Time-resolved THz emission from laser-accelerated electron bunches

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Introduction

Electron acceleration with lasers has recently created renewed interest through the observation of strong monoenergetic features in the electron spectrum, paired with a very low emittance of the accelerated beams[1-3]. These achievements reflect the advances in high-intensity laser technology, which allow for the first time to reach intensities and pulse durations suitable for approaching the highly nonlinear broken-wave regime of electron acceleration in plasmas, first reported in 3D PIC simulations by Pukhov [4]. In this regime there is a near-complete blow-out of electrons from the region of the laser pulse, leaving behind an electron void ("bubble") travelling behind the pulse. Such a bubble constitutes a quasi-stable region of acceleration fields, in which electrons are trapped and accelerated with the same phase resulting in a monoenergetic peak in the electron spectrum.

This experimental breakthrough might open the path for further practical exploitation of laser-accelerated electron bunches, e.g. for developing a table-top GeV accelerator or generating UV radiation in an undulator or optical wiggler scheme. In order to experimentally pursue and optimize these applications, a complete characterization of the bunch phase space is desirable.

To date, however, such studies have been limited to spectral, divergence and bunch-charge measurements. The investigation of the temporal structure of the laser-accelerated electron bunches has so far only been achieved using a multi-shot scanning technique. Given the large shot-to-shot variations in the electron-bunch spectrum and charge, these results can only give a rough estimate of the true bunch duration.

Here we report on the first single-shot time-resolved study of these electron bunches using the THz transition radiation emitted by the electrons crossing a material boundary. For a sufficiently sharp boundary, the duration of the radiated field reflects the duration of the electron pulse.

Methodology

The experimental setup is depicted in Fig. 1. The main part of the ASTRA 45 fs laser pulse (400 mJ) was used to accelerate electrons in a gas jet analogous to the experiment of Mangles *et al.*[1]. The electron-bunch spectrum was characterized with image plates in a magnetic spectrometer or a PIN diode (magnet turned off) as a detector, and its charge by using an integrating charge transformer (ICT). While the ICT has a large aperture and detects electrons in a large energy and angular range, the PIN diode only records collimated electrons entering the spectrometer or X-rays generated by such collimated high-energy electrons hitting the entrance aperture. An aluminium tape of 50 μm thickness was installed 5 mm behind the gas jet as a source for transition radiation (TR). The TR was collimated and refocused into a 200 μm thick ZnTe crystal by a pair of off-axis parabolas (OAPs), the first of which had a central hole for the electrons and the drive laser. Between the OAPs a Teflon filter blocked any scattered radiation from the laser. Part of the ASTRA pulse was split off and (negatively) chirped to 5 ps duration in a Treacy-type grating compressor. This chirped

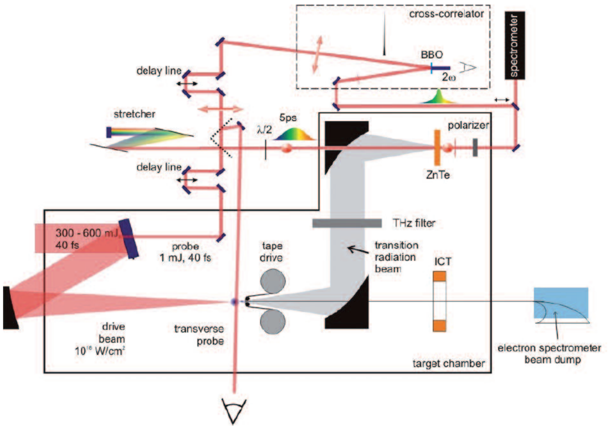

Figure 1. Experimental Setup.

probe (CP) pulse was sent through the ZnTe crystal and its polarization was changed by the transient birefringence induced by the THz field via the electro-optic Pockels effect, hereby encoding the temporal structure of the THz pulse into the CP polarization. This modified pulse was sent through a crossed polarizer setup to transfer the polarization pattern into an intensity modulation. By virtue of the CP's chirp, the temporal intensity modulation can also be detected in the spectral domain[5], which was used to time the CP relative to the electron pulse. Another part of the ASTRA pulse was used as a reference probe (RP) for a high-resolution cross-correlation measurement, directly in the time domain, representing the main diagnostic[6]. Finally, an interferometry setup utilizing a third, transverse probe (TP) was used to characterize the plasma density in the experiment.

