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TURN-BY-TURN MEASUREMENTS OF THE ENERGY SPREAD AT NEGATIVE MOMENTUM COMPACTION FACTOR AT KARA

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Abstract

The Karlsruhe Research Accelerator (KARA), the storage ring at KIT, allows short electron bunch operation with positive as well as negative momentum compaction factor. For both cases, the beam dynamics are studied. Using a line array camera KALYPSO (KArlsruhe Linear arraY detector for MHz rePetition rate SpectrOscopy), based on TI-LGAD, the horizontal intensity distribution of the emitted visible part of the synchrotron radiation is measured at a 5-degree port of a bending magnet on a turn-by-turn time scale. As the measurement is located at a dispersive section, the dynamics of the energy spread can be studied by measuring the horizontal bunch profile. The MHz acquisition rate and the low-light sensitivity of the line camera allow measurements at low bunch currents and the investigation of the microbunching instability. This contribution presents the results of the bunch profile measurements performed at positive and negative momentum compaction factor.

INTRODUCTION

The microbunching instability is a longitudinal single-bunch instability, which occurs above a certain current threshold depending on the bunch length. The microbunching instability does not lead to an immediate beam loss due to a self-stabilising effect. Above the threshold the bunch is continuously changing. The instability manifests itself in form of dynamic changes to the longitudinal charge distribution and leads to sawtooth-like dynamics of beam parameters like energy spread and bunch length. Therefore, this instability presents an important limitation on the bunch current for stable beam operation with short electron bunches [1].

To study this instability a bunch current above the threshold current during short bunch operation is required. The KIT storage ring KARA provides different operation modes such as a short bunch mode. This mode is available with positive as well as negative momentum compaction factors and allows the investigation of the microbunching instability in both operating modes [2].

In the following, the operation with a negative momentum compaction factor and the microbunching instability is introduced, followed by a brief overview of the experimental setup. Finally, the measured results are presented.

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NEGATIVE MOMENTUM COMPACTION FACTOR

Typically, electron storage rings operate with a positive momentum compaction factor. This factor is also related to the bunch length, so for the short-bunch mode, the absolute value of the momentum compaction factor is reduced. The momentum compaction is defined by the following equation:

$$\alpha_c = \frac{1}{L} \oint \frac{D_x(s)}{\rho(s)} \mathrm{d}s, \qquad (1)$$

where L denotes the circumference of the storage ring, $D_x(s)$ is the horizontal dispersion and $\rho(s)$ is the bending radius along the beam path. By changing the optics, especially the strength of one family of quadrupole magnets, the dispersion can be stretched and take on negative values in some places. These negative contributions reduce the integral in Eq. 1, thus the linear momentum compaction factor is reduced and can also take on negative values [2].

MICROBUNCHING INSTABILITY

The microbunching instability occurs due to the self-interaction of an electron bunch with the coherent synchrotron radiation (CSR) emitted by the bunch itself. The emitted synchrotron radiation covers a broad spectrum. In a specific range between the size of the emitting structure and an upper limit the coherent amplification of the emission of radiation occurs. The upper limit of the wavelength is approximately determined by the parallel plate shielding, which suppresses longer wavelengths, and depends on the dimensions of the vacuum pipe. Due to the bent path of the electrons in a bending magnet, the emitted CSR can lead to an interaction in forward direction. The CSR creates a wake potential, which acts back on the bunch and changes the charge distribution in the electron bunch [3]. Above a certain charge density, the self-interaction leads to the formation of substructures in the longitudinal phase space. A common way to visualise the dynamics of the microbunching instability is the so-called spectrogram. For this, the measurements of temporal fluctuations in the emitted CSR are Fourier transformed. A spectrogram is reproducible and a fingerprint of the current machine settings, mainly energy, RF voltage and momentum compaction factor. At high bunch currents, additional slower dynamics occur, which is visible in the spectrogram, shown in Fig. 1. These dynamics are the sawtooth-like bursts and their repetition frequency, which appear in the spectrogram. For the investigation, different parameters such as the bunch length, the intensity of

