ELECTRO-OPTICAL BUNCH LENGTH MEASUREMENTS AT THE ANKA STORAGE RING*

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Abstract

A setup for near-field electro-optical bunch length measurements has recently been installed into the UHV system of the ANKA storage ring. For electro-optical bunch length measurements during ANKA's low alpha operation, a laser pulse is used to probe the field induced birefringence in an electro-optical crystal (GaP in our case). The setup allows for both electro-optical sampling (EOS, multi-shot) and spectral decoding (EOSD, single- and multi-shot) measurements. This paper presents first results and discusses challenges of this method employed for the first time at a storage ring.

MOTIVATION

During the low-α_c-operation of the ANKA storage ring in Karlsruhe, the momentum compaction factor α_c is reduced to compress the bunches to generate coherent synchrotron radiation (CSR) in the THz range [1]. Previous measurements have shown a beam current dependent bunch lengthening and deformation effect at ANKA in this special operation mode [2, 3]. In addition, CSR exhibits a bursting behaviour [4, 5, 6] which could be caused by dynamic changes of the longitudinal bunch shape (e.g. microbunching). Previously we could only measure the bunch shape with a streak camera which requires averaging the bunch profile over many revolutions to obtain a sufficient signal to noise ratio, thus we could not resolve dynamic effects on shorter timescales, where these effects are expected.

Electro-optical spectral decoding (EOSD) offers the possibility to measure the longitudinal bunch profile and its arrival time in relation to the revolution clock (2.7 MHz at ANKA) with a sub ps time resolution without averaging. Additionally, it is sensitive to the vertically polarized component of the wake-fields generated by an electron bunch passing the EO set up. 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.

* This work has been supported by the Initiative and Networking Fund of the Helmholtz Association under contract number VH-NG-320 and by the German Federal Ministry of Education and Research under contract number 05K10VKC

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SETUP AT ANKA

The setup at ANKA consists of a Yb-doped fibre laser system developed at PSI [7] specifically for electro-optical bunch length measurements for SwissFEL and the European X-FEL. This system has been adapted to be used with the revolution frequency of 2.7 MHz at ANKA: The oscillator now operates at 62.5 MHz, the 23rd harmonic of 2.7 MHz [8]. The final laser pulses used for the experiment have a wavelength of around 1050 nm (60-80 nm FWHM) and a variable repetition rate of 0.9 to 2.7 MHz. The laser system is placed outside the radiation protection wall at ANKA, the amplified laser pulses are then sent via a 35 m long polarization maintaining fibre to the so-called electro-optical monitor (EO-Monitor).

The fibre-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 [9, 10] 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 EOM has been extended with a movable metallic shutter that can fully cover the hole inside the UHV beam pipe to minimise impedance effects during the 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. For more information see [11].

The detection of the modulated laser pulses in the laser hutch is done by either a fast InGaAs photodiode (for EOS) or a grating spectrometer (for EOSD).

EXPERIMENTAL RESULTS

For EOS measurements a preferably short laser pulse is sent through the setup and the delay between laser and electron bunch is scanned stepwise while measuring the peak intensity of the laser signal with a fast photodiode (we use 100 sweeps wave-form averaging with the oscilloscope per delay step). The vertically polarized component of the electric field seen by the GaP crystal renders it birefringent thus turning the originally linearly polarized laser beam into an elliptically polarized one. For our measurements a near-crossed polarizer set up is chosen in order to achieve a nearly linear relationship between electric field and intensity change.

In Fig. 1 the results for such an EOS scan at ANKA are shown. Showing the peak signal of the fast photodiode over the relative delay between laser pulse and electron bunch which was changed stepwise by delaying the laser pulse with a vector modulator. The first peak at a delay of 0 ps comes from the Coulomb field of the bunch, the following structure originates from the vertically polarized component of the wake-fields mainly caused by the structure of the crystal holder. The distance of the crystal from the electron beam was 5.3 mm. The half-wave plate retarder was set 5° away from the crossed polarizer setting. The bunch charge was 540 pC (1.46 mA for ANKA). The resolution of this multi-shot measurement is limited firstly by the length of the probing laser pulse (around 20 ps in our case), the accuracy and size of the delay steps (minimum step size of 488 fs with our vector modulator) and finally by any longitudinal instabilities or fluctuations between the laser pulses, which are synchronized to the storage ring radio frequency (500 MHz for ANKA) and electron bunches (there is no longitudinal feedback system at ANKA). The EOS results show that the trailing wake-fields have a non-vanishing field component at a delay of 2 ns where a consecutive bunch would be in a multi-bunch fill at ANKA.