Results

In order to draw conclusions from our measurements, we determined as many parameters of the electron bunch as possible, to allow for modeling of the experiment. The electron-energy spectrum was peaked in most cases, with strong shot-to-shot variations in its shape. Fig. 2 shows a number of typical spectra of individual shots, alongside the bunch charge of a series of shots (inset), with a mean value of ~30 pC. The interferometric measurement of the electron density yielded a value of 1.5×10^{19} cm^{-3}.

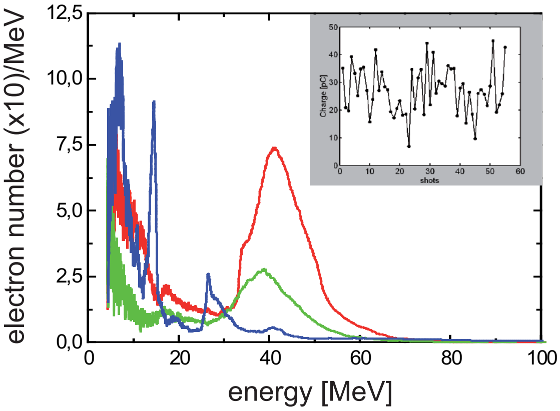

Figure 2. Electron spectra and bunch charge (inset).

Following a previous experiment in Jena, the Al foil tape was removed in the first part of the experiment, so that THz radiation emitted at the plasma-vacuum boundary was detected, analogous to the experiments by Tilborg et al. and Leemans *et al.*[7,8]. As shown in Fig. 3, a number of discrete half-cycle THz spikes were observed, with durations of ~300-400 fs and a separation of several ps. When the foil tape was added, all THz radiation from the gas jet was shielded by the tape and only a single half-cycle pulse (sometimes with a small pre- or postpulse) of ~200 fs duration was observed. When the gas jet was turned off, or the laser pulse was defocused, no signal was observed. The pulse height correlated with the signal of PIN diode inside the spectrometer.

Discussion

The electron spectra and numbers were used to model the angle- (or space) and time- (or frequency) dependent TR distribution generated by the electron bunch after exiting the Al foil following the lines of Tilborg *et al.*[9]. As a model case, we assumed a 40 MeV monoenergetic spike of 5×10^7 electrons on top of a 10 MeV exponential spectrum of 2×10^8 electrons (40 pC), emitted over a duration of 40 fs. If the THz wavelength is longer than the electron-bunch length, the fields from individual electrons add up coherently, which in effect leads to a half-cycle THz pulse resembling the bunch duration (see Fig. 4).

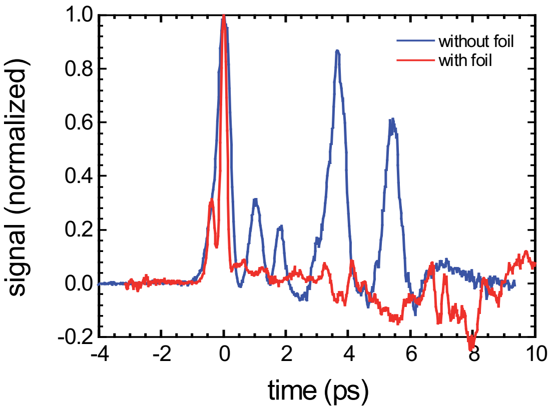

Figure 3. Measured single-shot THz signal with and without foil tape (signal in cross correlator).

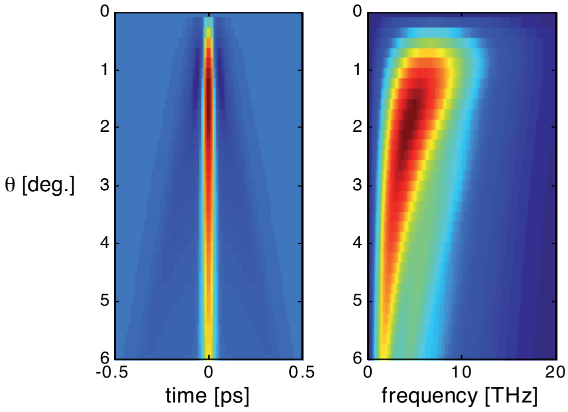

Figure 4. Temporal and spectral distribution of THz signal as a function of emission angle.

