ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-THPS079

FIRST PROTOTYPE MEASUREMENTS WITH AN ELECTRO-OPTICAL BUNCH PROFILE MONITOR FOR FCC-ee

M. Reissig*, E. Bründermann, S. Funkner, L. L. Grimm, B. Härer, G. Niehues, R. Ruprecht, A.-S. Müller, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
R. Corsini, A. Gilardi, S. Mazzoni†, C. Pakuza, A. Schloegelhofer, T. Lefevre
CERN, Geneva, Switzerland
P. Korysko, University of Oxford, Oxford, UK

Abstract

The future circular electron-positron collider (FCC-ee) is designed for highest luminosity to enhance the precision of high-energy particle physics experiments, spanning energies from the Z pole to the $t\bar{t}$ threshold. As outlined in its conceptual design report, high-precision measurements of the longitudinal bunch profile are required across multiple operation modes, which presents key challenges for beam instrumentation. As part of the feasibility study, a concept for an electro-optical (EO) bunch profile monitor has been developed to address these challenges, building on the existing EO beam diagnostic at the Karlsruhe Research Accelerator (KARA) at KIT.

The first EO monitor prototype for FCC-ee features a novel crystal-holder design using prisms, enabling a single-pass setup crucial for measuring the long bunches during Z operation. This contribution presents the first measurement results of the EO monitor prototype for FCC-ee, which were obtained in the in-air test stand at the CERN Linear Electron Accelerator for Research (CLEAR).

INTRODUCTION

Electro-optical (EO) methods are commonly used in Terahertz spectroscopy [1] and since their first application at particle accelerators in 2002 [2] they have been utilized for single-shot measurements of the longitudinal bunch profile. It allows non-destructive measurements with sub-picosecond resolution and is predominantly used at linear accelerators like FLASH [3] and the European XFEL [4]. The Karlsruhe Research Accelerator KARA was the first storage ring to use an in-vacuum electro-optical system for bunch profile measurements in 2011 [5]. In the following years, the setup has been improved by reducing the beam impedance [6] and applying the in-house built line array camera KALYPSO [7] to allow turn-by-turn measurements at a repetition rate of 2.7 MHz [8]. This system serves as the base model to evaluate the feasibility of an electro-optical bunch profile monitor and develop a prototype for the future circular lepton collider FCC-ee within the FCC innovation study (FCCIS).

The FCC-ee is a future electron-positron collider with 91 km circumference planned to be built at CERN in the Geneva area. It is aiming for the highest luminosities in multiple operation modes for precision measurements of the Higgs boson, top quark and more. Its physics case and the status of the accelerator design are described in the conceptual design report [9, 10] and recently in the feasibility study report [11, 12]. In order to monitor the bunch blow-up caused by the beam-beam effect of colliding bunches and for tracking the bunch profile during top-up injection, a dedicated diagnostics system for bunch length and bunch profile measurements is required [13].

To meet the challenging requirements, there are mainly two approaches under consideration: a setup based on Cherenkov diffraction radiation [14] and an electro-optical setup. This contribution focuses on the electro-optical approach and presents the first proof-of-principle measurements of a prototype monitor with a novel design.

PROTOTYPE DESIGN

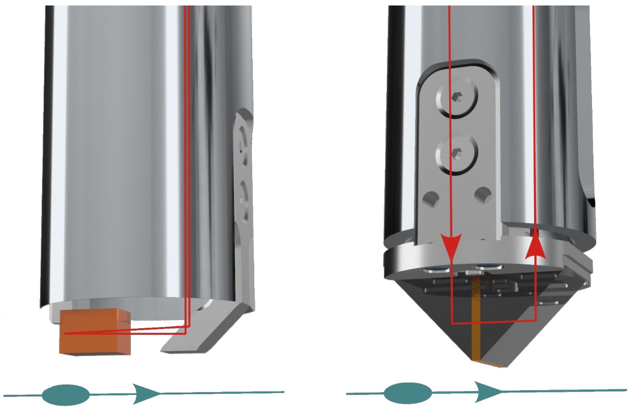
In general, the setup for an EO bunch profile monitor needs an EO crystal in the vicinity of the electron bunch orbit in the vacuum chamber and a probe laser. Due to the Pockels effect, the birefringence of the crystal changes with an applied electrical field. Consequently, the longitudinal profile of the electron bunch can be encoded onto the probe laser via the EO crystal. A common technique for retrieving the bunch profile from the laser pulse is electro-optical spectral decoding (EOSD), where a chirped laser pulse is used, thereby encoding the bunch profile in the spectrum of the laser. In this case, the laser pulse needs to have a length similar to the length of the longitudinal electrical field of the electron bunch and they need to have temporal overlap in the crystal. A rendered image of the crystal holder at KARA is presented in Fig. 1a, where the laser is reflected on the backside of the crystal and is supposed to overlap on the way back with the electrical field of the electron bunch.