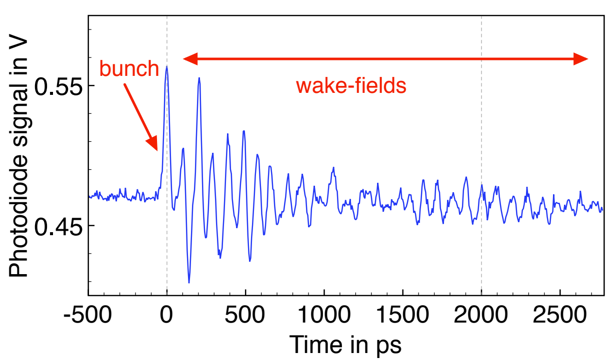

Figure 1: EOS measurement of the electric field induced birefringence inside the GaP crystal from a passing electron bunch.

For EOSD measurements the laser pulse needs to be chirped and stretched to a length longer than the electron bunch. The Coulomb-field induced temporal modulation of the laser pulse is converted to a spectral modulation because of the chirp. In our case, the fiber-coupled grating spectrometer equipped with a 512-pixel InGaAs photodiode array detector (Andor iDus) allows for single shot bunch length measurements.

For EOSD measurements a background spectrum (no laser light) is recorded in addition to a series of unmodulated spectra (laser pulse travels through the crystal without the presence of an electric field from the electron bunch). For the actual measurement the delay is adjusted to have full temporal overlap between laser pulse and electric field from the electron bunch and modulated spectra are recorded (all single measurements). The background spectrum is subtracted from both, the modulated and unmodulated spectra, then the modulated spectra are divided by the averaged unmodulated spectrum to obtain a relative modulation. To convert from the wavelength- (or pixel-) axis of the spectrometer to the time domain a delay scan is done for which the laser pulse is delayed stepwise with the vector modulator and the shift in peak position on the spectrometer is measured. From a fit to the spectral position of the peak position over the time delay, we achieve a time axis-calibration.

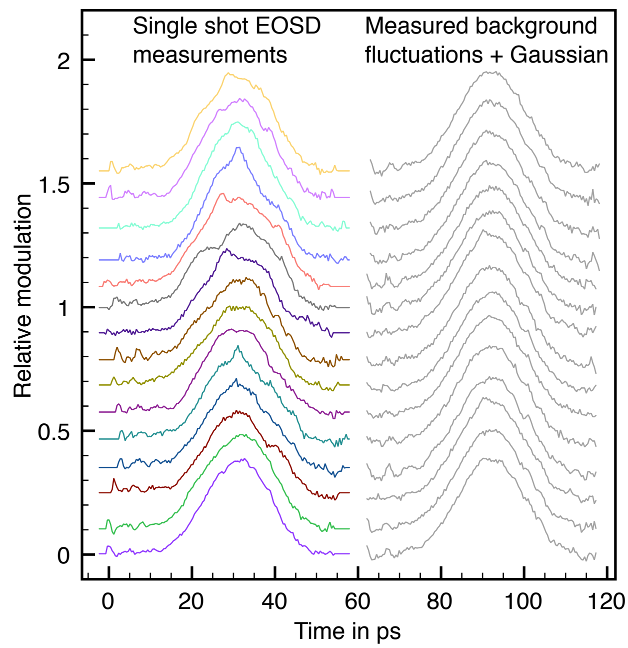

Figure 2: Left: 15 consecutive single shot EOSD measurements recorded at about 3 Hz. For better visibility, they have been displaced vertically and aligned horizontally to correct for any time of arrival fluctuations. Right: 15 unmodulated spectra divided by the same average modulated spectra as the measurement data on the left and added to a Gaussian to illustrate the influence of background fluctuations and noise for comparison (see main text).

