SIMULATION AND MEASUREMENT OF BEAM LOSS IN THE NARROW-GAP UNDULATOR STRAIGHT SECTION OF THE ADVANCED PHOTON SOURCE STORAGE RING *

J. C. Dooling† and M. Borland, ANL, Argonne, IL 60439, USA

Abstract

Simulations indicate the removal of a scraper/collimator in the Sector 37 straight section (SS) of the Advanced Photon Source storage ring (SR) results in increased beam loss in the 5-mm narrow insertion device chamber in sector 4. Modeling with `elegant` provides loss distributions in this chamber for simulated beam dumps, including rf muting and beam loading. The loss distributions are used as input to a MARS model of the SS that includes undulator geometry. Čerenkov detectors and fiber-optic cable bundles are used in this location to capture temporal profiles of beam loss events. Beam dumps deliver 2600 J to the vacuum chamber and surrounding hardware including undulators. Data indicate a variety of temporal profiles occur during the beam dumps, with the shortest lasting ≈ 6 μs FWHM (< 2 turns). Such high power and power densities can lead to physical damage of vacuum components if not handled correctly. Touschek scattering loss is also a concern for undulator demagnetization. Comparison of modeling and measurements will be presented.

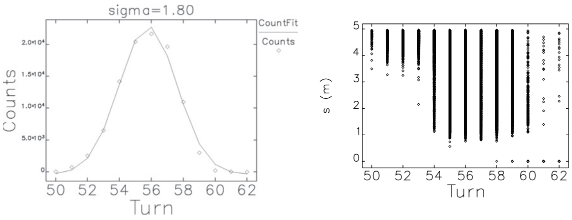
NARROW-GAP INSERTION DEVICE VACUUM CHAMBER

With the removal of a damaged collimator and beam dump, the 5-mm vertical aperture insertion device (ID) vacuum chamber in the Sector 4 straight section (4ID) acts as the collimator for the rest of the machine. Steady state losses here are typically two orders of magnitude higher than in adjacent sectors. We are interested in modeling both steady-state and transient loss distributions. Rare-earth, permanent magnet (PM) material such as NdFeB is often used in undulators because of its large remnant field, but can suffer demagnetization in the presence of high-energy radiation. For example, after experiencing field loss, both the upstream (US) and downstream (DS) undulators in 4ID were replaced with, respectively, an electromagnetic undulator and an undulator using SmCo PMs.

SIMULATIONS

elegant

Parallel `elegant` [1] is employed to generate loss distributions that are used as input to MARS [2]. Two distributions have been generated: first, a transient case assuming a hybrid fill pattern; and second, the steady state loss produced by Touschek scattering. In the former case, we simulated muting of both rf systems by a Machine Protection System (MPS) event. The simulation includes synchrotron radiation, including quantum excitation, as well as exponential decay of the fields in the 16 rf cavities. It also includes transient beam loading due to the unusual bunch distribution of hybrid mode, which features an isolated 16-mA bunch on one side of the ring with 56 smaller bunches on the other side of the ring, for a total of 100 mA. A particle is considered lost once its transverse position matches or exceeds the inner surface of the vacuum chamber. The loss process lasts for several turns as the electrons spiral inward. The distribution of particle loss versus turn number is given in Figure 1(a). The s-location in Fig. 1(b) is adjusted by 107.94 m to coincide with MARS geometry. The Gaussian fit indicates a FWHM duration of 4.2 turns or 16 μs. In Fig. 1(b), we see in the transient case, loss begins upstream then fills the entire straight section.



(a) temporal loss profile (b) long. loss position

Figure 1: `elegant` hybrid beam dump longitudinal behavior. s-offset in b) is 107.94 m to coincide with MARS.

The presence of canting dipoles in Sector 4 affects electron trajectories in the straight section. ID4 is unusual in that it has a 270-μrad inboard cant, which directs the beam toward the inboard horizontal aperture. Since there is also dispersion in the straight section, as the beam loses energy, the loss point gradually moves upstream. As a result, during beam dumps, losses spread along the upstream half of the vacuum chamber (≈ 2.5 m). A beam dump is typically simulated with 10^5 macroparticles, although simulations with 10^6 particles have also been performed. About 400 turns need to be simulated, mostly in order to ensure the beam is in a steady state condition. The beam dump itself occurs in about 40 turns.

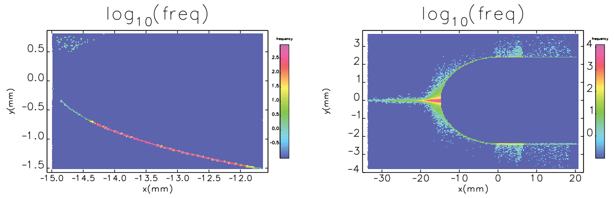
Transverse real-space loss distributions are presented for the hybrid beam dump in Figure 2(a). Complex patterns are observed. `elegant` indicates that during a beam dump approximately 77% of the simulation particles are lost in ID4; the remaining 23% are lost elsewhere in the ring.

---

* Work supported by the U.S. Department of Energy, Office of Science, under contract number DE-AC02-06CH11357.

