FEASIBILITY STUDY OF ELECTRON BEAM POLARIZATION MEASUREMENT USING TOUSCHEK LIFETIME*

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Abstract

Touschek lifetime depends on the electron beam polarization through intrabeam scattering. Hence, the polarization of the electron beam can be studied using lifetime measurement. In this paper, we will first discuss the dependency of Touschek lifetime on beam polarization. We will then report our feasibility study of using Touschek lifetime to measure polarization of the electron beam in the Duke storage ring.

INTRODUCTION

An electron beam circulating in a storage ring can be self-polarized through the Sokolov-Ternov effect [1]. Neglecting depolarization effects, the time constant T of the exponential build-up process of the electron beam polarization (approaching a maximum value of 92%) can be approximated as

$$T[\mathrm{s}] \simeq 98 \times \frac{\rho^2[\mathrm{m}]R[\mathrm{m}]}{E^5[\mathrm{GeV}]}, \tag{1}$$

where ρ and R is the bending radius of dipoles and the mean radius of the storage ring in meters, E is the beam energy in GeV, and T is the polarization time constant in second. For the Duke storage ring operated at 1.15 GeV, the time constant is about 60 min.

The polarized electron beam has a wide range of applications in accelerator physics, high energy physics, and nuclear physics research. For example, the polarized electron beam in a storage ring can be used to determine the electron beam energy by the resonant spin depolarization technique. The knowledge of polarization is essential for applications utilizing this beam. The degree of polarization can be measured by a polarimeter. While this measurement has a high degree of accuracy, the experiment setup is complicated and expensive.

The electron beam polarization in a storage rage ring can also be estimated from the increase of the Touschek lifetime which is related to the reduction of intrabeam scattering cross section due to polarization. However, this method is difficult and challenging for several reasons, including the requirements of a highly stable beam, a reproducible storage ring operation, and an accurate measurement of beam lifetime.

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In this paper, we first present a formula for the polarization-related Touschek lifetime. We then report our results of the feasibility study of using the Touschek lifetime to measure the polarization of the electron beam in the Duke storage ring.

TOUSCHEK LIFETIME AND BEAM POLARIZATION

In a storage ring, many mechanisms can lead to beam loss. Other than hardware failure, fast beam instability is the main source of rapid beam loss. Typically beam lifetime is associated with gradual beam loss mechanisms, such as quantum diffusion (quantum lifetime τ_q), residual gas scattering (gas lifetime τ_g), and intrabeam scattering (Touschek lifetime τ_t). The beam lifetime can be meaningful only if other rapid beam loss mechanisms are fully suppressed. Therefore, to study the electron beam polarization effect using the Touschek effect requires a very stable electron beam in the storage ring.

The electron beam lifetime τ, which is defined in terms of the relative beam loss rate, can be separated into different components according to the beam loss mechanisms as follows

$$\frac{1}{\tau} = -\frac{1}{N}\frac{dN}{dt} = \frac{1}{\tau_q} + \frac{1}{\tau_g(N)} + \frac{1}{\tau_t(N)}, \tag{2}$$

where N is the total number of particles in the beam. Typically, the quantum lifetime τ_q is much longer than other lifetimes, thus can be neglected from the total lifetime. The vacuum lifetime τ_g depends on vacuum pressure, beam current and other machine parameters. For a low-energy light source storage ring, the vacuum lifetime can often also be neglected compared to the Touschek lifetime.

For a flat beam with a non-relativistic transverse momentum, the Touschek lifetime can be analytically expressed as [2, 3]

$$\frac{1}{\tau_t} = a\int_{\xi}^{\infty} \frac{1}{u^2}\left[\frac{u}{\xi} - 1 - \frac{1+P^2}{2}\ln\frac{u}{\xi}\right]\exp(-u)du, \tag{3}$$

where

$$a = -\frac{N}{\gamma^2}\frac{r_e^2 c}{8\pi\sigma_y\sigma_s\sigma_x}\frac{1}{(\Delta p/p)^3}\xi^{3/2};\ \xi = \left(\frac{\Delta p/p}{\gamma}\frac{\beta_x}{\sigma_x}\right)^2; \tag{4}$$

r_e is the classical electron radius; c is the speed of light; γ is the Lorentz factor of the electron; $\sigma_{s,x,y}$ are longitudinal and transverse beam sizes; β_x is the twiss parameter; P is the degree of polarization of the electron beam; and $\Delta p/p$ is the RMS momentum acceptance.

Eq. (3) shows that the Touschek lifetime depends on the machine parameters which vary around the storage ring. Therefore, the actual (global) Touschek lifetime should be averaged over the entire storage ring, i.e.,

$$\frac{1}{\tau_t} = \frac{1}{2\pi R}\oint \frac{1}{\tau_t(s)}ds = \langle\frac{1}{\tau_t(s)}\rangle, \qquad (5)$$

where R denotes the mean radius of the storage ring, and the brackets "$\langle\ \rangle$" represent an average over the ring.

