TOUSCHEK LIFETIME CALCULATIONS FOR NSLS-II

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Abstract

The Touschek effect limits the lifetime for NSLS-II. The basic mechanism is Coulomb scattering resulting in a longitudinal momentum outside the momentum aperture. The momentum aperture results from a combination of the initial betatron oscillations after the scatter and the non-linear properties determining the resultant stability. We find that higher order multipole errors may reduce the momentum aperture, particularly for scattered particles with energy loss. The resultant drop in Touschek lifetime is minimized, however, due to less scattering in the dispersive regions. We describe these mechanisms, and present calculations for NSLS-II using a realistic lattice model including damping wigglers and engineering tolerances.

INTRODUCTION

Third-generation light sources, such as the NSLS-II, require very small transverse electron beam size in order to maximize photon beam brightness. One of the challenges of small beam size is due to the resultant inter-particle scattering, which may result in low beam lifetimes, via the Touschek Effect. Since Touschek scattering is inevitable, maintaining an adequate beam lifetime requires stability of particles with large energy deviation. The required energy acceptance is typically from 2-5%. Here we describe the formulae and considerations involved in the Touschek lifetime for NSLS-II. For information on NSLS-II beyond that described here, see [1], [2], and [5].

The Touschek scatter rate α and lifetime τ are calculated as [3]

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

The lifetime τ gives the time over which $\frac{1}{2}$ the particles would be lost(assuming constant loss rate). r_e denotes the classical electron radius, q the bunch charge, σ_z the bunch length, C the circumference of the storage ring, and $\sigma_x(s)$ and $\sigma_y(s)$ 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 function $F(x)$ is defined as[1]

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

[1]Note that there was a factor of $\frac{1}{2}$ error is [4].

LINEAR AND NON-LINEAR DYNAMICS MODELING

NSLS-II has a 15-fold periodic DBA lattice. The lattice functions for NSLS-II are shown in Figure 1. The linear lattice results in the equilibrium beam sizes around the ring that enter into Eqn. (1). Non-linear dynamics enter through the parameter $\delta_{\rm acc}(s)$. This is the maximum momentum change that a scattered particle can endure before it is lost. There are two elements to this stability question. The first is the amplitude of the initial orbit which comes from the off-momentum closed orbit (dispersion) and beta functions. These are shown in Figures 2 and 3. The amplitude of the induced betatron oscillation following a scatter with relative energy change $\delta = \frac{\Delta E}{E_0}$ is given by

$$x_2 = (\eta^{(1)}(s_2) + \sqrt{\mathcal{H}(s_1)\beta_x(s_2)})\delta + \eta^{(2)}(s_2)\delta^2 \quad (3)$$

where $\mathcal{H} = \gamma_x\eta_x^2 + 2\alpha_x\eta_x\eta_x' + \beta_x\eta_x'^2$ is the dispersion invariant. The first term of this function gives the linear result whereas the second term contains the second order dispersion. We note that the particles that scatter in the dispersion section ($\mathcal{H} = 9.3$mm) will have substantially larger oscillation amplitudes than those in the straight sections ($\mathcal{H} = 0$). We also note the asymmetry between scattering with positive and negative energy deviations. This is evident in both the closed orbit deviation in Fig. 2 and in the beta function in Fig. 3. This asymmetry results in an asymmetry between the positive and negative momentum acceptance.

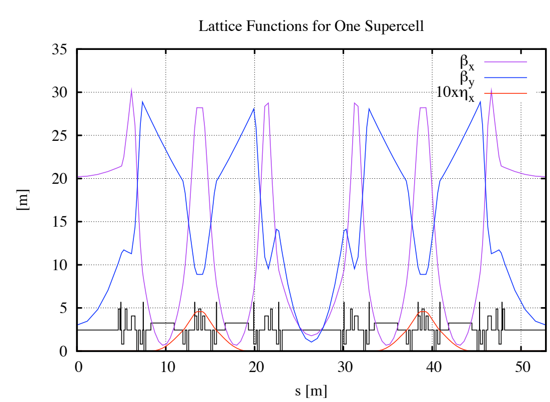

Figure 1: Twiss functions for one superperiod of lattice.

