TOUSCHEK LIFETIME MEASUREMENT WITH A SPURIOUS BUNCH IN UVSOR-II ELECTRON STORAGE RING

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Abstract

We have developed a method to measure the Touschek beam lifetime of an electron storage ring using spurious bunches in single-bunch operation by measuring changes in the single-bunch impurity over time. To measure a spurious bunch and the main bunch simultaneously, we use a photon counting method with sufficient dynamic range and response time. We demonstrate the method by measuring the Touschek beam lifetime in the UVSOR-II electron storage ring. We find that the Touschek beam lifetime dominates the total beam lifetime in UVSOR-II in the usual vacuum condition. The beam lifetime measurement in the multibunch condition indicates that the Touschek lifetime still dominates even in the multibunch operation in which the beam current is 12 times larger than that of the single-bunch condition.

BEAM LIFETIME IN ELECTRON STORAGE RING

In typical electron storage rings, such as synchrotron radiation (SR) light sources, the beam lifetime τ is mainly determined by two processes; one is the Touschek lifetime [1, 2] which comes from scattering between electrons in the same electron bunch, and the other is the beam–gas scattering lifetime which comes from scattering between electrons in the beam and residual gas molecules in the beam ducts. In case the quantum lifetime can be neglected, the total beam lifetime τ can thus be expressed as $1/\tau = 1/\tau_T + 1/\tau_g$, where τ_T is the Touschek lifetime and τ_g is the beam–gas scattering lifetime. The Touschek lifetime τ_T can be written as [2, 3]

$$\frac{1}{\tau_T} = \frac{r_c^2 c N_b}{8\pi\sigma_x\sigma_y\sigma_l}\frac{\lambda^3}{\gamma^2}D, \tag{1}$$

where r_c is the classical electron radius, c is the speed of light, N_b is the number of electrons in a bunch, σ_x, σ_y and σ_l are the standard values of the Gaussian bunch width, height and length, λ^{-1} is the momentum acceptance and γ is the Lorentz factor of the electron beam. D is the function [3] which gives dependence of τ_T on the momentum acceptance of the storage ring. For beam diagnostics, the Touschek lifetime is useful for measuring the basic parameters of the electron beam.

The beam lifetime τ consists of the Touschek lifetime and the beam–gas scattering lifetime; however, it is difficult to measure the two beam lifetimes separately because both depend on the beam current. The Touschek lifetime depends directly on the beam current; on the other hand, the beam–gas lifetime depends on the vacuum pressure, which depends on the beam current.

At the SuperACO SR facility [4] the Touschek lifetime was measured by storing two bunches with different bunch charges simultaneously and measuring their decay rates. The Touschek lifetime could then be analyzed by comparing the decay rate of each bunch, even though the vacuum conditions could change during the measurement, because both bunches experience the same vacuum conditions. The 'two unequal bunches' method of SuperACO is very effective for measuring the Touschek lifetime if it is assumed that the bunch volume does not change with the bunch charge, namely, the Touschek lifetime is inversely proportional to the number of electrons in the bunch. However, the assumption is not valid for electron storage rings in general because of perturbation of the bunch volume.

The need for the assumption can be avoided by preparing two bunches with extremely different bunch charges. If the Touschek lifetime of the weaker bunch of the two is very long compared with that of the more intense bunch, it is possible to measure the Touschek lifetime of the intense bunch without making any assumption about the dependence of the Touschek lifetime on the bunch charge. However, it is difficult to make two bunches that have extremely different bunch charges when the bunch charge of the intense bunch is small.

Spurious bunches in single-bunch operation in electron storage rings have extremely small charge compared with the main bunch charge regardless of the size of the main bunch charge, and can be generated automatically[5, 6]. Therefore, spurious bunches can be a useful probe for measuring the Touschek lifetime. Even though a spurious bunch can grow continuously during a measurement, it is possible to cancel the effects of the growth and measure the Touschek lifetime of the main bunch precisely using only the intensity of the main and spurious bunches, without requiring calculated beam or storage ring parameters.

THEORY

We consider the change with time in the number of electrons in a main bunch N_0 in single-bunch operation. We assume electron loss by the Touschek effect and beam–gas scattering, such that the change in N_0 with time is written as

$$\frac{dN_0}{dt} = -\frac{N_0}{\tau_T(N_0)} - \frac{N_0}{\tau_g}, \tag{2}$$

where the first term in the right-hand side represents the decay rate of the electrons from the Touschek effect and the second term represents that from beam–gas scattering.

