PRECISE BEAM ENERGY CALIBRATION AT THE SLS STORAGE RING

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Abstract

In addition to precise dipole field measurements the method of resonant electron spin depolarization can be utilized to determine the average beam energy with high precision [1]. Estimates for the expected equilibrium polarization level in the SLS storage ring are presented together with polarization rise-time measurements observing the polarization dependent Touschek scattering limited lifetime. Results from resonant spin depolarization and nonlinear momentum compaction factor measurements are presented.

1 INTRODUCTION

As first mentioned by Ternov, Loskutov and Korovina in 1961 electrons gradually polarize in storage rings due to sustained transverse acceleration while orbiting. The mechanism is the emission of *spin-flip synchrotron radiation*: While being accelerated, electrons radiate electromagnetic waves in quanta of photons which carry a spin. An extremely small fraction (10^{-11} of the emitted power) of the synchrotron emissions is *spin-flip radiation*. The difference between the two possible transition rates causes an injected electron beam to get *polarized* anti-parallel with respect to the guiding dipole field. The maximum achievable polarization level in a planar ring without imperfections is the *Sokolov-Ternov Level* [2]:

$$P_{ST} = \frac{W_{\uparrow\downarrow} - W_{\downarrow\uparrow}}{W_{\uparrow\downarrow} + W_{\downarrow\uparrow}} = \frac{8}{5\sqrt{3}} = 92.38\%$$

The time constant of the exponential build-up process of this *equilibrium polarization* by the initially unpolarized beam is:

$$\tau_p = (W_{\uparrow\downarrow} + W_{\downarrow\uparrow})^{-1} = \left(\frac{5\sqrt{3}}{8} \cdot \frac{e^2\hbar}{m_e{}^2 c^2}\right)^{-1} \frac{\rho^3}{\gamma^5} \qquad (1)$$

with $\tau_p = 1873$ s for the SLS storage ring ($E = 2.4$ GeV, effective bending radius $\rho = 11.48$ m).

However, spin-flip radiation is accompanied by depolarizing effects (for example from perpendicular fields) and therefore beam polarization must be understood as an equilibrium state. Depolarizing effects (over a time which is long enough to allow spin diffusion) are expected to show an exponential decay of the polarization with the decay time constant τ_d. The equilibrium state is therefore described by an exponential build-up:

$$P_{tot}(t) = P_{eff}\left(1 - \exp\left(-\frac{t}{\tau_{eff}}\right)\right) \qquad (2)$$

where

$$P_{eff} = P_{ST}\frac{\tau_d}{\tau_p + \tau_d} \quad \text{and} \quad \frac{1}{\tau_{eff}} = \frac{1}{\tau_p} + \frac{1}{\tau_d} \qquad (3)$$

Since depolarizing effects are small in low energy rings, we expect high equilibrium polarization values close to the Sokolov-Ternov level at the SLS storage ring.

2 POLARIZATION MEASUREMENTS

If beam lifetime is limited by Touschek scattering, changes in the level of polarization can be correlated with the Touschek scattering rate. Touschek scattering has a polarization dependent cross section [4]: Increasing beam polarization leads to a smaller Touschek cross section and therefore to smaller loss rates. On the other hand, a sudden decrease in beam polarization (due to a resonant depolarization for example) will lead to a rise of Touschek scattering losses. Recent experiments [3] have shown that beam lifetime in the SLS is Touschek dominated when using a single bunch current of $0.5 - 1.5$ mA. By filling only 90 buckets we remained at a low total beam current which guaranteed for low gas pressure and therefore small elastic scattering.

The product of Touschek lifetime and beam current is generally given by the *decay constant*: $\tau = -\dot{I}^{-1} \cdot I$. A change of τ can be identified with a possible polarization build-up. Furthermore, measurement of the equilibrium polarization build-up time allows the determination of the equilibrium degree of polarization: After observing the exponential build-up process τ_{eff} can be fitted. According to eq. 3 the equilibrium polarization level P_{eff} is obtained.

A fit of such a build-up is depicted in fig. 1. Several measurements [1] have shown that high polarization levels can be reached in the SLS storage ring with flat orbit correction and tunes $\nu_x = 20.38$, $\nu_y = 8.19$, $\nu_{ST} = 5.45$ (see eq. 4). After performing vertical beam based alignment (BBA) [5] levels of polarization close to the Sokolov-Ternov level were reached (see fig. 2).

