TOWARDS NEAR-FIELD ELECTRO-OPTICAL BUNCH PROFILE MONITORING IN A MULTI-BUNCH ENVIRONMENT

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Abstract

For electron accelerators, electro-optical methods in the near-field have been shown to be a powerful tool to detect longitudinal bunch profiles. In 2013, we demonstrated for the first time, electro-optical bunch profile measurements in a storage ring at the accelerator test facility and synchrotron light source ANKA at the Karlsruhe Institute of Technology (KIT). To study possible bunch-bunch interactions and its effects on the longitudinal dynamics, these measurements need to be performed in a multi-bunch environment. Up to now, due to long-ranging wake-fields the electro-optical monitoring was limited to single-bunch operation. Here, we present our new in-vacuum setup to overcome this limitation. First measurements show reduced wake-fields in particular around $t = 2$ ns, where the subsequent bunch can occur in a multi-bunch environment at ANKA.

INTRODUCTION

The accelerator test facility and synchrotron light source ANKA at KIT is the first storage ring in the world with electro-optical (EO) measurements in the far-field and near-field during short-bunch operation [1]. When operated in this mode, the bunches are compressed to generate coherent synchrotron radiation (CSR) in the THz range. In laser-based experiments, EO sampling (EOS) is a well-established technique for the detection of THz radiation since 1982 [2–4], but it is only since 2009 that its application to detect CSR in the far-field at a synchrotron light source during short bunch operation was demonstrated at ANKA [5]. Beyond these far-field measurements, a near-field EOS detection was successfully implemented for the first time in 2013 in a storage ring [6–8]. The main purpose is to study longitudinal dynamics during instabilities. In short bunch operation above a certain threshold current, sub-structures form on the longitudinal bunch profile caused by the self-interaction of the bunch with its own wake-field. Up to now, these measurements were performed in single-bunch environment due to long-ranging wake-fields induced by the in-vacuum setup. To overcome this limitation, here, we present the realization and first experiments with a new setup, optimized to reduce the effects of the wake-fields.

The measurement principle for EOS in the near-field is based on a crystal that is brought close to the electron beam and thus immersed in the near-field generated by the electrons. Due to the Pockels-effect, the crystal becomes birefringent when an external electric field E_y is applied. If a laser pulse is sent through the crystal, characterized by the Pockels coefficient r_{41}, this birefringence then turns the linear polarization of a laser pulse into an elliptical one. With the crystal thickness d, and the laser wavelength λ, the phase retardation is [10]

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

Using a polarizing beam splitter, this modulation then is turned into an intensity modulation.

There are two possible measurement options: To span time ranges of multiple nanoseconds, e.g. to scan wake-fields, the electric field inside the electro optical crystal can be sampled over many revolutions in the storage ring by delaying a short laser pulse with respect to the bunch arrival time. To resolve sub-structures on the electron bunch, that only persist for a small number of revolutions, a technique named electro optical *spectral decoding* (EOSD) can be used [11]. It allows the measurement of the bunch profile in a single shot by sending a long, chirped laser pulse through the crystal. The temporal profile of the electric field generated by the electron bunch is then encoded on the spectrum of the probing laser pulse and can be recovered by using a single-shot spectrometer. The results have proven to show clear evidence of the sub-structures [12].

The original setup (EOS v1) has been designed by PSI and DESY for near-field electro-optical bunch length mea-

