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NSLS-II BEAM LIFETIME MEASUREMENTS AND MODELING*

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Abstract

NSLS-II is a recently constructed 3 GeV synchrotron light source with design horizontal emittance values in sub-nm range. Achieving good beam lifetime is critically important for NSLS-II as it is closely tied to such important operational aspects as top-off injection frequency, injector components wear, radiation protection and control, and others. In this paper we present lifetime-related commissioning results and describe our present understanding of beam lifetime at NSLS-II.

INTRODUCTION

At 500 mA design beam current the beam lifetime in the NSLS-II ring is expected to be Touschek-dominated [1]; contributions from gas scattering could also be significant, especially when small gap in-vacuum undulators are in operation.

Direct measurements of just the Touschek lifetime are not possible, as the combined lifetime due to all of the effects is always measured. However, contributions due to gas scattering can be separated from the Touschek effect as they generally do not depend on beam dimensions (ignoring ion trapping) and only depend on the total beam current through current-dependent outgassing rates. These rates could be measured, and, at low beam intensity their current-dependence is negligible. Touschek lifetime, on the other hand, has a strong dependence on beam dimensions and is inversely proportional to single-bunch current.

For a simplified model of constant gas pressure, gas scattering lifetime results in the exponential time dependence of the total beam current,

$$I(t) = I(0)\,\mathrm{Exp}(-t/\tau), \qquad (1)$$

where two separate processes are responsible for the decay. Elastic gas-scattering lifetime is given by [2]

$$\frac{1}{\tau_{el}} = \frac{4 r_e^2 Z^2 \pi n c}{2\gamma^2}\left[\frac{\langle\beta_x\rangle}{A_x} + \frac{\langle\beta_y\rangle}{A_y}\right], \qquad (2)$$

where $A_{x,y}$ are horizontal and vertical acceptances, given by the minimum value of aperture, a(s), squared and divided by the beta function at that location, $A=\min(a(s)^2/\beta(s))$, n and Z are the concentration and the atomic number of the residual gas ions.

Lifetime due to inelastic gas-scattering, or Bremsstrahlung, is given by [2]

$$\frac{1}{\tau_{brem}} = \frac{16 r_e^2 Z^2 n c}{411}\ln\left[\frac{183}{Z^{1/3}}\right]\left[-\ln\varepsilon_{acc} - \frac{5}{8}\right], \qquad (3)$$

where ε_{acc} is the limiting momentum acceptance.

Touschek scattering process leads to the non-exponential decay of single-bunch current,

$$I_b(t) = \frac{I_b(0)}{1 + t/\tau_{tous\_1/2}}, \qquad (4)$$

where $\tau_{tous\_1/2}$ is the so-called Touschek half-life (but also called Touschek lifetime below), given by [3]

$$\frac{1}{\tau_{tous\_1/2}} = \frac{\sqrt{\pi}\, r_e^2 c N_b}{\gamma^3}\left\langle \frac{C(\zeta)}{\sigma'_x V \varepsilon_{acc}^2}\right\rangle, \qquad (5)$$

where N_b is the number of electrons per bunch, $C(\zeta) = -\frac{3}{2}e^{-\zeta} + \frac{\zeta}{2}\int_\zeta^\infty \ln(u)\frac{e^{-u}}{u}du + \frac{1}{2}(3\zeta - \zeta\ln\zeta + 2)\int_\zeta^\infty \frac{e^{-u}}{u}du$, $\zeta = \left[\varepsilon_{acc}/\gamma\sigma'_x\right]^2$, V is the beam volume, and the brackets denote averaging over the ring circumference.