As depicted in Fig. 5, the simulated THz distribution was then propagated through a model of THz refocusing optics, including diffraction on the OAPs and absorption in the Teflon filter, yielding the spatio-temporal field distribution in the focus of the OAP, located at the surface of the ZnTe crystal (Fig. 5, Fig. 6c). Note that this distribution was calculated using scalar fields, which is a good approximation for an off-axis part of the focus, where the CP beam was located (0.5 mm away from the axis).

In the next modeling step, we tracked the THz pulse and the CP through the crystal, using the model of Casalbuoni *et al.*[10].

Since the electron pulse duration is expected to be of the order of or shorter than the laser-pulse duration, the THz spectrum could extend up to 25 THz and above. ZnTe, however, exhibits a strong phonon absorption line at 5.3 THz (Fig. 6a), and therefore signal frequencies above 4 THz are strongly attenuated by the crystal (Fig. 6b). This leads to a strong modification of the pulse spectrum and

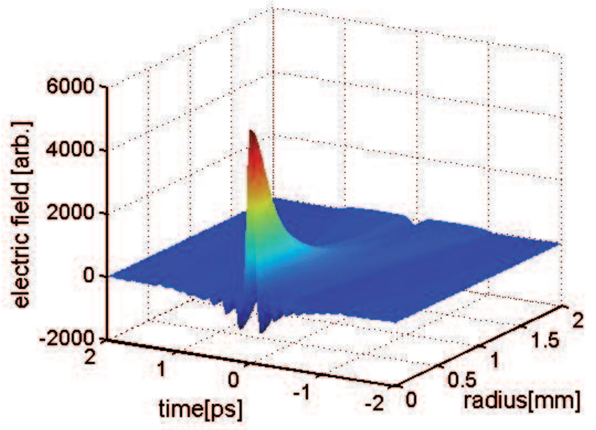

Figure 5. Temporal distribution in the focus of the second OAP (cf. Fig. 1), i.e. on the crystal surface. The CP beam crossed the crystal 0.5 mm from the center of the THz focus.

shape, which also imposes an upper limit on the intrinsic temporal resolution. Owing to the group-velocity mismatch between the TR and optical pulse some of the resulting fast oscillations are smeared out and one ends up with an effective polarization signal of ~330 fs imprinted into the CP electric field (Fig. 6d).

The CP pulse with the encoded polarization information is then passed through a crossed polarizer, which has been modeled using the Jones-matrix formalism. The finally measured optical pulse intensity is proportional to the square of the CP electric field, i.e. in our simulation it exhibits a duration of ~235 fs.

In Fig. 7 we compare this result of our simulation with an experimentally measured cross-correlation trace. This comparison shows good agreement of the measured and calculated signal durations. It should be kept in mind, however, that since a 40 fs true bunch duration only has a minor influence on a measurement with an intrinsic resolution of ~200 fs, we can only give an upper limit for the true duration of the electron bunch of ~100 fs. Also, the origin of the small prepulse in the measurement is unclear. Since it precedes the main pulse by ~300 fs, the two pulses cannot readily be attributed to structures in the electron bunch or time-of-flight differences between low-energy and high-energy electrons. We believe this structure is most likely caused by THz diffraction on parts in the THz optical path, such as the tape drive pulleys, which are currently not accounted for by our simulation. This assumption is supported strongly by the absence of these precursors when the Al foil tape was removed. However, investigations to verify this are still ongoing. A doubly peaked signal has also been reported in the experiment of Tilborg *et al.*[7], where the leading bunch was temporally separated from the main pulse by 230 fs. As an explanation for their observation Tilborg et al. suggest the presence of a second trapping phase several plasma periods behind the leading bunch, for which they also present two possible mechanisms. Such a scenario, however, would imply that the second trap contains and accelerates significantly more electrons than the first one, which to our knowledge has not yet been observed both experimentally and theoretically.
The combined result of the measurement with and without foil strongly suggests that in the latter case, TR from the plasma-vacuum boundary is only a minor contribution to the total measured THz emission from a gas jet, in contrast to Leemans et al.[8]. The large temporal separation between the emission peaks in this case cannot readily be explained by electrons driven by the laser, which would have to be emitted over a time much longer than the laser pulse duration. The absence of late peaks in the case with foil supports that conclusion. We believe that these peaks are either caused by the ponderomotively driven wake field inside the gas jet[11], or by sparks from the gas nozzle to the strongly positively charged plasma channel after the main interaction. From the number of accelerated electrons and the size of the plasma channel, one can deduce a potential of 105 – 106 eV, spatially separated from the conducting nozzle by approx. 0.5 mm, leading to electric fields far above the breakdown voltage of neutral gas. The 0.5 mm gap could readily explain the observed temporal structure of ~1 ps.