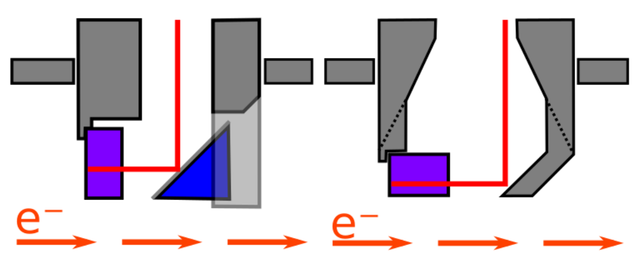

Figure 1: Sketches of EOS v1 (left) and EOS v2 (right). Metal parts are displayed in gray, the EO crystal (GaP) in purple. The blue triangle in EOS v1 is a glass prism with a metalized surface, serving as a 45° mirror. The laser (red) enters from the top, is reflected at the mirror, transverses the GaP crystal, is reflected at its back side and then travels back the same way (with a small offset angle to separate in- and output beams). For EOS v2, the prism has been replaced by a polished metal surface. The other main improvements are the conical shape inside the EO arm and the decreased distance between laser path and lower edge of the EO arm.

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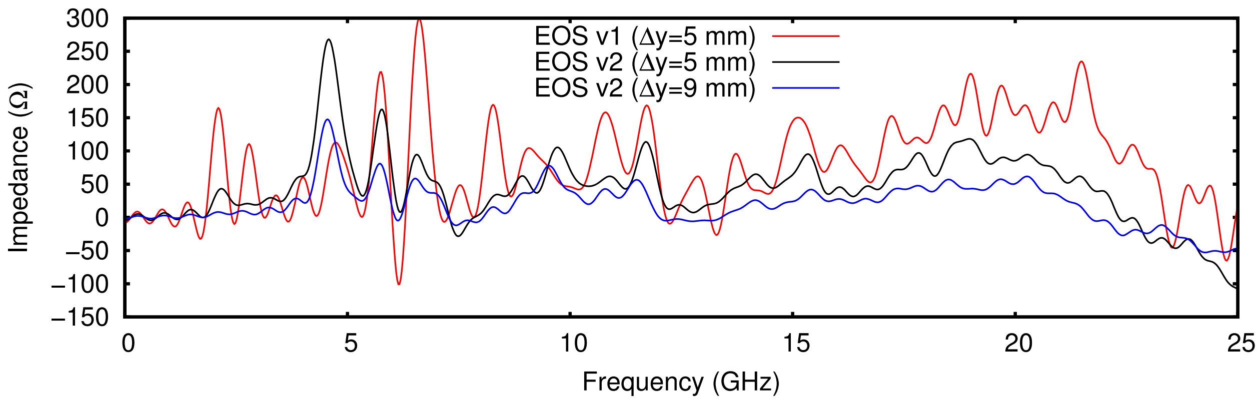

Figure 2: Real part of the longitudinal wake impedance for EOS v1 and v2 (corresponding to E_z at the beam orbit), simulated using CST Particle Studio [16]. Δy is the distance between the lowest part of the EO arm and the nominal electron beam orbit. For EOS v2 and $\Delta y = 5$ mm the EO signal is increased, at already reduced generation of wake-fields. The optimized distance between laser and lower edge of the arm leads to the possibility to further reduce the generation of wake-fields while keeping the original signal level by increasing the distance to $\Delta y = 9$ mm.

surements at SwissFEL and the European X-FEL [13]. It is laid out for electron bunches of a length of $\sigma_z \ll 1$ ps, with a spacing of $\Delta T \geq 200$ ns. The in-vacuum part (*EO arm*) consists of the electro optical GaP crystal, a prism with a silver coated surface which serves as a mirror, and the holding structures (see lhs. of Fig. 1). At ANKA, the system was installed with an added impedance protection shutter that can be closed to restore the closed surface of the beam pipe and to also shield the EO arm from radiation when it is not in operation. However, the first design was not optimized for the bunch properties at ANKA ($\sigma_z \geq 2$ ps and $\Delta T \geq 2$ ns).

