

# TIME-RESOLVED ENERGY SPREAD STUDIES AT THE ANKA STORAGE RING

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## Abstract

Recently, a new setup for measuring the beam energy spread has been commissioned at the ANKA storage ring at the Karlsruhe Institute of Technology. This setup is based on a fast-gated intensified camera and detects the horizontal profiles of individual bunches in a multi-bunch environment on a single-turn base. As the radiation source point is located in a dispersive section of the storage ring, this allows time-resolved studies of the energy spread. These studies are of particular interest in the framework of short-bunch beam dynamics and the characterization of instabilities. The system is fully synchronized to other beam diagnostics devices allocated in various places along the storage ring, such as the single-shot electro-optical spectral decoding setup or the turn-by-turn terahertz detection systems. Here we discuss the results of the synchronous measurements with the various systems with special emphasis on the energy spread studies.

## INTRODUCTION

ANKA, the synchrotron light source and accelerator test facility at Karlsruhe Institute of Technology (KIT) can be operated in a short-bunch mode [1]. In this mode, the magnetic lattice is changed to reduce the momentum-compaction factor  $\alpha_c$ . Above a certain threshold current, the charge density inside the bunches is high enough to trigger micro-bunching instabilities. Due to self-interaction of the bunch with its own wakefield, sub-structures form on the bunch profile. Due to their dimensions, they lead to increased emission of coherent synchrotron radiation (CSR) in the THz range, referred to as bursts. Previous studies on these instabilities showed that the energy spread starts to increase above this *bursting* threshold [2]. Also, bunch length and CSR fluctuations show a modulation with the same period [3,4]. Due to their relation in the longitudinal phase space the same behaviour is also expected for the energy spread. The energy spread  $\sigma_\delta$  can be determined from the horizontal bunch size  $\sigma_x$  in a dispersive section of the storage ring (see Eq. 1), given the horizontal dispersion  $D_x$ , horizontal emittance  $\epsilon_x$  and beta function  $\beta_x$  at the radiation source point.

$$\sigma_\delta = \frac{1}{D_x} \sqrt{\sigma_x^2 - \beta_x \cdot \epsilon_x} \quad (1)$$

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For time-resolved studies with single-turn resolution we use a setup based on a Fast-gated intensified camera (FGC) [5], while for the CSR investigations we use Schottky diodes [6,7] with KAPTURE [8] as read-out system.

## EXPERIMENTAL SETUP

### Fast-gated Intensified Camera

The setup, the design of which is based on previous works [9,10] is located at the ANKA Visible Light Diagnostics Port [11]. It consists of a commercial FGC and fast-rotating mirror (aperture 7 mm) that is used to sweep the image of the beam over the CCD sensor. The incoming light hits a photocathode and the resulting photo-electrons are accelerated towards a micro-channel plate (MCP) to amplify the charge. The voltage between the cathode and the entrance plane of the MCP can be switched on and off within 2 ns, sufficient to pick a single bunch out of a multi-bunch fill as ANKA is operated with an RF frequency of 500 MHz. This *gating* function acts as fast shutter or pulse picker. Given a revolution frequency of 2.7 MHz, the maximum repetition rate of 500 kHz of the camera results in a minimum gate separation of 6 turns for two consecutive measurements of the same bunch.

To get a robust measure for the position and size of the spots at the CCD screen we apply 2D Gaussian fits. The error bars on the plots showing the spot position and size are given by the error on the fit parameters. Depending on the statistics due to the image intensifier settings they can be quite small and thus not visible on the plots.

### CSR Measurements

To measure the CSR intensity Schottky barrier diodes with different bandwidths are used. They work at room temperature, and with a response time below 200 ps they are sufficiently fast for multi-bunch studies with single-bunch resolution. To read out these fast detectors we use the KAPTURE system [8]. This FPGA based system is dedicated to digitize the CSR intensity recorded with fast detectors continuously with a turn-by-turn and bunch-by-bunch capability. For the measurements presented here we configured KAPTURE to sample up to four detectors in parallel with one sampling point per bunch and turn with a fixed phase relative to the ANKA RF system.

