ISBN: 978-3-95450-230-1 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2021-MOOB01

ULTRA-FAST LINE-CAMERA KALYPSO FOR fs-LASER-BASED ELECTRON BEAM DIAGNOSTICS

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Abstract

A very common bottleneck to study short electron bunch dynamics in accelerators is a detection scheme that can deal with high repetition rates in the MHz range. The KIT electron storage ring KARA (Karlsruhe Research Accelerator) is the first storage ring with a near-field single-shot electro-optical (EO) bunch profile monitor installed for the measurement of electron bunch dynamics in the longitudinal phase-space. Using electro-optical spectral decoding (EOSD) it is possible to imprint the bunch profile on chirped laser pulses subsequently read out by a spectrometer and a camera. However, commercially available cameras have a drawback in their acquisition rate, which is limited to a few hundred kHz. Hence, we have developed KALYPSO, an ultra-fast line camera capable of operating in the MHz regime. Its modular approach allows the installation of several sensors e.g. Si, InGaAs, PbS, PbSe to cover a wide range of spectral sensitivities. In this contribution, an overview of the EOSD experimental setup and the detector system installed for longitudinal bunch studies will be presented.

INTRODUCTION

In an electron storage ring, investigation of ultra-fast dynamics in short electron bunches of a few ps length requires diagnostic methods that allow non-destructive measurements (e.g. longitudinal bunch profile of the electron bunches) at MHz repetition rate. Most commonly used methods involving the measurement of synchrotron radiation with a streak camera. This method is not capable of single-shot acquisitions, as this diagnostic tool averages the bunch profile over a few turns. On the other hand commercial line array cameras have a disadvantage of being slow with readout rate in the kHz range. In this paper, a diagnostic method based on EOSD combined with a novel line array camera KALYPSO (KArlsruhe Linear arraY detector for MHz rePetition-rate SpectrOscopy) developed at KIT will be presented. Electro-optic techniques are based on the so-called Pockels effect [1]. This effect leads to a phase or polarization modulation of the laser pulse passing through an electro-optic active crystal, e.g. gallium phosphide (GaP), in the presence of an external electric field. The phase modulation can be effectively converted to intensity modulation via a detection scheme based on one of different polarization-based methods [2].

EOSD is a well-known technique in THz spectroscopy. It dates back as early as 1998, when this method was used for the measurement of freely propagating sub-ps electromagnetic pulses using a linearly chirped optical beam [3]. Near-field EO measurements of sub-ps relativistic electron bunches were demonstrated for the first time at the linear accelerator FELIX, a free electron laser facility in the Netherlands [4]. Since then, several facilities have implemented this technique for characterizing electron bunches [5–12]. At the KIT storage ring KARA, far-field EO sampling measurements for the detection of CSR (Coherent Synchrotron Radiation) emitted by short electron bunches were pioneered in 2009 [13]. However, it was in 2013 when the first single-shot measurements based on near-field EO were performed in a storage ring [14].

Such measurements of the near-field in a storage ring are challenging due to the high repetition rate with a requirement for a single-shot non-destructive method without averaging. Another challenge is the deposited heat load on the EO crystal, especially on its coatings. The EOSD technique allows for the direct measurement of the Coulomb field, which gives additional insights into micro-bunching instabilities in storage rings [15].

While this method allows for single shot measurements of electron bunch profiles, the technological limitations posed by commercially available data acquisition systems (DAQs), e.g. low repetition rate of a few kHz, do not allow for the continuous study of the evolution of electron bunch dynamics. Hence, to overcome these challenges, a novel FPGA-based DAQ system combined with an ultra-fast line array camera was developed, KALYPSO [16, 17]. This line array camera offers a modular approach, allowing for the use of different micro-strip sensors based on Si, InGaAs, PbS, and PbSe depending on the required wavelength range. It has a maximum frame rate of 2.7 MHz, but a version operating at 12 MHz is currently being commissioned. In the further sections of this paper, the EOSD setup installed at KARA, the working principle of KALYPSO, data analysis and results from the experiment will be explained.