EO ARM REDESIGN

There are two aspects of the EO arm that have to be considered during the redesign process [14]: The overall geometry of the EO arm and the dimensions of the EO crystal. For the latter, two possible influences on the measured profile have to be taken into account. First, pulse lengthening due to dispersion of the field traveling inside the crystal. Therefore, the crystal should be of limited thickness in propagation direction of the electron bunch. For the bunch profiles at ANKA, estimations based on [10] show the effect should be small even with an increased thickness. Secondly, the measured profile can be distorted by electric fields leaking into the crystal from the bottom side [15]. Both fields travel inside the crystal, so this effect is of importance, when the crystal is thicker than the distance between laser path and the crystals bottom side. As the distortion is systematic and can be considered in data analysis, for the redesign of the arm we gave priority to an increased signal-to-noise ratio: The new crystal is thicker (6 mm instead of 5 mm) and has a decreased height (5 mm instead of 10 mm, see also Fig. 1).

For the metal parts, one design goal was the reduction of edges. As already discussed in [9], this is achieved by replacing the prism that served as a mirror, and its holder by a polished metal surface. To damp resonances inside the structure, the inner side has been laid out with a conical shape. The whole design process was backed by wake-field simulations using CST Particle Studio [16]. The new design shows a decreased impedance almost over the whole frequency range (see Fig. 2). As the crystal is now thicker and the distance of its bottom side and the laser beam is reduced, the previous maximum signal strength is now achieved with an increased distance between EO monitor and electron beam. As an alternative, the signal can be increased by moving the arm as close to the electron beam as before – even in this case the wake-fields should be reduced. The redesign also required some modifications of the EO monitor, i.e. the optics for coupling the light into the vacuum arm and back into a single mode fiber including a stretcher/compressor and several motorized polarization optics.

FIRST MEASUREMENTS

After the installation of the new arm in the ANKA vacuum pipe and optical alignment of the modified in and out coupling optics, the temporal overlap between the electron bunch and the laser signal was established. Afterwards, we performed first experiments.

As a test of the new geometry, we measured the wake-fields trailing a single bunch. Therefore, we applied the sampling technique using a photo diode and an oscilloscope. Figure 3 shows a comparison to the results obtained using EOS v1. For both of these measurements, the EO arm was moved to the electron beam as close as possible without loosing electrons.

The overall improvement is clearly visible: For EOS v2, the wake-field decays much faster in comparison to the measurement with EOS v1, where the wake-field persists over the entire measurement range of $t = 2.5$ ns. It is important to note that the wake-field at $t = 2$ ns, where, in a multi-bunch environment, the subsequent bunch would be located, has

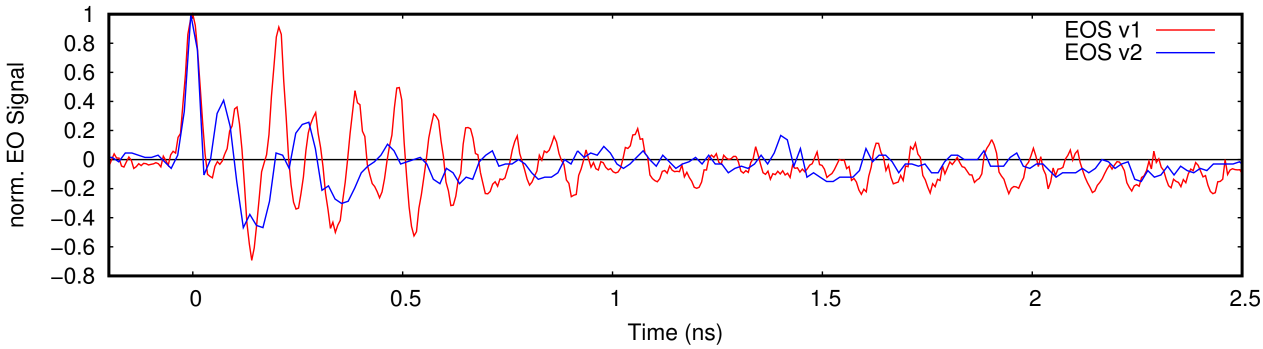

Figure 3: Comparison of a EOS wake-field scan measured with the old EO arm (EOS v1) and the new wake-field-optimized EO arm (EOS v2). Here both signals from a single bunch were normalized to the first peak (Coulomb-peak at $t = 0$). The wake-field is clearly reduced, especially at $t = 2$ ns, where the following bunch in a multi-bunch environment would be be located at ANKA. Notice that we measure the wake-field E_y at the location of the crystal, so the impedance shown in Fig. 2 does not correspond to the data shown here.

