CHARACTERIZING THz COHERENT SYNCHROTRON RADIATION AT THE ANKA STORAGE RING*†

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Abstract

In a synchrotron radiation source coherent infrared (IR) radiation is emitted when the bunch length is comparable to the wavelength of the emitted radiation. To generate coherent THz (far IR) radiation, the ANKA storage ring is operated regularly in a dedicated low-alpha optics. Different bunch lengths, corresponding to different spectral ranges of the THz spectrum and various electron beam energies can be offered, depending on user demand. The radiation emitted in the fringe field of a dipole magnet, the so-called edge radiation, is detected at the ANKA-IR beam line. This paper presents radiation properties like THz beam profiles and power measurements in the framework of characterising the coherent THz radiation to optimise the power, frequency and spatial output of the ANKA storage ring. First experiments showed a time averaged power of up to 0.2 mW suggesting a THz pulse peak power above 1 W.

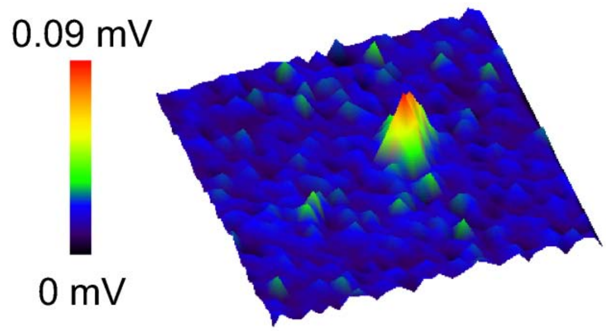

Figure 1: Transverse profile of incoherent THz synchrotron radiation at a beam energy of 1.3 GeV. The maximum detected signal at the detector was 0.09 mV for the peak intensity of the profile at a beam current of approximately 60 mA. The signal-to-noise ratio is approximately 3.

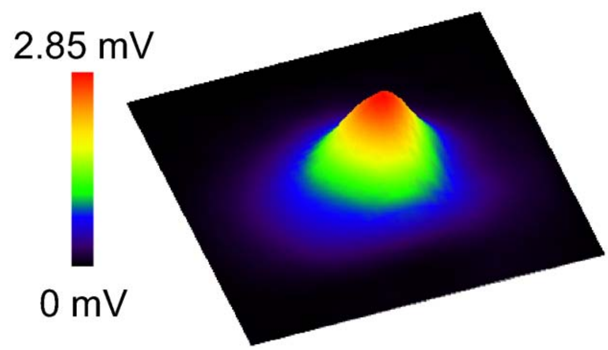

Figure 2: Transverse profile of coherent THz synchrotron radiation at a beam energy of 1.3 GeV. Although the beam current has dropped to approximately 30 mA, the maximum detected signal at the detector for the peak intensity of the profile was much higher, 2.85 mV, in comparison to the incoherent mode.

INTRODUCTION

To optimize the user operation with THz coherent synchrotron radiation at the ANKA storage ring [1], a detailed understanding of the radiation characteristics as a function of the operating conditions of the accelerator is of vital importance. To this aim, the THz power, spectrum and spatial output were measured in a series of dedicated machine experiments. This paper summarizes the results of power and profile measurements done in this framework. A first interpretation of the findings is given.

THE EXPERIMENTAL SETUP

The coherent synchrotron radiation emitted in the fringe field of a dipole magnet, the so-called edge radiation, is detected at the ANKA-IR beam line [2]. The radiation can be directed to a Fourier transform spectrometer (Bruker Vertex 60v) with an attached IR-microscope, to an IR-ellipsometer or it can directly be measured at a vacuum window consisting of silicon or CaF_2 with various thicknesses. A room temperature pneumatic (Golay) detector (QMC Instruments Ltd.) was used to detect the THz emission, since the Golay cell can achieve thermal background limited performance with a typical noise equivalent power (NEP) of 2×10^{-10} $WHz^{-1/2}$. The white high density polyethylene (HD-PE) window of the Golay cell defines an aperture of 6 mm diameter. The HD-PE window transmission decays linear in the region of interest. In addition, two 0.1 mm thick foils of black low density PE (LD-PE) are added in front of the detector to further reduce infrared and visible radiation. The THz radiation is marginally reduced by a few percent. For better spatial resolution the aperture was reduced by a thick metal plate with a hole of 1.9 mm diameter immediately attached in front of the detector. The radiation is either guided through air directly

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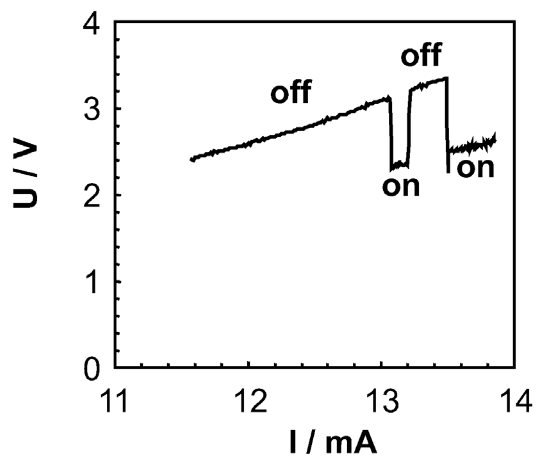

Figure 3: THz intensity as a function of total beam current. The effect of the white noise excitation of the strip line kicker on the detected THz power is clearly visible.

