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STATUS OF A MONITOR DESIGN FOR SINGLE-SHOT ELECTRO-OPTICAL BUNCH PROFILE MEASUREMENTS AT FCC-ee

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Abstract

At the KIT electron storage ring KARA (Karlsruhe Research Accelerator) an electro-optical (EO) near-field monitor is in operation performing single-shot, turn-by-turn measurements of the longitudinal bunch profile using electro-optical spectral decoding (EOSD). In context of the Future Circular Collider Innovation Study (FCCIS), a similar setup is investigated with the aim to monitor the longitudinal bunch profile of each bunch for dedicated top-up injection at the future electron-positron collider FCC-ee. This contribution presents the status of a monitor design adapted to cope with the high-current and high-energy lepton beams foreseen at FCC-ee.

INTRODUCTION

The future electron-positron collider FCC-ee is a planned high-energy, high-intensity accelerator located at CERN with approximately 100 km circumference and a beam energy up to 180 TeV [1]. To optimize luminosity, it will be operated with a top-up injection, which requires a detailed monitoring of the bunch profiles. In the frame of the Future Circular Innovation Study (FCCIS), a diagnostics tool for single-shot bunch-by-bunch measurements of the longitudinal bunch profile is under development at KIT. The design of this monitor is based on the electro-optical (EO) near-field monitor at the Karlsruhe Research Accelerator (KARA), which is able to perform turn-by-turn single-shot bunch profile measurements [2].

Bunch Profile Measurements at KARA

The EO near-field monitor at KARA offers turn-by-turn single-shot bunch profile measurements during an operation mode for short bunches. To resolve the bunch profile of single electron bunches with a length of 10 ps, a technique called electro-optical spectral decoding (EOSD) is used. Figure 1 shows the principle of an EOSD measurement at KARA in three consecutive steps.

In the first step, the electron bunch profile is encoded into the polarization of the chirped laser pulse. The electron's electric field changes the refractive index of the GaP (EO) crystal according to the Pockels effect. However, the change in refractive index in GaP depends on polarisation and propagation direction, because it is an anisotropic material. Therefore, the crystal becomes birefringent, which changes the polarization of the laser pulse from linear to elliptical in proportion to the electric field strength. The result is a modulation of the laser polarization that depends on the bunch charge density.

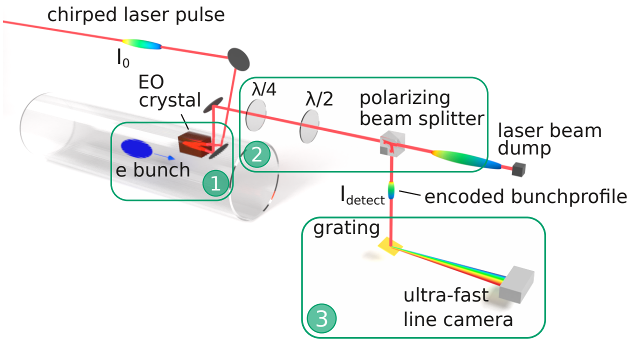

Figure 1: Scheme of the EO near-field setup at KARA. Adapted from [4].

In the second step, the bunch profile, which is now encoded in the laser polarization, is converted to an intensity modulation. This is achieved by a polarizing beam splitter (PBS), which only forwards light with a certain linear polarization to the spectrometer. A $\lambda/4$- and a $\lambda/2$-waveplate are set up in front of the PBS in a near-crossed configuration. This way, only very little light is transmitted if the laser pulse is not modulated and linearly polarized, but the transmitted intensity increases approximately linearly with the modulation of the polarisation.

In the third step, the intensity modulation of a single laser pulse is measured with a spectrometer containing the KIT-built, ultra-fast line camera KALYPSO [3]. In the spectrometer, the chirped laser pulse is refracted on a grating, which fans out the laser pulse according to the wavelength. The line camera then measures the laser intensity at different wavelengths, which corresponds to the longitudinal electron bunch profile.

