ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOTK055

BEAM LIFETIME MEASUREMENTS IN SIRIUS STORAGE RING

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Abstract

SIRIUS is the new storage ring-based 4th generation synchrotron light source built and operated by the Brazilian Synchrotron Light Laboratory (LNLS) at the Brazilian Center for Research in Energy and Materials (CNPEM). In ultralow emittance storage rings such as SIRIUS, the dominant contribution to the beam lifetime is due to Touschek effect. We used the strategy of storing simultaneously two bunches with different currents to measure their Touschek lifetime independently of other contributions to the total lifetime, such as gas scattering. The measurements were carried out in different conditions of bunch current and RF voltage to compare the experimental results with those expected from theory and simulations for SIRIUS.

INTRODUCTION

Details about SIRIUS main parameters and current operation status can be found in [1–3].

Electrons in the same bunch can undergo Coulomb scattering in which part of the transverse momentum is transferred to the longitudinal. With this scattering, after energy exchange between electrons, the final energy deviations may exceed the acceptance of the ring, causing particle losses. This process is called Touschek effect and its loss rate for each bunch can be obtained by [4]:

$$\alpha_{\mathrm{t}} = \frac{1}{\tau_{\mathrm{t}}} = \frac{r_e^2 I_b}{8\pi\gamma^2}\int_0^{L_0}\frac{F(\tau_m, B_1, B_2)}{\tau_m\sigma_z\sigma_h}\mathrm{d}s, \tag{1}$$

where r_e is the classical electron radius, I_b is the bunch current, γ the Lorentz factor, σ_z the bunch length, σ_h is related to transverse beam sizes, energy spread σ_δ and dispersion functions by $\sigma_h = \sqrt{\sigma_x^2\sigma_y^2 - (\sigma_\delta^2\eta_x\eta_y)^2}$. The parameter τ_m is related to the momentum acceptance by $\tau_m = \left(1-\gamma^{-2}\right)\delta_m^2 \approx \delta_m^2$. $F(\tau_m, B_1, B_2)$ is a functional of equilibrium parameters and lattice optics functions, parameterized in terms of $B_1(s)$ and $B_2(s)$ in an integral form that can be calculated numerically [4].

Other relevant contributions to the loss rate come from elastic and inelastic scattering between electrons and residual gas in the vacuum chamber, which depends mainly on vacuum pressure. In conditions in which quantum lifetime can be neglected, the total loss rate α_{total} is the sum of Touschek α_{t} and vacuum α_{v} contributions, such that $\mathrm{d}I/\mathrm{d}t = -\alpha_{\mathrm{total}}I = -(\alpha_{\mathrm{t}}+\alpha_{\mathrm{v}})I$.

METHOD

The simple measurement of beam current decay provides the total beam lifetime and separating each contribution is typically complicated [5–12]. In order to measure each contribution independently, some strategies have been proposed to study the lifetime behavior in different operation conditions. In Ref. [13] the authors proposed a method of storing two bunches with different charge densities. In this setup, the two bunches densities experience the same pressure and, therefore, the same vacuum loss rate. Measuring the current decay of each bunch and applying the constraint of equal vacuum conditions for both, one should be able to extract the Touschek lifetime contribution. The original method proposed in [13] assumed that beam equilibrium parameters are independent of beam current, so the Touschek loss rate could be obtained algebraically from the total loss rates and current of each bunch as a function of time.

Touschek Lifetime Effective Model

For SIRIUS storage ring, beam equilibrium parameters are highly current-dependent given the small beam volume and large beam coupling impedances due to small vacuum chamber radius. Details about collective effects simulations and measurements for SIRIUS are discussed elsewhere [14].

The bunch-lengthening with single-bunch current, caused mainly by potential-well distortion induced by wakefields, can be included in the effective model of Touschek loss rate. Considering a linear approximation of this effect as $\sigma_z \approx \sigma_{z,0}(1+\mu_z I_b)$, where $\sigma_{z,0}$ is the bunch-length at zero-current, the Touschek loss rate can be factored as:

$$\alpha_{\mathrm{t}} = \bar{\alpha_{\mathrm{t}}}\frac{I_b}{1+\mu_z I_b}, \tag{2}$$

where $\bar{\alpha_{\mathrm{t}}}$ is a normalized loss rate that should depend on zero-current equilibrium parameters and lattice optics.