NEAR-FIELD EOSD SETUP

The measurements were carried out during single bunch operation at the storage ring KARA accelerator at a beam energy of 1.3 GeV. In order to study the micro-bunching instability, a low-alpha optics setup was used to compress the longitudinal bunch length to a few ps. The experimental setup is illustrated in Fig. 1.

First, chirped laser pulses generated by a self-built ytterbium-doped fiber laser (emitting around 1060 nm) are

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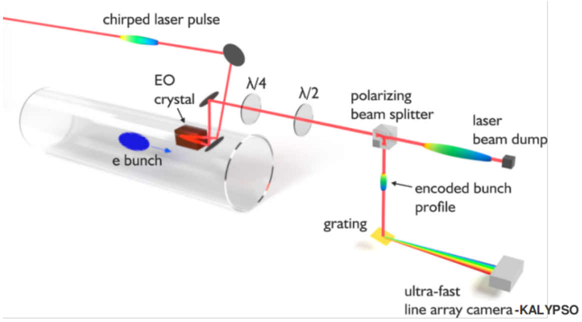

Figure 1: The near-field electro-optic spectral decoding setup for the measurement of longitudinal bunch profile of short electron bunches.

propagated into the storage ring with a 35-meter-long fiber which behaves like a pulse stretcher. The laser pulse passes the EO crystal located inside the beam pipe close to the electron bunch and is reflected at its back side. As the electron bunch and laser pulse are co-propagating, a transient birefringence is induced proportional to the electric field (Pockels effect). Thus, the bunch profile is imprinted on the spectral components of the laser pulse by turning the polarization from linear to elliptical. For decoding the information, the laser pulse is sent through polarization optics: a $\lambda/4$-waveplate is used for compensating the intrinsic birefringence of the crystal, a $\lambda/2$-waveplate and a polarizing beam splitter are used in almost crossed configuration. Therefore, changes of the polarization due to the Pockels effect in the crystal result in an intensity modulation of the spectral components. This can be measured with a spectrometer.

It is necessary to find the temporal overlap of the laser pulses and the electron bunches when they pass through the EO crystal. To adjust the temporal overlap between the laser and the electron bunch, the position of the laser peak intensity modulation is determined with a fast fiber-coupled photodiode. This configuration is then used for subsequent measurements. An oscilloscope is used to acquire the average peak signal of the photodiode (averaged over 100 sweeps) for EO sampling measurements. This signal is dependent on the relative time delay between the laser and the electron bunch, which can be modified by a vector modulator (VM). The readout of the oscilloscope and the VM are both controlled by a MATLAB script that has direct access to the oscilloscope and may access the EO setup control blocks of the accelerator control system (EPICS). Figure 2 shows an example of such a measurement.

For the final step, in order to measure the spectral intensity modulation, the laser pulses are sent through a grating setup and focused onto the Si-sensor of KALYPSO using a lens. The system is operated at a frame rate that is equal to and synchronized with revolution frequency of 2.7 MHz at KARA.

Table 1 shows the beam parameters at the time of the measurements performed for the data presented in this paper.

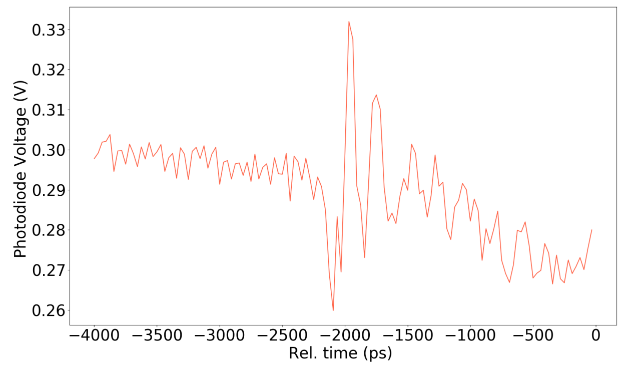

Figure 2: EO sampling traces measured using a fast photodiode combined with an oscilloscope clearly shows the wakefield of the electron bunches. The X axis corresponds to the phase steps of the VM and the Y axis to the maximum photodiode amplitude measured by the oscilloscope.

