AN EXPERIMENTAL STUDY OF RADIATION-INDUCED DEMAGNETIZATION OF INSERTION DEVICE PERMANENT MAGNETS*

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Abstract

High brilliance in the 3GeV new light source NSLS II is obtained from the high magnetic fields in insertion devices (ID). The beam lifetime is limited to 3h by single Coulomb scattering in the Bunch (Touschek effect). This effect occurs everywhere around the circumference and there is unavoidable beam loss in the adjacent low-aperture insertion devices. This raises the issue of degradation and damage of the permanent magnetic material by irradiation with high energy electrons and corresponding shower particles. It is expected that IDs, especially those in-vacuum, would experience changes resulting from exposure to gamma rays, x-rays, electrons and neutrons. By expanding an on-going material radiation damage study at BNL the demagnetization effect of irradiation consisting primarily of neutrons, gamma rays and electrons on a set of NdFeB magnets is studied. Integrated doses ranging from several Mrad to a few Grad were achieved at the BNL Isotope Facility with a 112 MeV, 90 μA proton beam. Detailed information on dose distributions as well as on particle energy spectra on the NdFeB magnets was obtained in realistic simulations with the MARS15 Monte-Carlo code. This paper summarizes the results of this study.

INTRODUCTION

The harsh radiation environment insertion devices and other key components are expected to experience in synchrotron radiation sources especially where higher beam energies, beam currents and smaller gaps are in place. Specifically, magnets operating under conditions of high radiation are especially susceptible to demagnetization caused by direct and scattered radiation induced by electrons, positrons, high-energy photons and neutrons. While degradation of magnetic properties of insertion devices is the primary cause of concern, there are additional issues regarding the effects of radiation on physical properties of other components. Changes in physical properties such as thermal conductivity and thermal expansion due to irradiation will have serious effects on the functionality of components that depend on the thermal or positional stability of the system.

While the radiation dose threshold that can trigger dramatic changes in key properties of materials, such as rare-earth permanent magnets, has been hard to establish, the fact remains that serious demagnetization has been observed in operating light sources. Doses of several Mrad received by ESRF insertion devices lead to field losses of as much as 8%. Prompted by the surprising high magnetization loss observed at ESRF, APS has also investigated radiation-induced degradation in its insertion devices and found that certain undulators were affected and needed restoration. To that effect, next generation light sources expected to reach much higher brilliances of should pay special attention to this potential issue that may induce machine performance limitation by examining the factors that have shown to play a role in the degradation of component performance. The questions addressed early on in the design need to focus primarily on (a) the identification of dose thresholds causing either magnet field degradation or other material property changes, (b) the significance of irradiation type materials are exposed to in the storage ring and front end and the correlation of effects between irradiating species, (c) the optimization of material selection for use in the harsh environment formed on a balance between functionality and cost, (d) identification of the anticipated radiation environment through detailed studies at key locations of the light source facility, and (e) the feasibility of corrective measures that can be implemented to allow for the maintenance of the machine performance at the required level.

In addition to operational experience from light sources, several experimental studies have been conducted under a variety of radiation fields such as electron, proton, gamma neutron and bremsstrahlung in an effort to assess irradiation-induced damage and identify ways to recover the magnetic as well as other key properties. While results from the different studies pose interpretation difficulties (i.e. not quite clear how the effects of different factors are quantified regarding damage they cause in the material), the overall message has been that charged particles and high-energy neutrons are very effective in demagnetizing magnets. Specific studies [2, 3] focused on differentiating the effects of both irradiation energy and type. Irradiation of NdFeB in NS1 revealed that approximately 3 MRad of charged particles induced 50 times the flux loss of what was observed from 50 Mrad gammas. This finding is significant in a broader sense since it should be expected that identical doses, irrespective of what generates them, should have identical effects on materials. Figure 1 depicts the differences observed. Experiments focusing on electron and gamma irradiation showed that 280 MRad of 1.17 MeV gammas did not cause any demagnetization in NdFeB while 260 MRad of 17 Mev electrons led to 9% flux loss. These findings point to the fact that it is crucial to identify the type of exposure the critical components will be subjected to in order to assess the potential for irradiation-induced degradation of their function.

