ANALYSIS OF THZ SPECTRA AND BUNCH DEFORMATION CAUSED BY CSR AT ANKA*

M. Klein, N. Hiller, A.-S. Mueller, K. G. Sonnad†, P. Tavares‡, Karlsruhe Institute of Technology

Abstract

The ANKA light source is regularly operated with a low momentum compaction factor lattice where short bunches are created for the generation of coherent synchrotron radiation (CSR). Short bunches with high electron density can generate strong self fields which act back on the bunch. This can lead to bunch shape deformation and a microbunching instability which were studied theoretically for the ANKA low alpha parameters [1]. We extended these studies to a comparison of calculated electron distributions and bunch profiles measured with a streak camera. The Haissinski equation was solved for the CSR impedance to obtain a prediction for the distortion of the bunches for different bunch lengths and bunch currents. The comparison shows that the theory predicts a much stronger deformation caused by CSR than the streak camera observes. However, high frequency components of measured FTIR spectra show a clear indication for strong deformation or small substructures.

INTRODUCTION

The intensity of coherent synchrotron radiation scales with the square of of the number of particles in the bunch while the intensity of incoherent emission has a linear dependence. This power increase allows us to use synchrotron radiation in the THz frequency range. Because only wavelengths longer than and equal to the bunch length are emitted coherently, optics with a low momentum compaction factor (so-called low α optics) are used to compress the bunches.

Short bunches lead to a high electron density and generate strong wake fields when interacting with the environment. In addition the CSR itself creates a wake field which acts back on the bunch. These wake fields cause a potential well distortion and, if strong enough, could lead to the microwave instability [2, 3]. The bunch deformation can be obtained from the Haissinski equation as a steady state solution of the Fokker-Planck equation [4]. The microwave instability generates bursts of CSR with a further increase in radiation power. The bursting stable threshold at ANKA was measured and agrees very well with the theoretical prediction [1].

* This work has been supported by the Initiative and Networking Fund of the Helmholtz Association under contract number VH-NG-320

† now at Cornell University

‡ on leave from ABTLUS, Brazil

MEASUREMENTS

The bunch profiles were measured with a streak camera during single bunch low α operation. The camera (C5680 by Hamamatsu) was operated with edge radiation in the visible range from a bending magnet at one of the two infrared beamlines (IR1 and IR2) at the ANKA storage ring. A further discussion of the experimental setup and the data analysis can be found in [5].

Spectra from a Michelson interferometer (Fourier transform IR spectroscopy - FTIR) were simultaneously recorded, using a silicon bolometer as detector. The detected CSR frequency range is between 0.1 THz and 1.2 THz. The lower and upper limits are set by the combined cutoff of the beam transfer channel and detector and the low radiation intensity respectively.

LONGITUDINAL LINE DENSITY

The longitudinal phase space distribution is given by the Fokker-Planck equation. A stationary solution of the Fokker-Planck equation regarding the line density $\lambda(t)$ is described by the Haissinski equation [4] and depends on the existing wake $W(t)$ and therefore on the impedances $Z(\omega)$ of the storage ring:

$$\lambda(t) = \kappa \cdot \exp\left[-\frac{t^2}{2\sigma_0^2} - \frac{1}{\dot{V}_{RF}\sigma_0^2}\int_{-\infty}^{\infty}\frac{\lambda(\omega)Z(\omega)}{\omega}e^{-i\omega t}d\omega\right] \tag{1}$$

$$W(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} Z(\omega)e^{i\omega t}d\omega \tag{2}$$

where σ_0 is the natural bunch length, $\dot{V}_{RF}$ the derivative of the RF-voltage with respect to the longitudinal position in the bunch t and the normalization constant κ.

CSR Impedance

Coherent synchrotron radiation is accompanied by increased an energy loss and an influence of the electron density ahead of the emitting particle. The equilibrium electron distribution can be calculated numerically by iteratively solving the Haissinski equation (Eq. (1)) for the corresponding impedance Z_{CSR} [6]:

$$Z_{CSR} = Z_0\frac{\Gamma(2/3)}{3^{1/3}}\left[\frac{\sqrt{3}}{2} + i\frac{1}{2}\right]\left(\frac{\omega}{\omega_0}\right)^{1/3} \tag{3}$$

where Z_0 is the vacuum impedance and ω_0 the angular revolution frequency. Shielding effects are neglected here.
The real part of the impedance is known to cause energy loss. This loss is compensated for in the cavities by means of a change in the synchronous phase beside the compensation of all other losses as radiation. This leads to asymmetric bunch shapes with its mean shifted toward the head. The streak camera measurements show an increasing asymmetry in bunch shape and a bunch lengthening with increasing current for all values α within the low α optics parameters. Thus the evaluated bunch shapes can help to determine this part of the impedance of the storage ring for the low α optics.