Table 1: KARA Beam Parameters in Short Bunch Mode Used During the Measurements

Energy (E)	1.3 GeV
Beam current (I_b)	1.13 mA
RF frequency (f_{RF})	499.744 MHz
Synchrotron frequency (f_s)	10.2 kHz
Momentum compaction factor (α_c)	6.5×10^{-4}

KALYPSO

KALYPSO is a line array detector that performs at a maximum frame rate of 12 MHz. KALYPSO's primary advantage over other detectors is its data streaming mode, which captures continuous data at MHz repetition rates and analyzes it with very little latency. Figure 3 depicts the most recent KALYPSO detector card developed and produced at KIT. The detector card comprises of a semiconductor based fine-pitch line-array sensor. A silicon (Si) sensor with an anti-reflection

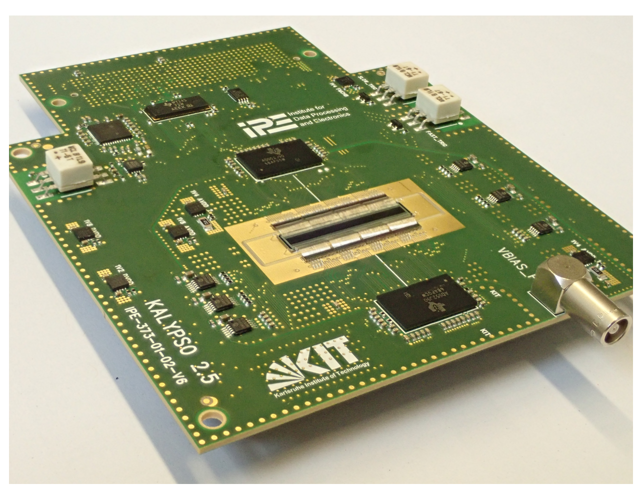

Figure 3: A fully assembled KALYPSO board with Si sensor and optimized sensitivity towards visible light.

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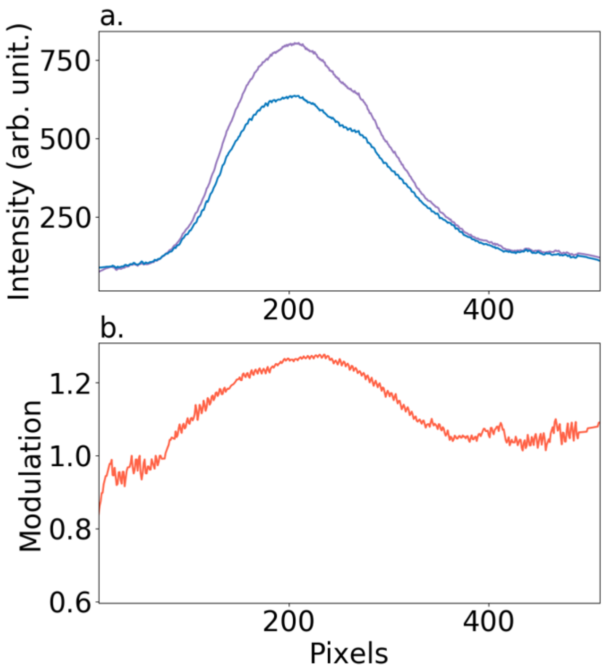

Figure 4: Laser pulse spectra measured using KALYPSO, a: modulated signal (purple) and unmodulated signal (blue), b: calculated EOSD signal (red).

coating (ARC) layer is used for applications requiring spectral sensitivity between 350 nm and 1050 nm [18]. Line arrays based on indium gallium arsenide (InGaAs), lead sellenide (PbSe), or lead sulphide (PbS) can be placed to detect wavelengths greater than 1050 nm. The sensor is read with a low-noise, highly linear front-end electronics ASIC, known as Gotthard-KIT, developed at KIT and PSI in UMC 110 nm CMOS technology [19]. The ASIC's analog outputs are digitized using a high-speed ADC-ADS52J90 linked via a JESD204b subclass 2 interface standard [20].

