INVESTIGATION OF THE TEMPORAL STRUCTURE OF CSR-BURSTS AT BESSY II*

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Abstract

Bursts of coherent synchrotron radiation (CSR) in the far IR and down to the μ-wave region have been observed in many synchrotron light sources [1]. The time between bursts is long compared to the period of the synchrotron frequency. At BESSY II the temporal fine-structure of these pulses in the THz-region was investigated as a function of current and as a function of the bunch length. It was found, that for a bunch length between 2 and 15 ps the first signs of time dependent CSR appear at frequencies which are generally higher than the zero current synchrotron frequency. The frequency related to the instability increases with the bunch length. Bursts with repetition rates small compared to the synchrotron frequency show up only at higher intensities. These bursts possess still the faster initial temporal structure. They are the result of sawtooth-type longitudinal bunch dynamics related to the mixing of azimuthal modes.

INTRODUCTION

Bursts of CSR are linked to stable coherent radiation if they are identical from one revolution to the next and are as short as the bunchlength. Other repetition rates or a longer duration (folded with the time response of the detector) indicate some kind of longitudinal instability. In order to explain those bursts and their temporal behaviour Venturini et al. have developed a dynamical theory based on the interaction of the bunch with its own coherently created radiation field [2]. Other observations favour geometrical wakes created by the vacuum chamber as the origin of the instability [3].

BESSY is a 3rd generation, high brilliance light source based on a 1.7 GeV electron storage ring. The double bend achromatic lattice can be operated with reduced momentum compaction factor and bunches as short as 1 ps can be produced [1]. Each year the facility is operated with 3 ps long bunches for nearly two weeks. During this time users perform experiments with stable coherent THz-radiation emitted by the static particle distribution within the short bunch or coherent radiation created by bursts at higher current. This application and the still unsettled questions on the origin of these bursts were the motivation for more systematic investigations on this subject.

EXPERIMENTS

At the THz-beamline dedicated for fs-slicing diagnostics [4] radiation down to ~60 GHz was observed with an InSb-detector from QMC which is sensitive up to 1 THz. The amplified AC-output with a signal bandwidth of 1 MHz is acquired in the control room with a digital oscilloscope (5 MHz sampling rate and 10^6 data points) or analyzed directly with a spectrum analyzer under LabView control. Data in the time domain is collected with the help of a Matlab-program which injects a small amount of charge, waits a few seconds, switches off the knock-out generator which is required for achieving a pure single bunch fill pattern, triggers the oscilloscope,

