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HIGH REPETITION RATE, SINGLE-SHOT ELECTRO-OPTICAL MONITORING OF LONGITUDINAL ELECTRON BUNCH DYNAMICS USING THE LINEAR ARRAY DETECTOR KALYPSO

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Abstract

High repetition rate diagnostics are required when detecting single-shot electro-optical profiles. The KIT storage ring KARA (Karlsruhe Research Accelerator) is the first and only storage ring that has a near-field electro-optical bunch-profile monitor in operation. By imprinting longitudinal electron bunch profiles onto chirped laser pulses, single-shot detection is feasible. However, limitations of available detection systems are still challenging. A fast readout is crucial for diagnostics at high repetition rates (above hundreds of kHz). We developed KALYPSO (KArlsruhe Linear arraY detector for MHz-rePetition rate SpectrOscopy), a linear detector array with a data acquisition system (DAQ) allowing high data-rates over long time scales. In this contribution, we present recent results on studies of longitudinal electron bunch dynamics using KALYPSO.

INTRODUCTION

In storage rings, electron bunches are stored over long time scales exhibiting short-term and long-term dynamics. During single bunch, low alpha operation an electron bunch interacts with its own radiation field, which can result in a microbunching instability [1]. In this process, bursts of synchrotron radiation - in the terahertz (THz) range - are observed with orders of magnitude higher intensity compared to conventional synchrotron radiation. This level of emission could be interesting for users (e.g. for non-linear spectroscopy). However, the complex and unsteady dynamics - and thus emission - limits the use. Insights to the phase space of the electron bunches can help to understand the complex dynamics, a first step towards developing tools to stabilize the THz radiation at high intensities. The longitudinal bunch profile is a projection of the phase space onto the time axis, which can be recorded with electro-optical sampling (EOS) by measuring the longitudinal component of the electron bunch Coulomb field [2]. To study the evolution of the phase space over time, single-shot detection is desired.

EOS is well-known in THz spectroscopy (e.g. [3, 4]). Electro-optical (EO) investigations can be performed in single-shot mode by imprinting THz pulses onto chirped laser pulses [5]. EOS is also used in the far-field to detect emitted THz radiation by short electron bunches [6]. The measurement of electron bunch profiles in the near-field was demonstrated for the first time in a linear accelerator [7]. EO measurements of electron bunches in the near-field in a storage ring are a special challenge due to the high MHz-repetition rate and wakefield excitations, which can disturb the measurement of closely following electron bunches, in addition, to the deposited heat load at the EO crystal. At KARA, in 2013, we demonstrated for the first time in a storage ring EO measurements of the near-field of electron bunches [8].

An additional bottle-neck for the experiment is the lack of high repetition rate detection systems for single-shot detection. There are mainly two strategies to overcome these limitations: Based on the photonic time-stretch method (e.g. [1, 9]) the picosecond laser pulses from the storage ring can be stretched to the nanosecond range using kilometer-long fibers. The readout with a very high-bandwidth oscilloscope then enables a single-shot detection at high repetition rate. The other strategy is the development of dedicated ultra-fast photodetector arrays allowing detection of the picosecond (ps) pulses at MHz repetition rates quasi continuously.

Here, we present studies of longitudinal electron bunch dynamics over long time scales at KARA using the ultra-fast

