ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-WEP012

THz SPECTROSCOPY WITH MHz REPETITION RATES FOR BUNCH PROFILE RECONSTRUCTIONS AT EUROPEAN XFEL

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Abstract

The European X-ray Free-Electron Laser generates most powerful and brilliant X-ray laser pulses. Exact knowledge about the longitudinal electron bunch profile is crucial for the operation of the linear accelerator as well as for photon science experiments. The only longitudinal diagnostic downstream of the main linac is based on spectroscopy of diffraction radiation (DR). The spectral intensity of the DR in the THz and infrared regime is monitored by a four-staged grating spectrometer and allows non-invasive bunch length characterization based on form factor measurements in the range 0.7 – 60 THz. As the readout and signal shaping electronics of the spectrometer allow MHz readout rates, the longitudinal bunch profile of all bunches inside the bunch train can be characterized non-invasively and simultaneously to FEL operation. In this paper, form factor measurements along the bunch train will be described and presented as well as the resulting reconstructed current profiles.

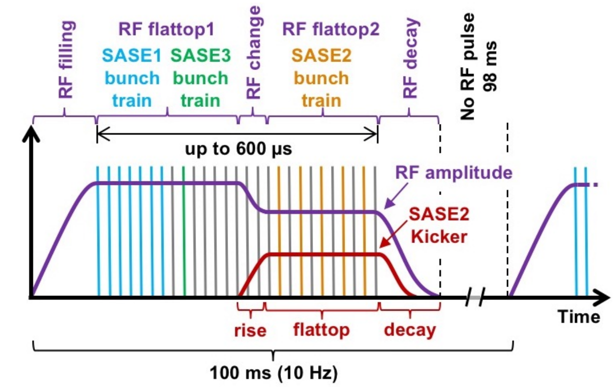

Figure 1: Simplified diagram of the EuXFEL bunch pattern. The RF accelerating pulses (purple line) can be split into two flattops to optimize independently the bunch compression for SASE1/SASE3 and SASE2.

INTRODUCTION

The European XFEL (EuXFEL) generates femtosecond X-ray laser pulses in the wavelength range 0.05 – 6 nm based on Self-Amplified Spontaneous Emission (SASE) at MHz repetition rates [1]. The super-conducting linear accelerator of EuXFEL [2] has recently been operated at a beam energy of 14 GeV, a bunch charge of 250 nC, and with 600 µs-long trains of up to 675 bunches at a rate of 10 Hz. The femtosecond electron bunches can be distributed into three different SASE undulator beamlines and serve three experimental stations in parallel for which a flexible bunch pattern can be adjusted independently as depicted schematically in Fig. 1.

For a stable operation of the accelerator, e.g. to suppress beam-loading in the accelerator modules, the full bunch train is filled with bunches. Bunches requested by the user experiments, marked as blue, green, and orange bars in Fig. 1, are distributed to the individual undulator beamlines SASE1, SASE2, and SASE3, whereas all other bunches are kicked out by a fast kicker-septum arrangement into a local dump upstream of the SASE undulators (grey bars in Fig. 1). The hard X-ray undulator SASE1 is located in a straight section and followed by the soft X-ray undulator SASE3 downstream of a bending magnet which separates the hard X-rays from the electron beam. A flattop kicker, indicated as a red line in Fig. 1, is used to deflect electron bunches into a septum which deflects the bunches into the undulator beamline SASE2. The radio-frequency (RF) accelerating pulses (solid purple line in Fig. 1) can be split into two flattop regions for which the RF accelerating voltage, i.e. amplitude and phase, can be adjusted within certain limits for independent optimization of the bunch compression and FEL power of SASE2. The SASE2 bunch train can also be swapped with the SASE1/SASE3 bunch trains to have the SASE2 bunch train in the RF flattop1. The bunches that are accelerated during the time between the RF flattops, required both for adjustment of the accelerating voltage and rise or decay time of the SASE2 flattop kicker, are taken out by the fast kicker-septum arrangement. A layout of the undulator beamlines is shown in Fig. 2.

The exact knowledge of the longitudinal current profile of the individual electron bunches is of high interest for the photon experiments as well as for accelerator operation. At EuXFEL the current profile at final compression is monitored by terahertz (THz) and infrared (IR) spectroscopy of coherent diffraction radiation (DR) just upstream of the undulator beamlines, see also Fig. 2. The spectral content of this coherently emitted radiation is determined by the modulus of the longitudinal form factor, the Fourier transform of the current profile. Therefore, the modulus of the longitudinal form factor $|F_l|$, which is accessible by measurements of the coherently emitted DR [3], yields information about the time structure of the electron bunch.

As the emission of DR does not influence the electron beam quality, it allows for non-invasive bunch length characterization. A four-staged single-shot grating spectrometer [4] has been utilized to measure the spectral intensity of the DR with single bunch resolution. Consequently, the longitudinal form factor of all bunches inside the bunch train can be measured simultaneously during FEL operation.

