ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB293

ELECTRO-OPTICAL DIAGNOSTICS AT KARA AND FLUTE – RESULTS AND PROSPECTS

G. Niehues*, E. Bründermann, M. Caselle, S. Funkner, M. J. Nasse, M. M. Patil, R. Ruprecht, M. Schuh, M. Weber, C. Widmann, A.-S. Müller
Karlsruhe Institute of Technology, Karlsruhe, Germany

Abstract

Electro-optical (EO) methods are nowadays well-proven diagnostic tools, which are utilized to detect terahertz (THz) fields in countless experiments. The world's first near-field EO sampling monitor at an electron storage ring was developed and installed at the KIT storage ring KARA (Karlsruhe Research Accelerator) and optimized to detect longitudinal bunch profiles. This experiment with other diagnostic techniques builds a distributed, synchronized sensor network to gain comprehensive data about the longitudinal phase-space of electron bunches as well as the produced coherent synchrotron radiation (CSR). These measurements facilitate studies of physical conditions to provide, at the end, intense and stable CSR in the THz range. At KIT, we also operate FLUTE (Ferninfrarot Linac- und Test-Experiment), a new compact versatile linear accelerator as a test facility for novel techniques and diagnostics. There, EO methods will be implemented to open up possibilities to evaluate and compare new techniques for longitudinal bunch diagnostics. In this contribution, we will give an overview of results achieved, the current status of the EO setups at KARA and FLUTE and discuss future prospects.

INTRODUCTION

While diagnostics is crucial for evaluation, verification and control, new accelerators and also advanced operation modes of accelerators lead to challenges for diagnostic methods. For electron accelerators, real-time measurements of bunch lengths from extended to ultra-short demand diagnostics covering a broad range of time scales. Nevertheless, only single-shot measurements (every bunch or every turn in case of a storage ring) give access to the full information of individual bunches and their temporal evolution, and thus push the possibilities for online control. Here, in particular high-repetition rates for single-shot diagnostics are a bottle-neck.

For storage rings operating with short pulses, the microbunching instability has been studied to gain insights on the emission and control of strong CSR bursts in the THz frequency range (e.g. [1]). In this context, electro-optical (EO) methods have been utilized to measure the longitudinal bunch profiles. The so called EO near-field diagnostics is based on the Pockels-effect: the presence of an electric field, here from the relativistic electron bunch, induces a change in birefringence of a nearby EO crystal. Thereby the longitudinal electron bunch profile is encoded onto the polarization of a probe laser pulse passing through the EO crystal, changing from linear to ellliptical. With polarization optics, this polarization modulation is converted into an intensity modulation. To enable single-shot measurements the electro-optical spectral decoding (EOSD) method based on chirped laser pulses, which was originally applied in THz time-domain spectroscopy (THz-TDS) [2], can be utilized.

EOSD was first applied in a linear accelerator to detect the near-field of electron bunches [3]. At KARA, the world's first near-field EO sampling monitor at an electron storage ring was developed and installed [4]. To cope with the high repetition rate of the storage ring (in the MHz range) and measure the bunch profile on a turn-by-turn basis, advanced detection methods like the photonic-time stretch mode [5] or modern ultra-fast line cameras (KALYPSO [6, 7]) are required. An EOSD system using KALYPSO for single-shot longitudinal bunch profile monitoring for electron bunch lengths is in operation at KARA, as well as at the European XFEL [8]. New accelerators aiming for shorter electron bunches (e.g. KIT FLUTE [9] and cSTART [10]) are calling for EO diagnostics covering shorter time scales.

This paper gives a short overview of the distributed sensor network, describes results and developments of EO diagnostics at KARA. We also discuss prospects for EO diagnostics at FLUTE. Finally, we give an outlook on new techniques and approaches for EO diagnostics for electron accelerators.

DISTRIBUTED DIAGNOSTICS AT KARA

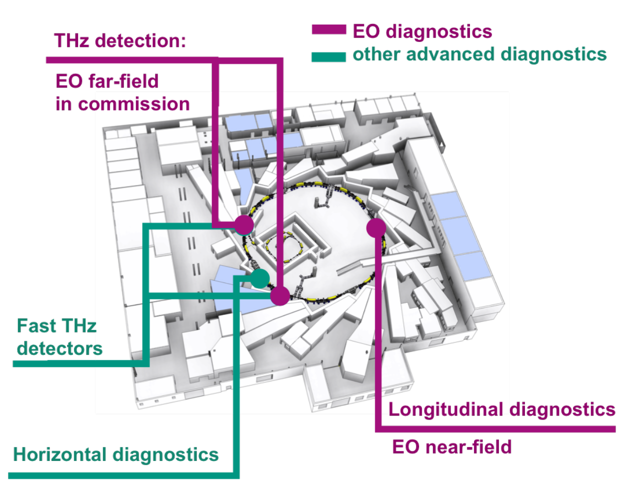

Figure 1: Displayed is the KARA layout with the diagnostic stations of the distributed sensor network. Adpated from image by U. Herberger, KIT IBPT.