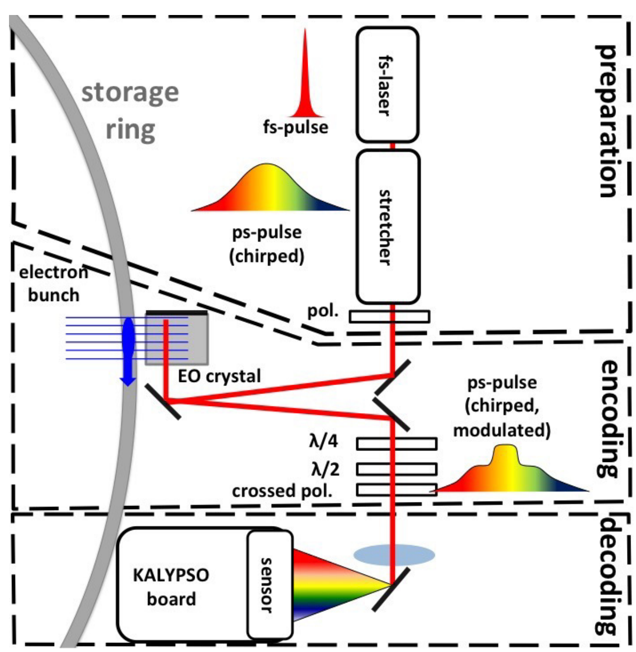

Figure 1: Sketch of the electro-optical experiment at KARA.

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linear sensor array and data acquisition board KALYPSO [10].

METHODS

The measurement was performed during single bunch operation of KARA with a beam energy of 1.3 GeV. To observe the microbunching instability, a low alpha optics was set up, i.e. the bunch was compressed longitudinally to a few picoseconds. [11]

Figure 1 displays the experimental setup. In a first step, for preparation, chirped laser pulses, generated by a self-built ytterbium-doped fiber laser (at 1060 nm), which is synchronized to the repetition rate of the storage ring, are sent through a 35 m-long fiber into the ring. Thereby, the intrinsic dispersion acts as a pulse stretcher. Polarization optics is used to ensure linear polarization.

To encode the charge density profile onto a chirped laser pulse, the Pockels-effect in an EO crystal (GaP) is used. Due to the electric field of the electron bunch passing by the EO crystal, it becomes birefringent. This birefringence changes the linear polarization of a simultaneously co-propagating linear polarized laser pulse into an elliptical polarization. (see e.g. [12] for details). Then, the laser pulses are led through polarization optics to turn the polarization modulation into an intensity modulation. We use a nearly crossed configuration at an angle of 4.6°. The line charge density, representing the longitudinal bunch profile, can then be calculated according to Ref. [13].

Finally, to decode the imprinted intensity profile, the laser pulses are sent through a grating setup and focused onto the 256 pixel Si-sensor of KALYPSO operating at a frame rate matched and synchronized to the 2.72 MHz repetition rate of KARA.

MEASUREMENTS

In Fig. 2, we visualized an example of measurements of the electron bunch line charge density, shown here for 200,000 revolutions spanning over 73.5 ms. Due to the