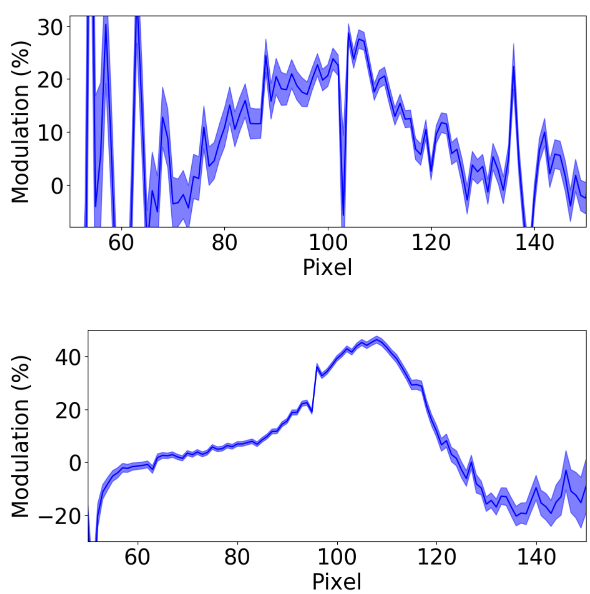

Figure 4: Unprocessed EO signal in the presence of an electron bunch, including pixel defects (e.g. pixel 104 in upper plot), using EOS v1 (top), and EOS v2 (bottom). The blue lines mark the change of the detected laser intensity due to the presence of an electron bunch. The error bands are due to the electronic noise. The increased modulation for EOS v2 is due to improvements in the alignment and the new design.

already dropped roughly to background level. This was the major goal of the redesign of the EO arm.

We also upgraded the spectrometer, and now use version 2 of the ultra-fast data acquisition board KALYPSO. It is a multi-purpose linear array detector for visible and near-infrared radiation [17] with *continuous* readout at 2.7 MHz repetition rate, developed in cooperation between DESY, Łódź University, PSI, and KIT. For ANKA, it allows the continuous acquisition of one bunch at every revolution. Figure 4 displays single-shot electron bunch profile measurements using KALYPSO 2 before and after the upgrade to EOS v2, showing a significant improvement in the data quality. The modulation is increased due to an optimized alignment and the new design. Due to continued firmware optimizations, the signal-to-noise is even further increased. The electronic noise contribution was reduced from $\sigma_{ADC} = 11.7$ to $\sigma_{ADC} = 6.8$. In total, we now expect a much higher sensitivity when observing sub-structures on the bunch profiles.

CONCLUSION AND OUTLOOK

We reported a new design for our EO system to detect the near-field of electron bunches at ANKA. Thereby, we demonstrated the reduction of the wake-field trailing the electron bunch, which might allow us to perform measurements in a multi-bunch environment, in the future. The upgraded KALYPSO firmware improved signal-to-noise ratio, already at unchanged signal levels. Additionally, due to the new arm geometry and improved alignment, the signal height has even increased. Therefore, we expect not only better detectability of sub-structures on the bunch profiles but also higher sensitivity to possible profile changes due to interactions between electron bunches in the storage ring.

Currently, we also develop a new revision of KALYPSO, aiming for a repetition rate of 10 to 12 MHz. Combined with the multi-bunch ready EO arm, it will allow to continuously track the longitudinal profiles of four electron bunches.

ACKNOWLEDGEMENTS

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