3 ENERGY CALIBRATION

The precession equation of motion for the spin $\vec{S}$ of an electron at rest in a magnetic field is the Larmor equation with the angular velocity $\vec{\Omega} = \vec{B} \cdot ge/2m_ec$. Using Lorentz transformations the last equation can be rewritten [6] for a highly relativistic ($\frac{1}{\gamma} \ll 1$) electron moving in the electromagnetic field of an accelerator, which, when substituted into the Larmor equation is called the *Thomas-BMT Equation* [7]. An electron traveling along the design orbit will

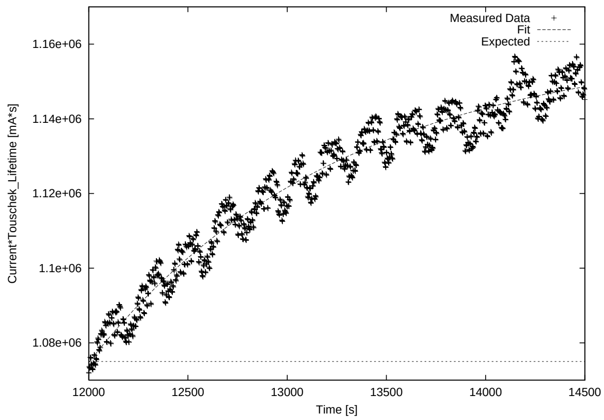

Figure 1: First observed polarization build-up and fit (flat orbit). The fit parameter for the characteristic build-up time is (1261 ± 12) s corresponding to an equilibrium polarization of 63%. In following measurements polarization values of up to 87% were observed.

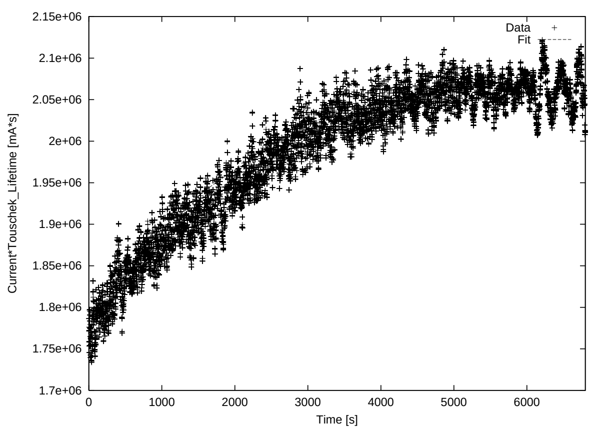

Figure 2: Polarization build-up and fit (flat orbit and vertical BBA). The fit parameter for the characteristic build-up time is (1837 ± 1) s corresponding to an equilibrium polarization of 91%.

only see the guiding magnetic dipole field $\vec{B}_\perp$ as well as the accelerating electric field. Therefore the spin precession frequency in the particle's rest frame (i.e. in machine coordinates) is [8] [9]:

$$\vec{\Omega_{sp}} = \frac{e\vec{B}_\perp}{m_e c\gamma} \cdot a\gamma = \vec{\omega_0} \cdot \nu \qquad (4)$$

where a is the anomalous magnetic moment of the electron, $\vec{\omega_0} = e\vec{B}_\perp / m_e c\gamma$ the revolution frequency in the storage ring and $\nu = a\gamma$ is the *spin tune* ($a\gamma = 5.45$ in the SLS at $E = 2.4$ GeV). An approximated solution for the flat machine leads to $\vec{S}_z$ remaining constant while $\vec{S}_x, \vec{S}_y$ are statistically distributed among the electrons in the beam and cancel. The time-integration of the remaining component in the ensemble leads to a certain degree of polarization.

If a time-varying radial magnetic field is applied in resonance with the electron's spin revolutions the mean spin vector can be tilted into the horizontal plane which (in conjunction with spin diffusion) leads to zero polarization. Thus finding the resonant depolarization frequency is equivalent to finding the beam energy (eq. 4).

In the experimental setup a sinusoidal signal is fed into a vertical tune kicker magnet. The frequency of this signal is swept over pre-defined intervals. As soon as the sweep frequency hits the resonant depolarizing frequency and the beam gets depolarized, the product of beam current and lifetime drops and loss monitor (a pair of scintillators installed downstream of the in-vacuum undulator U24) coincidence signals rise due to an increased number of pairs of Touschek scattered electrons (see fig. 3).

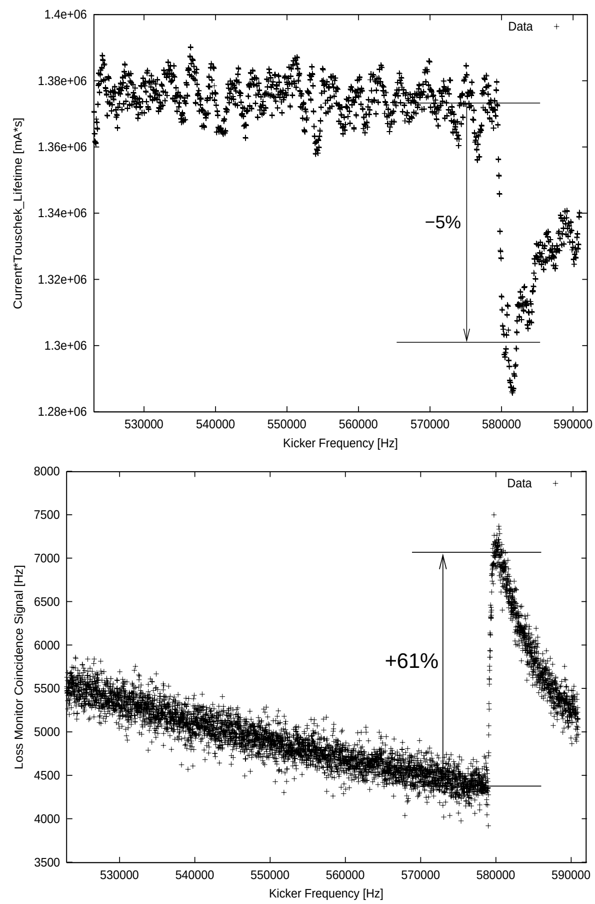

Figure 3: The resonant depolarizing frequency is reached at 580 kHz.

