BEAM STUDIES WITH COHERENT SYNCHROTRON RADIATION FROM SHORT BUNCHES IN THE ANKA STORAGE RING

A.-S. Müller, I. Birkel, E. Huttel, S. Casalbuoni, B. Gasharova, Y.-L. Mathis,
D.A. Moss, P. Wesolowski Karlsruhe Research Center, Germany
C.J. Hirschmugl, University of Wisconsin Milwaukee, USA

Abstract

In the ANKA storage ring it is possible to store bunches with RMS lengths of the order of 1 ps using a dedicated optics with reduced momentum compaction factor. For short bunch operation a beam energy of 1.3 GeV is chosen as a tradeoff between low energy longitudinal instabilities and the increase in natural bunch length with energy. At this medium energy (the energy range of the ANKA storage ring is 0.5 to 2.5 GeV) steady state emission of coherent synchrotron radiation is observed at the ANKA-IR beamline below the threshold current defined by the microbunching instability. At lower beam energies where the natural bunch length is significantly shorter, coherent synchrotron radiation is detected in spite of the longitudinal oscillation. The far infrared spectrum is sensitive to the dynamics of the charge distribution generating the radiation. Measurements of the frequency spectrum of the infrared detector signal add information on bunch dynamics. This paper gives an overview of the studies performed at the ANKA storage ring.

INTRODUCTION

Since last year the ANKA storage ring offers beam time for users of a special operation mode with short bunches that emit coherent synchrotron radiation in the far infrared [1]. This THz radiation is detected at the ANKA–IR beamline [2], where the synchrotron light is produced in the fringe field of a bending magnet. This edge radiation has the advantage of being more collimated than constant field radiation. Edge radiation allows the observation of frequencies down to 30 GHz through a modest vertical aperture of 15 mrad, which would not be possible with classical constant field emission due to the increasing beam divergence with decreasing frequency. In order to provide coherent synchrotron edge radiation to the experiments, the storage ring is filled at 0.5 GeV. The desired beam current is than ramped to 1.3 GeV, since the ANKA storage ring suffers from longitudinal instabilities at energies below 1.3 GeV [3]. At the end energy, the bunch length is gradually decreased by an optics change in a so-called "low-α_c squeeze". Measurements can be performed at any of the individual "squeeze states", allowing to adjust the bunch length to user demand. To improve understanding and control of the low-α_c mode, beam studies have been performed that are described in the following.

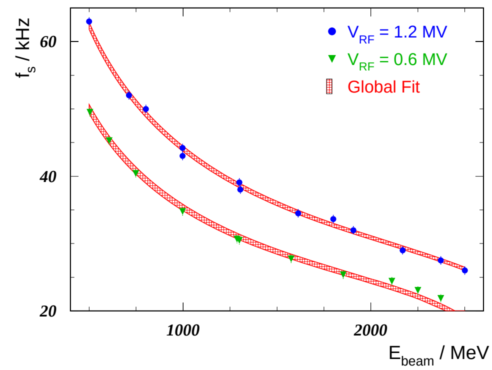

Figure 1: Measured synchrotron frequencies as a function of the beam energy for different total voltages in the RF cavities. The hatched areas denote the error bands of a global fit of the momentum compaction factor to the full dataset.

BUNCH LENGTH AND BEAM ENERGY

While the actual bunch length increases at lower beam energies due to longitudinal instabilities, the natural bunch length shrinks according to $\sigma_s \propto (E_0)^{3/2}$. To determine a common effective momentum compaction factor α_c for all beam energies during the ramp, measurements of the synchrotron frequency for two different total accelerating voltages were performed as a function of the beam energy. The measurements are shown in Fig. 1. The synchrotron

