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DEVELOPMENT OF AN ELECTRO-OPTICAL LONGITUDINAL BUNCH PROFILE MONITOR AT KARA TOWARDS A BEAM DIAGNOSTICS TOOL FOR FCC-ee

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Abstract

The Karlsruhe Research Accelerator (KARA) at KIT features an electro-optical (EO) near-field diagnostics setup to conduct turn-by-turn longitudinal bunch profile measurements in the storage ring using electro-optical spectral decoding (EOSD). Within the Future Circular Collider Innovation Study (FCCIS) an EO monitor using the same technique is being conceived to measure the longitudinal profile and center-of-charge of the bunches in the future electron-positron collider FCC-ee.
This contribution provides an overview of the EO near-field diagnostics at KARA and discusses the development and its challenges towards an effective beam diagnostics concept for the FCC-ee.

INTRODUCTION

An electro-optical near-field monitor can be used as a non-destructive method to measure the longitudinal bunch profile at high resolution and high repetition rate. The Karlsruhe Research Accelerator (KARA) at KIT has been the first electron storage ring to successfully perform single-shot bunch profile measurements using electro-optical spectral decoding (EOSD) in 2013 [1]. Since then, the setup has been improved to enable observations of the longitudinal electron bunch dynamics on a turn-by-turn basis using the KIT-developed ultra-fast line camera KALYPSO (KArlsruhe Linear arraY detector for MHz rePetition-rate SpectrOscopy) [2]. With a tomographic imaging technique, it is also possible to observe the dynamics of the longitudinal Phase-Space Distribution (PSD) including formation of microstructures caused by the microbunching instability [3]. As a result, EOSD is a promising technique for new particle accelerators like the future circular collider FCC-ee. It can be used as a non-destructive beam diagnostic tool to perform longitudinal bunch profile measurements with sub-picosecond resolution and the potential to observe phase-space dynamics on a microsecond time scale. In context of the Future Circular Collider Innovation Study (FCCIS), an adaption of the KARA EO setup is under investigation to be optimized for FCC-ee beam parameters.

REQUIREMENTS FOR FCC-ee

The FCC-ee is an electron-positron collider planned as a successor to the LHC at CERN with a circumference of around 100 km that operates at 4 different energies for precision measurements of different elementary particles [4].

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Table 1: Comparison of KARA in Low-Alpha Mode and Extrema of FCC-ee Parameters (Based on 2 IP layout [5])

	KARA low-alpha mode	FCC-ee extrema
Beam energy / GeV	1.3	182.5
Bunch charge / nC	2.2	38.0
Bunch length / mm	3	12.1

It starts with a centre-of-mass energy at the Z-boson pole of 45.6 GeV and increases later to the WW threshold, ZH production peak and finally the $t\bar{t}$ threshold at 182.5 GeV. In order to achieve high luminosities, the accelerator holds up to 12 000 bunches in which the number of particles is held constant with top-up injection [5]. This requires monitoring of the bunch profile and its center of charge for every bunch. EOSD has the potential to fulfill these requirements, but a detailed investigation is needed to adapt the setup at KARA to the demanding FCC-ee beam parameters.

A comparison of the most interesting parameters for EOSD measurements of KARA and FCC-ee are presented in Table 1, where the extrema out of all operation modes of FCC-ee are shown.

EO NEAR-FIELD SETUP AT KARA

The EO near-field setup at KARA is driven by a 1030 nm laser producing chirped ultra-short pulses in the range of some 10 fs. The modulation and detection of the laser pulse, which enables the measurement of the electron bunch profile, can be divided in three major steps as shown in Fig. 1.

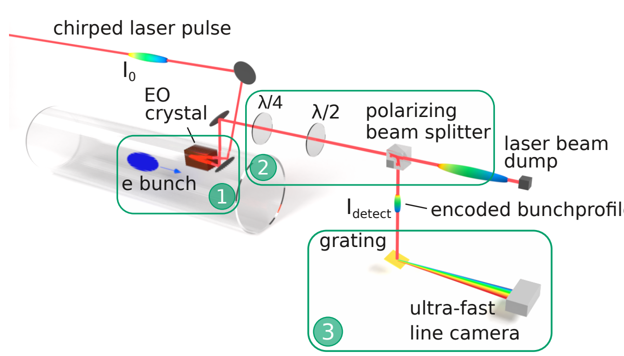

Figure 1: Scheme of the EO setup. Adapted from [3].

At first, the bunch profile is encoded in the polarization of the laser pulse. This is caused by the Pockels effect, where the birefringence of the crystal changes proportional to the

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applied electric field. As a result, a laser pulse changes its polarization when it propagates through the crystal, while an electron bunch is flying by. The crystal is oriented such that the modulation Γ of the polarization is proportional to the electric field E_y and is given by

$$\Gamma = \frac{2\pi d}{\lambda} n_0^3 r_{41} E_y. \quad (1)$$

The modulation therefore also depends on the crystal width d, the refractive index n_0, the Pockels coefficient r_{41} and the wavelength λ of the laser [6, 7].

