ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPGW014

A NON-INVASIVE THz SPECTROMETER FOR BUNCH LENGTH CHARACTERIZATION AT EUROPEAN XFEL

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Abstract

The European X-ray Free-Electron Laser provides one of the most powerful X-ray laser pulses to a wide range of experiments. These experiments strongly benefit from the exact knowledge of the electron bunch current profile and demand for stable and shortest-possible pulse lengths. During the 2018 summer shutdown, the 4-staged grating spectrometer CRISP has been installed at a diffraction radiation (DR) beamline just upstream of the undulator beamline switchyard. The DR at final electron beam energies of up to 17.5 GeV enables non-invasive bunch length characterization based on form factor measurements down to a few micrometers. Fast detectors and electronics allow for the characterization of the whole bunch train with repetition rates above 1 MHz. This contribution will present commissioning results of the THz beamline as well as first measured form factors and reconstructed electron current profiles.

INTRODUCTION

The European X-ray Free-Electron Laser is driven by a superconducting linear accelerator generating femtosecond electron bunches with energies of up to 17.5 GeV. Every 100 ms bunch trains of up to 2700 electron bunches can be accelerated with a repetition rate of 4.5 MHz and are distributed to the three undulator beamlines [1].

A widely used diagnostic for the temporal properties of electron bunches in X-ray free-electron lasers is the detection of coherent transition or diffraction radiation (DR) in the Terahertz and infrared regime. As the spectral intensity distribution is described by the longitudinal form factor F_l, which is the Fourier transform of the normalized current profile, measuring the spectral intensity distribution yields information about the longitudinal bunch shape. For this purpose, a single-shot multi-channel spectrometer has been developed at DESY, which covers the spectral range from 0.7 THz to 6.6 THz and 6.6 THz to 60 THz (5 µm - 45 µm and 45 µm - 450 µm) with two different grating sets [2]. Bunch length diagnostics is routinely being carried out at a transition radiation beamline at the free-electron laser FLASH [3].

Whereas at FLASH a fast magnetic kicker deflects one bunch of the bunch train onto a screen, at European XFEL the higher electron energies offer the use of a diffraction radiator with a 5 mm aperture. Here, the intensity above 10 THz is still sufficient. This is not the case for the electron beam energies at FLASH. The difference in the spectral intensity distribution of DR at difference electron beam energies and transition radiation is illustrated in Fig. 1. Thus, the form factor of all electron bunches inside the bunch train can be measured non-invasively with the multi-channel spectrometer.

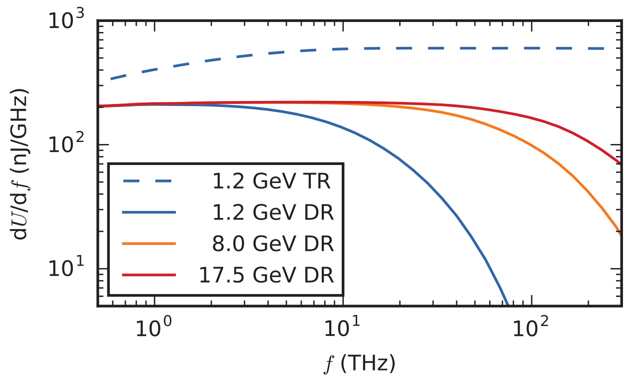

Figure 1: Numerically calculated single electron spectral intensity of transition and diffraction radiation according to Eq. (25) in Ref. [4]. A circular screen with 16 mm radius and 5 mm aperture for DR was used.

EXPERIMENTAL SETUP

The THz beamline for the transport of the DR from the screen station to the spectrometer is located downstream of the main linac and just upstream of the switchyard to the three FEL undulator beamlines. The screen station consists of a 80 mm x 32 mm aluminum screen of 1 mm thickness that can be moved vertically into the electron beam path by a mover [5]. The screen has an angle of 45° to the electron beam such that the radiation is emitted perpendicular to the electron beam direction. Two apertures in the bottom and top part of the screen divide the screen in a diffraction radiator with either 5 mm or 7 mm diameter and an on-axis transition radiator. In Fig. 2 the THz beamline and spectrometer are sketched together with the screen station and accelerator beam pipe. The THz beamline is separated from the accelerator vacuum by a diamond window with a free aperture of 20 mm. Four focusing gold mirrors with a projected radius of 50 mm transport the radiation from the screen to the spectrometer which is located below the accelerator beam pipe. An overview of the optical components is given in the top part of Fig. 3. The optical elements are sketched together with their focal lengths and the distances to the next element. Lens symbols represent the toroidal focusing mirrors and the polarizer marks the end of the beamline. The distances and optics inside the spectrometer are listed in Ref. [6].

