BURSTING PATTERNS OF COHERENT SYNCHROTRON RADIATION IN THE ANKA STORAGE RING

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Abstract

We report measurements of bursting patterns of coherent synchrotron radiation (CSR) for a wide range of single bunch currents at the ANKA storage ring. The radiation was detected with a fast THz detector, a Hot Electron Bolometer, and its signal acquired with both a spectrum analyzer and an oscilloscope (external sampling). Both analysis methods consistently show the onset of bursting at a threshold current with the appearance of strong high frequency bands with higher harmonics in the several 10th of kHz range. For currents higher than twice the threshold value an abrupt change in the bursting pattern occurs. These results are compared with different numerical models solving the one-dimensional Vlasov-Fokker-Planck equation.

INTRODUCTION

The ANKA storage ring at KIT is a multipurpose user facility for the use of X-ray synchrotron radiation. However, it is possible to operate the machine in the Low-α_c mode to create coherent radiation in the THz regime [1]. This special optics allows for small momentum compaction factor α_c and results in bunch lengths sufficiently small to emit coherent THz radiation.

Since the exact longitudinal charge distribution is linked to the properties of CSR, observation of its fluctuations allow for a non-inversive tool for the investigation of electron beam dynamics.

In this paper, we report on measurements of these fluctuations, and in form of their spectrograms, as bursting patterns for single bunch operation at ANKA. Compared to earlier measurements [2] we used combined acquisition of time and frequency domain data. To achieve high frequency resolution by using a fast Fourier transformation (FFT) of the time domain data, over 500 k consecutive turns were recorded. Furthermore, the bursting patterns are compared to beam dynamics simulations, that take different impedance models into account.

MEASUREMENT

Experimental Setup

Our measurements were done at the IR1 beamline of the ANKA storage ring, operating in the Low-α mode. We used an ultra fast Hot-Electron-Bolometer (HEB) detector [3] with a response time below 165 ps, which allows to resolve individual bunches. Its signal was acquired simultaneously by both a Tektronix RSA 3303 spectrum analyzer and an external sampling LeCroy 64xi 500 MHz oscilloscope. Using the latter's external sampling mode, we were able to record 500 k consecutive turns. The time domain signal of the oscilloscope was converted to the spectral domain by an FFT, yielding a spectral resolution of about 10 Hz and comparable to that of the spectrum analyzer. We reduced the attenuation during the measurement twice to avoid saturation effects of the detector.

Experimental Results

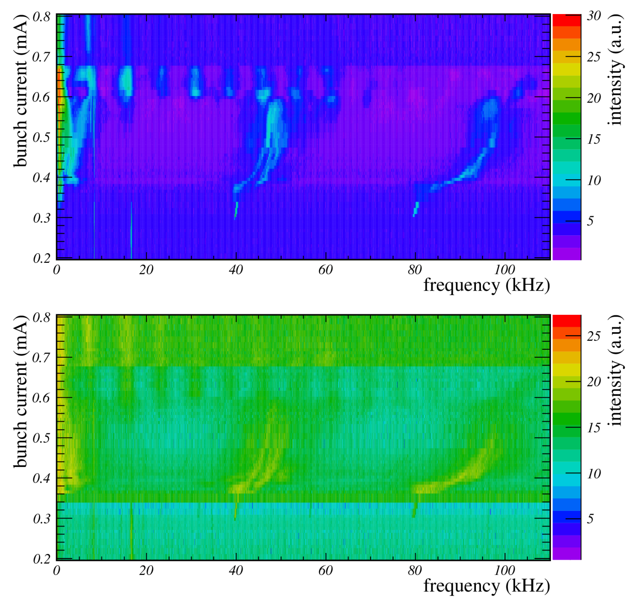

Figure 1: Spectra of THz radiation for different bunch currents measured directly with a spectrum analyzer (top) and indirectly using the FFT of an oscilloscope (bottom). The intensity changes at 0.37 and 0.72 mA are due to the attenuation change mentioned above. Both methods show the same bursting pattern and the line at f_s =8.36 kHz is present at all currents.