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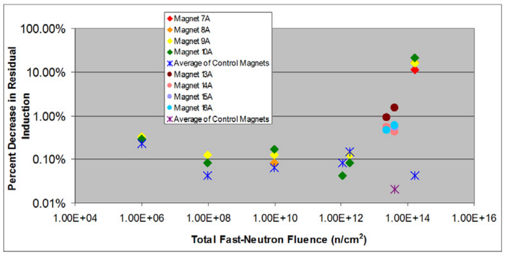
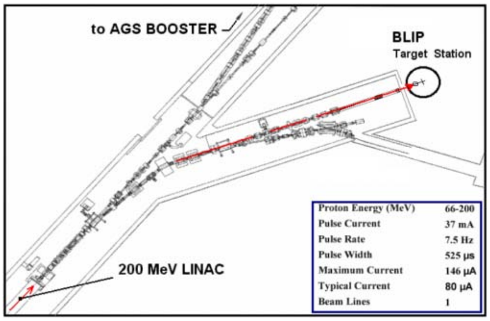


Figure 1: Decrease in residual induction of irradiated NdFeB magnets from fast neutron irradiation [2]

The various experimental studies also revealed that shape as well as magnetic field strength present during irradiation plays significant roles in the way magnets respond and demagnetize. Slight variations in the material microstructure (impurities, grain size) or thermal treatment are also important pointing to the fact that same materials made by different manufacturers may respond differently under irradiation exposure.

EXPERIMENTAL EFFORT

By utilizing the on-going material radiation damage study at BNL that focuses on a host of super-alloys and composites destined for high power accelerator targets, the demagnetization effect of irradiation consisting primarily of neutrons, gamma rays and electrons on a set of NdFeB magnets was undertaken. The permanent magnets that were used in this investigation are of typically commercially available and have dimensions of 5x4.75x0.7 cm. Also, the magnets used are similar to those used in the APS insertion devices and they have been plated with a thin coating of nickel to eliminate chipping. Prior to irradiation the magnets were measured with the help of a hall probe and were found to register approximately 0.15 Tesla at the center of each surface.



Proton Energy (MeV)	66-200
Pulse Current	37 mA
Pulse Rate	7.5 Hz
Pulse Width	525 μs
Maximum Current	146 μA
Typical Current	80 μA
Beam Lines	1

Figure 2: Irradiation facility layout and parameters of irradiating proton beam

The radiation of the magnets was done at the BNL Isotope Facility which receives a 112 MeV, 90 µA proton beam from the BNL Linac as shown in Figure 4. With a special configuration of upstream targets responsible from stopping the primary protons, a flux of neutrons, gamma and electrons was realized downstream where the NdFeB magnets were placed. Figure 5 shows the arrangement of the upstream targets and the NdFeB magnets as well as the primary proton and secondary particle tracks computed using the MARS15 Monte-Carlo code [4].

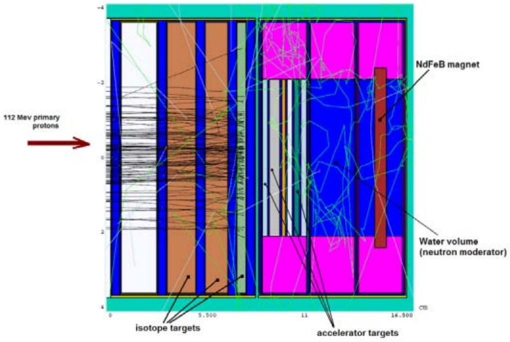


Figure 3: Schematic of NdFeB magnet integration into the isotope and high power target assembly including tracks of primary protons and secondary particles generated by the MARS15 Monte-Carlo code