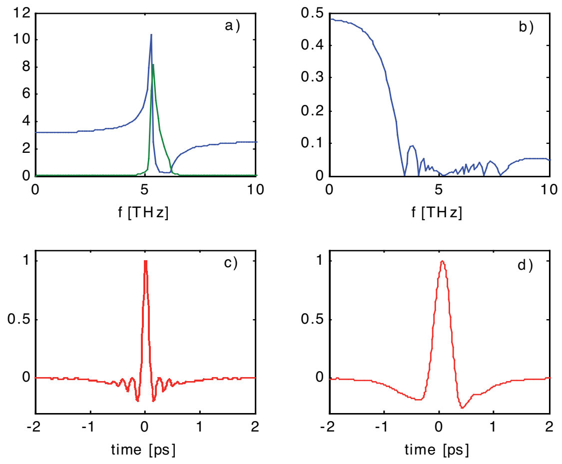

Figure 6. Propagation of TR pulse through the electro-optically active ZnTe crystal. a) real (blue) and complex (green) part of ZnTe refractive index. b) electro-optic response function of ZnTe. c) modeled THz input pulse d) resulting phase shift of chirped probe pulse.

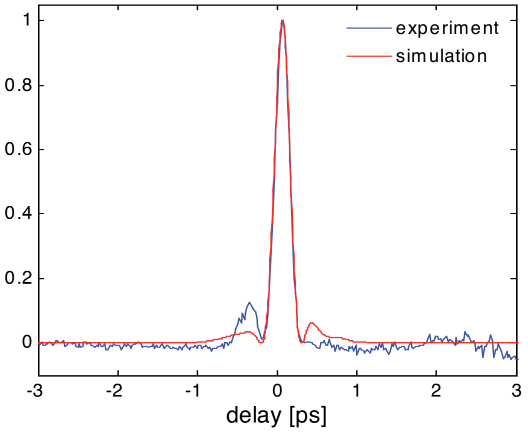

Figure 7. Comparison between experimental and theoretical THz pulse measured with the cross-correlator method

Conclusions

In summary, we have performed the first single-shot temporal characterization of THz emission from laser-accelerated electrons crossing a metal boundary, and derived an upper limit on the electron pulse duration from a laser accelerator. The result of this temporal characterization shows that a large part of the THz energy is not radiated as TR emission from the plasma-vacuum boundary of the gas jet, but originates from other sources in the underdense plasma. The metal foil, however, can only emit TR and therefore provides a reliable source for temporal characterization of electron pulses. Although the temporal resolution was insufficient due to the ZnTe absorption properties for fully resolving the electron-bunch structure, the measured duration nevertheless is well explained by full modeling assuming 40 fs electron pulses. However, shorter pulses as well as durations up to 100 fs are also consistent with our data. Owing to the strong signal we obtained it seems feasible to achieve sub-100 fs resolution in the near future by using thinner electro-optic materials with a better THz transmission characteristic. However, in order to fully resolve the temporal structure of electrons accelerated in the bubble regime, a resolution of the order of 10 fs will be needed, which can only be achieved by a combination of sub-10 fs laser pulses and a new measurement concept.

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