ELECTRO-OPTICAL MEASUREMENTS OF THE LONGITUDINAL BUNCH PROFILE IN THE NEAR-FIELD ON A TURN-BY-TURN BASIS AT THE ANKA STORAGE RING*

E. Roussel, C. Evain, S. Szwaj, S. Bielawski (PhLAM/CERLA, Villeneuve d'Ascq, France),
A. Borysenko, N. Hiller, A.-S. Müller, P. Schönfeldt, J.L. Steinmann (KIT, Karlsruhe, Germany)

Abstract

ANKA is the first storage ring worldwide with a near-field single-shot electro-optical bunch profile monitor. Previously, the method of electro-optical spectral decoding (EOSD) was employed to record single-shot longitudinal bunch profiles. The readout rate of the required spectrometer detector system limited the acquisition rate to a few Hz and thus did not allow us to study the evolution of the longitudinal bunch shape on a turn-by-turn basis. The setup at ANKA was combined with the novel method of photonic time-stretch [1] for which the modulated laser pulse is not detected in the spectral domain, but stretched to a few nanoseconds by a long fiber and, subsequently, detected in the time domain. This method allows the sampling of the longitudinal bunch profile on a turn-by-turn basis for several milliseconds, uninterrupted. Here, we present first results obtained with the photonic time-stretch method in the near-field at the ANKA storage ring.

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 [2]. Previous streak camera measurements have shown a beam current dependent bunch lengthening and deformation effect at ANKA in this special operation mode [3, 4]. In addition, the emitted CSR exhibits a bursting behavior [5–7], which we believe to be caused by dynamic changes of the longitudinal bunch shape (e. g., microbunching). Our near-field EO setup offers the possibility to obtain direct, single-shot measurements of the electric-field of the bypassing electron bunches which is directly linked to the longitudinal bunch profile. For this, the electric field of the electron bunch is modulated on a long, chirped laser pulse which is then analysed subsequently (Fig. 1). The laser pulses are synchronised to the electron bunch revolutions (f_{rev} = 2.7 MHz at ANKA) and with a fast enough detector, the bunch profile could be measured for every turn. Previously, the laser was detected in the spectral domain with a grating spectrometer housing a commercial line array that allowed for single-shot acquisitions, but only at a rather low readout rate of a few Hz (Fig. 1(a)). These measurements have revealed dynamic substructures on the electron bunches on a sub-ps time scale [8–10], but the dynamic evolution of the longitudinal bunch profile could not be studied on a turn-by-turn basis.

The novel method of photonic time-strech, based on Dispersive Fourier transform (DFT), also known as real-time Fourier transformation [11], is a powerful method that overcomes the speed of classical cameras and enables real-time measurements of fast non-repetitive events using fast detectors. This technique has already been used in optics, photonics, telecommunications and spectroscopy, etc [11–13]. The principle of time-stretch is simple and consists in imprinting the signal containing the information on laser pulses and then stretch these pulses so that the signal is slowed-down enough and can be acquired with classical oscilloscopes (Fig. 1(b)). The combination of the time-stretch with the electro-optic detection has enabled to reach acquisition rate in the tens of megahertz and thus, revealed the evolution of the microbunching instability on a turn-by-turn basis [1].

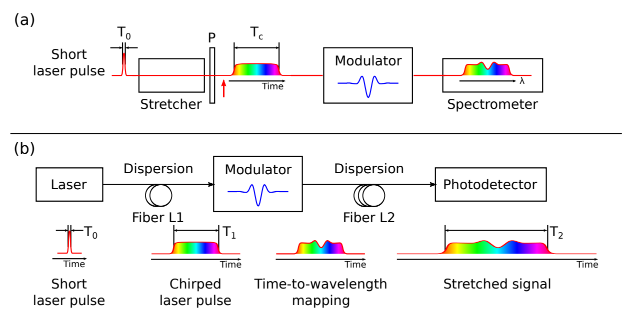

Figure 1: Principle of the detection. The information under inverstigation, here longitudinal bunch profile, is first encoded into a chirped laser pulse, using an electro-optic crystal ("Modulator"). Then the information encoded in the laser pulse is either detected in the spectral domain with a spectrometer (a), or futher stretched by propagation in a long fiber and detected in the time domain with a photodetector (b).

METHODS

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., [16]).

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 induces a time dependent birefringence in the EO crystal and this anisotropy modulates the polarization state of the linearly polarized probe laser pulse. This modu-

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lation 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 crystal and the half-wave plate regulates the transmission through the crossed polarizer (see e.g. [17] 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 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 can either be analyzed in a single-shot spectrometer - electro-optical spectral decoding (EOSD) - or the laser pulses are stretched in a long fiber to a few nanoseconds and can then be detected in the time-domain with a fast photodiode in combination with a fast oscilloscope with a bandwidth in the tens of gigahertz - time-stretch method (TS) (Fig. 1). Each method requires some means of absolute calibration of the time for which we delay the laser pulse in well known steps - in our case electronically, with a programmable vector modulator - and measure the shift of the EO signal within our acquisition window.

