FIRST TWO-BUNCH MEASUREMENTS USING THE ELECTRO-OPTICAL NEAR-FIELD MONITOR AT KARA

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Abstract

The Karlsruhe Research Accelerator (KARA) is an electron storage ring, which features an electro-optical near-field monitor as a tool for longitudinal bunch profile measurements. The device performs well in single-shot turn-by-turn measurements during single-bunch operation and over the years, the design has been optimized to be prepared for measurements in multi-bunch operation. The ability to work with multiple bunches and short bunch spacing is an important step to make the device suitable for more application purposes, such as a diagnostics tool for the future electron-positron collider FCC-ee. This contribution provides first tests of the monitor during two-bunch operation with minimum 2 ns bunch spacing. Challenges like crystal heating due to an increased beam current are discussed and strategies for mitigation are presented.

INTRODUCTION

Electro-optical (EO) crystals can be used to probe electrical fields with a laser pulse. In particle accelerators, possible applications are direct measurements of the Coulomb field of electron bunches or THz pulses from the synchrotron radiation. At the Karlsruhe Institute of Technology (KIT), an EO near-field monitor was installed at the Karlsruhe Research Accelerator (KARA) in 2013 [1] and an EO far-field monitor to detect the coherent synchrotron radiation (CSR) is currently being commissioned [2]. The near-field monitor uses electro-optical spectral decoding (EOSD) to measure the longitudinal charge density profile of electron bunches and has been optimized over the years to perform single-shot turn-by-turn measurements. In order to achieve the high repetition rate of 2.7 MHz for turn-by-turn measurements, it uses the in-house developed Karlsruhe linear array detector for MHz-repetition-rate spectroscopy (KALYPSO) [3]. Recently, these measurements have been used for tomographic reconstruction of the longitudinal phase space density, which allows us to observe the dynamics of substructures caused by the microbunching instability [4].

So far, all measurements have been done in a special operation mode of KARA with a single bunch stored in the ring. The reason is to protect the crystal from potential damage and to avoid disturbances of the bunch profile measurement by the wake field of previous electron bunches. Since the crystal holder design was optimized towards multi-bunch operation with a reduced impedance [5], it became possible to conduct first test measurements with two consecutive electron bunches with 2 ns spacing in the storage ring.

SETUP FOR EO SAMPLING

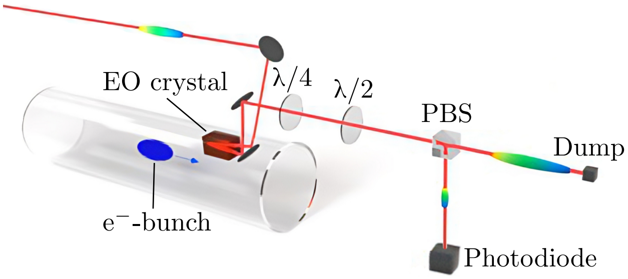

Figure 1: Schematic of EOS measurements at KARA. Adapted from [4].

In order to probe the wake field of the electron bunches, the measurements have been performed using electro-optical sampling (EOS). Figure 1 provides a schematic overview on the measurement setup. A laser pulse with a central wavelength of around 1030 nm is guided into the vacuum chamber of the accelerator, where a gallium phosphide (GaP) crystal is installed. When the crystal experiences the electrical field from passing electron bunches, its birefringence is modulated according to the Pockels effect. This change in birefringence modulates the polarisation of the laser pulse. The laser pulse then passes through a λ/4- and a λ/2-waveplate followed by a polarising beam splitter (PBS). The PBS separates the laser pulse into two polarized components by transmitting one polarization direction and reflecting the other. For this experiment, we only use the transmitted part, which is sent on a photodiode (PD). The waveplates are set in a nearly crossed orientation, which reduces the intensity of an unmodulated laser pulse to a low signal. As a result, the peak voltage on the photodiode changes (positive or negative), when the polarisation of the laser has been modulated by an electrical field in the EO crystal.

For sampling of the Coulomb and wake field of the bunch, the delay of the laser pulse is shifted in small time steps while the peak PD voltage is recorded with an oscilloscope[1] that averages over 12 pulses. It is important to note that in contrast to EOSD, EOS is not a single-shot measurement. The resulting graph of PD voltage over laser delay depicts the electric field of the electron bunch and the trailing wake field.

The crystal holder is mounted onto a motorized stage to adjust its distance to the electron beam. In the park position, the crystal is inside a small cabinet on top of the beam pipe that can be closed with a shutter. During the startup of the machine, the crystal is in this protected park position.

