DIAGNOSTICS OF LONGITUDINAL BUNCH INSTABILITIES AT KARA

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Abstract

KARA, the Karlsruhe Research Accelerator, can be operated in different modes, including a short-bunch mode. During this mode, where the dispersion is stretched in order to reduce the momentum-compaction factor, the micro-bunching instability can occur. At KARA, several measurement setups and techniques are used to investigate this instability further with the long-term perspective to suppress and control it. In this contribution, we give an overview about the different setups and the results achieved during the past years.

MOTIVATION

For wavelengths below the size of the emitting structure, electron bunches emit coherent synchrotron radiation (CSR), which is – if the bunches are sufficiently compressed longitudinally – not damped by the vacuum beam pipe and is thus transmitted. In bent sections of a circular accelerator the bunch interacts with its previously emitted CSR which leads to a deformation of the bunch. While this deformation is stationary for low bunch currents, it becomes dynamic for higher currents. This self-interaction can lead to a quick rise in amplitude of the resulting sub-structures which increases the intensity of the emitted CSR further. In addition, the charge distribution in the phase space is blown-up until radiation damping starts to shrink it again with the sub-structures smeared out due to diffusion. This interplay of the instability-driven blow-up and radiation damping leads to a bursting behaviour of the bunch. It shows as periodical outbursts of CSR and a sawtooth modulation of the energy spread and the bunch length.

DIAGNOSTICS

To study the dynamics of the charge distribution in the longitudinal phase space, its two projections – the energy and the temporal profile – can be measured. The relevant time-scales are given by the bunch spacing (at KARA 2 ns), the revolution time (at KARA 368 ns) and the timescale of the bursting behaviour, which is in the order of some milliseconds. Together with the goal to record for sufficiently long time scales, this sets stringent requirements to the detector systems. At KARA, we use Schottky barrier diode detectors to sample the CSR intensity, electro-optical spectral decoding (EOSD) to measure the longitudinal bunch profile and a fast-gated intensified camera and a KALYPSO system, respectively, to measure the horizontal bunch size as a measure for the energy spread.

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Coherent Synchrotron Radiation

To sample the CSR intensity, we use Schottky barrier diode detectors with response times below 200 ps, which is sufficient for single-bunch resolution. They are commercially available and offered in various frequency ranges. To digitize the signals, either an oscilloscope in the segmented mode or the KAPTURE system is used. KAPTURE is a picosecond sampling system for individual short pulses with a high repetition rate (500 MHz) [1, 2]. It has been developed at KIT and offers up to eight channels with an analog bandwidth of 18 GHz and 12 bit ADCs.

Longitudinal bunch profile

For measurements of the longitudinal bunch profile we use the technique of electro-optical spectral decoding. KARA is the worlds first storage ring where this principle is used in the near-field range [3, 4]. To do so, a gallium-phosphide (GaP) crystal is inserted into the vacuum beam pipe and brought close to the electron beam. The electric field of the passing bunch turns the crystal birefringent and the longitudinal bunch profile is imprinted into the crystal. Sending a long chirped laser pulse ($\lambda = 1050$ nm) through the crystal allows to probe the birefringence and thus the laser spectrum is modulated according to the longitudinal bunch profile.

To record and digitize the laser spectra we use the KALYPSO system [5, 6]. It is an ultra-fast line array with up to 1024 micro-strips and a maximum frame rate of 10 Mfps, which allows turn-by-turn studies at KARA as the storage ring has a revolution frequency of 2.7 MHz.

Energy spread

Although being an important parameter to study the micro-bunching instability, the energy spread cannot be measured directly. Therefore, the horizontal bunch size σ_x is studied as it is coupled to the energy spread σ_δ:

$$\sigma_x = \sqrt{\beta_x \epsilon_x + (D_x \sigma_\delta)^2}. \tag{1}$$

In addition, it depends on the horizontal beta function β_x, the horizontal dispersion D_x and the horizontal emittance ϵ_x. To measure the horizontal bunch size, we use incoherent synchrotron radiation in the visible range. At KARA, we have a dedicated beam port for visible light diagnostics [7], which uses bending radiation from a dipole magnet. For time-resolved measurements of the horizontal bunch size we use a fast-gated intensified camera (FGC) [8] and a KALYPSO system [9]. The data analysis is the same for both devices and takes the particularities of the optical setup and the imaging process into account: During the acquisition, the bunch is moving horizontally and the imaging system contains two off-axis paraboloid mirrors. This leads to a distortion of the image which is expressed numerically by the filament beam-spread function (FBSF) [10]. We determined the FBSFs from simulations of the optical setup and the imaging process using OpTaliX [11].

