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MEASURING THE COHERENT SYNCHROTRON RADIATION FAR FIELD WITH ELECTRO-OPTICAL TECHNIQUES

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Abstract

For measuring the temporal profile of the coherent synchrotron radiation (CSR) a setup based on electro-optical spectral decoding (EOSD) will be installed as part of the sensor network at the KIT storage ring KARA (Karlsruhe Research Accelerator). The EOSD technique allows a single-shot, phase-sensitive determination of the complete spectrum of the CSR far-field radiation at each turn. Therefore, the dynamics of the bunch evolution, e.g. the micro-bunching, can be observed in detail. Especially, in synchronized combination with the already established near-field EOSD, this method could provide deeper insights in the interplay of bunch profile and CSR generation for each individual electron bunch.

For a successful implementation of the EOSD single-shot setup, measurements with electro-optical sampling (EOS) are performed. With EOS the THz pulse shape is scanned over several turns by shifting the delay of laser and THz pulse. In this contribution, different steps towards the installation of the EOSD far-field setup are summarized.

INTRODUCTION

The KIT storage ring KARA (Karlsruhe Research Accelerator) can be operated in a short-bunch mode, the so-called low-α_c mode, in which the bunch self-interaction with its emitted coherent synchrotron radiation (CSR) leads to microstructures in the bunch profile and the micro-bunching instability. In this low-α_c mode, the bunch length is reduced to a few picoseconds at a beam energy of ≤ 1.3 GeV and a beam current of some milliamperes. Coherent synchrotron radiation (CSR) in the THz range is emitted in intense bursts. These dynamics of the micro-bunching instability are studied continuously [1–7]. Sophisticated measurement techniques are necessary to take a snapshot of the bunch at every turn, i.e. at MHz repetition rates. Therefore, several synchronized detectors are implemented in the distributed sensor network at KARA to measure the longitudinal bunch profile, the energy spread and the temporal profile and spectrum of the THz pulses.

The longitudinal bunch profile is measured using electro-optical spectral decoding (EOSD) of the near-field of the electron bunch. With this near-field EOSD setup the evolution of the longitudinal bunch profile in low-α_c operation mode at KARA could be studied in detail [2] and a 2D image of the longitudinal phase space could be reconstructed by tomography [8].

The energy distribution is measured indirectly by measuring the horizontal bunch profile in a dispersive section of KARA [5]. The change in the energy spread can be deter-mined from the change in the horizontal bunch size.

The intensity of the emitted THz radiation is measured with fast THz detectors and KAPTURE or KAPTURE-2 as readout system [3, 4, 9]. With the EOSD far-field setup [10], the temporal resolution of the THz bunch profile measure-ment will be increased and, therefore, the THz spectrum can be determined.

For the EOSD near-field, the EOSD far-field and the horizontal bunch profile measurements different versions of KALYPSO, a fast line array detector developed at KIT, are implemented [11, 12]. KALYPSO features a frame rate of 2.7 MHz, allowing the continuous resolution of each turn in single-bunch operation.

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EOSD FAR-FIELD SETUP FOR KARA

With EOSD, a method originally applied in THz spec-troscopy [13], the temporal profile of the THz pulse is en-coded on the spectrum of an ultra-short laser pulse. The laser pulse is stretched to a pulse length of a few picoseconds and is overlapped collinearly with the THz pulse inside an electro-optical (EO) crystal (see also Fig. 1). The Pockels-effect causes a change of the birefringence of the EO crystal scaling linearly with the electrical field strength of the THz pulse. This results in a change of the polarization of the laser pulse from linear to elliptical. By analyzing this polarization change, the electrical field strength of the THz pulse can be determined. The complete profile of the THz pulse can be analyzed in a single shot using an optical spectrometer. This method is applied to measure the far-field of the CSR at ac-celerators [14]. To increase the sensitivity of the system, the changes in both polarization planes - horizontal and vertical - can be analyzed using a balanced detection scheme [15].

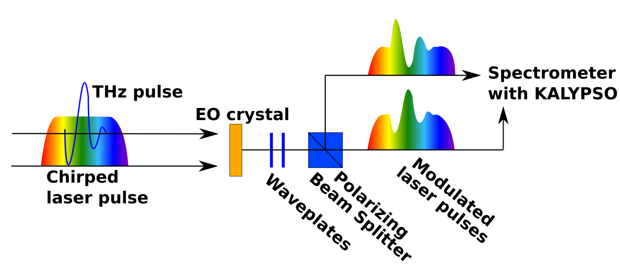

Figure 1: EOSD to measure the THz pulse shape with a chirped laser pulse: THz pulse and laser pulse are overlapped in the EO crystal. The electrical field of the THz pulse generates a modulation of the laser pulse spectrum. Both polarization directions are analyzed in a spectrometer.

