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# IMPLEMENTING ELECTRO-OPTICAL DIAGNOSTICS FOR MEASURING THE CSR FAR-FIELD AT KARA

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*Abstract*

For measuring the temporal profile of the coherent synchrotron radiation (CSR) at the KIT storage ring KARA (Karlsruhe Research Accelerator) an experimental setup based on electro-optical spectral decoding (EOSD) is currently being implemented. The EOSD technique allows single-shot, phase-sensitive measurements of the far-field radiation on a turn-by-turn basis at rates in the MHz range. Therefore, the resulting THz radiation from the dynamics of the bunch evolution, e.g. the microbunching, can be observed with high temporal resolution.

This far-field setup is part of the distributed sensor network at KARA. Additionally to the information acquired from the near-field EOSD spectral decoding and the horizontal bunch profile monitor, it enables to monitor the longitudinal phase-space of the bunch.

In this contribution, the characterization of the far-field setup is summarized and its implementation is discussed.

## INTRODUCTION

In the short-bunch mode at the KIT storage ring KARA (Karlsruhe Research Accelerator), the so-called low-$\alpha_c$ mode, the electron bunch interacts with itself and its emitted radiation [1]. This leads to varying microstructures in the bunch, the micro-bunching instability, and intense emission outbursts of coherent synchrotron radiation (CSR) in the THz range. One aspect of studying the microbunching is to understand the dynamics and to be able to predict them with simulations [2–6]. The second aspect is to be able to control the THz emission by tuning accessible parameters in the storage ring [7]. For both it is necessary to track the evolution of the longitudinal phase space of the bunch with sophisticated methods. Single-shot measurement techniques ideally being able to take a snapshot of the bunch at every turn or even of several bunches each turn are necessary.

In the short-bunch mode, the electron bunch length is reduced to some picoseconds (ps) at a beam energy of ≤1.3 GeV and a current of some mA. The revolution frequency is 2.7 MHz (for a detailed parameter list, see e.g. [3]). Several diagnostic tools for the observation of the longitudinal phase space in low-$\alpha_c$ mode were developed, all part of the distributed sensor network at KARA [5].

### *Distributed Sensor Network at KARA*

The distributed sensor network at KARA consists of synchronized sensors measuring the longitudinal bunch profile,

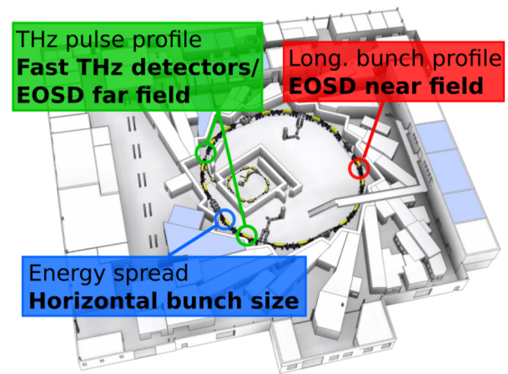


Figure 1: Location of a selection of sensors of the distributed sensor network at KARA.

the energy spread and the temporal profile of the THz pulses (Fig. 1).

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-$\alpha_c$ operation mode at KARA could be studied in detail [2] and a 2D image of the longitudinal phase space could be reconstructed [8].

The energy distribution is measured indirectly by measuring the horizontal bunch size in a dispersive section of KARA [5]. The bunch profile is imaged on a line array camera. The energy spread can be determined from the change in the horizontal bunch size.

For both diagnostic setups KALYPSO, a fast line array detector developed at KIT, is used [9, 10]. KALYPSO features a frame rate up to 12 MHz allowing measurements in single-bunch mode turn-by-turn. Depending on the type of line array used, KALYPSO has a resolution of 256 to 1024 pixels.

For measuring the THz pulse profile fast THz detectors with KAPTURE-2 as readout system is used [3]. KAPTURE-2 has 8 channels for read-out with a sampling rate of up to 1 GSa/s [11]. Therefore, also in multi-bunch mode a tracking of the emitted THz radiation is possible, but it is not possible to resolve the pulse shape for pulses that are shorter than the impulse response of the Schottky barrier diode used as a detector.

To increase the temporal resolution of the THz bunch profile in single-shot measurements an alternative setup using EOSD is currently under commissioning at KARA. In this far-field EOSD setup we use KALYPSO as detector, i.e. the setup will be capable to capture THz bunch profiles in single-bunch mode turn-by-turn.

