CHARACTERIZATION OF SINGLE-CYCLE THz PULSES AT THE CTR SOURCE AT FLASH

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Abstract

At the coherent transition radiation (CTR) source at the Free-Electron Laser in Hamburg (FLASH) at DESY, single-cycle THz pulses with MV/cm electric field strengths are generated. We present the temporal and spatial characterization of this source with the technique of electro-optic sampling using a laser system synchronized with the accelerator to better than 100 fs. This method offers a quantitative detection of the electric field of the THz pulses in the time domain. Compared to other electron accelerator driven sources like undulator radiation, the transition radiation source provides pulses with a high bandwidth and durations shorter than one picosecond. This enables time-resolving and non-destructive experiments with radiation in the THz regime including THz pump / THz probe experiments. Broadband and intense THz pulses are expected to be valuable tools for the study of dynamics of excitation of complex materials in transient electric and magnetic fields.

INTRODUCTION

Far-infrared (FIR) radiation with wavelengths from 3 µm to 3 mm or frequencies in the terahertz (THz) regime offers the possibility for the non-destructive investigation of non-linear effects in various materials [1, 2, 3].

In addition to laser-driven sources [4], electron accelerator-based sources, i.e. undulator radiation, light generated in the free-electron laser (FEL) process and transition radiation offer single- or few-cycle THz pulses of microjoule pulse energy and MV/cm electric field strengths [5].

Free-electron lasers require a peak current of several kiloamperes for lasing [6] which enables in parallel coherent transition radiation sources for THz generation.

When a charged particle passes the boundary of two media with different dielectric constants, transition radiation is emitted [7]. For a bunch of charged particles, a coherent superposition occurs for wavelengths longer than the bunch length. The spectral intensity distribution $dU/d\lambda$ now depends on the number of particles in the bunch N squared and on the 3-dimensional form factor F [8].

$$\frac{dU}{d\lambda} = \left(\frac{dU}{d\lambda}\right)_{\text{one particle}} \cdot \left(N + N(N-1) \cdot |F(\lambda)|^2\right)$$

A well established method for detection of THz radiation is the electro-optic sampling using a scanning delay (EOS) [9]. The *electro-optic* or *Pockels* effect is the induced change in birefringence of a medium by external electric fields and can be probed by laser pulses. In the electro-optic crystal, the incident linear polarization of the laser is transformed into an elliptical polarization state depending linearly on the electric field strength applied on the crystal. Using an analyzer consisting of a retarder and a Wollaston beam splitter, two orthogonal polarization components are separated and detected by two photo detectors in a balanced detection scheme. Without the THz field, the analyzer is set for equal intensities I_1 and I_2. In the presence of the electric field, the photo detector intensities are modulated and the electric field strength E can be deduced following

$$\begin{aligned}\Gamma(\alpha) &= \frac{\pi\, d}{\lambda}\, n_0^3\, t\, E\, r_{41}\, \sqrt{1 + 3\cos^2(\alpha)} \\ &= \sin^{-1}\left(\frac{I_1 - I_2}{I_1 + I_2}\right)\end{aligned}$$

with the laser wavelength λ, the crystal refractive index n_0 and thickness d, the Fresnel coefficient for reflective losses t and the angle α between the optically active crystal axis X and the THz field E [10]. The Pockels coefficient r_{41} is the response of the crystal in phase retardation.

The temporal resolution of EOS is restricted by the temporal laser pulse width as well as the phase matching bandwidth in $\langle 110 \rangle$ cut gallium phosphide (GaP) which is limited to frequencies smaller than 8 THz by a phonon resonance. Furthermore, the temporal jitter between the laser and the CTR pulses leads to temporal averaging and thus, to a reduction in peak field strength detected by EOS.

EXPERIMENT

The CTR source at FLASH is located behind the last accelerating module providing electron energies up to 1.2 GeV. The screen made of silicon of 380 µm thickness and coated with aluminum is placed in the electron beam pipe at an *off-axis* position horizontally shifted from the standard electron trajectory. A kicker magnet enables a complementary operation to the FEL by deflecting one electron bunch onto the screen out of a pulse train in 10 Hz repetition rate.

After passing through a wedge-shaped diamond window, the radiation is guided into an external laboratory by a transfer line of approx. 21 m length. An optical system of seven gold-coated toroidal and plane mirrors images the radiation source into the setup described below. The

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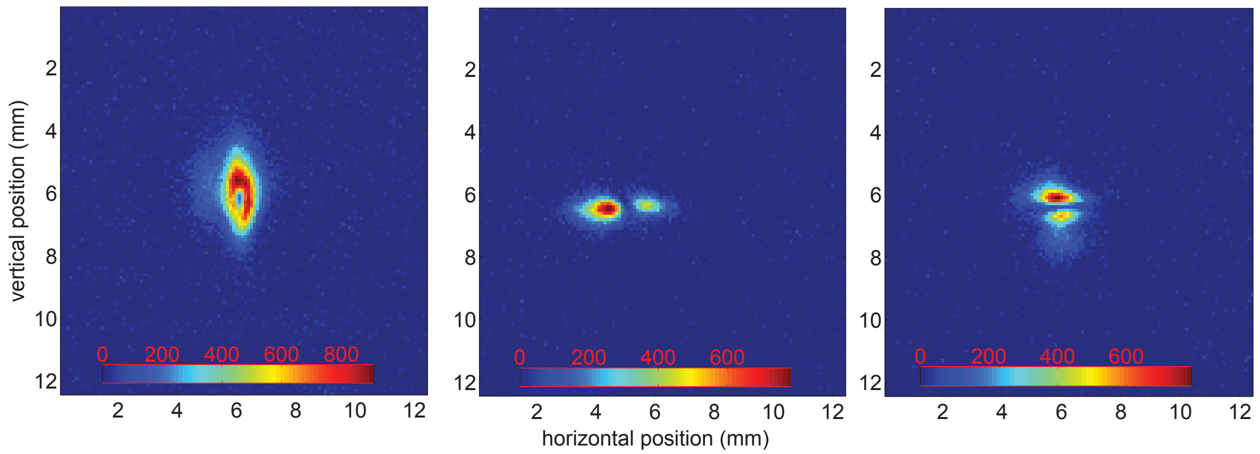