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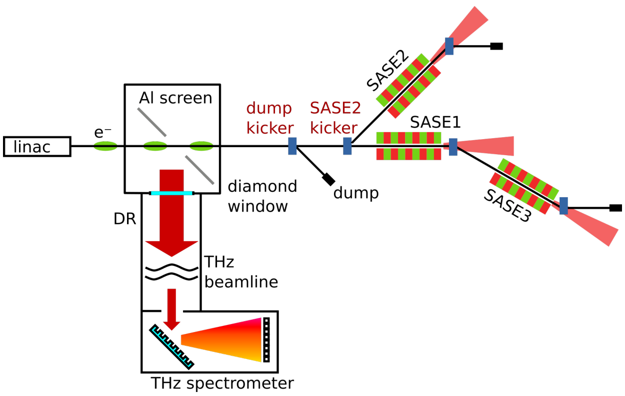

Figure 2: Schematic overview of the coherent radiation diagnostic station and the undulator switchyard at EuXFEL. The coherent radiation emitted at a DR screen is monitored non-invasively by the THz spectrometer.

EXPERIMENTAL SETUP

The aluminum diffraction radiation screen, with a dimension of 80 mm × 32 mm and 1 mm thickness, has a circular aperture of 5 mm diameter. The screen is mounted under 45° with respect to the incoming electron beam such that the radiation is emitted perpendicular to the electron beam path (indicated by the red arrows in Fig. 2). In order to prevent absorption of the THz radiation in air, the beamline is evacuated and decoupled from the accelerator vacuum by a diamond window, which has an aperture of 20 mm. Four focusing gold mirrors transport the DR to the THz spectrometer. A detailed description of the THz beamline can be found in Ref. [5].

The THz spectrometer consists of four consecutive blazed gratings with decreasing grating constants. Each grating serves as an efficient dispersive device, which will spread a certain frequency range into the first dispersive order. In addition, it also serves as a low-pass filter by efficiently reflecting the radiation below the dispersive frequency range onto the next grating. Focusing ring mirrors focus the dispersive radiation onto the detector planes. The spectral intensity is detected by pyroelectric line array detectors with 30 channels at every grating stage. Together with the possibility to remotely change between two different grating sets, this results in 240 frequency bins covering the range from 0.7 THz to 60 THz. A detailed description of the THz spectrometer can be found in Ref. [4].

After a charge-sensitive preamplifier (Cremat CR-110), the signals of the pyroelectrical detectors are shaped by a Gaussian filter amplifier with selectable shaping times. Finally, the analog signals are converted to digital signals, which are available within the EuXFEL control system. The shaping and analog-to-digital conversion are done by four MicroTCA.4 compliant electronic boards [6]. Each board holds 32 ADCs with a sampling rate of 54 MHz.

SIGNAL PILE-UP AND CORRECTION

The pyroelectrical crystal $LiTaO_3$ of the detector absorbs the radiation inducing a thermal expansion of the crystal and leading to a surface charge change. The charge sensitive preamplifier converts this charge to an exponential step voltage signal with a decay-time constant of 1.4 µs. For the purpose of signal sampling and analog-to-digital conversion, these step functions are filtered by Gaussian filter amplifiers leading to pulses with 100 ns RMS duration.

Since the $LiTaO_3$ crystals are as well piezo-electric, the pyroelectric voltage change leads to mechanical vibrations of the crystal with a characteristic resonance frequency in the MHz range and a decay time of ~20 µs. These vibrations are in the bandwidth of the shaping amplifier and thereby noticeably in the sampled ADC signals as a ringing following the signal. The dots in the top of Fig. 3 illustrate the amplitude of these oscillations at the positions of subsequent bunches in the ADC signal of one bunch. The decay time of the oscillations is larger than the bunch spacing on a 1.1 MHz pattern. Consequently, the pyrodetector signal of a bunch train is distorted due to signal pile-up. The red curve in the bottom of Fig. 3 shows such a distortion on the signal of a bunch train with 555 bunches. The ringing is reproducible in amplitude and phase and scales linearly with the amplitude of the initial signal. Experimentally determined single bunch patterns can be used to correct for this effect. The result of this correction (green curve in Fig. 3) shows that the baseline after the bunch train is well recovered, which is an indicator for a successful correction of the pile-up. In addition, it can be seen how the different RF phases in the two flattops change the electron bunch compression and thus the height of the pyroelectric signal.

