TOUSCHEK LIFETIME CALCULATIONS AND SIMULATIONS FOR NSLS-II

C. Montag, J. Bengtsson, B. Nash, Brookhaven National Laboratory, Upton, NY 11973, USA

Abstract

The beam lifetime in most medium energy synchrotron radiation sources is limited by the Touschek effect, which describes the momentum transfer from the transverse into the longitudinal direction due to binary collisions between electrons. While an analytical formula exists to calculate the resulting lifetime, the actual momentum acceptance necessary to perform this calculation can only be determined by tracking. This is especially the case in the presence of small vertical apertures at insertion devices. In this case, nonlinear betatron coupling leads to beam losses at these vertical aperture restrictions. In addition, a realistic model of the storage ring is necessary for calculation of equilibrium beam sizes (particularly in the vertical direction) which are important for a self-consistent lifetime calculation.

INTRODUCTION

In most modern medium energy ($\approx 3\,\mathrm{GeV}$) synchrotron radiation sources, the beam lifetime is limited by the Touschek effect, which describes the collision of two electrons inside a bunch due to transverse focusing. These collisions lead to momentum transfer from the transverse planes into the longitudinal direction. In the event that the resuting particle momentum exceeds the momentum acceptance $\delta_{\rm acc}$ of the storage ring, the electron is lost.

The resulting Touschek lifetime is calculated as [1]

$$\tau^{-1} = \frac{r_e^2 cq}{8\pi e\gamma^3\sigma_s}\cdot\frac{1}{C}\cdot\oint_C \frac{F\left(\left[\frac{\delta_{\rm acc}(s)}{\gamma\sigma_{x'}(s)}\right]^2\right)}{\sigma_x(s)\sigma_{x'}(s)\sigma_z(s)\delta_{\rm acc}^2}\,\mathrm{d}s, \quad (1)$$

where r_e denotes the classical electron radius, q the bunch charge, σ_s the bunch length, C the circumference of the storage ring, and $\sigma_x(s)$ and $\sigma_z(s)$ the rms horizontal and vertical beam radii, including the dispersion term. c is the vacuum velocity of light, e the electron charge, and γ the relativistic Lorentz factor of the beam.

The beam divergence $\sigma_{x'}$ for $x = 0$ is expressed as

$$\sigma_{x'} = \frac{\epsilon_x}{\sigma_x(s)}\sqrt{1+\frac{\mathcal{H}(s)\sigma_\delta^2}{\epsilon_x}}, \quad (2)$$

where $\mathcal{H}(s)$ is the chromatic invariant

$$\mathcal{H}(s) = \gamma_x\eta^2 + 2\alpha_x\eta\eta' + \beta_x{\eta'}^2, \quad (3)$$

and ϵ_x and σ_δ denote the horizontal beam emittance and the rms momentum spread, respectively. The function $F(x)$ is defined as

$$F(x) = \int_0^1\left(\frac{2}{u}-\ln\frac{1}{u}-2\right)\cdot\exp\left(-\frac{x}{u}\right)\,\mathrm{d}u. \quad (4)$$

The Touschek lifetime depends linearly on both the bunch length σ_s and the vertical beamsize σ_z, as Equation 1 indicates. However, the dependence on the horizontal beamsize (or the horizontal beam emittance) is more complicated. If the horizontal beamsize is large, the particle density within the bunch becomes very small, and subsequently the probability of two electrons coliding decreases. On the other hand, a large horizontal beam size corresponds to large horizontal angular divergence that can be transferred into the longitudinal direction due to a Touschek scattering event. This complicated dependence of the Touschek lifetime on the horizontal beam size is therefore best evaluated by numerical integration of Equation 1 for a fixed (position-independent) value of the momentum acceptance $\delta_{\rm acc}$. Figure 1 depicts the resulting Touschek lifetime in NSLS-II as a function of the horizontal beam emittance for a momentum acceptance of $\delta_{\rm acc} = 0.03$ and a vertical emittance of $1\cdot 10^{-11}\,\mathrm{m}$.

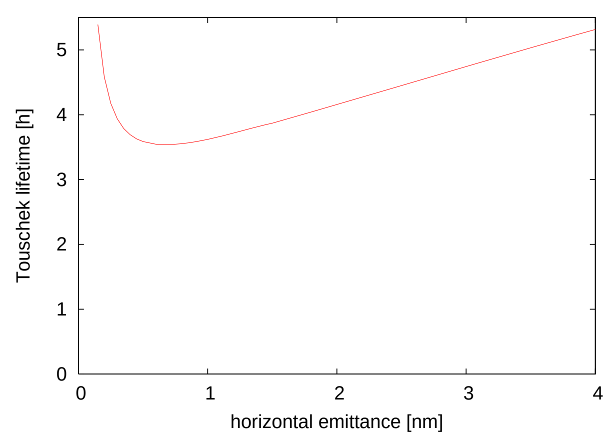

Figure 1: Touschek lifetime in NSLS-II as a function of horizontal emittance.

