SYSTEMATIC STUDIES OF SHORT BUNCH-LENGTH BURSTING AT ANKA

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Abstract

At ANKA, the Karlsruhe synchrotron radiation source, the so called short bunch-length operation mode allows the reduction of the bunch length down to a few picoseconds. The micro-bunching instability resulting from the high degree of longitudinal compression leads to fluctuations in the emitted intensity in the THz regime, referred to as bursting. For extremely compressed bunches at ANKA bursting also occurs, in a certain current range, below the main bursting threshold. This contribution shows measurements of this short bunch-length bursting and makes first comparisons with theory.

INTRODUCTION

ANKA is a synchrotron radiation source located in Karlsruhe, Germany, and is operated by the Karlsruhe Institute of Technology. A special short-bunch operation mode at 1.3 GeV allows the reduction of the momentum compaction factor and therefore reduces the electron bunch length down to a few picoseconds. The bunch-by-bunch feedback system [1] provides custom filling patterns from a single bunch to complex multi-bunch filling patterns.

In the short-bunch operation mode the effect of coherent synchrotron radiation (CSR) plays an important role in the beam dynamics. CSR is emitted for wavelengths in the order of or longer than the emitting structure. The compressed bunch length of a few picoseconds leads to the emission of CSR in the low THz frequency range connected to a modulation of the longitudinal phase space due to the CSR impedance. This modulation manifests in substructures in the longitudinal particle distribution and is therefore called micro-bunching [2]. The changing substructures lead to strong fluctuations of the emitted power in the THz range, often referred to as bursts of THz radiation, while the whole effect is called bursting. The bunch current above which this phenomenon occurs is called bursting threshold and depends strongly on the natural bunch length and therefore on various machine parameters [3].

At ANKA as well as at MLS [4] a second region of bursting was observed for very short bunches below the main bursting threshold. This instability is referred to as short bunch-length bursting (SBB) in the following.

THEORETICAL DESCRIPTION

The interaction of the electrons inside an electron bunch with their emitted CSR radiation leading to the micro-bunching instability can be described using the Vlasov-Fokker-Plank equation [2]. The result depends on how the influence of the conductive beam pipe is taken into account as boundary conditions for the emitted electromagnetic field. The model, to which the measurements in this contribution will be compared, considers the influence of the beam pipe as a pair of parallel plates with a distance of $2h$. The resulting equation for the threshold of the instability was published in 2010 by Bane, Stupakov and Cai [3]. Using the dimensionless parameters S_{CSR}, the CSR strength, and Π, the shielding parameter, the threshold is described by:

$$(S_{\mathrm{CSR}})_{\mathrm{th}} = 0.5 + 0.12\,\Pi \tag{1}$$

$$\text{with } \Pi = \frac{\sigma_{z,0} R^{1/2}}{h^{3/2}} \tag{2}$$

$$\text{and } S_{\mathrm{CSR}} = \frac{I_{\mathrm{n}} R^{1/3}}{\sigma_{z,0}^{4/3}} \tag{3}$$

where $\sigma_{z,0}$ is the natural bunch length, R the bending radius, h half of the spacing between the parallel plates and I_{n} the normalized current:

$$I_{\mathrm{n}} = \frac{r_{\mathrm{e}} N_{\mathrm{b}}}{2\pi \nu_{s,0} \gamma \sigma_{\delta,0}} = \frac{I_{\mathrm{b}} \sigma_{z,0}}{\gamma \alpha_{\mathrm{c}} \sigma_{\delta,0}^2 I_{\mathrm{A}}}$$

with N_{b} the number of electrons, I_{b} the bunch current, r_{e} the classical electron radius, $\nu_{s,0}$ the nominal synchrotron tune, $\sigma_{\delta,0}$ the nominal energy spread, α_{c} the momentum compaction factor, γ the Lorentz factor and I_{A} the Alfvén current[1].

Equation (1) was obtained by implementing a Vlasov-Fokker-Plank (VFP) solver, which numerically solves the VFP equation using an algorithm established by Warnock and Ellison [5]. Equation (1) is the result of a linear fit to the linear distribution of the thresholds $(S_{\mathrm{CSR}})_{\mathrm{th}}$ from the simulation when displayed as a function of Π. The equation neglects a dip in the simulated thresholds at a value of the shielding parameter of $\Pi \approx 0.7$. A closer look in [3] at the simulated energy spread revealed an unstable region with a smaller threshold than expected by Eq. (1) and a stable region above it before another region of instability starts at a threshold described by Eq. (1).

