4-CHANNEL SINGLE SHOT AND TURN-BY-TURN SPECTRAL MEASUREMENTS OF BURSTING CSR

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Abstract

The test facility and synchrotron radiation source ANKA at the Karlsruhe Institute of Technology (KIT) in Karlsruhe, Germany, can be operated in a short-pulse mode. Above a threshold current, the high charge density leads to microwave instabilities and the formation of sub-structures. These time-varying sub-structures on bunches of picosecond duration lead to the observation of bursting coherent synchrotron radiation (CSR) in the terahertz (THz) frequency range. The spectral information in this range contains valuable information about the bunch length, shape and sub-structures.

We present recent measurements of a spectrometer setup that consists of 4 ultra-fast THz detectors, sensitive in different frequency bands, combined with the *KAPTURE* readout system developed at KIT for studies requiring high data throughput. This setup allows to record continuously the spectral information on a bunch-by-bunch and turn-by-turn basis. This contribution describes the potential of time-resolved spectral measurements of the short-bunch beam dynamics.

INTRODUCTION

The self-interaction of the bunch with its emitted electric field leads to deformation in the longitudinal phase space. Above the microwave instability threshold this results in the formation of sub-structures and the emission of coherent synchrotron radiation at wavelengths in the order of the size of the sub-structures. In storage rings with a short-bunch operation mode and picosecond long bunches this is in the range of some hundred gigahertz to a few terahertz. The changing sub-structures emit coherently in a different spectral range in each turn. Observing the radiation with single-shot detectors turn-by-turn gives insights to the evolution of these structures.

MEASUREMENT SETUP

Measurements have been performed at the "Infrared2" beamline at the test facility and synchrotron radiation source ANKA [1]. The storage ring is operated in a short-pulse mode (low-alpha operation) above the microwave instability threshold [2]. Important machine parameters during the measurement are summarized in Table 1.

Table 1: ANKA Machine Parameters

Beam energy	1.287 GeV
Circumference	110.4 m
Vacuum chamber full height	32 mm
Revolution frequency	2.716 MHz
RF frequency	499.72 MHz
Synchrotron frequency	8.2 kHz
Calculated bursting threshold [3]	0.2 mA
Calculated momentum compaction α_c	5×10^{-4}

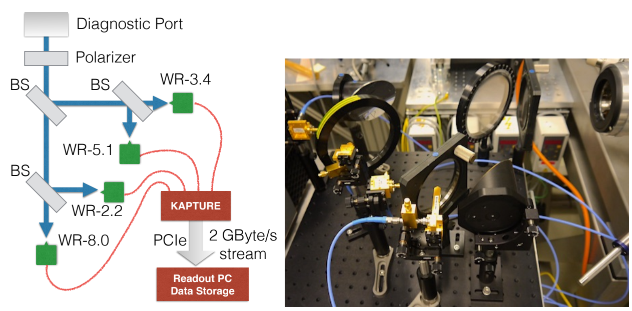

Figure 1: The incoming synchrotron radiation is first polarized and then divided into four beams by 3 wire-grid beam splitters. The split beams are focused onto four detectors, each one sensitive at different frequency range. The single shot measurements are sampled and read out by the *KAPTURE* system.

The radiation is coupled out at the diagnostic port of the infrared beamline through a z-cut quartz window. With a set of four wire grid polarizers the beam is first horizontally polarized and then split into four equally powered parts, each focussed to a commercially available waveguide coupled Schottky barrier diode (SBD) detector [4] sensitive in a different frequency range. Each detector signal is simultaneously read out with *KAPTURE* [5], which for each turn measures the detector signal by a 12 bit ADC. This setup is sketched in Fig. 1. To improve the used ADC range, the three highest SBD detectors (WR5.1, WR3.4, WR2.2) are amplified using a 15 dB, 18 GHz amplifier. Table 2 shows the frequency bands and average responsivity of the used detectors.

Table 2: Schottky Barrier Diode Detectors Used

VDI Model	RF (GHz)	DC Responsivity (avg) (V/W)
WR8.0ZBD	90-140	2000
WR5.1ZBD	140-220	2000
WR3.4ZBD	220-325	1500
WR2.2ZBD	325-500	1250