As the final image is the convolution of the FBSF with the horizontal bunch profile, the FBSF has to be deconvolved to retrieve the horizontal bunch size. Since a numerical deconvolution is slow and numerically unstable, we use a numerical convolution of the FBSF with a Gaussian curve as a fit function [12, 13].

The FGC has intrinsic limits as the number of data points per image is limited and there are mechanical as well as electrical delays. To overcome these limits, a KALYPSO system is used here as well. Therefore it is equipped with a Silicon sensor and thus turn-by-turn images are possible with the potential for continuous streaming [9].

SYNCHRONIZATION

In order to reconstruct the dynamics in the longitudinal phase space, the different measurement setups have to be synchronized on a single-turn basis. We use our timing system to provide a common trigger to all devices. By adjusting the trigger delays at the different setups, the setup-intrinsic delays are compensated and thus a simultaneous start of the recording is achieved [14], see Fig. 1 for a schematic principle. The measurement trigger is an *arm trigger*, which does not start the measurement directly. This is done by the next incoming pulse from the revolution clock, which is indicated by the small vertical arrow in Fig. 1.

MEASUREMENTS

The fully synchronized detector systems allow simultaneous measurements of the different bunch parameters. In the following, two examples for these measurements are discussed. Both were taken during the occurrence of the micro-bunching instability.

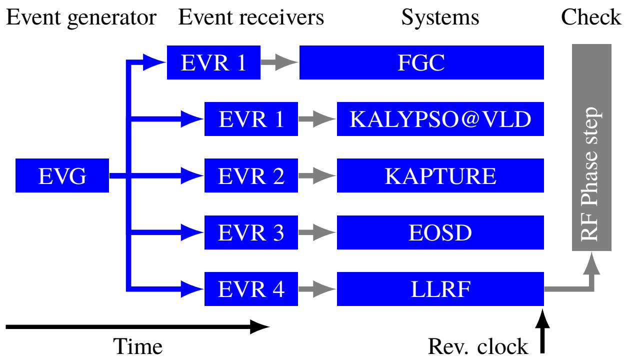

Figure 1: Schematic principle of the synchronization scheme at KARA. The timing system – which consists of one event generator (EVG) and several event receivers (EVR) – provides a common measurement trigger that arms the setups to start recording data with the next incoming trigger pulse from the revolution clock.

Longitudinal bunch profile at onset of burst

In this first example we measured the longitudinal as well as the horizontal bunch profile with two KALYPSO systems and in parallel the CSR intensity with a narrow-band Schottky diode (220 GHz to 330 GHz) read-out by an oscilloscope. Figure 2 shows the corresponding signals for 120.000 turns (approx. 44 ms).

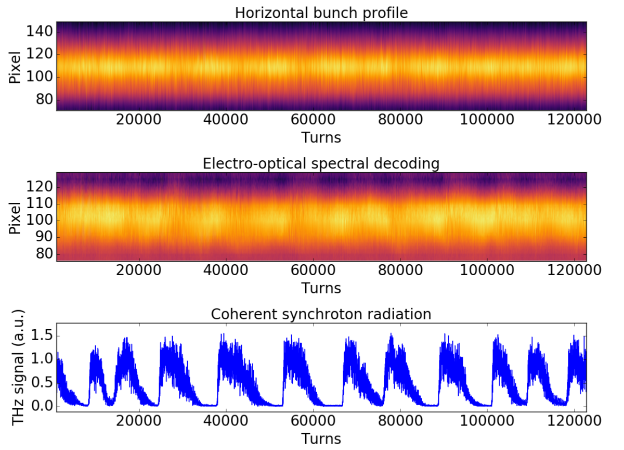

Figure 2: Top: Color-coded horizontal bunch profiles recorded using a KALYPSO system for 120.000 consecutive turns; Center: Corresponding longitudinal bunch profile from EOSD measurement using KALYPSO; Bottom: CSR intensity sampled by a narrowband Schottky diode.
Data previously published in [15, Fig. 1].

On the CSR intensity the sawtooth pattern is clearly visible which indicates the bursting behaviour of the bunch.

