TIME-RESOLVED SPECTRAL OBSERVATION OF COHERENT THz PULSES AT DELTA*

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Abstract

Coherent THz pulses induced by a laser-electron interaction are routinely produced and observed at DELTA, a 1.5-GeV synchrotron light source operated by the TU Dortmund University. At a dedicated THz beamline, measurements using a Fourier-transform spectrometer have been performed between 1 THz and 7 THz. Recently, an ultrafast Schottky-diode detector and a novel polarizing Fourier-transform spectrometer were installed, which enable turn-by-turn-resolved spectral measurements in the frequency range below 1 THz. The commissioning results of the new spectrometer and simulations are presented.

INTRODUCTION

DELTA, a 1.5-GeV electron storage ring with a circumference of 115.2 m and a revolution frequency of 2.6 MHz, is a synchrotron light source operated by the TU Dortmund university. A short-pulse source using the coherent harmonic generation (CHG) [1, 2] principle for the generation of ultra-short VUV and THz pulses has been constructed since 2011. A 40-fs Ti:sapphire laser system operating at 1-kHz repetition rate with a pulse energy of 8 mJ is used in an interaction with a short slice of an electron bunch during the transition through the electromagnetic undulator U250. The undulator is divided into three parts, the modulator (7 periods), the chicane (3 periods) and the radiator (7 periods). A sinusoidal energy modulation is imprinted onto the center of the electron bunch. The energy modulation is converted into a density modulation by the chicane and hence microbunches are formed which emit coherent VUV radiation at harmonics of the laser wavelength in the radiator. The longitudinal electron distribution further changes in the subsequent magnetic lattice due to energy-dependent path lengths in the bending magnets. In consequence, a sub-picosecond dip in the longitudinal density is created, giving rise to emission of coherent THz radiation. This radiation is extracted at a dedicated THz beamline (BL5a) [3, 4]. The THz beam is guided over the radiation protection wall to the experiments by in-vacuum toroidal aluminium mirrors. The THz laboratory is equipped with different detectors, such as an InSb hot-electron bolometer, an ultrafast detector (<17 ps FWHM response time) based on the high-temperature superconductor $YBa_2Cu_3O_7$ (YBCO) [5, 6], an ultrafast Schottky-barrier diode detector and a Fourier-transform spectrometer with an Si-composite bolometer. In the scope of the short-pulse facility, the THz beamline serves as both a source for sub-millimeter radiation for future pump-probe experiments and as a diagnostics tool for the optimization of the laser-electron interaction.

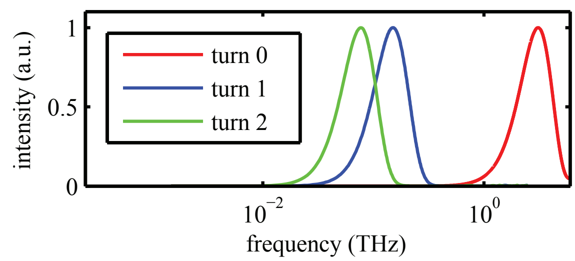

Figure 1: Simulated coherent THz spectra from turn 0 to turn 2 normalized to peak intensity (see text for details). The simulation is based on the code THzSMe [7, 8].

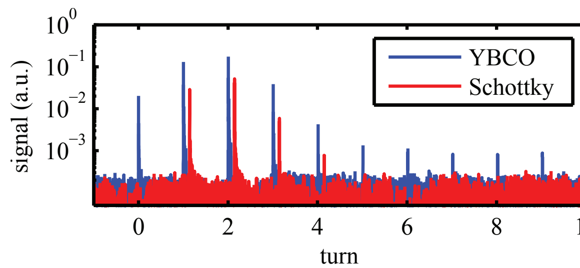

Figure 2: Signals of the YBCO and Schottky-barrier detector several revolutions after the laser electron interaction. For better visibility the signal of the Schottky diode is shifted by 30 ns.

TIME-RESOLVED MEASUREMENTS

Previous experiments [9] have shown that the modulation of the electron density persists for at least half a synchrotron oscillation period which corresponds to about 80 revolutions in the storage ring. During this process, the ps-scale substructure in the longitudinal electron distribution smears out and the spectral content shifts from above to frequencies below 1 THz. So far, only the first turn could be studied experimentally [10], but simulations [7, 9, 11] (c.f. Fig 1) using the *elegant* [8] particle tracking code were also carried out for the signals of up to 100 revolutions. In the past, the spectral composition of the radiation was studied for the THz signal of the first revolution which predominantly lies above 1 THz [10]. However, the spectral range of the