Additionally, the card has digital-to-analog converters (DACs) for voltage and current biasing the GOTTHARD ASIC, as well as low-jitter clock conditioners for on-board clock distribution. The KALYPSO detector card is connected to the HighFlex FPGA-based readout card through a VITA 57.1 FMC connector. The HighFlex is a KIT-developed FPGA-based readout card equipped with a Xilinx Virtex 7 FPGA, 4 GB DDR3 memory, and a PCIe Gen3 interface [21]. Streamed data can be processed on either a CPU or a GPU.

DATA ANALYSIS AND RESULTS

To calculate the bunch profile, we begin by determining the line array's background signal through laser beam blocking. The signal from the laser pulses propagating through the EO (GaP) crystal, without overlap with the electron bunch is then recorded in the following stage. To do this, the phase of the laser synchronization mechanism is altered such that the laser pulse gets to the EO crystal before the electron bunch. We remove the sensor background signal from both, the overlapped and non-overlapping samples to produce the modulated and unmodulated signals. Figure 4a. the modulated and unmodulated signals and Fig. 4b. the calculated EOSD signal, which is the quotient of Fig. 4a. Furthermore, a time calibration is then needed to convert the pixels to time.

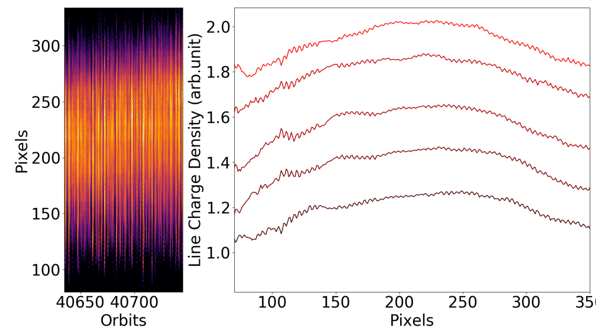

Figure 5: Evolution of the bunch profile in a time window of 40.48 µs. The data representation as a revolution plot allows for comparing different time frames and identify patterns in electron bunch dynamics at various time ranges. For example, the revolution plot of the 100 consecutive measurements indicate the shift in the center of bunch profiles towards higher pixel numbers. This shift can be seen in Fig. 6 as a part of the synchrotron oscillation equivalent to 10.2 kHz.

The unprecedented frame rate provided by the novel DAQ system KALYPSO allows for the precise recording of every single turn, up to a maximum of 10,000,000 turns corresponding to a time period of 3.67 s [22]. Figure 5 shows a small window with the centroid drifting of the bunch profiles, a part of the synchrotron oscillation, which gives an insight into measuring short-term bunch dynamics.

On the other hand, the long acquisition time at a framerate up to 12 MHz provided by the DAQ allows the revelation of dynamics such as the oscillation seen in Fig. 6 with an oscillation frequency of around 10.2 kHz. This matches the synchrotron oscillation frequency measured by the bunch-by-bunch feedback system of the KARA storage ring.

OUTLOOK AND FUTURE WORK

We have repeatedly proven the method's potential for studying longitudinal beam dynamics in this experiment by measuring the near-field of a squeezed relativistic electron bunch in a storage ring using single-shot EOSD. In combination with KALYPSO, we have been successful in obtaining single-shot measurements with high frame-rates over long time periods to study the short-term and long-term evolution of the longitudinal bunch and beam dynamics [23, 24].

The data acquired from such an experiment has also been used to study the bursting behavior of electron bunches by reconstructing the phase space distribution of the electron bunches using phase space tomography and also validated with the Vlasov-Fokker-Planck solver Inovesa [25, 26].

