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SIMULATIONS OF AN ELECTRO-OPTICAL IN-VACUUM BUNCH PROFILE MONITOR AND MEASUREMENTS AT KARA FOR USE IN THE FCC-ee

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Abstract

The Karlsruhe Research Accelerator (KARA) is an electron storage ring for accelerator research and the synchrotron of the KIT light source at the Karlsruhe Institute of Technology (KIT). KARA features an electro-optical (EO) in-vacuum bunch profile monitor to measure the longitudinal bunch profile in single shot on a turn-by-turn basis using electro-optical spectral decoding (EOSD). A simulation procedure has been set up to evaluate its suitability as a beam instrumentation for the operation of the future electron-position collider FCC-ee. In order to assess the simulations, this contribution focuses on a comparison to EO sampling (EOS) measurements at KARA and a study on the heat load of the EO crystal due to the expected high bunch repetition rate envisioned for FCC-ee.

INTRODUCTION

The Future Circular Collider (FCC) innovation study aims to investigate the technical viability of a new particle collider with 90.7 km circumference at CERN [1]. The first stage is the electron-positron collider FCC-ee for high precision measurements. FCC-ee will run with a top-up injection scheme, with the goal to keep the bunch charge on a constant level during operation. This provides a challenge, since monitoring of the longitudinal charge density profile and bunch length is desired. Thus, the development of a diagnostics tool is necessary, which needs to perform single-shot measurements at high repetition rates, while still maintaining a sub-picosecond resolution and keeping the influence on the particle beam at a minimum.

Promising candidates are electro-optical techniques, where an electro-optical crystal is installed at the inner edge of the vacuum chamber. Due to the Pockels effect, the Coulomb field of the electron bunch changes the birefringence of the crystal, which causes a shift in the polarisation of the laser pulses. The intrinsic birefringence is compensated with a $\lambda/4$ waveplate and a following $\lambda/2$ waveplate and polarising beam splitter (PBS) is set in a near-crossed configuration, such that a modulation of the laser polarisation results in a modulation of the laser intensity. The longitudinal bunch profile can then be retrieved by analysing the laser pulse with single-shot techniques like electro-optical spectral decoding (EOSD) [2].

The Karlsruhe Research Accelerator (KARA) is an electron storage ring used as test facility and synchrotron light source that has an electro-optical bunch profile monitor installed since 2013 [2]. This monitor was continuously developed to perform single-shot turn-by-turn bunch profile measurements at 2.7 MHz. To benefit from the years of experience, the development of a first bunch profile monitor concept for FCC-ee is based on the KARA setup and corresponding simulations [3, 4].

In the following sections, these simulations are put to the test in a detailed comparison with electro-optical sampling (EOS) measurements at KARA. In these measurements, the intensity of the laser pulses is recorded with a photodiode while scanning the time delay between the laser pulse and the electron bunch. The photodiode does not resolve single pulses but integrates the laser intensity over the laser pulse length. As a result, the EOS scan corresponds to a moving average over the Coulomb field and the trailing wake field of the electron bunch.

EOS MEASUREMENTS AT KARA

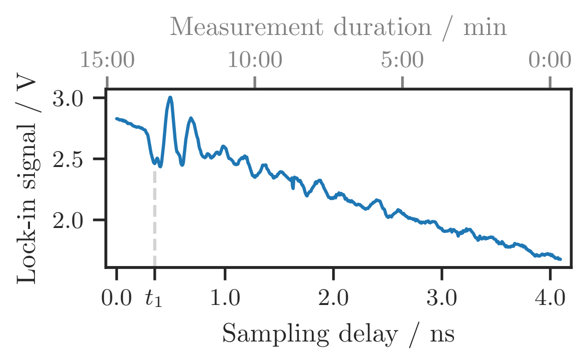

Figure 1: EO sampling of the electrical field of an electron bunch and the trailing wake field. It shows the laser signal detected by a photodiode recorded with a lock-in amplifier to increase the signal-to-noise ratio. The overlap of laserpulse and Coulomb field of the electron bunch is marked as t_1. The following oscillation corresponds to the wake field.