However, other well-known current-dependent effects on beam parameters, such as intrabeam scattering (IBS) [15], are more involved to be captured with an effective model. For example, the functional $F(\tau_m, B_1, B_2)/\sigma_h$ in Eq. (1) generally has a non-trivial dependence on parameters $(\epsilon_x, \epsilon_y, \sigma_\delta)$ that are increased by IBS.

Fitting the Data

A possible approach to fit the loss rate is dividing the measured current decay data in small time segments and fit a linear decay to each one, although this process may be highly susceptible to data noise. In addition, the choice of the time span is not straightforward and may not attend both bunches data simultaneously due to the large difference in decay rates.

A fitting approach that is robust to noise relies on the solution of the differential equation by numerical integration.

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Let us define the transformation $\mathscr{F}$ by

$$\mathscr{F}(\alpha, I_{\text{meas}}) = I_{0,\text{meas}} - \int_0^t I_{\text{meas}}(t')\alpha\left(I_{\text{meas}}(t')\right) \mathrm{d}t', \quad (3)$$

where $I_{\text{meas}}(t=0) = I_{0,\text{meas}}$ is the initial current. The transformation $\mathscr{F}$ takes as input the measured current decay at discrete times $I_{\text{meas}}(t_i)$ and returns a corresponding current based on the loss rate model. The parameters of the effective model defined by $\alpha(I)$ can be adjusted to reproduce the measured current decay by means of minimizing the cost function $\chi^2 = \sum_{i=1}^{N}\left[\mathscr{F}(\alpha, I_{\text{meas}}(t_i)) - I_{\text{meas}}(t_i)\right]^2$.

The data set can be divided in time segments in which the vacuum lifetime is assumed to be constant. Note that the assumption of linear decay in these data segments is not necessary and a generic loss rate can be used. Even if an effective model with analytic expressions can not be determined, this fitting approach still can be applied just substituting the step of evaluating the formula for $\alpha(I)$ by a simulation code.

Lifetime and Momentum Acceptance

The storage ring momentum acceptance can be investigated using the Touschek lifetime dependence with RF voltage as a probe [16–18]. As shown in Eq. (1), the Touschek loss rate depends on the momentum acceptance with δ_m^{-2} and with a non-trivial dependence in the function $F(\tau_m, B_1, B_2)$. The momentum acceptance in a storage ring is s-dependent and defined by non-linear dynamics and RF acceptance. Figure 1 shows SIRIUS nominal momentum acceptance for one section of the model without random errors and RF voltage of 1.575 MV. Details of the calculation procedure can be found in Ref. [19].

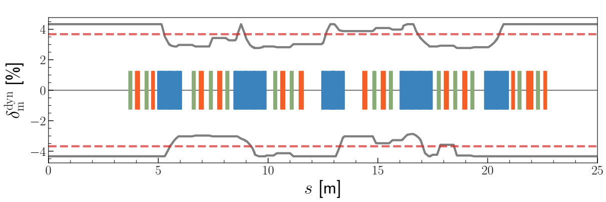

Figure 1: Momentum acceptance for one section of SIRIUS storage ring. The gray curve is the nominal acceptance from non-linear dynamics and the dashed red lines represent the RF acceptance. Dipoles, quadrupoles and sextupoles are represented as blue, orange and green blocks, respectively.

RESULTS

Lifetime with Two Bunches

Raw data at ADC rate (382 points per turn) for all four antennas of a BPM located at a straight section were used to measure the current decay of each one of the two bunches independently. Two previously measured counts-to-current calibration curves, one for each bunch, were used to deconvolve the individually-induced signal during the experiment. The resulting sum of both reconstructed currents was compared with the DCCT measurement, showing a discrepancy of only 2 µA, much smaller than the current of each bunch. Data from 100 turns was acquired and averaged to decrease noise contributions. The chosen buckets numbers to fill were 1 for the high charge bunch and 550 for the low charge so mutual signal interference could be minimized.