Figure 1: Transverse intensity distributions of CTR in the focus of the parabolic mirror. (*Left*) without polarizer, (*middle*) horizontal polarization and (*right*) vertical polarization. The camera pixel spacing is 0.1 mm.

transfer line is maintained in vacuum with pressures below 0.1 mbar to reduce transmission losses in humid air.

In the laboratory setup, the radiation from the CTR transfer line is focused on the detection crystal of gallium phosphide by a 3 inch parabolic aluminum mirror. The electro-optic signal, i.e. the phase retardation imprinted on a femtosecond laser pulse is acquired in balanced detection and digitized by fast analog to digital converters (ADCs).

The Ti:sapphire oscillator used in the experiment delivers laser pulses of approx. 30 fs length at a repetition rate of 81.25 MHz. The laser pulse train is synchronized to the accelerator master RF oscillator in a phase-lock loop (PLL) based on RF downmixing – Fig. 2. The laser pulse train is exposed to a photo detector providing a bandwidth larger than 10 GHz. The output signal also contains high harmonics of the laser pulse train repetition rate. The 16th harmonic is filtered out and compared in a mixer with the corresponding 1.3 GHz reference signal generated by the FLASH master RF oscillator. The mixer output is processed by a digital signal processing (DSP) unit which adjusts the laser cavity in length and hence, in repetition rate using a piezo-electric transducer. In this scheme, a timing stability between the laser pulse train and the master RF oscillator better than 40 fs (RMS) can be maintained. Taking into account the additional timing instabilities due to the acceleration process, the timing jitter between the electron bunches or the CTR pulses and the laser pulse train is estimated to be in the order of 100 fs [11].

The transverse beam profile is obtained by a pyroelectric camera Spiricon PyroCam III providing an active element with size of (12.4×12.4) mm and sensitivity from approx. 1 µm to $>$ 1 mm wavelength. The pixel spacing is 0.1 mm.

RESULTS

As depicted in the left of figure 1, the transverse intensity distribution of the radially polarized coherent transition

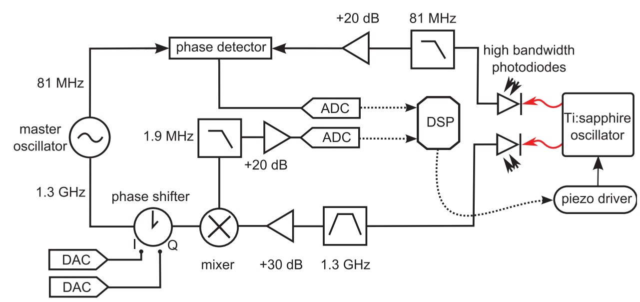

Figure 2: PLL for the synchronization of the laser pulse train with the accelerator.

radiation has a diameter of approx. 1 mm. Figure 1 also shows the horizontal and the vertical polarization filtered with a wire grid polarizer. The temporal pulse shape acquired by EOS is depicted in Fig. 3. The single-cycle pulse is clearly observable and has a length of < 500 fs. The peak field strength is 660 MV/cm. In this measurement, the THz beam was attenuated with a pair of polarizers to avoid the effect of over-rotation in the crystal due to a phase retardation Γ larger than π [10]. Regarding the non-ideal transmission of the polarizers, the electric field strength of the THz pulse is in the order of one MV/cm. The spectrum included in Fig. 3 acquired by Fast Fourier Transform indicates a spectral bandwidth of more than 2.5 THz [13].

The electron beam generating CTR had an energy of 500 MeV and the bunch charge was 0.6 nC.

OUTLOOK

The current RF based synchronization described in this paper is going to be extended by optical synchronization techniques enabled by the optical synchronization system at FLASH. In the method of optical cross-correlation of laser pulses by an optical reference and those of the Ti:sapphire laser, a timing stability better than 50 fs with

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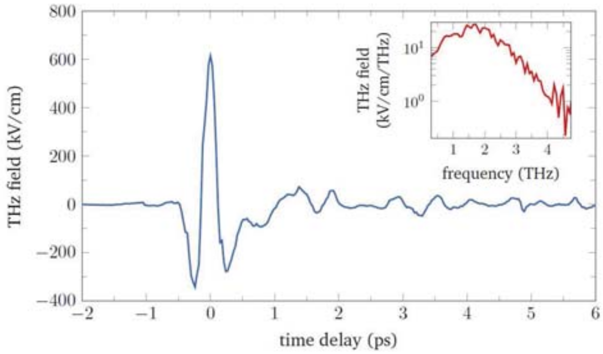

Figure 3: Temporal THz pulse shape acquired by EOS and the spectrum calculated by Fast Fourier Transform [13].

respect to the electron bunches is expected [12]. This will increase the resolution and the peak THz field detected by EOS by reducing the averaging effects due to timing instabilities.

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