Figure 1 shows the two measured waterfall plots. Both methods show the same bursting pattern. Since the unattenuated signal would saturate the HEB, the attenuation was adjusted at currents of 0.37 and 0.72 mA. These adjustments result in different noise levels due to normalization. However, the observation of the different bursting regimes is unaffected by this. The f_s line at 8.36 kHz is present at all currents. Other features are only present within a certain current range and divide the THz emission into four dif-

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ferent regimes. *Steady state* emission occurs for currents below 0.28 mA. In this region, a modulation of the THz signal with 2 f_s is seen as well, which ceases for currents above 0.4 mA. *Regular bursting* exists within the current range from 0.28 to 0.36 mA. The dominant mode at about 400 Hz exists in all bursting regimes. Furthermore, regular bursting is characterized by a relatively sharp frequency at about $5f_s \approx 40$ kHz and its higher harmonics. The higher current marks a threshold where the bursting pattern changes. In this regime, the $5f_s$ line and its higher harmonics spread out and we refer to it as *spread bursting*. For higher currents, they drift to higher frequencies. Finally, another threshold is reached at a current of about 0.6 mA where the bursting pattern changes abruptly. This time the $5f_s$ line, together with its higher harmonics, ceases. They are replaced by modulation bands occurring at multiples of $f_{\rm burst} \approx 6.7$ kHz, which is close to, but slightly smaller than, the synchrotron frequency f_s of 8.36 kHz. Only a minor drift with current is observed, but the higher harmonics decrease in intensity. This *resonant bursting* persists up to the highest measured current of 1.4 mA (not shown in Fig. 1). Notice that no chaotic bursting is observed over the entire investigated current range.

SIMULATION

To simulate the evolution of the electron bunch, we numerically solve the 1D Vlasov-Fokker-Planck equation for the phase space density distribution $f(q,p,t)$. The generalized coordinates q and p denote the longitudinal position w.r.t. the reference particle, normalized by the zero-current bunch length σ_z, and the energy deviation normalized to the energy spread σ_e, respectively. The VFP equation includes the force F due to collective effects, radiation damping, and diffusion [4]:

$$\frac{\partial f}{\partial \tau}+p\frac{\partial f}{\partial q}-[p+I_{\rm c}\,F(q,f,\tau)]\,\frac{\partial f}{\partial p}=\frac{2}{\omega_{\rm s}t_{\rm E}}\left(p\,f+\frac{\partial f}{\partial p}\right). \quad (1)$$

Here, time $\tau \equiv \omega_{\rm s}\,t$ is expressed in terms of the angular synchrotron frequency $\omega_{\rm s}$, and $t_{\rm E}$ denotes the damping time. The collective force $F(q,f)$ of the N electrons with charge e depends on the longitudinal wake function $W(q)$ and the longitudinal charge density $\rho(q,\tau)$ through

$$F(q,f)=-e\,N\int_{-\infty}^{\infty}W\left(q-\tilde{q}\right)\,\rho\left(\tilde{q},\tau\right)\mathrm{d}\,\tilde{q}\,. \quad (2)$$

We calculate the wake function from the Fourier transform of the impedance $Z(n)$

$$W(q)=2\,\frac{\omega_0}{2\pi}\mathrm{Re}\left[\sum_{n=0}^{\infty}\mathrm{e}^{\mathrm{i}\,\sigma_z\,q/R}\,Z(n)\right], \quad (3)$$

where ω_0 denotes the frequency of the reference particle and n the wave number. The influence of the environment on the beam, thus, is contained in the impedance model used. In [5] the free field CSR impedance [6], which excludes any effects of the vacuum chamber, was used to calculate the bursting threshold. Here, we use either the parallel plates impedance [8], which treats the vacuum chamber as two infinite and perfectly conducting vertical plates, or the pillbox impedance [7], which also includes the outer wall together with its conductivity. In the pillbox model, the outer wall allows TE and TM modes to propagate along the outer beam pipe and interfere constructively at certain points of the orbit. By this resonance, or whispering gallery, mechanism, a bunch can influence trailing bunches or experience its own wake field after one turn.

