SINGLE-SHOT ELECTRO-OPTICAL DIAGNOSTICS AT THE ANKA STORAGE RING*

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Abstract

ANKA is the first storage ring in the world with a near-field single-shot electro-optical (EO) bunch profile monitor. The method of electro-optical spectral decoding (EOSD) uses the Pockels effect to modulate the longitudinal electron bunch profile onto a long, chirped laser pulse passing through an EO crystal. The laser pulse is then analyzed with a single-shot spectrometer and from the spectral modulation, the temporal distribution can be extracted. The setup is tuned to a sub-ps resolution (granularity) and can measure down to bunch lengths of 1.5 ps RMS for bunch charges as low as 30 pC. With this setup it is possible to study longitudinal beam dynamics (e. g., microbunching) occurring during ANKA's low-α_c-operation, an operation mode with longitudinally compressed bunches to generate coherent synchrotron radiation in the THz range. In addition to measuring the longitudinal bunch profile, long-ranging wake-fields trailing the electron bunch can also be studied, hinting bunch-bunch interactions.

INTRODUCTION

During the low-α_c-operation of the ANKA storage ring at the Karlsruhe Institute of Technology, the momentum compaction factor α_c is reduced to compress the bunches longitudinally and thus generate coherent synchrotron radiation (CSR) in the THz range [1]. Previous streak camera measurements have shown a beam current dependent bunch lengthening and deformation effect at ANKA in this special operation mode [2, 3]. In addition, the emitted CSR exhibits a bursting behavior [4–6], which we believe to be caused by dynamic changes of the longitudinal bunch shape (e. g., microbunching). EOSD offers the possibility to measure the longitudinal bunch profile and its arrival time relative to the revolution clock (f_{rev} = 2.7 MHz at ANKA) with a sub-ps time resolution without averaging. First single-shot measurements with the setup have indicated the formation of substructures on the compressed bunches [7], and we have now performed systematic studies of this behavior for different accelerator conditions. Additionally, the EO near-field setup is sensitive to the vertically polarized component of the wake-fields generated by an electron bunch passing the setup. Studying the transverse wake-fields, which are coupled to the longitudinal ones, and comparing them to simulations, helps greatly to improve the simulation model for longitudinal wake-fields [8]. The observed wake-fields range further than our minimum bunch spacing of 2 ns and could influence a following bunch. An increase of CSR has previously been observed at ANKA when the ring impedance was changed by inserting a copper scraper in order to induce strong wake-fields [9].

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METHOD

Electro-optical bunch length measurement techniques rely on the field-induced Pockels effect to modulate the longitudinal electron bunch profile onto a laser pulse passing through an EO crystal (further reference e. g., [10]). Figure 1 illustrates the working principle of EOSD.

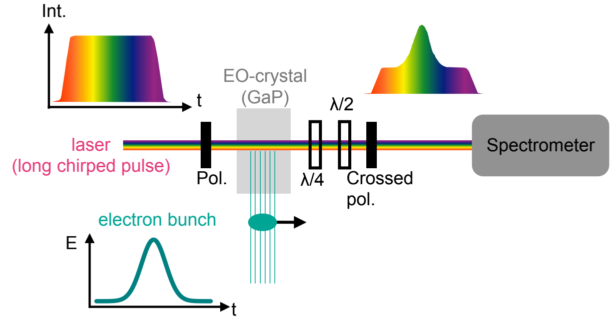

Figure 1: Schematic of EOSD (see text for details).

For the near-field measurements at ANKA, the EO crystal is brought close to the electron beam, so the direct Coulomb field of the bunch causes a modulation of polarization of the initially linearly polarized laser. This can be turned into an intensity modulation with the depicted optical components (quarter- and half-wave plates in combination with a crossed polarizer). Practically, the electric field of the bunch acts as a field-dependent phase retarder for the electric field of the laser pulse with the phase retardation being directly proportional to the field strength. For this to hold true, the crystal axis orientation, the direction of polarization of the Coulomb field and the laser need to be aligned in a specific way. Furthermore, the angles of the wave-plates need to be set in a way that the quarter-wave plate compensates the intrinsic birefringence of the the crystal and the half-wave plate regulates the transmission through the crossed polarizer (see e.g. [11] for a detailed description).
The laser system needs to be in sync with the bunch repetition rate and its delay with respect to the electron bunch

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passing by needs to be adjustable to ensure temporal overlap between the laser pulse and the modulating electric field.

