SPECTRAL FINGERPRINTS OF FEMTOSLICING IN THE THz REGIME*

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Abstract

Femtosecond (fs) coherent THz pulses are observed as a consequence of laser-induced energy modulation of electrons in the BESSY II storage ring in order to generate fs x-ray pulses. The spectral characterization of these coherent pulses as performed by fourier transform spectroscopy (FTIR) demonstrates their diagnostic potential and that this novel THz source of excellent signal-to-noise is sufficiently strong and stable for time-resolved THz spectroscopy.

INTRODUCTION

The layout of the BESSY fs x-ray source – based on an elliptical undulator – being now in routine operation [1], is illustrated by Fig. 1. Typically, here pulses from a Ti:sapphire laser system (wavelength λ_L=780 nm, pulse duration 45 fs (fwhm), pulse energy E=2.1 mJ at 1 kHz repetition rate [2] co-propagate with electrons of 1.7 GeV energy in an undulator (U139, the "modulator", a planar undulator with a period length of λ_U=139 mm and 10 periods at a deflection parameter of K=16). A detailed description of the layout and operation of the novel source, which is based on femtoslicing [3], is given in [1]. The laser-induced energy modulation of electrons in the modulator also causes a longitudinal density modulation emitting coherent THz pulses at a THz-radiator (bending magnet, see Fig. 1)[7]. Coherent signals of that kind have been observed at the ALS [4], at BESSY [5] and (very) recently also at the SLS [6]. Temporal- and spectral properties of coherent THz pulses, their pulse energy of a few nJ and their evolution over many revolutions have been already reported in [7]. The present paper describes the potential of applying rapid-scan THz spectroscopy as diagnostics of laser-electron interaction and shows by examples, that this novel coherent THz source is sufficiently strong and stable for time-resolved spectroscopy experiments up to 3 THz.

PRINCIPLE

The coherent spectral power density emitted by the longitudinal density modulation in the THz radiator at radiation frequencies ω can be written as:

$$P_{coh}(\omega) \sim \left(N_0 \frac{\sigma_L}{\sigma_0}\right)^2 p(\omega) |F(\omega)|^2 . \qquad (1)$$

Here, σ_L is the laser pulse length, N_0 is the number of electrons in the bunch, σ_0 is the bunch length, $p(\omega)$ is the incoherent power emitted by a single electron and $|F(\omega)|$ the magnitude of the Fourier transform of the longitudinal electron density. As discussed in [7], the THz intensity from the slice may exceed the incoherent spectral power density $P_{inc} = N_0 p(\omega)$ from the regular bunch by a factor of 10^4. Even for slicing in a multibunch fill, the incoherent radiation of up to 400 regular electrons does not exceed the THz power from one slice. This is the reason why THz detection is possible without gating on the individual bunch. Basically, $|F(\omega)|$ can be measured by correcting power spectra, obtained by THz spectrometers, by the transmission of the beamline. On the other hand, if the beamline has a rather flat transmission over the spectral range of interest, the fourier transform of the density modulation can be measured moreless directly. An "afterglow" of the THz pulse as well as spontaneous bursts of coherent synchrotron radiation (CSR) have to be further considered [7]. By designing a special THz beamline [5], modifying spectrometers (originally made for thermal sources) and using time resolved detection techniques, spectral flatness over the range of interest as well as removal of sub-THz backgrounds have been achieved in the examples described below.

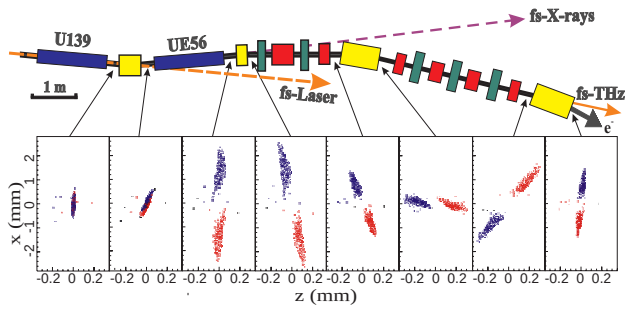

Figure 1: Footprint of the BESSY femtoslicing facility and calculated transverse evolution of energy-modulated electrons along the magnetic lattice. After laser-induced modulation of the electron energy in the modulator (U139), fs x-rays are emitted by the radiator (UE56) after angular short pulse separation by the intermediate bend magnet (yellow). Laser-induced energy modulation is probed by spectra from coherent THz pulses at a bending magnet (yellow, the "THz radiator") 11 m downstream of the modulator.