Figure 2 shows, in the left, 15 consecutive single shot EOSD measurements with an already converted time axis. The bunch charge was 420 pC (1.13 mA at ANKA) with an average bunch length of 8.1 ps RMS. The distance between EO crystal and electron beam was 5.3 mm (those settings also apply to the following figures). The bunch profiles which were recorded during heavy bursting behaviour in the low-α_c-mode show substructures along the longitudinal profile as expected. In order to be sure that those substructures are really on the bunch and not just some artifact from laser signal fluctuations, on the right of Fig. 2, 15 measured

ISBN 978-3-95450-122-9

background signals are shown and a Gaussian profile has been added to them to get an idea how those fluctuations would influence the measurement. One can see that small (< 0.05) and especially short time scale fluctuations (< 1-3 ps) can be explained by laser fluctuations and noise as they are also visible in the right, but the larger distortions visible on the left we attribute to modulations of the electron bunch which seem to agree well with theoretical predictions [5]. For the above measurements, the usable range of the laser spectrum covers about 130 pixels. After a time calibration, this corresponds to a time window of about 50 ps. The signal from a very narrow-band laser pulse on the spectrometer has a width of 9 pixels (3.5 ps), which we take as our point spread function. We can compress the laser pulses further to improve the temporal resolution, but it will narrow the time window we can observe. In Fig. 3, a comparison of the averaged bunch profile recorded with a streak camera and the 1000-shot average of the EOSD signal are displayed. The averaged profiles show very good agreement, but the streak camera data shows a larger asymmetry of the peak.

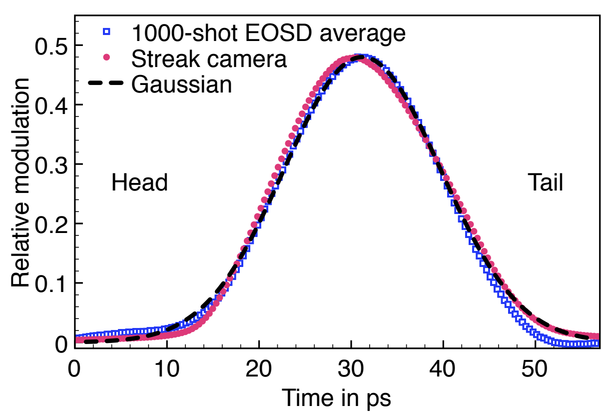

Figure 3: Comparison of the bunch profile recorded with EOSD by averaging over 1000 aligned single-shot measurements and an averaged bunch profile (average over 100 images, aligned slice-wise) recorded by our Hamamatsu streak camera simultaneously. In addition a Gaussian profile is plotted as reference. The data sets agree very well in bunch length, but the profile recorded with the streak camera shows a small asymmetry at the peak.

In Fig. 4, a scatter plot is displayed which shows a correlation between the RMS bunch length retrieved by Gaussian fits to 1000 consecutive EOSD measurements and their relative arrival time to the laser pulse which is synchronised to the bunch revolution clock. It can be seen that the bunches arriving earlier are on average a bit shorter than the ones arriving later. Beam dynamics simulations predict a decrease in bunch length in the turning points of the synchrotron oscillation [12]. This however is only the case, when the oscillation is symmetric around the stable phase, it could be, that for higher currents and during bursting this oscillation is shifted and thus the bunches do not get shorter for later arrival times.

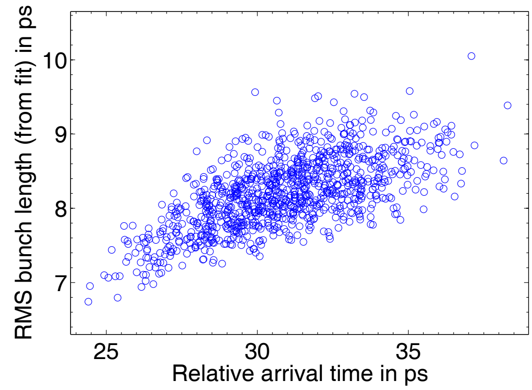

Figure 4: Scatter plot showing a correlation between the RMS bunch lengths retrieved by Gaussian fits for 1000 consecutive single shot EOSD measurements and their arrival time relative to the laser pulse.

CONCLUSION

For the first time near-field electro-optical bunch length, profile and wake-field diagnostics are operational at a storage ring allowing the acquisition of single shot bunch profiles with a resolution of 390 fs and a point spread function of 3.5 ps FWHM (further improvements possible). This set up allows for the detection of dynamic changes of bunch length and profile. Furthermore a correlation between the bunch length and arrival time of a bunch can be detected. The setup is sensitive enough to allow single shot measurements down to a bunch charge in the order of 40 pC with an RMS bunch length of about 3 ps. This opens up many possibilities for interesting beam dynamics studies during ANKA's low-α_c-mode. The resolution and acquisition speed can and will still be increased.

ACKNOWLEDGMENTS

Many thanks to the entire technical staff both at PSI and ANKA who helped us to get the experimental setup running. Also many thanks to the beamline scientists of the IR, FLUO and SUL beamlines at ANKA who helped us with many little but important things.

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