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OBSERVATION OF COHERENT PULSES IN THE SUB-THz RANGE AT DELTA*

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Abstract

Coherent ultrashort 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. The turn-by-turn evolution of the radiation spectrum is known to shift to the sub-THz regime after the initial laser-electron interaction. Recently, an ultrafast YBCO-based THz detector has been permanently installed and a Schottky diode has been tested at the THz beamline. Measurements with these detectors showing the temporal evolution of the coherent signals after several revolutions are presented. Furthermore, the concept of a recently designed Fourier-transform spectrometer optimized for the sub-THz region is shown.

INTRODUCTION

The 1.5-GeV electron storage ring DELTA operated by the TU Dortmund University is a light source with a circumference of 115.2 m and a revolution frequency of 2.6 MHz. Since 2011, a source for ultrashort VUV and THz pulses based on the coherent harmonic generation (CHG) principle [1, 2] was commissioned. At this source, 40-fs Ti:sapphire laser pulses interact with a short slice of an electron bunch in the first section of the electromagnetic undulator U250, causing an energy modulation of the electrons. The energy modulation is converted into a density modulation forming microbunches by a dispersive section (center of the U250). In the last part of the U250, the microbunches emit coherent VUV radiation at harmonics of the laser wavelength. Energy-dependant path-length differences in the subsequent bending magnets lead to the formation of a sub-picosecond dip in the longitudinal electron density which gives rise to coherent THz radiation. The filling pattern of the storage ring during the operation of the short-pulse facility is a single bunch or a hybrid pattern in which a single bunch is injected in addition to a multi-bunch train.

A dedicated THz beamline (BL5a) for the extraction of the pulses is part of the DELTA short-pulse facility [3]. The beamline uses telescopes consisting of toroidal aluminium mirrors to transfer the THz radiation over the radiation shielding wall to an optical table. The THz laboratory is equipped with an indium-antimonide hot-electron bolometer, an ultrafast detector (<17 ps FWHM response time) [4, 5] based on the high-temperature superconductor $YBa_2Cu_3O_7$ (YBCO) and a Fourier-transform spectrometer with an Si composite bolometer.

Optimization of the laser-electron interaction relies on THz radiation as a diagnostics tool to improve the spatial and temporal laser-electron overlap. In addition, the THz radiation allows for the investigation of the turn-by-turn evolution of the density modulation induced by the ultrashort laser pulse [6, 7]. Particle-tracking simulations based on *elegant* [8] showed that the electron density modulation is present for at least 10 revolutions after the initial laser electron interaction [6, 9]. Recently, coherent THz pulses were observed for even more revolutions by means of an ultrafast oscilloscope. Furthermore, in cooperation with the Karlsruhe Institute of Technology (KIT), a Schottky diode sensitive in the sub-THz range was used to detect the laser-induced radiation at DELTA.

DETECTION OF MULTI-REVOLUTION RADIATION PULSES

As a first device for the detection of coherent pulses at the THz beamline, a liquid-helium cooled InSb hot-electron bolometer has been used [3, 10]. Because the signal repetition time is 384 ns when DELTA is operated in single-bunch mode, the InSb detector with a rise time of 350 ns is not fast enough for the investigation of the temporal evolution of the laser-induced density modulation. After first test measurements with an NbN hot-electron bolometer (<160 ps response time) and a YBCO detector (see above) [6, 7], an ultrafast YBCO detector was permanently installed at DELTA.

Figure 1 shows the response of the YBCO detector to coherent THz radiation at BL5a at DELTA acquired with an ultrafast Keysight Z-Series DSA-Z 634A real-time oscilloscope providing a bandwidth of 63 GHz at a sampling rate of 160 GS/s. Due to the high bandwidth, weak signals after several revolutions are not broadened by the readout. Hence, the coherent signals were acquired for up to 20 turns after the laser-electron interaction. Previous simulations of the evolution of the electron density distribution and spectral measurements showed that only the first turn has a significant spectral content above 1 THz [6, 7, 9]. Accordingly, the in-

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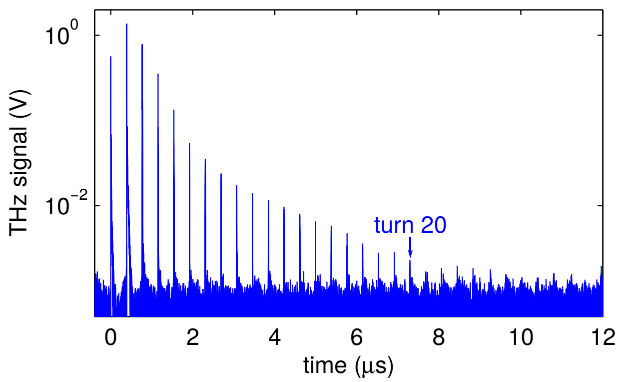

Figure 1: Multi-turn signals from the YBCO detector following a single laser-electron interaction at $t = 0$ acquired with a 63-GHz oscilloscope showing coherent signals for 20 revolutions.

vestigation of later signals requires a fast detector optimized for the sub-THz range.