MEASUREMENT PRINCIPLE

For the measurements in this paper we used a broad-band quasi-optical Schottky barrier diode from ACST [6], which is operated at room temperature. To detect the fluctuations

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[1] Alfvén current $I_{\mathrm{A}} = 4\pi\varepsilon_0 m_{\mathrm{e}} c^3/e = 17\,045$ A

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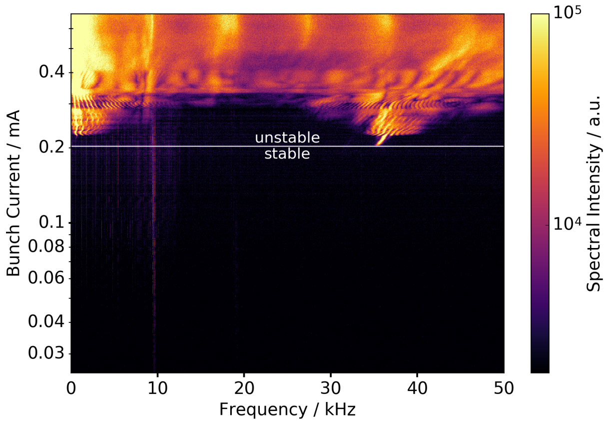

Figure 1: This spectrogram of the fluctuations of the THz intensity as a function of the decaying bunch current shows the micro-bunching instability. It was obtained with a several hours lasting measurement while the bunch current decreased. No short bunch-length bursting occurs, because the bunch was not compressed strongly enough.

in the emitted THz radiation for each bunch in a multi-bunch filling pattern individually, the fast detector was combined with the ultra-fast DAQ system KAPTURE [7]. The KArlsruhe Pulse Taking and Ultrafast Readout Electronics (KAPTURE) system samples the detector response to the THz pulse of each bunch at four points [8]. In principle KAPTURE can sample the signal continuously with a global rate of the RF frequency of ANKA (≈ 500 MHz). For this publication, the signal was recorded simultaneously for every bunch at every 10th revolution for a period of one second, to limit the acquired data volume.

The so called snapshot measurement technique was used to decrease the time necessary for measuring the bunch current dependence of the behavior of the instability: The combination of a custom filling pattern and a data acquisition system which allows the measurement of the THz signal of each bunch individually allows a reduction of the measurement time down to a second [9].

SHORT BUNCH-LENGTH BURSTING

Figure 1 shows the characteristic patterns of the fluctuation frequencies of the emitted THz radiation for different bunch currents. The instability passes different regimes at different bunch currents and ends at the bursting threshold (in Fig. 1 at ≈ 0.2 mA).

For most machine settings the beam is stable for all currents below the bursting threshold (compare Fig. 1). Nevertheless, observations at ANKA show that for magnet optics with a momentum compaction factor $\alpha_c \leq 2.64 \times 10^{-4}$ combined with high RF voltages leading to a natural bunch length $\sigma_{z,0} \leq 0.723\,\text{mm} \,\hat{=}\, 2.43\,\text{ps}$, an instability occurs again for bunch currents below the main bursting threshold (see Fig. 2). The spectrogram shown in Fig. 2 was obtained by a snapshot measurement within one second. To compensate for the limited current resolution of this measurement method the filling pattern was chosen in such a way that the region of interest corresponding to small currents is sampled with a sufficient resolution. This is visible in the limited bunch current resolution in the upper part of Fig. 2. The figure shows the lower bound of the main bursting and the complete occurrence of the short-bunch length bursting. This second region of instability occurs in a bunch current range from 0.038 mA down to 0.016 mA.

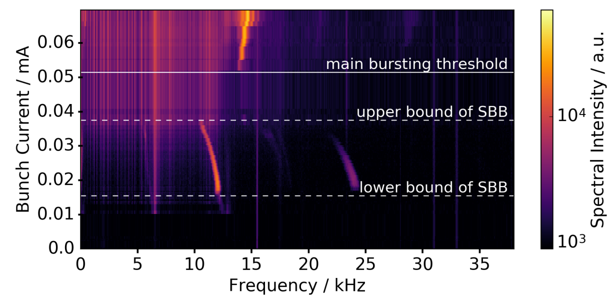

Figure 2: Spectrogram of the fluctuations of the THz intensity as a function of bunch current for a synchrotron frequency of 6.55 kHz. A second unstable region is clearly visible between 0.038 mA and 0.016 mA, below the end of the micro-bunching instability (main bursting threshold) around 0.052 mA. The limited number of current bins were distributed in a way that gives a high bunch current resolution in the region of the short bunch-length bursting.

The frequencies of the intensity fluctuations are located below twice the synchrotron frequency ($2 \times f_s = 2 \times 6.55$ kHz in Fig. 2) and approach this frequency with decreasing bunch current. A frequency line at the first harmonic of the intensity fluctuation is visible (below $4 \times f_s$).

RESULTS AND COMPARISON WITH THEORY

Snapshot measurements of the lower current range, similar to Fig. 2, were taken for different values of the momentum compaction factor and the natural bunch length by changing the magnet optics as well as the RF voltage.

The bunch currents at the lower and upper bound of the short bunch-length bursting as well as the main bursting threshold for each measurement are displayed in Fig. 3 using the dimensionless parameters S_{CSR} and Π (Eqs. (2) and (3)) following the notation of [3].

