STATUS OF SCHOTTKY DIAGNOSTICS IN THE ANKA STORAGE RING*

K. G. Sonnad, N. Hiller, Universität Karlsruhe (TH), Germany
F. Caspers, CERN, Geneva, Switzerland,
I. Birkel, S. Casalbuoni, E. Huttel, A.-S. Müller, N. Smale, FZK, Karlsruhe, Germany
R. Weigel, MPI-MF, Stuttgart, Germany

Abstract

The status of observations of longitudinal Schottky signals at the ANKA storage ring is presented. After a short review of the theory, experimental setup and results are discussed. Special care had to be taken to control and mitigate the impact from strong coherent lines of the short bunches on the signal processing chain. Evidence for Schottky-like signals was observed.

INTRODUCTION

Over the years, it has been widely regarded that Schottky signals cannot be observed in electron rings because the coherent signal dominates over the incoherent one. This is largely because (1) shorter bunches lead to a strong coherent signal, (2) synchrotron radiation contributes to background noise. However, one should note that signals obtained from pick-ups always contain a mixture of coherent and incoherent lines for bunched beams. [1]. For example the coherent signal problem was overcome at the SPS at the revolution harmonic after careful filtering of unwanted frequencies [2]. In this paper, we discuss that it may be possible to observe Schottky-like signals in an electron storage ring with appropriate signal processing and frequency band selection. In fact the first detection of these signals in a d.c. electron beam was done in 1918 [3]. As an interesting point in the context of optical stochastic cooling (THz range), which requires the availability of incoherent signals in order to identify individual particels, demonstration experimetns using electron beams have been proposed and discussed [4].

ANKA is an electron storage ring used as a synchrotron radiation source operating in the energy range from 0.5 to 2.5 GeV. The revolution frequency is about 2.7 MHz. In addition to the regular 2.5 GeV mode of operation, the storage ring is periodically operated in a "low-α_c mode" at energies of 1.3 or 1.6 GeV for the generation of coherent THz radiation from short bunches. The study of the longitudinal spectrum will help to understand the complex dynamics in this operation mode.

THEORETICAL CONSIDERATIONS

A charged particle bunch can be viewed, e.g., as a rigid body or a large number of discrete particles. The "rigid body" model can be generally associated with global quantities such as total charge, etc. Effects arising form the discrete particles are referred to as Schottky noise. The spectrum produced by the "rigid bunch" is referred to as the coherent signal, while the incoherent signal arises from random phases of the individual particles. The amplitude of the coherent signal would be proportional to N^2 while that of the incoherent one would be proportional to the number of particles N.

Bunch with Fixed Density Profile

Following [5], we start with the analysis for a bunch with a fixed profile given by $g(t)$. In this case, the beam current $I(t)$ can be expressed as

$$I(t) = eN \sum_{n=-\infty}^{\infty} g(t - nT_0) \tag{1}$$

where, e is the fundamental charge, N is the number of particles, T_0 is the beam revolution period. This could be expressed as a Fourier sum given by

$$I(t) = \sum_{n=-\infty}^{\infty} I_n \exp(-in\omega_0 t) g(t) \tag{2}$$

where ω_0 is the angular revolution frequency and

$$I_n = I_0 \tilde{g}(n\omega_0) \tag{3}$$

is the n^{th} Fourier component of the bunch profile and $\tilde{g}$ is the Fourier transform of g. This may be expressed as

$$I_n = \frac{1}{T_0}\int_0^{T_0} dt I(t) \exp(-in\omega_0 t) \tag{4}$$

The average current is given by $I_0 = Ne/T_0$, and we employ the normalization $\tilde{g}(0) = 1$

Bunch with Individual Particles

The current contributed by a single particle can be represented as

$$I(t) = e \sum_{n=1}^{\infty} \delta(t - nT_0) \tag{5}$$

Employing the same procedure of Fourier decomposition, we get

$$I(t) = ef_0 \sum_{n=-\infty}^{\infty} \exp(in\omega_0 t) \tag{6}$$

For a sum of N particles, this could be expressed as

$$I(t) = ef_0 \sum_{p=1}^{N} \sum_{n=-\infty}^{\infty} exp(in\omega_0^{(p)} t) \tag{7}$$

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where (p) is the index of the specific particle. In this expansion, we assume that each particle has a different revolution frequency ω_0. The spread in the revolution frequency is associated with the energy spread of the particles through the slippage term η, As a result, we get

$$\frac{\Delta E}{E_0} = -\frac{1}{\eta}\frac{\Delta(\omega_n)}{n\omega_0} \tag{8}$$

where the observed frequency $\omega_n = n\omega_0$. Thus the observed spread is amplified by a factor of n the revolution harmonic.

