RADIATION DOSES TO INSERTION DEVICES AT THE ADVANCED PHOTON SOURCE

E.R. Moog, P.K. Den Hartog, E.J. Semones, and P.K. Job
Advanced Photon Source, Argonne National Lab, Argonne, IL 60439

Abstract

Dose measurements made on and around the insertion devices (IDs) at the Advanced Photon Source are reported. Attempts are made to compare these dose rates to dose rates that have been reported to cause radiation-induced demagnetization, but comparisons are complicated by such factors as the particular magnet material and the techniques used in its manufacture, the spectrum and type of radiation, and the demagnetizing field seen by the magnet. The spectrum of radiation at the IDs has been measured and found to include a large high-energy (7 GeV) component, at least during some runs. Lead shielding installed immediately upstream of the IDs has been found to decrease the dose to the upstream ends of the IDs. It has almost no effect on the dose to the downstream ends of the IDs, however, since much of the radiation travels through the ID vacuum chamber and cannot be readily shielded. Opening the gaps of the IDs during injection and at other times also helps decrease the radiation exposure.

INTRODUCTION

The insertion devices (IDs) at the Advanced Photon Source (APS) use Nd-Fe-B permanent magnets to produce their magnetic field. Although NdFeB magnets are known to be sensitive to radiation damage [1-10], no radiation damage has yet been observed in ID magnets at the APS. We seek to anticipate whether the dose levels presently being observed at the IDs are high enough to cause demagnetization within the desired 20-year lifespan of the IDs. The dose received by an ID at the European Synchrotron Radiation Facility (ESRF) after being installed for only one year was high enough to cause partial demagnetization of the ID magnets [1], so there is cause for concern at the APS as well.

These questions give rise to other questions: What is the dose required to damage the magnets and how does that depend on the spectrum of the radiation? What is the dose actually received by the ID magnets and what is its spectrum? How effective are the measures that have been and are being taken to reduce the dose to the ID magnets? These different questions will be examined below.

WHAT DOSE IS REQUIRED TO DAMAGE THE ND-FE-B MAGNETS?

Others have exposed magnets to various types of radiation and determined the exposure level at which damage occurred. Some of the work that has been done is not directly applicable to insertion device magnets, however, because the type of radiation used in the study (e.g., neutrons as opposed to electrons or photons) is not what is expected to cause radiation damage in a storage ring [11].

Some flux loss vs. dose results that are relevant

to storage rings include work by Luna et al. [2] who exposed magnets to an 82 MeV direct electron beam. They measured a 1.5% remanence loss after only a 36 krad exposure. When the radiation exposure was to bremsstrahlung from an 85-MeV electron beam, a 14% remanence loss was seen after exposure of one sample to 450 Mrad, whereas another magnet from a different manufacturer showed only 7% remanence loss after 1370 Mrad. At ESRF, the dose received by the ID whose magnets were partially demagnetized [1] was estimated to be 6.7 Mrad for the first upper magnet and 5.1 Mrad for the first lower magnet [12]. The peak field loss at the upstream end of the ID was nearly 8%, but the section of the magnets immediately above or below the particle beam showed greater demagnetization than the rest of the magnet [13]. Colomp and Bräuer [3] exposed some magnets to the direct 200 MeV electron beam from the ESRF linac. They observed demagnetization of from 1.9% to 2.7% after an exposure of 300 krad. These experiments were troubled, however, by a spatial variation of the dose by a factor of at least 200. The observed demagnetization could have actually consisted of higher levels of demagnetization that were localized to small regions of the magnet block where the actual dose was much higher. Measurements made of an ID at HASYLAB showed no radiation-induced effects despite an estimated exposure of 7.2 Mrad directly above the beam and 3.3 Mrad and 12 Mrad at positions horizontally displaced by 4 cm [14]. Another study irradiated magnet blocks with 17 MeV electron beams and found a 9% flux loss after an exposure of 260 Mrad [4].