Additionally, bursting thresholds measured at machine settings, where no short bunch-length bursting occurs [10], show that the main bursting threshold is described by Eq. (1) and is independent of the occurrence of short bunch-length bursting.

The biggest value of the shielding parameter Π where the short bunch-length bursting occurs at ANKA (right-most red square in Fig. 3) is $\Pi_{\text{SBB}} = 0.845 \pm 0.013$. The smallest value of the shielding parameter where the short bunch-length bursting does not occur (left-most greed diamond in

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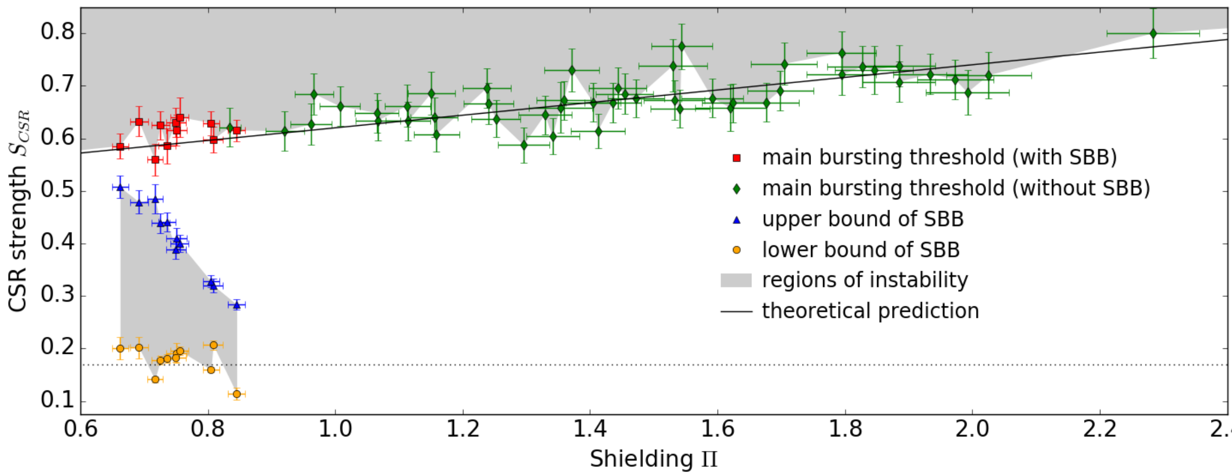

Figure 3: CSR strength vs. shielding for measurements at different machine parameters as well as the prediction (lines). The lower bound (orange discs) as well as the upper bound (blue triangles) of the short bunch-length bursting are shown. The dotted horizontal line indicates the value for the lower bound of the unstable region of the short bunch-length bursting given by the simulation. The main bursting threshold is shown in red (squares) for machine settings where short bunch-length bursting occurred and in green (diamond) for settings where it did not occur. The error bars display the standard deviation error.

Fig. 3) is at $\Pi_{\text{no SBB}} = 0.835 \pm 0.017$, and therefore smaller than Π_{SBB}. This is not expected but might occur due to non-linear effects in the optics when the magnet optics is changed, as the two values ($\Pi_{\text{no SBB}}$ and Π_{SBB}) were obtained at different combinations of momentum compaction factor and RF voltage resulting in similar values of Π. Nevertheless, the limit agrees within the uncertainties with the results obtained by Bane, Stupakov and Cai using the Vlasov-Focker-Plank solver [3]. The authors observed a dip around $\Pi = 0.7$, while the threshold for $\Pi = 1$ is again on the theoretical predicted linear fit given by Eq. (1). Values below $\Pi = 0.66$ were not accessible for our measurements. This gives us no possibility to check if the short bunch-length bursting vanishes for even smaller values of the shielding parameter as predicted in [3].

The onset of this second region of instability was given by the VFP solver at a value for the CSR strength of $S_{\text{CSR}} = 0.17$. Figure 3 shows that the measured values are clustered around this value (dotted line) in agreement with [3].

The fact that the measurements show a stable region between the short bunch-length bursting and the bursting threshold supports the observation of a stable region in the simulated energy spread. For a shielding of $\Pi = 0.7$ the VFP solver gave an upper bound for the second region of instability of $S_{\text{CSR}} = 0.54$. Our measurements give a slightly smaller value of $S_{\text{CSR}} = 0.48 \pm 0.02$ (at $\Pi = 0.7$) for the upper bound. Following the discussion in [3] this small difference between the measurements and the simulation might be explained by differences in the simulated and actual energy spread. This will be studied further and in more detail with future measurements and VFP solver simulations.

SUMMARY

The short bunch-length bursting, observed at ANKA for certain machine settings, corresponds to behavior observed in the results of the VFP solver in [3]. This second region of instability occurs below the bursting threshold of the main micro-bunching instability for values of the shielding parameter below $\Pi = 0.85$. The features and limits agree with the prediction. The difference in the bunch current given by measurement and simulation for the upper bound of the short bunch-length bursting might be explained by a difference in the energy spread for ANKA and the VFP solver.

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