Observation of Coherent Pulses Delayed by Half a Synchrotron Oscillation Period

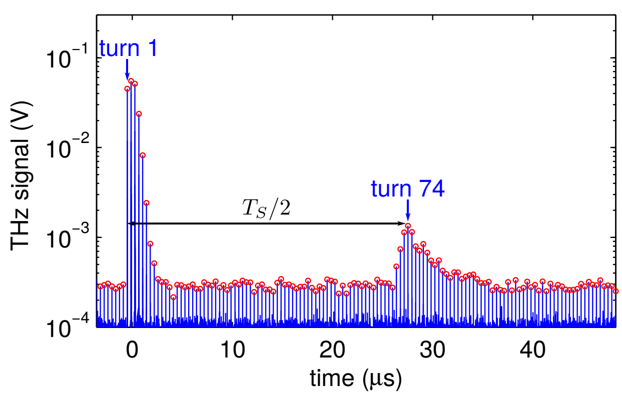

Figure 2: Observation of two pulse trains of laser-induced THz radiation with a time delay matching half a synchrotron oscillation period T_S.

Recently, measurements of coherent pulses using a Schottky diode were carried out in cooperation with KIT. The detector features a sensitivity range from 50 GHz to 1.2 THz. Figure 2 shows the detector signal measured at BL5a. Two pulse trains with a delay of $T_S/2$ were observed after only one laser-electron interaction at $t = 0$. Even though the initial laser-induced density modulation broadens during the subsequent revolutions the modulation is still present, while no coherent signal is visible between the two pulse trains. The rotation in the longitudinal phase space changes the width of the dip in the longitudinal electron density and inhibits the generation of coherent radiation visible. Hence, the measurement does not show a detector response between turn 20 and turn 70.

In order to investigate the generation of THz pulses after half a synchrotron oscillation period, a particle-tracking simulation using *elegant* [8] was performed. In this simulation, an energy-modulated distribution of 40000 electrons was tracked along 130 turns in the storage ring. As a measure proportional to the radiation spectrum, the squared Fourier transform of the longitudinal electron density was calculated.

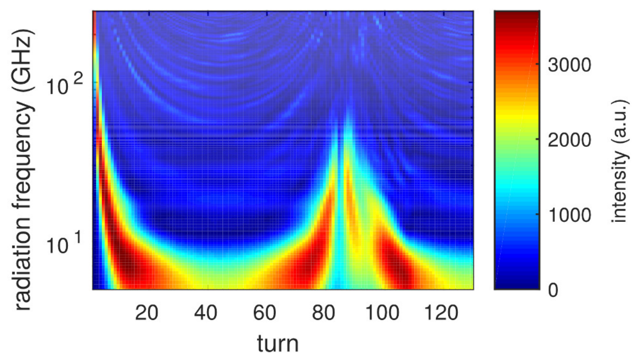

Figure 3: Simulated evolution of the Fourier-transformed longitudinal electron density distribution as function of the number of revolutions.

Figure 3 shows the evolution of the Fourier-transformed electron density distributions. After about 20 turns, the radiation frequency has decreased to less than 10 GHz, which is below the beamline cut-off frequency. Around turn 80, the frequency shifts to the range of 50 GHz again. This can be understood regarding the longitudinal phase space (Fig. 4). After half a synchrotron oscillation period, the slice of energy modulated electrons has rotated by 180°, giving rise to (sub-)ps structures in the density modulation.

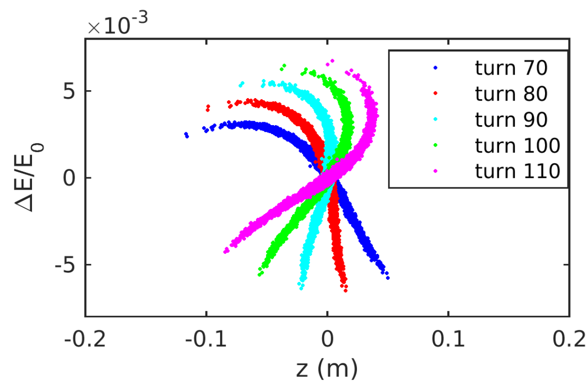

Figure 4: Distribution of energy-modulated electrons in the longitudinal phase space several revolutions after the laser electron interaction.

Taking the spectral response of the detector into account, the detector signal can be estimated based on the simulation data. The result is shown in Fig. 5. The appearance of two pulse trains seen in the measurement resembles the simulation result. The simulated signal shows a local minimum at turn 83 which is not visible in the measurement. The different pulse-train delays in the simulation and the measurement are caused by slightly different synchrotron oscillation frequencies.