LOCAL SCATTERING RATE

The considerations from the previous section suggest that it is easier to maintain a large momentum aperture in

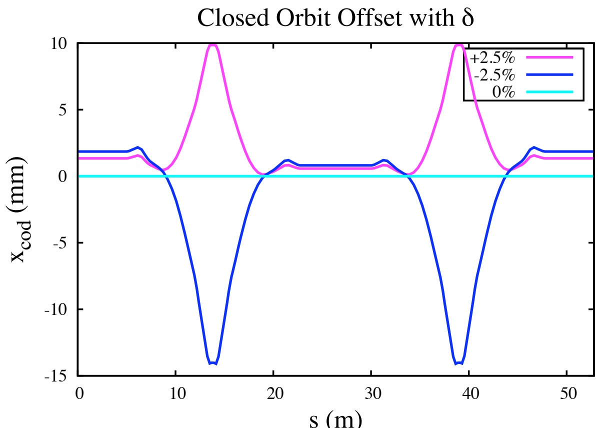

Figure 2: Dependence of horizontal closed orbit on momentum. One superperiod is shown.

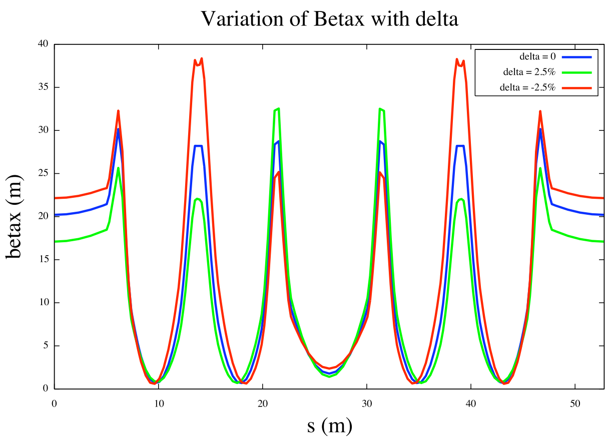

Figure 3: Dependence of β_x on momentum.

the straight section than in the dispersion region. In order to understand the impact of this on the total Touschek lifetime, we compute the effect on Touschek lifetime from varying $\delta_{\rm acc}$ using the beam parameters in Table 1. We vary the momentum acceptance in the straight sections and in the dispersion region and compute the lifetime for each value. The results are given in Table 2. We note that decreasing the momentum acceptance in the dispersion region has a relatively small impact on the overall lifetime. To understand this, consider Figure 4 where the local scattering rate is computed. This is defined as the inverse lifetime that would result if the beam stayed at the given local position. Thus, the total scattering rate is simply the average of the local scattering rate. We see that the peak scattering rate comes from short straight section with the small beam sizes designed to achieve high brightness from the ID's. The beam in the dispersion region is substantially larger and thus the scattering rate is relatively small. We illustrate the effect of a decreased momentum aperture in the dispersion region. The straight sections have $\delta_{\rm acc} = 2.5\%$. By reducing $\delta_{\rm acc} = 2.5\%$ (blue), to $\delta_{\rm acc} = 1.5\%$ (red) in the dispersion region, the total lifetime drops only from 3.3 and 2.9 hours.

Table 1: NSLS-II parameters used in Touschek lifetime calculations

q	1.3 nC
ϵ_x	1 nm
ϵ_y	1pm
σ_z	4.5mm
σ_δ	10^{-3}

Table 2: Touschek Lifetime vs. Momentum Aperture

$\delta_{\rm acc}$ (str) %	$\delta_{\rm acc}$ (disp) %	τ(hrs)
3	3	6.2
3	2.5	5.5
3	2	4.6
3	1.5	3.3
2.5	2.5	3.3
2.5	2.0	2.9
2.5	1.5	2.3

We assume a higher harmonic cavity (baseline) is installed which will approximately double the bunch length of 4.5 mm, and correspondingly double the lifetime.

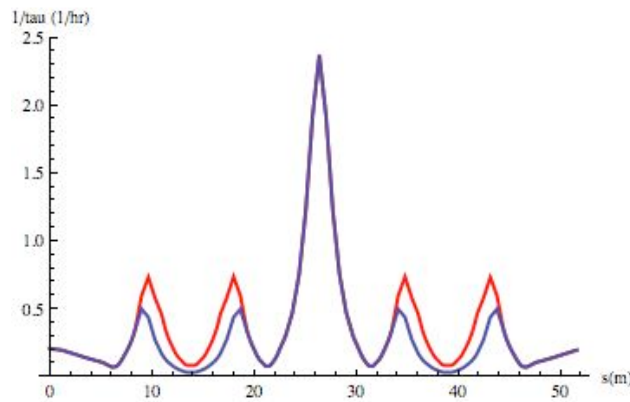

Figure 4: Local Touschek scattering rate for a single superperiod of the lattice. The straight sections have $\delta_{\rm acc} = 2.5\%$. The dispersion region has $\delta_{\rm acc} = 2.5\%$ (blue), $\delta_{\rm acc} = 1.5\%$ (red). The total Touschek lifetimes are accordingly 3.3 and 2.9 hours.