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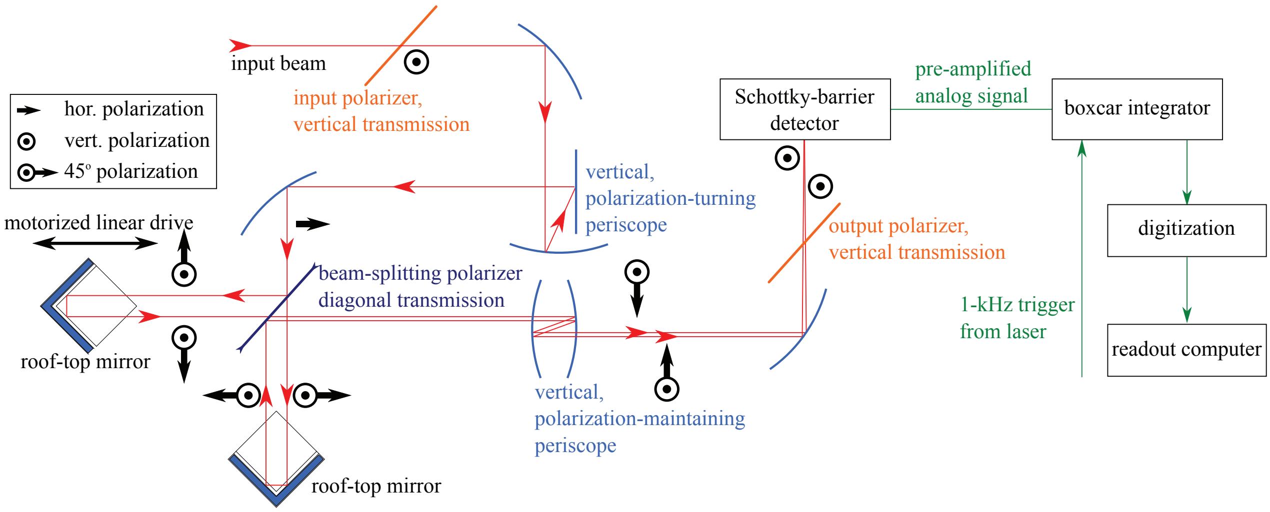

Figure 3: Setup of the polarizing spectrometer commissioned at the short-pulse facility (see text for details).

present spectrometer is between 1 THz and 240 THz and therefore excludes experimentally studying THz signals of higher revolutions.

Besides a new spectrometer for the sub-THz regime, a detector is needed which has a response time which is lower than one revolution (384 ns) in the storage ring. Figure 2 shows coherent THz signals acquired by the YBCO and Schottky-barrier detector during several revolutions after the initial laser interaction. It is noticeable that the signal directly after the interaction is suppressed in the case of the Schottky-barrier detector. The reason is its spectral response which is highest at about 120 GHz and vanishes for frequencies larger than 1.2 THz. In order to allow time-resolved spectral studies, a new polarizing Fourier-transform spectrometer was built to validate the simulations and to allow further studies.

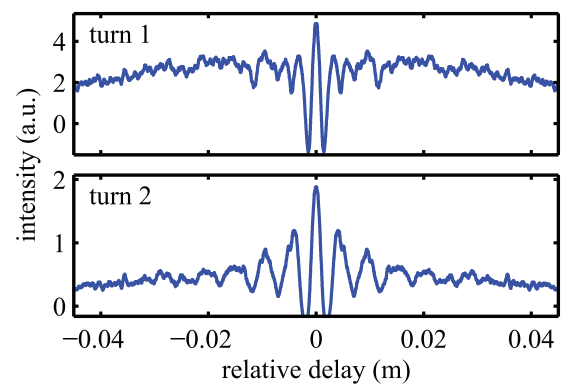

Figure 5: Interferograms of the turn-1 (top) and turn-2 signal (bottom) (see text for details).

COMMISSIONING OF THE POLARIZING SPECTROMETER

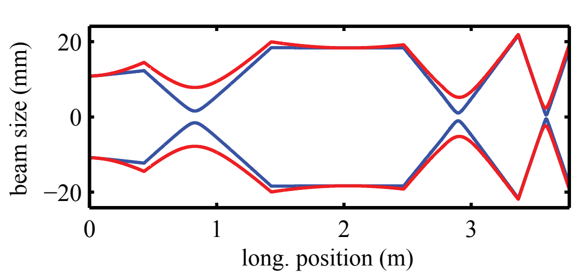

Figure 4: Evolution of the beam size inside the spectrometer along the longitudinal coordinate (see text for details).