TIME-STRETCH UPGRADE OF EO 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. We use an Yb-doped fiber laser system (RF synchronized oscillator, pulse picker and amplifier) developed at PSI [18] 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 2.7 MHz (f_{rev}). The laser was operated in a bursting regime with one burst every storage ring revolution period. The burst contains 2 or 3 laser pulses (one pulse every 16 ns) in order to get one pulse modulated by the electron bunch through the EO crystal and an other one has a reference background signal (Fig. 2). The reference signal is then subtracted from the modulated signal in the post data analysis.

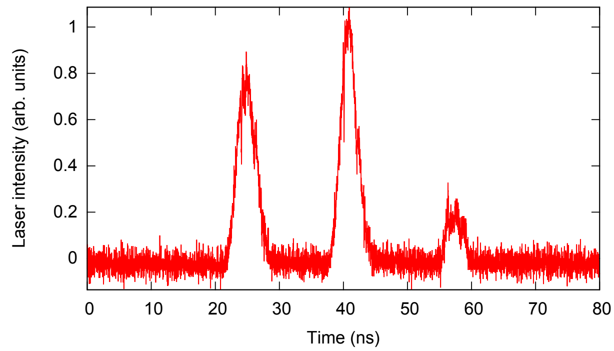

Figure 2: One burst of three laser pulses. The first pulse interacts with the electron beam in the EO crystal while the second one is used as a reference signal. Note that these stretched pulses are recorded using the fast photodetector after propagation in the photonic time-stretch setup.

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 [19, 20] which has been extended by a grating compressor to control the laser pulse length right before the pulses are sent to the EO crystal. 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 (see [10] for a detailed description).

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 [14]). 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.

For the actual measurement, temporal overlap between the laser pulse and the electron bunch needs to be achieved

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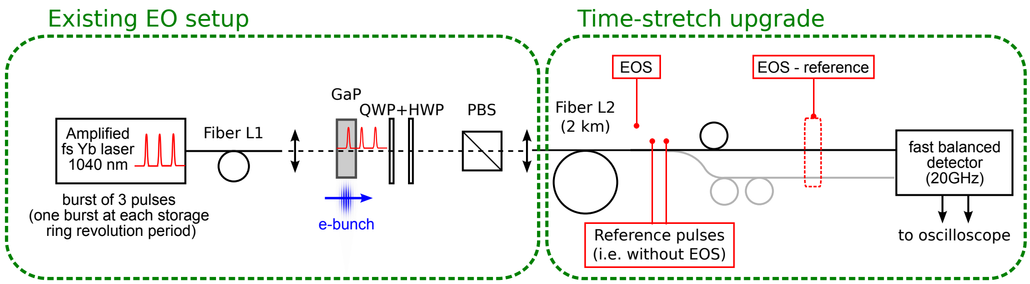

Figure 3: Upgrade of the electro-optical spectral decoding setup with the photonic time-stretch method. The modulated pulses are no more detected in the spectral domain but are stretched in a 2-km-long fiber (L2) and detected in the time domain with a fast photodetector ("Time-stretch upgrade"). With this new strategy, two detection schemes are possible: two laser pulses are detected one a single detector with one pulse that contains the information and an other one as a reference signal; or the signal is split and one part is delayed by one laser period (i.e. 16 ns) and analogically subtracted from the other part in a balanced detector in order to remove the laser envelope background.

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.

The detection of the modulated laser pulses in the laser hutch was upgraded using the time-stretch strategy (Fig. 3). Instead of detecting the laser pulses with a grating spectrometer, they are stretched in a 2-km-long fiber[1] before detection, in order to get a final pulse duration of around 4 ns and are then detected using a balanced photodetector[2] with a 20 GHz bandwidth and 2800 V/W gain (specified at 1500 nm). The two differential outputs of the detector are sent on a Lecroy LabMaster 10i oscilloscope with 36 GHz bandwidth, 80 GS/s sample rate on each channel, and a memory of 256 Mega samples. This setup permits two different detection schemes. The first one consists in recording the laser pulses on one single detector and to subtract the reference signal containing the envelope of the unmodulated laser pulse in the post-process analysis. The second configuration used a balanced detection strategy. In that case, the signal is split and one part is optically delayed using a fiber longer by one laser period (i.e. 16 ns) (gray path in Fig. 3). The unmodulated laser envelope is then subtracted analogically from the other part in a balanced detector.

The readout of the previous setup using a commercial line array inside the spectrometer has a limited acquisition rate of about 7 fps (193 fps is the limit of the hardware). The time-stretch recording system is able to acquire 62.5×10^6 bunch profiles per second. This allows us to record the longitudinal bunch profiles at each turn in the storage ring, i.e. every 368 ns.