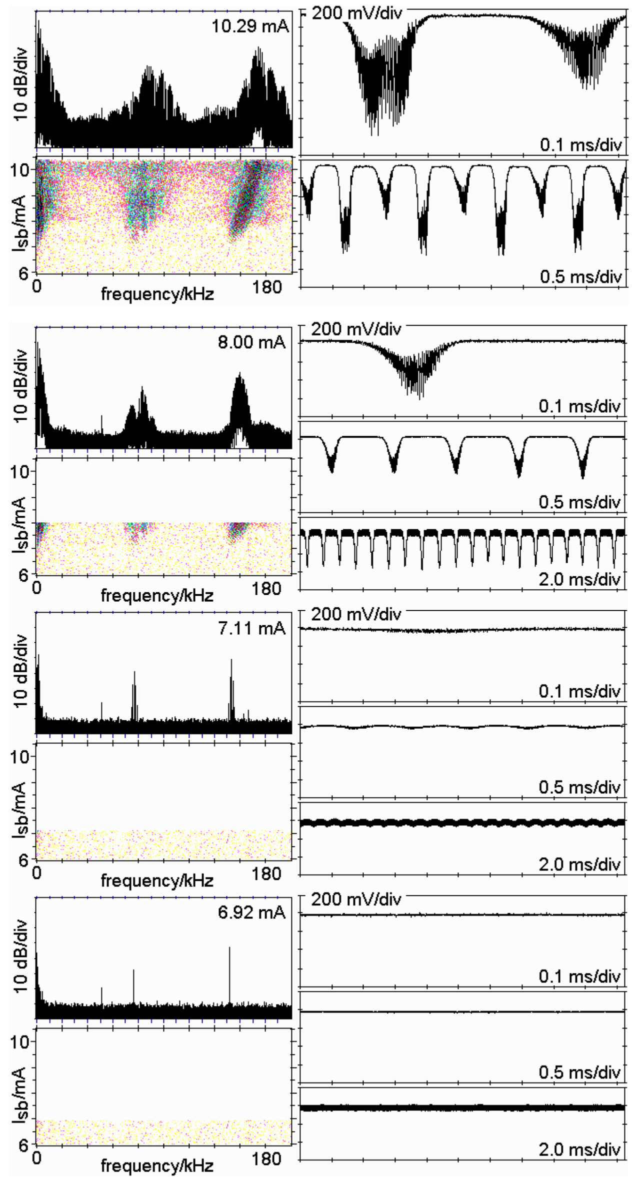

Figure 1: Time dependent CSR-signals for different single bunch currents (right) and the offline Fourier analysed spectra and the related spectral waterfall displays (left). Between 6.92 mA and 6.59 mA spectral lines are visible at multiples of 76 kHz. Below 6.59 mA only the noise related line at 52 kHz survives.

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and waits for the completion of the data transfer between the scope and the PC. The steps are repeated and for each set of collected data the PC reads the current from the standard DCCT with a resolution of 1 μA or from a dedicated monitor with a much better resolution [5]. This is needed for the investigation of short bunches with low threshold currents of the longitudinal instability.

RESULTS

Figure 1 shows a typical result for the normal user operation with four superconducting insertion devices (sc IDs) in operation: a 7T-wiggler, two 7T- and one 4T-wavelength shifters. They lead to a significant increase of the energy spread, the bunch length, and the longitudinal damping. The onset of the instability occurs at 6.59 mA and is only visible in the FFT data of 512 k data points. Signs of the instability are the spectral lines at 76 kHz and 152 kHz (and higher multiples of 76 kHz with decreasing amplitude – not shown here). At 7.11 mA very regular bursts start to show up in the oscilloscope trace and they produce sidebands around zero frequency and the above mentioned spectral lines with a spacing given by the repetition rate of the bursts. With increasing current larger bursts and more and more sidebands appear. The envelope of the sidebands changes and the initial spectral lines shift to higher frequency with increasing bunch current. Looking at the results in frequency domain is obviously easier and more compact than doing it in the time domain. Due to the insufficient single bunch purity of the data shown in Fig. 1 the measured current was too high and thresholds have to be taken with some caution.

Figure 2 shows waterfall displays of the spectrally analysed CSR-signals. This time the data were taken directly with a Rhode and Schwarz spectrum analyser and with all four sc IDs in operation. Instability thresholds are rather high in comparison to the results without the IDs as shown in Fig. 3. In both cases the instability starts with a few single spectral lines. Sidebands appear at higher current and are better resolved now (in the right). The sidebands come from the pulsed and sawtooth-type characteristics of the instability [6], believed to originate from the mixing of nearby azimuthal modes. At around 7 mA the spectra in Fig. 2 show a transition of the most intense cluster of lines around 80 kHz. The next higher azimuthal mode becomes dominant. There are more similar transitions at higher currents. Note the doubling of the sidebands just above 9 mA. It corresponds to the case shown in Fig. 1 with 10.29 mA. At even higher currents

