ELECTRO-OPTICAL SAMPLING OF TERAHERTZ RADIATION EMITTED BY SHORT BUNCHES IN THE ANKA SYNCHROTRON*

A. Plech†, S. Casalbuoni, B. Gasharova, E. Huttel, Y.-L. Mathis, A.-S. Müller, K. Sonnad,
Institute for Synchrotron Radiation, Forschungszentrum Karlsruhe, PO box 3640, D-76021 Karlsruhe
A. Bartels, Center for Applied Photonics, U. Konstanz, Universitätsstr. 10, D-78457 Konstanz
Ralf Weigel, Max-Planck Institute for Metals Research, Stuttgart

Abstract

Short electron bunches down to 1 ps are achieved at the synchrotron ANKA by the quasi-isochronous mode with low alpha optics. In order to characterize the Terahertz (THz) emission and beam oscillations in this mode a femtosecond laser system has been set up. This allows resolving the THz electrical field by electro-optical sampling in a ZnTe crystal. The laser system consists of a 500 MHz repetition rate oscillator that can be phase locked to the repetition rate of the synchrotron. First results are presented. In contrast to previous approaches the high repetition rate is used in conjunction with a novel detection scheme in order to increase the sensitivity of the detection largely.

INTRODUCTION

Coherent radiation from electron pulses in a storage ring is emitted, when the wavelength of the radiation is longer than the pulse length. Typical pulse lengths at modern synchrotron radiation sources range at about 30 - 100 picoseconds. By reducing the so-called momentum compaction factor α (thus "low-alpha optics") pulses as short as 500 femtoseconds (root mean square) can be achieved. The emission of these pulses is coherent considerably above 1 THz frequency, which is an interesting spectral region due to low-energy excitations in condensed matter. An efficient source point for the emission of coherent and as well incoherent radiation is the entry point of the electron beam in the magnetic field at the bendings. This edge radiation is used for a number of experiments at infrared beamlines around the world. ANKA offers beamtime in low alpha mode regularly for users.

Within the coherent regime all electrons in the pulse radiate in phase, which has several important consequences: the emitted power scales with the square of the pulse charge, while incoherent emission only scales linearly. Therefore with bunch charges in the range of 100 pC an enormous gain in power is expected for the coherent emission [1, 2, 3]. At ANKA a coherent flux of 0.2 mW is found in a spectral region from 0.2 to 2 THz [3]. Another consequence is the phase stable emission within one pulse. Assuming a regular pulse spacing and a stable pulse shape the emitted electrical field will directly image the charge distribution within the pulses. Consequently a direct pulse and beam dynamics diagnostics are accessible, if the THz emission could be recorded by a phase sensitive method. Earlier experiments have used Fourier transform infrared spectroscopy setups to determine the field autocorrelation function, which, however does not give the full phase information, but may be used within some limits for the modeling of charge distributions. One direct method to determine the electric field oscillation with amplitude and phase is the electro-optical sampling technique. It uses an ultrafast laser pulse to probe the momentary polarization rotation within an electro-optically active crystal, which is directly proportional to the applied electrical field [4, 5, 6]. This sampling is straightforward for THz emission and probe pulses originating form the same source, an ultrafast laser. In the case of a synchrotron as ANKA in order to adapt this setup, a femtosecond laser has to be synchronized.

Typically a femtosecond oscillator of around 80 MHz repetition rate is synchronized to the bunch clock of synchrotrons by a piezoelectric feedback loop [7, 8]. A short term stability of some 3-5 ps is achieved routinely, while long-term drifts due to a variable phase of the electron pulses relative to the radio frequency with bunch charge amount for some more picoseconds. This jitter is clearly too large to resolve a THz oscillation. Very recently large efforts have been invested in synchronizing lasers to the free electron laser FLASH, achieving a sub-100fs precision in using a master oscillator to drive the photo-gun of the injector [9]. At a synchrotron, in contrast a continuous dynamic feedback from the ring current has to be used to correct for drifts in repetition rate and for the amplitude of synchrotron oscillations.

