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ELECTRON BEAM POLARIZATION MEASUREMENT USING TOUSCHEK LIFETIME TECHNIQUE*

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Abstract

Electron beam loss due to intra-beam scattering, the Touschek effect, in a storage ring depends on the electron beam polarization. The polarization of an electron beam can be determined from the difference in the Touschek lifetime compared with an unpolarized beam. In this paper, we report on a systematic experimental procedure recently developed at Duke FEL laboratory to study the radiative polarization of a stored electron beam. Using this technique, we have successfully observed the radiative polarization build-up of an electron beam in the Duke storage ring, and determined the equilibrium degree of polarization and the time constant of the polarization build-up process.

INTRODUCTION

With the completion of recent major hardware upgrades, the High Intensity γ-ray Source (HIγS) facility at Duke University has produced an unprecedented level of gamma flux for a wide range of scientific research programs [1]. However, an accurate and direct measurement of gamma-ray beam energy in the tens to about 150 MeV region remains a challenge. One alternative method to determine the gamma-beam energy is to measure the energy of the electron beam used in collision [2]. The electron beam energy in a storage ring can be measured using the Resonant Spin Depolarization (RSD) technique [3]. This technique measures the energy-dependent precession frequency of the electron spin. Consequently, it requires a polarized electron beam. It is well known that an electron beam in a storage ring can become self-polarized due to the Sokolov-Ternov effect [4]. Therefore, the study of the self-polarization process of the electron beam in the Duke storage ring is of great importance for our continued development of the HIγS.

Electron beam polarization can be measured using Touschek technique, which has been suggested and demonstrated in papers [5, 6]. However, in these works, a depolarizer was used to depolarize the beam and the resulting change in the local beam loss rate was measured to determine the electron beam polarization. In this paper, we report our recent measurements of the radiative polarization of an electron beam in the Duke storage ring using the global Touschek lifetime technique without depolarizing the beam.

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POLARIZATION RELATED TOUSCHEK LIFETIME

If an unpolarized electron beam is injected into a storage ring, the electron beam can gradually build up its polarization due to the Sokolov-Ternov effect [4]. The polarization build-up process can be described by an exponential function [7]

$$P(t) = P_{ST}\left[1-\exp\left(-\frac{t}{T_{ST}}\right)\right], \tag{1}$$

where the equilibrium degree of polarization P_{ST} is about 92.38%; and the time constant T_{ST} is given by

$$T_{ST}[\mathrm{s}] = 98.66\times\frac{\rho^2[\mathrm{m}]R[\mathrm{m}]}{E^5[\mathrm{GeV}]}, \tag{2}$$

where ρ is the bending radius of the storage ring dipoles; R is the mean radius of the storage ring; and E is the electron beam energy. For example, for the Duke storage ring ($\rho = 2.10$ m and $R = 17.10$ m) operated at $E = 1.15$ GeV, the time constant for polarization build-up process is roughly 62 minutes. In reality, however, the polarized electron beam can be depolarized due to many causes [7]. As a result, the equilibrium degree of polarization will be reduced by a factor of $T_d/(T_{ST}+T_d)$, where T_d is a time constant describing depolarization effects. In the mean time, the time constant for the polarization build-up process will be decreased by the same factor.

The Touschek lifetime of an electron beam in a storage ring is related to the electron beam polarization through intra-beam scattering effect. For a flat beam with a non-relativistic transverse momentum, the Touschek lifetime τ_t can be expressed as [8, 9]

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

where

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

$\frac{1}{\tau_t}$ is the beam loss rate due to Touschek effect; $\sigma_{x,y,s}$ are the transverse beam sizes and longitudinal bunch length; β_x is the horizontal beta-function at the collision point of electrons; $\Delta p/p$ is the momentum acceptance; and P is the degree of polarization of the electron beam. Since ξ depends on the machine parameters which vary around the storage ring, the global Touschek loss rate should be averaged over the entire storage ring, i.e.,

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

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where the brackets "$\langle\ \rangle$" represent an average over the storage ring. To explicitly show the dependency of the Touschek lifetime on the electron beam polarization, Eq. (3) after averaged over the ring can be rewritten as [9]