Synchrotron Oscillations w. Fixed Bunch Profile

With synchrotron oscillations, the current for a bunch profile $g(t)$ is given by,

$$I(t) = eN \sum_{n=-\infty}^{\infty} g[t - nT_0 + A\cos(\omega_s t + \phi)] \tag{9}$$

where ω_s is the synchrotron frequency, ϕ is an arbitrary phase, and A is an oscillation amplitude. For synchrotron frequencies much smaller than the revolution frequency, we can make a Fourier decomposition of the current as follows.

$$I(t) = \sum_{n=-\infty}^{\infty} I_n \exp\{in\omega_0[t + A\cos(\omega_s t + \phi)]\} \tag{10}$$

Here, I_n has the same expression as in the coasting beam case. Using the identity $\exp[iz\cos(\theta)] = \sum_{k=-\infty}^{\infty} i^k J_k(z)\exp(ik\theta)$, we can further expand the above expression as follows,

$$I(t) = \sum_{n,k} I_{nk} \exp[i(n\omega_0 + k\omega_s)t] \tag{11}$$

with the coefficient I_{nk} given by,

$$I_{nk} = I_0 \tilde{g}(n\omega_0) J_k(n\omega_0 A)\exp(ik\phi) i^k \tag{12}$$

Synchrotron Oscillations w. Individual Particles

The current due to a bunch with individual particles executing synchrotron oscillations may now be expressed as

$$I(t) = e\sum_{n=-\infty}^{\infty}\sum_{p=1}^{N} \delta[t - nT_0^{(p)} + A^{(p)}\cos(\omega_s^{(p)}t + \phi^{(p)})] \tag{13}$$

Using Eq (12) this can be expanded as follows,

$$I(t) = \sum_{p}\sum_{n,k} I_{nk}^{(p)} \exp[i(n\omega_0^{(p)} + k\omega_s^{(p)})t] \tag{14}$$

This equation indicates that, for $\omega_0 \gg \omega_s$, and $n \gg k$, the spread in the peak is dominated by the contribution from the revolution frequency spread $\Delta\omega_0$ while the contribution from $\Delta\omega_s$ is insignificant. In electron storage rings, the conditions are such that the synchrotron side bands are usually separated from the revolution harmonic band, which translates to $\omega_s \geq n\Delta\omega_0$. This condition would hold true even for $n \approx 1000$. On the other hand, with hadron storage rings, one could expect that the synchrotron side bands are buried in the revolution harmonic spread, so $\omega_s \leq n\Delta\omega_0$.

In the above equation, the coefficient $I_{nk}^{(p)}$ is given by

$$I_{nk}^{(p)} = \frac{e}{T_0} J_k(n\omega_0^{(p)} A^{(p)})\exp(ik\phi^{(p)}) i^k \tag{15}$$

Here, the phase $\phi^{(p)}$ for the individual particle is random. As a result of this, for $k \geq 0$, the power of the signal is proportional to N, the number of particles, corresponding to an incoherent signal. It is easy to see that this is not true when $k = 0$, the revolution harmonic, because of the absence of the factor $\exp(ik\phi^{(p)})$ in I_{n0}. Thus, while electron storage rings suffer from the disadvantage of a high coherent to incoherent signal ratio at the revolution harmonic, they also offer the advantage that the synchrotron side bands are separated from the revolution harmonic spread, where this ratio is much smaller. The coherent signal in the side band is a result of the longitudinal oscillation of the beam centroid and is given by Eq (11).

EXPERIMENTAL RESULTS

For the measurements, the signal of an annular electrode (AE) installed in the ANKA storage ring was subjected to a band pass filter around the RF harmonic. This helps to reduce the amount of signal that could otherwise affect adversely the spectrum analysis. The filtered signal is then amplified to bring the rather small synchrotron sidebands out of the noise level. A sketch of the setup is shown in Fig. 1. The spectrum analyzer used was a HP 8562E (range of 30 Hz to 13.2 GHz). The AE used for the measurements described in the following is a narrow ring-like pick-up with a single feed-through. In order to determine the frequency response of the system consisting of the AE and the total cable length (about 20 m) the signal amplitude of the RF harmonics was measured as a function of frequency. The result is displayed in Fig. 2. Up to about 3 GHz the amplitudes only show a small decay. The total phase noise of RF system and klystron measured directly (without amplifier or filter) at a wave guide pick-up is shown together with an AE signal recorded with identical settings in Fig. 3. The shape of the total phase noise clearly dominates the shape of the revolution peak's base.

The noise floor of the setup was determined to be −105 dBm at a central frequency of 2.7 GHz for a 500 kHz span and a resolution bandwidth of 1 kHz. Two frequency bands were studied: one close to the 500 MHz RF harmonic at 465 MHz and one at 2732 MHz (that is close to the vacuum chamber cut-off of ≈ 2600 MHz). The higher frequency range sees slightly less signal from the AE and the filter with 1.65 MHz bandwidth has a loss of 5 dB. The amplifier for this range operates with a gain of 32 dB. The measurement is shown in Fig. 4. For this dataset the noise

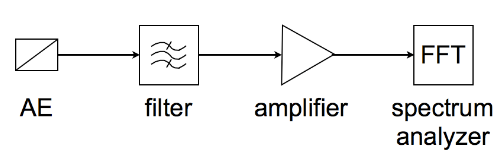

Figure 1: Sketch of the measurement setup for the annular electrode (AE). The amplifier and filter for each frequency band under study were matched. The spectrum analyzer used was a HP 8562E.

