OBSERVATION OF COHERENT THZ RADIATION FROM THE ANKA AND MLS STORAGE RINGS WITH A HOT ELECTRON BOLOMETER*†

A.-S. Müller, I. Birkel, E. Huttel, Y.-L. Mathis, N. Smale, FZK, Karlsruhe, Germany
H.-W. Hübers, A. Semenov, DLR, Berlin, Germany
J. Feikes, M. v. Hartrott, G. Wüstefeld, HZB, Berlin, Germany
R. Klein, R. Müller, G. Ulm, PTB, Berlin, Germany
E. Bründermann, Ruhr-Universität Bochum, Germany
T. Bückle, M. Fitterer, S. Hillenbrand, N. Hiller, A. Hofmann,
V. Judin, M. Klein, S. Marsching, K.G. Sonnad, Universität Karlsruhe (TH), Germany

Abstract

In synchrotron radiation sources coherent radiation is emitted when the bunch length is comparable to or shorter than the wavelength of the emitted radiation. A detector system based on a superconducting NbN ultra-fast bolometer with an intrinsic response time of about 100 ps jointly developed by the University of Karlsruhe (Institute of Micro- and Nanoelectronic Systems) and German Aerospace Center (Berlin) was used to resolve the radiation emitted from single bunches. This paper reports the observations made during first measurements at the MLS [1] and ANKA [2] storage rings.

INTRODUCTION

Coherent synchrotron radiation (CSR) is emitted from electron storage rings for wavelengths equal to or larger than the length of the electron bunches (see for example [2–4]). The high-intensity CSR typically covers the frequency range up to about 1.5 THz. In the emission of coherent radiation, the amplitudes of the electromagnetic fields add up linearly, resulting in a quadratic enhancement of the radiation's intensity. The total power radiated by a bunch consisting of N particles can be expressed as

$$P_{\text{total}} = N P_{\text{incoherent}} \left(1 + N f_\lambda\right)$$

where f_λ is a form factor describing the effect of the longitudinal charge distribution in the bunch. For a Gaussian charge distribution with RMS length σ_s the form factor is given by $f_\lambda = \exp\left(-(2\pi\sigma_s/\lambda)^2\right)$. This shows that the radiated intensity for a given wavelength will increase with decreasing bunch length. An ultra-fast detector, such as a hot electron bolometer can resolve single bunches of a multi-bunch filling, thus making it possible to study not only single bunch effects with varying currents in a single shot but also possible influences on the THz emission from the filling pattern. In the following, we describe observations made with such a detector during measurements at the MLS [1] and ANKA [2] storage rings.

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THE HOT ELECTRON BOLOMETER

To resolve radiation from single bunches, a detector system based on a superconducting NbN ultra-fast bolometer [5] with an intrinsic response time of ≈100 ps was used. The system was jointly developed by the University of Karlsruhe (Institute of Micro- and Nanoelectronic Systems) and the German Aerospace Center (Berlin). The NbN bolometer is embedded into a planar log-spiral antenna which is integrated with an elliptical silicon lens. The detector covers the spectral range from 10 to 150 cm^{-1} mainly determined by the antenna [6]. The response to a few picoseconds long radiation pulse had the full width at half maximum of 165 ps that was defined by readout electronics. A system noise equivalent power of 6×10^{-9} W Hz$^{1/2}$ was optically measured for cw radiation at 0.8 THz. Figure 1 shows a photograph of the hot electron bolometer (HEB). The HEB signal of two consecutive bunches measured at the MLS is displayed in Fig. 2. The resolution of the bunch length is in this case limited by the bandwidth of 2.5 GHz of the oscilloscope used for the measurement.

The nonlinear dependence of the emitted THz radiation on the bunch current can be shown directly for an inhomogeneous filling of the storage ring [7]. For the measurements displayed in Fig. 3, the ANKA storage ring was filled with three trains of about 30 bunches each. The filling pattern was made as inhomogenous as possible in or-

Figure 1: Photograph of the detector system used for the experiments described in this paper.

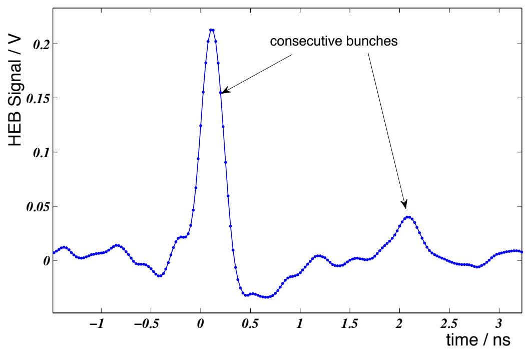

Figure 2: Hot electron bolometer signal as a function of time showing in high resolution two consecutive bunches of different current in the MLS. The resolution of the bunch length is in this case limited by the bandwidth of 2.5 GHz of the oscilloscope used for the measurement. The FWHM of the signal from the readout electronics of the bolometer is 165 ps.

der to study, among other things, the dynamic behaviour of the detector system and the dependence on the individual bunch currents. The relative bunch currents also shown in the plot were determined from the sum signal of the four button electrodes of a beam position monitor. As expected, the bunches with higher currents show a much stronger dependence on the current than those with currents below the threshold for bursting emission. This will be discussed in more detail in the following section.