The overall transmission is limited by the reflectivity of the gold mirrors to $0.97^4 = 0.89$ and by the diamond window

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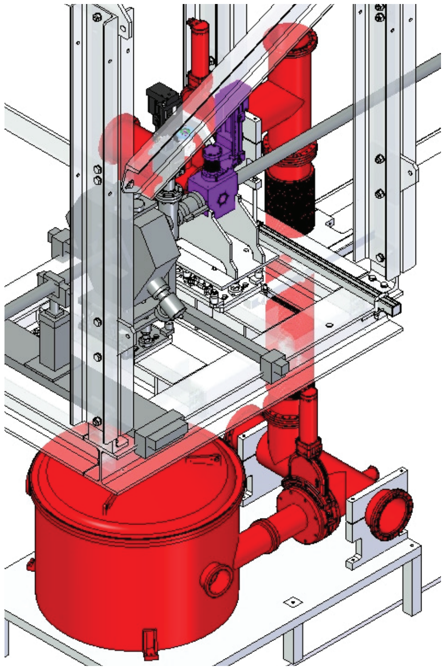

Figure 2: Sketch of the THz beamline at European XFEL. The electrons pass the station from the right to the left through the beam pipe shown in gray. Purple marks the screen station with the mover while the THz beamline and spectrometer are displayed in red.

to 0.71 [7] . In the simulated transmission T presented in Fig. 3, the excitation of phonons in the diamond window at 60 THz and etalon oscillations below 1 THz are clearly visible. The etalon oscilations are less pronounced for the vertical polarization due to the 1°-wedge of the diamond window.

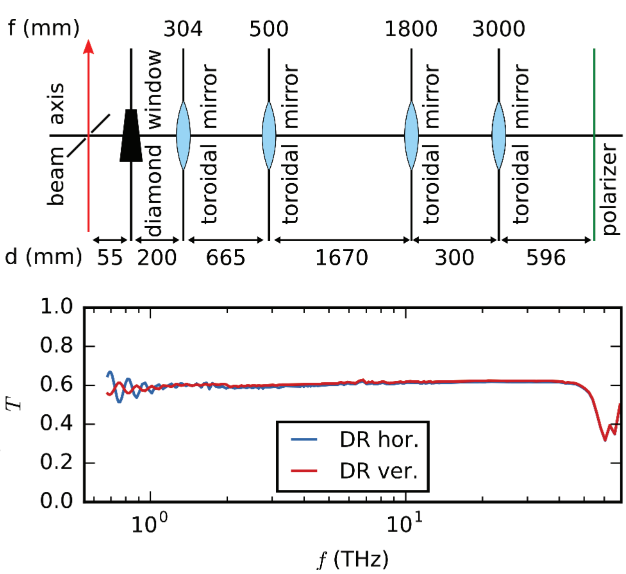

Figure 3: Optical setup (top, not to scale) and transmission as function of frequency (bottom) of the THz beamline. See text for details.

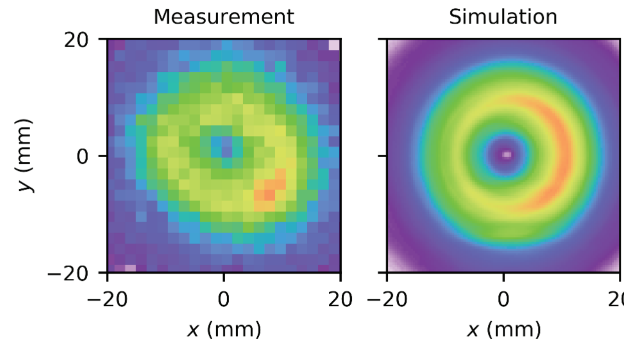

Figure 4: Measurement and simulation of the 2D beam profile at the end of the THz beamline.

After the installation of the beamline during the spring shutdown 2018, good understanding of the radiation emission and transport through the beamline has been proven by comparisons between simulations and measurements. One example is illustrated in Fig. 4, where the transverse profile after the beamline was scanned with a pyroelectric detector and compared to a simulation. The characteristic donut-shape of transition and diffraction radiation is clearly visible. The insertion of neither the 5 mm nor the 7 mm DR screen showed an effect on FEL performance.

The spectrometer as described in Ref. [2] has been equipped with different signal shaping electronics to meet the requirements for MHz-readout rates. For the preamplifiers the custom made model Cremat CR-110 with a time constant of 1.2 µs is used. The Gaussian shaping amplification with selectable shaping times of 100 ns, 1 µs or 10 µs and the analog to digital signal conversion (ADC) is done by MTCA.4 compliant electronic boards [8]. The 120 channels of the spectrometer are connected to four boards, each equipped with 32 ADCs and sampling rates of 54 MHz.