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

where

$$\begin{aligned} C(\xi) &= \xi^{3/2}\int_\xi^\infty \frac{1}{u^2}\left[\frac{u}{\xi} - 1 - \frac{1}{2}\ln\frac{u}{\xi}\right]\exp(-u)du, \\ F(\xi) &= -\frac{\xi^{3/2}}{2}\int_\xi^\infty \frac{1}{u^2}\ln\frac{u}{\xi}\exp(-u)du. \end{aligned} \tag{7}$$

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

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

where $\tau_t(0)$ and $\tau_t(P)$ represent the Touschek lifetimes for the electron beam with and without polarization, respectively. Equation (8) is the basic formula which can be used to determine the electron beam polarization through the Touschek lifetime measurement. In practice, to use this formula, we first need to establish an unpolarized beam which has the same beam conditions (except for the degree of polarization) as the polarized one. Second, the increase of beam lifetime due to electron beam polarization must be substantially higher than the accuracy of the lifetime measurement.

EXPERIMENT METHOD

According to Eq. (8), in order to extract the electron beam polarization P from the measured Touschek lifetime $\tau_t(P)$, the lifetime $\tau_t(0)$ of an unpolarized electron beam must be first obtained as a reference. This unpolarized beam should have the same beam conditions as the polarized one. At the Duke storage ring, with a recently developed booster injector [10] and a longitudinal feedback system, an unpolarized electron beam can be established by filling the storage ring with a fresh beam.

The reproducibility of the beam condition is critical. This has been tested by injecting electron beams with the same amount of current at different times and monitoring the beam parameters, such as the transverse beam sizes, longitudinal bunch length, vacuum pressure and beam orbits. The results have shown that highly reproducible unpolarized reference beams can be established by filling the Duke storage ring with a fresh beam [11, 12]. In addition, we have experimentally demonstrated that the measured beam lifetime is dominated by the Touschek effect [12, 13]. Therefore, it is a good approximation to use the measured lifetime as the Touschek lifetime in this study.

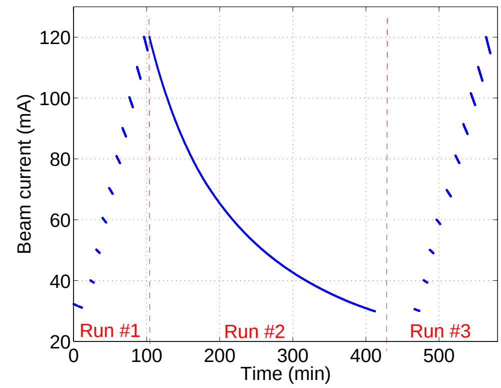

Figure 1: Measured electron beam currents as a function of time for polarization measurements. Three subsequent runs were carried out. For the first run, the electron beam was increased to 120 mA by incremental injection of 10 mA per step. For each 10 mA injection, the beam current was monitored for about 5 min. For the second run, the beam current was monitored for about 300 minutes as the current decayed from 120 mA to 30 mA. The third run was a repeat measurement of the first run.

Three subsequent runs were carried out to study the polarization build-up process of an electron beam in the Duke storage ring, which was operated in an equally filled 8-bunch mode. The beam current as a function of the time for these three runs are illustrated in Fig. 1. For the first run, the electron beam was increased to 120 mA by incremental injection of 10 mA per step. After each 10 mA injection, the beam current was monitored with a DC current transformer (DCCT) for about 5 min, followed by the next injection. After the first run, the second run was immediately carried out with the stored beam current starting at 120 mA. In this run, the injection was stopped, and the electron beam current was monitored for about 300 minutes as it decayed to 30 mA. Then, the electron beam was dumped, and the third run was carried out using the same procedure as the first one. In this experiment, the electron beams obtained in the first and third runs can be considered as mostly unpolarized, while the beam obtained in the second run a partially polarized beam.