In a second step, the polarization modulation is converted to an intensity modulation. An arrangement of a $\lambda/4$ waveplate, a $\lambda/2$ waveplate and an polarizing beam splitter are setup in a near-crossed configuration [1]. In this setting, the laser intensity I_{detect} on the detector is very small. But if the polarization is modulated in the crystal by Γ, the intensity I_{detect} increases according to

$$I_{\text{detect}} = \frac{1}{2} I_0 \left(1 - \cos\left(\Gamma - 4\theta\right)\right), \quad (2)$$

where θ describes the angle of the $\lambda/2$ waveplate relative to the crossing angle and I_0 is the initial laser intensity [1].

The last part belongs to the data acquisition. For EOSD, this is a spectrometer with KALYPSO as an ultra-fast line camera to measure the spectrum of individual pulses [2]. Since the laser pulse is chirped, each laser wavelength is encoded to a position in the laser pulse and therefore the spectrum also corresponds to the longitudinal bunch profile. A photodiode can also be used instead of the spectrometer to perform electro-optical sampling (EOS) measurements [8]. With EOS, the sampled wakefield over multiple turns can be scanned by shifting the time delay of the laser pulse, while measuring the laser pulse intensity. EOS is also used in preparation of EOSD measurements to find temporal overlap of the laser pulse with the E-field of the electron bunch.

SIMULATION SETUP

For a complete simulation of the EO near-field measurements, the first step is to simulate the electric fields inside the crystal. For this task, a simplified 3D-model of the crystal with its holder inside the beam pipe was created in CST Studio Suite [9] and its wakefield solver was used to simulate the electric field of an electron bunch travelling through it.

The laser first propagates anti-parallel to the electron beam through the crystal, until it is reflected back and moving downstream. For bunch profile measurements, only the first peak of the downstream signal is important and it should not overlap with a peak of the upstream signal. The simulated up- and downstream sum of the electric field along the laser path inside the crystal is presented in Fig. 2. It is simulated for typical beam parameters at KARA in low-alpha single-bunch operation and shows that in this case, the first peak of the downstream signal has just a slight overlap with the upstream signal.

The modulation Γ of a laser pulse following this path is calculated based on the sum of the electric field of the

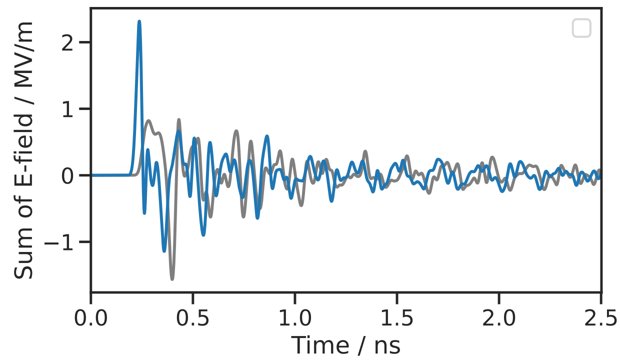

Figure 2: Upstream (grey line) and downstream sum (blue line) of the E-field along the laser path inside the crystal. The first downstream peak does not overlap with the upstream peak, which is important to avoid distortions of the EOSD signal.

moving probe and Eq. (1). The conversion of the polarization modulation to an intensity modulation follows Eq. (2), with $\theta = 4.6°$. This angle of the waveplate is optimized to enable the dependency of I_{detect} to be as linear as possible [1].

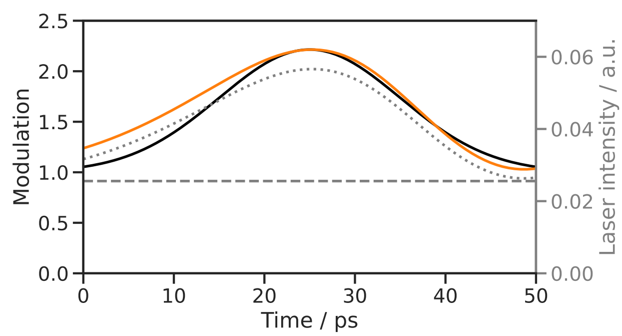

Figure 3: The resulting modulation (orange line) is calculated by dividing the modulated laser signal (dotted grey line) by an unmodulated laser signal (dashed grey line). The modulated laser signal corresponds to the first peak of the detected laser signal I_{detect}. A comparison to the shape of the original Gaussian bunch profile (black line) shows a slight asymmetry at the beginning of the pulse.

In the last step, the laser intensity I_{detect} can be used to emulate the result of an EOSD measurement by dividing the modulated signal of the first peak by an unmodulated signal, where the laser pulse does not overlap with the electron bunch. The resulting modulation is shown in Fig. 3. It additionally shows a Gaussian profile with $\sigma = 3$ mm, which corresponds to the shape of the original simulated bunch profile. A comparison to the modulation signal shows an asymmetry of the modulation, which leads to a deviation to the Gaussian distribution towards the beginning of the signal. However, the overall shape of the bunch is visible and the deviation can be taken into account during analysis.