[1] HI1060 from Corning

[2] DSC-R412 InGaAs amplified balanced photodetector (photoreceiver) from Discovery Semiconductors

MEASUREMENT RESULTS

The ANKA storage ring was operated in low-α_c configuration with a beam energy of 1.3 GeV, in single-bunch mode. The current per bunch was around 3 mA.

In order to convert the stretched time of the recorded signal at the input of the oscilloscope, which is in the nanosecond range, we calibrate the time-stretch setup by delaying the probe laser pulse in well-know step over few picoseconds and measure the shift of the EO signal in the stretched laser pulses. Figure 4 shows the calibration curve. The slope gives the conversion factor from the stretched time in ns to the real time of the phenomenon in ps. Here, 1 ns corresponds to a real time of 12.8 ps, which corresponds to a stretch factor of 78.

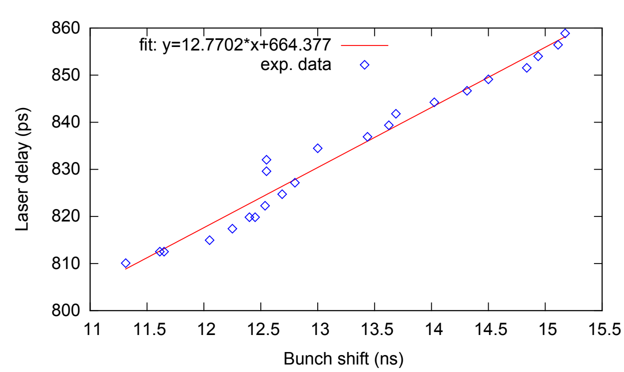

Figure 4: Calibration of the stretch factor. The curve represents the delay in picosecond of the probe laser pulse versus the shift of the bunch profile in the EO signal in nanosecond.

The upgrade of the existing EOSD setup at ANKA with the time-stretch setup allowed us to record longitudinal bunch profile for each revolution turn in the ring. Figure 5 shows 10 successive single-shot longitudinal profiles. In practice, the acquisition is done using one single detector with two laser pulses, one containing the EO signal and an other one used as a reference signal to subtract the laser envelope.

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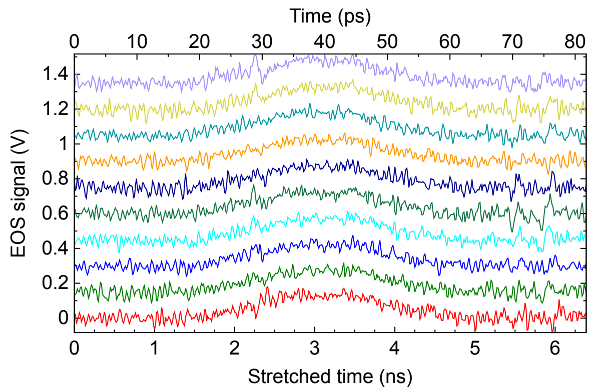

Figure 5: Single-shot recordings of longitudinal bunch profiles using the time-stretch strategy. The curves are shifted vertically for better clarity. The lower scale corresponds to the time at the oscilloscope input (i.e., after the photonic time stretch by a factor 78). The time between pulses is of 368 ns, i.e. equal to electron bunch revolution period.

The EO signal has been compared to the longitudinal bunch profile recorded with the streak camera. The rms bunch length measured with the streak camera was equal to 8 ps. Figure 6 shows a single-shot EO acquisition of a bunch profile (blue dots) and its gaussian fit (red line). The measured bunch length with the EO setup is 8.4 ps, which is in good agreement with the streak camera measurements.

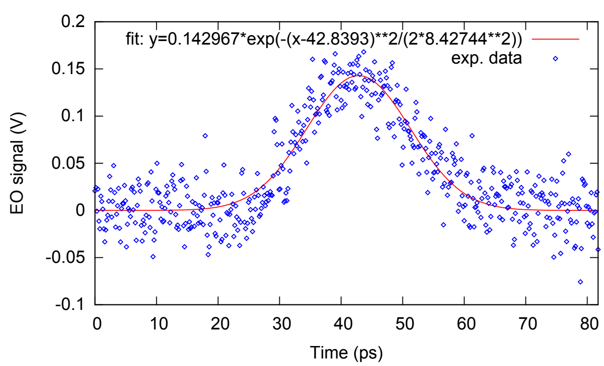

Figure 6: Single-shot longitudinal bunch profile recorded with the time-stretch strategy.

CONCLUSION

We have successfully upgraded the existing near-field EOSD measurements of the ANKA storage with the photonic time-strech. The time-stretch permits single-shot, high-acquisition rate detection of ps shapes. We applied the time-stretch EOSD setup to the direct real-time monitoring of the near-field longitudinal bunch profile turn-by-turn over several milliseconds. These measurements open new perspectives for a detailed comparison between the evolution of the longitudinal bunch shape and the bursting behavior of the CSR emission. In parallel, there is a joint collaboration ongoing for the development of an ultra-fast linear detector array that will allow a continuous data readout at up to 5 Mfps [22].

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