Monitoring the Beam Depolarization with a DC Current Transformer at BESSY I

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Abstract

Measurements of the beam energy of electron storage rings based on the resonant spin depolarization method usually take the rise of the count rate of electrons scattered by the spin dependent Touschek effect as the indication of the depolarization. We present experimental results showing that the rise of Touschek scattering due to depolarization may as well be monitored by the change of the lifetime of the beam. At BESSY I the lifetime is determined by current measurements taken with a commercially available high precision Parametric Current Transformer (PCT). We present our experiences with a newly installed PCT showing a high signal-to-noise ratio and a low offset drift. The presented method in monitoring the depolarization offers a simple way to high precision energy determination at low emittance storage rings, where Touschek scattering is the dominant contribution to the lifetime.

1 INTRODUCTION

The electron storage ring BESSY I is used by the Physikalisch-Technische Bundesanstalt as a primary radiation standard i.e. as a radiation source of calculable spectral photon flux Φ_λ [1]. One of the important parameters involved in the determination of Φ_λ is the electron energy E which has to be known with a relative uncertainty of less than $\Delta E/E = 10^{-4}$. This high accuracy may be reached by determining the precession frequency Ω_z of the electron spinvector $\vec{\xi}$ in the vertical (z) magnetic guide field [2] which for relativistic particles is given by:

$$\Omega_z = (1+\nu_s)\,\omega_0 = (1+\gamma a)\,\omega_0 = (1+\tfrac{E}{m_0c^2}\,a)\,\omega_0\ . \quad (1)$$

In Eq. 1 the electron magnetic moment anomaly a, the electron rest mass m_0c^2 and the revolution frequency ω_0 are known with an uncertainty of better than 10^{-6}. The spin tune ν_s is the number of precessions per revolution. At energies of several hundred MeV we have to determine Ω_z with an accuracy of ± 1 kHz in order to reach the aspired accuracy of E. The principle of measuring Ω_z is to determine the resonance frequency at which the polarization of the stored electron beam is destroyed by a horizontal magnetic field applied in a short section of the storage ring.

2 BEAM POLARIZATION

The electron beam polarizes due to the Sokolov-Ternov effect [3]. The z-component of the spinvectors of individual electrons are oriented parallel (up) or antiparallel (down) to the vertical guide field. Initially the population of the up and down states is equal, i.e. the beam is not polarized. A small fraction ($\approx 10^{-11}$) of the emission processes of synchrotron radiation is connected with the change of the spin state (spin flip synchrotron radiation). Due to the fact that the transition rate from up states to down states is much higher (95%) than the opposite transition rate, polarization $P(t)$ builds up gradually according to

$$P(t) = P_\infty(1 - e^{-\frac{t}{\tau_p}})\,, \quad (2)$$

with $P_\infty = 92.4$ % in the ideal case. Ignoring depolarizing effects, the polarization time constant τ_p is given by

$$\tau_p = 98.66\frac{\rho^2 R}{E^5} \quad (3)$$

with ρ being the bending radius of the dipoles and R the ring average radius. For VUV light sources like BESSY I τ_p is approx. 3 h at 800 MeV and 1 h for BESSY II at 1.7 GeV.

3 BEAM DEPOLARIZATION

The motion of the spinvector $\vec{\xi}$ in an electromagnetic field is described in the quasiclassical approximation by the Thomas-BMT equation [4]. In this description the beam is depolarized by rotating the spin vectors of all particles into the horizontal plane. This is done by opening the precession cone of the individual particles. Each time the electrons fly through the horizontal field of the depolarizer, $\vec{\xi}$ precesses a small angle Θ ($\approx \frac{2\pi}{10^9}$ at BESSY I) around the field direction. If the frequency of the depolarizer ω_{Dp} is in resonance with Ω_z these perturbations add up and the spin is rotated into the horizontal plane. Depolarization is reached if $\Theta = \pi/2$. The resonance condition for depolarization is:

$$\omega_{Dp} = \Omega_z \pm n\omega_0 = (\gamma a \pm k)\,\omega_0 \quad (4)$$

with $n, k \in$ N. The depolarization time τ_{Dp} is given by [6]:

$$\tau_{Dp} = \frac{\delta\omega_{Dp}}{|\Omega_x|^2} \quad (5)$$

$\delta\omega_{Dp}$ is the modulation bandwidth of the depolarizer and Ω_x is the spin precession frequency in the depolarizing fields. In the case of stochastic depolarization by a sinusoidal, horizontal, transverse magnetic field of amplitude H_x and length l_{Dp}, Ω_x is given by

$$\Omega_x = \nu_s\,\omega_0\,\frac{H_x\ l_{Dp}}{\langle H_z\rangle\,2L}\,(1+F(y)) \quad (6)$$

with the average guide field $\langle H_z\rangle$ and the circumference of the storage ring L. The characteristic spin response function $F(y)$ of the storage ring [5] covers the depolarizing action of betatron oszillations forced by the depolarizer in resonance with ν_s.