In order to demodulate the desired signal from the laser pulse, it is analyzed with a single-shot spectrometer and the temporal distribution of the electron bunch can be extracted from the spectral modulation by performing a time calibration measurement. For this time calibration measurement, we delay the laser pulse in well known steps - in our case electronically, with a programmable vector modulator - and measure the position of the centroid of the modulation within the spectrum as a function of the applied delay.

SETUP AT ANKA

The EOSD setup at ANKA consists of a laser system (EO-Laser), several single-mode and polarization maintaining fibers, the fiber-coupled EO-Monitor through which the laser beam is coupled into the UHV system of the storage ring, a set of detectors used to measure the modulated laser pulse, a beam position monitor (BPM) which we use as absolute timing reference, and a loss rate counter to ensure that the crystal is far enough from the electron beam to not cause any significant beam losses. Figure 2 illustrates the setup at ANKA and the individual components are described in more detail below.

We use an Yb-doped fiber laser system (RF synchronized oscillator, pulse picker and amplifier) developed at PSI [12] specifically for electro-optical bunch length measurements for SwissFEL and the European X-FEL. The laser oscillator is tuned to 62.5 MHz (23rd harmonic of f_{rev}) and the amplified laser pulses used for the experiment have a wavelength of around 1050 nm (60-80 nm FWHM) and a repetition rate tuned to 0.9 MHz ($f_{\text{rev}}/3$).

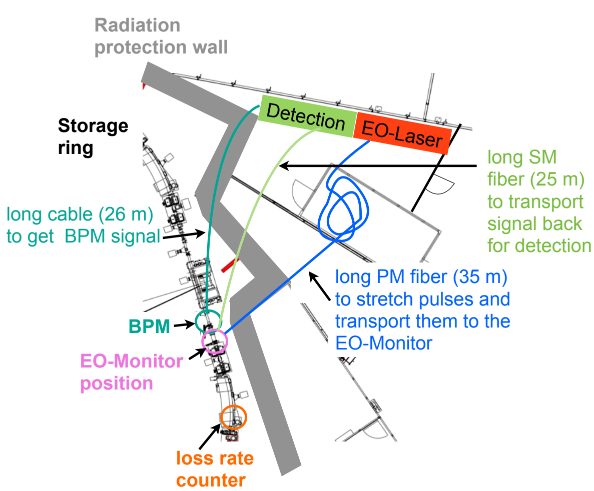

Figure 2: Near-field EOSD setup at ANKA.

The laser system is placed outside the radiation protection wall of the storage ring, the amplified laser pulses are then sent via a 35 m long polarization maintaining fiber to the EO-Monitor. The fiber-coupled EO-Monitor transports the laser beam into the UHV of the storage ring and back out to the laser hutch for analysis. It is based on a design from PSI [13, 14] which has been extended by a grating compressor to control the laser pulse length right before the pulses are sent to the EO crystal. Figure 3 depicts the in-vacuum components of the EO-Monitor. After the laser enters the UHV through a viewport, it is reflected by a silver coated prism used as a mirror and sent towards the 5 mm thick GaP crystal. The laser light enters the crystal through the front surface and is then reflected by its high-reflex coated back surface.

