TOUSCHEK LIFETIME AND UNDULATOR DAMAGE IN THE ADVANCED PHOTON SOURCE*

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Abstract

The Advanced Photon Source (APS) has two insertion devices (IDs) with small-aperture vacuum chambers. The full vertical aperture in these chambers is 5 mm, while the inboard horizontal aperture is 15 mm. These devices suffer significant radiation damage, requiring frequent retuning. We recently hypothesized that the damage resulted from loss of Touschek-scattered particles on the *horizontal* aperture of the chambers. This results partly from the small size of the aperture and partly from the pattern of the dispersion and beta functions in the low-emittance APS lattice. The horizontal scrapers are located near the middle of the arcs where the dispersion was high in the original lattice, but now, in the low-emittance lattice, the dispersion there is much reduced. Similarly, the dispersion at the IDs was originally zero but is now close to the maximum for the lattice. In this paper, we summarize simulations and experiments that support our hypothesis and discuss remedies.

INTRODUCTION

Like other third-generation storage rings, the beam lifetime for the APS is dominated by Touschek scattering [1]. Touschek scattering results from a Coulomb collision of two electrons in a bunch. Such scattering transfers transverse momentum into longitudinal momentum, nominally giving equal and opposite longitudinal deviation changes to the two electrons. If the resulting deviations are outside the energy aperture, the electrons are lost.

The issue we are interested in is, at what location do these losses occur? The simplest analysis is that they will be lost at the location where $\eta_x(s)/A_x(s)$ is maximum, where η_x is the horizontal dispersion and A_x is the horizontal aperture. However, the reality is more complex than this. 1. Scattering events occur all around the ring, and losses will occur at the first aperture that is sufficiently small to intercept the scattered particles. 2. For large momentum deviations, the nonlinear dispersion must be taken into account. 3. In addition to the energy deviation, scattered particles also execute horizontal betatron oscillations when the scattering occurs at a location with non-zero dispersion. Hence, losses will tend to occur not only where η_x/A_x is large, but also where β_x/A_x is large. 4. If the energy deviation is such that no loss occurs immediately, the electrons will execute (presumably large) synchrotron oscillations. Because APS is run with non-zero chromaticity, particles executing such an oscillation may cross a horizontal or vertical betatron resonance and be lost.

Other sources of beam loss are beam dumps and injection losses. Beam dumps at the APS are initiated by gating off the rf systems in response to orbit deviations or other considerations. Hence, the beam is lost in a way that is very similar to what happens with Touschek scattering. Injection inefficiency, on the other hand, is a different mechanism and is related to injection trajectory, injected beam emittance and matching, and, perhaps most importantly, horizontal-to-vertical coupling. Hence, it makes sense to lump the Touschek and beam dump losses together as they are likely to be lost at similar places.

To assess the contribution of Touschek scattering and beam dumps to radiation damage, we note that injection efficiency η is typically 80% and that we run in top-up mode [2] most of the time. Electrons that are not lost at injection are stored and eventually lost via Touschek scattering or a beam dump. The ratio of the number of particles lost due to Touschek or a beam dump to those lost at injection is $\eta/(1-\eta) \approx 4$. Thus, controlling the location of Touschek losses and beam dumps should have a bigger payoff in radiation protection than reducing injection losses.

TRACKING METHODS

The most direct way to determine where losses occur is through simulation and experiment. In this section, we discuss tracking studies performed with `elegant` [3]. Two types of tracking were performed: tracking with synchrotron radiation but no rf voltage, which simulates a beam dump; and tracking with rf voltage and Touschek scattering. In both cases, accelerator components were simulated with canonical integration using the exact Hamiltonian. In particular, energy dependence is present to all orders. Synchrotron radiation was included on an element-by-element basis. Scrapers and insertion device (ID) chamber apertures were included. In particular, the small (5 mm) internal vertical aperture chambers in sectors 3 (ID3) and 4 (ID4) straight sections were included. These have an internal horizontal aperture of 15 mm, which is the smallest horizontal aperture in the ring.

Simulations used a calibrated lattice model [4] to ensure accurate reproduction of the accelerator optics. The chromaticities were adjusted slightly from the model to match the measured values.

BEAM DUMPS

Experiments were performed in which we deliberately dumped beam. Since we do not have radiation detectors

* Work supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

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that can integrate the radiation from a beam dump, we instead measured the time between gating off the rf drive and the loss of beam. Since the cavity fields do not go to zero instantaneously when the rf drive is gated off, we measured the rf voltage decay as a function of time and used this data in the simulations (using the `RAMPRF` element in `elegant`). We assumed the phase was constant, which is a good approximation since in these experiments we used low current. By varying a closed horizontal beam bump in ID3 and ID4 for successive dumps, we can determine whether there is an aperture limit at these locations.

