STUDIES OF BUNCH-BUNCH INTERACTIONS IN THE ANKA STORAGE RING WITH COHERENT SYNCHROTRON RADIATION USING AN ULTRA-FAST TERAHERTZ DETECTION SYSTEM*

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Abstract

In the low-alpha operation mode of the ANKA synchrotron light source, coherent synchrotron radiation (CSR) is emitted from short electron bunches. Depending on the bunch current, the radiation shows bursts of high intensity. These bursts of high intensity THz radiation display a time evolution which can be observed only on long time scales with respect to the revolution period. In addition, long range wake fields can introduce a correlation between the bunches within a bunch train and thus modify the observed behaviour. A novel detection system consisting of an ultra-fast superconducting THz detector and data acquisition system was used to investigate correlations visible on the bursting pattern and to study the interactions of very short pulses in the ANKA storage ring.

INTRODUCTION

At the ANKA storage ring, a special user operation mode with short bunches that emit coherent synchrotron radiation (CSR) in the far infrared is offered on regular basis since 2004 [1]. In the course of a constant optimisation process to better adapt to the needs of the user community, continuous studies with CSR are needed to further the understanding of the underlying accelerator physics. This usually involves a substantial effort in long term data taking. With the new, ultra-fast detection system used for the studies presented in this paper, however, the process is substantially simplified and accelerated. Online analyses and parameter tuning are now well within reach. A very important aspect of these studies is the analysis of the temporal behaviour of the emission of bursting coherent synchrotron radiation (CSR) above the micro bunching instability threshold [2, 3]. In previous measurements, clear indication for a correlation between adjacent bunches has been observed [4]. This could be caused, for example, by the presence of long range longitudinal wake fields as indicated in earlier studies [5]. Numerical studies also confirmed the influence of one bunch on the bursting dynamics of a second bunch [6].

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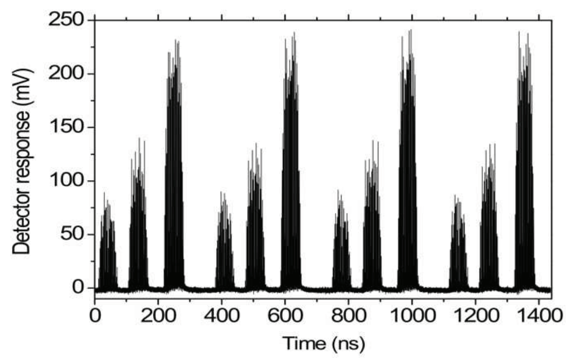

Figure 1: Consecutive turns of an inhomogeneous filling pattern consisting of three trains filled with 33 bunches each monitored with the YBCO THz detector.

DETECTOR AND DATA ACQUISITION SYSTEM

For the studies presented in this paper, several detector systems were used. One such system, the Hot Electron Bolometer (HEB), which has been described in detail elsewhere [7] is a detector system based on a superconducting NbN ultra-fast bolometer [8] with an intrinsic response time of 100 ps to resolve radiation from single bunches. It is sensitive in the spectral range from 10 to 150 cm^{-1} (0.3 to 4.5 THz) [9].

Recently, a breakthrough with respect to response times was achieved with a system based on the high-temperature superconductor $YBa_2Cu_3O_{7-\delta}$ (YBCO) due to a very fast electron energy relaxation time of the order of single picoseconds. The new THz detection system allows to monitors the CSR THz pulses directly in the time domain. The THz detector operates at high critical temperatures ($T_C \approx 84\,K$) in a cryogen-free cooling system which is operated fully automatically. Fig. 1 shows the YBCO detector response to the ANKA synchrotron radiation in the THz frequency range in the low-α_c mode (1.3GeV). The filling pattern with three trains consisting of 33 bunches with a repetition rate of 2.7MHz is clearly visible. Due to a very broad dynamic range of the YBCO THz detector of more than 30dB [10] the detector response scales linearly with the input THz power, thus recording the increase of emitted THz power from the first to the third train.

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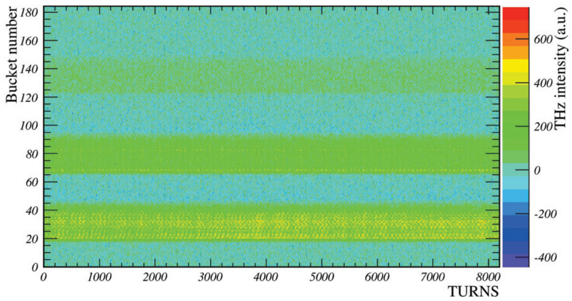

Figure 2: THz signals measured with the HEB detector system and the fast DAQ for $f_s = 6.25$ kHz and calculated bunch length at zero current of about 3.7 ps. The 3 trains were filled to cover a wide range of bunch currents (see Fig. 1) with some bunches above and some below the bursting threshold around 0.146 mA.