Bunch 1 was filled initially with 2.36 mA and bunch 2 with 0.21 mA. Data acquisitions were done for 12 h during a machine studies night shift with all IDs transverse fields set to minimum values. The data set was divided into 24 segments, with 30 min-duration each, where the vacuum contribution to the lifetime was regarded as constant. Current decays were fitted with Eq. (3), using the effective model of Touschek loss rate of Eq. (2) plus a constant term α_{v} related to the vacuum loss rate for each time segment. Therefore, we used 26 parameters (24 α_{v}, 1 $\bar{\alpha_{\text{t}}}$ and 1 μ_z) to fit more than 15k data points. Considering the discrepancy of 2 µA between DCCT and BPM-calculated currents, fitting residues lower than this value was used as an indication of overfitting.

Since the main goal of the two bunches setup is to obtain the Touschek contribution regardless of vacuum conditions, we set the upper bound for the vacuum lifetime as 150 h just to avoid overfitting. In Table 1 the Touschek parameters obtained are presented. Even though the fitting error of these parameters is lower when τ_{v} has no bounds, the fitting residue is still close 2 µA and the effective model seems to overfit the data. The parameters for the "nominal model" were obtained by fitting Eq. (2) to simulated data of Touschek rate vs. current. A careful error propagation analysis, including repeatability of fitting parameters, still needs to be carried out to obtain more realistic error bars.

A larger value for the fitting parameter μ_z was expected, since it was accounting for all effects that increase the "beam volume". Including a I_b^2 term in the denominator of Eq. (2) was attempted, since from simulations and streak-camera measurements, the bunch-length vs. current is well described by a quadratic polynomial [14]. However, the fitting reduced the quadratic coefficient to zero and the linear coefficient was basically the same reported in Table 1. Hence, we chose to keep only the linear term in the denominator to avoid unnecessary fitting parameters.

With the fitted parameters presented in Table 1, for 100 mA with uniform filling ($I_b = 0.116$ mA), the Touschek lifetime estimate is 19 h. With a vacuum lifetime of 150 h, the total lifetime would be close to 17 h, which is consistent with the values observed during user shifts.

Table 1: Touschek Lifetime Fitting Parameters

Fitting condition	$\bar{\alpha_{\text{t}}}$ [h^{-1}mA^{-1}]	μ_z [mA^{-1}]
$\tau_{\text{v}} \leq 150$ h	0.4318 ± 0.004	0.249 ± 0.001
Free τ_{v}	0.4589 ± 0.002	0.3083 ± 0.0005
Nominal model	0.5040	0.6105

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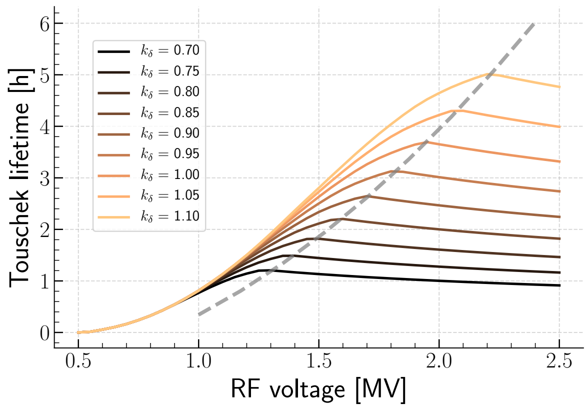

Figure 2: Simulated Touschek lifetime vs. RF voltage for 1 mA single-bunch current. The color-coded curves represent different dynamic momentum acceptances. The dashed gray curve highlights the maximum Touschek lifetime with corresponding RF voltage for each k_δ curve.

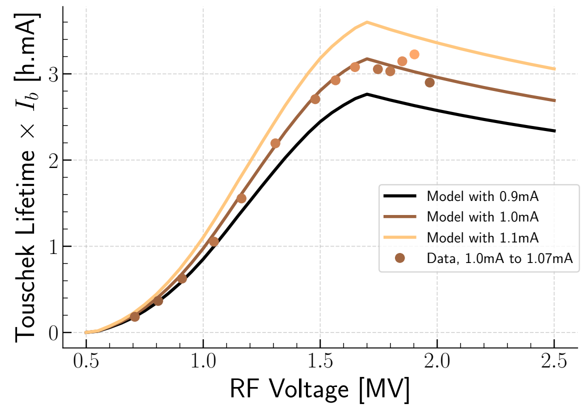

Figure 3: Measured Touschek lifetime × I_b vs. RF voltage for single-bunch currents close to 1 mA. With $k_\delta = 0.9$ and multiplying the lifetime values by 1.2, the measured $V_{\rm rf}^{\rm (c)}$ is reproduced. The colormap encodes the single-bunch current value, where lighter colors means higher currents and vice-versa.