COMPARISON OF MEASUREMENTS AND CALCULATIONS

Bursting Threshold

Initial small fluctuations of the electron density can be excited by existing wake fields and result in microbunching effects. The substructures, which now radiate coherently themself, are thereby damped again and lead to chaotically occurring bursts of radiation [3]. This instability arises from high currents in short bunches. The threshold was identified for the ANKA storage ring to be [1]

$$I_{Th} = 0.11 \cdot \sigma_0^{7/3} \tag{4}$$

for $V_{RF} = 4{\cdot}150$ kV at an energy of $E = 1.3$ GeV. For the different investigated optics - which are represented by the measured synchrotron frequency f_s - the natural bunch length, the current range during measurements and the expected threshold currents are printed in Table 1. The natural bunch length was calculated from the measured synchrotron frequencies.
The streak camera measurements were done in both regimes, bursting and stable emission. As the camera is only sensitive to visible light, the bursting of the THz frequencies can not be observed directly. Since the Haissinski equation describes an equilibrium state, it is in question if the predictions also apply for the turbulent bursting.

Table 1: Streak Camera and Interferometric Measurements: Synchrotron frequency, current range, bursting threshold and natural bunch length.

f_s [kHz]	$I_{R,meas}$ [mA]	I_{Th} [mA]	σ_0 [mm]
5.6	0.17 - 1.47	0.088	0.91
9.3	0.34 - 1.58	0.326	1.60
15.1	0.3 - 1.71	1.010	2.59

Expected Deformation by CSR

In Figure 1 - 3 the theoretically calculated bunch shapes, distorted by the free space CSR wake, were compared with the measured shapes. The expected asymmetry was much higher than the measured one, especially for high currents and short bunches. The shape itself is not reproduced by the theoretical predictions. The reason for the mismatch could be a shielding effect by the beam pipe or an additional wake which compensates the deformation. It is also likely that the streak camera measurements have smeared out the exact shape because of averaging over many damping periods.

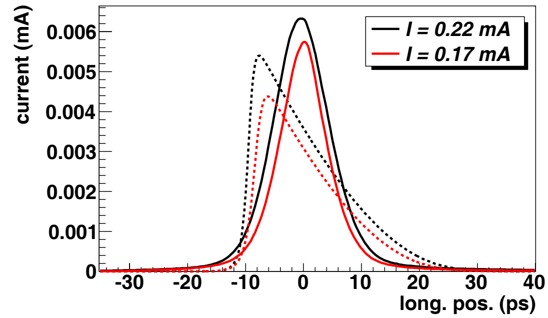

Figure 1: Comparison of measured and calculated bunch shapes for $f_s = 5.6$ kHz: Solid lines are streak camera measurements, dashed lines are calculated using the free space CSR wake.

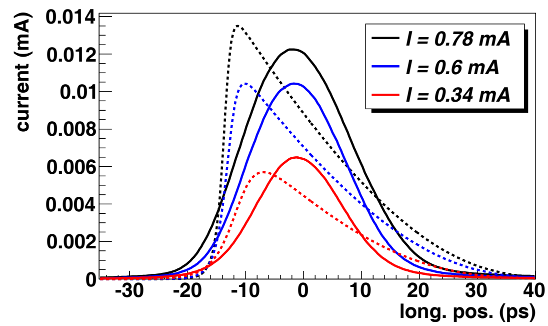

Figure 2: Comparison of measured and calculated bunch shapes for $f_s = 9.3$ kHz.

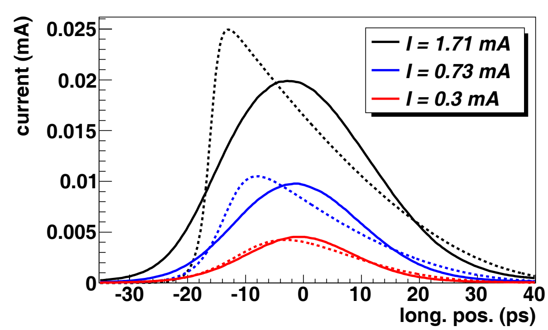

Figure 3: Comparison of measured and calculated bunch shapes for $f_s = 15.1$ kHz.

