STUDIES OF CURRENT DEPENDENT EFFECTS AT ANKA

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Abstract

The ANKA electron storage ring is operated at energies between 0.5 and 2.5 GeV. A major requirement for a synchrotron light source, such as ANKA, is to achieve a high beam current. A multitude of mostly impedance related effects depend on either bunch or total beam current. This paper gives an overview over the various beam studies performed at ANKA in this context, specifically the observation of current dependent detuning, the determination of the bunch length change with current from a measurement of the ratio between coherent and incoherent synchrotron tune and an assessment of the effective longitudinal loss factor from the current dependent horizontal closed orbit distortion.

INTRODUCTION

The transverse impedance is commonly described by several broadband resonators of the form

$$Z_1^{\perp}(\omega) = \frac{c}{\omega}\frac{R_s}{1 + iQ\left(\frac{\omega_r}{\omega} - \frac{\omega}{\omega_r}\right)} \quad (1)$$

where ω_r is the angular resonance frequency, and R_s has dimensions of $\Omega\mathrm{m}^{-2}$. The horizontal impedance Z_x is related to R_s by $R_s = Z_x\omega_r/c$. The complex frequency shift for the $l = 0$ head-tail mode of a Gaussian bunch is [1]

$$\Omega - \omega_\beta = -i\frac{N_b ec^2}{4\sqrt{\pi}(E/e)T_0\omega_\beta\sigma_z}\,(Z_1^{\perp})_{\text{eff}} \quad (2)$$

where $\omega_\beta = Q_\beta\omega_0$ is the angular betatron frequency (including integer part), Q_β the betatron tune, ω_0 the angular revolution frequency, N_b the bunch population, e the electron charge, c the speed of light, σ_z the RMS bunch length, and E the beam energy. The frequency shift is proportional to the effective impedance [2] defined by

$$(Z_1^{\perp})_{\text{eff}} = \frac{\sum_{p=-\infty}^{\infty} Z_1^{\perp}(\omega_p)h_0(\omega_p - \omega_\xi)}{\sum_{p=-\infty}^{\infty} h_0(\omega_p - \omega_\xi)} \quad (3)$$

where, for a Gaussian beam, $h_0(\omega_p) = \exp(-\omega_p^2\sigma_z^2/c^2)$, $\omega_p = p\omega_0 + \omega_\beta$ and $\omega_\xi = \xi\omega_\beta/\alpha_c$ with $\xi = Q'/Q_\beta = \frac{\Delta Q_\beta}{Q_\beta}/\frac{\Delta p}{p}$ denoting the chromaticity and α_c the momentum compaction factor. The chromaticity enters in Eq.(3) only through the frequency shift ω_ξ.

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DETUNING WITH TOTAL CURRENT

The tune shift with bunch current is given by the real part of the complex frequency shift, *i.e.*, $\Delta Q_\beta/\Delta I_{\text{bunch}} \propto \text{Re}(\Omega - \omega_\beta) \propto \text{Im}(Z_1^{\perp})_{\text{eff}}$.

Figure 1 shows the measured vertical betatron tune as a function of total beam current. The solid line is a straight line fit to the data. The measurement was done at the injection energy of 0.5 GeV because the effect is expected to be largest there and therefore has the highest impact on machine operation. The vertical tune shift with bunch

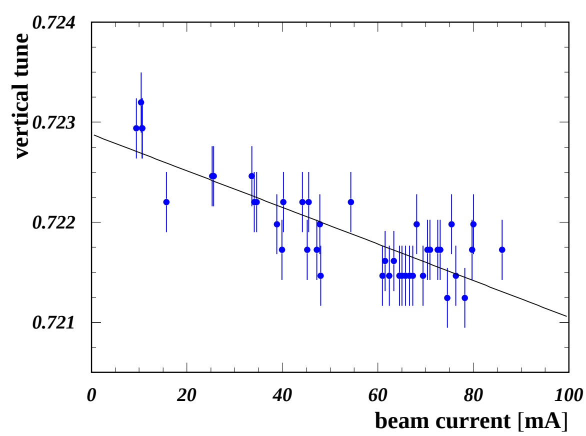

Figure 1: Vertical betatron tune as a function of total beam current. The solid line is a straight line fit to the data. The detuning with current derived from this measurement at a beam energy of 0.5 GeV amounts to $\Delta Q_y/I_{\text{bunch}} = -(0.55 \pm 0.06)$ 1/A.