MEASUREMENTS

Studies of the Bursting Threshold

The HEB signal of Fig. 3 as a function of the corresponding single bunch current is shown in Fig. 4 and compared to the expected bursting threshold for the given accelerator parameters ($E_0 = 1.3\,\mathrm{GeV}$, $V_{\mathrm{RF}} = 150\,\mathrm{kV}$) derived from theoretical calculations [8]. At low currents the radiated

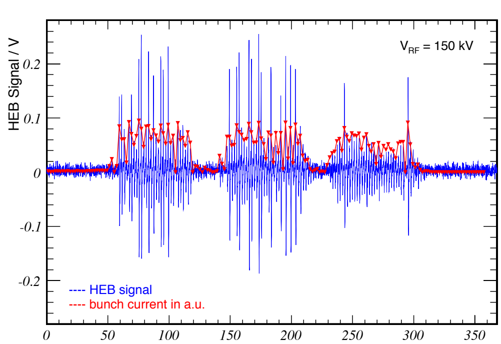

Figure 3: HEB signal showing clearly the filling pattern in the ANKA storage ring (blue). The red data points represent the relative bunch currents derived from the sum signal of four button electrodes. In order to have as broad a range in bunch currents as possible, a very inhomogeneous filling pattern was enforced.

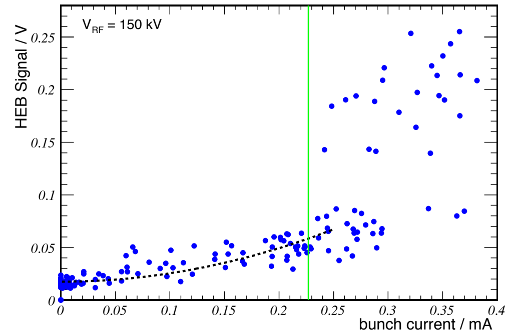

Figure 4: HEB signal of Fig. 3 as a function of the corresponding single bunch current. The line marks the expected bursting threshold for the given accelerator parameters. The dashed curve, a fit of a quadratic dependence on bunch current to the measurements, was added to guide the eye.

power is described by a quadratic dependence on bunch current. For bunch currents above the threshold value, the quadratic dependence breaks down and the bursting with higher emitted THz power dominates.

Saturation and Linearity

To find the limitations of the HEB w.r.t. incident power, the ANKA storage ring was operated with a higher RF voltage resulting in shorter bunches and a corresponding increase in emitted power. Figure 5 shows the HEB signal for an RF voltage of $V_{\mathrm{RF}} = 400\,\mathrm{kV}$. Maximum signal levels of around 0.4 V were observed. For these high signal levels, the HEB signal of the individual bunches does not follow the variations seen in the filling pattern and shows a largely current independent behaviour, pointing towards saturation effects in the detector.

Far away from the saturation region, however, the detector shows a perfectly linear behaviour. This is demonstrated in Fig. 6, where the signal strength is displayed as

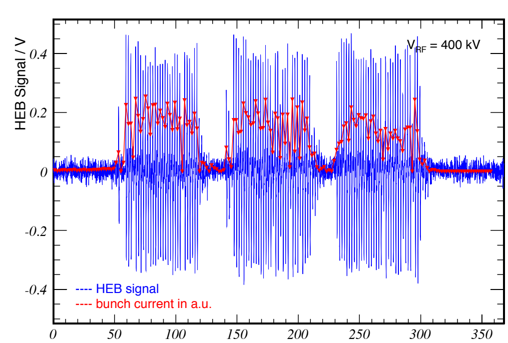

Figure 5: HEB signal for a different set of accelerator parameters ($E_0 = 1.3\,\mathrm{GeV}$, $V_{\mathrm{RF}} = 400\,\mathrm{kV}$) resulting in shorter bunches and an increased power of the THz signal (blue). The red data curve shows the relative bunch currents. For large currents the HEB signal shows clear signs of saturation, i.e. it becomes largely independent of the bunch current.

a function of absorber thickness. Four absorbers consisting of $(360 \pm 5)\,\mu$m thick black paper were used. For the measurement bunches with currents of $I_{bunch} = (0.39 \pm 0.03)$ mA were selected. The attenuation of the signal is well described by an exponential decay.

Bunch-by-Bunch Multi-Turn Studies

Multi-turn studies of the HEB signal were performed for bunches with current above and below the stable-bursting threshold. Basis for these measurements was the continuous acquisition of the HEB signal with a 6 GHz oscilloscope over a period of about 1.5 ms (about 4100 turns). In order to become independent of sampling induced phase shifts, a peak-finding algorithm was employed to select the signal for each turn. The THz signal from 4100 turns was then analyzed by an FFT. Figure 7 shows the results for a high current bunch. In a addition to a long-term structure of the THz signal one clearly sees the synchrotron tune of the machine as well as some higher harmonics. The same analysis for a low-current bunch as displayed in Fig. 8 shows no significant features.