To address the different operation modes of FCC-ee, the EO setup needs to be able to handle long bunches with up to $\sigma \approx 15.2$ mm and short bunches with down to $\sigma \approx 2.33$ mm with as few hardware changes as possible [12]. However, the EO setup at KARA is designed for short bunches and simulations show that for longer bunches, the laser additionally overlaps with the electrical field on its first pass through the crystal, which leads to distortions of the profile measurement [15]. Based on simulations, a novel design was developed, where the EO crystal is placed between two prisms [16, 17]. This allows the laser to pass only once through the crystal, while keeping the setup compact. In addition, we can utilize total internal reflection in the prisms

* micha.reissig@kit.edu
† Deceased.

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-THPS079

for guiding the laser beam, so that a reflective coating, prone to thermal effects and degradation, is not required.



(a) KARA (b) CLEAR

Figure 1: 3D rendered images of different crystal holder designs. The red line indicates the laser path and the blue line shows the electron bunch trajectory.

A prototype using the prism setup has been built based on the KARA EO monitor. A rendered image of the crystal holder is presented in Fig. 1b, which is designed for a proof-of-principle test at the CERN Linear Electron Accelerator (CLEAR) [18]. Due to the availability of an 780 nm laser system at CLEAR, a ZnTe crystal was used to achieve good phase-matching. At KARA, to achieve a high time resolution, a GaP crystal with a larger bandwidth than ZnTe is used. For phase matching to GaP a laser with a central laser wavelength of 1030 nm [19] was built.

The crystal dimensions can be tuned to adjust the sensitivity, resolution and to modify the impedance. In general, a thicker crystal in the direction of the laser improves sensitivity but limits the resolution due to increasing phase mismatch. For KARA, these considerations led to crystal dimensions of 5 × 5 × 7 mm for high sensitivity while keeping the impedance low [6]. For the prototype test at CLEAR, the crystal dimension is 10 × 10 × 2 mm. These dimensions met the sensitivity requirements for the proof-of-principle test at CLEAR while ensuring short-term availability from manufacturers. For the setup at FCC-ee, additional simulations are needed to optimize the crystal size. In general, the transverse size can be reduced to minimize the impedance, while high charge densities allow the use of thin crystals.

EXPERIMENTAL SETUP

CLEAR has an in-air experimental area [18], where it can provide a 200 MeV electron beam. For the following measurements, it provided bunches with a length of $\sigma \approx 7.5$ ps and a bunch charge of $q \approx 1$ nC. It produced a bunch train of three bunches with ~ 666 ps spacing with a repetition rate of 10 Hz. The electron bunches exit the vacuum chamber through a window, where they travel across the optical table on which the experiment is installed. The crystal holder is placed on a linear stage, which allows for adjusting the