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### *EOSD Far-Field Setup at KARA*

EOSD is a method originally applied in THz spectroscopy [12]. An ultra-short laser pulse is overlapped collinearly with the THz pulse inside an electro-optical (EO) crystal (see also Fig. 2). The electric field of the THz pulse changes the birefringence of the EO crystal due to the Pockels-effect. This results in a change of the polarization of the laser pulse from linear to elliptical. The change is proportional to the electrical field strength. By analyzing this polarization change the electrical field strength of the THz pulse can be determined. Using a chirped laser pulse, i.e. a laser pulse with a defined correlation of the temporal delay of the spectral components, the temporal shape of the electrical field of the THz pulse is encoded on the spectral components of the laser pulse. Therefore, the temporal profile of the THz pulse can be analyzed in single-shot measurements using an optical spectrometer. This method is applied to measure the far-field of the CSR at synchrotrons [13, 14].

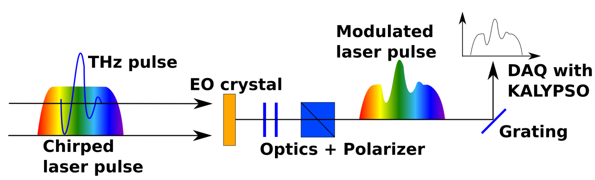


Figure 2: Principle of EOSD of a THz pulse with a chirped laser pulse: THz and laser pulse are overlapped collinearly in the EO crystal. The electrical field of the THz pulse generates a modulation in the intensity of the laser pulse spectrum, which can be analyzed in a spectrometer.

Using this EOSD technique and KALYPSO as a detector, the CSR emitted at KARA can be measured single-shot with the revolution frequency of 2.7 MHz. Two KALYPSO versions based on InGaAs will be integrated, first a line array with 512 pixels with a pitch of 25 µm. This version will be replaced by a line array with 1024 pixels operating up to 12 Mfps in the future.

## EOSD FAR-FIELD DEMONSTRATOR

For tests independent of the accelerator KARA a first demonstrator setup was designed. The test setup not only gives the opportunity to align large parts of the system independently of the accelerator, but also to test optical components including different EO crystals. A commercial laser system with a free space output of the laser beam and an integrated THz emitter is used [15]. The emitter provides THz pulses of more than 4.5 THz bandwidth, but weaker in intensity than the THz pulses emitted 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 Demonstrator Setup

| **Laser system** | |
|---|---|
| center wavelength | 1 560 nm |
| spectral width | 70 nm |
| min. pulse duration | 90 fs |
| average power | 210 mW |
| pulse repetition rate | 62.5 MHz |
| synchronization to external source possible | |
| **EO components** | |
| bandwidth THz emitter | ≥4.5 THz |
| EO crystal | GaAs (110) |
| crystal thickness | 0.5 mm / 1.0 mm |

### *Design and Requirements*

The setup consists mainly of four parts: the beam path of the THz pulse, the beam path of the laser pulse, the modulation section, where the temporal structure of the THz pulse is imprinted on the laser pulse spectrum, and the detection part. In Fig. 3, a picture of the demonstrator setup is shown.

The major constraint designing the demonstrator setup is the temporal overlap of the THz pulse and the laser pulse, i.e. the laser path length has to match the THz beam path. As propagation of the THz pulse in air over long distances due to strong water absorption lines should be avoided, the laser path of the setup has to be as compact as possible. Compactness is further a necessity, if at a later stage operation in a water-vapour-free atmosphere is considered, e.g. by using dry air or nitrogen. For adjusting the temporal overlap a delay stage of 25 cm travel length is integrated in the setup.

To set the required laser pulse length a grating stretcher with a Treacy [16] grating compressor is used. This stretcher

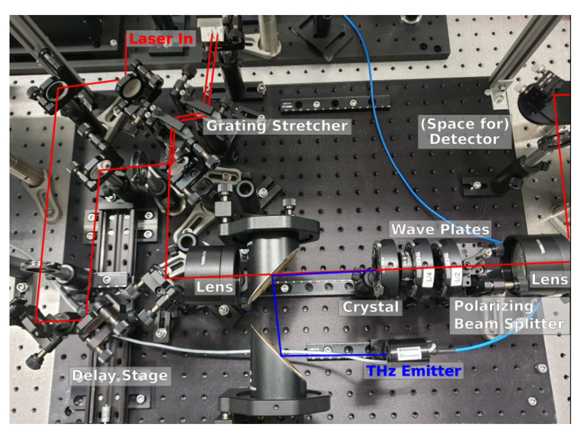


Figure 3: Picture of the optical setup of the EOSD far-field demonstrator. The laser beam path is shown in red, the THz beam path in blue. In this configuration a commercial spectrometer is integrated for diagnostics, during the EOSD measurements an optical spectrometer with KALYPSO as detector is integrated.