current is determined from the slope of the straight line in Fig. 1: $\Delta Q_y/I_{\text{bunch}} = -(0.55 \pm 0.06)$ 1/A. This leads to an effective impedance according to Eq.(3) of $(Z_1^{\perp})_{\text{eff},y} = (0.34 \pm 0.03)$ MΩ/m for a betatron tune of 2.72 and a bunch length of about 20 mm [3].

A measurement of the horizontal tune shift with bunch current is shown in Fig. 2. Again, the measurement was performed at a beam energy of 0.5 GeV. The solid line is a straight line fit to the data. The resulting horizontal detuning with bunch current of $\Delta Q_x/I_{\text{bunch}} = -(0.06 \pm 0.06)$ 1/A is about a factor 10 smaller than in the vertical plane and compatible with zero. However, the observed detuning corresponds to the effective impedance $(Z_1^{\perp})_{\text{eff},x} \approx 0.09$ MΩ/m for a betatron tune of 6.79 which is a bit less than factor two expected from the aspect ratio of the vacuum chamber dimensions (the ANKA storage ring has an elliptical chamber of dimensions 70×32 mm) [4] but is still in reasonable agreement with it, considering the large uncertainty of the horizontal tune shift.

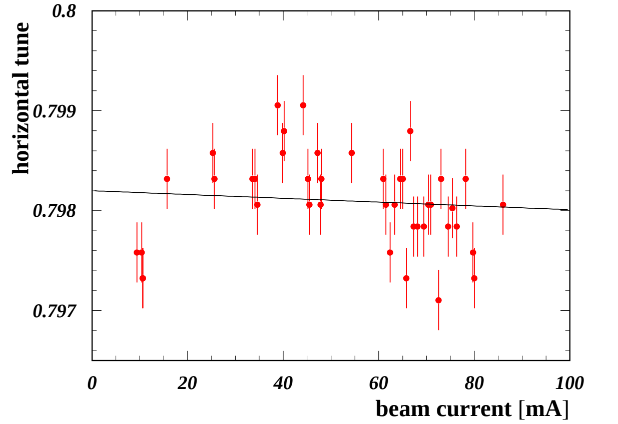

Figure 2: Horizontal betatron tune as a function of total beam current at a beam energy of 0.5 GeV . The solid line is a straight line fit to the data. The resulting detuning with current is a factor 10 smaller than in the vertical plane and compatible with zero: $\Delta Q_x/I_{\text{bunch}} = -(0.06 \pm 0.06)$ 1/A.

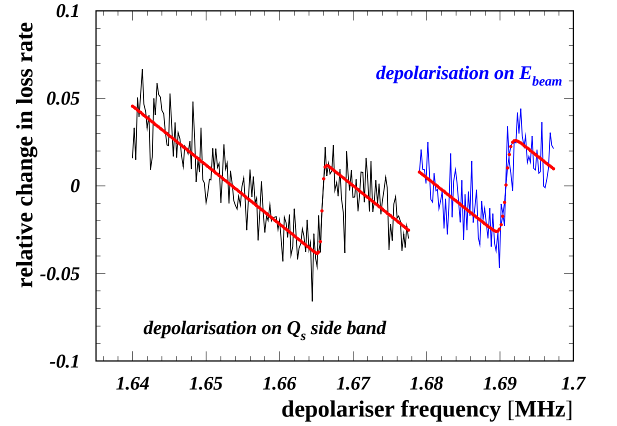

Figure 3: Relative change in the counting rate of a Pb-Glass loss monitor positioned in a Touschek sensitive region of the storage ring as a function of depolariser frequency. The visible jumps in the rate occur for resonances with spin tune (at 1.69 MHz) or with a incoherent synchrotron side band of the latter (at 1.65 MHz). The measurements were done at a beam energy of 2.5 GeV.