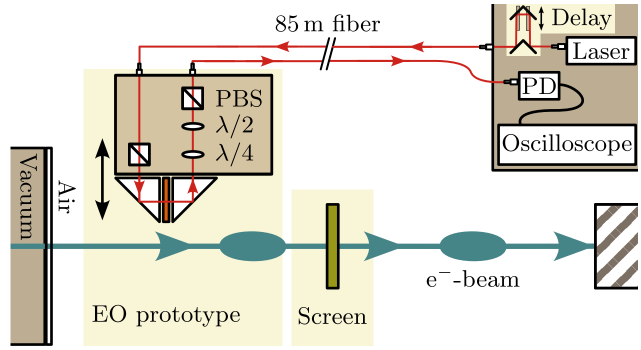


Figure 2: Simplified schematic of the EO prototype experiment at CLEAR. A laser pulse is sent from a laboratory to the EO prototype through polarization maintaining fibers. Prisms guide the laser light through the EO crystal close to the electron beam and through a $\lambda/4$ and $\lambda/2$ waveplate followed by a polarizing beam splitter (PBS). It returns in single-mode fibers for analysis with a photodiode (PD) and an oscilloscope.

distance to the electron beam. A YAG screen positioned directly behind the crystal holder was used to monitor the transverse beam size and determine whether the electron beam was clipped by the crystal. For the following measurement, the crystal was positioned as close to the beam center as possible, while ensuring minimal beam clipping. This resulted in a distance of 2 mm, at which only slight clipping was observed at the beam's outer edges.

Figure 2 presents a simplified schematic of the experimental setup at CLEAR, with the 780 nm laser system and the data acquisition system located in a nearby laboratory. The setup is designed for electro-optical sampling (EOS) measurements, with the aim of detecting the Coulomb field of the electron bunches and the trailing wakefield. These measurements are intended to serve as a proof-of-principle demonstration of the novel crystal holder design.

The laser was equipped with an optical delay stage to shift the laser pulses by up to ~ 1 ns. It was transported to the experimental area via polarization-maintaining fibers with a total length of 85 m. A collimator at the fiber output launched the pulses into free space, where they are directed through a beam splitter cube towards the crystal holder to ensure linear polarization. The first prism leads the laser downstream through the crystal, where a second prism is used to deflect the laser away from the electron beam.

It follows a polarization analyzer consisting of a $\lambda/4$ waveplate, $\lambda/2$ waveplate and a polarizing beam splitter (PBS). While the $\lambda/4$ waveplate compensates for the intrinsic birefringence of the crystal, the $\lambda/2$ waveplate and PBS can be used to convert the polarization modulation to an intensity modulation. The laser intensity I_{det} is described by

$$I_{\text{det}}(\theta, \Gamma) = \frac{I_0}{2}[1 - \cos(\Gamma + 4\theta)], \qquad (1)$$

for the initial intensity I_0, the angle θ of the $\lambda/2$ waveplate and the phase retardation Γ in the crystal [3]. In the idealized

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-THPS079

case of a crossed polarization ($\theta = 0$), no light is transmitted through the PBS, except if its polarization was modulated by the electrical field of the electron beam ($|\Gamma| > 0$).

Subsequently, the intensity-modulated laser pulse is coupled into single-mode fibers with a total length of 85 m and guided back to the laboratory, where it is connected to a 12 GHz photodiode (PD). For data acquisition, the PD is connected to a 10 GHz oscilloscope, for which the bandwidth was digitally limited to 3 GHz to reduce the high frequency noise from the nearby klystrons.

MEASUREMENT RESULTS

In order to measure the modulation of the laser pulse intensity, three sequential laser pulses have been recorded within one waveform on the oscilloscope. Only one of the three pulses was expected to be modulated by the electron bunch, since the oscilloscope trigger was set to the repetition rate of the electron bunch trains at 10 Hz, which is orders of magnitude slower than the repetition rate of the laser at 75 MHz. The modulation is therefore calculated by dividing the amplitude of the modulated laser pulse by an unmodulated laser pulse.