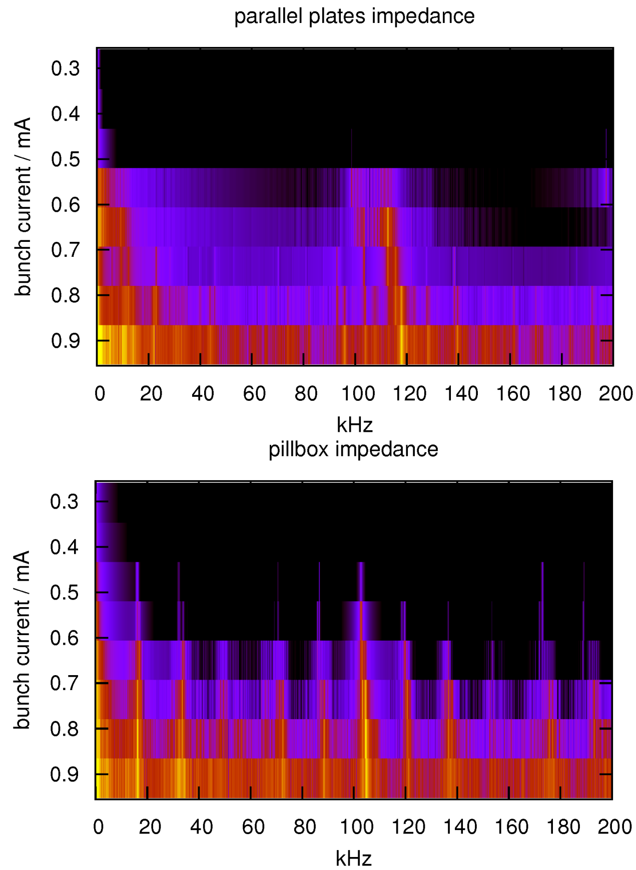

Figure 2: Simulated THz radiation spectra for different bunch currents using the parallel plates impedance (top) and the pillbox impedance (bottom) [7].

Details of the simulation can be found in [7]. The results are shown in Fig. 2. The simulation using the parallel plates impedance shows a low frequency band below 1 kHz for all currents. At a current of 0.52 mA (corresponding to a bunch with 12×10^8 electrons) this mode increases in intensity. Furthermore, this current marks a threshold for the appearance of another mode at about 110 kHz, which drifts to higher frequencies with higher currents. Its higher harmonics share these properties as well [7]. Notice that the intensity of all modes increases with currents and that no other prominent threshold is observed. Using the pillbox impedance, we again find a low frequency band at all currents. However, at a current of about 0.44 mA several sharp modes appear, the most prominent being at around

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100 kHz. They slightly drift with current, but increase in strength with increasing current. The presence of sharp modes is due to the sharp spikes of the pillbox impedance, caused by the whispering gallery modes. In comparing the simulation to the experiment, one must keep in mind that the vacuum chamber at ANKA has a hexagonal cross section and is flared at the IR beamlines, contrary to the rectangular cross section assumed in the pillbox model.

DISCUSSION

The frequency- and the time-domain based spectra in Fig. 1 are consistent with each other. The onset of regular bursting at a current of $I_{\mathrm{thr}} \sim 0.28\,\mathrm{mA}$ agrees with the theoretically expected bursting threshold [5]. Independent of the impedance model used, simulations show no onset of bursting at this current. This might, however, be due to the limited resolution and will be investigated further in the future. The parallel plates impedance describes the data qualitatively for currents below 0.6 mA, in particular the drift to higher frequencies. Quantitatively, the frequency is not at the measured 40 kHz, but off by a factor of about 2.5. Obvious factors of $\sqrt{2\pi} \approx 2.5$ can be excluded, since both measurement and simulation show integer multiples of the synchrotron frequency. At currents above 0.6 mA the spectra in Fig. 1 qualitatively resemble the simulations based on the pillbox impedance. Notice that this second threshold is about twice I_{thr}.

We interpret these findings as follows: The regular bursting regime starts at the bursting threshold, which, in turn, is calculated from the free space CSR impedance. In the spread bursting regime of currents between 0.36 mA to about 0.6 mA, the spectra qualitatively resemble the simulations with the parallel plates impedance. The switch from regular bursting to spread bursting is, thus, interpreted as transition from a beam dominated by its free space CSR wake to one that is affected by the wake from the vertical plates of the vacuum chamber. Similarly, the abrupt bursting pattern change at 0.6 mA from the spread to the resonance regime is understood as a change from a parallel plates impedance dominated beam to one that also experiences the effect of the outer beam pipe. Further measurements and simulations are planed to test this scenario.

SUMMARY

We have measured CSR bursting patterns for a single bunch current in the range of 0.2 to 1.2 mA. The two acquisition methods yield consistent bursting patterns. These patterns show several bursting thresholds that separate different bursting regimes. The onset of bursting agrees with theoretical predictions based on free field CSR impedance. The other regimes are described, qualitatively, by simulations using the parallel plates impedance and the pillbox impedance. Hence, we interpret the different bursting patterns arising from different dominant wakes. Further studies to test this scenario, both experimentally and theoretically, are planed.

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