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INSTRUMENTATION AND DETECTION

Spectrometers

The spectroscopic setup to measure time resolved THz spectra (from the first turn) is illustrated by Fig. 2. Either a step-scan spectrometer as used in [7] or a VERTEX 70 rapid-scan FTIR spectrometer [8] are available. The latter was extended to the far infrared by using a 25 μm beamsplitter and a large entrance aperture. The available bandwidth ranges from 10 cm^{-1} to 150 cm^{-1} (4.5 THz). The high energy cut-off is given by a z-cut quartz window separating the storage ring vacuum from the THz beamline. Using the VERTEX, there is no need to use external filters to suppress sub-THz spectra from later turns [7], but important after the step-scan spectrometer, which has a low energy cut-off at 2 cm^{-1} (50 GHz). THz pulses after the spectrometer are detected either with a 4.2 K- Si-bolometer (broad band 10 THz, 0.2 ms time resolution) or 4.2 K InSb-hot-electron bolometers (1 THz low frequency cut-off, 0.3 μs time resolution) as well as broad-band detectors operated at room temperature (1 ms time resolution) [8]. An ideal detection scheme would consist of a broad-band *and* fast detector being able to cover the spectral range and allowing a gating on the sliced bunch. Using the fast InSb detector a gating on one turn is possible, but only the low energy part of the spectrum upt to 1 THz can be measured. Therefore, in the present case, for spectral characterization of coherent THz pulses, the slower Si-bolometer at 4.2 K suitable for broadband spectral measurements was employed together with a 370 cm^{-1} (18 THz) low-pass cold filter and the VERTEX 70 spectrometer [8], which was modified for pulse detection.

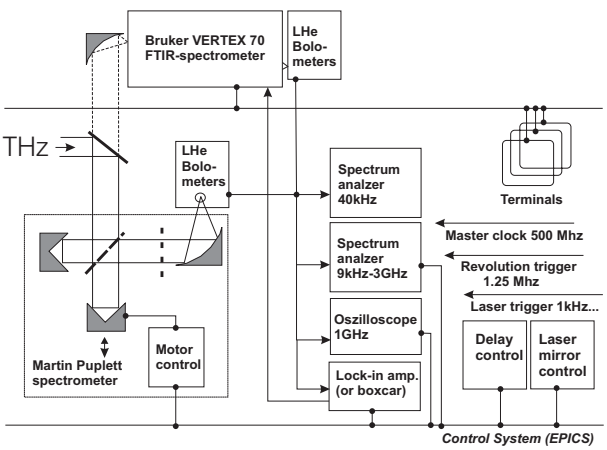

Figure 2: Instrumentation, detection- and trigger schemes for time-resolved spectral characterization of laser-induced coherent THz pulses at BESSY.

Detection Techniques

THz detector signals at the laser rate of 1 KHz can be analyzed either with (i) spectrum analysers, an oscilloscope (ii), a boxcar-integrator (iii) or a lock-in amplifier (iv). For step scan spectroscopy preferentially (i) and (ii) are used, while rapid-scan spectroscopy is done feeding the outputs of (iii) or (iv) to the bolometer signal input of the VERTEX 70 spectrometer. Examples below are measured with a lockin-amplifier (Perkin Elmer 7280, 0.5 Hz-2 MHz bandwith) using a trigger derived from the laser and synchronized to the bunch clock (or its harmonics) as a reference signal.

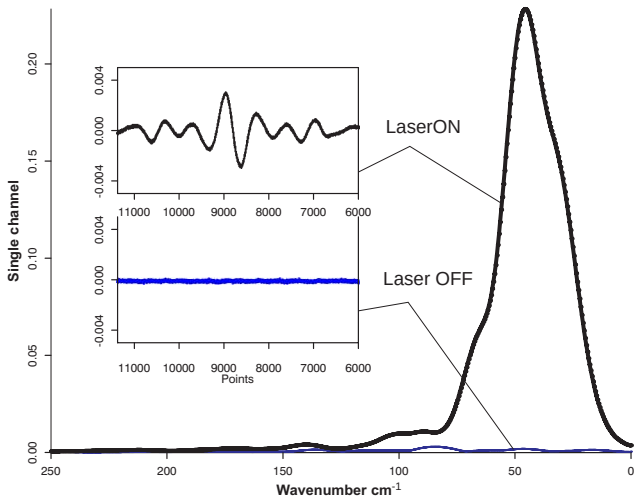

Figure 3: Typical raw interferograms and rapid-scan FTIR spectra measured at 4 mA bunch current during a regular femtoslicing shift. The acquisition time is 3 s at 10 cm^{-1} spectral resolution.