4 DEPOLARIZATION MONITORS

There are a number of spin dependent phenomena which can be used as a polarimeter [6]. As suggested by Baier we utilize the rate of electron-electron scattering within a bunch (Touschek scattering) since the Møller cross section depends on the relative orientation of the spins of the scattering electrons. In the collision transverse momentum from betatron oscillations is transfered to the longitudinal direction. The relativistic transformation to the laboratory system increases this effect by a factor of γ. In passing through bending magnets, the dispersion leads to the loss of the scattered electrons. In the past pairs of scattered electrons were detected by scintillation counters indicating depolarization as a jump to higher count rates.

Recently we could show that the increase of the Touschek scattering rate due to depolarization may as well be observed as a reduction of the beam lifetime. To our knowledge this method was never applied experimentally before although mentioned in [6] as a possible monitor for depolarization. If the Touschek effekt was the only particle loss mechanism and if the ideal degree of polarization could be reached the reduction of the lifetime due to depolarization would amount to $\approx$ 10% at BESSY I and even $\approx$ 20% at BESSY II [7, 8]. Generally the situation is less favourable because of two reasons. Full polarization is difficult to reach because of depolarizing effects by the real lattice and there are other lifetime limiting processes like inelastic scattering on residual gas molecules.

5 PERFORMANCE OF THE PCT

At BESSY I the lifetime is determined by current measurements taken with a commercially available high precision DC parametric current transformer (PCT) . From start of operation of BESSY I two PCTs were installed [9]. One of these voluminous devices was replaced in 1993 by a new compact version with better resolution and higher offset stability [10, 11]. The magnetic beam sensor consists of 5 seperate magnetic cores packed closely together in a compact toroid assembly. The sensor is placed around an insulating ceramic gap of the storage ring. In addition to the internal magnetic shielding by many layers of a highly permeable material we placed the sensors in a housing with two layers of mumetal. As a prevention against high frequency stray fields generated by the bunched electron current through the ceramic gap the housing is RF-tight.

In 1993 a new PCT was operated in parallel to an old one. At higher ring currents the new PCT became unstable depending strongly on the operating conditions of the ring. In single bunch mode it did not work at all. This problem was solved by inserting RF-filter connectors into the interconnection wires of the sensor. Fig. 1 shows a comparision of the currents measured with the new and the old PCT before (Fig. 1a) and after (Fig. 1b) the insertion of the RF-filters. A comparision of the offset stability and the noise level is given in Fig. 2 showing offset measurements at zero current during a weekend. At an integration time of 1 s the short time fluctuations of the new PCT are about ± 0.3 μA. Within minutes sometimes sudden changes of up to $\pm$ 2 μA occur and a total uncertainty of $\pm$ 3 μA may be reached within hours. The calibration factor can be determined

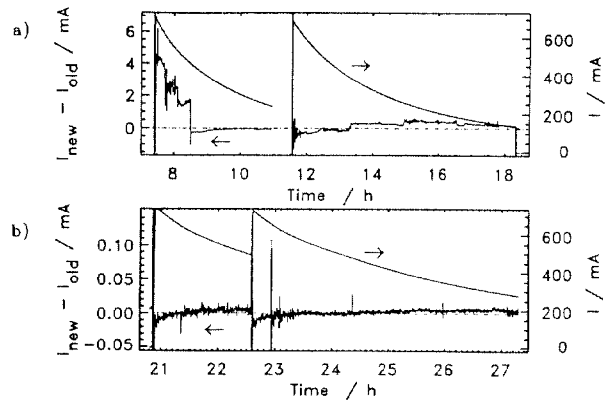

Figure 1: Comparison of the performance of the new and the old PCT a) without b) with RF-filters inserted in the interconnection wires of the sensor of the new PCT. The beam current I (right scale) and the difference between the signals of the old and the new PCT are displayed (left scale).

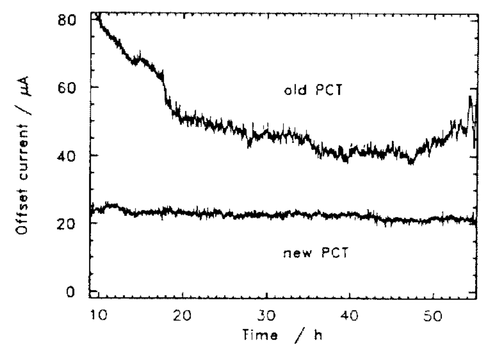

Figure 2: Drift and noise of the offset of the old and the new PCT at zero beam current within two days.

by a calibration current through an additional coil with a relative uncertainty of less than 1×10^{-4}.