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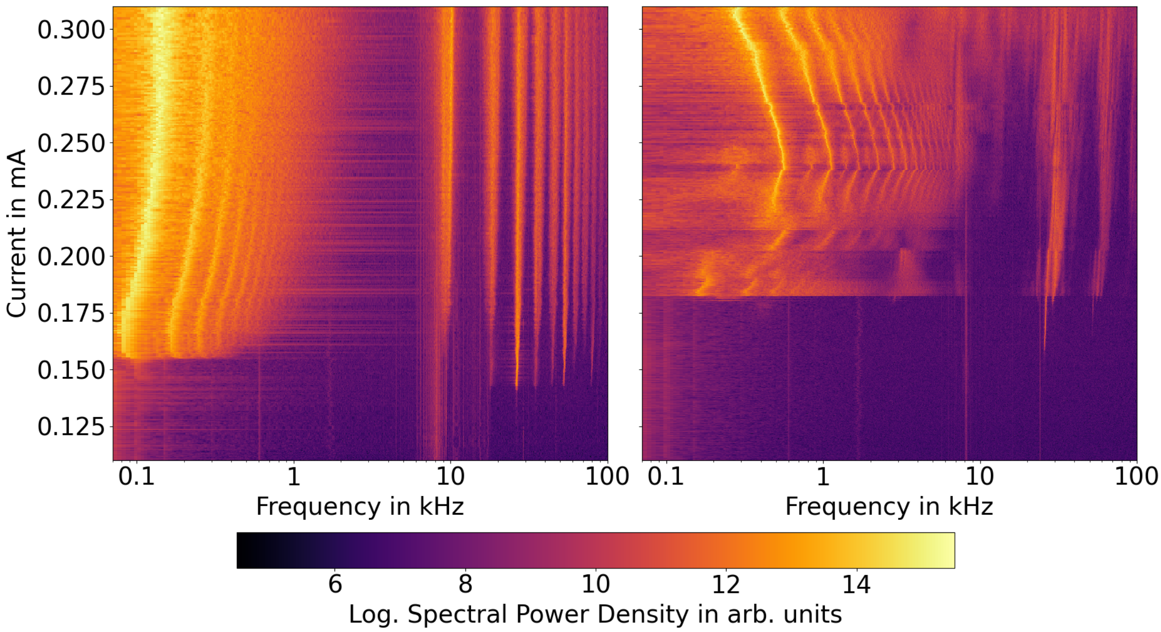

Figure 1: Two spectrograms for THz emission at the same absolute momentum compaction factor (left: negative, right: positive) with logarithmic frequency axis. Visible are the low frequencies corresponding to the bursts repetition frequency and the high frequencies corresponding to the sub-structures rotating in phase space.

CSR emission and the energy spread can be used [4, 6]. The dynamics in longitudinal phase space differ for positive and negative momentum compaction factors, since e.g. the orientation of rotation in longitudinal phase space is opposite. A different behaviour of the microbunching instability for positive and negative momentum compaction factors was observed in measurements [5].

EXPERIMENTAL SETUP

The aim of this work is the investigation of the microbunching instability at positive and negative momentum compaction factors. To receive comparable results, the same absolute value for the momentum compaction factor and the same RF voltage are used for the measurements. For the measurement, two different systems, a detector KALYPSO and a Schottky diode coupled with KAPTURE are employed [7, 8]. With these systems, the horizontal bunch profile and the intensity of the emitted CSR are measured on a turn-by-turn timescale. In previous experiments, only THz radiation was measured [5]. In this experiment, the goal is synchronous measurement with different detector systems. The horizontal bunch size is described by the following equation:

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

Here, σ_x is the horizontal bunch size, σ_δ is the relative energy spread, ϵ_x is the horizontal emittance, $\beta_x(s)$ is the beta function and $D_x(s)$ describes the horizontal dispersion. The measurement is carried out at one position in a dispersive region of the storage ring and at constant electron energy, therefore the emittance as well as the beta function and the dispersion are considered to be constant during the measurement. It follows that a change in the bunch size is due to a change in the relative energy spread. This allows the measurement of the evolution of the energy spread by measuring the horizontal bunch profile [9].

KALYPSO

The KALYPSO detector is employed for turn-by-turn measurements of the horizontal bunch profile [8]. The used KALYPSO detector, based on TI-LGAD [10], features a high sensitivity which allows measurements at small bunch currents down to 4.3 pC (at KARA 12 µA), which is one order of magnitude smaller than the threshold current of the microbunching instability for the used machine parameters. Hence, measurements of the bunch profile even below the threshold current are possible [11].

In this experiment, KALYPSO is employed to detect the visible part of the incoherent synchrotron radiation at a five-degree port of a bending magnet. The linear detector array measures the horizontal bunch profile, the position and the bunch size are extracted from these data.

KAPTURE

The second readout system uses the visible part and the THz radiation of the edge radiation of a bending magnet at one of KARA's infrared beamlines. The KArlsruhe Pulse Taking Ultra-fast Readout Electronics (KAPTURE) system is an in-house developed fast digitizer for experiments generating a high data throughput [7]. The visible part of the light is measured using a fast photodiode, and a Schottky barrier diode detector (SBD-Detector) is used for the detection of the emitted THz radiation [12].

