Progress Report – April, 2007

Radiation Damage Studies of Materials and Electronic Devices Using Hadrons

Classification (Accelerator) LCRD 2.9

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Project Overview

Many materials and electronic devices must be tested for their ability to survive in the radiation environment expected at any future linear collider (LC). Radiation-sensitive components of the accelerator and detectors will be subjected to large fluences of hadrons as well as electrons and gammas during the lifetime of the accelerator. Examples are NdFeB permanent magnets which have many potential uses in the damping rings, injection and extraction lines and final focus, even though the linacs will be superconducting; electronic and electro-optical devices which will be utilized in the detector readout, possible gamma channels and accelerator control systems; and CCDs or other particle sensors which will be required for the detector.

UC Davis has two major facilities which can be used to provide needed information on hadron radiation damage, the McClellan Nuclear Reactor Center (MNRC), located in Sacramento (approximately 50 mi. round trip from the Davis campus), and the UC Davis Crocker Nuclear Laboratory (CNL) cyclotron (on campus). This project has been funded by the US Department of Energy under LCRD contract DE-FG02-03ER41280. It is described more fully in the 2004 LCRD Accelerator Proposal, Sec. 2.9. The main study concerns radiation damage from fast neutrons in samples of NdFeB permanent magnet materials from different vendors using the MNRC facilities.

Permanent magnet beam optical elements have been in use in the SLAC damping rings and their injection and extraction lines since 1985. They are also candidates for use in final focus quads, damping rings, wigglers and possibly elsewhere in the LC. It appears advantageous to use NdFeB for such magnets due to its lower cost and its higher energy product, $(BH)_{\mathrm{max}}$, relative to SmCo. However, because its Curie temperature, T_C, is much lower than that of SmCo, one needs to better understand and characterize the degradation of its magnetic properties due to radiation damage.

Neutrons from photonuclear reactions are expected to be an important source of radiation damage to most materials in the beam tunnels and damping ring enclosures. The radiation doses were estimated for the proposed NLC beam tunnel using a simulation based on electron losses [1]. These losses create showers of secondary particles dominated by electrons, positrons, photons and neutrons. The neutron energy spectrum is broad but peaked near 1 MeV. In a region under a magnet, approximately 25 cm below the beam line, the equivalent fluence of 1 MeV neutrons (normalized to radiation damage in silicon) was estimated to be 1.9×10^{14} cm^{-2} for 10 years of operation. Permanent magnets used as beam elements are likely to see much higher neutron fluences, especially in other locations, such as damping rings. The existence of significant neutron fluences has been demonstrated along the beam line in the SLC electron damping ring and their sources have been studied [6].

Brown and Cost [2] have shown that the remanence of NdFeB permanent magnets may be reduced significantly for neutron fluences of this order of magnitude and higher when irradiated at an elevated temperature (350 K). We know that the rate of reduction with fluence depends on the type of magnet, its operating point during irradiation, the intrinsic coercivity of the material and the manufacturer of the material [3]. Thus, it is necessary to characterize the radiation damage of candidate materials for LC NdFeB permanent magnets using neutron fluences to determine the useful life of any proposed devices based on using such materials. Our measurements appear to be unique in their ranges of loading or operating points and they complement the measurements of Ito, et al. using 200 MeV protons [4]. As Ito et al. make clear, there are discrepancies between available measurements with protons and the damage mechanisms which are not understood. Further, there also appear to be inconsistencies between the available neutron damage studies and the proton measurements so that this work is needed if NdFeB magnets are to be considered for use in a future linear collider. Clearly, the measurements will be useful for other applications.

Of course, high doses of gammas and electrons are also present in these areas but the associated radiation damage is expected to be much less than from the neutrons [3]. SLAC is in a good position to verify this with bremsstrahlung on candidate materials. Samples of NdFeB and SmCo have been tested at SLAC (with Lockheed Martin) together with many other materials using Co^{60} gammas with no observable effects up to 1 MGy – as expected [5].

These considerations led us to begin our study with the effects of 1 MeV-equivalent neutrons on NdFeB samples with different values of coercivity and from different manufacturers. The presence of B^{10} in the material with its very large thermal neutron capture cross section greatly increases the radiation dose delivered for a given thermal neutron fluence relative to fast neutrons, so measuring the effect of thermal neutrons is also important since this effect leads to irreparable damage in contrast to Co^{59} conversion to Co^{60} or the possible use of Gd as a substitution dopant for Nd.

The latter part of this project includes tests of electronic and electro-optical devices and materials for LC accelerator and detector applications [7].

Current Research Progress

In the following, we briefly describe our progress on the project and the ongoing work planned to bring it to conclusion. More detailed information has been presented at conferences and is available on the web [3,8,9]. New results will be presented at PAC07.