SUMMARY AND OUTLOOK

First results from a study of THz emission from short bunches with a hot electron bolometer have been presented. The device shows excellent time resolution with 165 ps FWHM and linear response for signal levels within the region of interest. The stable/bursting threshold was seen in a single shot measurement in good agreement with theoretical expectations. In multi-turn studies of THz radiation from individual bunches above the bursting threshold, the harmonic modulation of the THz emission with the synchrotron tune and its higher harmonics was observed. In summary, the results underline the high potential of the hot electron bolometer for accelerator physics. Future measurements with this detector system are planned to further explore the influence of the filling pattern on the emission characteristics and the time evolution of the signal of the individual bunches.

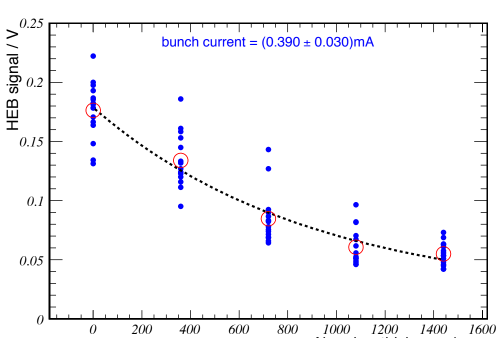

Figure 6: HEB signal as function of absorber thickness. The red circles represent the average of the dataset for each absorber thickness. The dashed curve is a the result of an expontial fit to the data.

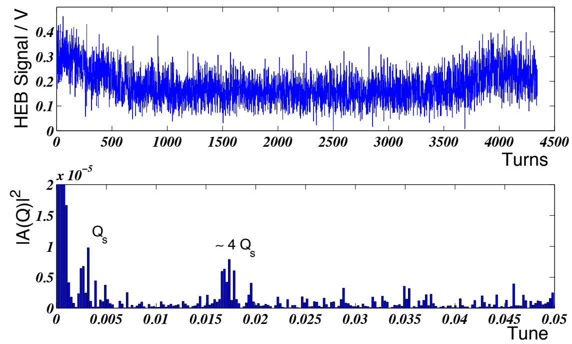

Figure 7: HEB signal of single bunch with a high bunch current above the bursting threshold for about 4100 consecutive revolutions (top) and FFT of signal (bottom). The frequency spectrum shows the synchrotron tune and the fourth harmonic of the synchrotron tune.

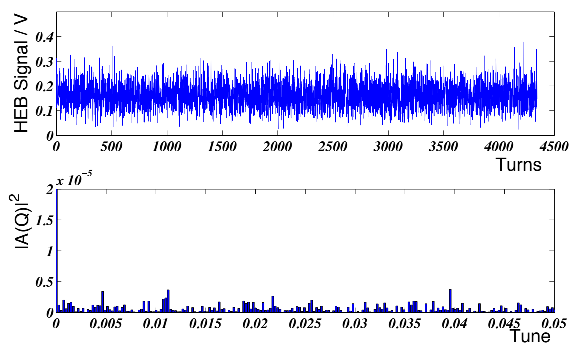

Figure 8: Top: HEB signal of single bunch with a low bunch current for about 4100 consecutive revolutions (top) and its FFT (bottom). No significant features are seen.

REFERENCES

[1] R. Klein, *et al.*, Operation of the Metrology Light Source as a primary radiation source standard, Phys. Rev. ST Accel. Beams, 11 (2008) 110701.

[2] A.-S. Müller *et al.*, Far Infrared Coherent Synchrotron Edge Radiation at ANKA, PAC05 Knoxville, USA (2005) 2518.

[3] M. Abo-Bakr *et al.*, Coherent mm-Radiation Experiments at the BESSY II Storage Ring, EPAC 2000 Vienna, Austria (2000) 720.

[4] G. Wüstefeld *et al.*, Low Alpha Operation of the MLS Electron Storage Ring, PAC09 Vancouver, Canada (2009).

[5] Yu.P. Gousev, G.N. Gol'tsman, A.D. Semenov *et al.*, Broadband ultrafast superconducting NbN detector for electromagnetic radiation, J. Appl. Phys. 75 (1994) 3695.

[6] A.D. Semenov, H. Richter, H.-W. Hübers *et al.*, Terahertz performance of integrated lens antennas with a hot-electron bolometer, IEEE Transactions on Microwave Theory and Techniques 55 (2007) 239.

[7] H.-W. Hübers, *et al.*, Time domain analysis of coherent terahertz synchrotron radiation. Appl. Phys. Lett. 87 (2005) 184103.

[8] M. Klein *et al.*, Studies of Bunch Distortion and Bursting Threshold in the Generation of Coherent THz Radiation at the ANKA Storage Ring, PAC09 Vancouver, Canada (2009).