Figure 1 shows the experimental results. Given the clear variation in the time to lose beam as with bump height, the ID3 and ID4 chambers must be the aperture limit for beam dumps. Figure 2 shows simulation result. We see that the simulated slope of turns needed for 50% loss to bump height is the same to within the error bar.

Using this simulation model, we predict that with the horizontal scraper at the normal location (based on the previous high-emittance lattice), essentially 100% of the dumped beam is lost at the insertion devices ID3 and ID4. To protect the IDs, we would have to insert the scraper to such an extent that injection efficiency would be greatly reduced. This is partly a result of the small dispersion at the scraper's present location.

One could instead operate with the beam bumped toward the outside at ID3 and ID4, but this is inconvenient for beamline operation because of the required bump size.

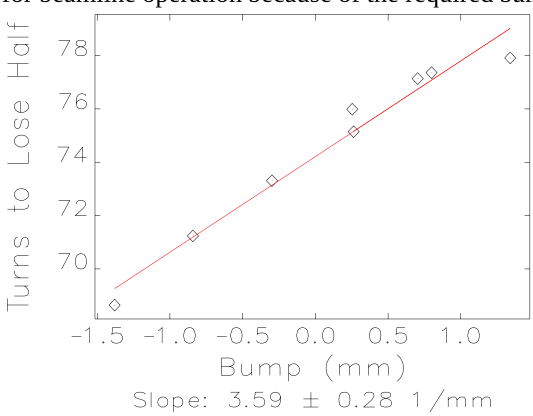

Figure 1: Measured number of turns required for half the beam to be lost following gating off of the rf drive, as a function of bump height in ID3 and ID4.

TOUSCHEK SCATTERING

`elegant`'s `DSCATTER` element supports user-defined scattering using a distribution in an SDDS file [5].

The distribution D for Touschek-related momentum offset changes can be obtained from the Touschek loss rate $R(\Delta)$ as a function of energy aperture Δ:

$$D(\Delta) = -\frac{1}{R(\Delta_{min})}\frac{\partial R}{\partial \Delta}, \tag{1}$$

where Δ_{min} is the minimum energy deviation for which we expect a loss. The energy aperture for APS is about

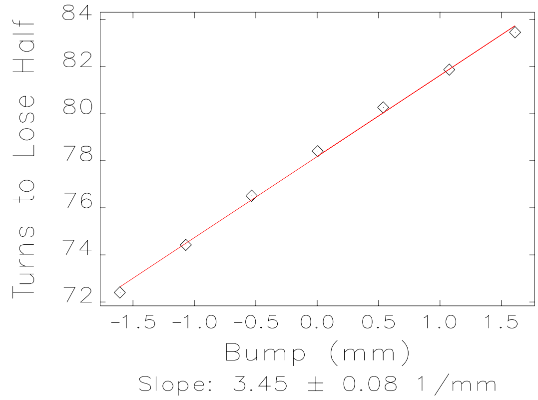

Figure 2: Simulated number of turns required for half the beam to be lost following gating off of the rf drive, as a function of bump height in ID3 and ID4.

$\pm 2.2\%$, so we used $\Delta_{min} = 1\%$ to be conservative. (Making Δ_{min} small simply means that we will simulate scattering of particles that don't get lost.)

We computed $D(\Delta)$ numerically from the output of `beamLifetimeCalc` (distributed with `elegant`). The scattering was performed by putting a `DSCATTER` element at the center of each of the 40 straight sections and providing $D(\Delta)$ as the distribution. Each `DSCATTER` was allowed to scatter only $1/40^{\text{th}}$ of the particles, giving an azimuthally-uniform scattering distribution. Each particle was scattered only once, with an equal probability of a positive or negative energy deviation. Typically 4000 simulation particles were used, a practical limit based on CPU time requirements.

This Touschek scattering model does not include the reduction in x and y momenta due to the scattering event. It does, however, include the betatron oscillation amplitude induced by the instantaneous change in momentum in a dispersive region, which is a larger effect. To see this, consider that the dispersion value is 0.17 m. For an energy kick of 1%, the induced betatron oscillation has a 1.7 mm amplitude, compared to the betatron beam size of 220 μm.

We performed an initial simulation with the horizontal scraper in its standard position, 5.5 mm inboard from the beam centerline (β_x is 5.1 m at the scaper, while β_x is 19.5 m at the IDs). Figure 3 shows the distribution of "hits" in each straight section. The scraper only intercepts about 30% of the scattered particles. Many of the remaining particles hit ID3, and a smaller number hit ID4.

Simulations show that to protect the IDs, we would need to insert the scraper to under 4 mm from the beam centerline, which is not consistent with good injection. Figure 4 shows the results of measurements of radiation rates using detectors near several IDs, as a function of scraper position, along with simulations. The comparison between simulation and measurement shows initial agreement in the scraper position at which the radiation begins to go down, but then shows increasingly poor agreement. The radiation eventually goes up as the scraper is inserted further. This is a result of scattering primary beam particles from the scraper, an effect not included in the simulations.