For short time intervals, the current decay is relatively small, which is what is happening during top-off operations or during typical lifetime measurements. In such instances both (1) and (4) are well approximated by a linear time-dependence, so the total lifetime is given by

$$\tau_{total} = 1/(\tau_{el}^{-1} + \tau_{brem}^{-1} + \tau_{tous\_1/2}^{-1}). \qquad (6)$$

In NSLS-II ring the standard (total) beam lifetime measurements are performed by linearly fitting the decaying beam current signal, measured by DCCT, over the specified time interval (typically 5 minutes). The lifetime is simply the average current over this interval divided by the fitted slope. However, for low beam currents we found the DCCT-derived lifetime to be too noisy, especially when we could not afford long averaging times. This is why the so-called “BPM lifetime” measurement was implemented as well. Instead of the DCCT signal, it uses the average sum signal from 180 BPMs, resulting in much lower noise, even when the time averaging is performed over 30s or shorter intervals. This is the measured lifetime reported below.

MEASUREMENTS AND ANALYSIS

Phase I Commissioning

We start with the single bunch measurements from 05/08/14 as well as the 20-bunch train data from 05/11/14 (both data sets are with emittance coupling corrected to an estimated value of $\kappa=\varepsilon_y/\varepsilon_x=0.32\%$). The RF cavity voltage at the time was 1.9 MV (close to the maximum allowed) corresponding to the momentum acceptance of $\varepsilon_{RF}=2.5\%$. The measured lifetime vs. single bunch current is plotted in Fig.1 (circles). Note that the trends vs.

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current for both of the data sets are reasonably close, however scaling the 20-bunch train data to 18 bunches (the result is shown in crosses, but not used below) makes them even closer. A simple explanation for this is that NSLS-II ring bunch trains are usually not very uniform, and the first few leading and the last few trailing bunches tend to have somewhat lower intensity.

We start by fitting the single bunch data to two different 2-parameter models described below; the fit results are plotted in solid lines in Fig. 1. Obviously both curves fit well with the 20-bunch data as well. Both models ignore current-dependent outgassing and simply assume that the total lifetime consists of current-independent gas-scattering contribution, as well as the Touschek contribution that depends on the single bunch current.

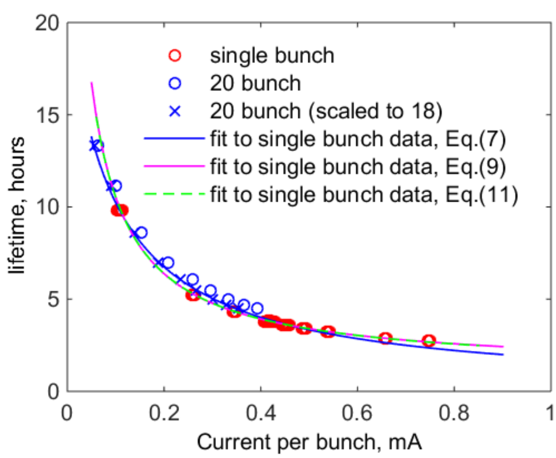

Figure 1: Measured and fitted lifetime data, ε_{RF}=2.5%.

Specifically, the first model, shown in blue, is given by

$$\tau_{total}(I_b) = \frac{\beta\,\alpha / I_b}{\alpha / I_b + \beta}, \qquad (7)$$

where α and β are the fit parameters, and I_b is the single bunch current. This simple model already describes the data reasonably well. However, the Touschek effect modeling it includes, $\tau_{tous\_1/2} = \alpha / I_b$, is somewhat incomplete, because even at these low beam intensities, significant bunch-lengthening does occur, which somewhat weakens the inverse lifetime dependence on beam current.

The bunch-lengthening has been measured with a streak camera. The results (for this RF cavity voltage) are well-approximated by a simple linear dependence,

$$\sigma(I_b) \approx 12.0 + 11.4 \times I_b, \qquad (8)$$

where the bunch length is given in ps, and beam current in mA (see e.g. [4]).

In the second fit, shown in magenta, we incorporated this bunch-lengthening effect into the Touschek lifetime component of the model so that

$$\tau_{total}(I_b) = \frac{\beta\,\alpha\sigma(I_b) / I_b}{\alpha\sigma(I_b) / I_b + \beta}. \qquad (9)$$

This fit seems somewhat better for the higher current points, although we still have to perform more detailed measurements to reliably confirm this.