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At KARA single-shot measurements using an optical spectrometer with the ultra-fast line array detector KALYPSO will be realized. The KALYPSO version to be implemented features 512 pixels with a pitch of 25 µm and can record the spectra at the revolution frequency of 2.7 MHz. It will be replaced in future with a new version with an array of 1024 pixels operating with up to 12 Mfps (megaframes per second).

Design and Components of the Setup

A commercial laser system, which is part of a THz time-domain spectrometer [16], is used as laser source with a central wavelength of 1560 nm. The THz emitter integrated in the system provides THz pulses of more than 4 THz bandwidth, but it is weaker in intensity than the THz pulses available at the IR2 beamline at KARA in short-bunch operation at maximum beam current. All parameters of the laser system and the EO section of the setup are listed in Table 1.

Table 1: Parameters of the Commercial Laser System and the EO Components used in the EOSD Setup.

Laser system	
Center wavelength	1560 nm
Spectral width	70 nm
Min. pulse duration	90 fs
Average power	210 mW
Pulse repetition rate	62.5 MHz
EO components	
Bandwidth THz emitter	≥ 4 THz
EO crystal	GaAs (110)
Crystal thickness	0.5 mm / 1.0 mm

To reduce the noise level of the detected signal, several aspects of the far-field setup had to be optimized. The setup is shown in Fig. 2. The mechanical stability of several components was improved, i.e. mounts were replaced by more compact and lockable optical mounts. The delay stage in the laser beam path for scanning the temporal delay between THz pulse and laser pulses for EOS measurements and for adjusting the overlap in EOSD measurements was removed. Instead, the delay stage integrated in the commercial THz system, which shifts the delay of the THz emitter with respect to the laser pulse timing, is used to reduce vibrations in the laser beam path. It has the additional advantage, that the timing of the detected laser pulses is constant with respect to the trigger signal of the laser system while the THz pulse is scanned. Furthermore, the flexibility for signal processing and readout has been increased. These changes also reduce the size of the setup such that the laser system can be integrated on the same breadboard. An optical enclosure was installed to reduce noise due to air fluctuations and stray light.

The THz pulses from the emitter are collimated with a first parabolic mirror and focused to the crystal by a second parabolic mirror. To minimize the focal spot size of the THz pulses, a small focal length of 5 cm is chosen for the second parabolic mirror. The laser beam path of the EOS setup consists basically of the EO section with the EO crystal, waveplate and a polarizing beam splitter cube (PBS): Inside the EO crystal the laser pulse polarization is modulated by the electrical field of the THz pulse. A $\lambda/4$ waveplate compensates for the intrinsic birefringence of the EO crystal. A $\lambda/2$ waveplate and the PBS are used to adjust the transmitted laser intensity and to transform the polarization modulation of the EO crystal into an intensity modulation. The laser pulse is focused to the EO crystal with an achromatic lens (focal length 10 cm) and collimated after the waveplates with a second achromatic lens of 15 cm focal length. To increase the temporal resolution of the EOS measurements, the laser pulse stretcher for introducing the necessary chirp for EOSD measurements was removed. Instead, the minimum pulse length of 90 fs, offered by the laser system, was used. In-tegrating again the stretcher with holographic gratings of 600 lines/mm, the pulse width can be varied in the range of 2 ps to 8 ps.

For further noise reduction a balanced photodetector (bandwidth 100 MHz) is used for detection. Additional to the laser pulses transmitted through the PBS, the reflected pulses are detected as "negatively modulated" signal on the second input of the balanced detector. To improve the polarization ratio of that beam and to adjust its intensity to the same level as the first beam, a second $\lambda/2$ waveplate and PBS are installed in the beam path. The remaining part of the laser beam, which is not used for the balanced detection, can be used as timing reference on an additional photodiode in combination with e.g. the synchrotron radiation in the vis-

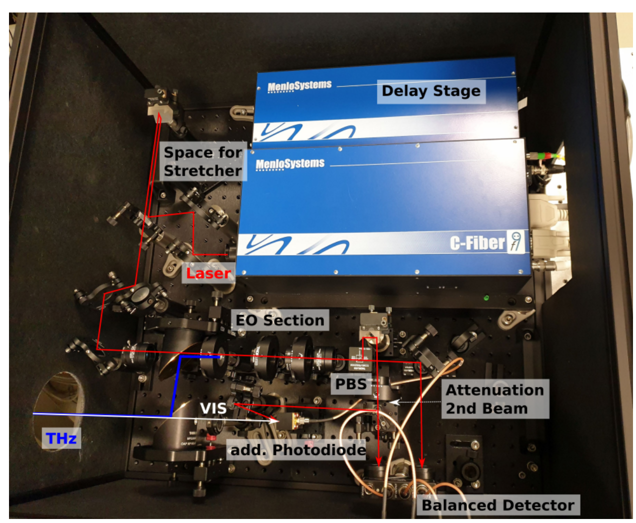

Figure 2: The EOSD far-field setup: The laser beam path is shown in red, the THz beam path in blue, the synchrotron ra-diation in the visible range (VIS) in white (only available at the beamline). In this configuration the balanced photodetector is integrated, which will be replaced by a spectrometer with KALYPSO as detector for the single-shot measure-ments.