MOTIVATION

While top-up injection relaxes the constraint on Touschek lifetime, it remains a limiting factor due to the increased demands on small beam emittance and current stability from the users. For a realistic design then, it is crucial that it is estimated correctly.

It is well known [2, 3, 4, 5, 6] that e.g. the lattice symmetry and small (5 mm) vertical apertures from mini-gap insertion devices have a strong impact on the Touschek life time. Losses can then occur due to coupling (linear and nonlinear) between the horizontal and vertical planes. Moreover, just because a particle is stable for some initial conditions in simulations without radiation damping, this does not mean that it is stable when damping is included. After a Touschek event, due to amplitude dependent tune shift and residual (linear and nonlinear) chromaticity, the particle crosses resonances and be lost during its return to equilibrium through damped (anharmonic) betatron oscillations. Correspondingly, to correctly estimate and control the Touschek life time, a realistic model is required. The model should also include the correction schemes for control of the dynamics for a realistic lattice. In other words, the dynamics for a nontrivial Hamiltonian needs to be evaluated, i.e., that includes: engineering tolerances, insertion devices, and corrections.

For a self consistent approach, the following aspects need to be included:

- magnetic alignment and field tolerances,
- damping wigglers and insertion devices,
- control of the impact of these on, i.e. orbit, vertical beam size [7], and the (linear) optics perturbations [8],
- physical apertures,
- and radiation damping.

Having established such a model, realistic estimates of the Touschek life time can then be provided. Guidelines can thus be worked out for e.g.:

- RF voltage (RF bucket).
- Top-up period.
- Min vertical physical aperture.
- Choice of working point.
- Can Touschek life time/momentum aperture be improved further?
- Lattice symmetry requirements?
- What are the beam loss patterns from top-up and Touschek scattering?
- Potential radiation damage of mini-gap undulators.
- Could vertical scrapers be used for effective control of the loss pattern; without significant reduction of the Touschek life time?

A SELF CONSISTENT APPROACH

We have implemented the ideas described in the previous section in order to get a realistic estimate of Touschek lifetime for NSLS-II. Misalignment errors with orbit correction have been applied to the design lattice. We also must add a realistic suite of damping wiggler and additional insertion devices for a realistic model. For these calculations, we have included three damping wigglers and one CPMU. Vertical emittance is controlled by adding vertical dispersion in such a way that coupling is not strongly increased [9, 7]. The induced vertical dispersion wave is shown in Figure 2. The resulting vertical beam size is shown in Figure 3, and the coupling angle is shown in Figure 4. The vertical beam size should be set to the diffraction limited value. Larger than that degrades beam brithtness, whereas smaller than that degrades Touschek lifetime.

Once the lattice elements and physical apertures are appropriately set, the momentum aperture and resulting Touschek Lifetime is computed. Figure 5 shows the momentum aperture for the nominal ID gap width of ± 2.5 mm. Note that in the dispersive regions, the aperture has decreased from its nominal value of 3%.

Gap width is a crucial parameter to understand in relation to Touschek lifetime, and thus we have varied the gap in the CPMU and computed the resulting Touschek lifetime. Figure 6 shows a drop in lifetime in the 2 to 5 mm range. 2.5 mm has been chosen as a reference guideline for minimal gap size.

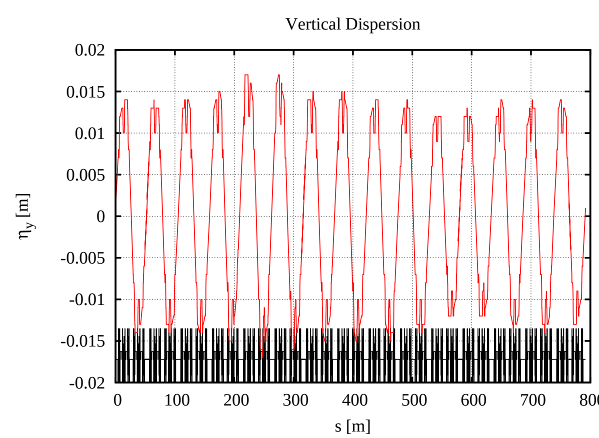

Figure 2: Vertical dispersion wave around the ring.