### Synchronisation

To achieve a synchronous measurement of the different beam parameters we use a synchronisation scheme based on the ANKA timing system [12]. It is calibrated using RF

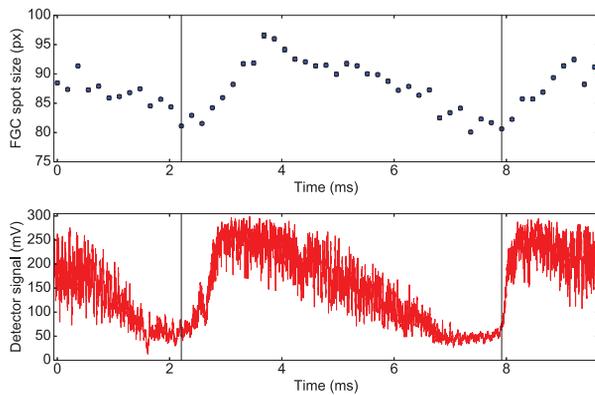


Figure 1: Horizontal bunch size recorded using the FGC with a gate separation of 500 turns (top) and the synchronously measured CSR signal recorded using a Schottky diode (bottom). The horizontal bunch size (and thus the energy spread) have the same modulation period as the CSR, as indicated by the thin vertical black lines.

Beam parameters:

$$f_s: 8.1 \text{ kHz}, V_{RF}: 1500 \text{ kV}, I_{\text{bunch}}: 0.88 \text{ mA}.$$

phase steps, as the signatures of such a step can be measured by all systems covered by the scheme. This allows us to assign a turn to each data point recorded with the various systems [13]. This calibration is especially important for the FGC as this setup requires a certain preparation time for each measurement. While the gate separation between two consecutive FGC spots is constant the *global* phase is a parameter to be defined by the calibration. For this calibration a systematic error for the FGC of 6 turns ( $\sim 2.2 \mu\text{s}$ ) is assumed.

## MEASUREMENTS

### CSR and Energy Spread

The fully synchronised setups allow us to study the evolution of the horizontal bunch size (and thus the energy spread) and the CSR intensity in parallel. Such a measurement is shown in Fig. 1. At the onset of the burst the energy spread starts to increase up to a level where damping effects start to become dominant. This leads to a shrinking of the energy spread until a certain lower limit is reached. At this point the next bunch is blown up again coupled to the onset of the next burst.

A second example for different machine parameter settings (different  $\alpha_c$  and bunch current) is shown in Fig. 2. Again the energy spread and the CSR intensity show the same modulation period. In this case, the CSR intensity starts to increase while the energy spread is still decreasing. This can be explained by the effect of the overall bunch size, which is still small enough to partly emit coherently even without sub-structures. This shrinking lasts until the onset of the next burst.

Numerical studies using the Vlasov-Fokker-Planck solver Inovesa [14] support this view. They show an abrupt increase

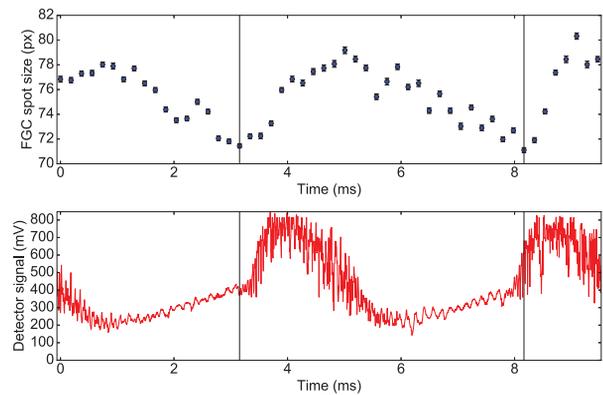


Figure 2: Horizontal bunch size recorded using the FGC with a gate separation of 504 turns (top) and the synchronously measured CSR signal recorded using a Schottky diode (bottom). The two curves have the same modulation period length, as indicated by the thin vertical black lines. In this case the CSR intensity starts to increase again while the energy spread is decreasing due to the reduction of bunch size.

Beam parameters:

$$f_s: 6.9 \text{ kHz}, V_{RF}: 1500 \text{ kV}, I_{\text{bunch}}: 0.25 \text{ mA}.$$

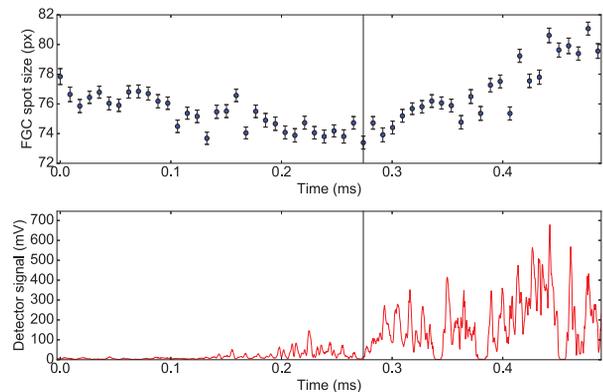


Figure 3: Horizontal bunch size from the FGC recorded with a gate separation of 24 turns to achieve a good timing resolution (top) and the corresponding CSR intensity (bottom) sampled with a narrowband Schottky barrier diode. The thin black line shows the coincidence of the onset of the CSR burst with the point of minimum bunch size and thus energy spread. The error bars for the spot size are large compared to the ones in Fig. 2 due to the lower amplification of the MCP leading to less counts on the CCD.