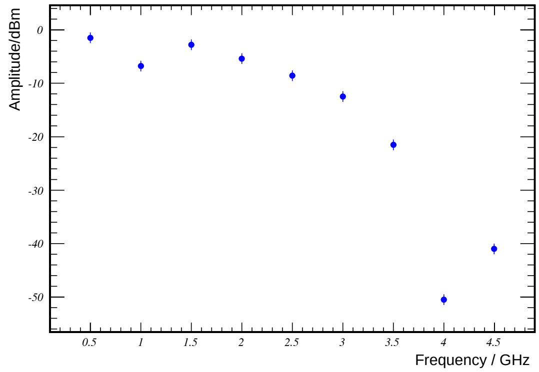

Figure 2: Amplitude of an RF harmonic as a function of frequency. This measurement represents the characteristics w.r.t. frequency of the annular electrode (including cables etc.) used in the studies presented here. Up to about 3 GHz the curve is reasonably flat.

level measurement translates to a floor of −115 dBm. From Fig. 2 we see that the lower frequency range experiences a slightly higher signal level from the AE. The band pass filter used here had 2 dB loss and a bandwidth of 0.643 MHz. The amplifier has a gain of 40.1 dB. The result is displayed in Fig. 5. In this case the noise floor is roughly −110 dBm. Both Fig. 4 and Fig. 5 show clearly the first synchrotron sideband. For the higher frequency band, even the second harmonic is just visible. Although the expected total signal level should be lower, the base seems to be elevated in comparison to the lower frequency band. One possible explanation could be an influence from a detection of coherent synchrotron radiation from the short bunches (<50 ps). It seems safer, therefore, to measure far away from the waveguide cut-off. This is the case for Fig. 5. A closer look reveals an asymmetric (triangular) shape of the synchrotron sidebands, an effect that has been described for the case of peak detected Schottky signals in a proton machine [1]. The ratio between the coherent central peak and incoherent sidebands is expected to be proportional to the number of

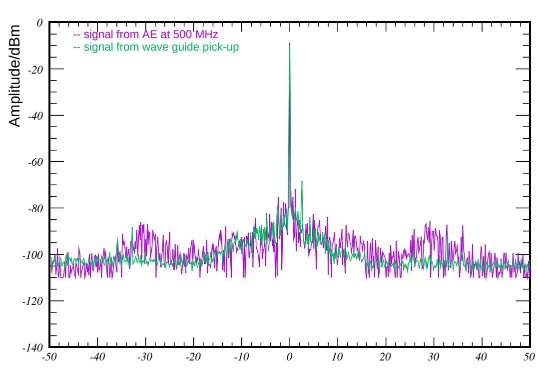

Figure 3: Spectrum of the AE at the 500 MHz revolution harmonic showing the upper and lower first synchrotron sideband and the signal obtained from a wave guide pick-up. The total phase noise of RF system and klystron clearly dominates the shape of the central peak's base.

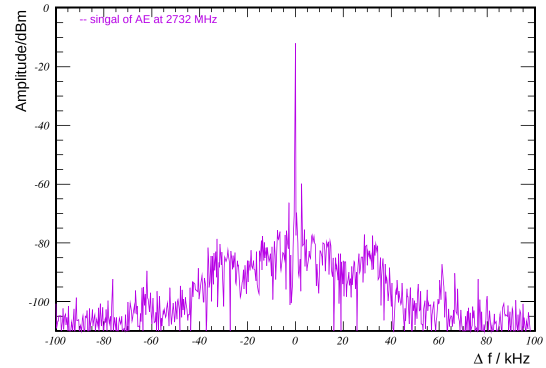

Figure 4: Spectrum of the AE at the 2732 MHz revolution harmonic showing the upper and lower first synchrotron sideband. The second sideband is just visible. The spectrum was recorded with a resolution bandwidth of 100 Hz and for a span of 200 kHz.

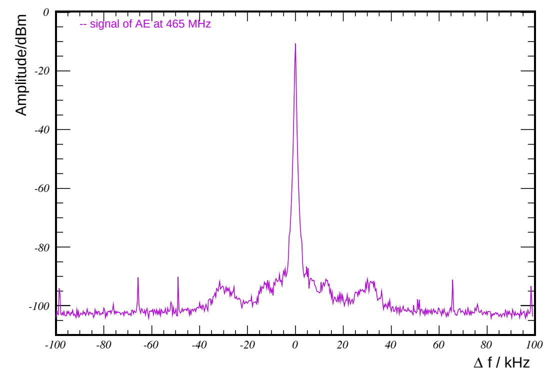

Figure 5: Spectrum of the AE at the 465 MHz revolution harmonic showing the upper and lower first synchrotron sideband. The second sideband is not visible. The spectrum was recorded with a resolution bandwidth of 300 Hz and for a span of 200 kHz with video averaging turned on.

particles, that is to be about 90 dB. Figure 5 shows a ratio of roughly 80 dB, which could be an indication that we observe a mixture of coherent and incoherent (Schottky-like) signals. The fact that the width of the sidebands is larger than the one of the revolution harmonic points in the same direction.

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