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[1] Teledyne LeCroy HDO9404-MS

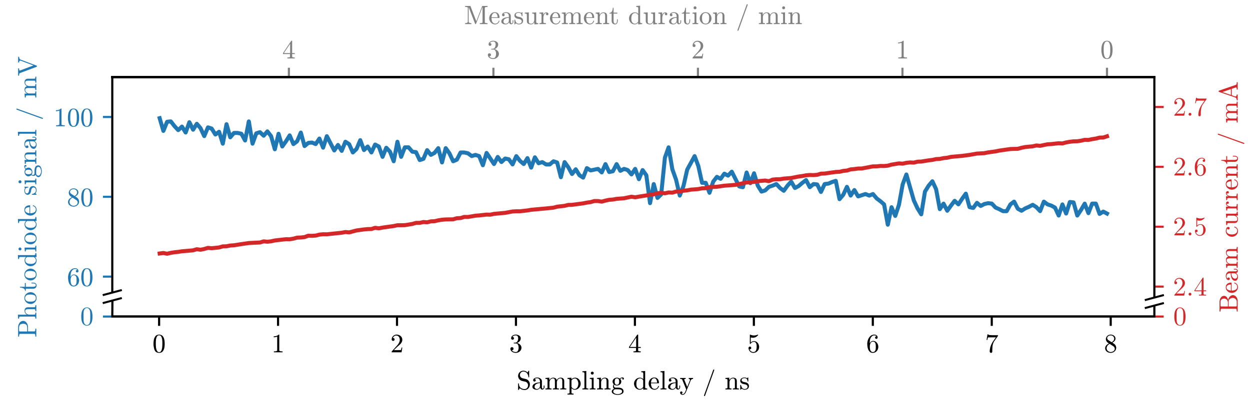

Figure 2: EO sampling of the electric field during operation with two bunches. The blue curve shows the averaged amplitude of the electric field detected by the photodiode over 12 laser pulses. It is sampled over a range of 8 ns with peaks originating in the electric field of the bunches and their wake field with the front of the bunch on the left. The measurement took approximately 5 min and in that time, the beam current (red) dropped from 2.65 mA to 2.45 mA.

TWO-BUNCH MEASUREMENTS

The goal of the EOS measurement with two electron bunches in the storage ring is to probe the electric field of the bunches and their wake field. With this data it is possible to evaluate, if the wake field of the first bunch overlaps with the electric field of the second bunch and therefore would potentially disturb a bunch profile measurement of the second bunch with EOSD. Thus, the measurements serve as a test for previous design optimisations of the crystal holder, which were done to prepare the setup for multi-bunch operation [5].

In previous measurements with a single bunch in the storage ring, the bunch would pass the crystal approximately every 368 ns, which provides enough time for the wake field to decay. For the measurements with two bunches, they are filled in neighbouring RF-buckets to reach the minimum bunch-spacing, which, at KARA, gives it a bunch-spacing of 2 ns. In order to measure the wake field of both bunches, the sampling range is set to 8 ns with a step size of 31.2 ps.

The result of the measurement is presented in Fig. 2, with the maximum of the photodiode signal in blue and the beam current in red. The measurement time in the figure runs from right to left and during the five minutes of measurement, the beam current decreased by 7.5 %, as expected in this operation mode. The photodiode signal shows two regions with distinct peaks that correspond to a modulation of the laser pulses. These are the two areas of interest, which are further analysed in the upcoming paragraphs. It is also visible, that the baseline of the photodiode signal increases by about 24.5 % over the duration of the measurement. This phenomenon is not fully understood and is subject to further investigations, but it seems likely that the laser polarisation drifts over time, which might be at least partly caused by temperature changes of the crystal. Local heating in the crystal results in mechanical stress, which induces a change in birefringence and therefore a modulation of the laser polarisation. In Fig. 3, the drift of the baseline is approximated by an exponential function that is fitted to the signal.

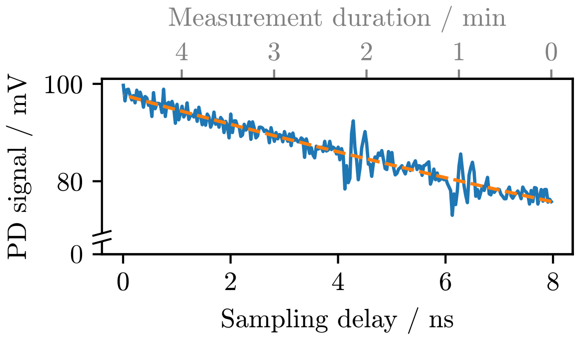

Figure 3: EOS measurement (blue) of two bunches with exponential fit (orange) to approximate the signal drift over time.

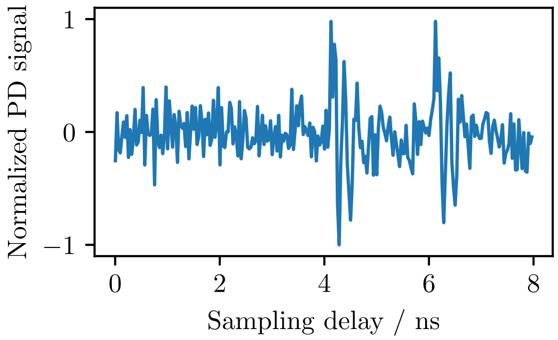

Figure 4: Normalized EOS data with corrected slope. The signal of the two bunches with 2 ns spacing and their wake field are clearly visible.

