MV/cm THz pulses from a coherent transition radiation source

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Abstract— **THz pulses with energies up to 100 μJ and corresponding electric fields up to 1 MV/cm were generated by coherent transition radiation from 500 MeV electron bunches at the free electron laser FLASH. The pulses were characterized in the time domain by electro-optical sampling by a synchronized femtosecond laser with jitter of less than 100 fs.**

I. INTRODUCTION AND BACKGROUND

INTENSE single-cycle THz pulses are increasingly being used to observe extreme nonlinear optical phenomena in at high field strengths [1]. Coherent transition radiation (CTR) is a source of single cycle electro-magnetic radiation with a broad spectrum spanning the terahertz through infrared region. At the soft x-ray free-electron laser FLASH [2] transition radiation is generated from collision of electrons bunches with energies up to 1.2 GeV with a metal screen and then guided through an evacuated beam line [3] with 20 m length into a user accessible lab. While the main purpose of this beam line has been high-resolution diagnostics of the longitudinal electron bunch characteristics, it can also serve as a powerful and broadband source for experiments with sub-picosecond single cycle pulses. The pulses obtained have energies up to 100 μJ and span a frequency band of 200 GHz to 100 THz. Here we determine the temporal structure and the electric field of the THz pulse below 10 THz directly in the time domain using electro-optic sampling with a femtosecond laser.

The CTR source at FLASH is located in a straight section between the superconducting linear accelerator and the undulator. The last electron bunch within a sequence of up to 800 bunches with a spacing of 1 μs can be deflected onto an off-axis CTR target by a fast kicker magnet without interfering with routine FEL user operation at the VUV undulator downstream. The CTR radiation is produced on a metal screen of 150 nm Al on a 380 um Si Wafer within the high vacuum part of the FLASH beam line and then transported to a dedicated optical laboratory outside the accelerator tunnel. In order to obtain the largest possible bandwidth, diamond window with a 20 mm diameter and 0.5 mm thickness is used to separate the high vacuum inside the accelerator tube from the beam line. The beam line itself is evacuated to better than 0.1 mbar to prevent atmospheric absorption. The transport tube has a minimum diameter of 200 mm to maintain low frequencies.

II. SYNCHRONIZATION

In order to enable direct characterization of the THz field in the time domain it is vital to use a synchronized lasers system with a jitter on the order of 100 fs or less relative to the electron bunch. For our experiments a Ti:sapphire femtosecond oscillator is synchronized to the FLASH master oscillator of the accelerator by high frequency to baseband mixing (Fig. 1). An electrical frequency comb is generated from the laser pulse train by a fast photodiode with >10 GHz bandwidth. The 16th harmonic of the laser repetition rate is filtered out, amplified and used as the local oscillator input of a frequency mixer. The RF signal provided by the master oscillator passes a digitally-controllable modulator which enables to shift the laser phase with respect to the electron beam. The down-mixed signal is processed in a DSP controller, acting on a piezo stack attached to a laser cavity end mirror thus providing synchronization to the accelerator. Since a high harmonic of the repetition rate is used for precise synchronization, the phase-locked loop (PLL) can lock on at 16 possible zero-crossings which results in an ambiguity of the relative timing between the laser and THz pulses. To overcome this, a similar phase detector operating at the fundamental repetition rate of the laser is installed. Its output is also fed into the PLL and the software automatically locks the laser first at the fundamental frequency to ensure the correct timing and then switches over to the higher frequency for a tighter synchronization. Using this scheme, a synchronization accuracy of better than 40 fs (RMS) can be achieved between the laser oscillator and the master oscillator.

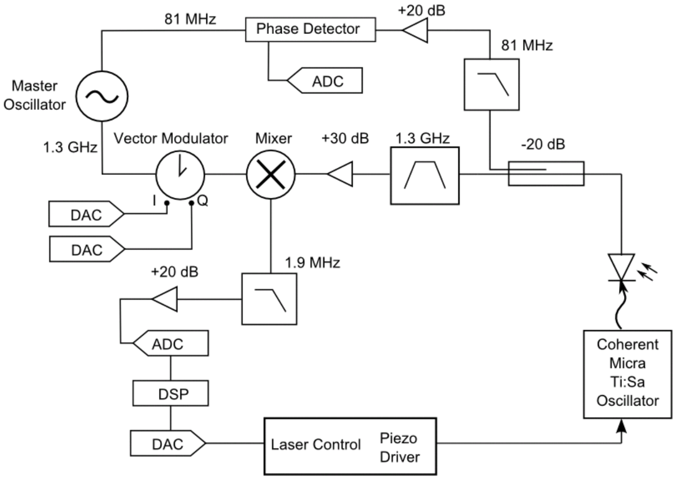

Figure 1: laser synchronization scheme used at the CTR beam line laser lab at FLASH

It should be noted that the actual timing jitter between electron bunch and laser oscillator is larger due to additional jitter introduced by the acceleration process and estimated to be on the order of 100 fs.