Due to a sampling with ω_0 there is the ambiguity that the resonance has to be distinguished from its mirror above the half-integer spin tune. This is done by a slight variation of the RF main frequency leading to a change in beam energy and thus to a shift of the resonance in the same direction and to a shift of the mirror in the opposite. The resonance also carries sidebands (the spin tune is modulated by synchrotron oscillations) which are equally distanced from the resonant frequency by multiples of the synchrotron tune Q_s; a variation of the RF voltage leading to a change in distance between main resonance and sidebands allows the identification of the unshifted main resonance (see fig. 4).

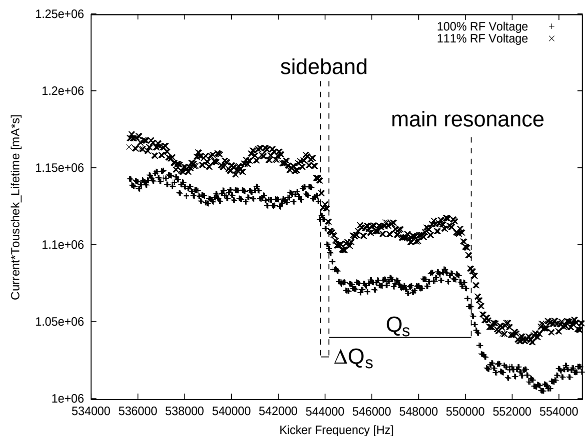

Figure 4: Dip patterns of two sweeps differing due to a 11% increase of RF voltage. The main resonance and its sideband are separated by the synchrotron tune $Q_s = 6.17 \cdot 10^{-3}$ respectively by $Q_s + \Delta Q_s = 6.48 \cdot 10^{-3}$ (an increase of Q_s by $\approx 5\%$).

Once these checks had been done the precise energy calibration was obtained with a fit using the Froissart-Stora formula for resonance crossing [10]. We specify the energy uncertainty with the half-FWHM of the fit, since the resonance uncertainty is independent of the signal generator driving the sweep. Applied to the data in fig. 5 this leads to an energy of (2.4361 ± 0.00024) GeV.

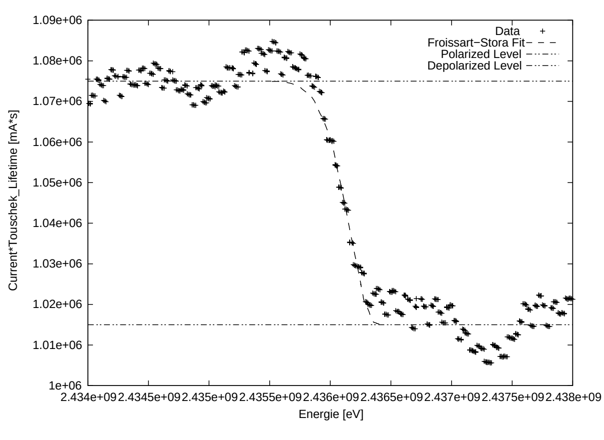

Figure 5: Resonance with fit according to the Froissart-Stora equation for resonance-crossing.

By decreasing the sweep dwell and the kicker power a higher accuracy can be reached. A series of measurements [1] has been performed finally leading to the energy calibration of $E = (2.4361 \pm 0.00018)$ GeV with a very low uncertainty of $\frac{\Delta E}{E} = 4.5 \cdot 10^{-5}$ which we expect to be able to under-run in upcoming measurements.

The energy calibration results are supported by independent measurements [11] of characteristic line spectra of undulator U24 revealing $E = (2.44 \pm 0.02)$ GeV which is in excellent agreement to the presented measurements.

4 APPLICATION: MEASUREMENT OF THE NONLINEAR MOMENTUM COMPACTION

Due to the high precision of the energy measurements the presented techniques can be used to obtain the nonlinear momentum compaction factor α_2.

$$-\frac{\Delta f_{rf}}{\Delta f_{rf}} = \alpha_1 \left(\frac{\Delta E}{E}\right) + \alpha_2 \left(\frac{\Delta E}{E}\right)^2$$

After changing the RF main frequency the shift in energy can be measured. From the first measurement $\alpha_1 = 5.6 \cdot 10^{-4}$ and $\alpha_2 = 4.4 \cdot 10^{-3}$ for the SLS storage ring (uncertainties are missing because only three data points have been obtained). Self-consistency checks with the machine model through dispersion measurements [5] and detuning measurements lead to $\alpha_1 = 6.0 \cdot 10^{-4}$ and $\alpha_2 = 4.2 \cdot 10^{-3}$.

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