We consider next the change in the number of electrons as a function of time in the RF bucket immediately following the main bucket. The number of electrons in the next bucket, N_1, also decreases due to Touschek and beam–gas scattering; however, some electrons expelled from the main bucket by Touschek scattering can enter the next bucket[6]. The change in N_1 with time is written as

$$\frac{dN_1}{dt} = N_0 C_0 - \frac{N_1}{\tau_T(N_1)} - \frac{N_1}{\tau_g}, \qquad (3)$$

where the first term on the right-hand side represents the growth of the spurious bunch due to electrons transferred from the main bucket. The parameter C_0 represents growth of the single-bunch impurity in a unit time. The second and third terms represent the decay rates of the spurious bunch due to the Touschek effect and beam–gas scattering.

We now consider the single-bunch impurity defined as the ratio of the charge of the first spurious bunch to that of the main bunch. From Eqs. (2) and (3), the change in the single-bunch impurity with time is written as

$$\frac{d}{dt}\left(\frac{N_1}{N_0}\right) \approx C_0 + \frac{1}{\tau_T(N_0)}\frac{N_1}{N_0}, \qquad (4)$$

where the approximation is valid when $1/\tau_T(N_1) \ll 1/\tau_T(N_0)$. If the growth of the single-bunch impurity in one Touschek lifetime period can be neglected compared with the single-bunch impurity, namely, if $N_1/N_0 \gg C_0\tau_T$, then the Touschek lifetime τ_T can simply be written as

$$\frac{1}{\tau_T(N_0)} = \frac{d}{dt}\log\left(\frac{N_1}{N_0}\right). \qquad (5)$$

If the approximation $N_1/N_0 \gg C_0\tau_T$ is not valid, it is still possible to measure the Touschek lifetime by repeating the measurement with a different spurious bunch charge with the same main bunch charge. For spurious bunch charges N_1 and N_1^* ($N_1 > N_1^*$) and main bunch charge N_0, from Eq. (4), $\tau_T\ (N_0)$ can also be written simply as

$$\frac{1}{\tau_T(N_0)} = \frac{d}{dt}\log\left(\frac{N_1 - N_1^*}{N_0}\right). \qquad (6)$$

We note that both Eqs. (5) and (6) can be written with only N_0, N_1 and N_1^*, which can be determined from measurement such as photon counting method [6, 7] ; the equations contain no calculated beam parameters or storage ring parameters.

OBSERVATION

To observe both the main bunch and a spurious bunch simultaneously, we used a photon counting method [6, 7] with a dynamic range greater than 10^5. To separate the signals from individual bunches, we used a microchannel plate-photomultiplier tube (MCP-PMT, Hamamatsu R2809U) with good time resolution (rise time of 150 ps and transit time spread of 55 ps). Fig. 1 shows a typical change with time in the intensity of the main and spurious bunches, measured by photon counting in single-bunch condition in UVSOR-II electron storage ring [7]. By measuring the change in the single-bunch impurity with time we can analyze the Touschek beam lifetime with Eq.(5) or (6); in case of the UVSOR-II we used Eq.(6) because of the condition of the approximation. Fig. 2 shows the Touschek lifetime from Eq.(6) and the total beam lifetime with different skew quadrupole magnet conditions. The Touschek lifetime from Eq.(6) is almost equal to the total beam lifetime even in larger skew quadrupole current. Even though the Touschek scattering effect decreased and the Touschek lifetime increased because of the skew quadrupole field, the lifetime was still dominated by the

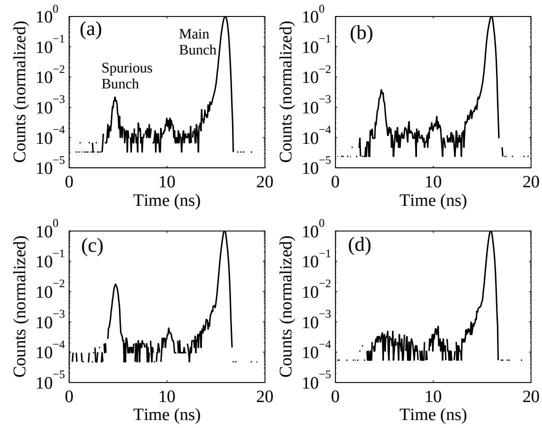

Figure 1: Change in temporal structure with time in single-bunch operation. Temporal structure (a)just after injection (total current 63.7mA), (b) after 10min(48.0mA), (c) after 87min (15.2mA), and (d) temporal structure without spurious bunches.

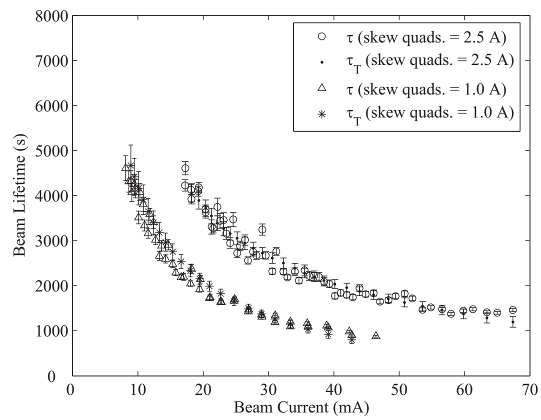

Figure 2: Touschek and total beam lifetimes for two skew quadrupole conditions. The dots/stars and circles/triangles correspond to the analyzed Touschek lifetime and the total beam lifetime, respectively, when the skew quadrupoles were set at 2.5/1.0 A.