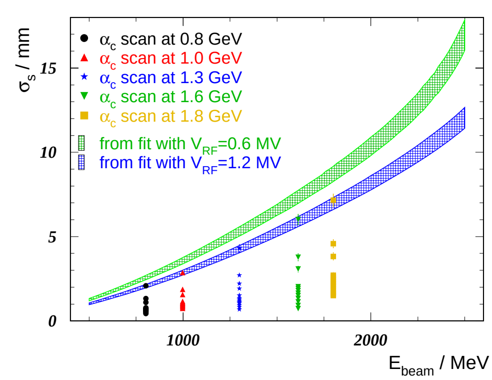

Figure 2: RMS Bunch length derived from measurements of f_s (see Fig. 1) as a function of beam energy. The hatched regions are error bands obtained by a full error Monte Carlo. The markers represent bunch lengths derived from synchrotron frequency measurements for different beam energies.

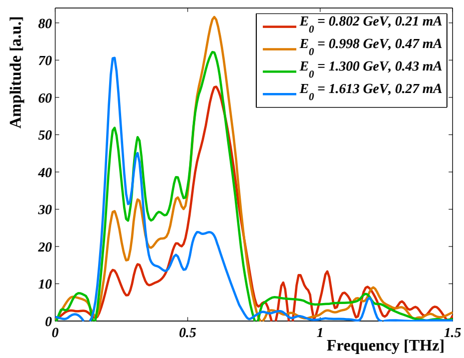

Figure 3: The spectrum in the far infrared (FIR) for different electron beam energies. The shift from higher to lower frequencies with increasing beam energy is clearly visible and denotes the increase in natural bunch length with beam energy.

tune can be expressed by

$$Q_s^2 = \left(\frac{\alpha_c h}{2\pi E}\right)\sqrt{e^2\, V_{\mathrm{RF}}^2 - U_0^2} \tag{1}$$

where U_0 is the energy loss, V_{RF} the total accelerating voltage and h the harmonic number. A global fit of this function to the f_s measurements shown in Fig. 1 yields an effective momentum compaction factor for all energies of $\alpha_c = (6.6 \pm 0.1) \cdot 10^{-3}$ which is reasonably close to the value determined at the beam energy for regular user operation of 2.5 GeV with resonant depolarisation of $(7.39 \pm 0.01) \cdot 10^{-3}$ [4]. The hatched areas in Fig. 1 denote the error bands of the global fit. The RMS Bunch length as a function of beam energy derived from the measurements of the synchrotron frequency shown in Fig. 1 is displayed in Fig. 2. The hatched regions show the error bands of the calculated bunch length dependence on total accelerating voltage and beam energy as obtained by a full error Monte Carlo. The markers represent the bunch length derived from synchrotron frequency measurements during the "low α_c squeeze" for different beam energies. The energy dependence of the resulting far infrared (FIR) spectrum due to the change in natural bunch length is clearly visible in Fig. 3: with increasing beam energy the spectrum shifts to lower frequencies, that is lower bunch lengths. The fact that the low frequency content is reduced for shorter bunches could hint at detector non-linearities. Since for small bunch currents the low energy instabilities are less pronounced, a scan of the stable/bursting threshold could be performed with a low-α_c scan at 0.998 GeV. The transition to steady-state radiation was clearly seen. A comparative analysis of threshold scans at different beam energies is in progress.

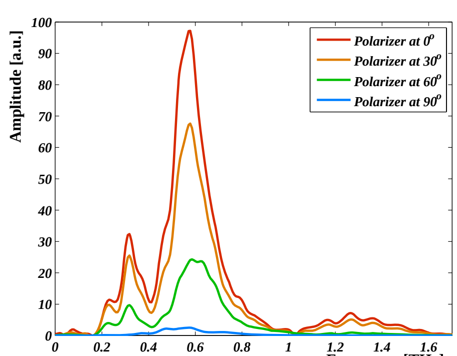

Figure 4: The FIR spectrum measured at a beam energy of 1.3 GeV (V_{RF}= 1.2 MV, f_s = 7.1 kHz) for different orientations of the polarising grid. The 0^o position corresponds to a horizontal, the 90^0 to a vertical orientation.