Figure 1 shows an EOS measurement with a scanned delay range of around 4 ns in steps of 5.86 ps. The Coulomb field shows as a modulation of the laser intensity in the first negative peak at $t_1 = 0.35$ ns, followed by intensity modulations of the wake field. The measurement took 15 min and was taken from right to left. Before the measurement, the polarization optics after the crystal were set to a near-crossed configuration, with the $\lambda/4$ waveplate compensating for the intrinsic birefringence and the $\lambda/2$ waveplate set to $\theta = -4.6°$, where the zero angle is defined to be at the

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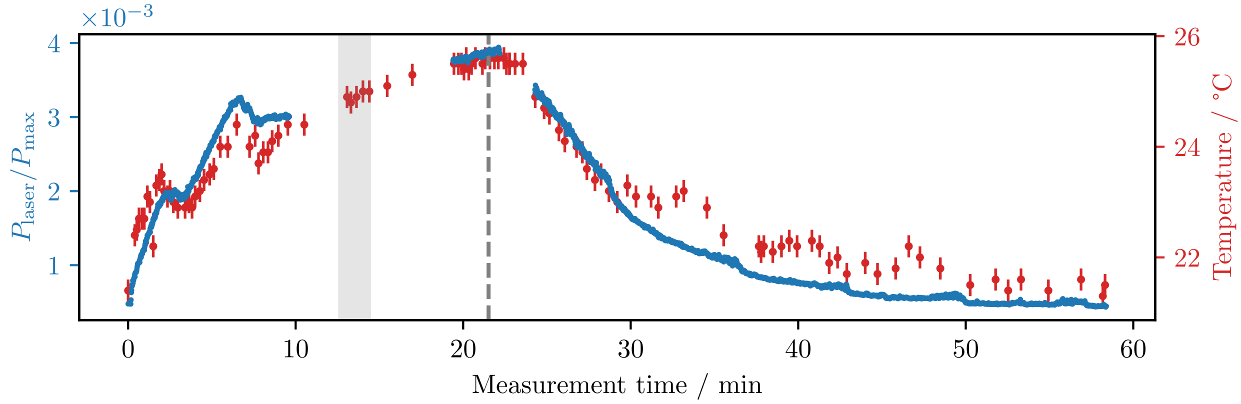

Figure 2: Normalized laser power (blue points) and temperature of the crystal (red points) over time. The data points include an estimated error of the equipment. During the heating process scans of the quarter waveplate were perfomed (grey area). After 20 min the heater was turned off (dottet line).

crossed configuration. The laser intensity after the polarization optics I_{det} is described by

$$I_{\mathrm{det}}(\theta,\phi,\Gamma) = \frac{I_{\mathrm{laser}}}{2}[1-\cos(\Gamma-2\phi+4\theta)\cos^2(\phi) + \cos(\Gamma+2\phi-4\theta)\sin^2(\phi)] \quad (1)$$

with the phase modulation Γ [5].

During the 15 min EOS measurement, the bunch charge decreased from approx. 0.35 nC to 0.27 nC, which itself directly affects the modulation amplitude, but not the unmodulated lock-in signal. With the bunch charge, the bunch length also decreases from $\sigma_{t,0} = (10.83 \pm 0.02)$ ps to $\sigma_{t,1} = (9.87 \pm 0.02)$ ps, which has been measured with a streak camera directly before and after the EO measurement [6].

A scan of the $\lambda/2$ waveplate after the EOS measurement revealed, that even though the waveplates did not move, to get back to the near crossed configuration, the waveplates needed to be rotated by $\Delta\phi \approx 8°$ and $\Delta\theta \approx 2°$. According to Eq. 1, the relative change of the polarization optics leads to a change in laser intensity I_{det}, which shows in the measurement as a steady increase of the lock-in signal over the 15 min duration of the measurement.

To improve the understanding of EOS measurements, two important aspects are investigated in the following chapters: Firstly, the reason for the slow increase of the signal over time is investigated in a separate experiment in a laboratory. Secondly, the measured modulation caused by the Coulomb and wake field is simulated and compared to the EOS measurement at KARA.