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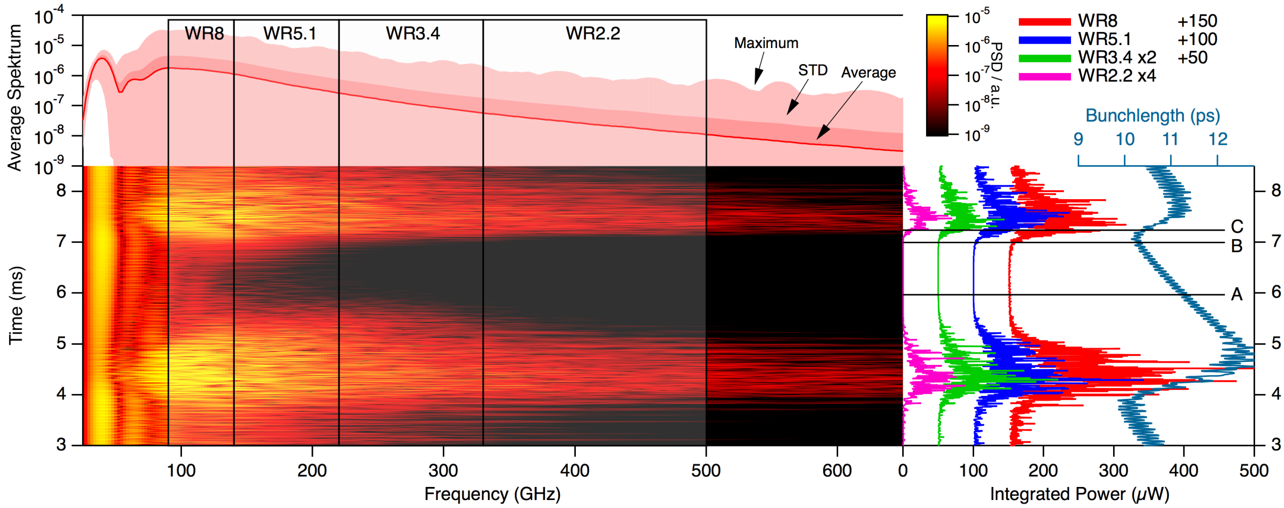

Figure 2: *Inovesa* Simulations: The projection to the time axis of the simulated longitudinal phase space gives the bunch profile and the form factor of the radiation. The image shows the emitted radiation due to the changing bunch profile over time. On top is an average simulated spectrum. The expected power in the frequency bands of SBD is integrated and shown in the right panel together with the instantaneous rms bunch length. For better visibility, the WR2.2 signal is scaled by 4, the WR3.4 is amplified by 2 and shifted by 50. WR5.1 and WR8 are shifted by 100 and 150, respectively.

The shown responsivity, however, is only indicative of the sensitivity of the detector system, i.e. the diodes should not be compared quantitatively. To do that, it has to be taken into account, that the measured synchrotron radiation pulse is broad band and the frequency acceptance of diodes in its band is not uniform. Moreover, the synchrotron pulse is shorter than the response time of the detector, with the consequence that the signal is dominated by the impulse response of the diodes, which for all diodes has been measured to be above 18 GHz. The measured pulse amplitude is therefore highly dependent on the quality of the RF readout path of the individual diode, which has not been measured, and less on the individual DC-responsivity. The different sensitivity has therefore not been compensated in the following plots and the reader has to keep in mind, that quantitative comparisons have to be taken with special care. All these properties, however, do not change during the experiment, so that a qualitative comparison is possible.

SIMULATION

Simulations have been carried out with *Inovesa*, an open source parallelized Vlasov-Fokker-Planck solver developed at KIT [6]. *Inovesa* simulates the longitudinal phase space influenced by an impedance. In this simulations, only CSR impedance with shielding by parallel plates has been taken into account [7]. The projection on the time axis provides the bunch structure and from that the emitted THz radiation is calculated. Note that in a real measurement the lower frequencies are additionally shielded by the beam-line geometry and transmission properties of the used vacuum windows and mirrors.

Figure 2 presents simulated data for a bunch current of 800 μA. The image shows the changing THz spectrum over time. In the top panel, an average spectrum, as it would be detected by a slow detector is shown. Also indicated are the frequency bands of the four detectors. The right panel shows the THz intensity in those four observed spectral bands as well as the overall rms bunch length at that time. The small but fast modulation is due to a dipole motion and shows therefore a periodicity with twice the synchrotron frequency. The rms bunch length decreases due to radiation damping, until a threshold is reached, then the strong CSR instability drives micro-structures and blows up the bunch. This blow up in combination with diffusion and damping in phase space homogenizes the bunch shape and the sub-structures vanish. The bunch length as well as the energy spread fluctuation shows therefore the same periodicity as the burst (see [8]).