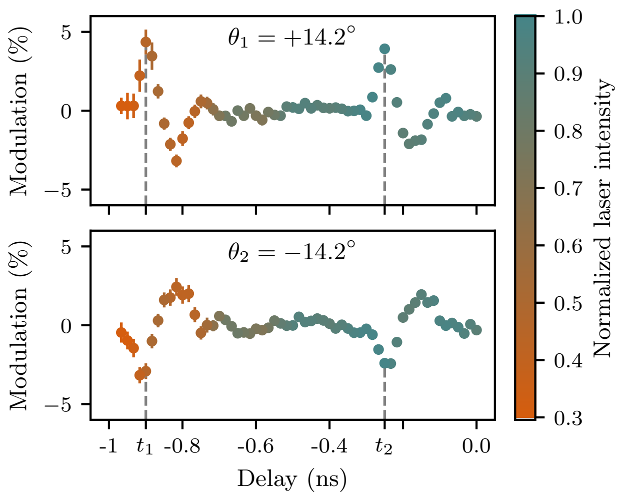


Figure 3: Electro-optical sampling of two electron bunches at different angles θ_1, θ_2 of the $\lambda/2$ waveplate with opposite sign. Every data point is the mean value over 100 shots, with the standard error of the mean indicated as error bar. The marker color indicates the absolute laser intensity, which changed during the scan of the optical delay stage due to non-optimal alignment.

The EOS scans presented in Fig. 3 were performed by changing the delay of the laser pulses to up to 1 ns with the optical delay stage. They show the amplitude modulation of the second laser pulse compared to the first (unmodulated) laser pulse. At each step, 100 measurements were used to calculate the average pulse amplitude and its standard error. By changing the time delay using the optical delay stage, the coupling efficiency into the fiber changes due to slight misalignments. This results in a change of the laser intensity, which is indicated by the color of the data points. With decreasing laser intensity, the signal-to-noise ratio became smaller and the standard error of the mean increased.

Figure 3 shows measurements with the $\lambda/2$-waveplate set to $\theta = 14.2°$ (upper plot) and with the waveplate at $\theta = -14.2°$ (bottom plot). The angle magnitude was selected qualitatively, guided by Eq. (1) and empirical assessment of the data acquisition noise floor. The comparison of both plots shows a sign inversion of the modulation, as expected by Eq. (1). The magnitude of the modulation of the main peaks at t_1 and t_2 decreased from ~ 5 % to ~ 2.5 %, which was probably caused by a high uncertainty on the angle θ and a slightly lower bunch charge during the measurement with θ_2.

The two peaks at t_1 and t_2 are 666 ps apart, which resembles the temporal distance between two electron bunches in the bunch train of CLEAR. Therefore, it is likely that at this time, the Coulomb field of the electron bunch and the laser pulse overlapped inside the EO crystal. Accordingly, the following ringing corresponds to the wakefield of the electron bunch, which is mainly caused by the impedance of the crystal holder.

CONCLUSION

Based on the in-vacuum electro-optical bunch profile monitor at KARA and previously performed simulations, a novel crystal holder design was developed to match the requirements for the future circular lepton collider FCC-ee. The new design is a compact, single-pass design using prisms to guide the laser through the EO crystal. This enables measurements of the long bunches during the Z-operation mode at FCC-ee, while still keeping the ability to measure shorter bunches in other operation modes.

A prototype was built to allow for a first proof-of-principle test of the new prism design at the in-air experimental area at the CLEAR facility. An EOS scan resulted in clear signals of the Coulomb and wakefield of two consecutive bunches, which successfully shows the feasibility of the novel crystal holder design.

To continue the development towards a beam instrumentation for FCC-ee, the next step is to use the prototype for bunch profile measurements with EO spectral decoding at a circular accelerator, e.g. at KARA. Additional considerations concerning radiation hardness and placement of the EO monitor at FCC-ee are necessary to finalize the technical design of the EO monitor.

Note added. While this manuscript was under preparation, one of the coauthors, Stefano Mazzoni, passed away.

ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754 (FCCIS) and No 101057511 (EURO-LABS). M. R. acknowledge funding from BMBF contract number 05K22VKB.

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-THPS079

REFERENCES

[1] E. Bründermann, H.-W. Hübers, and M. F. Kimmitt, *Terahertz techniques*. Heidelberg ; New York: Springer, 2010.