Challenges for EO at FCC-ee

Simulations of the EO monitor at KARA for FCC-ee beam parameters showed, that there will be two major challenges that need to be tackled [5].

First, the operation mode for production of Z bosons at a collision energy of 90 GeV features a bunch length of $\sigma^{\mathrm{FCCee\ Z}} = 15.4\,\mathrm{mm}$, which is very large compared to the typical length during measurements at KARA of around $\sigma^{\mathrm{KARA}} \approx 3\,\mathrm{mm}$. The monitor at KARA is designed for short bunches. The laser pulse passes the crystal twice: first against the bunch direction (upstream) and after reflection at the back of the crystal, the laser pulse travels parallel to the bunch (downstream). Only the downstream modulation of the laser contributes to the bunch profile measurement, the upstream modulation is treated as a disturbance. For short bunches, the up- and downstream modulations do not

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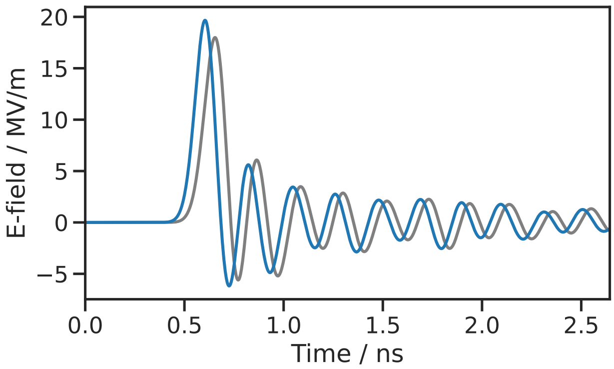

Figure 2: Simulation of the total E-field that the laser pulse experiences up- and downstream (grey and blue) with the KARA design, but with FCC-ee Z-mode beam parameters.

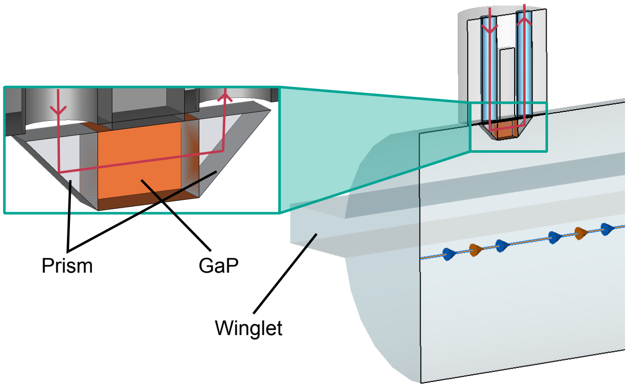

Figure 3: Concept design in CST [6] for the EO crystal holder for FCC-ee.

overlap, which allows a clean measurement of the bunch profile [5]. For long bunches however, the up- and downstream modulation do overlap, which is presented in Fig. 2 in a simulation of the KARA monitor under FCC-ee Z-mode beam conditions. Therefore, an EO monitor for FCC-ee should be designed to avoid the upstream signal.

The second major challenge is the large charge density, which causes a larger phase modulation of the laser pulse. According to simulations, the phase modulation at KARA is a few degrees, whereas it would be up to 100° for the same setup under FCC-ee Z-mode beam conditions [5]. This has the potential to provide a stronger signal, but the downside is that the relation of the bunch profile to the detected spectrum becomes non-linear. Additionally, it might cause distortions of the signal due to heat build-up in the crystal and its holder. For these reasons, the monitor should be designed in a way that phase modulation of the laser pulse is in a similar order of magnitude as in the monitor at KARA.

Besides these issues, the EO monitor for FCC-ee should introduce a small impedance in order to avoid disturbance of the beam and to reduce the wakefield. This is also important for the monitor itself, since the wakefield could overlap with the field of the next bunch and therefore disturb the bunch profile measurement.

CONCEPT IDEA FOR EO NEAR-FIELD AT FCC-ee

To address the mentioned issues, a first design concept has been developed and was tested in simulations.