Small magnet test structures with NdFeB sample blocks (nickel plated to prevent oxidation) and thin iron flux returns have been fabricated to fit into the MNRC reactor irradiation chambers. They provide a broad variation in effective operating points over the different constituent blocks. A schematic diagram is shown in Fig. 1 giving the relative placements of three specific Sumitomo blocks reported on here (Blocks 3, 5 and 7). The basic configuration is an asymmetric quadrupole magnet with simple two-pole geometry with a gap that can be varied through the choice of the flux return pieces. Typical block dimensions are in the range 6-9 mm so gaps were made in the range of 2-7 mm. In Fig. 1, the load-line of Block 5 is in the first B–H quadrant (from the field of Block 3 and the rest of the magnetic circuit) and is nearly uniform throughout the block. Its matching partner at the top (Block 7) has material that is clearly in the second quadrant, as is also the case with Block 3. As the gap is decreased, the load-line difference between Blocks 7 and 5 increases, making the upper one more susceptible to damage.

Isolated (open-circuit) blocks from Shin-Etsu (N50M and N34Z) and Hitachi (HS36E and HS46A) were also irradiated to provide a wide variation in magnetization characteristics. The pertinent magnetic characteristics of the open-circuit irradiated blocks are summarized in Table 1.

Accurate measurements of the effective vector magnetizations of individual blocks are made

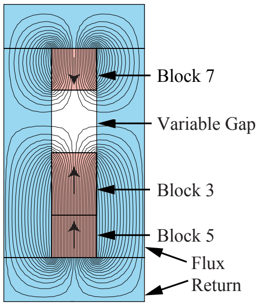

Figure 1: Schematic diagram of three block magnet test structure showing sample locations and magnetization vectors (not to scale).

Table 1: Characteristics of open-circuit irradiated blocks.

Block	B_r (kG)	H_{ic} (kOe)	H_{bc} (kOe)	BH_{max}
N34Z	11.60	30	11.3	32.7
N50M	14.15	15	13.1	47.7
HS36EH	11.60	24	11.3	32.8
HS46AH	13.41	14	12.9	44.3

using the SLAC Magnetic Measurements Group Helmholtz coil facility. Easy axis field component measurements are repeatable within small errors even for the small blocks. Details of the design of the magnet test assemblies and results of initial field measurements are given in the report by Spencer and Volk [3].

Hall probe scans are also being done to look for changes in the field distributions resulting from radiation damage. Such measurements are especially relevant for damping ring wigglers where nonlinear dynamics can limit beam lifetime and damping efficiency. Comparisons with expected field distributions are made using RADIA, a Mathematica-based three-dimensional magnetostatic simulation code developed at the European Synchrotron Radiation Facility in Grenoble, France.

An initial irradiation of the magnet test structure containing Blocks 3, 5 and 7 was performed directly downstream of a hydrogen target in the A-Line at SLAC, achieving a dose of 10 kGy of gammas and 1 kGy of 1 MeV-equivalent neutrons (stated as tissue equivalent dose to simplify comparisons). This was followed by a continuing series of irradiations using 1 MeV-equivalent neutrons at the MNRC reactor. The irradiation takes place within the reactor containment vessel outside the reactor core inside the NIF facility, a suspended shielded container which absorbs thermal neutrons and significantly attenuates the γ flux. Magnets are attached to a hexagonal structure inside the container which is rotated during irradiation to insure uniform neutron doses. Various forms of dosimetry were provided. The irradiations have been performed in a sequence of relatively short runs (of order one hour) to allow safe handling of the irradiation vessel by reactor personnel and to avoid long delays for the induced radioactivity to decay prior to shipping to SLAC for measurement.

The magnetization losses of Blocks 3, 5 and 7 after the irradiation in End Station A and three runs at MNRC were consistent with the fast neutron damage being proportional to dose, but depending as well on the disposition of the effective load lines relative to the nonlinear part of the hysteresis curve. The two larger blocks bracket the smaller one (Block 4) and the variation of the damage with dose is roughly twice as great for Block 7 as for Block 5. Results on demagnetization rate due to radiation dose $-\delta M_{xy}/\delta D$ (in G/Gy) are given in Table 2 after three additional doses at MNRC. In this table, $< M_y >$ is the average over all runs of one component of M (with x defined as the easy axis direction) and M^i_{xy} is the initial measurement, before irradiation, of the easy axis projection in the xy plane. The table is based on 6 doses totaling 77.8 Gy (Si) for the Shin-Etsu blocks and 2 doses totaling 28 Gy (Si) for newer magnet blocks using materials from Hitachi (HS36, HS46).

In the past year we have completed 5 more irradiations. A comparison of the decreases in magnetization with fluence for 4 different samples is shown in Fig. 2. All points include multiple measurements at the same exposure levels for all blocks. This clearly shows that the sensitivity to radiation damage is higher for the samples with high B_r and low H_c. The falloff with dose is roughly linear for the N50M and HS46 blocks but a preliminary polynomial fit shows some indication of nonlinearity.