POLARISATION IN THE FIR

The edge radiation observed at the ANKA–IR beamline is expected to show a radial polarisation. For very low frequencies, however, the annular structure is enlarged with respect to the mid-IR wherefore only a slice of the radiation in the orbit plane will be visible. The measured polarisation should be mostly linear. To test this, the FIR spectrum was detected in standard operating conditions (that is, at 1.3 GeV) for different orientations of a polarising grid. The dependence on the polariser orientation is clearly visible in Fig. 4 and confirms the expected linearity: the highest transmission was achieved for an orientation perpendicular to the orbit plane, the lowest for an orientation parallel to the orbit plane. The resulting degree of polarisation, $A = (P_{\max} - P_{\min})/(P_{\max} + P_{\min})$, is shown in Fig. 5 as a function of the frequency. A measurement with an internal source (Globar) also plotted in Fig. 5 indicates a residual polarisation of the detection system that needs to be included in an analysis of the polarisation degree. The observed "intrinsic" polarisation could be due to the placement of the polariser in the focal point inside the sample compartment of the spectrometer. This leads to a strong divergence at the polariser that can bias the results. The polarisation experiment therefore will be repeated with the polariser located at a position where the IR beam is parallel to suppress the influence of the divergence.

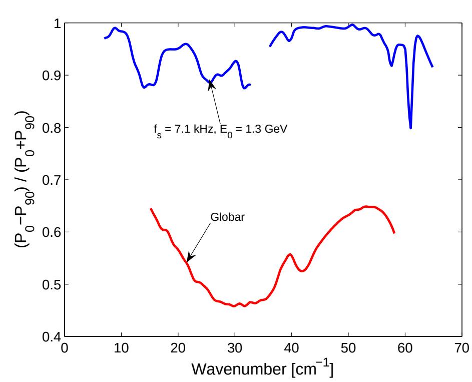

Figure 5: Degree of polarisation derived from the measurements shown in Fig. 4 and from a measurement with an internal source (Globar) as a function of frequency. The visible polarisation of the internal source indicates a residual polarisation of the detection system.

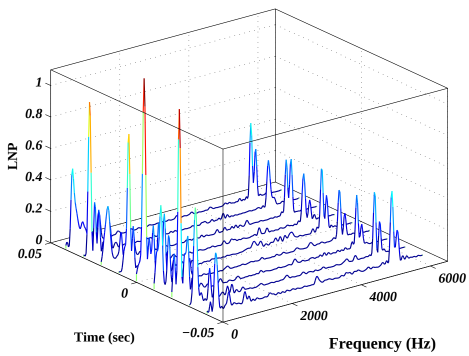

Figure 6: Lomb Normalised Periodograms of the bolometer signal during the evolution of a burst (at $t = 0$). This dataset was recorded at a relatively high bunch current (0.47 mA) and at a beam energy of 1.3 GeV.

FREQUENCY SPECTRUM & CURRENT

Measurements of the raw bolometer signal show a clear evolution in the time domain (for an example see [1]). For the following studies, the signal was subjected to a harmonic analysis using the method of Lomb Normalised Periodograms (LNP) [5]. To study the change of the frequency contents during the build-up of a burst, the signal around a burst was cut in slices and analysed separately. Figures 6 and 7 show such a sequence of Lomb Normalised Periodograms of the bolometer signal for bunch currents of 0.47 and 0.16 mA, respectively, and at 1.3 GeV. The maximum of the radiation burst is located at $t = 0$. The high current dataset clearly shows a double peak structure around the synchrotron frequency of 5.5 kHz that could be due to bunch length oscillations. For lower currents the structure around f_s is no longer present and the maximum of the burst is more pronounced. The long term evolution of the bunch spectrum as a function of beam current is shown in Fig. 8, where the spectrogram is shown in the left hand part and the corresponding beam current in the right hand part. Again, f_s is visible for higher currents but finally disappears. The low frequency contents clearly shows a current dependent behaviour. Figure 9 shows the spectrogram for a constant current but a changing bunch length. The two changes in optics are denoted by the step-wise change in f_s. The onset of bursting emission for shorter bunches is obvious.