In Fig. 3, a 3D model, created with CST [6], is presented with a vertically mounted EO crystal holder concept on top of the FCC-ee beam pipe. The principle is similar to the KARA setup, which is presented in Fig. 1, but the design of the crystal holder inside the beam pipe has been changed. Instead of the laser being reflected at the back of the crystal, it is now transmitted through it and therefore the unwanted upstream signal is avoided. The laser pulse is only propagating downstream through the crystal with the aim to get a cleaner signal without overlap of a disturbing signal. Instead of metal mirrors, prisms are used in this concept to guide the laser pulse through the crystal. With prisms, the goal is to reduce the impedance especially since one of the prisms is in front of the crystal, where a metal mirror would shield the crystal from the electric field of the electron bunch and therefore disturb the bunch profile measurement. The setup is mounted on the outer part of the beam pipe, with the crystal just sticking out of the inner pipe wall. This is to maximize the distance to the beam in order to reduce the electric field strength and therefore avoid a non-linear relation of the bunch profile and the measured EOSD signal. To reduce the field strength in the crystal further, it would also be possible to place the crystal and its holder horizontally into the winglet. But it should be on the winglet of the beam pipe on the inner side of the accelerator ring to avoid issues with synchrotron radiation.

Repetition Rate

The RF frequency of the cavities at FCC-ee during Z production is 400 MHz, which determines the maximum repetition rate of the electron bunches. The maximum repetition rate for EO near-field bunch profile measurements is limited by the length of the stretched laser pulse at the spectrometer and the decay of the wakefield, so that it does not overlap with the next bunch. A bottleneck will be the repetition rate of the line camera, which is already very fast at KARA, with the in-house developed KALYPSO at 2.7 MHz. The next version of KALYPSO, which is currently under development, will reach a repetition rate of up to 12 MHz [3] and might increase further by the time the FCC-ee will be build. At present, in order to reach 400 MHz, multiple setups will be necessary. On the one hand, multiple line cameras could be used at one EO monitor, where the laser pulse is split up and e.g. two line cameras are alternately taking measurements. On the other hand, multiple EO monitors can be set up around the ring to measure the bunch profile of different bunches. For example at a camera repetition rate of 10 MHz, a total of 40 EO monitors, each spaced about 2.5 km apart, around the ring would be able to track each bunch once per turn.

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SIMULATION RESULTS

In order to evaluate the EO monitor concept, the laser path and its modulation by the electric field of the electron bunch has been simulated. For the simulation of the electric field, the numerical wakefield-solver by CST [6] has been used on a 3D model of beam pipe and crystal holder. The modulation of the laser pulse and the optics to convert the polarization modulation into an intensity modulation have been calculated analytically [5]. In the following subsections, the EO monitor concept is simulated using the most recent beam parameters of the 4 IP layout of the FCC-ee at the Z-pole energy [7] with a bunch length of $\sigma_z^Z = 15.4$ mm and a bunch charge of 38.93 nC.

Avoidance of the Upstream Signal

The primary change of the new monitor design compared to the KARA setup is that the laser is propagating through the crystal once, thus avoiding any disturbance by an upstream signal. The importance of avoiding the upstream signal has been shown in Fig. 2, where the up- and downstream signals overlap and therefore distort the bunch profile information. With the new concept, there is no upstream signal since the laser only propagates downstream through the crystal. This is presented in the simulation results for the phase modulation of the laser pulse in Fig. 4, where only the downstream signal contributes to the phase modulation, which helps to get a cleaner signal of the bunch profile.

