TEMPORAL AND SPECTRAL OBSERVATION OF LASER-INDUCED THz RADIATION AT DELTA*

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Abstract

Coherent THz pulses caused by a laser-induced density modulation of the electron bunches are routinely produced and observed at DELTA, a 1.5-GeV synchrotron light source operated by the TU Dortmund University. New measurements performed with a fast hot-electron bolometer allow insight into the turn-by-turn evolution of these pulses. Furthermore, first results from a Fourier transform infrared spectrometer, which is currently under commissioning, are presented.

INTRODUCTION

Operated by the TU Dortmund University, DELTA is a 1.5-GeV electron storage ring with a circumference of 115.2 m and a revolution frequency of 2.6 MHz.

Starting 2011, a new short-pulse facility based on the so-called Coherent Harmonic Generation (CHG) principle [1] has been established and commissioned at DELTA [2, 3]. Caused by a laser-electron interaction in the electromagnetic undulator U250, coherent ultrashort VUV pulses are generated with a repetition rate of 1 kHz and delivered to a diagnostics hutch (beamline BL4) or an experimental station with a plane-grating monochromator (beamline BL5) [4].

Due to the laser-induced energy modulation of a short section in the electron bunch, the longitudinal dispersion of the subsequent magnet lattice leads to a sub-picosecond modulation of the electron density, which gives rise to coherent radiation pulses in the THz regime. Similar to so-called femtoslicing experiments, e.g., at BESSY [5], these pulses are extracted from the storage ring by a dedicated THz beamline (BL5a) [6].

The THz radiation is routinely used as a diagnostics tool for the laser-electron overlap in the U250 and for studying the electron bunch profile under variation of several storage ring parameters [7]. Recent experiments performed in cooperation with the KIT in Karlsruhe allow insight into the turn-by-turn evolution of the laser-induced density modulation. Furthermore, first spectra of the coherent THz pulses could be recorded by a newly installed FT-IR spectrometer.

SETUP

Figure 1 shows a sketch of the current setup at the THz beamline (BL5a), comprising a water-cooled gold-coated copper mirror (1), an evacuated beamline with four remotely controllable toroidal aluminium mirrors (2), and a z-cut quartz window (3) separating the beamline vacuum from the ultrahigh storage-ring vacuum. Until 2012, the beamline ended after the fourth mirror with an additional z-cut quartz window (4) and THz radiation was detected using a liquid-helium-cooled InSb hot-electron bolometer (5) with a sensitivity range of 60 to 500 GHz and a response time of about 1 μs.

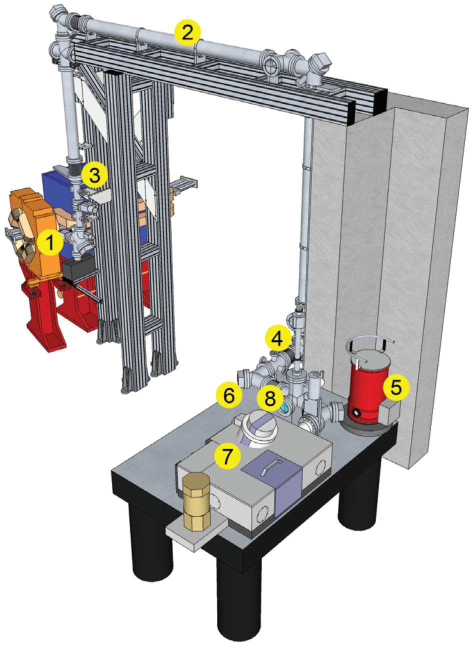

Figure 1: Sketch of the THz beamline. See text for details.

After a major upgrade in the beginning of 2013, the vacuum beamline including additional focusing mirrors continues on an optical table (6) and is directly connected to a vacuum FT-IR spectrometer (Bruker Vertex 80v), which uses a liquid-helium-cooled Si bolometer as detector (7). A spectral range of 0.3 to 240 THz can be covered with a maximum resolution of 1.8 GHz. Selectable by a mirror on a linear-rotary feedthrough (8), the THz pulses can still be coupled out into air and sent to the InSb bolometer (5).

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RECENT RESULTS

Turn-by-Turn Observation of THz Pulses

In November 2012, a NbN-based hot-electron bolometer with a response time of less than 160 ps and a frequency range of 160 GHz to 3 THz [8, 9] from the KIT in Karlsruhe was used at DELTA in order to study the evolution of the laser-induced density modulation over several revolutions in the storage ring. With a polarizer used as a beam splitter, THz radiation could be detected simultaneously with the NbN and the slower InSb bolometer.

Figure 2 shows a comparison between both available detector signals. At 0 μs, a laser pulse interacts with a single bunch in the undulator U250. When the single bunch passes beamline BL5a, a first coherent THz signal is detected by the NbN bolometer ('turn 0'). As the InSb bolometer shows no turn-0 reaction, the spectral maximum of this THz pulse is expected to be above 1 THz, which is consistent with simulation results [6].