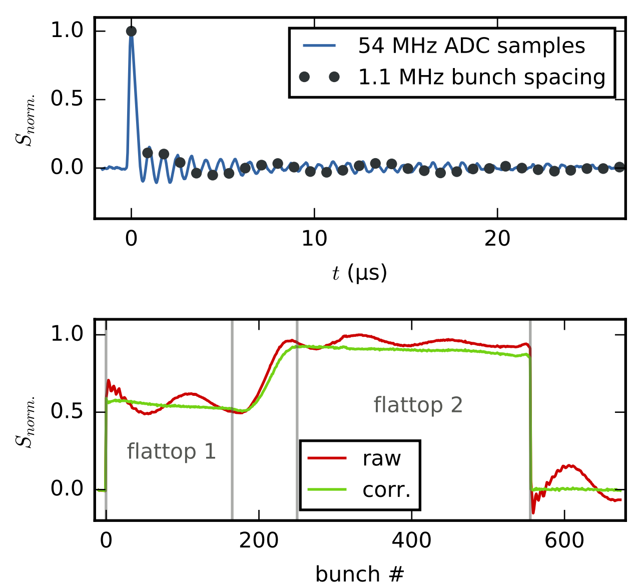

Figure 3: Normalized ADC signal of a pyrodetector for a single bunch against time (top). With this information the pile-up on a bunch train (red) with 555 bunches at a repetition rate of 1.1 MHz can be corrected (green).

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EXPERIMENTAL RESULTS

The successful application of the pile-up correction enables form factor measurements for each bunch inside the bunch train. In Fig. 4, the longitudinal form factors of bunch #50 and bunch #500 are shown. The lines represent the averages of 100 RF pulses. The error bands include the RMS fluctuations as well as the influence of any remaining pile-up on the signal. This was estimated by the largest signal deviation from the baseline after the bunch train. This is also the estimate of the detection limit of the spectrometer, which is represented by the gray area.

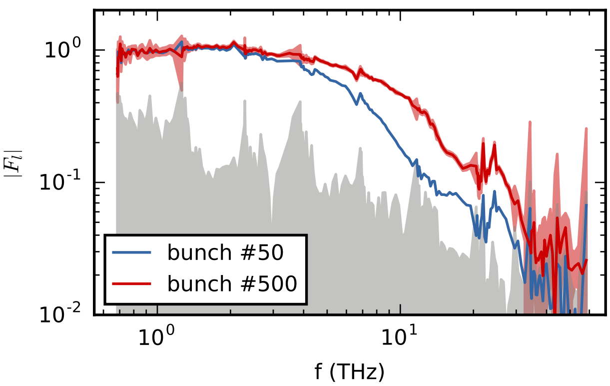

Figure 4: Measured longitudinal form factor modulus $|F_l|$ averaged over 100 RF pulses for bunch #50 and #500 out of a bunch train with 555 bunches at a repetition rate of 1.1 MHz. The gray area indicates the detection limit of the spectrometer. Different bunch compressions for two RF flattops are clearly visible.

The longitudinal form factor of bunch #50, which is part of the first RF flattop, clearly shows a faster fall-off at higher frequencies than bunch #500 of the second RF flattop. This indicates a shorter overall bunch length and thus higher compression of the second RF flattop. It is the result of empirical optimization of the bunch compression for optimum SASE power in the undulator beamlines SASE1 and SASE2.

Based on the algorithm described in Refs. [5, 7], the longitudinal bunch profiles have been reconstructed from the measured spectral intensities, which are depicted in Fig. 5. Here, the different overall bunch compression of the two RF flattops are clearly visible. The RMS bunch length of bunch #50 is 1.3-times larger than the one of bunch #500, while the peak current decreases by a factor of 1.5.

CONCLUSION AND OUTLOOK

The DR beamline at EuXFEL enables non-invasive spectroscopy of the coherently emitted THz and IR radiation simultaneously to FEL operation. The electronics of the THz spectrometer are fast enough to detect each bunch inside the bunch train. The detrimental ringing of the detector signals due to the piezoelectric oscillations of the pyroelectric sensors can be corrected by utilizing a single bunch measurement. The resulting measured longitudinal form factors for

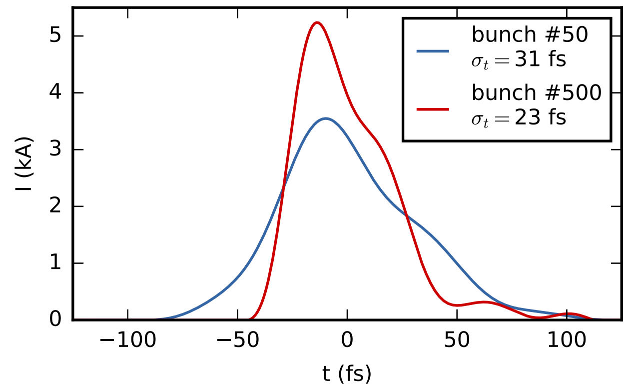

Figure 5: Current profile reconstructions of one bunch of the two respective RF flattops from the form factor measurement shown in Fig. 4.

each RF flattop show clear differences in the bunch compression for an optimal lasing process in the respective SASE beamline. This is also visible in the reconstructed current profiles.

Currently, the pile-up correction is getting implemented in the accelerator control system and will enable a live measurement of the longitudinal form factor for each bunch inside the bunch train with single bunch resolution. This information can then be used as a feedback to optimize and stabilize the accelerator operation.

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