A novel real-time and high accuracy data acquisition systems complements the experimental setup. The system is described in detail in [11]. This system allows the quasi-instantaneous recording of THz signals from all 184 buckets in the ANKA storage ring for many consecutive revolutions. The first version of the electronics can acquire data in blocks of roughly 10000 turns. Figure 2 shows an example for a dataset acquired with this system. Knowing the current distribution over the bunches, it is thus possible to determine the threshold for bursting emission with a single data block (see Fig. 3). With the new detection and acquisition setup it is also possible to analyse each bunch in a multi-bunch filling pattern individually as shown in Fig. 4.

BURSTING INSTABILITY AT LOW CURRENT

In single bunch studies, the HEB detector system was used to study the temporal behaviour of the emission of synchrotron radiation down to very low single bunch currents. From Fig. 5 the well-established threshold for the transition from bursting to steady state emission of CSR [2, 3] can be seen to occur at a current of about 60 μA

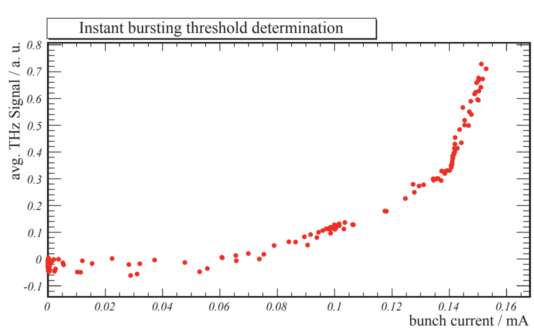

Figure 3: Quasi-instantaneous determination of the bursting threshold based on the dataset displayed in Fig. 2. The observed threshold is slightly below the prediction of 0.146 mA. This shift which might caused by the above mentioned long range wake field interactions.

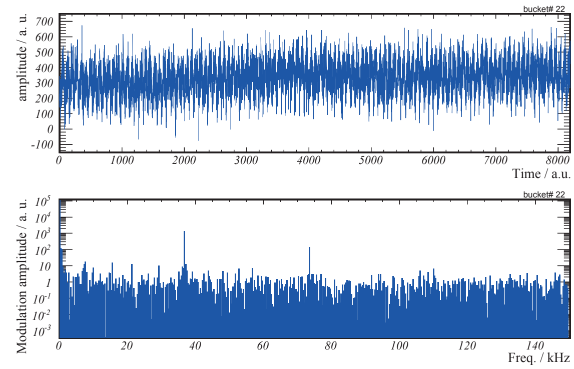

Figure 4: Example of an 'extracted' analysis on bucket No. 22 of the dataset displayed in Fig. 2. The upper plot shows the temporal evolution of the THz signal, the lower plot the corresponding frequency spectrum. The latter displays prominent lines at 2 and 5 f_s.

which is in excellent agreement with the calculated threshold value. At very low currents, around 44 μA, another transition into bursting emission is observed. This could be the instability described in the bunched beam theory [12]. In this work, a local reduction of the threshold current for bursting instability is predicted for a shielding parameter of $\chi = \sigma_z b\sqrt{\rho b} = 0.25$ where ρ is the bending radius, b the vacuum chamber height, and σ_z the bunch length at zero current. For the ANKA storage ring this corresponds to a bunch length of 2.02 ps. The bunch length at zero current for the data presented in Fig. 5 is 2.0 ps, the bunch length extrapolated from streak camera measurements for the onset of the low current bursting is (2.4 ± 0.5) ps and therefore in excellent agreement with the theoretical prediction.

BUNCH-BUNCH CORRELATIONS

With the high data acquisition rates provided by the new DAQ system, a completely different type of analysis becomes possible for the first time: In order to verify the existence of long range interactions, for example caused

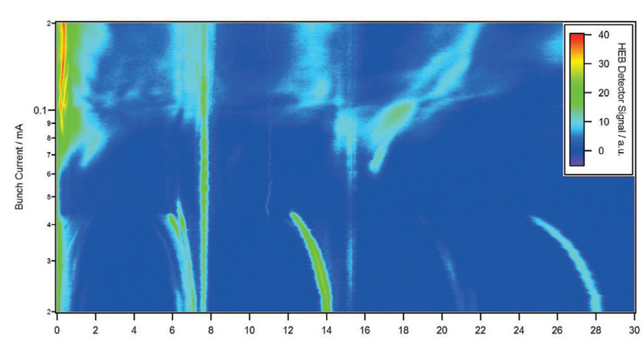

Figure 5: Spectrogram of the turn-by-turn THz signal measured with the HEB detector system as a function of the single bunch current with $f_s = 7.8$ kHz. The frequencies prominently involved in the bursting emission of CSR are clearly seen.