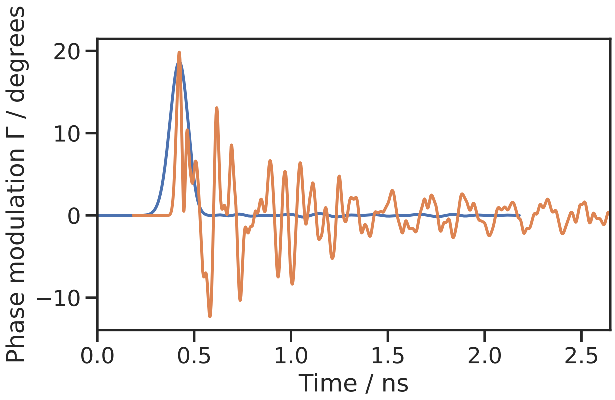

Figure 4: Comparison of the simulated phase modulation of the KARA monitor during low-alpha operation in orange and the new concept for FCC-ee during Z-mode in blue. The new concept manages to achieve a similar amplitude, even though the bunch length at FCC-ee for Z-operation $\sigma^{\mathrm{FCCee\ Z}} = 15.4$ mm is longer then for KARA with $\sigma^{\mathrm{KARA}} \approx 3$ mm and it has almost twenty times the bunch charge.

Reduction of the Impedance

By replacing the mirrors with prisms, the goal was to further reduce the impedance of the monitor and reduce disturbances of the signal caused by the wakefield. The phase modulation of the FCC-ee concept in Fig. 4 shows a pronounced first peak, whereas the following wakefield is very small in comparison. This will help the measurements, since the bunch profile is encoded in the first peak. A low amplitude of the wakefield is important, because at FCC-ee the bunch spacing might go down to 2.5 ns and the remaining wakefield could affect the next bunch. With a proper design of the in-vacuum EO arm, this can be overcome and the wakefields at 2 ns reduced for 500 MHz operation at KARA as shown in [8]. The distance of the crystal to the beam is an important factor as well, and due to the high E-fields at FCC-ee, the crystal is placed at 32 mm distance, whereas at KARA the crystal needs to be closer to around 14 mm distance to achieve a good signal amplitude. Fig. 4 shows that these measures lead to a strongly reduced wakefield at the FCC-ee concept in comparison to the KARA setup. Figure 5 presents the corresponding longitudinal impedance of the FCC-ee concept and the KARA monitor, which shows the same effect of a lower impedance for the FCC-ee concept due to the larger distance and updated design.

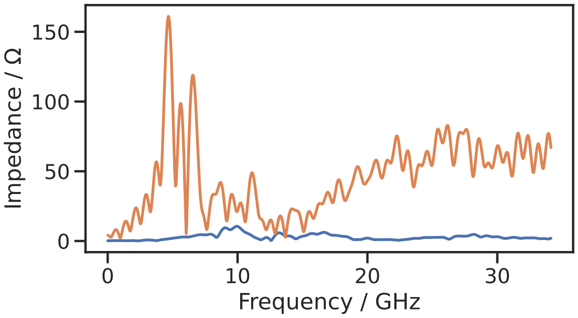

Figure 5: Comparison of the simulated longitudinal impedance of the KARA monitor during KARAs low-alpha mode in orange and the new concept for FCC-ee during Z-mode in blue. The new concept has a smaller impedance, which is caused by increasing the distance of the crystal to the beam and replacing the metal mirror by prisms.

Adjustments to High Bunch Charge

The strength of the electric field inside the crystal is an important factor for a successful bunch profile measurement and is dependent on the bunch charge density. If the electric field is weak, measurements are difficult, because the signal-to-noise ratio becomes small. If the E-field is strong, there is a risk of heating up the crystal and its holder, which can lead to misalignments of the laser and to mechanical stress on the crystal that changes the local birefringence. Additionally, strong fields lead to a larger modulation of the laser polarisation. For a larger modulation the impact of higher-order terms is stronger. The result is that the linear approximation of the relation between the bunch profile and the measured EOSD signal is not viable anymore.

In the simulations of the KARA monitor, the maximum field reaches 350 kV m^{-1} at a distance of the crystal to the beam of 14 mm. For the FCC-ee concept at operation for Z-pole energy, the crystal is positioned at the edge of the beam pipe, 32 mm away from center, to maximize the distance to the beam. In this setting, the maximum E-field in the center of the crystal reaches 260 kV m^{-1}. As a result, the maximum field is weaker, but as shown in Fig. 4, the concept still achieves a maximum phase modulation of the laser pulse of around 20°, which is very similar to the modulation at the KARA monitor.