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MAJOR CHALLENGES AT FCC-EE

A comparison of the polarization modulation Γ at KARA and FCC beam properties is presented in Fig. 4. It shows a peak modulation of $\Gamma_Z^{\text{FCC-ee}} \approx 100°$, which is very high in comparison to $\Gamma^{\text{KARA}} \approx 9°$. According to Eq. (2), I_{detect} is approximately linearly proportional to small Γ ranges, but with the large bunch charge at FCC-ee this is not the case. As a result, the laser intensity I_{detect} does not correspond to the bunch profile, because it is distorted by $\cos(\Gamma - 4\theta)$. To mitigate this issue, the distance of the crystal to the electron bunch could be increased, or the crystal properties can be adjusted, for example by using a smaller crystal.

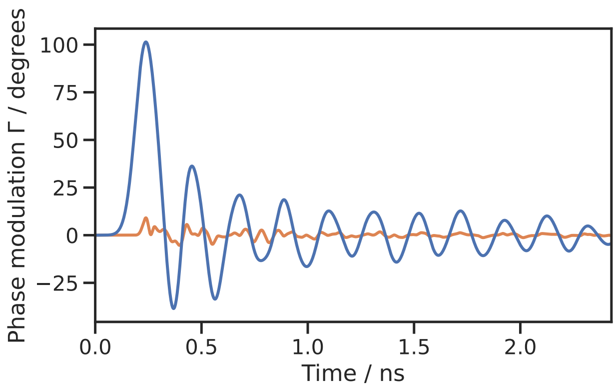

Figure 4: Comparison of the simulated phase modulation Γ at KARA low-alpha beam parameters (orange line) and FCC-ee at Z-boson pole energy (blue line). The large modulation Γ at FCC-ee parameters leads to a non-linear behavior of $I_{\text{detect}}(\Gamma)$ (see Eq. (2)). This should be avoided to prevent distortions of the EOSD signal.

The second major challenge is the bunch length at FCC-ee, which increases to $\sigma_Z^{\text{FCC-ee}} = 12.1$ mm during the operation at Z-boson pole energy. A larger bunch causes the upstream signal to increase, because the temporal overlap of the upstream laser pulse in the crystal with the electric field of the electron bunch increases with bunch length. Since the EOS and EOSD signal is a result of the sum of up- and downstream signal, but only the first peak of the downstream signal represents the electron bunch profile, a large upstream signal distorts the measurement signal. To avoid the upstream signal, a transmission setup, where the laser is not reflected back through the crystal, could be considered. Such a setup is more challenging because it requires an additional mirror in front of the crystal, but it would allow to reduce the crystal size and therefore decrease the modulation Γ to help with the issue of high electric fields at FCC-ee.

COMPARISON OF FCC-EE MODES

The different operation modes of FCC-ee come with large differences in bunch length and bunch charge [5]. To evaluate the effect on EOSD measurements, simulations have been done of the phase modulation Γ for all FCC-ee operation modes. The longest bunches are present during operation for Z-boson production with $\sigma_Z^{\text{FCC-ee}} = 12.1$ mm and the shortest with $\sigma_{t\bar{t}}^{\text{FCC-ee}} = 2.6$ mm during operation at $\bar{t}$ threshold energy. As discussed in the previous subsection, a transmission setup would be better suited for long bunches, because the laser pulse is only propagating downstream through the crystal and the unwanted upstream signal is avoided.

The peak phase modulation amplitude $\Gamma_{\text{Z, max}} \approx 100°$, $\Gamma_{\text{WW, max}} \approx 120°$ and $\Gamma_{\text{ZH, max}} \approx 150°$ are in a range that one EOSD measurement setup could be sufficient to be used for all three modes with minor adjustments. For $t\bar{t}$ mode however, the peak amplitude is $\Gamma_{t\bar{t}\text{, max}} \approx 400°$ more than double of the other modes due to the higher charge density of the electron bunches. Thus, the measurement setup needs to be adjusted, for example by increasing the distance of the crystal to the beam or by decreasing the crystal size.

SUMMARY AND OUTLOOK

EOSD is a non-destructive method to measure a single-shot bunch profile and has been used at KARA since 2013. To investigate its potential as a bunch diagnostics tool for FCC-ee, a simulation environment has been set up to emulate the complete measurement procedure from the electric field in the crystal to the optical components manipulating the laser pulse. Simulations of the KARA measurement setup under FCC-ee beam parameters provide a first insight to the challenges, that an EOSD setup will face at FCC-ee. The two major differences are the longer bunches during Z-operation mode and the large electric fields especially during $t\bar{t}$-mode operation. To mitigate these issues, a transmission setup is suggested, where the laser pulse is not reflected back through the crystal. This would avoid issues with a disturbing upstream signal and would allow to decrease the crystal size to reduce the impact of large electric fields.

The next step is to develop a design for the EOSD transmission setup and perform preliminary tests in simulations. Since the current design of the FCC-ee beam pipe features a circular cross section with additional winglets to the sides, it should be investigated, if the crystal could be placed inside a winglet. This would help to cope with the large electric fields and could reduce the impedance impact.

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