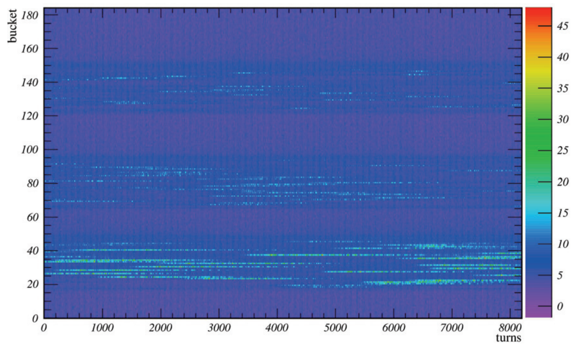

Figure 6: Quasi-simultaneous measurement of THz signals from all bunches measured with the YBCO detector system and the fast DAQ for $f_s = 10.2\,\text{kHz}$. The bursting signature is clearly visible in all three trains.

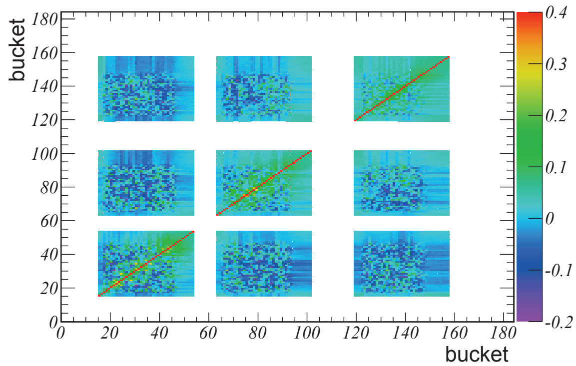

Figure 7: Matrix of correlation coefficients obtained according to Eq.(1) from 17 consecutive datasets similar to the data shown in Fig. 6.

by long range wake fields acting on following bunches, a statistical correlation analysis can be performed. The correlation coefficient between two buckets x and y is given by

$$\rho(x,y) = \frac{\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{N}(x_i - \bar{x})^2 \cdot \sum_{i=1}^{N}(y_i - \bar{y})^2}} \tag{1}$$

where N is the number of acquired revolutions. The average correlation coefficient as a function of the distance between bunches is a convenient means to quantify the amount of inter-bunch correlation.

To study the influence of the bursting on the bunch-bunch correlation, it is particularly interesting to analyse datasets with all bunches above the bursting threshold (see Fig. 6). 17 consecutive such datasets were used to obtain the matrix of correlation coefficients displayed in Fig. 7. The symmetry of the $\rho(x, y)$ is clearly visible. The average correlation coefficient as a function of the distance between bunches for the same measurements finally are shown in Fig. 8. The data exhibit a clear, albeit small, correlation, decreasing with distance from the generating bucket in accordance with earlier, indirect, observations by other methods. The presence of long range wake fields in the ANKA storage ring is also confirmed by recent measurements with electro-optic methods [13, 14].

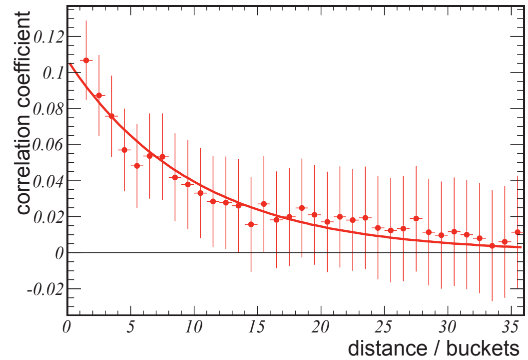

Figure 8: Correlation coefficients as a function of the distance between the analysed buckets. A clear, albeit small, correlation, decreasing with distance from the generating bucket, is observed. The curve is a fit of an exponential to the coefficients to guide the eye.

SUMMARY

The detection system consisting of an ultra-fast superconducting THz detector and data acquisition system provides new possibilities for the study of the dynamics of short bunches and CSR emission. Studies with a first version of the readout electronics allowed to confirm the existence of long range correlations between bunches of one train. Furthermore, a sensitive THz detection system was used to study the temporal behaviour of CSR emission at very low currents. A bursting instability was observed in excellent agreement with theoretical predications.

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