Employing the approximate relation between transverse and longitudinal impedance $Z_{||}/n \approx a^2/(2R)(Z_1^{\perp})_{\text{eff}}$ where a is the chamber dimension and R the average radius of the accelerator, one can also derive an estimate for the longitudinal impedance. This estimate should be based on the true transverse impedance and not on $(Z_1^{\perp})_{\text{eff}}$ which was derived from a tune shift that is in fact a combination of impedance and detuning wake. For the vacuum chamber dimensions of the ANKA storage ring one finds $(Z^{\perp}) \approx 1/2(Z^{\perp})_{\text{eff}}$ [4]. This leads to a longitudinal impedance of $Z_{||} \approx 1.3\ \Omega$. (to be compared with the calculation of 0.5 Ω).

INCOHERENT SYNCHROTRON TUNE

The dependence of the bunch length σ_s on the bunch current I_{bunch} and in particular the sign of the change in length contains useful information about the longitudinal impedance. Furthermore a change in bunch length and therefore of the impedance with current has to be taken into account in all analyses of current dependent effects. The RMS bunch length can be calculated from the energy spread and the incoherent synchrotron tune using

$$\sigma_s = \frac{\sigma_\varepsilon}{E}\frac{\alpha_c R}{Q_s^{\text{inc}}}. \qquad (4)$$

for momentum compaction factor α_c and average radius R. According to [5] the ratio of coherent and incoherent synchrotron tune can be expressed as

$$\frac{Q_s^{\text{coh}}}{Q_s^{\text{inc}}} = 1 - \lambda I_{\text{bunch}} \qquad (5)$$

which clearly indicates the current dependence. The main difficulty lies in the determination of Q_s^{inc} because measurements of Q_s from a power spectrum of a beam oscillation detected with e.g. a strip line only yield the coherent synchrotron tune Q_s^{coh}. Measurements of the true ANKA beam energy with the method of resonant depolarisation [6] have shown that it possible to depolarise the beam not only for a kicker frequency corresponding to the beam energy – the spin precession frequency, or spin tune – but also on its synchrotron side bands. Figure 3 shows such a scan of kicker frequency featuring two depolarisations: one at the beam energy and one on a synchrotron side band. Due to the single particle nature of the depolarisation process, this happens at kicker frequencies f_{dep} with

$$\frac{f_{\text{dep}}}{f_{\text{rev}}} = [\nu] \pm Q_s^{\text{inc}} \qquad (6)$$

where $[\nu]$ stands for the fractional part of the spin tune, f_{rev} for the revolution frequency and Q_s^{inc} for the incoherent synchrotron tune. A simultaneous measurement of Q_s^{coh} therefore allows a direct assessment of the lengthening factor λ in Eq.(5).

Figure 4 shows the results of such simultaneous measurements with different total RF voltages to study the relation of coherent and incoherent Q_s. The average coherent/incoherent ratio from the different measurements in Fig. 4 is (1.02 ± 0.03). This corresponds to a lengthening factor of $\lambda = -(0.0057 \pm 0.014)$ A^{-1}. This means that there is no evidence for a change of bunch length with current at ANKA which could influence the determination of the current dependent detuning.

LONGITUDINAL LOSS FACTOR

The longitudinal impedance of a storage ring can be estimated from a determination of the longitudinal loss factor, $\kappa_{||}$, which is proportional to the integral over the resistive part of the impedance times the bunch power spectrum. This loss factor causes an energy loss proportional to the bunch current. The parasitic losses in the RF regions are compensated by the cavities themselves but by measuring the closed orbit shift Δx_{co} for different bunch currents

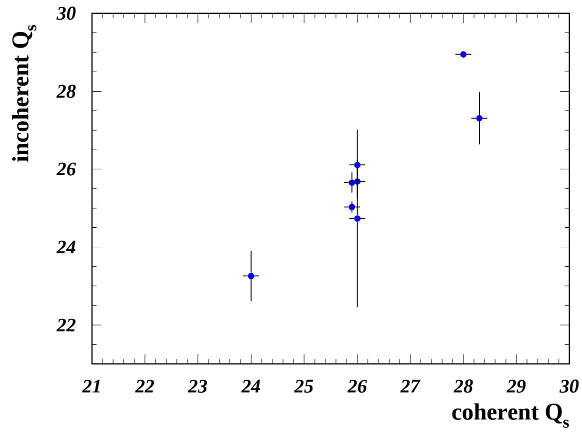

Figure 4: Incoherent synchrotron tune at a beam energy of 2.5 GeV as a function of the coherent synchrotron tune. The incoherent tunes were determined from resonant depolarisation scans (see Fig. 3) with different RF voltages, the coherent tunes were obtained from a beam frequency spectrum measured with a strip line.