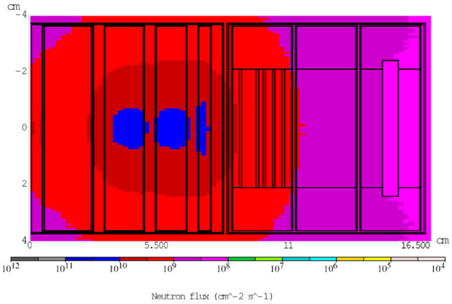


Figure 4: Neutron flux calculated by the MARS15 code

Calculations were performed to estimate the flux of neutrons, secondary protons, photons and electrons resulting from the interaction of primary protons with the isotope targets. Figures 6 and 7 depict calculated fluxes of neutrons and photons. Detailed information on dose distributions as well as on particle energy spectra on the NdFeB magnets was also obtained in realistic simulations with the MARS15 code. To address the effect of the dose on the demagnetization, five different magnets were irradiated placed one at a time into the irradiating assembly while varying the time of exposure to the beam. As a result, the five exposed exposed magnets experienced integrated dose levels ranging from several tens of Mrad to a few Grad.

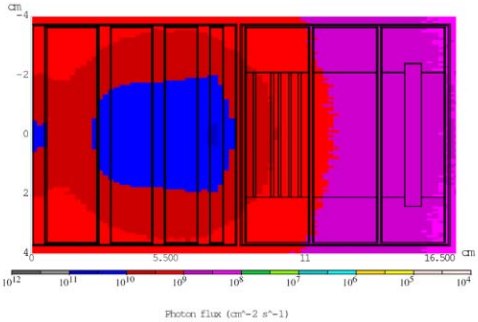


Figure 5: Photon flux calculated by the MARS15 code

POST-IRRADIATION RESULTS

The five magnets, following exposure to the radiating filed were allowed to “cool-down” for a period of approximately 12 months. Table 1 lists the estimated total dose received by each of the magnets irradiated during this investigation. As seen in Table 1 the lowest dose is 50 Mrad while the peak integrated dose received by magnet 11A is of the order of 1.8 Grad. These estimates were made based on the registered beam current, the beam profile and the fluxes computed by the MARS15 code. At the end of cool-down period the magnets were transferred to the BNL Hot Cell Facility were post-irradiation measurements were performed using a remote operation. The hall probe used the post-irradiation measurements within the hot cell was calibrated against the probe used to measure the flux prior to the exposure of the magnets.

Table 1: Integrated beam current and dose of magnets achieved during the BNL irradiation

Magnet	Current	Dose
Magnet 11A	78,000 µA-hrs	(1.8 Grad)
Magnet 12A	45,000 µA-hrs	(1.0 Grad)
Magnet 3A	50,000 µA-hrs	(1.2 Grad)
Magnet 20A	11,000 µA-hrs	(240 Mrad)
Magnet 6A	2,300 µA-hrs	(50 Mrad)

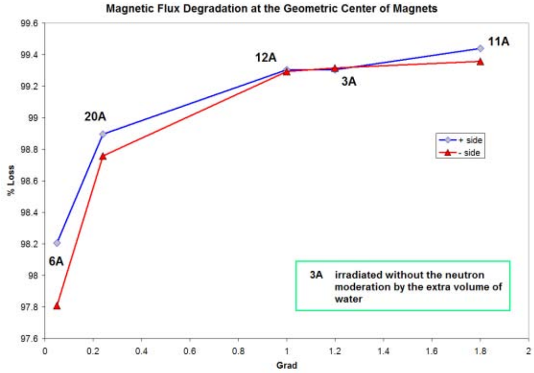


Figure 6: Measured loss of magnetic flux at the center of irradiated magnets (BNL experiment)