To show the dependency of the Touschek lifetime on the electron beam polarization, Eq. (3) can be rewritten as

$$\frac{1}{\tau_t(P)} = \langle aC(\xi)\rangle + \langle aF(\xi)\rangle P^2, \qquad (6)$$

where

$$\begin{aligned} C(\xi) &= \int_\xi^\infty \frac{1}{u^2}\left[\frac{u}{\xi} - 1 - \frac{1}{2}\ln\frac{u}{\xi}\right]\exp(-u)du, \\ F(\xi) &= -\frac{1}{2}\int_\xi^\infty \frac{1}{u^2}\ln\frac{u}{\xi}\exp(-u)du. \qquad (7) \end{aligned}$$

Here, the Touschek lifetime $\tau_t(P)$ has been expressed as a function of the electron beam polarization P. The term $\langle aC(\xi)\rangle$ represents the polarization independent contribution to the Touschek lifetime, while $\langle aF(\xi)\rangle$ represents the polarization dependent contribution.

Since $\langle aF(\xi)\rangle$ is a negative quantity, the Touschek lifetime increases with the polarization of the electron beam. It can be easily shown that the relative increase of $\tau_t(P)$ due to the electron beam polarization is given by

$$\frac{\tau_t(P) - \tau_t(0)}{\tau_t(P)} = -\frac{\langle aF(\xi)\rangle}{\langle aC(\xi)\rangle}P^2 \qquad (8)$$

where $\tau_t(0)$ and $\tau_t(P)$ represent the Touschek lifetimes for unpolarized and polarized beams, respectively.

Eq. (8) is the basic formula which can be used to determine the electron beam polarization. In practice, to use this formula, we first need to obtain an unpolarized beam which has the same beam conditions (excepting the degree of polarization) to the polarized beam. Second, the increase of beam lifetime due to electron beam polarization must be substantially higher compared with the accuracy of the lifetime measurement. This requirement can be satisfied for few GeV storage rings where the beam loss is usually dominated by the Touschek effect.

FEASIBILITY STUDY

RF voltage scan

The relationship between beam lifetime and momentum acceptance is very different for the residual gas scattering and the Touschek effect. The momentum acceptance can be controlled by changing the RF gap voltage of the storage ring. The beam lifetime as a function of the RF voltage is shown in Fig. 1 for the Duke storage ring operated at 1.15 GeV with a 10 mA single bunch beam. The amount of lifetime change due to the varied RF voltage is what we expected when the beam loss is dominated by the Touschek effect. Fig. 1 also shows that the momentum acceptance is determined by the maximum RF voltage, not by nonlinear dynamics of off-momentum particles. For the maximum RF gap voltage of 800 kV, the momentum acceptance is about 2.3%.

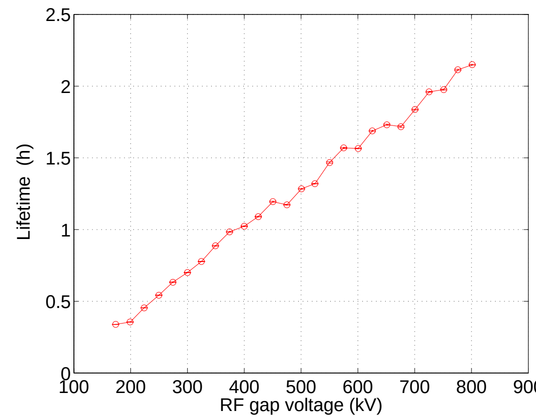

Figure 1: Lifetime as a function of the RF gap voltage. The storage ring is operated at 1.15 GeV with a 10 mA single-bunch beam.

Estimation of lifetime increase

According to Eq. (8), in order to extract the electron beam polarization from the lifetime difference, the ratio between $\langle aF(\xi)\rangle$ and $\langle aC(\xi)\rangle$ needs to be evaluated for the entire ring. For this purpose, a MATLAB code has been developed. When the Duke storage ring operated at 1.15 GeV, the estimated value of $\langle aF(\xi)\rangle/\langle aC(\xi)\rangle$ is about 0.2. Thus, the relative increase of the Touschek lifetime is about 17% when the degree of polarization of the electron beam reaches its maximum value of about 92%. Compared to the accuracy of lifetime measurement of about 2-5%, this amount of lifetime increase is expected to be measurable.

Reproducibility of injection

According to Eq. (8), in order to extract the electron beam polarization from the Touschek lifetime difference, we need to have an unpolarized electron beam as a reference. This unpolarized beam must have the same beam conditions (excepting the degree of polarization) as the polarized one. At the Duke storage ring, such an unpolarized electron beam can be established via subsequent refills of the storage ring. The reproducibility of the beam condition is critical. This can be tested by injecting electron beams with the same mount of current at different runs while monitoring the beam parameters.