The polarizing spectrometer which was recently commissioned at the short-pulse facility is based on the Martin-Puplett interferometer setup [12]. This type of interferometer works as a Michelson interferometer which carries out the beam splitting based on polarization. The spectrometer is operated in air, after a z-cut quarz beamline window. Because the THz beamline comprises a polarization-turning periscope, the radiation on the optical table is predominantly vertically polarized. As shown in Fig. 3, the spectrometer starts with a wire-grid polarizer defining the input polarization. The beam is focussed by toroidal aluminium mirrors which are set up as Gaussian beam telescopes, i.e., the focussing elements are separated by the sum of their focal lengths, such that the location of the beam waist is independent of the radiation wavelength. For the layout of the optics diffraction has to be taken into account. The effects are presented in Fig. 4 in which the beam size is plotted as a function of the longitudinal position after the z-cut quarz window. The red curve shows the beam size of a 150-GHz beam and the blue trace is the beam size for a 2-THz beam. The central part of the interferometer ranges from 1.4 m to 2.5 m. It is particularly important that the beam size at the detector position is independent of the position of the movable interferometer arm, since a transverse overlap of the delayed signals is necessary for an interference of the full beam. The interferometer uses a polarizing wire grid at an angle of 45° to the incident polarization to split the beam. The polarizers are made of gold-plated tungsten wire with a diameter of 10μm and a wire pitch of 50μm. Simulations and test measurements of the polarizers show a decent splitting efficiency up to approximately 4 THz [13].

During the alignment procedure, the polarizing beam splitter was replaced by an optical beam splitter (N-BK7) and an alignment laser was used. Since the beam-splitter material offers a reflectivity of approximately 10 % in the submillimeter wavelength range [14], the same splitter was used for a further alignment with THz radiation in conjunction with visible bending-magnet radiation. The detector is either read out by an oscilloscope or by a gated integrator and a digitizer. The radiation of a specific revolution after the laser-electron interaction is chosen by adjusting the trigger delay of the readout which is synchronized to the laser.

FIRST SPECTRAL MEASUREMENTS

Single-turn spectral measurements of radiation after one and two storage ring revolutions were acquired by the Schottky-barrier detector while operating the short-pulse facility with a seed-laser wavelength of 400 nm by means of a second-harmonic generation unit. Figure 5 shows the central part of the corresponding interferograms which were acquired during a scan of the interferometer delay at a constant speed of 1 mm/s. In general, any interferogram needs to be axially symmetric about the zero-delay position [14]. Hence the data were mirrored above the zero-delay position and averaged in order to correct for phase noise and to fulfil the criterion of axial symmetry.

The respective spectra which are the Fourier transform of the interferograms are shown in Fig. 6. The spectra were corrected for the spectral response of the Schottky-barrier detector. The shift of the spectral center to lower frequencies indicated by the simulations is also noticeable in the measurements. However, the maxima of the spectra are systematically lower than compared to the simulation. This observation may result from an influence of the transmission of the beamline or the spectrometer transmission which can only be theoretically estimated by an optical model. Further simulations will be performed which study the influence of the laser-pulse properties and other parameters in detail.

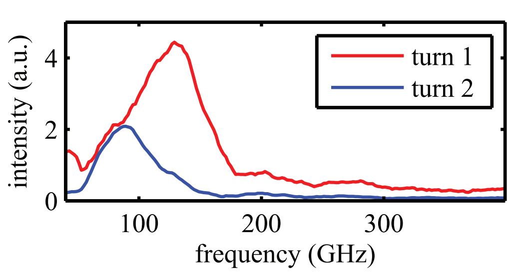

Figure 6: Coherent spectra of the first two turns (see text for details).

OUTLOOK

The new spectrometer supports the further characterization of the THz radiation at DELTA and serves as a diagnostics tool for the laser-electron interaction.

Further studies will include an operation of the spectrometer with the simultaneous readout of two detectors, the Schottky-barrier diode and the YBCO detector. This will allow for measurements in a continuous frequency range from about 50 GHz to 4 THz. This mode of operation is especially important in the view of the narrowband, frequncy-tunable THz source based on the chirped-pulse beating principle [15,16] which was tested in 2014 [7,17] and is currently under commissioning. This scheme allows for the generation of narrowband radiation by sending a chirped, uncompressed pulse from the laser amplifier through a Michelson interferometer. The laser pulses with a duration of several picoseconds are sinusoidally modulated due to the chirp and the relative delay introduced by the interferometer. Hence, the electron density is periodically modulated which results in a narrow radiation spectrum. In the past, the detection of sub-THz narrowband radiation during the measurement campaigns was limited by the spectrometer.

Furthermore, the spectrometer setup will be upgraded to a single-output spectrometer which uses a two-fold transition through the interferometer [9]. Hence, the effective delay of the interferometer and the spectral resolution are doubled which improves the overall performance of the device.

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