RESULTS

Energy Modulation

Raw interferograms in rapid-scan mode are plotted in the inset of Fig. 3 together with corresponding spectra for laser-on and laser-off (at 2.1 mJ laser-pulse energy, 0.9% energy modulation, 4 mA bunch current), respectively. A signal-to-noise of 2% is observed for single scans between 20 and 100 cm^{-1}. Because incoherent synchrotron radiation from the regular bunches (in multibunch) is 2-3 orders of magnitude lower, only a noise spectrum is measured without laser. The peak intensity in the spectra strictly scales with the square of the bunch current but the spectral shape sensitively depends on the laser-induced energy modulation. A laser pulse co-propagating with an electron bunch in an undulator modulates the electron energy if the resonance condition $\lambda_U = \left(\lambda_L/2\gamma^2\right)\left(1+K^2/2\right)$ is fulfilled, i.e., if the laser wavelength λ_L equals the wavelength of spontaneous undulator radiation. At the U139 it corresponds to a magnetic gap of 19.85 mm. In Fig. 4, THz spectra were acquired while the resonance condition in the modulator was detuned, decrasing the energy modulation. The shape of the resonance curve (right) integrating different parts of the spectra (left) was studied. The low energy tails more rapidly decrease than the high energy parts, lead-

ing to different shapes of the resonance curve. Assisted by simulations, it can be explained by the fact that wavetrains from the two side lobes in the longitudinal density modulation destructively interfere, producing the low-energy depletion in THz spectra, while the high energy part is mainly determined by the "dip" in electron density, being less sensitive to energy modulation. In general, at very high energy modulation the bunch approaches the CSR spectrum from a short Gaussian bunch, since energy-modulated electrons are longitudinally dispersed over large distances not emitting coherently. At small energy modulation the distribution is similar to a limited sine-modulation on the bunch emitting a line spectrum. By cross-calibration with other methods [9], it was found that if the low-energy half value of the spectra reaches 20 cm^{-1}, an energy modulation of 0.9% is achieved. The width of these spectral "fingerprints" represents another important tool for setting up the fs xray source.

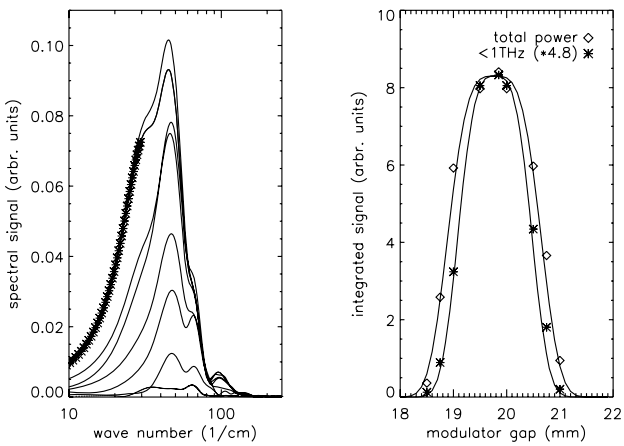

Figure 4: Evolution of rapid-scan THz spectra (left) while detuning the resonance in the modulator. Two resonance curves fromt different integrated parts of the spectra are also shown (right).

Pulse Length

Moving the extraction mirrors at the THz beamline, also radiation from the upstream dipole fan at - 30 mrad from the edge can be accepted. According to the numerical simulations illustrated again in the inset of Fig. 5, a shorter longitudinal density modulation is expected there. THz spectra mesured for both sources show, that now the high energy tail and the maximum shifts to higher frequencies as expected. Repeated spectra, plotted together for each case, demonstrate the available signal-to-noise, which is exclusively given by fluctuations of the laser-electron interaction rather than by statistics. Spectral features at 40, 60 and 80 cm^{-1} arise from residual absorption caused by the dry ambient atmosphere within the spectrometer.

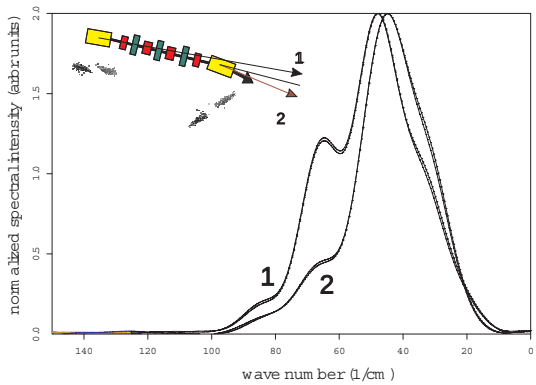

Figure 5: Comparison of normalized THz spectra from upstream and downstream dipole after the slicing section. The inset indicates that a shorter longitudinal density modulation is expected at the upstream dipole which is 5.2 m closer to the modulator.

SUMMARY AND OUTLOOK

Spectral characterization of laser-induced THz pulses can be performed at BESSY with excellent signal-to-backround by rapid-scan FTIR spectroscopy. The shape of the spectra allows on-line diagnostics of the laser-induced density modulation of the electrons. Because the source accompanies the operation of the fs x-ray source, time-resolved THz spectroscopy experiments are possible in regular user operation. Real-time reconstruction of the density modulation as well as time-domain THz experiments employing a part of the laser power (arriving with variable delay at the THz beamline) as well as time domain cross-correlation of fs laser- and THz pulse are in preparation.

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