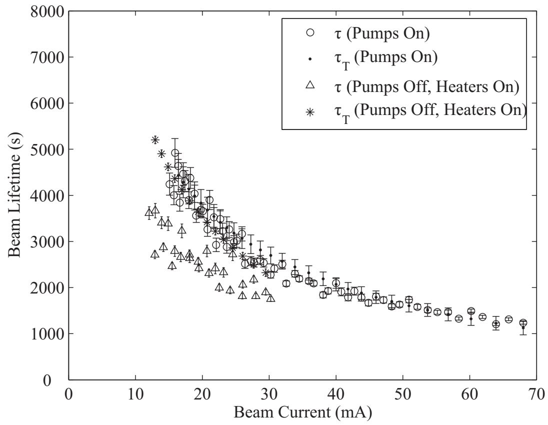

Figure 3: Touschek and total beam lifetimes for the same skew quadrupole condition (2.5 A) but different vacuum conditions. The dots and circles correspond to the Touschek lifetime and the total beam lifetime, respectively, under normal vacuum conditions (the same as for Fig. 2). The stars and triangles correspond to the Touschek and the total beam lifetimes, respectively, with all the SIPs and DIPs turned off and the baking heaters turned on.

Touschek effect. To make a situation where the Touschek lifetime and the beam–gas scattering lifetime are comparable, we tried to decrease the beam–gas scattering lifetime drastically. We turned off all the SIPs and DIPs in the storage ring and partly raised the temperature of the beam ducts with heaters, which are usually used for bake-out evacuation of the beam ducts. The vacuum pressure measured using the vacuum gauges increased from 2×10^{-8} Pa to 1×10^{-6} Pa. We injected and stored a single bunch under this condition and measured the beam lifetime. The Touschek and total beam lifetimes are shown in Fig. 3. In this experiment, we could only measure the beam lifetime below a beam current of 30 mA. As seen in the figure, the total beam lifetime clearly decreased compared with that under the normal vacuum condition. On the other hand, the Touschek lifetime kept the same value as that under the normal vacuum condition. This clearly demonstrates that we can measure the Touschek lifetime and the beam–gas scattering lifetime separately using this method.

We have estimated the vacuum pressure of the beam orbit using a model [7] of scattering between residual gas atoms and high energy electrons in the beam. From the estimation of the scattering cross section which leads the beam loss, we assume CO gas contributes to the beam–gas scattering lifetime in the UVSOR-II [7]. From the beam–gas scattering lifetime in poor vacuum condition in Fig. 3, the averaged CO pressure is estimated to be $1.12 \times 10^{-6} \pm 2.03 \times 10^{-7}$ Pa, which is close to the pressure measured using the vacuum gauges.

BEAM LIFETIME IN MULTIBUNCH OPERATION

We measured the beam lifetime in multibunch (successive 12 bunches + successive 4 vacant buckets) and single-bunch condition with the same operating mode; the same RF voltage and optical functions. Fig. 4 shows the $I\tau$ product in the multibunch and the single-bunch condition. The beam lifetime in the multibunch condition is slightly larger than that of the single-bunch condition. As discussed in the previous section, in the single-bunch condition the Touschek lifetime dominates the beam lifetime in the UVSOR-II. The result in Fig. 4 then indicates that even in the multibunch condition in which the total beam current is 12 times larger than that in the single-bunch condition the Touschek lifetime still dominates the beam lifetime. Small difference between the multibunch and the single-bunch may come from perturbation of the bunch volume due to wake field. Precise measurement of the Touschek lifetime in the multibunch condition is the next subject.

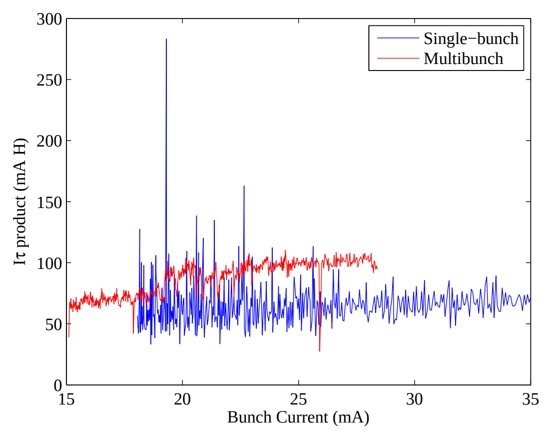

Figure 4: $I\tau$ product in multibunch and single-bunch operation in the same condition. The multibunch operation has 12 bunches; the total beam current is 12 times larger than the bunch current.

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