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ible spectral range at the beamline (see Fig. 2). The intensity of the laser beams on the photodetector is adjusted such that it is close to the maximum allowed input power of 20 mW per detector. The configuration can still be considered as "almost crossed" as the intensity per detector corresponds to around 7 % of the total laser intensity.

EOS Measurement with the Commercial Emitter

For readout of the balanced detector a lock-in amplifier is used. The modulation in the signal is generated by a modulation of the emitter bias voltage (modulation frequency 90 kHz). A complete temporal overlap of the two input laser beams on the balanced detector was not possible and, therefore, single spikes in the signal appeared. An electronic low pass filter was integrated after the detector to eliminate these peaks.

The temporal delay between THz signal and laser pulse is varied linearly with the delay stage integrated in the commercial laser system. The temporal delay of the stage is already calibrated by the supplier. A typical EOS scan is shown in Fig. 3. After the first THz pulse, reflections with a delay of around 10.7 ps are visible. This corresponds to a distance of around twice 0.45 mm taking into account the refractive index of GaAs, which is 3.5 for a wavelength of 1550 nm. During the measurements a crystal with thickness 0.5 mm was installed. The EOS scans are necessary to find the optimum delay between THz and laser pulses. As the reflections do not affect this position and will have no influence on the single-shot measurements, they can be neglected here.

Next, after getting reproducible EOS scans with the setup, the system has to be modified such that EOSD single-shot scans can be performed. A laser pulse stretcher has to be integrated and the balanced detector has to be replaced by an optical spectrometer with the fast line-array detector KALYPSO. To keep the balanced detection scheme, the two laser beams from the PBS will both be detected.

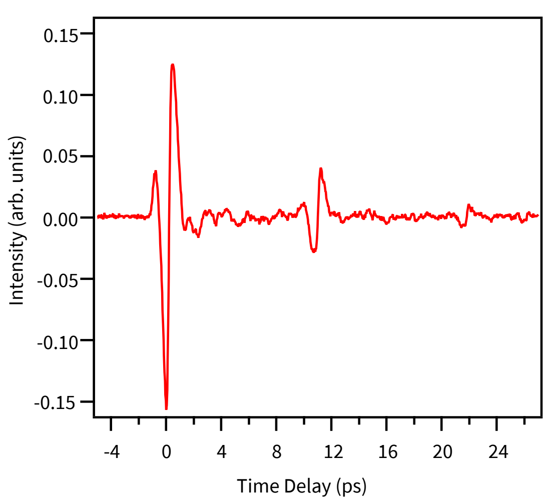

Figure 3: EOS scan of the THz pulse generated by the com-mercial emitter.

Implementation at the Beamline

The EOSD setup will be installed at the IR2 beamline at

The EOSD setup will be installed at the IR2 beamline at the storage ring KARA. The CSR pulses will replace the THz signal from the commercial emitter. Again, an optical enclosure and a passively damped optical table will reduce the noise level on the signal significantly.

To adjust the timing between the laser and CSR pulses, the repetition rate of the laser is locked to the master clock of KARA. For scanning the delay, a slight shift of the laser frequency with respect to the revolution frequency of the storage ring can be applied for a single scan. For scanning a certain delay range a sine- or saw-tooth-like modulation of the phase of the laser synchronization can be applied. An additional fast photodiode is integrated in the setup detecting a part of the laser beam and the synchrotron radiation in the VIS range. The delay of these two signals serves as a reference for the delay of THz and laser pulse, see also Fig. 2.

Adjusting the overlap is still challenging for two reasons: Only every 23rd laser pulse is modulated as the laser repeti-tion rate is 62.5 MHz and the revolution frequency i.e. the frequency of the THz signal in single bunch operation, is 2.7 MHz. Therefore, the modulation is significantly reduced when averaging the signal over several laser pulses. Addition-ally, the measurements were performed above the bursting threshold where the THz signal itself varies in strength and slightly in shape and timing. As a possible improvement we investigate the installation of a pulse picker in the laser system reducing the laser repetition rate to the revolution frequency.

SUMMARY

As an important step towards the implementation of the EOSD far-field setup at the IR2 beamline at KARA, success-ful EOS measurements were performed with a commercial THz emitter. Main factors for improving the setup were the integration of mechanically more stable components, the installation of an optical enclosure to minimize stray light and air fluctuations and using a balanced detection scheme.

Now, being able to adjust the temporal delay, a pulse stretcher and a spectrometer with the line-array detector KALYPSO can be integrated for performing single-shot EOSD measurements.

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