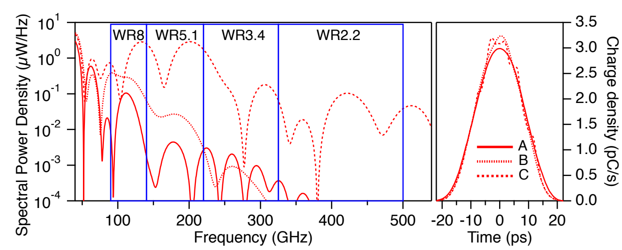

Figure 3: Calculated emitted spectrum and bunch profile at selected times A, B and C of Fig. 2

Four marked time points are shown in more detail in Figure 3. The spectrum as well as the bunch profile at these times are shown. Case (A) is between two bursts: the substructures have decayed, the shape is almost Gaussian and the bunch is further shortening according to the damping time. The WR2.2 and WR3.4 diode receive a very low signal. At (B), the shortened bunch implies an increased wake potential which leads to bunch deformations and drives the

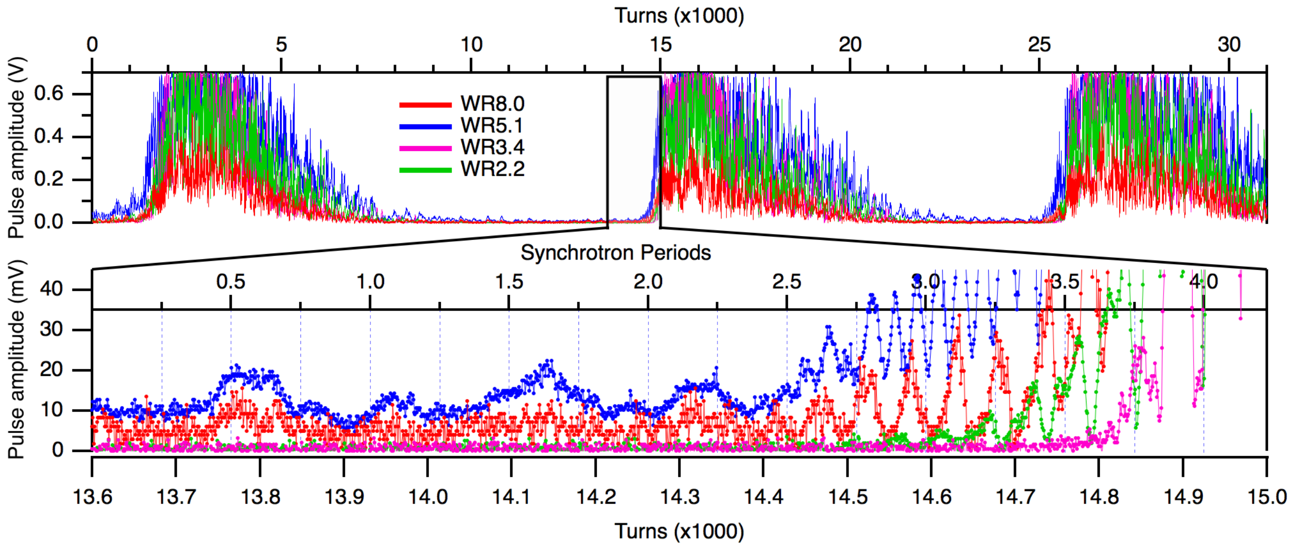

Figure 4: Measured turn-by-turn amplitudes of the four different diodes (1000 turns ≈ 0.368 ms ≈ 3 synchrotron periods). The bottom panel shows a zoom-in to the beginning of a burst. Every point is a measured pulse amplitude, the line is to guide the eye.

micro-bunching instability, resulting in more radiation as seen first at the lower frequencies. This increases also the intensity of the wake potential, which in return drives the sub-structures even more, and the outburst of radiation is seen at all detectors in case (C). Then, due to the increased bunch size, the particle density in the sub-structures shrinks, the bunch becomes stable again and damps until the next burst.

RESULTS

In comparison to the simulations above, it has to be taken into account, that the beamline has a low-frequency cutoff due to its geometry in combination with the frequency dependent beam divergence. Fourier Transform Infrared Spectroscopy (FTIR) measurements indicate that at the beamline the maximum power is observed around 200 GHz [9]. Turn-by-turn data of the four SBD detectors of a bunch with a current of 800 µA is shown in Fig. 4. In agreement with the simulations, the amplitude of the WR8.0 and WR5.1 diodes have a constant signal before the burst which is modulated with twice the synchrotron frequency due to the dipole motion (see Fig. 2). Note that the grid shows the coherent synchrotron frequency as it has been measured by the bunch-by-bunch feedback system, while the phase space rotates with the incoherent synchrotron frequency which is expected to be slightly lower. The high frequency diodes do not measure coherent radiation until the burst starts and its observation happens later compared to the lower frequencies.

SUMMARY AND OUTLOOK

Our discrete setup of an ultra-fast single shot spectrometer with beam splitters and individual detectors gave promising results. The micro-bunching instability can be observed in four frequency bands turn-by-turn in a multi-bunch environment. Furthermore, the found features agree with simulations by a Vlasov-Fokker-Planck solver which opens the door to a better understanding and possible influencing of the bursting dynamics. In the future, we plan to use an integrated detector array [10] in combination with the next *KAPTURE* version, that will provide 8 readout channels and an improved readout path [5].

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