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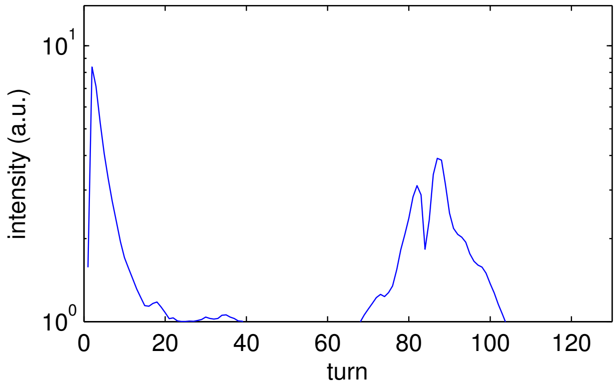

Figure 5: Schottky-diode response derived from particle-tracking simulation.

AN IMPROVED POLARIZING SPECTROMETER

As mentioned before, the evolution of the density modulation is shifted away from the THz region to the sub-THz frequency range after several revolutions. An evacuated commercial FT-IR spectrometer is available at the DELTA THz beamline. The observable spectrum ranges from 1.3 THz (beamsplitter absorption) to 7 THz (transmission limit of a z-cut quartz window) [6]. Therefore, the signals after the first turn are not detected by the spectrometer.

To carry out spectrometric measurements below 1.3 THz an FT-IR spectrometer based on the Martin-Puplett interferometer [11] was designed [12]. The approach uses only two wire-grid polarizers which are tilted by 45° with respect to their polarization planes. The commonly used third (output) polarizer is replaced by a plane mirror which redirects the beam into the spectrometer while leaving the polarization unaffected. Hence, the beam passes back through the complete spectrometer while being reflected at the input polarizer due to the interferometer-induced polarization change. The evolution of the polarization along the beam path in the spectrometer is shown in Fig. 6.

This method has the benefit of being cost-effective because only two wire-grids are needed. In addition, the resolution is expected to be increased by a factor of two compared to the classical approach because the path length difference of the interferometer is introduced twice. This allows for a more compact design of a high-resolution spectrometer. Furthermore, the two-pass spectrometer also allows to increase the scanning speed by a factor of two. At DELTA, the design of a spectrometer according to Fig. 6 has been finished and the construction is almost completed. First measurements with the fully commissioned device are expected for summer 2015.

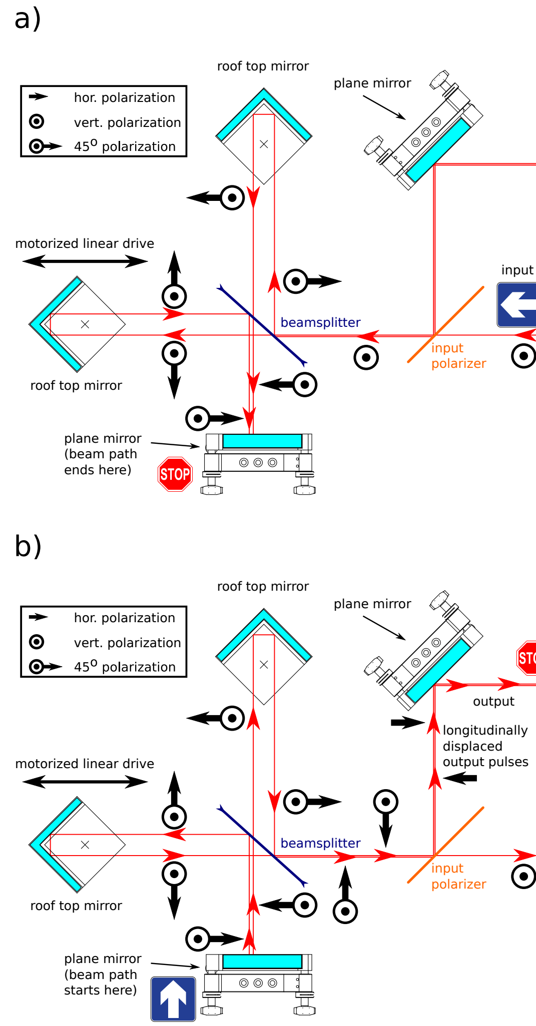

Figure 6: Schematic of the beam path in the two-pass polarizing Fourier-transform spectrometer. The beam polarization is shown for the a) forward and the b) backward pass through the spectrometer.

OUTLOOK

The permanent installation of the YBCO detector further improved the insight into the temporal evolution of the energy-modulated electron distribution. More detailed investigations with the Schottky detector will be carried out soon. After the full commissioning of the recently designed Fourier-transform spectrometer, the spectral measurements will be extended to the sub-THz scale. In addition, the installation of a setup to generate narrowband THz radiation [6] is planned for the next years.

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