Within this communication we show that by using a high frequency femtosecond oscillator and establishing a feedback control at the 2.5 GHz overtone of the RF frequency a high resolution synchronization can be achieved. By further introducing the asynchronous sampling technique a very sensitive detection of the THz field from the synchrotron is possible.

EXPERIMENTAL SETUP

The centerpiece of the optical setup consists in the electro-optically active crystal, which rotates the polarization of a femtosecond laser upon impact of an electrical field, which is formed by the THz pulse. As the THz os-

* Work supported by Deutsche Forschungsgemeinschaft within the Heisenberg program (AP) and by the Helmholtz Association within the Young Investigator groups (ASM).

† anton.plech@iss.fzk.de

cillation period is longer than the width of the femtosecond laser the electrical field can be sampled. The THz emission is coherent, which implies a constant phase between the electrical field and an external femtosecond laser, which is synchronized to the emission from the synchrotron. Two difficulties have to be solved in order to achieve the stable sampling. Firstly the limited peak power of the THz pulse demands for a high sensitivity detection method rejecting fluctuations and noise. Secondly the synchronization of the laser to the synchrotron emission has to be much better than the period of the THz emission to be resolved. This is demanding due to the intrinsic beam excitation at the synchrotron frequency. Both items are efficiently tackled by using a femtosecond oscillator of the same repetition frequency as the synchrotron at 500 MHz, and additionally employing a recently developed asynchronous pump-probe method [10] with excellent signal-to-noise due to the rapid inherent scanning of the delay between THz pulse and laser pulse. In brief, a Ti:Saphire oscillator (Gigaoptics, 0.2 nJ pulse energy, 800 nm center wavelength, <30 fs pulse length) is stabilized in repetition rate by a fast feedback loop to the synchrotron but with a slight detuning of 10 kHz. Thus the delay is not fixed, but a function of time and varies in the present case from 0 to 2 ns (the pulse spacing) within a 100 μs period. By recording the laser intensity by a photodiode (New Focus) and a fast digitizer (GaGe) a physical detection bandwidth of 100 MHz is sufficient for resolving a minimal delay change of 200 femtoseconds.

In order to test the optical rotation by an intensity variation a ZnTe crystal is placed between an polarizer / analyser combination for the femtosecond laser beam [5] at nearly crossed orientation. Crossed polarizations of laser and THz field are used at the $< 110 >$ surface of the ZnTe crystal (0.5 mm thickness). The linearity of the response to the electrical field is sufficient for the detected intensity changes of 10^{-5}.

The synchronization is done by comparing a photodiode pickup from the laser emission to an electronic pickup from the synchrotron at the 5th harmonics of the master frequency. Both a strip line detector and a ring electrode were tested, which give similar signals of the carrier frequency and the synchrotron frequency side bands. A comparison of the phase noise between the master clock and the ring electrode at the given settings (1.3 GeV beam energy, 8.4 kHz synchrotron frequency) predicts a 200 fs jitter due to the beam dynamics in low-alpha mode.

As the feedback system for the laser acts on two different piezo actuated cavity mirrors, one of them is foreseen for a high resonance frequency around 7-9 kHz, which can partly compensate for the synchrotron frequency oscillation. The second piezoactuator corrects for drifts on a second time scale. It is, however, expected that the sidebands also carry transversal excitation despite the targeted longitudinal excitation. The feedback loop allows to set the amplitude and bandwidth of the response in order to optimize the correction scheme.

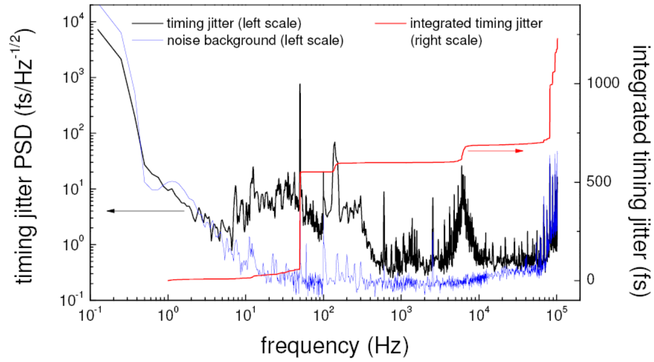

Figure 1: Spectral power of the phase noise of the pickup signal from the ring electrode compared to the reference signal from the bunch clock at 500 MHz together with the accumulated jitter below the given frequency. The synchrotron frequency is seen at 8.4 kHz contributing about 200 fs.