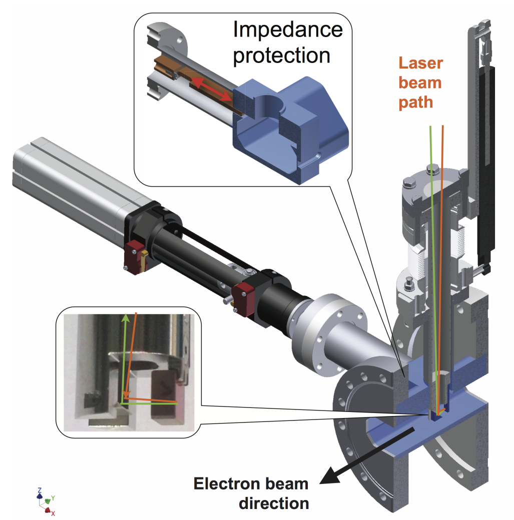

Figure 3: In-vacuum components of the EO-Monitor.

The modulation of the laser pulse by the electric field of the bypassing electron bunch happens when both the electron bunch and the laser pulse co-propagate in the crystal. The distance of the EO-crystal to the electron beam can be adjusted precisely via a linear motion feedthrough that moves not only the crystal, but also the whole EO-Monitor, this ensures that the optical delay remains unchanged when moving the crystal in. For operation at a storage ring, the EO-Monitor has been extended with a movable metallic shutter (impedance protection) that can fully cover the hole inside the UHV vacuum chamber to minimize impedance effects during normal user operation when the crystal is fully retracted from the beam pipe. With the current design, measurements are only possible during single- or dual-bunch operation because of thermal power generated by wake-fields (see [8]).

For the actual measurement, temporal overlap between the laser pulse and the electron bunch needs to be achieved inside the EO-crystal. To adjust the temporal overlap with an accuracy in the order of 1 ns, we use the direct signal of one of the four buttons of a nearby button BPM and compare its arrival time in relation to the signal of the laser pulses (measured with a fast photodiode) with an oscilloscope. The fine adjustment of the time delay (sub-ps accuracy) is then done with a step wise scan of the vector modulator that lets us delay the laser pulse very precisely while monitoring the amplitude of the modulated laser signal. Each time

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the synchronization between laser and RF is interrupted (e.g. when the laser is turned off), this procedure has to be repeated.

The detection of the modulated laser pulses in the laser hutch is done by either a fast InGaAs photodiode[1] in combination with an oscilloscope (for EOS, see below) or a grating spectrometer[2] (for EOSD). A more detailed description of the whole setup and measurement procedure can be found in [15]. The readout of the commercial line array inside of the spectrometer limits our acquisition rate of single-shot measurements to about 7 Hz.

Typical distances of the EO crystal from the electron beam are in the order of 5-6 mm (center of beam pipe to bottom tip of crystal) for which we detect no significant increase in the local beam loss rate with a very sensitive loss detector (lead glass scintillator coupled with a photomultiplier tube) that is placed in a dispersive section a few meters downstream of the EO-Monitor.

MEASUREMENT RESULTS

The results presented here are divided into single-shot bunch profile measurements obtained with EOSD and the study of long-ranging wake-fields measured with EOS.

Single-Shot Bunch Profile Measurements

Figure 4 shows longitudinal bunch profiles recorded for three different low-α_c-machine parameters. While plots b), c) and d) show single-shot profiles recorded with EOSD, plot a) shows bunch profiles recorded with our streak camera at approximately the same time as the profiles shown in b).

The error bands for the EOSD profiles in the plots give a measure of the one-σ-fluctuation retrieved from background measurements. They confirm that the bunch deformations and the substructures in the order of a few picoseconds are highly significant. While the data set in b) shows substructures on an otherwise rather smooth profile, the data set in d) for which the bunch charge was comparatively high shows rather triangular bunch shapes. For the data set in c), the bunch compression was not as high, and deformations and substructures do not seem to occur as strongly and frequently.

Figure 5 shows EOSD bunch profiles with the settings from a) and b) in Fig. 4, but for different bunch currents during the decay of a single bunch. While the substructures are clearly visible for the higher currents, they become less significant for lower currents. The average bunch length for the data set recorded at the lowest current (0.08 mA) was measured to be (3.31 ± 0.45 ± 0.24) ps (RMS) with the first uncertainty coming from the statistical fluctuations of fits to the 11 shots, and the second uncertainty coming from the fluctuation of the time calibration measurements for this fill.