[2] I. Wilke, A. M. MacLeod, W. A. Gillespie, G. Berden, G. M. H. Knippels, and A. F. G. v. d. Meer, "Single-Shot Electron-Beam Bunch Length Measurements", *Phys. Rev. Lett.*, vol. 88, no. 12, p. 124801, Mar. 2002. doi:10.1103/PhysRevLett.88.124801

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

[4] B. Steffen *et al.*, "Compact single-shot electro-optic detection system for THz pulses with femtosecond time resolution at MHz repetition rates", *Rev. Sci. Instrum.*, vol. 91, no. 4, p. 045123, Apr. 2020. doi:10.1063/1.5142833

[5] N. Hiller *et al.*, "A Setup for Single Shot Electro Optical Bunch Length Measurements at the ANKA Storage Ring", in *Proc. IPAC'11*, San Sebastian, Spain, 2011, paper TUPC086, pp. 1206–1208. https://jacow.org/IPAC2011/papers/TUPC086.pdf

[6] 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

[7] L. Rota *et al.*, "KALYPSO: Linear array detector for high-repetition rate and real-time beam diagnostics", *Nucl. Instrum. Methods Phys. Res. A: Accel. Spectrom. Detect. Assoc. Equip.*, vol. 936, pp. 10–13, Aug. 2019. doi:10.1016/j.nima.2018.10.093

[8] S. Funkner *et al.*, "High throughput data streaming of individual longitudinal electron bunch profiles", *Phys. Rev. Accel. Beams*, vol. 22, no. 2, p. 022801, Feb. 2019. doi:10.1103/PhysRevAccelBeams.22.022801

[9] A. Abada *et al.*, "FCC physics opportunities", *Eur. Phys. J. C*, vol. 79, no. 6, Jun. 2019. doi:10.1140/epjc/s10052-019-6904-3

[10] A. Abada *et al.*, "FCC-ee: the lepton collider", *Eur. Phys. J. Spec. Top.*, vol. 228, no. 2, pp. 261–623, Jun. 2019. doi:10.1140/epjst/e2019-900045-4

[11] M. Benedikt *et al.*, "Future Circular Collider Feasibility Study Report Volume 1: Physics and Experiments", CERN, Geneva, Rep. CERN-FCC-PHYS-2025-0002, 2025. doi:10.17181/CERN.9DKX.TDH9

[12] M. Benedikt *et al.*, "Future Circular Collider Feasibility Study Report Volume 2: Accelerators, technical infrastructure and safety", CERN, Rep. CERN-FCC-ACC-2025-0004, 2025. doi:10.17181/CERN.EBAY.7W4X

[13] S. Mazzoni *et al.*, "Overview of the FCC-ee beam instrumentation R&D", in *Proc. IBIC'24*, Beijing, China, Sep. 2024, pp. 1–4. doi:10.18429/JACoW-IBIC2024-TUAC2

[14] A. Schlögelhofer, "Non-invasive beam diagnostic development for FCC using Cherenkov diffraction radiation in dielectric materials", Ph.D. thesis, Technische Universität Wien, Vienna, Austria, 2024. doi:10.34726/hss.2024.96000

[15] 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, 2022, pp. 296–299. doi:10.18429/JACoW-IPAC2022-MOPOPT025

[16] M. Reissig *et al.*, "Status of a monitor design for single-shot electro-optical bunch profile measurements at FCC-ee", in *Proc. IBIC'22*, Kraków, Poland, 2022, pp. 455–459. doi:10.18429/JACoW-IBIC2022-WEP26

[17] M. Reissig *et al.*, "Simulations of an electro-optical in-vacuum bunch profile monitor and measurements at KARA for use in the FCC-ee", in *Proc. IPAC'24*, Nashville, TN, USA, 2024, pp. 2354–2357. doi:10.18429/JACoW-IPAC2024-WEPG56

[18] D. Gamba *et al.*, "The CLEAR user facility at CERN", *Nucl. Instrum. Methods Phys. Res. A: Accel. Spectrom. Detect. Assoc. Equip.*, vol. 909, pp. 480–483, 2018. doi:https://doi.org/10.1016/j.nima.2017.11.080

[19] B. Wu, L. Cao, Q. Fu, P. Tan, and Y. Q. Xiong, "Comparison of the Detection Performance of Three Nonlinear Crystals for the Electro-optic Sampling of a FEL-THz Source", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, Jun. 2014, pp. 2891–2893. doi:10.18429/JACoW-IPAC2014-THPRO017