* gudrun.niehues@kit.edu

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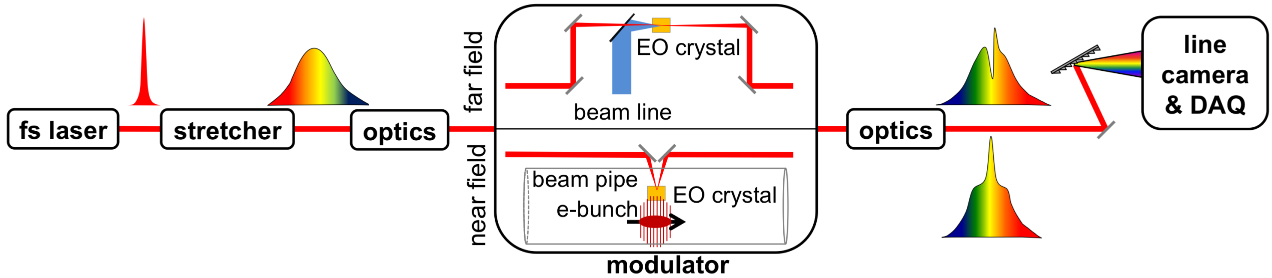

Figure 2: Schematic illustration of EO far- and near-field detection systems: The preparation of the laser pules is for both systems implemented by chirping fs pulses mapped to the ps range. For EO *far-field* diagnostics, the modulation of the laser pulses is induced by leading emitted CSR through a crystal, which changes its birefringence, resulting in a change of the laser pulse polarization. For EO *near-field* diagnostics the birefringence is induced by the electric field of the electron bunch passing close to the EO crystal (inside the vacuum pipe). The analysis of this polarization change is performed for both methods by converting the polarization modulation into intensity modulation, followed by detection using a grating and a fast linear camera and DAQ system (KALYPSO).

At KARA, we operate a distributed sensor network covering various synchronous measurements at three beam lines and one setup in the ring. Figure 1 displays these diagnostic stations around the KARA ring.

For electron accelerators, EO diagnostics can be employed at the near-field as well as the far-field (see Fig. 2). A near-field EO setup is installed in the ring. Two infrared (IR) beam lines enable CSR intensity measurements with fast THz detectors and fast read-out systems (KAPTURE) [11]. Here, at these beam lines, CSR spectral measurements using EO far-field setups are currently in commissioning [12]. Furthermore, in a dispersive section of KARA - at the visible light diagnostics (VLD) port - horizontal beam profiles can be measured using the ultra-fast line camera KALYPSO enabling determination of the energy spread [13].

Synchronous, turn-by-turn measurements at the diagnostic stations have been performed to detect the longitudinal bunch profile and horizontal bunch size as well as the emitted CSR intensity [1, 14]. These measurements reveal correlations between the emitted CSR intensity, deformations in the longitudinal bunch profile and the horizontal bunch size during the microbunching instability.

EO DIAGNOSTICS AT KARA

For near-field measurements, the modulation of the laser pulses takes place in the vacuum pipe, close to the electron beam, where the relativistic Coulomb field of the electron bunch is leaked into the EO crystal. For far-field measurements, the modulation takes places at a beam line guiding the emitted CSR through the EO crystal. The preparation of the chirped laser pulses and analysis (cf. Fig. 2) are very similar for the EO near- and far-field setups.

At KARA, first experiments of far-field CSR detection using EO sampling has been applied averaging over 10^5 individual traces [15]. At the moment, new setups for EO far-field measurements are in commissioning using a 1560 nm fiber laser [12]. Such EO far-field measurements enable the detection of the electric field in amplitude and phase and

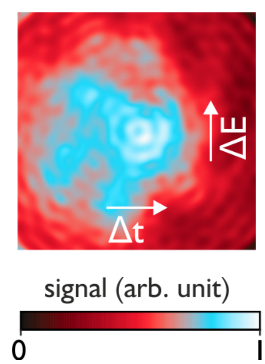

Figure 3: A 2D reconstruction example of the electron bunch phase space density during a microbunching instability cycle at KARA using experimental data measured with the EO near-field diagnostics setup (for details see [16]).

thus full spectral information of CSR in the frequency and time domain. In contrast, direct detectors, such as fast THz detectors, measure the CSR intensity only. The latter type of measurements were performed at KARA with the ultra-fast read-out DAQ KAPTURE [1], which can be operated at repetition rates of hundreds of MHz. Both types of measurements are complementing each other to cover a broad range of applications. While the near-field EO sampling monitor at KARA has been demonstrated for the first time in 2013 [4], improvements have been achieved and are ongoing. The bottleneck of commercial cameras for single-shot detection of the chirped laser pulses is the rather low repetition rate (in the kHz regime). Here, KALYPSO, the KIT-built ultra-fast line camera dedicated for MHz repetition rate spectroscopy, opened up new possibilities [17]. Turn-by-turn single-shot measurements allowed synchronous measurements with various other detectors [1, 14].