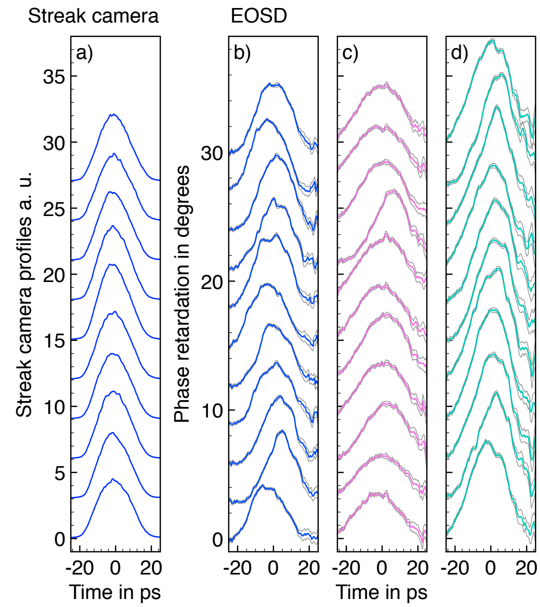

Figure 4: Bunch profiles for different machine settings. The curves have been displaced vertically for better visibility. a) Streak camera profiles for single images (averaged over 2700 bunch revolutions). b) Single-shot EOSD profiles recorded around the same time. Beam parameters for a) and b): Fully compressed beam (V_{rf} = 1.8 MV, f_s = 7.7 kHz) with 1.13 mA (418 pC) bunch current, average bunch length 8.79 ± 0.63 ps. c) Single-shot EOSD profiles for a slightly compressed beam (V_{rf} = 0.72 MV, f_s = 8.3 kHz) with 1.14 mA (422 pC) bunch current, average bunch length 13.56 ± 1.26 ps. d) Single-shot EOSD profiles for a heavily compressed beam (V_{rf} = 1.8 MV, f_s = 10.4 kHz) with a high beam current of 1.75 mA (648 pC), average bunch length 7.97 ± 0.81 ps.

Influence of Long-Ranging Wake-Fields on Following Bunches

The electro-optical setup is also sensitive to the vertically polarized component of the wake-fields trailing an electron bunch passing the setup. Typically, for this measurement we want to cover time periods in the order of a few nanoseconds, so single-shot measurements, which typically have a time window in the order of 50 ps, are not feasible, therefore only the peak amplitude of the whole laser pulse is measured while the delay between electron bunch and laser pulse is scanned step-wise. This averaging technique is referred to as electro-optical sampling (EOS). The top of Fig. 6 shows two such EOS measurements, one for a single-bunch in the accelerator and one for two consecutive bunches. For better comparison, the signals are normalized with the charges of the first bunches respectively. One can clearly see, that at the position of the second bunch (2000 ps), the wake-fields are still present. The plot on the bottom is a zoom into the time range around the first peak of the first bunches. Additionally, the signal from the second bunch (normalized

[1] EOT ET-3010
[2] Andor iDus A-DU490A-1.7

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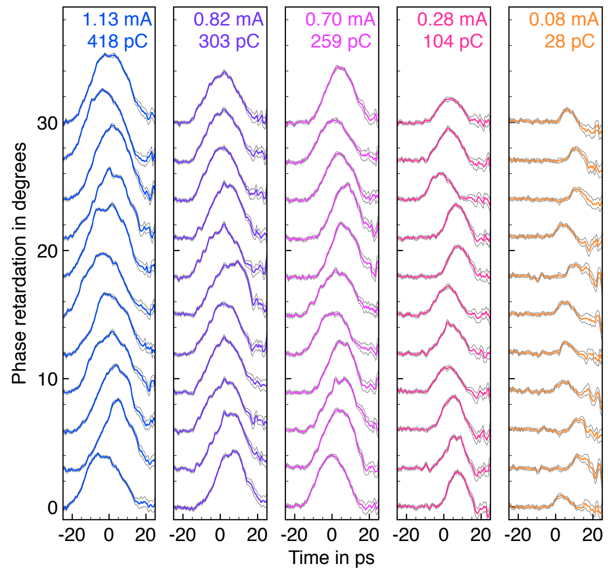