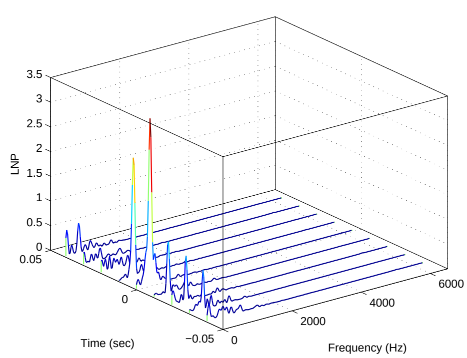

Figure 7: Lomb Normalised Periodograms of the bolometer signal during the evolution of a burst for a bunch current of 0.16 mA. The intensity maximum of the burst is also visible in the frequency spectrum.

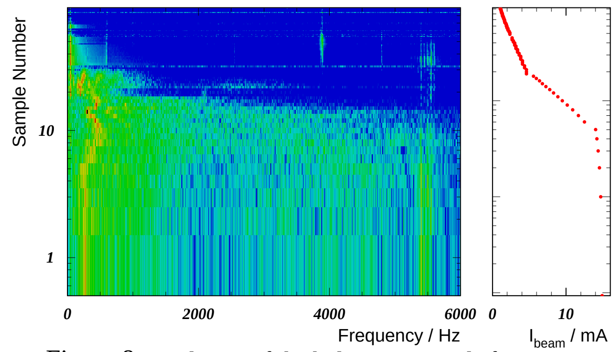

Figure 8: Evolution of the bolometer signals frequency spectrum with decreasing beam current (increasing sample number). The synchrotron frequency is 5.5 kHz.

SUMMARY

Measurements at different beam energies confirme the possibility to generate steady-state coherent synchrotron edge radiation at ANKA. First polarisation studies show the expected linear behaviour but also systematic effects that need to be taken into account. The frequency spectrum of the IR signal displayes a dependency on current and bunch length. Furhter work is needed to correlate the findings to theoretical predictions.

REFERENCES

[1] A.-S. Müller et al. Far Infrared Coherent Synchrotron Edge Radiation at ANKA. In *Proceedings of the 21st Particle Accelerator Conference*, 2005.

[2] D. Moss Y.-L. Mathis, B. Gasharova. Terahertz radiation at ANKA, the new synchrotron light source in Karlsruhe. In *Journal of Biological Physics 29*, pages 313–318. 2003.

[3] F. Perez et al. Beam Size and Bunch Length Measurements at the ANKA Storage Ring. In *Proceedings of the 20th Particle Accelerator Conference*, 2003.

[4] A.-S. Müller et al. Momentum Compaction Factor and Nonlinear Dispersion at the ANKA Storage Ring. In *Proceedings of the 9th European Particle Accelerator Conference*, 2004.

[5] N.R. Lomb. In *Astrophysics and Space Science*, volume 39, pages 447–462. 1976.

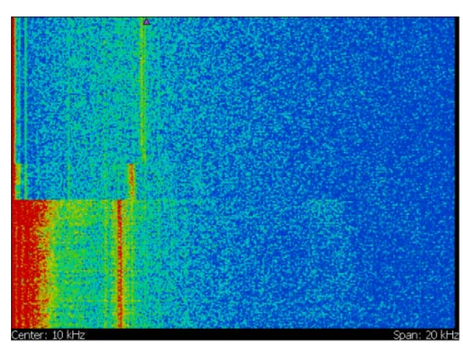

Figure 9: Spectrogram of the bolometer signal as a function of time (moves downward) during a “low α_c squeeze” at a (constant) low bunch current. The steps in synchrotron frequency are clearly visible.