6 BEAM ENERGY MEASUREMENT

At BESSY I $\omega_0/2\pi$ is 4.8 MHz and the spin tune ν_s is 1.8 at a nominal energy of 800 MeV. From Eq. 4 with $k = -1$ we expect $\omega_{Dp}/2\pi$ to be about 3.9 MHz. Fig. 3 shows the signals of the two depolarization monitors during a recent energy measurement. In Fig. 3a) the number of counts of a scintillation counter N_{Sc} are displayed. The raw data are shown in the upper part while in the lower part the counts are normalized to the square of the beam current. In Fig. 3b) the beam lifetime during the energy measurement is displayed. In this example the central frequency of the depolarizer was increased in 21 steps from 3.880 MHz to 3.920 MHz with a step height of 2 kHz. At each step the radial magnetic field is applied for 60 s while the frequency is swept by $\delta\omega_{Dp}/2\pi = \pm 1.02$ kHz around the central frequency with a modulation frequency of 10 Hz. Then the depolarizer is turned off and the scintillation events are counted for 60 s. The lifetime in Fig. 3b is a linear fit to 30 current readings taken every 1.5 s. After the depolarizer was set

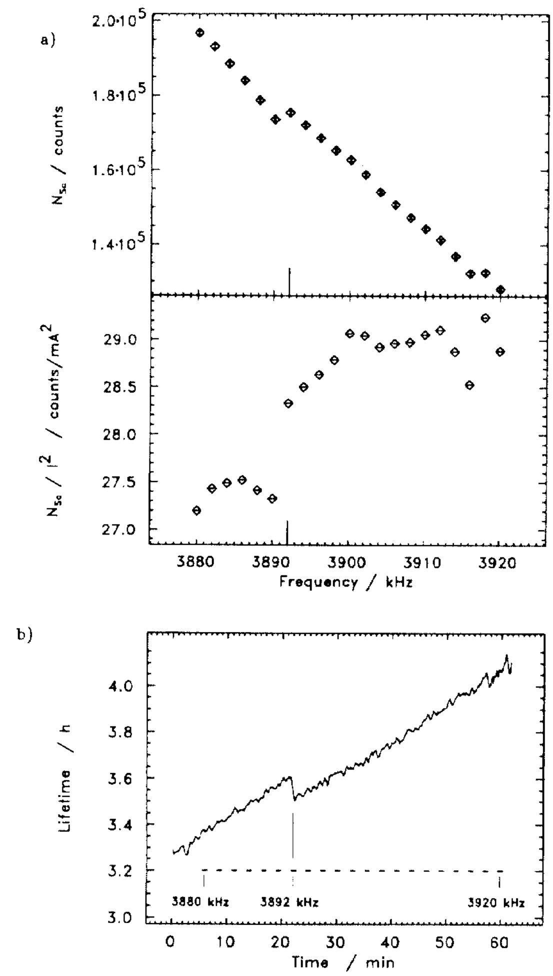

Figure 3: Example of an energy measurement. a) counts of scattered electrons: raw data upper, normalized data lower curve b) lifetime of the beam; the bars indicate the times when the depolaricer was active. In each case the step indicates depolarization after the depolarizer was set to 3892 kHz and frequency modulated by ± 1.02 kHz for 60 s.

to 3892 kHz the step to higher count rate and to lower lifetime indicates depolarization. With $\omega_{\rm Dp}/2\pi = 3892 \pm 1.02$ kHz and the actual $\omega_0/2\pi$ of 4.80430 MHz Eq. 1 yields an energy of 797.6 ± 0.1 MeV.

A closer look at the lifetime during the time interval when the depolarizer hits the resonance (Fig. 4) shows that the lifetime of the beam is already reduced after 20 s, i.e, the depolarization time $\tau_{\rm Dp}$ is ≤ 20 s. The lifetime data of Fig. 4 are fitted to 10 current readings in order to reach a higher time resolution. With $L = 62.4$ m, $\langle H_z \rangle = 1/L \times 1.5\,\mathrm{T} \times 2\pi\rho = .27\,\mathrm{T}$, $H_x \approx 25\,\mu$T and $l_{\rm Dp} = .42$ m from Eq. 5 and 6 follows $\tau_{\rm Dp} \approx 5$ min taking the action of the depolarizer only into account ($F(y) = 0$). Thus we have determined the spin response function at the position of the depolarizer $F(y) \approx 3$ which may be compared to $F(y) = 1.5$ the value we obtained by numerical calculation [12] for the low β_z section where the depolarizer is installed. The difference we attribute to additional horizontal fields of the real lattice which do not enter the calculation.

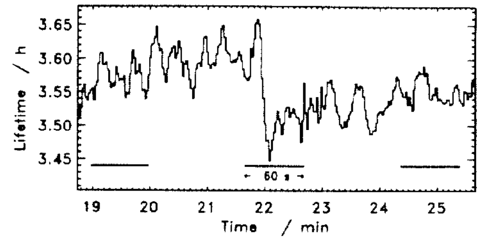

Figure 4: Lifetime during an energy measurement. The times when the depolarizer was active are indicated. When the depolarizer hits the resonance frequency full depolarization is reached after $\tau_{\rm Dp} \leq 20$ s.

7 CONCLUSION

Resonant depolarization of the electron beam in a storage ring may be monitored with a DC current transformer. This new method of detecting the resonant depolarization offers a simple way to high accuracy energy measurements not only at BESSY I but at any low emittance storage ring, where the beam can be polarized and Touschek scattering is the dominant lifetime limitation.

8 REFERENCES

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