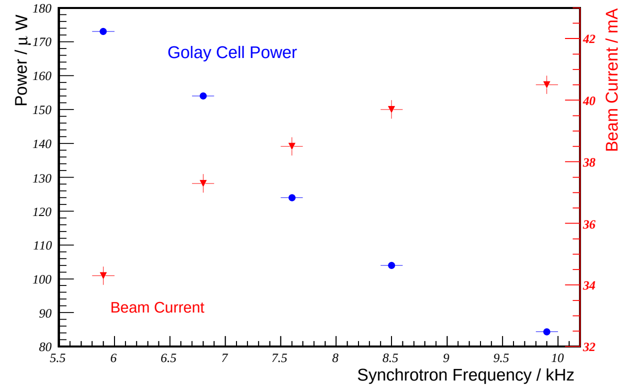

Figure 4: Average power emitted by 34 bunches of one train measured with the Golay cell as a function of the synchrotron frequency (blue, left hand ordinate axis). The total beam current for each measurement is overlayed in red (right hand ordinate axis).

to the detector with aperture for beam profiling or focused via a curved mirror to determine the integral power. The Golay detector responsivity is 32 kV/W at 10 Hz (NEP of 3.2×10^{-10} WHz$^{-1/2}$).

The radiation exiting the vacuum window is modulated by a chopper at a rate of 10 Hz. We used phase-sensitive detection for which the chopper frequency serves as the reference signal guided to a Lock-In amplifier (LIA, EG&G 7260) while the signal from the Golay detector amplifier is analyzed in amplitude and phase. A time constant of typically 200 ms is used with a band pass of 24 dB per octave. An in-house LabView program (National Instruments) handles the data acquisition via A/D-converters in a CompactRIO interface and controls the DC motor-driven stages for the x-y imaging stages (Physik Instrumente, model PI M-415.DG). The detector and aperture is mounted on the x-y imaging stage and scanned as a function of distance and the lateral position relative to the vacuum window.

RESULTS AND DISCUSSION

Figure 1 and Fig. 2 show the spatial distribution of the THz synchrotron radiation as seen at the direct port of the ANKA-IR beam line for a beam energy of 1.3 GeV. The lateral dimensions of the shown profiles are 35 mm × 40 mm. To obtain short bunches, the current is injected at 0.5 GeV and ramped to the final energy (in this case 1.3 GeV). An optics change (“squeeze”) then brings the momentum compaction factor down to the chosen end value in several steps to allow intermediate orbit and central frequency corrections. The profile of the incoherent THz signal was obtained for a beam current of about 60 mA and a bunch length of roughly 4 mm. After a squeeze to a bunch length of about 1 mm a strong coherent signal is observed. The profile displayed in Fig. 2 was measured for an average total beam current of about 30 mA. Although the current is reduced by a factor of two the observed peak voltage is significantly higher (about factor 30). The integral over the given aperture is larger by several orders of magnitude.

In low-α_c operation the beam lifetime can be as low as only about one hour depending on the machine settings. In order to increase the lifetime a white noise excitation of a horizontal and vertical strip line kicker (normally used for tune measurements) can be applied. The noise excites a vertical instability thus increasing the effective vertical beam size which in turn leads to a significant change in lifetime of up to one day. Figure 3 shows the impact of the white noise excitation on the THz power measured with the Golay detector. With excitation switched on a reduction of about 20 % is observed, probably caused by part of the radiation hitting aperture limitations. Even though the emitted power is slightly lower, the tremendous increase in life-

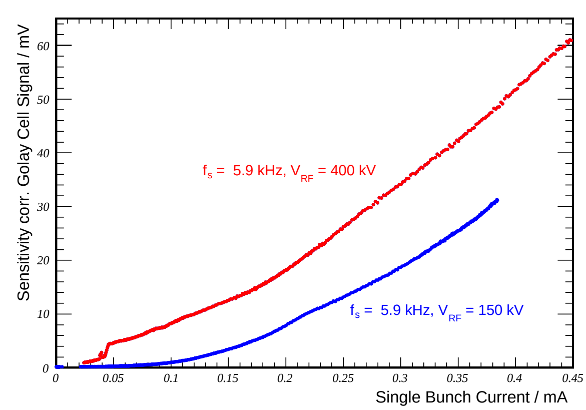

Figure 5: THz intensity as a function of the average single bunch current in the 34 bunches of one train. The upper (red) curve represents measurements at an RF voltage of 400 kV, whereas the measurements for 150 kV, corresponding to a longer bunch are shown in the lower (blue) dataset. The increase in THz intensity for a shorter bunch length is clearly visible.