$I_{\rm bunch}$ with beam position monitors (BPMs) it is possible to extract the local properties of the loss factor along the storage ring circumference:

$$\frac{\Delta x_{\rm co}}{D_x} \approx \frac{\Delta E}{E_0} = \frac{1}{E_0}\,\kappa_{||} e T_0 \Delta I_{\rm bunch} \qquad (7)$$

where T_0 is the revolution time, D_x the horizontal dispersion function and E_0 the beam energy. To measure the longitudinal loss factor, horizontal orbits have been recorded at a beam energy of 0.5 GeV for beam currents between 30 and 100 mA distributed equally over the 30 bunches of one train. The average energy loss in the dispersive regions of the storage ring is shown in Fig. 5 as a function of total beam current. The solid line is a fit to the data. The average longitudinal loss factor derived from this measurement amounts to $\kappa_{||} = (50 \pm 2)$ V/pC. This value seems to be

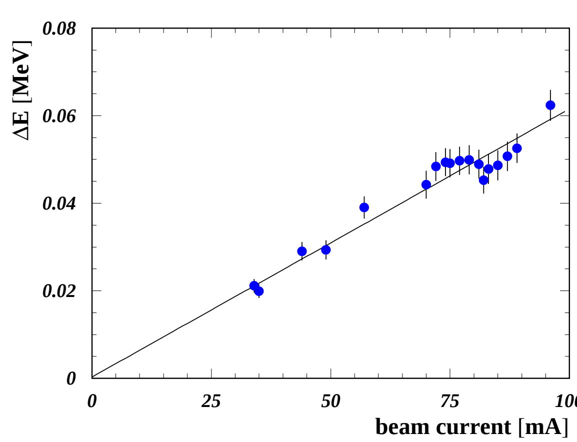

Figure 5: Average energy loss in the dispersive storage ring sections due to longitudinal impedance as a function of total beam current. The solid line is a fit to the data. The average longitudinal loss factor derived from this measurement amounts to $\kappa_{||} = (50 \pm 2)$ V/pC.

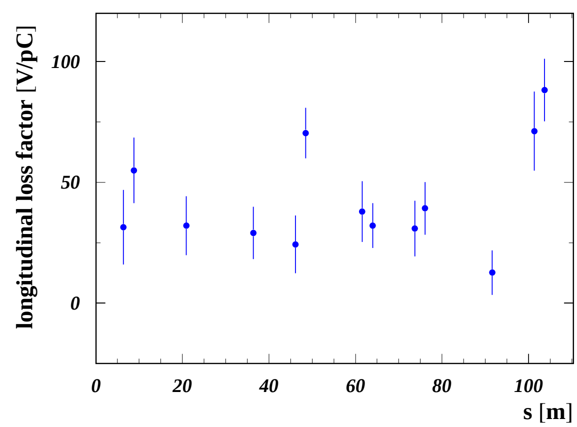

Figure 6: Longitudinal loss factor derived from the closed orbit shift in dispersive regions for different bunch currents as a function of BPM position. For an example of the underlying fit of current dependent energy loss see Fig. 5 which depicts the average loss as a function of current.

on the high side. However, a detailed analysis is still pending. The distribution of the individual measurements of the local loss factor at the BPM location is displayed in Fig. 6. The individual loss factors were obtained from the fits of current dependent energy loss at the BPM in question.

SUMMARY

Various methods have been used to determine horizontal, vertical and longitudinal impedances of the ANKA storage ring. Measurements of detuning with bunch current have been employed to determine the transverse impedances. The longitudinal impedance was determined from observations of the current dependent energy loss by detection of the closed orbit shift in dispersive regions. Furthermore the bunch lengthening factor could be determined independently from the ratio of incoherent and coherent synchrotron tune. Comparisons between the different approaches show an overall consistent picture.

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