Subtracting the exponential fit from the data and normalising the results to the global maximum results in a flattened graph with a baseline around zero that is presented in Fig. 4. For better readability, the graph is also inverted such that the first peak shows a positive amplitude, which corresponds to the modulation from the Coulomb field of the electron bunch. An analysis of the two largest peaks shows a spacing of 1.999 ns, which fits well to the expected 2 ns bunch-spacing, but it cannot be resolved properly considering the sampling step size of 31.2 ps. With a peak signal-to-noise ratio (PSNR) of 1.082 for the largest peak in the first region of interest from 4 ns to 5 ns and 1.081 for the largest peak in the second region from 6 ns to 7 ns, the peaks are visible and fit to the expected signal of the two electron bunches.

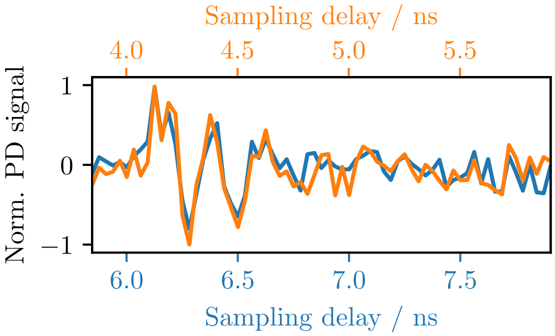

Figure 5: Overlay of the EOS signal of both bunches. The data set between 6 ns to 7 ns (orange) is shifted by −2 ns and overlapped with the data set between 4 ns and 5 ns (blue). The main peaks and the following minima and maxima also overlap, which shows that the wake field of the first bunch does not have a big impact on the second bunch measurement.

In order to evaluate the impact of the first wake field on the measurement of the second bunch, the region between 6 ns and 7 ns is shifted by −2 ns to place both data traces on top of each other and align the main peaks (Fig. 5). This allows to compare the signals of both bunches and their wake fields. The correlation of both regions of interest is quantified by Pearson correlation coefficient (PCC), which would equal one for a perfect positive correlation, zero for no correlation and a negative one for a perfect negative correlation. In this case, for the regions from 4 ns to 5 ns and 6 ns to 7 ns, the PCC is 0.90, which confirms the visual impression, that there is a strong correlation between the two data sets. It is important to highlight that the wake field of the first bunch does not seem to have a measurable impact on the EOS signal of the second bunch. Therefore, it should not only be possible to use EOS in a multi-bunch environment but also perform well for single-shot bunch profile measurements with EOSD and bunch spacings of 2 ns.

Besides an analysis of the mentioned signal drift over time, turn-by-turn EOSD measurements of one bunch in a two-bunch environment should be the next step on the way towards measurements during multi-bunch operation at KARA.

CONCLUSION

The first electro-optical sampling measurements with two consecutive electron bunches stored in KARA were done as a first test towards EO measurements in a multi-bunch environment. The obtained photodiode signal drifts over time, which needs further investigation and might be caused by the electron beam heating up the crystal. However, a characterisation of the data allowed to compensate for the drift and use it for further analysis. The results show, that despite the short spacing of 2 ns, the wake field of the first bunch does not show a noticeable impact on the measurement of the second bunch. This is a promising outcome that can now be further explored in the next step by using electro-optical spectral decoding for single-shot bunch profile measurements in the two-bunch environment, where one of the main challenges will be to get a good peak signal-to-noise ratio (PSNR) despite the larger beam current and potentially stronger signal drift. It is also a promising result for the development of the diagnostics for the future lepton collider FCC-ee, where an electro-optical bunch profile monitor for a bunch spacing of down to 2.5 ns needs to be considered in multi-bunch operation [6], based on the monitor design at KARA [7].

ACKNOWLEDGEMENTS

The Future Circular Collider Innovation Study (FCCIS) project has received funding from the European Union's Horizon 2020 research and innovation programme under grant No 951754. M. R. and M. M. P. acknowledge the support of the DFG-funded Doctoral School "Karlsruhe School of Elementary and Astroparticle Physics: Science and Technology". M. M. P. was funded by BMBF contract number 5K19VKD and number 05K22VKB.

REFERENCES

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

[2] C. Widmann *et al.*, "Implementing electro-optical diagnostics for measuring the CSR far-field at KARA", in *Proc. IPAC'21*, Campinas, SP, Brazil, May 2021, pp. 931-934. `doi:10.18429/JACoW-IPAC2021-MOPAB294`

[3] M. M. Patil *et al.*, "Ultra-fast line-camera KALYPSO for fs-laser-based electron beam diagnostics", in *Proc. IBIC'21*, Pohang, Rep. of Korea, May 2021, pp. 1-6. `doi:10.18429/JACoW-IBIC2021-MOOB01`

[4] S. Funkner *et al.*, "Revealing the dynamics of ultrarelativistic non-equilibrium many-electron systems with phase space tomography", *Sci Rep*, March 2023, Vol. 13.1, pp. 1-11. `doi:10.1038/s41598-023-31196-5`

[5] 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`

[6] 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`

[7] 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, September 2022, pp. 455-459. `doi:10.18429/JACoW-IBIC2022-WEP26`