QUALITATIVE INVESTIGATION OF CRYSTAL HEATING

During EOS measurements at KARA as in Fig. 1, the laser intensity is often slowly increasing or decreasing over time. This effect has not been observed, if there is no electron beam in the accelerator and is suspectedly caused by the electron beam heating up the EO crystal, which changes its intrinsic birefringence. To further investigate this effect in a qualitative approach, a duplicate of the EO monitor at KARA has been set up in-air in a laboratory. The crystal was heated with hot air, while monitoring its temperature using an IR camera. Figure 2 shows the normalized laser power and the temperature of the crystal center over time. The laser power was monitored similar to the setup at KARA with a fiber coupled power meter with the polarizer set up in a crossed configuration. To determine the waveplate angles for the crossed configuration, a scan of both waveplates has been performed before and after the experiment, as well as during the measurements, which is marked as a grey area in the figure. The crossed configuration during the measurement is shifted compared to before and after the measurement by $\Delta\phi \approx 2°$ and $\Delta\theta \approx 0.5°$.

As a result, this first qualitative test of crystal heating shows a change of measured laser power with the crystal temperature. This is caused by a change of the laser polarization after the crystal, which would require adjusting the waveplates to get back to a crossed polarizer setting. It is a similar behaviour to what is observed during EOS experiments at KARA and shows, that the heating effect of the crystal is at least partly causing the drift in laser intensity during EOS measurements. However, for a more precise analysis of this effect, additional measurements with an improved setup are necessary, for example by emulating the electron bunch with a hot wire and measuring the temperature of the crystal with a temperature probe.

EOS SIMULATION WITH MEASUREMENT PARAMETERS

The simulation of EOS measurements is based on a numerical simulation of the electrical fields inside the crystal using the CST Studio Wakefield Solver [7]. This includes a simplified geometry of a section of the KARA vacuum chamber with the EO crystal and its holder [8]. The follow-

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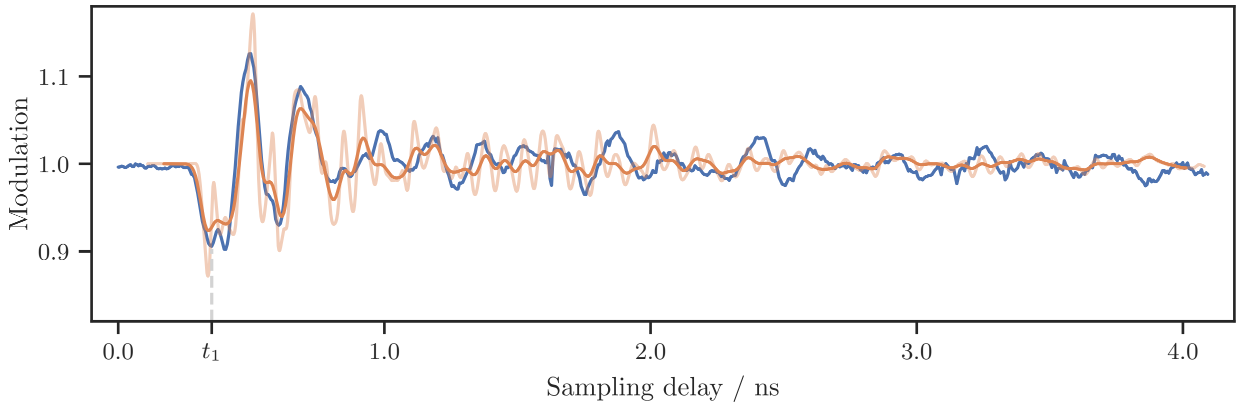

Figure 3: Comparison of the simulated EOS modulation (orange), approximating the measurement at KARA with a Gaussian probe laser pulse with a duration of $\sigma_t = 20.2$ ps, and the actual measurement (blue). The simulated modulation for a probe point using the CST Studio Wakefield Solver is also shown (light orange).

ing input parameters have been taken from the measurement at the time of the overlap of laser pulse and coulomb field t_1 and were approximated to be constant during the EOS scan. This includes a bunch charge of $q \approx 0.274\,\mathrm{n}C$, a distance between crystal and electron bunch center of $d \approx 4.5$ mm and a bunch length of $\sigma_{\mathrm{t,\,bunch}} \approx 9.9$ ps. In the next step, the electrical field is further processed to calculate the phase modulation Γ of a laser pulse propagating through the crystal, which is described in [3]. The simulation procedure has been improved to approximate the laser pulse to have a Gaussian longitudinal profile with $\sigma_{\mathrm{t,\,laser}} \approx 20.2$ ps and to include the $\lambda/4$ waveplate according to Eq. 1. Based on the unmodulated signal strength, the waveplate angles at the overlap have been estimated to be $\phi_{\mathrm{overlap}} \approx 7°$ and $\theta \approx 2°$.