The THz pulses are extracted at the direct diagnostics port of the IR1 beamline at ANKA [3] through a 6 mm z-cut quarz window and focused onto the ZnTe crystal by an off axis paraboloid mirror (50 mm diameter, 75 mm focal length).

RESULTS AND DISCUSSION

Fig. 2 displays the change in laser intensity after passing through the Glan-Laser prism analyser. For this trace a number of 10^5 individual traces were recorded, which amounts for a total integration time of 100 seconds. The noise floor is at 10^{-7} of the full intensity at a modulation of $3{\cdot}10^{-5}$.

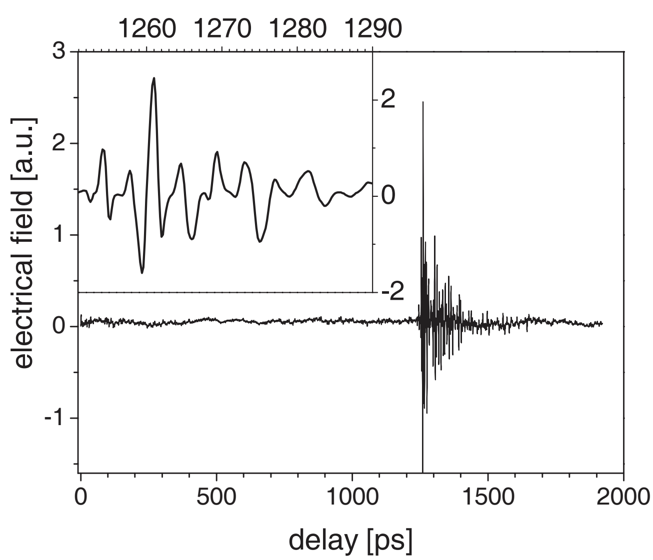

Figure 2: Electro-optical AC signal within the ZnTe crystal within the complete 2 nanosecond pulse-to-pulse separation and a magnification of the prompt signal of the THz pulse as inset.

A large oscillating signal is seen to appear for a given (arbitrary) delay between the two pulses followed by a number of subsequent ringings. Looking closer on the strongest cycle one recognizes the picosecond variation of the field in accordance to the pulse length at this synchrotron settings. The subsequent oscillations have a slightly longer period.

This observation allows several direct conclusions:

- The synchronization of the laser is indeed better than the electron pulse width proving the concept of cavity feedback loop
- The arrival time of the different electron pulses within the filling scheme (three trains of about 30 bunches each were filled) is of the same accuracy.
- The mechanism of the detection allows only for recording of coherent emission signals, i.e. with a fixed phase relationship between the pulse arrival time and the position of the oscillations (carrier-envelope stability).

The ideal emission from a symmetric electron pulse should be a single cycle emission of field strength [11, 12], which is not detected here. Two effects contribute here to the deviation from a narrow pulse. Firstly the THz pulse propagated in air for a short distance of about 60 cm after exiting the quartz viewport. The absorption in humid atmosphere adds absorption bands from water vapor, some of them which are located at around 0.57, 0.76 and 0.96 THz. These bands cause an after-ringing of the electric field oscillation according to the Fourier theorem at the resonance frequency. Secondly the THz propagation can't be described by geometrical optics any more, if the numerical aperture is small. The beamline has been designed and optimized for IR extraction. However, in the THz region diffraction effects and reflections on the beam tubes cause a distortion of the wavefront, which is seen as multiply oscillating signals and delayed emission as recorded for some hundred picoseconds. Other observations have shown complicated emission characteristics [13] at the synchrotron BESSY.