† dooling@aps.anl.gov

In the case of Touschek scattering, `elegant` predicts that all particle loss takes place in 4ID. Though this is approximately true, we will show that Touschek losses take place throughout the ring. Touschek loss real-space diagrams are given in Figure 2(b). In the steady-state case, temperature rise due to beam loss is negligible.



(a) (b)

Figure 2: x-y hybrid dump (a) and Touschek loss (b) transverse coordinates at loss.

MARS

Starting with the `elegant`-generated loss trajectories as input, MARS allows an estimate of dose distribution (energy density) within the volume of the undulator by modeling the resulting shower. Knowing the material properties, we can determine the instantaneous temperature rise in the case of a beam dump. For chronic dose, measurements made at SLAC [3] and elsewhere are used to determine demagnetization times.

A y-z slice of the geometry used in MARS is shown in Figure 3 indicating the location of the copper transition piece as well as magnet and pole pieces of the undulator. Here z=0 is arbitrarily chosen at the upstream end of the vacuum chamber. Two x-y slices of the modeled undulator geometry are presented in Figure 4 indicating pole and magnet details.

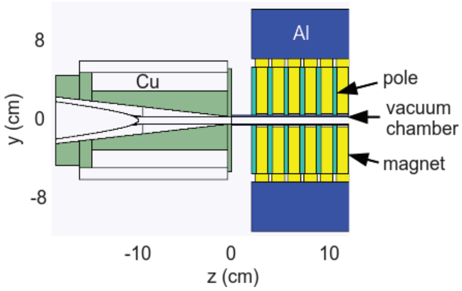
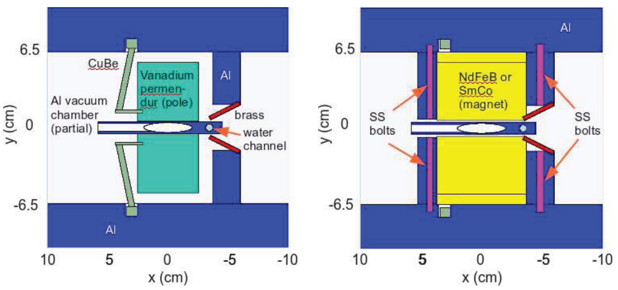


Figure 3: y-z slice of MARS geometry showing transition piece and undulator components.

Simulations of total dose and neutron fluence are presented in Figure 5 for a hybrid beam dump. The dose and flux for Touschek losses are given in Figure 6. In the latter case, no difference is observed in total dose between upper and lower undulator regions, whereas in the former the dose at $y < 0$ is greater, as expected from 2(a).

MARS gives the maximum beam dump total dose D_T as 611 Gy. Assuming the specific heat $C_p = 0.44$ J $g^{-1}K^{-1}$ [4], the instantaneous temperature rise in the $Nd_2Fe_{14}B$ magnet compound is $\Delta T \approx D_T C_p^{-1}$=1.4 K. While this is insufficient to produce demagnetization, the accumulated dose does have semi-permanent effects. Assuming a PM material similar to that of N40SH in the H configuration tested in Ref. [4], a single beam dump leads to a peak demagnetization of 0.024%. Since 25 beam dumps with ID gaps closed typically happen during user time in one run, a 0.6% field reduction might have been observed if NdFeB magnets were in place. This is roughly consistent with what had been observed prior to the replacement of these magnets with SmCo in 2005.



(a) z=2.1 cm. (b) z=3.0 cm.

Figure 4: MARS transverse undulator geometry.

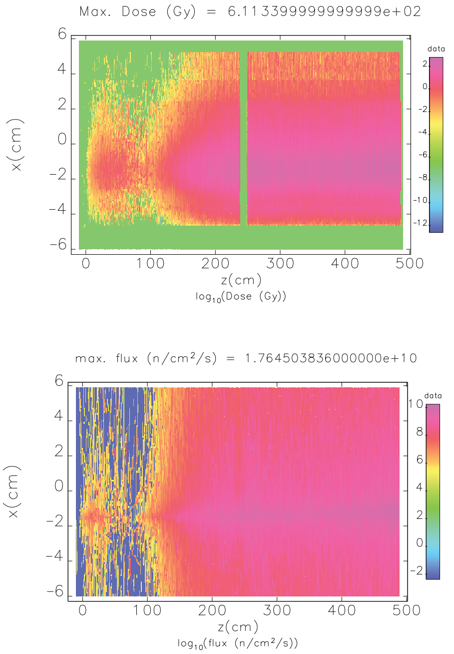


Figure 5: x-z total dose (top) in the first 0.5 cm below the vacuum chamber and neutron flux (bottom) in a 0.5-cm slice about beam elevation from hybrid-mode beam dump simulation.