Beam parameters:

$$f_s: 13.35 \text{ kHz}, V_{RF}: 1500 \text{ kV}, I_{\text{bunch}}: 1.57 \text{ mA}.$$

in the amplitude of the sub-structures when the shrinking of the energy spread reaches the critical level – leading to the onset of the next burst [15].

By choosing a higher gate repetition rate it is possible to study the dynamics at the onset of the burst in more detail (see Fig. 3). Here a time range of  $500 \mu\text{s}$  was chosen with

a gate separation of 24 turns. At the beginning the energy spread shows a slight decrease while the CSR intensity is almost zero. At  $t=0.14$  ms the CSR intensity for the wavelength of the used Schottky diode (200 - 300 GHz) starts to increase slightly. This is a signature for the occurrence of sub-structures on the bunch profile but they are too small in amplitude to lead to an overall increase of the bunch size so it is still shrinking due to damping effects. At  $t=0.28$  ms the bunch size and thus the energy spread has reached a minimum value and an abrupt increase of CSR intensity can be observed coupled to a strong increase of the energy spread.

The examples shown here demonstrate the potential of the fully synchronized setups but also the drawback of the FGC setup. It only allows a certain number of data points so one has to choose between a good timing resolution or the ability to study the dynamics on longer time scales in the order of milliseconds.

### Bursting Threshold

In the previous subsection we showed three examples of synchronized energy spread and CSR measurements revealing a modulation of the energy spread. For the average horizontal bunch size we observe an increase with beam current (see Fig. 4). For bunch currents below the bursting threshold (calculated according to [16]) the horizontal bunch size remains constant. There the equilibrium between quantum excitation and synchrotron radiation damping leads to a constant (*natural*) energy spread. This observation confirms that using the setup described above, we are able to study the energy spread also for these bunch currents.

## SUMMARY AND OUTLOOK

Using a fast-gated intensified camera and fast THz detectors integrated in a synchronisation scheme allows further

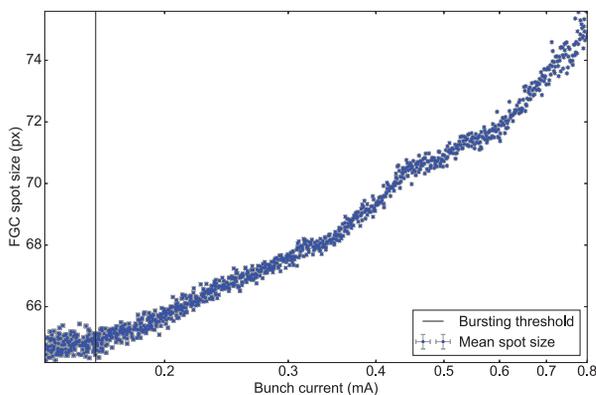


Figure 4: Average horizontal bunch size (averaged over each FGC image) plotted over bunch current with the bursting threshold calculated according to [16]. Below the bursting threshold the bunch size and thus the energy spread remains constant while it increases continuously for increasing bunch currents.

Beam parameters:  $f_s$ : 10.8 kHz,  $V_{RF}$ : 1500 kV

insight into beam dynamics in the ANKA short-bunch mode. We could show that the energy spread and the CSR intensity undergo fluctuations with the same period length. We could also show that the mean energy spread starts to increase for bunch currents above the bursting threshold. To overcome the limited number of data points and the minimum gate separation of the existing FGC setup an upgrade is planned by using a KALYPSO based system [17] for turn-by-turn imaging of the horizontal bunch profile.

## ACKNOWLEDGEMENTS

We would like to thank Anton Plech, Yves-Laurent Mathis and the ANKA IR-group for their support. We also thank Tobias Boltz for providing results of numerical studies on the longitudinal phase space evolution during the bursts.

This work has been supported by the Initiative and Networking Fund of the Helmholtz Association under contract number VH-NG-320 and by the BMBF under contract number 05K13VKA. Miriam Brosi, Patrik Schönfeldt and Johannes Steinmann acknowledge the support of the Helmholtz International Research School for Teratronics (HIRST) and Edmund Blomley the support of the Karlsruhe School of Elementary Particle and Astroparticle Physics (KSETA).

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