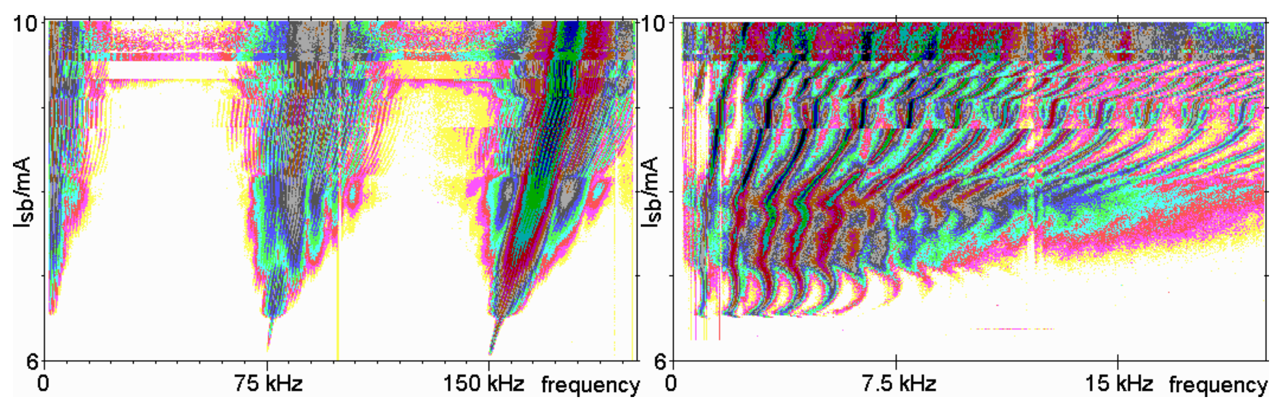

Figure 2: Spectral waterfall displays of the time dependent CSR-signals as a function of the single bunch current. The storage ring was operated with 4 sc IDs. The first time dependent signal shows up at 6.1 mA with a frequency ten and twenty times larger than the synchrotron frequency, Fsyn=7.5 kHz. The low frequncy spectral content up to 20 kHz is shown on the right.

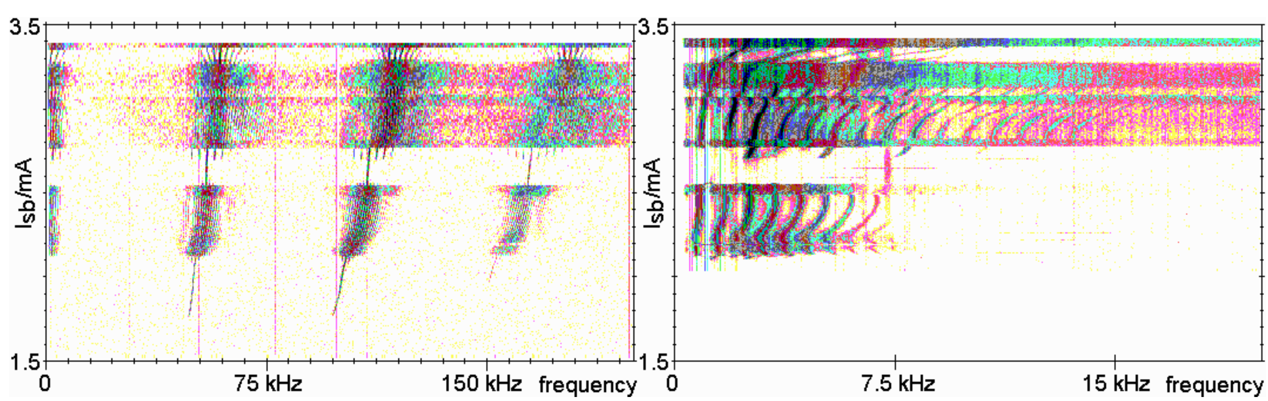

Figure 3: Waterfall displays like in Fig. 2, without the superconducting insertion devices. At 1.8 mA the first spectral lines appear at 44 kHz and 48 kHz. As in the previous figure the synchrotron frequency is 7.5 kHz. In both cases the low frequency signals ("bursts") have a higher threshold.