The simulated and measured EOS modulation is presented in Fig. 3. To calculate the modulation in the measurement and compensate for the signal increase over time, the lock-in signal is divided by a fitted exponential function. The simulated modulation of a probe point instead of a prolonged pulse is also shown (cf. Fig. 3). It represents the actual probed electrical field inside the crystal and illustrates the smoothing effect of the photodiode integrating over the single laser pulse intensity in an EOS scan.

Comparing EOS measurement and simulation reveals a good agreement of the first peaks, where the simulation is able to replicate the most prominent features. The simulation shows a slightly lower modulation amplitude that could originate in an error of the estimated rotation angle of the $\lambda/2$ and $\lambda/4$ waveplates. The simulation also does not account for the dynamic change of input parameters like bunch charge, bunch length and the mentioned heating effect, which are possible reasons for the deviation to the EOS measurement.

All in all, the comparison shows that it is possible to simulate the EO measurements with the simplified model and still receive a good estimation of the modulation. This is especially important with respect to the prototype development for FCC-ee, since no accelerator exists which can replicate its beam parameters for testing purposes and therefore the development relies on simulations [4].

CONCLUSION

The comparison of an EOS measurement and a simulated EOS scan of the Coulomb field and wake field of an electron bunch at KARA shows that the simulation is able to successfully replicate the most prominent features of the electrical field despite including some simplifications. This is especially important with respect to the development of an EO bunch profile monitor prototype for FCC-ee, which is based on the design at KARA, but adjusted to the beam parameters of FCC-ee using simulations.

In order to investigate the drift in laser intensity over time during EOS measurements, a duplicate of the EO monitor has been set up in the lab. The qualitative impact of a change in the crystal temperature on the measured laser intensity has been measured. It shows a similar behaviour than what was observed during EOS measurements and it is suspected that the passing electron bunch is causing this effect by heating up the crystal over time. The concept for FCC-ee has a smaller impedance due to a greater distance to the crystal, which reduces the heating effect [4]. Further investigation is needed to assess the impact of the different beam parameters during different operation modes.

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REFERENCES

[1] A. Abada *et al.*, "FCC-ee: The lepton collider", *Eur. Phys. J. Spec. Top.*, June 2019, Vol. 228, pp. 261–623. doi:10.1140/epjst/e2019-900045-4

[2] N. Hiller, "Electro-optical bunch length measurements at the ANKA storage ring", Ph.D. thesis, Karlsruher Institut für Technologie (KIT), Karlsruhe, Germany, 2013. doi:10.5445/IR/1000041159

[3] M. Reißig *et al.*, "Development of an Electro-Optical Longitudinal Bunch Profile Monitor at KARA Towards a Beam Diagnostics Tool for FCC-ee", in *Proc. IPAC'22*, Bangkok, Thailand, 12-17 June 2022, pp. 296–299. doi:10.18429/JACoW-IPAC2022-MOPOPT025

[4] M. Reißig *et al.*, "Status of a Monitor Design for Single-Shot Electro-Optical Bunch Profile Measurements at FCC-ee", in *Proc. IBIC'22*, Krakow, Poland, 11-15 September 2022, pp. 455-459. doi:10.18429/JACoW-IBIC2022-WEP26

[5] B. Steffen, "Electro-optic methods for longitudinal bunch diagnostics at FLASH", Ph.D. thesis, Universitat Hamburg, Hamburg, Germany, 2007.

[6] N. Hiller *et al.*, "Status of Bunch Deformation and Lengthening Studies at the ANKA Storage Ring", in *Proc. IPAC'11*, San Sebastian, Spain, Sep. 2011, paper THPC021, pp. 2951–2953.

[7] CST Studio Suite 2021, https://www.3ds.com/products-services/simulia/products/cst-studio-suite

[8] P. Schönfeldt *et al.*, "Towards Near-field electro-optical bunch profile monitoring in a multi-bunch environment", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 227-230. doi:10.18429/JACoW-IPAC2017-MOPAB055