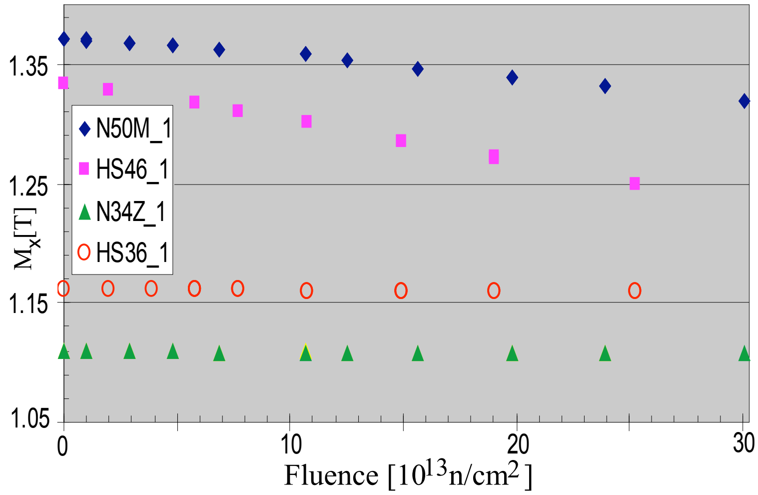

Figure 2: Comparison of magnetization losses for nominal 33 and 46 MGOe blocks from Shin-Etsu and Hitachi Magnetics listed in Tables 1 and 2.

Table 2: Demagnetization results for irradiated blocks.

Block	$< M_y >$ (G)	M^i_{xy} (T ± G)	$-\delta M_{xy}/\delta D$ (G/Gy)
HS36EH	-62 ± 29	1.1595 ± 0.8	0.00 ± 0.03
HS46AH	-154 ± 18	1.3298 ± 2.0	3.84 ± 0.07
N34Z1	-301 ± 35	1.1106 ± 1.8	0.49 ± 0.02
N50M1	-50 ± 38	1.3706 ± 1.1	1.81 ± 0.02
Block 3	-350 ± 57	1.0748 ± 6.7	0.78 ± 0.08
Block 5	93 ± 177	1.0622 ± 2.2	0.64 ± 0.03
Block 7	466 ± 183	1.0714 ± 0.9	1.04 ± 0.03

Gamma ray spectroscopy was performed on the magnet samples at MNRC after irradiation to characterize the radiation dose and induced radioactivity. We can use this information to evaluate the doping of the material (by the manufacturer) with other rare earth substitutions such as Tb and its effect on radiation resistance [8]. The sources of most γ lines were identified e.g. n-capture on Fe^{58}, Nd^{146}, Nd^{150} or the substitution element Tb^{159}. Neutron knockout (n,2n) on Nd^{148} also has a cross section comparable to capture leading to Nd^{147} while (n,p) exchange reactions on Fe^{54}, Ni^{60} or trace contaminants from the rare earths are also seen. Pm^{151} results from $Nd^{150}(n,\gamma)Nd^{151}$ followed by β^- decay. The results indicate that N50Z has about 55% as much Tb as N34Z which improves strength but reduces radiation resistance. Based on known capture cross sections for Fe^{58} and Tb^{159} and their relative abundances one infers a large substitution in N34Z that greatly improves its radiation resistance although HS36E is better whereas HS46A is the most susceptible. Further information on material doping and its relation to radiation hardness is given in [9]. This will be updated in a paper to be submitted to PAC07.

We are also investigating radiation-induced changes in the detailed distributions of the normal component of the magnetic field along the center of the surface of one pole face of the magnetized blocks. This is done with an automated Hall probe measurement stand which we have constructed using accurate stepping-motor-actuated linear stages attached to a small optical bench and controlled by a LabVIEW program. Since the field is a strong function of displacement normal to the magnet surface and the changes in the field distributions due to irradiation are expected to be small, the Hall probe positioning needs to be repeatable to μm accuracy relative to the magnet pole face. We have had difficulties with the reproducibility of these measurements. A comparison with RADIA calculations of the expected field showed that the variations from run to run could be explained by (a) microscopic variations in the position of the magnet in its holder on the measuring stand when it is removed and replaced and (b) the Hall probe approaching the block at a slight angle, eventually coming into contact with the surface of the block at different places, depending on the block position in its holder. Improvements were made in the alignment of the probe relative to the block surface and the method of holding the block during the scan. We are working on additional improvements so that accurately reproducible scans can be made for the final series of irradiations in this program.

In the course of this project, three outstanding physics undergraduates have been employed as student assistants to develop and maintain the LabVIEW program for the measurement stand, make field scans of the blocks and record them in a web-based log of their own design, perform analysis of the data, particularly the RADIA calculations, and work on improvements to the apparatus. One student is currently completing a Senior Honor's Thesis on this topic, which will update our results on a June '07 time frame. The third student is now learning the system to carry on this work.

We have irradiated a variety of electro-optic samples including some high purity fiber optic materials such as Suprasil 300. We have also begun to irradiate HTSM materials from American Superconductor. This has proved difficult due to induced radioactivity, e.g., from the metastable levels in the Ag matrix. Waiting for the activity to decay delays shipment of our irradiated samples to SLAC for measurement, so the logistics must be improved if we are to make further progress in this area. We will not let this delay our primary program on magnet irradiation. Further materials of interest might include diamond particle sensors.

Our goal is to continue magnet irradiations for approximately 5 more runs at the recent higher dose levels to look for nonlinearity in the in the curves of magnetization vs. fluence and for changes in the field patterns using an improved Hall probe measurement stand.

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