During each run, the beam parameters, such as transverse beam sizes, longitudinal bunch length, vacuum pressures and beam orbits around the storage ring, were monitored to assure stable and repeatable beam conditions.

DATA ANALYSIS

The beam lifetime is determined by fitting the beam current decay in a time window. To estimate the lifetime measurement error, several consecutive time windows are used, and the error is estimated using the standard deviation of the fit lifetimes in these time windows. The measured life-

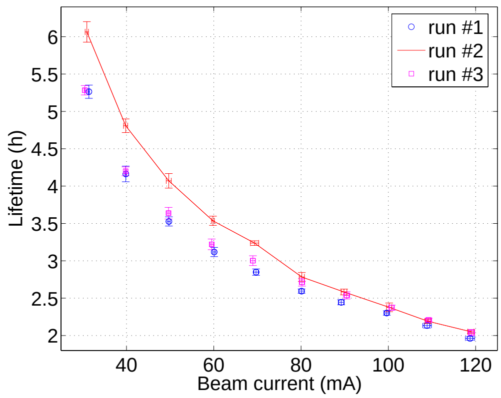

Figure 2: The beam lifetime at different electron beam currents for three different runs shown in Fig. 1.

time as a function of the beam current for three runs are shown in Fig. 2.

It should be pointed out that due to the duration of the injection and beam current measurement in the first and third runs, the electron beam accumulate some polarization. Thus, the lifetime of the beam obtained in these two runs does not represent that of a completely unpolarized beam. To correct for this, a simple model based upon the theoretical calculation was developed to estimate the electron beam polarization at each injection step. The lifetime results for the first and third run shown in Fig. 2 have been corrected using this model.

Using the differences between the lifetime of the polarized beam (the second run) and that of the unpolarized beam (the average of the first and third run), the electron beam polarization can be estimated according to Eq. (8). The results of electron beam polarization as a function of time t are shown in Fig. 3. An exponential fit of the data gives $P_0 = 0.85 \pm 0.03$, and $T = 60 \pm 9$ min. To include the accumulated polarization of the electron beam at the beginning of the second run ($t = 0$), an initial time t_0 has been introduced in the fitting model shown in Fig. 3.

The measured degree of polarization of a 1.15 GeV eletron beam in the Duke storage ring is about 0.92 times the maximum degree of polarization of a stored beam in an ideal storage ring without any source of depolarization, i.e., $P_0/P_{ST} = 0.85/0.9238 = 0.92$. This is a strong evidance that depolarization effects in the Duke storage ring are relatively weak and a highly polarized electron beam can be obtained via the Sokolov-Ternov effect. In addtion, the measured polarization time constant is consistent with the expected value.

CONCLUSIONS

The radiative polarization of an electron beam in the Duke storage ring has been observed using a set of systematic experimental procedures based upon the Touschek effect. The polarization time constant as well as the equilibrium degree of polarization have been successfully de-

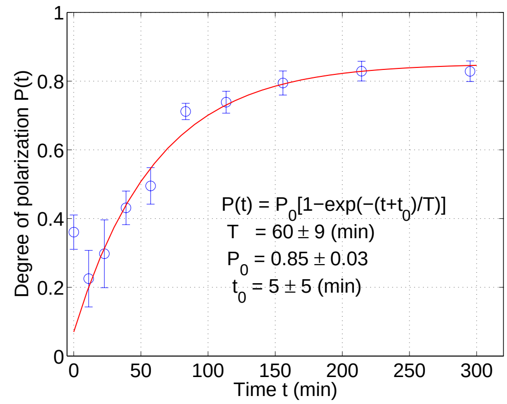

Figure 3: The build-up process of the electron beam polarization $P(t)$. The solid line is the exponential fit of the data. The fitting model as well as the fit results are also shown in the plot.

termined. Although not accurate, this simple method based upon the Touschek effect can be a powerful tool to obtain useful information about the self-polarization process of the electron beam in a storage ring.

The polarized electron beam is critical for the future development of the HIγS facility at Duke University. It allows us to accurately determine the gamma-ray beam energy via the measurement of the electron beam energy using the Resonant Spin Depolarization technique.

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