FIRST RESULTS

The installation of the spectrometer was completed in the summer shutdown of 2018, and the alignment was done in the first days of the following user operation period. During standard FEL operation, there is sufficient intensity along the spectral range of the spectrometer to determine the electron bunch form factor modulus. An example of measured longitudinal form factor moduli $|F_l|$ for different compression settings, which was realized by changing the electron beam energy chirp h_{L1} in front of the second bunch compressor, is shown in a double-logarithmic plot in Fig. 5. The electron beam had an energy of 14 GeV and bunch charge of 0.25 nC. In this case the form factor is an average of 50 shots for both grating sets in a single bunch pattern, and the transparent area marks the rms values of these shots. The gray area indicates the detection limit of the spectrometer. A form factor below this threshold cannot conclusively be distinguished from the noise of the system.

For the same compression settings, the current profile was also measured with the transverse deflective structure (TDS) downstream of the last bunch compressor. Using

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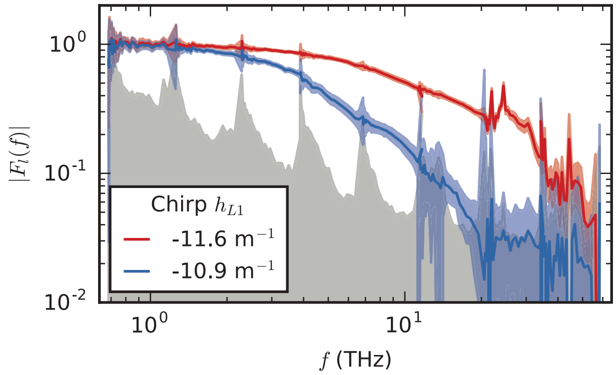

Figure 5: Measured form factor moduli $|F_l|$ and their standard deviations for two different compression settings for the electron energy chirp h_{L1}. The gray area indicates the sensitivity limit.

the local beam dump and elaborative accelerator optics, a longitudinal resolution of about 8 fs was achieved. The form factors computed from the measured current profiles agree very well with those from the spectrometer, and also the evolution of the bunch length during a compression scan is consistent on both devices.

Even more notable is the excellent resemblance of the reconstructed current profiles with those measured by the TDS. The results are presented in Fig. 6. Starting from the best suited model of a list of models for the initial guess of the longitudinal density profile, the reconstruction was done by the iterative phase retrieval algorithm described in Ref. [3]. For a better comparison the reconstructed current profiles were convoluted with the temporal resolution of the TDS.

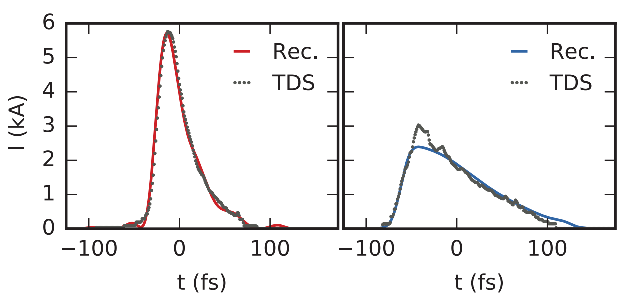

Figure 6: Current profiles measured with the TDS together with the current profile reconstruction from the form factors shown in Fig. 5.

CONCLUSION AND OUTLOOK

Due to high electron beam energies, the intensity cutoff for DR at European XFEL is above 100 THz. This opens up the possibility to utilize DR for non-invasive monitoring of the longitudinal bunch profiles simultaneously to FEL operation. The measured transverse beam profiles of the DR transported through the THz beamline agree very well with simulation results. The spectrometer electronics have been modified to meet the requirements for bunch resolved measurements and the electronic signal processing is realized in MTCA.4 crate standard. First tests of the spectrometer have been carried out, and the reconstructed current profiles show an excellent agreement with those measured by a TDS.

The electronic signal shaping enables bunch resolved measurements with MHz repetition rates. However, ringing due to the piezoelectric properties of the detectors influences the signal of subsequent bunches. As these oscillation are phase-stable, they can be corrected with the information of a single bunch measurement. This is part of an on-going development for bunch resolved form factors of all bunches in a bunch train. A server to calculate and provide the form factors live is currently being implemented.

The multi-channel spectrometer is the only longitudinal diagnostic at European XFEL at final electron energy and will provide full information about the longitudinal beam profile within the bunch train in the future.

ACKNOWLEDGEMENTS

We would like to thank K. Ludwig, L. Petrosyan, J. Roever, P. Schmüser, P. Smirnov for their support and advice as well as the whole European XFEL team to make these measurements possible.

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