A consideration in attempting to use published results to determine lifetimes of APS ID magnets is that wide variation in radiation sensitivity between magnets from different vendors has been reported in a number of studies [2, 3, 5 - 8]. Some differences can be attributed to the manufacturing process of the magnets [5], and some differences can be attributed to the presence of small amounts of other materials in the magnet mix [7]. Nd magnet technology has developed rapidly in recent years so that the magnet material used in the APS insertion devices was not available eight years ago; it would be expected that these advances in magnet technology might make a significant difference in the magnets' radiation sensitivity.

In addition to effects based on the magnet material itself, there has been found to be an effect due to the strength of the demagnetizing field in which the magnet is placed while it is irradiated [6,7]. If the demagnetizing field is stronger, the magnet will more readily demagnetize. This would mean that the probability of radiation-induced demagnetization in a particular ID would be a function of the magnetic design of that ID.

Any stabilization that the magnets may have undergone, either by exposure to a reverse field or to

elevated temperature, may also influence the likelihood of radiation-induced demagnetization. If the small regions of a magnet block that will change their magnetization easily have already had their magnetization changed by the stabilization procedure, the block should be more resistant to further flux loss. The APS magnets were all stabilized before the IDs were assembled, so that temperatures up to 60 °C would not cause any demagnetization, nor would a demagnetizing field up to 1.2 H.

It is an interesting point that the magnet blocks that have demagnetized as a result of radiation damage can be remagnetized to full strength [4, 8-10]. While this would mean that ID magnets that have been partially demagnetized by radiation do not need to be replaced, it would not eliminate the need for a complete disassembly and reassembly of the ID magnetic structure. Also, the remagnetized and restabilized magnets might need to be sorted differently for the best overall magnetic results, and the ID would need a full magnetic tuning procedure. Therefore, although it would be possible to recover from radiation demagnetization of the ID magnets without purchasing new magnets, the recovery would not be painless.

The published results that are probably most applicable to the APS IDs are those from the study of Okuda et al. [4]. The magnet blocks that were used in that study were manufactured by Shin-Etsu, as were many of the magnet blocks used in the APS IDs. The study was published in 1994; if the magnets were not manufactured much before that time then they would probably have used similar technology to that of the APS magnets from Shin-Etsu, which were purchased in 1995. The 9% flux loss observed after a 260 Mrad exposure is probably overly optimistic for APS ID magnets, however, since the study was performed with single magnet blocks rather than with an assembled ID magnetic structure in which a demagnetizing field is imposed on the blocks. A different demagnetizing field can change the dose required for a particular flux loss by well over one order of magnitude [7].

WHAT DOSE LEVELS ARE OBSERVED AT APS?

The **first** running period with IDs installed and with the smaller gap vacuum chamber was in the late fall of 1995 through January 1996. Dose measurements made during that time alerted us to the need to provide some radiation shielding for the insertion devices. Injection efficiency was quite low during much of the run, and for long periods of time beam was being injected even though it was not being successfully stored. When the dosimeters were removed and read out, two of the three installed IDs were found to have been exposed to extremely high radiation doses. The response of the TLDs used flattens out at exposures over about 300 krad, so it is difficult to know the actual dose to within a factor of 2, but it is estimated to have been as high as 5.4 Mrad on one ID and 1.1 Mrad on the other. The gap on the third ID had been kept open during the entire run, so its dose was only 52 krad on the first pole. However, a second dosimeter that was placed to measure what the dose would have been for that ID if it had been at minimum gap for the entire run gave an estimated dose of 3 Mrad. The ID with the highest dose has since accumulated another 120 krad at the upstream end and 260 krad at the downstream end. The magnetic fields of the undulators that have received the highest doses were rechecked most recently in March 1997, and no demagnetization was found.

After these surprisingly high dose rates and knowing what the experience had been at ESRF, it was decided that measures to reduce the exposures encountered by the installed insertion devices were warranted. As a result, insertion devices are now installed in the downstream part of the ID straight section whenever possible, and Pb shielding is installed in the open space upstream of the ID. The effect of the Pb shielding will be discussed below.