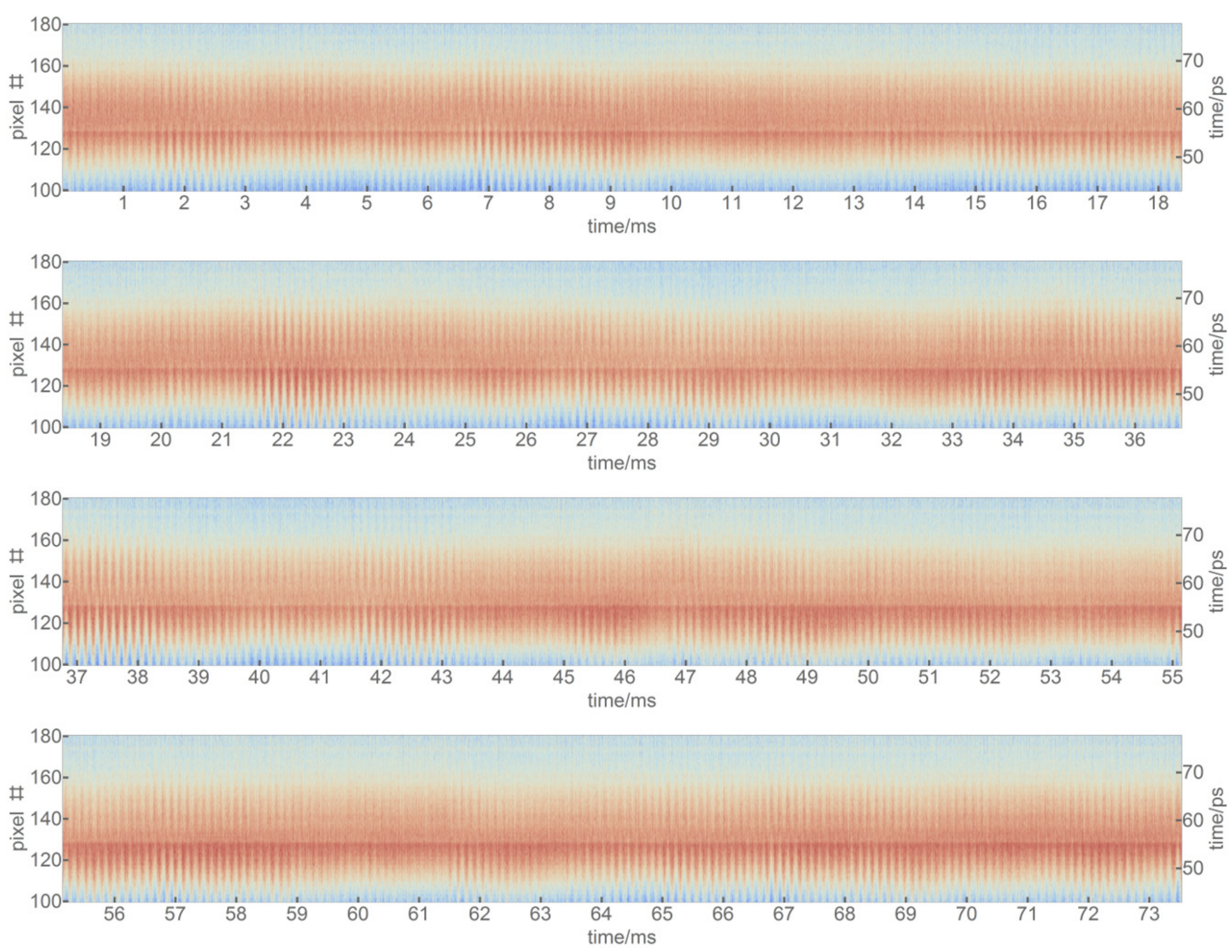

Figure 2: Four consecutive plots of the electron bunch line charge density. The vertical axes display on the left side the pixel number and on the right side the time obtained by calibration measurements with the laser synchronization system (giving a conversion factor of 0.43 ps/pixel). The horizontal axis gives the time in ms, calculated using the number of revolutions and the repetition rate. In total (all 4 rows), 200,000 revolutions (one revolution corresponds to 368 ns for the storage ring KARA) are displayed spanning over about 73.5 ms.

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high frame rate of KALYPSO, we are able to measure every revolution in single-shot detection. Visible is the synchrotron oscillation with varying magnitude. Here, we chose to display a rather long time section to demonstrate the capability of our experiment with high data-rates over long time scales. The amount of data illustrated here is limited by the image resolution. Furthermore, representations of longer time frames suffer from aliasing effects, because of the periodicity of the synchrotron oscillation. From the experimental side the limitation is given by the memory of the computer. With this experiment, the longest data set we acquired so far is 3.6 seconds (i.e. nearly 10 millions uninterrpted subsequent revolutions).

The long time frame, illustrated in Fig. 2, allows now detailed analysis from short-term (turn-by-turn) to long-term (seconds) dynamics - covering up to seven orders of magnitude in time resolution.

CONCLUSION AND OUTLOOK

We demonstrated single-shot electro-optical monitoring of longitudinal electron bunch dynamics over long time scales spanning seven orders of magnitude. We were able to record high-throughput data using an in-vacuum EO-arm especially designed for high repetition rate electron bunch near-field diagnostics [2] in combination with KALYPSO [10] enabling to resolve the longitudinal profile of a single bunch at KARA at every revolution.

In-depth longitudinal bunch profile studies on a turn-by-turn basis will enhance the knowledge about the complex dynamics during the microbunching instability. In addition, measurements over long time scales providing large amounts of data (e.g. a single measurement of 3.6 s produces 5 GB) contain a wealth of information necessary for detailed modeling.

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