For the injection study, a highly stable, both transversely and longitudinally, electron beam was established

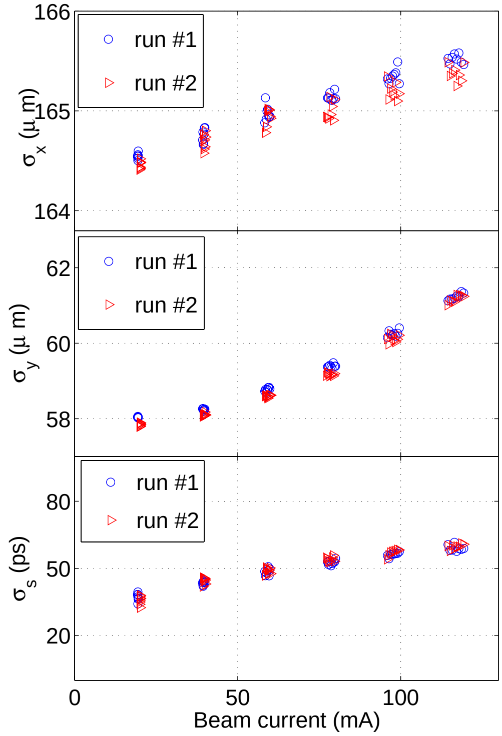

Figure 2: Transverse sizes and longitudinal bunch length of the electron beam as functions of the beam current for two different runs. The storage ring is operated at 1.15 GeV with 8 bunches. Top: the horizontal RMS beam size monitored by a synchrotron radiation profile monitor; Middle: the vertical RMS beam size; Bottom: the longitudinal RMS bunch length monitored by a dissector.

at 1.15 GeV with eight electron bunches evenly distributed around the storage ring. The high degree of beam instability was achieved using an advanced bunch-by-bunch longitudinal feedback system [4]. The electron beam remained stable during the entire injection study as the beam current was increased to a maximum of about 120 mA.

There are 34 horizontal and vertical BPMs distributed along the Duke storage ring, so we can monitor the beam orbit using the BPMs. The experiment results shows that the orbits are consistent and stable for each run.

Since the Touschek lifetime depends on the electron bunch volume, it is important to make sure that it remains consistent for each run. A synchrotron radiation profile monitor and a dissector system have been used to monitor the transverse beam sizes and bunch length. The result is shown in Fig. 2. Clearly, we can see that the bunch volume of the electron beam are consistent between these two runs.

Other machine parameters such as the vacuum parameter and RF readback have also been checked for these two runs. Good consistencies are also found. As pointed out earlier, if the beam condition and machine status are similar for each run, lifetimes should be also close to each other. Fig. 3 shows that the beam lifetimes for these two runs

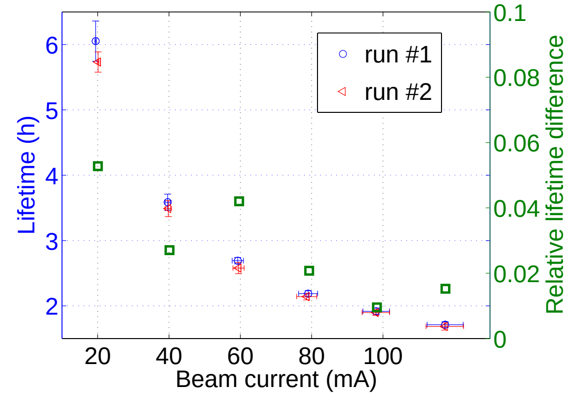

Figure 3: Lifetime as a function of the beam current for two different runs with the same beam conditions as in Fig. 2. The relative discrepancies of the measured lifetime of two runs are plotted using squares.

are consistent and the relative discrepancy between them is within the accuracy of the lifetime measurement.

Another test was carried out in a different day, and good consistencies were also observed. Thus, it is believed that we can establish an unpolarized reference beam which has the same beam conditions (excepting the degree of polarization) as the polarized beam via subsequent refills of the Duke storage ring.

SUMMARY

Based upon the polarization-dependent Touschek lifetime, the electron beam polarization can be extracted from the lifetime difference between a polarized and unpolarized electron beam. In order to use this technique to study the electron beam polarization, a stable and reproducible storage ring operation is crucial. In this paper, we have estimated the lifetime increase due to the polarization of the electron beam in the Duke storage ring. We also carried out the stability and reproducibility study of the storage ring. The results indicate that Touschek lifetime can be used as a tool to study the polarization buildup process of the electron beam in the Duke storage ring which will be explored in our followup studies.

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