The doses to the upstream and downstream ends of the ID magnetic structures have been monitored during all of the run times. Doses have also been monitored on the ID vacuum chambers and in the vicinity of the IDs.

Fig. 1. Total accumulated dose recorded by dosimeters on the upstream (first bar for each sector) and downstream (second bar) ends of the ID magnetic structure near the gap. These dosimeters open and close with the gap. This dose was accumulated during the approximately 21 weeks of total running time between when a run began on 10 Sept. 96 and when a run ended on 4 May 97. Note that there are 2 IDs installed in sector 2, 2U is upstream.

Fig. 2. Total accumulated dose recorded by dosimeters on the ID vacuum chamber immediately upstream of the ID. at the same distance from the vacuum chamber as the dosimeters from Fig. 1 would be at minimum gap. These dosimeters do not move with the gap. The time span is the same as for Fig. 1.

The dosimeters used have been TLDs and radiachromic [15] and GafChromic [16] films. Doses are not uniform from sector to sector, even for those sectors that are far from the injection point. In the early runs, there would usually be a sector where the dose was much higher than other sectors, but this high-dose sector would vary from run to run. Now that more operational experience has been gained so that the operation of the storage ring is more routine, some systematics in where the dose levels are higher are beginning to be seen. Unexplained incidences of a high dose somewhere that only occurs during one run are still found, however.

It is of interest to look at the doses that have been accumulated during the approximately 21 weeks of total running time that occurred from when a run began on 9/10/96 until a run ended on 5/4/97. Dosimeters are mounted on the upstream and downstream ends of the ID magnetic structures, fastened to the outside of the last pole, near the ID gap. The doses recorded here will be a measure of the exposure to the magnetic structure because they open and close with the gap. The accumulated dose by sector from these dosimeters is shown in Fig. 1. (This accumulated dose may not all have been to one particular ID, however, because some IDs were swapped out between runs for mechanical upgrades.) Additional dosimeters have also been mounted on the ID vacuum chambers immediately upstream of the ID and at the same distance from the vacuum chamber as the dosimeter on the magnetic structure when the ID is a minimum gap. The total dose in this location, shown in Fig. 2, reflects the sector-to-sector variation in the dose levels. The sector-to-sector variation is not the same for each run, however.

As can be seen in Fig. 1, the IDs in three separate sectors have accumulated a total dose of 1.1 or 1.2 Mrad during this time period, and IDs in three other sectors have accumulated 0.5 Mrad. In yet another sector (35), the total of 0.5 Mrad was accumulated in the approximately 8 total weeks of running time between 2/18/97 and 5/4/97 (no ID was installed there for any earlier runs).

WHAT DIFFERENCE DOES THE TYPE OF RADIATION MAKE?

The type of radiation to which the magnets are exposed has been found to be significant. A number of studies that exposed magnets to 1.17 MeV ^{60}Co γ -rays [2, 4, 8] found no radiation-induced demagnetization, despite total doses as high as 280 Mrad [4]. This, combined with the demagnetization seen with lower doses of higher-energy radiation quanta, suggests that the spectrum of the radiation is very important in determining whether there will be damage. It is probably not important whether the energy quanta in the incident radiation are electrons or photons as long as the energy of the incident quanta is high enough to cause a radiation shower, because the shower will consist of both electrons and photons no matter what the incident radiation.

Clearly, then, because 1 MeV gammas do not cause demagnetization whereas 17 MeV electrons do [4], one needs to know the spectrum of radiation to which the magnets are exposed in order to predict the likelihood of damage. An experiment was carried out at the APS to determine whether the dose rates being measured at the IDs were from high or low energy quanta. A multi-layered sandwich of alternating Pb and film dosimeters was placed so the dosimeters were approximately 30 mm directly above the positron beam, as shown in Fig. 3. The dose as a function of depth of Pb was measured, and the

Fig. 3. A schematic of the arrangement for a dose-depth experiment. The stack continues for many more layers than shown here.