Regarding Touschek losses, a peak neutron flux of 3.01×10^{10}n $cm^{-2}s^{-1}$ is predicted in the upstream end of the upstream undulator. The lifetime with a hybrid bunch pattern is $\tau = 9$ h, leading to a loss current of 11.4 pA for a 100-mA store (368 nC). The neutron flux in Fig. 6 represents the fluence after one τ. Assuming near-0° data from Ref. [3], a fluence of 1×10^{11}n cm^{-2} results in a 0.01% demagnetization of NdFeB magnets of the type used in the LCLS. Assuming similar magnet material, a fluence of 3.01×10^{10}n cm^{-2} would reach a demagnetization of 1% in approximately 3000 hours or roughly 2 APS run cycles. On the other hand, the peak total dose from Touschek losses is 1.8 kGy. Using the scaling from Ref. [4], 1% demagnetization would be expected in 127 hours, leading to a 13% demagnetization in 1 run cycle. Simulations show the regions of highest dose in the magnets to be spatially localized, especially at the US end of the US device. Large regions of these magnets not as strongly irradiated will maintain magnetization and allow the integrated total field to be fractionally reduced. We recognize that dose non-uniformities are significant and are presently working to include these effects in field calculations.

Based on previous measurements of demagnetization made in 3ID and 4ID [5], the locations of magnetic field loss appear consistent with a combination of hybrid beam dump and Touschek radiation distributions.

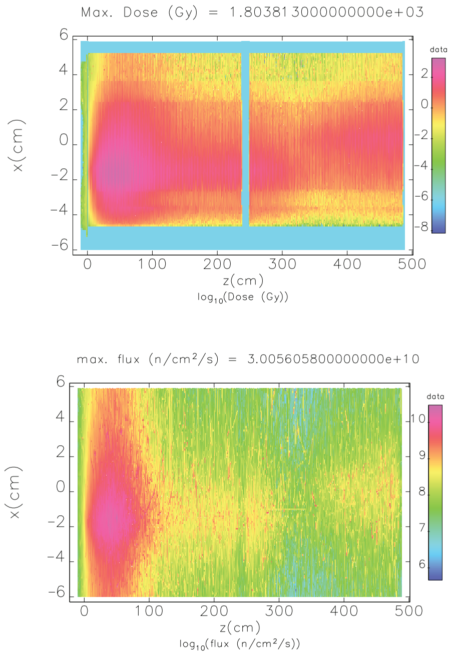


Figure 6: x-z total dose (top) and neutron flux (bottom) in the first 0.5 cm above the vacuum chamber from Touschek beam loss.

MEASUREMENTS

The loss of high-energy electrons generates an electromagnetic shower and thus fast electron/positron diagnostics are the best choice; in addition, the detectors must discriminate against synchrotron radiation. These requirements lead to the use of Čerenkov radiation. Černkov-detector-based counters provide an accurate low-noise record of steady state beam losses; however, the electronics typically leaves them blind to fast beam loss (beam dumps).

Fast beam loss data are detected with fused-silica fiber-optic (FO) cable and dedicated Čerenkov detectors in 4ID and also 33ID. These data are recorded using networked oscilloscopes; the waveform data are then transferred and stored for post-processing. Examples of recent beam dumps are presented in Figure 7; these data indicate that the beam spirals in faster than predicted (compare with Fig. 1).

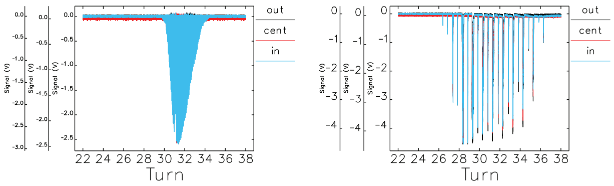


Figure 7: Beam dump data for 24-bunch (left) and hybrid-mode (right) SR fill patterns.

DISCUSSION

According to Ref. [5], demagnetization in the narrow-gap chambers was most severe at the "upstream end of the upstream device and the downstream end of the downstream device." Simulations indicate that total dose and neutron fluence from Touschek losses are greatest at the upstream end of the chamber; whereas, beam dump radiation peaks in the downstream undulator section. Thus one may suspect that both forms of loss lead to demagnetization at spatially distinct regions of the undulator. Also, comparing neutron fluence with total dose (mainly due to electromagnetic shower) the losses appear to come mainly from the latter component, implying the presence of a thermal spike damage mechanism [6].

ACKNOWLEDGMENT

Thanks to R. Soliday and H. Shang for their assistance with data analysis scripts.

REFERENCES

[1] Y. Wang *et al.*, Proc. ICAP09, 355-360 (2009); M. Borland, APS LS-287, Sept. 2000.

[2] N.V. Mokhov, "The Mars Code System User's Guide," Fermilab-FN-628 (1995); N.V. Mokhov, S.I. Striganov, "MARS15 Overview," AIP Conf. Proc. 896, pp. 50-60 (2007); http://www-ap.fnal.gov/MARS/.

[3] M. Santana-Leitner et al., "Mitigation of the Radiation Damage from the LCLS Tune Up Dump," SLAC-PUB-14020, April 29, 2010.

[4] A. B. Temnykh, Nucl. Instrum. Methods. A **587** (2008) 13.

[5] S. Sasaki et al., "Radiation Damage to Advanced Photon Source Undulators," Proc. 2005 PAC, Knoxville, Tennessee, p. 4126 (2005).

[6] Y. Asano et al., J. of Synchrotron Radiat., **16**, (2009) 317.