STATUS OF SINGLE-SHOT EOSD MEASUREMENT AT ANKA*

N. Hiller, A. Borysenko, E. Hertle, V. Judin, B. Kehrer, S. Marsching, A.-S. Müller, M.J. Nasse, P. Schönfeldt, M. Schuh, N.J. Smale, J. Steinmann, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, B. Steffen, P. Peier, Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany, V. Schlott, Paul Scherrer Institute (PSI), Villigen PSI, Switzerland

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 modulation can be extracted. The setup has 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 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, revealing 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 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 could 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 the minimum bunch spacing at ANKA and can influence a following bunch.

Electro-Optical bunch length measurement techniques rely on the Pockels effect to modulate the longitudinal electron bunch profile onto a laser pulse passing through an EO crystal (further reference e. g., [9]). 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 a certain choice of 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.

Subsequently, the laser pulse is analyzed with a single-shot spectrometer and the temporal distribution can be extracted from the spectral modulation by performing a time calibration measurement.

SETUP AT ANKA

The setup at ANKA consists of a Yb-doped fiber laser system (RF synchronized oscillator, pulse picker and amplifier) developed at PSI [10] 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 ($f_{\mathrm{rev}}/3$). 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 so-called 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 [11, 12] which has been extended by a grating compressor to control the laser pulse length right before the pulses are sent to the EO crystal. Inside the vacuum, the laser is reflected by a silver coated prism used as a mirror and sent towards the 5 mm thick GaP crystal. The light enters the crystal through the front surface and is then reflected by its high-reflex coated back surface. 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 are co-propagating in the crystal. In addition, the EO-Monitor has been extended with a movable metallic shutter that can fully cover the hole inside the UHV vacuum

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chamber to minimize impedance effects during normal user operation. With the current design, measurements are only possible during single- or dual-bunch operation because of thermal power generated by wake-fields (see [8]). A more detailed description of the setup can be found in [7].

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). The readout of the current spectrometer is limiting our acquisition rate of single-shot measurements to about 7 Hz.

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.

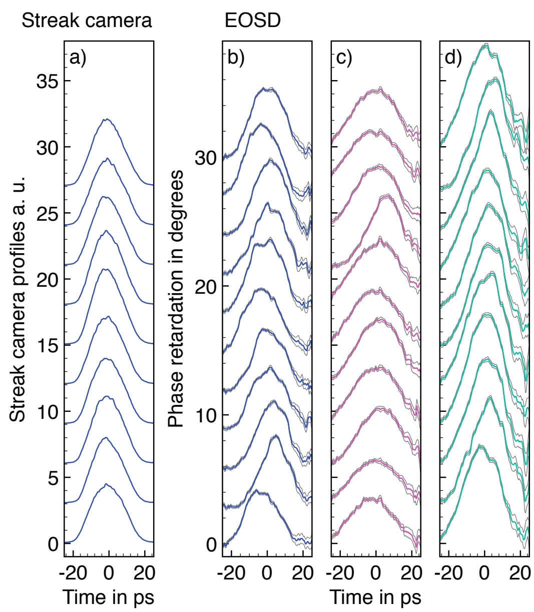

Figure 1: Bunch profiles for different machine parameters. The curves have been displaced vertically for better visibility. a) Streak camera profiles for single images (averaged over 2700 bunch revolutions). b) Single-shot EOSD profiles recorded around the same time. Beam parameters for a) and b): Fully 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.

[1] EOT ET-3010

[2] Andor iDus A-DU490A-1.7

Single-Shot Bunch Profile Measurements

Figure 1 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.

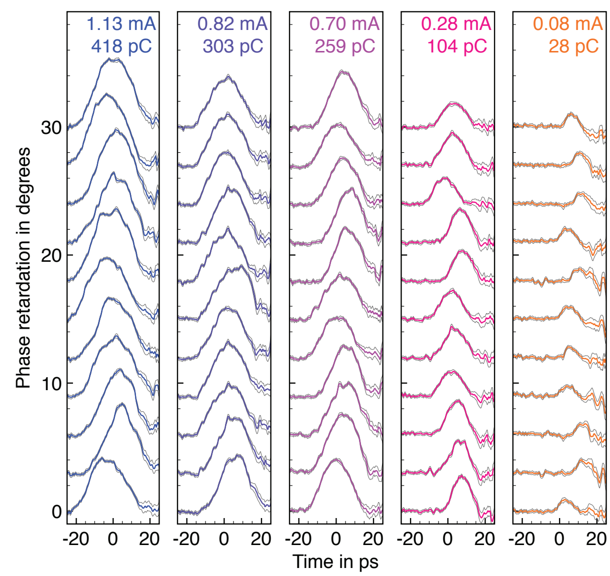

Figure 2: Single-Shot EOSD profiles for different beam currents during one fill (V_{rf} = 1.8 MV, f_s = 7.7 kHz).

Figure 2 shows EOSD bunch profiles with the settings from a) and b) in Fig. 1 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.

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

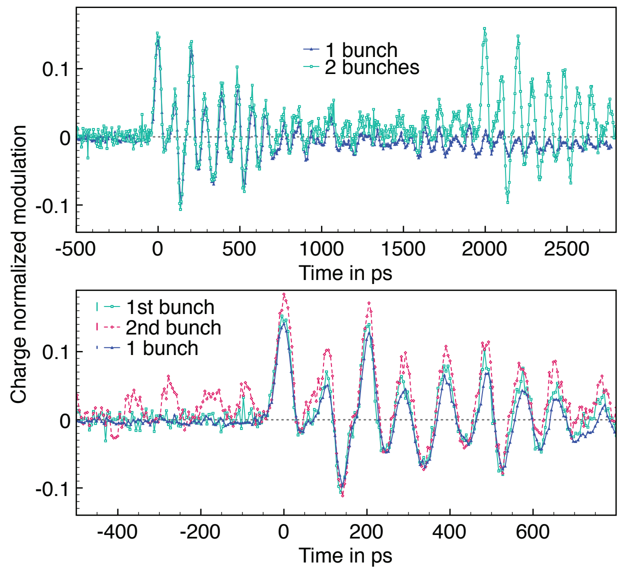

Figure 3: Top: Two EOS scans over a time range of 3 ns. One for a pure single bunch and one for a 2-bunch fill. The EOS-signal is normalized to the charge inside the first bunches. Bottom: Zoom into the region around the first peak for which in addition the signal of the second bunch has been displaced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

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. 3 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 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 [13] 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

ANKA is 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 390 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, a 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.

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