We note in passing that the model given by Eq. (9) (also with bunch-lengthening linear with I_b) was very accurate in predicting beam lifetime at arbitrary fill patterns and beam currents at the NSLS X-ray ring.

The values of α, obtained from these two fits, result in the Touschek lifetime values (taken at 0.5 mA single bunch current) of 4.0 and 3.7 hours, respectively, while fitted βs give 21 and 47 hours for the gas lifetime.

Finally, we attempted to improve the model even further and account for the current-dependent outgassing. We approximated the ring-average vacuum pressure (around 05/08/14) available from the machine history as

$$P(I) = (1.5 + I[mA]) \times 10^{-10}\,\text{Torr}. \qquad (10)$$

Eq. (10) expresses the average gas pressure as a function of total current at the locations of the vacuum gauges, rather than along the beam orbit. The two could be different. In addition, the residual gas composition is not continuously available, and there is some uncertainty about other parameters that define the gas scattering lifetimes in Eqs. (2)-(3). Thus we still fitted for the overall gas lifetime scale-factor parameter β, modelling the total lifetime as (I_b in mA, I= N×I_b),

$$\tau_{total}(I_b) = \frac{\beta(1.5 + N \times I_b)^{-1}\alpha\sigma(I_b)/I_b}{\alpha\sigma(I_b)/I_b + \beta(1.5 + N \times I_b)^{-1}}. \qquad (11)$$

This fit is plotted in Fig. 1 in dashed green, and, to the resolution of the figure, it is identical to the previous fit (to Eq. (9)), basically arguing that the current-dependent outgassing is not important at these conditions with relatively low average but high single-bunch current. With the fit parameters obtained, Eq. (11) results in 3.8 hours Touschek and 34 hours gas lifetimes at 0.5 mA single bunch current.

Note that for all three models the fitted values for the Touschek lifetime, 4.0, 3.7 and 3.8 hours, are rather close. At this point it is impossible to estimate the systematic error, while the statistical error from the data we presented comes out to be about 10%.

We compared these fitted values for the Touschek lifetime to the one predicted by the analytical formula, Eq. (5). At 0.5 mA/bunch and taking the best measured or inferred values available at the time, specifically 2.5% momentum acceptance, ε_x=2.1 nm horizontal emittance, $\kappa=\varepsilon_y/\varepsilon_x$ =0.32% emittance coupling and σ=18 ps, we obtain $\tau_{tous\_1/2} \approx$ 4.3 hours, which is reasonably close to the fitted values quoted above.

Also note that the momentum acceptance in Eq. (5) generally includes both the RF and lattice contributions (the latter varies around the ring). However, for the estimates above we simply assumed ε_{acc}=ε_{RF}=2.5%. The fact that the analytical estimate came out fairly close to the fitted measurement values indicates that our lattice does not significantly degrade the average momentum aperture, at least up to the 2.5% level.

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Results with SC RF cavity

In May 2014 a superconducting cavity (SC) was installed to replace the normal conducting PETRA-III one. A number of IDs including the damping wigglers (DW) were also installed, and the ring commissioning (phase II) resumed in the summer. Some of the lifetime measurements from phase-II commissioning are presented below. Note that the SC cavity needed a substantial time for conditioning to come up in voltage, so these were done at somewhat lower RF voltage. Also, for lack of space we do not discuss preliminary measurements that were done with DW or other ID gaps closed, thus concentrating on the bare lattice machine.

Another relevant development in early May was the successful commissioning of the bunch-by-bunch (BxB) feedback system procured from DIMTEL [5]. For lifetime studies the bunch cleaning feature of this system proved to be very useful, as it allowed us to quickly create few bunch fill patterns with single-bunch intensity variation of less than 10% or better, and with an arbitrary number of empty RF buckets between the bunches, see Fig. 2.