MOMENTUM APERTURE RESULTS

To evaluate the momentum and dynamic aperture, we need to set up a realistic lattice model and perform particle tracking. See [10] for details on the Tracy tools used for these calculations. We may consider slices through phase space in order to understand the dynamics. The tracking data may then be analyzed using the method of Frequency Map Analysis (FMA) [9].

One of the focusses of the work on Touschek lifetime for NSLS-II has been the specification of higher order multipole errors. In [6] we describe the specifications and modelling of higher order multipole field errors in the NSLS-II quadrupoles and sextupoles. In Figure 5 we show the effect of the systematic higher order multipole errors on the off-momentum frequency map. We see that the multipole errors have reduced the dynamic aperture, particularly at negative energy deviation. This effect can be traced to the larger closed orbit deviation and beta function at negative momentum as seen in Figures 2 and 3.

The main impact from the multipole field errors for off-momentum dynamics comes from the quadrupoles and sextupoles near the maximum dispersion of 0.46 m. By increasing the bore radius of these magnets, the higher order multipole errors have been reduced. Looking at Figure 5, we see that even with the NSLS-II multipole field tolerances, 2.5% momentum aperture is still attained in the dispersion region.

In addition to the multipole errors, there are many other effects that impact the momentum aperture. Non-linearities from insertion devices, breaking of symmetry from misalignments, and physical apertures from e.g. small vertical gaps (+/- 2.5 mm) from the in vaccuum undulators may reduce the momentum aperture. To calculate the lifetime, the momentum aperture at each point of the lattice can be determined by tracking particles with momentum offsets around the lattice and finding the largest positive and negative momentum that survives at least one damping time. See Ref. [8]. The resulting momentum aperture for one lattice including all of these effects is shown in Figure 6. Here, we have tracked for 5000 turns, including radiation damping and synchrotron oscillations. We use an RF acceptance of 3% and find that the momentum aperture drops to around 2.5% in the dispersion regions. This gives a fair amount of margin for any further effects not so far included such as the effect of EPU's and other lattice tunings such as those with increased vertical chromaticity to provide damping for transverse instabilities.

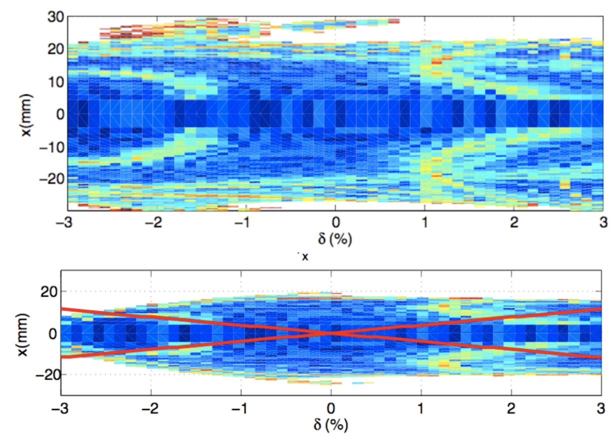

Figure 5: Off-momentum frequency map for lattice with no field errors and with systematic field errors in quadrupoles and sexutpoles. The red lines show the scattering amplitude for particles in the dispersive region. The color represents the tune change on a log scale, with blue representing small change and orange substantial diffusion.

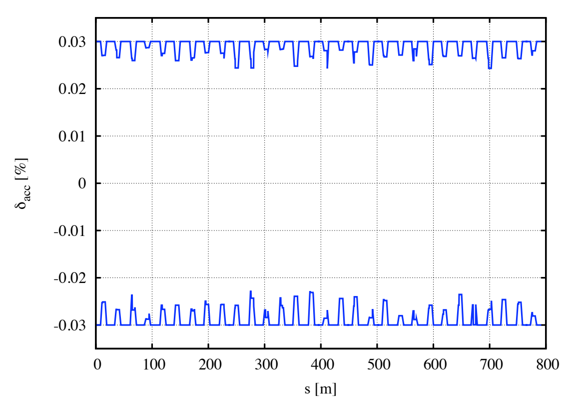

Figure 6: Momentum aperture with damping wigglers, three in-vaccuum undulators, +/- 2.5 mm vertical gaps, misalignment errors and field errors.

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