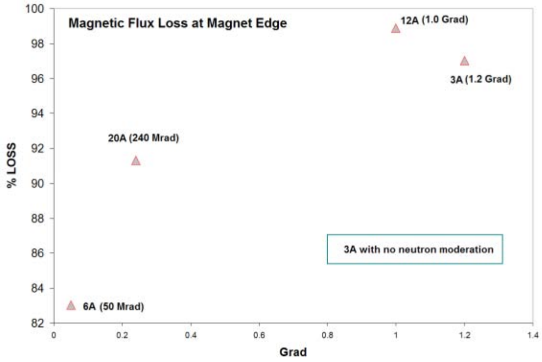
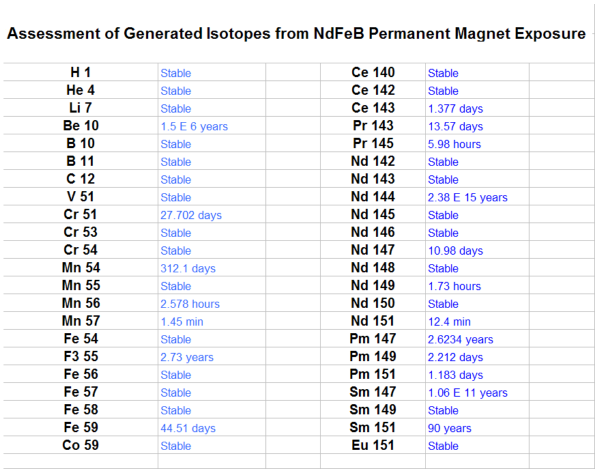


Figure 7: Measured loss of magnetic flux at the edge of irradiated magnets (shown in parenthesis is the integrated dose of each magnet)

To satisfy the requirements of the Isotope Facility used for this investigation but also gain valuable information regarding the effects of radiation on these magnets, a detailed study was performed to assess the types of isotopes that have been generated by the NdFeB exposure to the radiating field. This estimate was reached by using the ORIGEN code. Table 2 lists the isotopes and the corresponding half-lives. Such information will be of value during magnet replacement and handling operations.

Table 2: Identification of isotopes resulting from the exposure of the NdFeB magnet and associated half-lives as computed by the ORIGEN code



Assessment of Generated Isotopes from NdFeB Permanent Magnet Exposure

H 1	Stable	**Ce 140**	Stable
He 4	Stable	**Ce 142**	Stable
Li 7	Stable	**Ce 143**	1.377 days
Be 10	1.5 E 6 years	**Pr 143**	13.57 days
B 10	Stable	**Pr 145**	5.98 hours
B 11	Stable	**Nd 142**	Stable
C 12	Stable	**Nd 143**	Stable
V 51	Stable	**Nd 144**	2.38 E 15 years
Cr 51	27.702 days	**Nd 145**	Stable
Cr 53	Stable	**Nd 146**	Stable
Cr 54	Stable	**Nd 147**	10.98 days
Mn 54	312.1 days	**Nd 148**	Stable
Mn 55	Stable	**Nd 149**	1.73 hours
Mn 56	2.578 hours	**Nd 150**	Stable
Mn 57	1.45 min	**Nd 151**	12.4 min
Fe 54	Stable	**Pm 147**	2.6234 years
F3 55	2.73 years	**Pm 149**	2.212 days
Fe 56	Stable	**Pm 151**	1.183 days
Fe 57	Stable	**Sm 147**	1.06 E 11 years
Fe 58	Stable	**Sm 149**	Stable
Fe 59	44.51 days	**Sm 151**	90 years
Co 59	Stable	**Eu 151**	Stable

SUMMARY

By integrating the permanent magnet study with an ongoing material irradiation study at the BNL isotope facility, demagnetization effects were studied at dose levels ranging from 50 Mrad to 1.8 Grad. Post-irradiation measurements revealed that these magnets experience a serious loss of their magnetic properties. The findings appear to be in agreement with those of studies which investigated the effects of neutron irradiation.

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