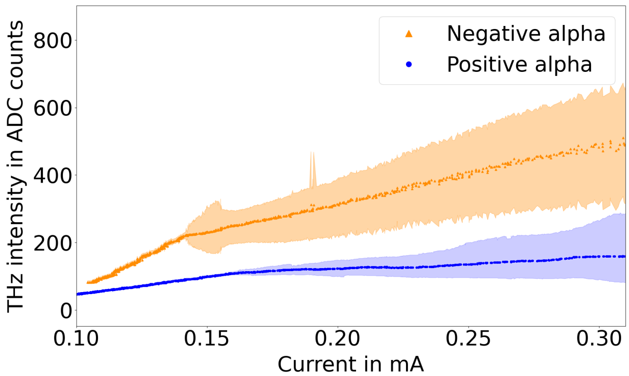

Figure 2: Averaged terahertz emission at positive and negative momentum compaction factor. The 1σ-interval of the THz emission is shown as a coloured area.

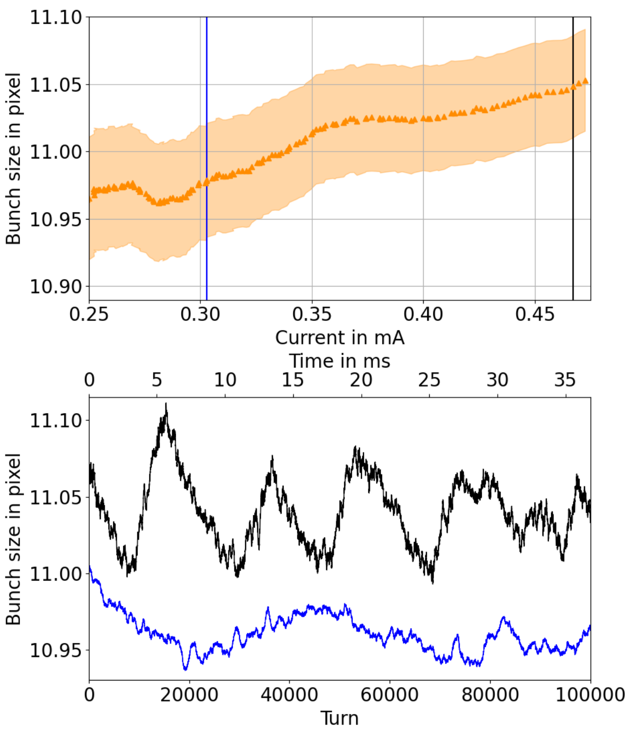

Figure 3: Current dependence of the bunch size and energy spread with respect to the bunch current for negative momentum compaction factor (upper part). For two selected currents, marked as vertical lines, the bunch size is shown as a function of time (lower part).

MEASUREMENTS

The THz signal is well suited for the analysis of the microbunching instability due to the significant increase of the emitted THz power during the bursting. Figure 1 shows two spectrograms, generated from the THz intensity measurements, recorded with the KAPTURE readout system. The left spectrogram is calculated based on a measurement with a negative momentum compaction factor, and the right one is based on a measurement with a positive momentum compaction factor. The bursting threshold is lower for negative alpha and there is also a difference at the lower bursting frequencies up to several kHz, these bursting frequencies are significantly lower for negative alpha. At higher frequencies, there appear more higher harmonics of the synchrotron frequency at negative momentum compaction factor.

Besides the spectrogram, the current dependence of the average THz emission, as well as the standard deviation of the THz signal, can be calculated and the result is shown in Fig. 2. With the negative momentum compaction factor, the THz emission is higher and increases faster. A significant increase in the standard deviation of the THz emission occurs above the bursting threshold for the experiments with negative momentum compaction factor. The reason is the bursting, which leads to strong temporal fluctuation of the THz emission. In the case of the measurement with a positive momentum compaction factor, there is also an increase of the standard deviation of the THz emission visible, but not as significant as for the measurements with a negative momentum compaction factor. The mentioned differences between positive and negative momentum compaction factors were previously already observed and published in [5].

Figure 3 in the upper part shows the current dependence of the average horizontal bunch size for a negative momentum compaction factor. The standard deviation is added as a coloured highlighted area. The bunch size increases with the bunch current. The two selected bunch currents correspond to four and six times the bursting threshold, respectively. Especially with the higher bunch current, the sawtooth structure can be seen in the time evolution of the bunch size. The amplitude of the fluctuations decreases with the bunch current. Therefore, it is smaller for the lower bunch current. From the spectrogram, shown in Fig. 1, it can be seen that the bursting repetition rate decreases with the current.

CONCLUSION

Both KALYPSO and KAPTURE systems are well suited for the investigation of the microbunching instability and allow the measurement of the fluctuations of the THz emission and the energy spread on a turn-by-turn timescale. A clear difference can be observed between the microbunching instability at positive and negative momentum compaction factors. The instability starts for negative momentum compaction factor at a lower threshold current and has a higher THz emission. The lower bursting frequencies are in case of positive momentum compaction higher.

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