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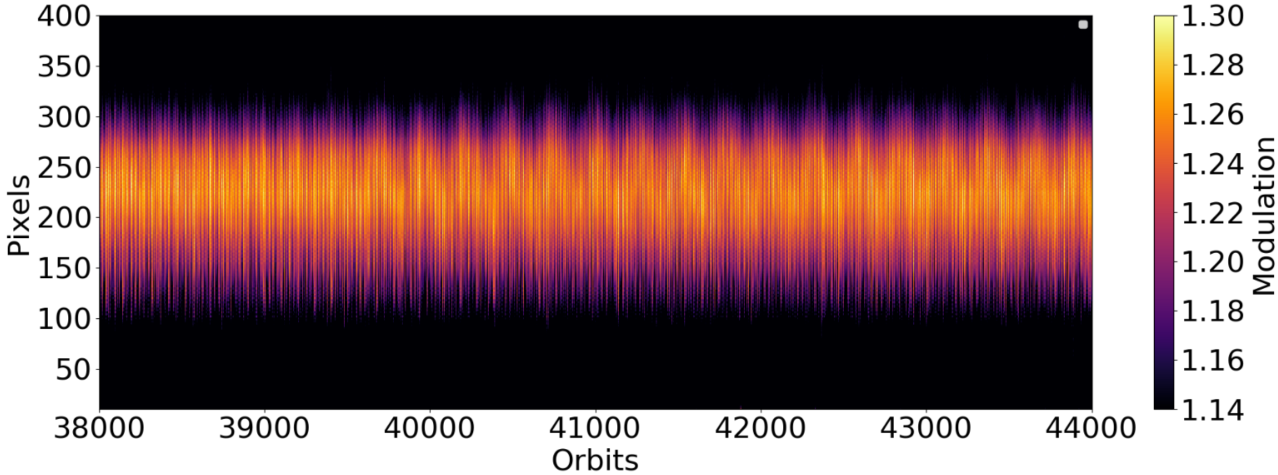

Figure 6: A section of 5,500 samples of the 100,000 continuously acquired bunch profiles spanning a total time period of 36.7 ms. On the X-axis an orbit corresponds to a single revolution with a time of 367 ns and the Y-axis corresponds to the modulation calculated from Fig. 4.

An experimental setup based on electro-optical spectral decoding (EOSD) is now under commission to measure the temporal profile of CSR at the KIT storage ring KARA. The EOSD approach enables for turn-by-turn observations of far-field radiation at MHz rates. Thus, the THz radiation from bunch evolution dynamics, e.g. microbunching, may be studied with high temporal resolution [27].

We have developed KALYPSO, an ultra-fast line array camera, for wide spectral range applications currently operating with frame rates up to 2.7 MHz. The detector has been installed in several experiments in KARA and other accelerator facilities [28, 29]. The detector presented in this paper is the latest version and is currently being commissioned at the EOSD experiment as well as at the energy spread measurement experiment at the visible light diagnostic port at KARA [30, 31]. The next version of this detector, capable of working up to 12 MHz, is in its final stages and will soon be available for measurements.

In an ongoing research towards harnessing high THz radiation, stable coherent synchrotron emission is required. Thus, a feedback loop based on reinforcement learning implemented with an FPGA-based readout card is being investigated. Initial efforts have shown promising results towards a machine learning based feedback system [32].

ACKNOWLEDGEMENTS

The authors would like to thank the former colleagues Nicole Hiller, Patrik Schönfeldt, Lorenzo Rota, and Benjamin Kehrer for their contribution towards the EOSD diagnostic installation at KARA. The authors would like to thank Pia Steck, Simon Hans Jürgen, and Alexander Dierlamm for their constant support in the integration of the ASICs and sensors. Aldo Mozzanica and Roberto Dinapoli for the support in ASIC development. M. M. P. acknowledges the support by the DFG-funded Doctoral School „Karlsruhe School of Elementary and Astroparticle Physics: Science and Technology“. The work is in part supported by the BMBF project 05K19VKD (Federal Ministry of Education and Research).

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ISBN: 978-3-95450-230-1 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2021-MOOB01

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