Recently, using an approximation of the electron bunch dynamics by a rigid rotation of the phase space density during half of a synchrotron oscillation period, we could demonstrate a robust method to reconstruct the phase space den-

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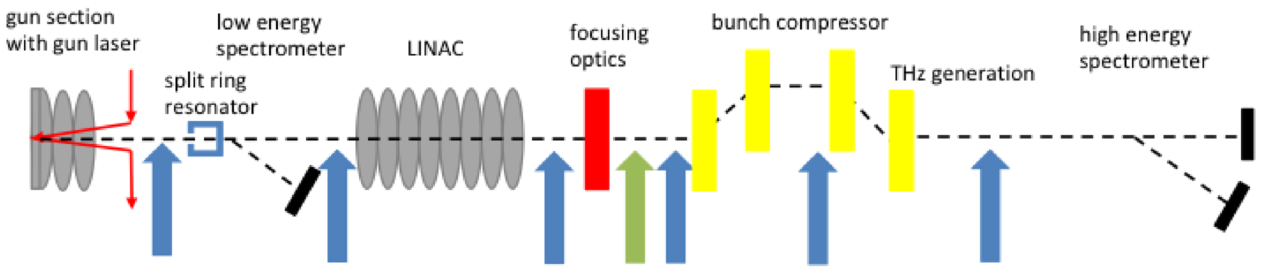

Figure 4: Simplified overview of the FLUTE layout. The green arrow displays the position of first choice for an EO near-field setup, blue arrows mark additional positions where EO near-field setups can be installed.

sity using single-shot EO measurements of the longitudinal bunch profile [16]. To calculate this 2D longitudinal phase space density, filtered back-projections of sinograms (revolution plots) are used enabling phase space tomography of the electron bunch. Figure 3 shows an example of such a 2D phase space density plot during a cycle of the microbunching instability at KARA.

EO DIAGNOSTICS AT FLUTE

FLUTE, the new compact versatile linear accelerator at KIT serves as a test facility for novel techniques and diagnostics [9]. EO near-field setups for FLUTE have been designed in a flexible way, so that an exchange of the EO arm (and thus EO crystal) can be conducted without the need of breaking the vacuum in the FLUTE beam pipe. Furthermore, windows in the beam cube enable online optical inspection of the EO crystal. Thus, experiments with novel modulation techniques can be performed.

Moreover, it is possible to place near-field setups at various positions of FLUTE. Figure 4 gives an overview of FLUTE, where a green arrow shows the first choice for an EO near-field setup and the blue arrows denote possible additional positions. Systematic studies at different positions (and eventually using more than one setup at the same time) enable investigations of the electron bunches along the accelerator as well as comparisons of EO techniques and devices.

SUMMARY AND OUTLOOK

In this paper, we showed a broad range of applications of EO diagnostics at KIT, at the storage ring KARA as well as at the linear accelerator FLUTE. EO diagnostics is a single-shot, non-destructive, online tool enabling various applications. The combination of near-field and far-field EO measurements at electron accelerators opens up the perspective to gain comprehensive information on the phase space of the electron bunches, and to gain time and frequency domain information of the emitted CSR pulses.

In particular, the usage of 1.5 µm laser technology for EO diagnostics can facilitate developments due to the broader availability of such lasers compared to 1 µm lasers.

While the development in the direction of shorter bunches enforces diagnostics and new challenges on smaller time scales, EO methods can also be applied for diagnostics on large time scales and frequency ranges in the GHz range. For example, new highly efficient silicon photonic modulators are currently under development at KIT [18].

ACKNOWLEDGEMENTS

S.F. was funded by BMBF contract No. 05K16VKA, C. W. by BMBF contract number 05K19VKD. G.N. and E.B. acknowledge support by the Helmholtz President's strategic fund IVF "Plasma Accelerators". M.M.P acknowledges the support by the DFG-funded Doctoral School "Karlsruhe School of Elementary and Astroparticle Physics: Science and Technology".

Special thanks to S. Schott and IBPT vacuum group for the excellent design and technical support.

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