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generates a negative chirp of the laser pulse. To achieve an efficiency of more than 55% holographic transmission gratings (600 lines/mm) optimized for the vertical polarization of the laser pulse are used. Further advantages of the transmission gratings are a flexible and compact stretcher setup. The grating distance can be set such that the laser pulse length is around 2 ps, which is needed for adjusting the initial rough temporal overlap. Increasing the grating distance, a pulse length up to 8 ps is reached, which is necessary for sampling the whole THz pulse during th EOSD measurements. The laser pulse length is measured with a commercial autocorrelator [17].

### *Alignment and Settings*

The THz beam is imaged from the THz emitter on the crystal using two off-axis parabolic mirrors with a focusing length of around 10 cm. For the focusing and collimation of the laser beam achromat lenses with a focal length of 15 cm are used. To ensure spatial overlap of the foci in the crystal an aperture at the crystal position was used for maximizing both signals.

Both, the laser and the THz beam, are polarized perpendicular to the table surface. The crystal is oriented with one axis parallel to the beam polarization. A $\lambda/4$ waveplate is used to compensate for the intrinsic birefringence of the crystal. The $\lambda/2$ waveplate is adjusted such that the laser polarization is perpendicular to the transmitted polarization of polarizing beam splitter (PBS), i.e. the power of the beam transmitted through the PBS is minimized. For the EOSD measurements a nearly crossed configuration of the PBS with respect to the laser beam is used. Therefore, the $\lambda/2$ waveplate is rotated 5° from the minimum position to have a linear response of the signal to the electric field of the THz pulse. This angle might be adapted for optimizing of certain EOSD measurement configurations. As the output power of the laser system is 210 mW and the grating stretcher has an efficiency of slightly above 55 % in the current configuration around 5 mW of the laser beam are transmitted by the PBS.

In the current setup, the beam reflected from the PBS is guided to a beam dump. It is planned to use also the information of the second beam in a balanced detection scheme as used at SOLEIL [18].

For the characterization and rough alignment a commercial spectrometer or a photo diode are used. In the next step KALYPSO with a spectrometer consisting of a reflection grating (600 lines/mm) and a cylindrical lens is integrated for the EOSD measurements.

## IMPLEMENTATION AT KARA

A second setup is currently designed for implementation at the Infrared 2 (IR2) beamline at KARA to measure the CSR emitted by the storage ring. The requirements for this setup are slightly different than those of the EOSD demonstrator: The hard constraint in matching the path length for THz and laser pulse is not required anymore as there is no fixed correlation for the timing. Adjusting the temporal overlap can be done using the synchronization of the laser system to the timing signals at KARA. Therefore, a delay stage is not necessary for the measurements at KARA.

At the same time the setup has to be more stable than the demonstrator setup to be capable of long-term operation and - as no permanent installation is possible at the moment - transport and installation at the beamline. For increasing the stability it was decided to use lockable mirror mounts and define single mirrors and apertures in the setup for alignment after moving the setup. Flip mirrors are included to have access for characterizing the laser pulses at any time without changes in the beam path for the EOSD setup.

A spectrometer with KALYPSO as detector, a setup similar to the one used in the demonstrator, is included for recording the EO-modulated laser spectra. Currently the optics for imaging of the spectrum on KALYPSO matching the width of the detector is optimized.

The main challenge for the installation will be the alignment of the emitted CSR and the temporal overlap of it with the laser pulse. Tests for the alignment are performed at the moment at the demonstrator setup to prepare a good workflow for the implementation at the beamline.

## SUMMARY

For the implementation of a new EOSD setup for measuring the temporal CSR profile a demonstrator setup for offline tests independent of the accelerator was set up. A first characterization of the system is finished, but tests and the preparation for the EOSD measurements are ongoing.

In parallel, an optimized setup is designed for the implementation at the IR2 beamline at the storage ring KARA. First measurements are planned during the next months.

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