Lifetime vs. RF Voltage

In Fig. 2, results of Touschek lifetime calculations with SIRIUS model are shown. The equilibrium parameters for 1 mA were calculated including the effects of wakefields and IBS [14]. Let $V_{\rm rf}^{\rm (c)}$ be the critical RF voltage in which the Touschek lifetime is maximum. This quantity is determined by the dynamic momentum acceptance, as can be seen in Fig. 2. The parameter k_δ is a scale factor used to artificially change the nominal dynamic acceptance by $\delta_m^{\rm dyn}(s) \to k_\delta \delta_m^{\rm dyn}(s)$. It was observed in simulations that, while keeping the model dynamic momentum acceptance fixed, changing other parameters as emittance ratio just affects the lifetime vs. RF voltage curves by a scale factor and does not change the value of $V_{\rm rf}^{\rm (c)}$. Therefore, one can measure $V_{\rm rf}^{\rm (c)}$ to estimate the machine momentum acceptance.

We measured the current decay of a single-bunch, also using BPM waveform acquisitions, while scanning the RF voltage. For each voltage, a current close to 1 mA was accumulated in a bunch and the acquisitions ran until the current dropped to about 0.95 mA. Based on the previous measurement, we considered a fixed vacuum lifetime of 150 h and fitted the parameter $\bar{\alpha_{\rm t}}$ for the Touschek lifetime.

In Fig. 3 the measurement results are presented and compared with calculations using the nominal model for single-bunch currents around 1.0 mA. The similarity between data and model results is quite remarkable. The quantity $\tau_{\rm t} \times I_b$ is equal to $\bar{\alpha_{\rm t}}^{-1}$ and, when collective effects are absent, should be independent of current, for a fixed RF voltage.

Since the value of $V_{\rm rf}^{\rm (c)}$ is crucial to estimate the momentum acceptance, we measured the incoherent synchrotron frequency as a function of RF voltage to calibrate the RF voltage readout value [16]. The measured critical RF voltage was $V_{\rm rf}^{\rm (c)} = 1.705$ MV. This voltage corresponds to a factor $k_\delta = 0.9$, which was used to calculate the curves of Fig. 3. This obtained k_δ value is quite reasonable since non-linear optimization studies have not been carried out so far. Thus, it should be possible to find optimum sextupole settings to improve the dynamic momentum acceptance and consequently Touschek lifetime. Furthermore, we had to scale up by a factor 1.2 the lifetime curves calculated with the model to match the measured data. These higher values for the measured lifetime could be explained by a difference between the estimated and measured equilibrium parameters, for example the emittance ratio not measured yet. This issue is being investigated.

CONCLUSIONS

Lifetime studies were carried out in SIRIUS storage ring. The method of storing two bunches and measuring their current decays was applied to measure the Touschek lifetime contribution independently of vacuum conditions. The fact that beam equilibrium parameters have a strong dependence on single-bunch current for SIRIUS has proven to be an essential feature to be considered. For 100 mA with multi-bunch uniform filling, the present SIRIUS operation mode, the fitted parameters estimate a Touschek lifetime of 19 h. Despite being an interesting setup to measure the Touschek lifetime, when the total lifetime is heavily dominated by this effect, the two bunches method provides poor information about vacuum lifetime. Other methods to study the gas lifetime contribution are being investigated. Measurements of Touschek lifetime vs. RF voltage indicate that the machine momentum acceptance is a factor 0.9 lower than the acceptance obtained from the nominal model. It is still not completely clear how to properly include collective effects as an effective model that fits the beam current decay and results in parameters consistent with theory and simulations. Further studies are planned to explore these issues.

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