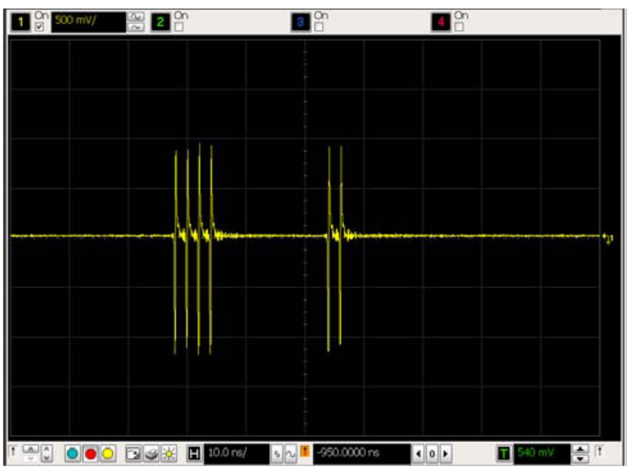

Figure 2: A 4+2 bunch fill pattern created with the bunch cleaning feature of DIMTEL BxB system.

In Fig. 3 we present the lifetime data from 7/13/14 (symbols), where we varied the number of bunches stored in the ring as well as the current per bunch. The coupling was corrected to an estimated value of κ=0.4%). The RF cavity voltage at the time was 1.2 MV corresponding to the momentum acceptance of ε_{RF}=1.8%.

A similar analysis to the one described earlier was performed to fit these data. The solid lines show the fits to the data using Eq. (7) (red) as well as Eq. (9) (blue, with bunch-lengthening, Eq. (8), replaced by that for 1.8 MV RF voltage). For this set of data there is hardly any difference in the resulting fits. The Touschek lifetime we get from either of these fits, at 0.5mA/bunch, is 2.1 hours +/-10%. This number is very close to the analytical estimate from Eq. (5) of 2.1 hours. The gas lifetime cannot be determined that well from these data (because the Touschek lifetime dominates at these conditions), but the fitted value does come out to be larger than 50 hours.

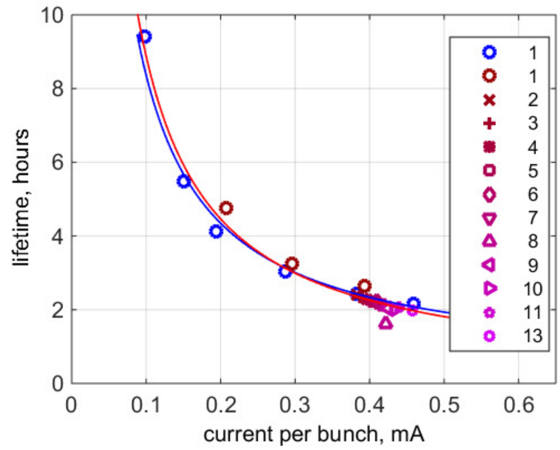

Figure 3: Measured and fitted lifetimes with different number of bunches stored, ε =1.8%.

CONCLUSIONS AND OUTLOOK

We presented a number of dedicated beam lifetime measurement studies performed in the course of NSLS-II commissioning. We also introduced an analysis technique that allows one to clearly separate the Touschek and gas scattering contributions to the total lifetime. So far no lifetime-related surprises were discovered. The Touschek lifetime agrees well with the analytically calculated values, provided we use the measured bunch length and emittance coupling. Also our measurements indicate that up to ~2.5% level, the momentum acceptance limitations from the lattice are negligible. This was also confirmed in separate measurements of high single bunch current beam lifetime vs. RF voltage, which show no signs of levelling off up to the highest achieved ε_{RF}=2.5%.

Provided that the average momentum acceptance remains close to the 2.5% value as more IDs are installed we should expect the design value of Touschek lifetime of >3 hours to be achievable at the design values of beam current, horizontal emittance and coupling.

Future studies will include more detailed measurements for a larger number of fill patterns, as well as with closed ID gaps. We are also exploring an alternative technique, that allows one to separate the contributions of gas and Touschek scattering by simultaneously measuring the lifetime of individual bunches in a train that has some intensity variation between the bunches. Separately, we have started performing scraper measurements that will allow us to better model the elastic scattering lifetime and understand the limiting apertures.

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