A more convincing demonstration was obtained by making a large beam bump in sector 35 straight section. We bumped the beam toward the inside of the chamber, using it effectively as a thick scraper. In this case, we saw significant reduction in radiation levels at all detectors, as shown in Figure 5.

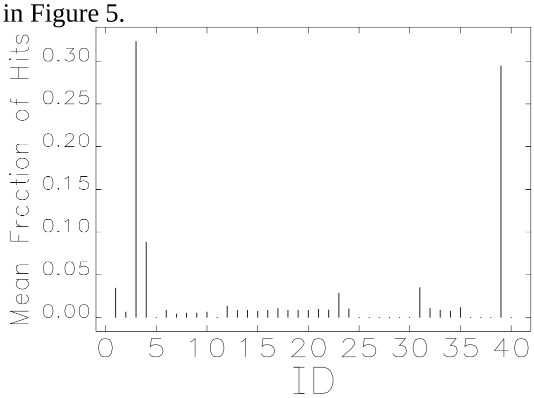

Figure 3: Simulated distribution of losses in the APS due to Touschek scattering, with the horizontal scraper in its nominal position.

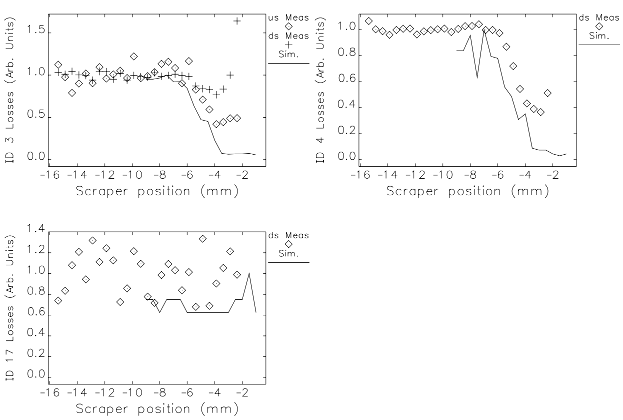

Figure 4: Simulated and measured loss rates at several IDs as a function of scraper position.

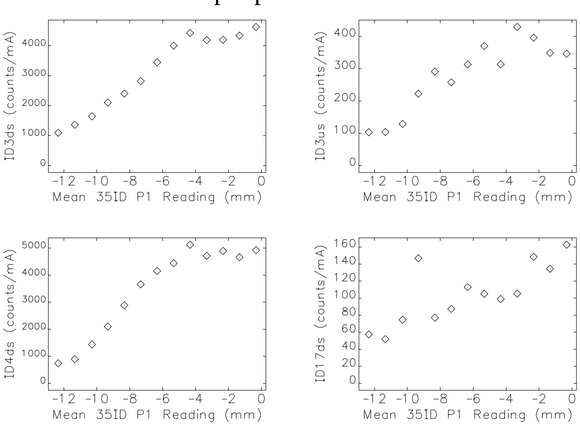

Figure 5: Measured loss rates at several IDs as a function of bump position in ID35.

ID PROTECTION WITH FAST SCRAPERS

Since Touschek scattered and dumped particles are likely responsible for most ID damage, we looked for ways to intercept these particles. Attempts to design a lattice with large dispersion at the the scraper location did not succeed in improving the situation. The problem is that we want both large dispersion and large beta functions at the scraper, which is incompatible with good injection efficiency.

Our conclusion is that we cannot protect the IDs with a fixed collimator. Instead, we need a scraper or bump that is in place when the beam is stored, but moved out for top-up or filling. The best place for such a scraper is in a straight section, where the lattice functions are the same as those in the ID straight section and where the lattice functions at the straight sections are easy to manipulate.

Designing such scrapers will be a challenge. APS operates for 5000 hours a year and does top-up about 75% of the time, with a two-minute injection interval. This implies 100,000 scraper actuations per year, which presents a serious reliability challenge. We are also considering moving to faster top-up, which will only make matters worse. The scrapers would have a stroke of about 10 to 15 mm.

We also considered a time-dependent bump, which would move the beam toward a scraper except during top-up events, at which time the beam would be moved away from the scraper. However, it would still be necessary to relocate the scraper to a straight section. Otherwise, the bump amplitude would be quite large. In any case, making a several millimeter bump would change the APS optics and potentially compromise either injection efficiency or beam lifetime, since we can only correct the optics for one case. Finally, using bumps doesn't give us a way to clean positive and negative energy deviations.

CONCLUSION

We have presented evidence from simulation and experiment that APS undulators with small gap chambers are being damaged by Touschek-scattered particles, as well as from particles lost when the beam is dumped. We find that solving this problem requires scrapers that move in for stored beam and out for injection, which will present a mechanical engineering challenge.

ACKNOWLEDGEMENTS

The authors acknowledge discussions and assistence from N. Arnold, W. Guo, K. Harkay, and V. Sajaev.

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