Fig. 4. a) Dose measured as a function of Pb depth using the setup of Fig. 3. b) For comparison, absorbed energy vs. depth of Pb from a 6.3 GeV electromagnetic cascade is shown [data taken from 17]. The similarity of these curves suggests that the incident radiation in the current measurement was at an energy near 7 GeV.

results are shown in Fig. 4a. For comparison, the absorbed energy as a function of depth in Pb due to a 6.3-GeV cascade is shown in Fig. 4b [17]. The depth at which the peak dose occurs is a function of the energy of the incident quanta. The similarity between these curves suggests that 7 GeV quanta made up a large fraction of the incident radiation in the APS test. This radiation is high enough in energy to demagnetize the magnets.

The depth-dose experiment was repeated during the subsequent run. In that experiment, the peak dose occurred at a shallower depth, suggesting that some of the cascade had already taken place before the radiation

reached the experiment. It may be that the spectrum of the dose reaching the ID varies strongly with events or beam characteristics that are specific to the particular run. More experiments will be conducted to further characterize the exposure.

WHAT IS THE EFFECT OF THE MEASURES TAKEN TO REDUCE RADIATION DOSE TO THE IDS?

The Pb shielding mentioned above that has been installed immediately upstream of the IDs is more than 30 radiation lengths thick and should reduce the radiation levels to something too small to measure. The measured effect of the Pb gives us insights into the spatial distribution of the radiation. Fig. 5 shows the dose measured during a 3.5-week run by film dosimeters laid flat on the upper and lower faces of the (10-mm outside dimension) vacuum chamber and laid flat on the pole faces of the ID. This ID was kept at 100 mm gap throughout the run. The position of the Pb shielding is marked on the graph; note that it has no effect on the distribution of doses measured at the face of the vacuum chamber, despite the fact that there is no gap between the Pb shielding and the vacuum chamber. The Pb does dramatically reduce the dose at the upstream face of the first pole where the unshielded doses were highest, however; that point is not shown on the graph because the dose there was too small to measure with the film dosimeters that were used. The Pb shielding has essentially no effect on the dose at the downstream end of the ID. This shows that, while there is radiation traveling through the air above the vacuum chamber, there is also a non-negligible amount of radiation that will reach the magnets of an ID at closed gap by traveling through the vacuum chamber. So although the shielding dramatically reduces the radiation dose at the upstream end of the ID,

Fig. 5. Effect of the Pb shield on the dose to the ID. The shielding has no effect on the dosimeters that were placed flat on the top and bottom faces of the ID vacuum chamber, showing that much of the radiation travels through the vacuum chamber rather than through the air outside the chamber. The dose at the pole faces at the upstream end of the ID was too low to measure; it has been markedly decreased by the Pb. The Pb has no effect on the dose level at the downstream end of the ID. The ID was kept at 100 mm gap during this run.

Fig. 6. Doses measured by dosimeters fastened to the upstream ends of the ID magnetic structures and by dosimeters mounted on the ID vacuum chambers immediately upstream of the ID, at the same height above the vacuum chamber as the ones on the magnetic structure would be at minimum gap. The difference between the two shows the dose the ID was spared by not always being at minimum gap.

where it would otherwise usually be highest, it has essentially no effect on the lower dose levels at the downstream end. The other drawback of the Pb shielding is that it cannot be placed in every sector. In some sectors, the total ID length is nearly as long as the small-gap region of the vacuum chamber, so that no Pb can be installed with a small enough gap to protect the ID.

Another means that is used to reduce the radiation dose to the magnets is to open the gaps for injection. This is also being done at the Advanced Light Source (ALS) in Berkeley and has been found to be effective there [18]. Figure 6 shows the total dose measured during a 6-week running period at the first poles of each of the installed insertion devices. Dosimeters were also mounted immediately upstream of the first pole of each ID, at the same distance from the vacuum chamber as the dosimeter on the first pole would be if the ID were at minimum gap. Thus, the difference in dose rates indicates the amount of dose the upstream end of the ID was spared by having the gap open when the ID was not being used.