III. EXPERIMENT

THz pulses with up to 100 µJ energy were produced by electron bunches with 0.6 nC charge and a few hundred fs duration at a repetition rate of 10 Hz. The pulses were focused by a 3 inch diameter 3 inch focal length off axis parabolic mirror inside a vacuum vessel where the beam profile was characterized using a pyroelectric camera, yielding a minimum spot size of 1 mm FWHM at the focus. The pulse train of the femtosecond oscillator was gated electronically to select for temporal coincidence with the THz pulses while time delay was achieved by changing the oscillator cavity length with a piezo driver. The THz electric field was measured by electro-optical sampling [4] with 0.2 mm <110> cut GaP crystal mounted on inactive <100> substrate. For the highest field strengths, the THz radiation had to be attenuated with a pair of wire grid polarizers in order to prevent over-rotation of the probe ellipticity inside the detection crystal.

IV. RESULTS

A typical field trace at 80 µJ pulse energy and the corresponding frequency spectrum obtained by Fourier transformation is shown in the Figure 2. For this measurement 30 THz pulses were averaged at every time step. The field strength was calculated from the known electro-optical coefficient of GaP [5], taking into account Fresnel losses but neglecting phase mismatch of laser and THz pulse inside the GaP crystal.

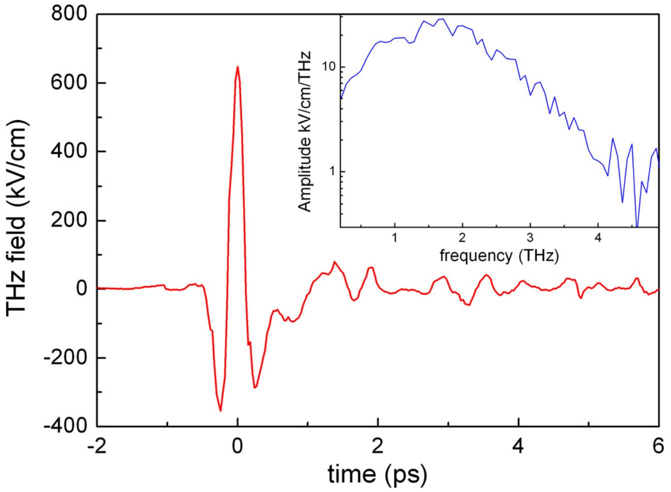

Figure 2: Single cycle THz pulse with MV/cm field strength and corresponding amplitude spectrum

The pulse is clearly single cycle with a peak field strength of 700 kV/cm. Frequency components extend up to 4 THz. The bandwidth of our measurement is limited by the timing jitter which is on the order of 100 fs. When taking into account corrections for phase mismatch in the detection crystal and synchronization jitter, the peak field strength is estimated to exceed 1 MV/cm which is consistent with the value obtained from spot size and total energy measurements. By inserting bandpass filters (QMC Instruments), narrowband THz pulses were generated. Figure 3 shows the electro-optical signal for a pulse with 2 THz center frequency and 0.5 THz spectral bandwidth. The field strength still exceeds 100 kV/cm.

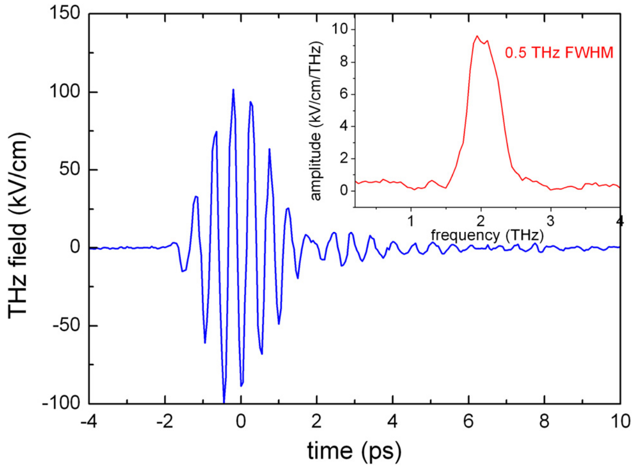

Figure 3: Narrowband pulse shape after a bandpass filter with center frequency 2 THz

V. CONCLUSION

The CTR beam line at FLASH delivers single cycle THz pulses with field strength on the order of 1 MV/cm in a table top user laboratory. These pulses have larger bandwidth and almost one order of magnitude more energy than similar pulses obtained by optical rectification [1]. Their field can be directly characterized in the time domain using a femtosecond laser synchronized with 100 fs jitter. Accuracies well below 10 fs [6] can be achieved by synchronizing to an optical reference [7] using a cross-correlation technique and and sorting by corresponding arrival times from bunch arrival monitors [8]. This unique combination THz fields with extreme intensity from an accelerator with ultrafast timing will allow for observation of novel nonlinear THz phenomena.

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