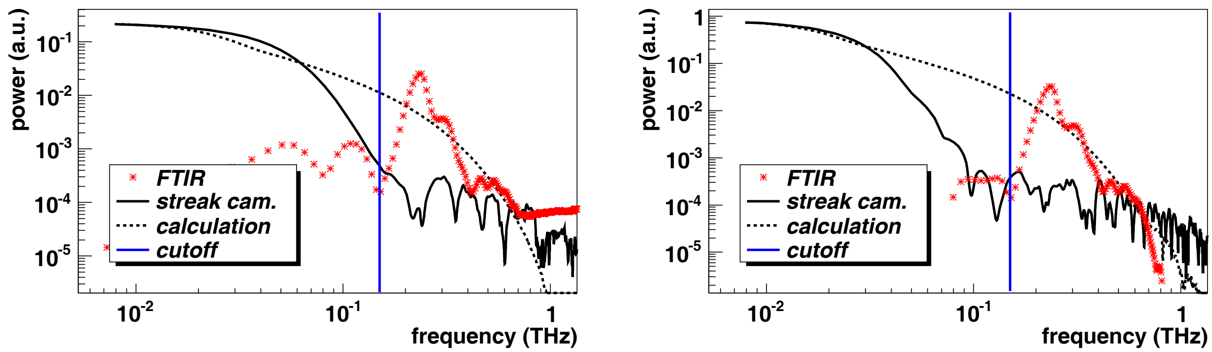

Figure 4: Comparison of expected spectra and measurements for $f_s = 5.6$ kHz and $f_s = 9.3$ kHz: The black line shows the estimated spectrum as Fourier transform of the streak camera measurements. The dashed line is calculated from the expected bunch shape deformation by the CSR wake. The result of the interferometric measurement is plotted in red. The blue line indicates the cutoff of the detector.

THz Spectra

The coherent THz power spectrum of a bunch $dP/d\omega$ is proportional to the spectum of a single electron $dp/d\omega$ and the Fourier transform of the electron distribution [7]:

$$\left(\frac{dP}{d\omega}\right) = (\underbrace{N}_{incoh.} + \underbrace{N(N-1)}_{coh.} g(\omega)) \left(\frac{dp}{d\omega}\right), \quad (5)$$

with the so-called CSR form factor $g(\omega)$:

$$g(\omega) = \left| \int_{-\infty}^{\infty} \lambda(t) e^{i\omega t} dt \right|^2 \quad (6)$$

Figure 4 shows a comparison of the expected spectra, obtained through Fourier transformation of the streak camera profiles and the predicted distributions distorted by the CSR wake and the measurement with the interferometer. The blue line is the estimated cutoff of the detector at 0.15 THz, but it is seen that a reduction in radiation intensity begins already at 0.23 THz. In the case of a bunch length above 2 mm no coherent radiation is detectable.
If the streak camera would tell the whole story, CSR above cutoff would not exceed the noise level. The extension of the measured spectra up to 0.6 THz could be generated by strongly distorted bunch shapes as calculated or by substructures within the bunch of around 500 μm. If those substructures are generated by the microbunching instability, they could not be detected by the streak camera, measuring over several damping periods.

SUMMARY

The expected deformation by the CSR wake could not be seen with the streak camera whereas the recorded spectra give indication for this. Reason for the observation of much lower deformation could be a shielding effect of the beam pipe or an additional wake counteracting, especially for short bunches and high currents. However, a substructure in the range of 500 μm has to exist to explain the high frequency part. This substructure could be generated by microbunchig due to the CSR instability.
Further investigations are needed to distinguish the exact reason for the extension of the spectra. The high frequency part of the ring's impeadance can be probed with different short bunch lengths. Therefore additional work should help to develop a complete impedance model for ANKA in dependance of different values of the momentum compaction factor within the low α mode of operation.

REFERENCES

[1] M. Klein et al. "Studies of Bunch Distortion and Bursting Threshold in the Generation of Coherent THz-Radiation at the ANKA Storage Ring", PAC'09.

[2] K. Bane, S. Krinsky and J. B. Murphy, "Longitudinal potential well distortion due to the synchrotron radiation wakefield", AIP Conf. Proc., 1996.

[3] G. Stupakov and S. Heifets, "Beam instability and microbunching due to coherent synchrotron radiation", Phys. Rev. ST Accel. Beams 5, 054402 (2002)

[4] J. Haissinski "Exact Longitudinal Equilibrium Distribution of Stored Electrons in the Presence of Self-Fields", Nuovo Cimento, 1973, 18B, No1, 72

[5] N. Hiller et al. "Observation of Bunch Deformation at the ANKA Storage Ring", these proceedings.

[6] J. B. Murphy, S. Krinsky, R. L. Gluckstern, "Longitudinal wakefield for synchrotron radiation" PAC '95

[7] F. Sannibale et al., "A Model Describing Stable Coherent Synchrotron Radiation in Storage Rings", Phys. Rev. Lett. 93, 094801 (2004)