Simulated Bunch Profile Measurement

The usual procedure for an EOSD bunch profile measurement is to take the spectrum of one modulated laser pulse, subtract the background and divide the result by the spectrum of an unmodulated laser pulse. The background is measured by blocking the laser while taking a measurement with the line camera and the unmodulated signal is an EOSD measurement while no electron bunch is modulating the laser pulse. The result is a ratio of the modulated vs. the unmodulated laser intensity and is called modulation. Figure 6 presents the simulation of the modulation with the new monitor concept for FCC-ee during operation at Z-pole energy in comparison to a scaled Gaussian, which has the same width as the simulated bunch profile. This allows to compare the result of the simulated EOSD measurement with the shape of the initial bunch profile. It shows that the modulation is slightly asymmetric and the peak is more narrow than the initial bunch profile. This is caused by the electric field inside the crystal, which does not perfectly correspond to the bunch profile due to reflections and disturbances caused by the crystal edges and the prisms. However, the modulation is still very similar to the original bunch profile and since it is a systematic distortion, it can be taken into account during the analysis of the spectrum.

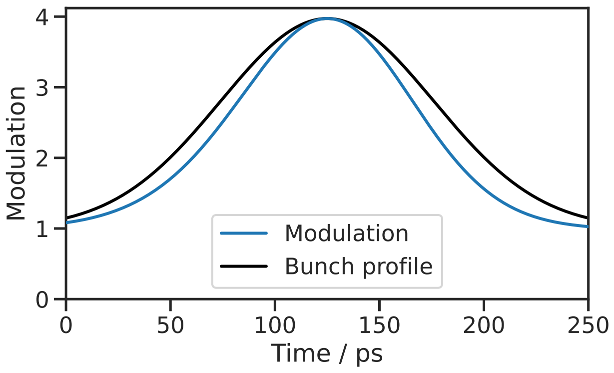

Figure 6: Simulated EOSD signal of the bunch profile with beam parameters of the FCC-ee at Z-pole energy in blue. The black line shows a scaled Gaussian with the same shape as the initial bunch profile. The simulated EOSD signal deviates slightly from the original bunch profile, which is caused by disturbances of the electric field in the EO crystal.

CONCLUSION AND OUTLOOK

FCC-ee is in need of a single-shot, bunch-by-bunch, bunch profile monitor and an EO near-field monitor as used at KARA is a promising candidate that is proposed as a baseline. The different beam properties, especially the longer bunches and higher charge density, require an adapted design for the crystal holder. Guiding the laser pulse through the crystal with prisms instead of metal mirrors allows a setup, where the beam propagates through the crystal only once and therefore avoids an unwanted upstream signal. This new design concept has been successfully tested in simulations under the conditions of FCC-ee during operation at Z-pole energy. The new design has a much lower impedance and therefore the wakefield is small enough to not interfere with the next electron bunch. Additionally, the new design achieves a similar amplitude of the laser modulation as the KARA design, despite the high bunch charge at FCC-ee. This is very important, since a smaller modulation reduces the signal-to-noise ratio and a larger modulation gives rise to non-linear effects that distort the bunch profile measurement. The simulated laser modulation is very similar to the initial bunch profile with only a small systematic deviation that can be taken into account during the analysis. The required repetition rate for bunch-by-bunch measurements at FCC-ee could be achieved by using a faster line camera and multiple EO monitors.

Since the suggested EO monitor concepts proves to be successful in the simulations for FCC-ee during operation at the Z-pole, future studies have to analyze the functionality for the three other operation modes as well. Especially the short bunches in combination with a high bunch charge during operation at the $t\bar{t}$ threshold will be challenging and might require adjustments to the crystal and / or its holder. For example to reduce the amplitude of the E-field, it might be beneficial to put the crystal into the winglet of the beampipe. In the next step, a proof-of-principle of the monitor design with prisms instead of mirrors should be tested, e.g. by adjusting the monitor at KARA and test it at an electron beam.

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