SUMMARY

The rate of radiation dose accumulation for the APS IDs has been and will continue to be measured. No radiation-induced demagnetization of the APS IDs has been observed to date. Attempts to compare these dose levels to dose levels where damage has been reported by others are complicated by factors such as the energy spectrum of the radiation and type of radiation, the magnet manufacturing technique and the demagnetizing field at the magnet blocks. The radiation spectrum has been measured and found to be high enough in energy to cause demagnetization. Lead shielding placed upstream of the IDs has helped reduce the dose to the upstream ends of the IDs but has much less effect at the downstream ends. Opening the ID gaps during injection and when the ID is not in use is also effective in reducing the dose.

ACKNOWLEDGEMENTS

The authors would like to thank John Grimmer, Tim Roberts, and others for their help in placing the dosimeters. We also thank Elwyn Dolecek and the ANL dosimetry group for all their unstinting help in preparing and reading out the TLDs. Thanks, too, to Jenny Erdmann and Jerry Moore who helped with the film dosimeter readings.

This work was supported by the U.S. D.O.E., BES-Materials Sciences, under Contract #W-31-109-Eng-38.

REFERENCES

- [1] J. Chavanne, P. Elleaume, and P. Van Vaerenbergh, ESRF Machine Technical Note 1-1996/ID, "Partial demagnetization of ID6 and dose measurements on certain IDs," (Jan. 1996).
- [2] H.B. Luna, X.K. Maruyama, N.J. Colella, J.S. Hobbs, R.S. Homady, B. Kulke, and J.V. Palomar, Nucl. Instrum. Meth. Phys. Res. A285 (1989) 349.
- [3] P. Colomp and E. Bräuer, ESRF Report 143/93/EB, "Measurements on demagnetization of the ID magnets by irradiation with the linear accelerator," (30 Mar 1993).
- [4] S. Okuda, K. Ohashi, and N. Kobayashi, Nucl. Instrum. Meth. in Phys. Res. B 94 (1994) 227.
- [5] R.D. Brown, J.R. Cost, G.P. Meisner and E.G. Brewer, J. Appl. Phys 64 (1988) 5305.
- [6] R.D. Brown and J.R. Cost, J. Appl. Phys 63 (1988), 3537.
- [7] R.D. Brown and J. R. Cost, IEEE Trans. Magn. 25 (1989) 3117.
- [8] J.R. Cost, R.D. Brown, A.L. Giorgi, and J.T. Stanley, Mat. Res. Soc. Symp. Proc. Vol. 96 (1987) 321.
- [9] E.W. Blackmore, IEEE Trans. on Nucl. Sci. NS-32 (1985) 3669.
- [10] J. Cost, R. Brown, A. Giorgi, and J. Stanley, IEEE Trans Magn 24 (1988) 2016.
- [11] Some neutrons are produced in the storage ring environment, but in the experiments of Luna et al. [2], no loss of remanence was seen that would have been attributable to the neutrons produced by using an 85 MeV electron beam to produce bremsstrahlung.
- [12] P. Van Vaerenbergh, personal communication.
- [13] P. Elleaume, personal communication.
- [14] J. Pflüger, G. Heintze, and I. Vasserman, Rev. Sci. Instrum. 66 (1995) 1946.
- [15] B.J. Mincher and M.K. Zaidi, Rad. Protection Dosimetry 47 (1993) 571.
- [16] B.J. Mincher, M.K. Zaidi, R.E. Arbon, W.L. McLaughlin, and G.L. Schwendiman, Rad. Protection Dosimetry 66 (1996) 233.
- [17] G. Bathow, E. Freytag, and K. Tesch, Nucl. Phys. B2 (1967) 669.
- [18] G.F. Krebs and M. Holmes, to be published in the proceedings of the 1997 Particle Accelerator Conference, held 12-16 May 1997 in Vancouver, B.C., Canada.