After one revolution in the storage ring (384 ns), the single bunch emits another coherent THz signal ('turn 1'), which is also detected by the InSb bolometer with about 350 ns rise time. Signals from even later revolutions can be detected by the NbN bolometer and might also be indicated by the modulation of the InSb signal's falling edge. The spectra from later turns are therefore expected to be shifted to lower frequencies.

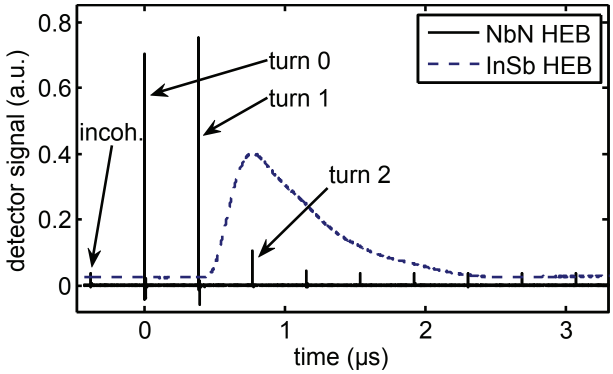

Figure 2: Signals from the InSb and NbN bolometers showing the THz radiation emitted by a single bunch over several storage ring revolutions (384 ns revolution time) after a single laser shot at 0 μs.

Under further optimized conditions, coherent THz signals from up to 8 revolutions in the storage ring could be detected by the NbN bolometer (Fig. 3). As the attenuator used during this and several other measurements also acted as a low-pass filter, the turn-0 signal is suppressed.

Figures 4 and 5 show the intensity of NbN bolometer signals from several turns under variation of the transverse overlap (by moving a mirror in the laser beamline) and the longitudinal overlap (by shifting the laser pulse delay). The decreasing length of the longitudinal profiles indicates that the density modulation is weaker in later turns for a non-optimal longitudinal overlap. The transverse profiles are getting broader, indicating that coherent THz signals from later turns might be dominated by effects in the transverse electron distribution rather than in the longitudinal one. Simulations of the radiation process based on a one-dimensional (longitudinal) theory support this assumption, as they show almost no longitudinal density modulation after one turn.

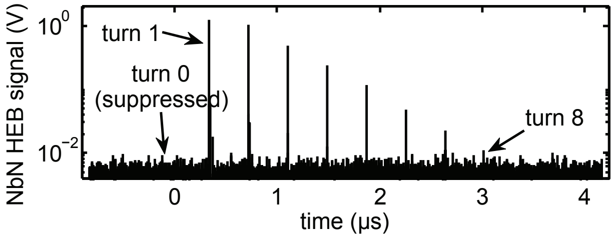

Figure 3: NbN bolometer signal from up to 8 revolutions of a single bunch after a single laser shot. Turn 0 is suppressed by a low-pass attenuator.

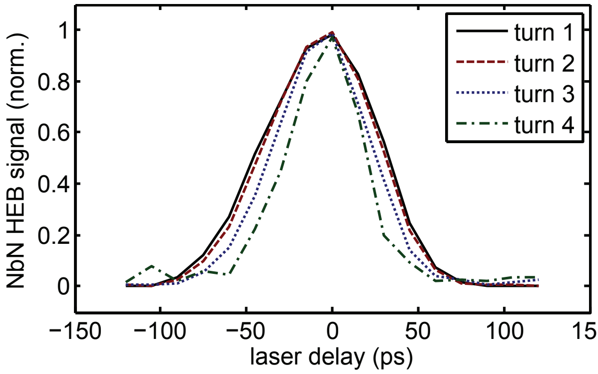

Figure 4: NbN bolometer signals showing THz radiation from revolutions 1 to 4 under variation of the laser delay (normalized to the intensity at optimum overlap).

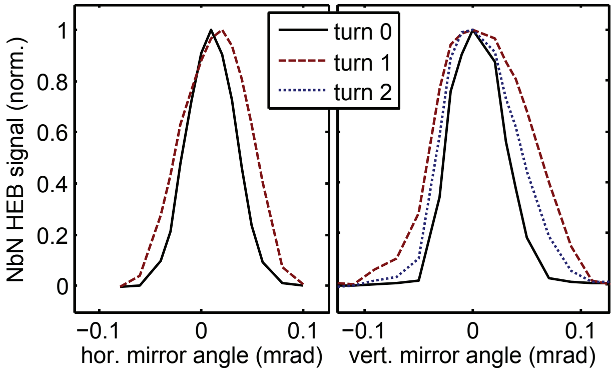

Figure 5: NbN bolometer signals showing THz radiation from revolutions 0 to 2 under angular variation of a mirror in the laser beamline (normalized to the intensity at optimum overlap).

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First Spectral Measurements

First spectra of the laser-induced THz radiation have been recorded with the newly installed FT-IR spectrometer. Shown in Fig. 6 is the spectral intensity of radiation from the THz beamline BL5a with and without laser-electron overlap. A separately measured spectrometer background (recorded with radiation from BL5a blocked) was subtracted from both spectra.