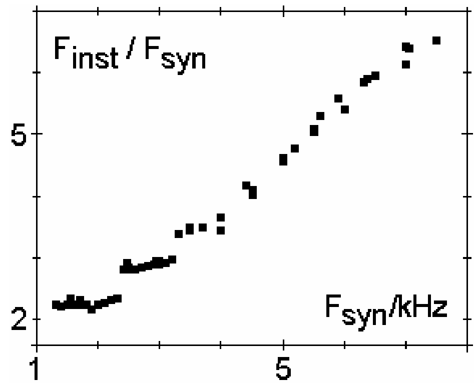

Figure 4: Normalized fundamental frequency of the first time dependent CSR-signal, F_{inst}/F_{syn}, as a function of bunch length (synchrotron frequency, F_{syn}). This shows that well defined azimuthal modes are initially unstable. Measurements were taken without the sc IDs and the rms bunch length is ~13 ps with F_{syn}=7.5 kHz.

the sidebands become very broad and can no longer be resolved. The bunch goes through different stages of the instability until a turbulent state is reached, where the gross azimuthal features are still visible, however, less pronounced. This happens at around 9.5 mA in Fig. 2 and slightly below 3.4 mA without the sc IDs as presented in Fig. 3. In this case the system clearly exhibits the transitions between pure azimuthal modes, layers of mode mixing, and the final turbulence of the bunch. Note, that BESSY routinely offers 20 mA in a single bunch for time resolved experiments. At this high current the bunch is very unstable and it will be a challenge to model its dynamical behaviour theoretically.

The resolution of the spectrum analyzer is superior to the oscilloscope with 8 bit resolution only. Nevertheless very similar results are obtained for the time domain measurement of the CSR-signal and the offline analysis. This technique is much faster and hence a larger range of parameters is accessible. Fig. 4 shows the frequency of the CSR-signal at the onset of the instability, F_{inst}, as a function of the bunch length – proportional to the synchrotron frequency. The step-like behaviour shows that for a certain range of the bunch length the instability always starts with the same azimuthal mode. Theoretically, except for the dipole mode, all higher modes shift downwards with increasing bunch current and the spacing between higher modes is considerably smaller than the synchrotron frequency. Thus, for the shortest bunches with a synchrotron frequency between 1.2 and 2.4 kHz, presumably the sextupole mode is the first unstable mode. With longer bunches the instability sets in with higher azimuthal modes. In Fig. 4 modes as high as 6 or 7 can be distinguished by counting the steps. A similar behaviour was already predicted by A. Mosnier who used a simple broad-band-impedance as a model for the impedance of the SOLEIL storage ring [8]. In these analytical calculations the bunch length was kept fixed and the frequency of the resonator was varied. This is analogue to the case studies here where the bunch length is varied and the chamber impedance is always the same.

SUMMARY

CSR-bursts have been observed in time domain over a large range of bunch length and bunch intensity well into the regime of turbulent instability. The Fourier transformed data show, that at BESSY the longitudinal single bunch instability starts with a well defined azimuthal mode. The longer the bunch the higher is the number of the first unstable mode. Above a certain second threshold the CSR-signals are pulsed quite regularly and additional sidebands show up in the spectrum. This is explained by mode mixing and mode competition leading to the well known saw tooth type bunch dynamics. With even more current the next higher azimuthal mode becomes unstable and a mixture of neighbouring modes occurs. Finally, with more and more modes being involved, a turbulent state is reached where CSR-bursts are emitted randomly and dominant modes or sidebands are not visible any more in the spectra. This is the route to chaos or turbulent bunch lengthening due to the microwave instability, at least for the BESSY storage ring. There is a region between the potential well deformation with a static distortion of the initial Gaussian distribution and the turbulent lengthening regime accompanied by energy widening where the bunch is in a very regular and predictable time dependent state with just a single unstable azimuthal mode. All this shows the power of THz-diagnostics of the emitted CSR for the analysis of the microwave instability of short bunches.

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