CONCLUSIONS

We have presented a summary of our approach to modelling Touschek lifetime for the NSLS-II. In particular, we have stressed the importance of self-consistent calculations in which the equilibrium beam sizes and the momentum aperture tracking both come from the same lattice model. Once the infrastructure for such calculations is in place, the results can be used to determine and optimize the Touschek lifetime. We have given one example of such optimization

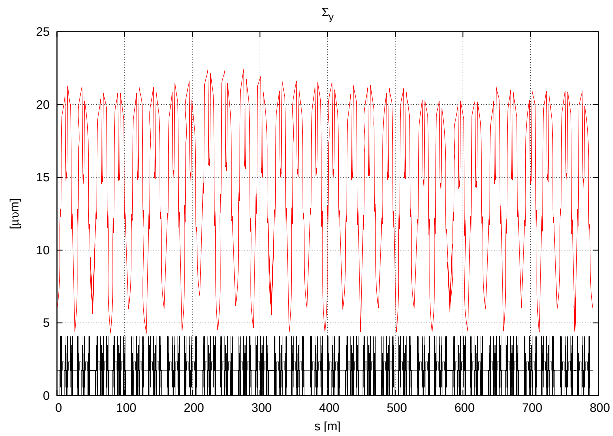

Figure 3: Vertical beam size around the ring.

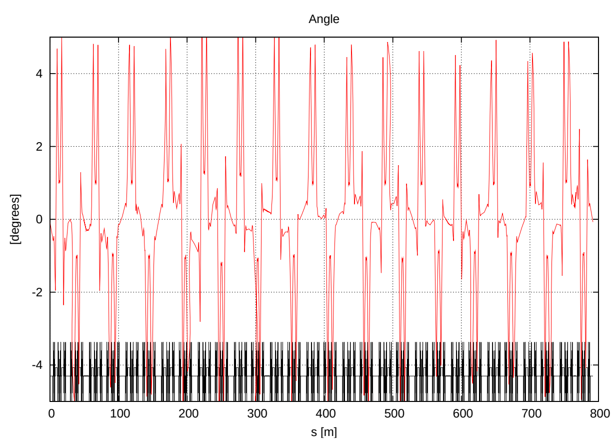

Figure 4: Transverse coupling angle around the ring.

by plotting the effect on lifetime of vertical gap size in the insertion devices. Because small vertical gap size and large Touschek lifetime are conflicting demands, such a detailed study is required in order to find an appropriate balance.

ACKNOWLEDGMENTS

Work performed under the auspices of the United States Department of Energy.

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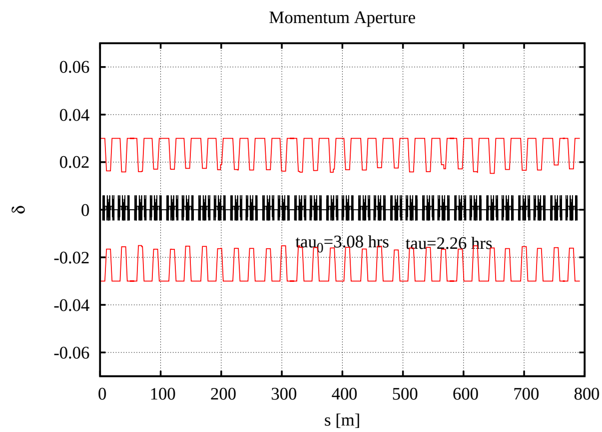

Figure 5: Momentum Aperture for vertical gap of ± 2.5 mm in CPMUs.

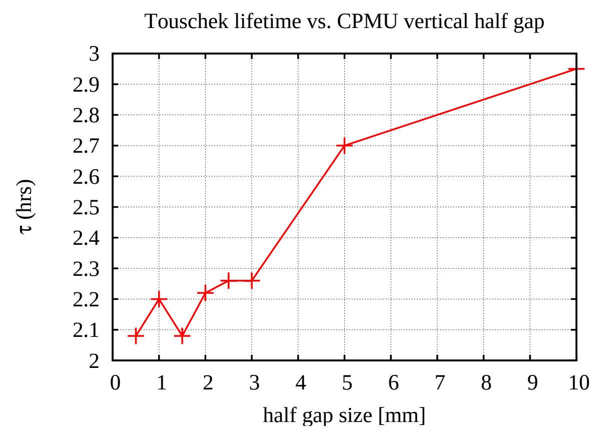

Figure 6: Touschek lifetime in NSLS-II for varying vertical gap size in CPMUs.

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