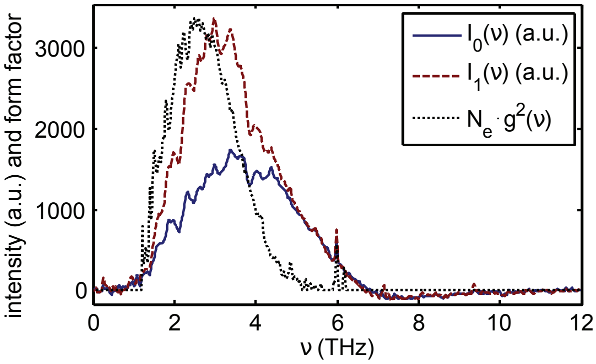

Figure 6: THz spectra without (I_0) and with (I_1) laser-electron overlap (background subtracted, equally scaled) and resulting form factor $N_e \cdot g^2(\nu)$.

Compared to the synchrotron radiation spectrum of a bending magnet, which would be almost constant over the frequency range shown, the incoherent spectrum I_0 appears to be quite narrow. It is given by

$$I_0(\nu) = N_e \cdot I_e(\nu) \cdot t(\nu) \tag{1}$$

with the number of electrons N_e in the single bunch, the single electron spectrum $I_e(\nu)$, and the beamline transfer function $t(\nu)$. The low-frequency cut-off due to the beam splitter inside the spectrometer is well understood. The high-frequency cut-off might be caused by the window in BL5a (Fig. 1, (3)), although the transmission of z-cut quartz should extend up to 10 THz. Further investigation and possibly the replacement of this window will follow.

The spectrum with laser-electron overlap I_1 lies well within the accessible frequency range and is given by [6]

$$I_1(\nu) = N_e \cdot I_e(\nu) \cdot \left[1 + N_e \cdot g^2(\nu)/2600\right] \cdot t(\nu) \tag{2}$$

with the form factor $g(\nu)$, which is the Fourier transform of the longitudinal electron density. The numerical factor 2600 takes into account the number of incoherent bunch signals which are detected between two coherent signals (2.6 MHz revolution frequency, 1 kHz laser repetition rate). Using equations 1 and 2, the form factor can be calculated by

$$N_e \cdot g^2(\nu) = 2600 \cdot \left(\frac{I_1}{I_0} - 1\right). \tag{3}$$

The longitudinal electron density modulation can be estimated by an inverse Fourier transform (Fig. 7). To obtain the correct sign of the density function, which can not be reconstructed from an amplitude spectrum only, the sign is partially flipped in accordance with the model described in [6]. A fit by the sum of two zero-centered Gaussian distributions reveals widths in the sub-picosecond regime, which is similar to previous simulation results [6].

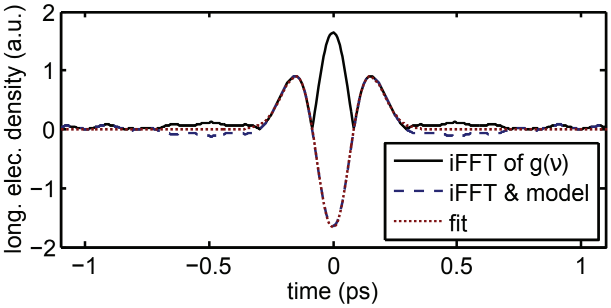

Figure 7: Longitudinal electron density based on an inverse Fourier transform (iFFT), combined with a model from [6] (iFFT & model), and a double-Gaussian fit thereof.

OUTLOOK

A new 3D simulation taking into account transverse effects in the electron density is planned in order to understand the multi-turn signals discussed above. Commissioning of the FT-IR spectrometer will be continued, e.g., by suppressing the spontaneous background using a lock-in amplifier locked to the 1 kHz laser repetition rate. Future plans include the permanent installation of a fast THz detector and the generation of narrow-band THz radiation in cooperation with groups from PhLAM, Lille, and UVSOR, Okazaki [10, 11].

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REFERENCES

[1] R. Coisson and F. D. Martini, Phys. of Quant. Electron. 9, 939 (1982).
[2] H. Huck et al., Proc. of FEL 2011, Shanghai, 5.
[3] S. Khan et al., Sync. Rad. News 24, No. 5, 18-23 (2011).
[4] M. Huck et al., this conference (WEPWA005).
[5] K. Holldack et al., Phys. Rev. Lett. 96, 054801 (2006).
[6] M. Höner et al., Proc. of IPAC 2011, San Sebastián, 2939.
[7] P. Ungelenk et al., Proc. of IPAC 2012, New Orleans, 768.
[8] A. D. Semenov et al., Proc. of IRMMW-THz 2009, 5324688.
[9] A.-S. Müller et al., Proc. of PAC 2009, Vancouver, 1153.
[10] S. Bielawski et al., Nature Physics 4, 390 (2008).
[11] C. Evain et al., PRST-AB 13, 090703 (2010).