of the phase of a Fourier integral. I". In: Trans. Amer. Math. Soc. 83 (1956), pp. 179 to 192.
- [4] R Lai and A.J Sievers. "On using the coherent far IR radiation produced by a charged-particle bunch to determine its shape: I Analysis". In: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 397.2-3 (1997), pp. 221 to 231.
- [5] Christopher Behrens and Christopher Gerth. "Measurement of Sliced-Bunch Parameters at FLASH". In: FEL Proceedings. MOPC08. 2010.
- [6] C. Behrens et al., Phys. Rev. ST Accel. Beams 15, 030707 (2012).
- [7] H. Delsim-Hashemi. "Infrared Single Shot Diagnostics for the Longitudinal Profile of the Electron Bunches at FLASH". desy-thesis-08-024. University of Hamburg, 2008.
- [8] S. Casalbuoni et al. "Ultrabroadband terahertz source and beamline based on coherent transition radiation". In: Phys. Rev. ST Accel. Beams 12 (3 2009),p. 030705.
- [9] Christopher Behrens. "Detection and Spectral Measurements of Coherent Synchrotron Radiation at FLASH". DESY-THESIS-2010-02. diploma thesis. University of Hamburg, 2008