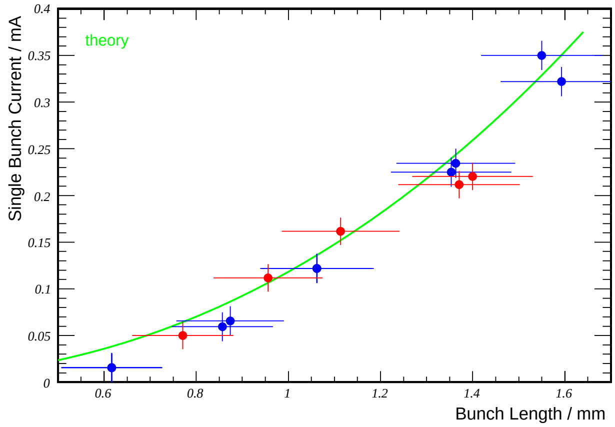

Figure 6: Equivalent single bunch currents for the threshold between steady state and bursting emission of coherent synchrotron radiation as a function of bunch length. The bunch length was derived from measurements of the coherent synchrotron frequency. The data from two different series of measurements are in good agreement and consistent with the theoretical scaling law of $I_{\mathrm{threshold}} \propto \sigma_s^{7/3}$ [3].

time still makes it a worthwhile alternative, especially since the impact of the excitation on the measured THz spectrum (not shown here) is negligible.

Figure 4 shows the time averaged THz power measured with the Golay cell detector as a function of the synchrotron frequency which is proportional to the bunch length. Also shown is the total beam current for the individual measurements. In spite of decreasing beam current, a rise THz power for decreasing bunch length is observed. Since the bursting spectrum for shorter bunches extends to higher photon energies, this observation is caused by a larger part of the emitted spectrum entering the spectral acceptance of the detector / beam line system. The maximum detected time averaged power is about 0.2 mW. Given 34 0.5 mm bunches within one train in the ANKA storage ring (h =184, T_{rev} =368 ns) this translates to a peak power of about 1.3 W.

The evolution of the THz power as a function of average single bunch current (over all 34 bunches of on train) is displayed in Fig. 5 for two different settings of the RF voltage per cavity. The increase in power for shorter bunches due to increased RF voltage ($\sigma_s \propto 1/\sqrt{V_{\mathrm{RF}}}$) is clearly visible. The growth of power with current is clearly stronger than linear. The total power radiated by sufficiently short bunch of N particles is described by

$$P_{\mathrm{total}} = N\, P_{\mathrm{incoh}}(1 + N\, f_\lambda).$$

The regions of different curvature observed in Fig. 5 could be an indication that the form factor f_λ varies for different current regimes. A change is expected, for example, at the threshold current between stable and bursting emission. The relation between bunch length and single bunch current at the threshold is shown in Fig. 6. For the shorter bunches (V_{RF} =400 kV) the expected transition is around 0.04 mA, for the longer ones around 0.12 mA. A clear jump in power at the expected current is seen for the shorter bunches in Fig. 5. For the longer bunches, a change in curvature happens at the threshold current. Additional transitions in the bursting regime seem to appear at larger currents for both bunch lengths. Furthermore multi-bunch effects might have an influence. This will be addressed once the new single bunch electron gun foreseen for installation in the 2008 winter shutdown of the ANKA facility is operational.

SUMMARY AND OUTLOOK

Coherent THz synchrotron radiation from the ANKA storage ring has been investigated using a Golay cell detector. The transverse profile of the incoherent and coherent THz beam at the ANKA-IR beam line has been determined. It has been shown that a white noise excitation used to increase the beam lifetime by up to an order of magnitude leads to only a 20 % reduction of THz power. Variation of the bunch lengths with momentum compaction factor reduction allows to adjust the power output to the detector. The peak power achieved in this setup was about 1.3 W. Studies of the THz radiation power as a function of the average single bunch current with the Golay cell indicate several distinct regimes. The transition between steady state radiation and bursting emission, for example, is clearly seen. An independent study of the bursting / stable threshold current as a function of bunch length based on measurements with a Si bolometer shows very good agreement with theoretical predictions of the bursting threshold [3].

Future studies will exploit a single bunch electron gun and a Hot Electron Bolometer able to resolve individual bunches. In addition single and multi-bunch effects in the polarisation of THz coherent synchrotron radiation will be investigated.

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