Figure 5: Single-Shot EOSD profiles for different beam currents during one fill (V_{rf} = 1.8 MV, f_s = 7.7 kHz).

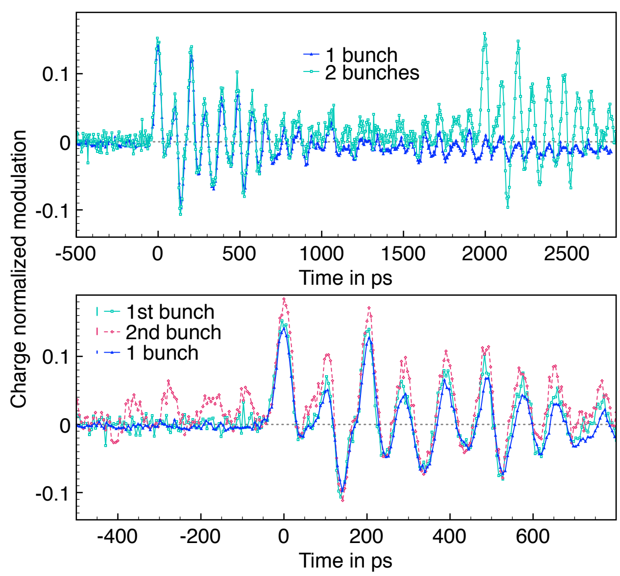

Figure 6: Top: Two EOS scans over a time range of 3 ns. One for a pure single bunch and one for a 2-bunch fill. The EOS-signal is normalized to the charge inside the first bunches. Bottom: Zoom into the region around the first peak for which in addition the signal of the second bunch has been displaced by -2 ns and has been normalized with the charge inside the second bunch.

with the bunch charge of the second bunch) is displaced by -2 ns, so all three signals can be compared easily. The second bunch shows a significantly higher signal than the first bunch and the corresponding measurement for just one bunch, which might be an indication of the influence of the wake-field of the 1st bunch on the 2nd bunch.

Clear indications of bunches influencing the bursting behavior of following bunches have previously been observed at ANKA [9] and this is believed to be caused by wake-fields. While the exact shape of the wake-fields we observe with EOS depends predominantly on the geometry of the in-vacuum setup holding the crystal [8], other structures in the storage ring (e. g., a scraper) could cause similar wake-fields, leading to bunch-bunch interactions.

CONCLUSION

We have successfully adapted the method of near-field EOSD measurements to work at a storage ring. Thus is ANKA the first storage ring in the world with a near-field single-shot EO bunch profile monitor allowing the acquisition of single-shot longitudinal bunch profiles with a sub-ps resolution (down to 330 fs granularity) down to bunch lengths of 1.5 ps RMS. The setup is sensitive enough to measure bunch charges as low as 30 pC. Measurements for different bunch compression settings have revealed the anticipated dynamic substructures on the bunch profiles and strong bunch deformations for high bunch charges. Furthermore, we have detected long-ranging wake-fields which could influence following bunches.

OUTLOOK

The acquisition rate of single-shot bunch profiles is currently limited by the readout rate of our commercial line detector inside the spectrometer. It is of great interest to compare the bunch substructures directly to the bursting behavior of the CSR; therefore we plan to increase the readout rate to at least 0.9 MHz, ideally even to the full 2.7 MHz repetition rate of ANKA. To achieve this, an ultra-fast readout system for an InGaAs-based line-array sensor is being developed in collaboration with the Institute for Data Processing and Electronics (IPE) at KIT [16].

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