The role of the averaging process on the signal shape may be questioned when taking into account the beam oscillation. Therefore we have performed a stepwise reducing of the number of averages from 10^5 to a single trace. A single trace can be recorded in a oscilloscope manner, where a given time point is only sampled once. We find (within the limits of noise level) that the transient THz signal is preserved in shape even during a single sweep. Only the amplitude of the electrical field is about twice the averaged signal. Already after averaging 10 traces the signal is of the same amplitude as the shown average in fig. 2. Consequently the signal is to a certain extent influenced by the averaging procedure, e.g. by longitudinal oscillation of the pulses in the RF field. The oscillations are, in any case not detrimental for the detection of the THz field.

CONCLUSIONS AND OUTLOOK

In conclusion a reliable method to detect the coherent synchrotron radiation in low alpha mode at ANKA has been established by phase-locking a femtosecond high repetition laser to the synchrotron repetition rate. The electrical field is detected in amplitude and phase by the electro-optical effect in a birefringent crystal. This information may allow for a more detailed diagnostics of the electron pulses stored in the ring. The THz radiation can be used in time-domain spectroscopy as has been demonstrated for lab-based THz sources. The spectroscopic information that is obtained in such an experiment allows for the measurement of the complex dielectric function in this region without the use of the Kramers-Kronig relation.

REFERENCES

[1] M. Abo-Bakr, J. Feikes, K. Holldack, G. Wüstefeld and H.-W. Hübers, Phys. Rev. Lett. **88** (2002) 254801.

[2] E. Karantzoulis, G. Penco, A. Perucchi, M. Ortolani and S. Lupi, Proceedings of EPAC08 Genoa, Italy (2008) 2043.

[3] A.-S. Müller, I. Birkel, S. Casalbuoni, B. Gasharova, E. Huttel, Y.-L. Mathis, D. A. Moss, N. J. Smale, P. Wesolowski, E. Bruendermann, T. Bueckle and M. Klein, Proceedings of EPAC08 Genoa, Italy (2008) 2091.

[4] P. C. Planken, H.-K. Nienhuys, H. Bakker and T. Wenckebach, J. Opt. Soc. Am. B **18** (2001) 313.

[5] A. Bartels, R. Cerna, C. Kistner, A. Thoma, F. Hudert, C. Janke and T. Dekorsy, Rev. Sci. Instr. **78** (2007) 035107.

[6] S. Casalbuoni, H. Schlarb, B. Schmidt, P. Schmüser, B. Steffen, and A. Winter, Phys. Rev. STAB **11** (2008) 072802.

[7] F. Schotte, S. Techert, P. A. Anfinrud, V. Srajer, K. Moffat and M. Wulff, in *Third-Generation Hard X-ray Synchrotron Radiation Sources* (John Wiley and Sons, Berlin, 2002) .

[8] A. Plech, P. Leiderer and J. Boneberg, Laser & Phot. Rev. **3** (2009) Early view.

[9] F. Loehl, V. Arsov, K. Hacker, B. Lorbeer, F. Ludwig, K. Matthiesen, H. Schlarb, B. Schmidt, A. Winter, S. Schulz, J. Zemella, J. Szewinski and W. Jalmuzna, Proceedings of EPAC08 Genoa, Italy (2008) 3360.

[10] A. Bartels, F. Hudert, C. Janke, T. Dekorsy and K. Köhler, Appl. Phys. Lett. **88** (2006) 041117.

[11] F. Sannibale, J. M. Byrd, A. Loftsdóttir, M. Venturini, M. Abo-Bakr, J. Feikes, K. Holldack, P. Kuske, G. Wustefeld, H.-W. Hübers and R.Warnock, Phys. Rev. Lett. **93** (2004) 094801.

[12] A.-S. Müller, S. Casalbuoni, M. Fitterer, E. Huttel, Y.-L. Mathis and M. Schmelling, Proceedings of EPAC08 Genoa, Italy (2008) 2094.

[13] H.-W. Hübers, A. Semenov, K. Holldack, U. Schade, G. Wüstefeld and G. Gol'tsman, Appl. Phys. Lett. **87** (2005) 184103.