In Fig. 3, the longitudinal profile as well as the CSR intensity are plotted for a shorter time range which covers the onset of a CSR burst. On the longitudinal profile the occurrence of sub-structuress can be seen at the same time

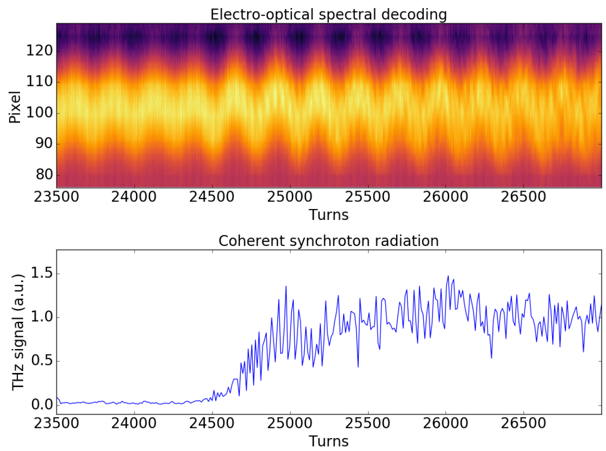

Figure 3: Detailed zoom-in into Fig. 2 around the onset of the CSR burst.
Data previously published in [15, Fig. 2].

when the CSR intensity rises, which supports the process discussed in the introduction [15].

Energy spread and CSR

To study the energy spread during the micro-bunching instability, the horizontal bunch size is determined from KALYPSO measurements at the VLD port. In Fig. 4, such a measurement covering approx. 36 ms is plotted together with the corresponding CSR intensity.

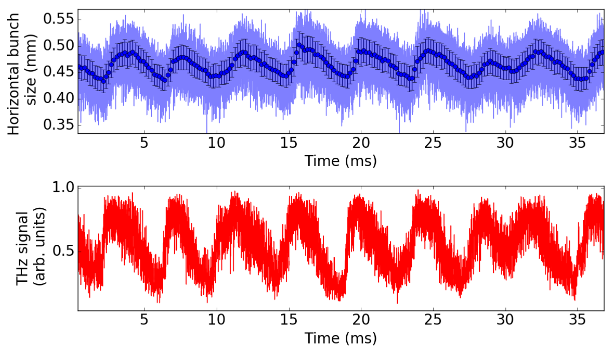

Figure 4: Top: Horizontal bunch size recorded with KALYPSO with a profile histogram applied to the data. Bottom: Corresponding CSR signal recorded by a broadband Schottky diode.
Previously published in [9, Fig. 5]

The horizontal bunch size – which is a measure for the energy spread – shows a sawtooth modulation with the same modulation period length as the bursting behaviour of the CSR in the bottom panel. At the beginning of a burst, the horizontal bunch size and thus the energy spread has a minimum and increases quickly afterwards.

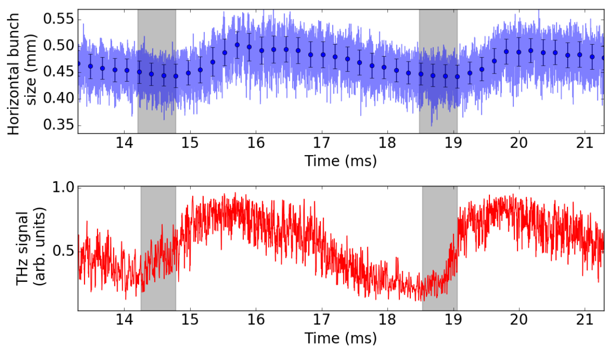

Figure 5: Detailed zoom-in into the data from Fig. 4. Top: Horizontal bunch size recorded with KALYPSO with a profile histogram applied to the data. Bottom: Corresponding CSR signal recorded by a broadband Schottky diode. The grey bars depict the time ranges, where the horizontal bunch size is still decreasing, while the CSR intensity already starts to increase.
Previously published in [9, Fig. 6]

As KALYPSO allows turn-by-turn studies, the onset of the CSR bursts can be studied in more detail. Figure 5 shows a zoom-in into the data set from Fig. 4.

The grey bars indicate the phase offset between the increase of the horizontal bunch size and the onset of the CSR burst. This offset indicates that at the beginning of a CSR burst, the sub-structures – which lead to the emission of the CSR – do not lead to an overall increase of the energy spread and thus the energy spread is still shrinking caused by synchrotron radiation damping. Here it takes for approx. 5 ms – in this case this corresponds to 4 synchrotron periods – before also the energy spread starts to increase due to the instability driven blow-up [16].

SUMMARY AND OUTLOOK

Time-resolved measurements of the different bunch parameters allow to investigate the micro-bunching instability in more detail. At KARA, several measurement setups are used for time-resolved studies with a single turn resolution. All detector systems are synchronized on a single-turn basis. These synchronous measurements are a first step towards the reconstruction of the longitudinal phase space. In addition, this can also be used as input for a potential feedback to control the micro-bunching instability.

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