Project Name
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 abilities to survive in the radiation environment expected at the proposed 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 and accelerator control systems; and CCDs which will be required for the vertex detector.

UC Davis has two major facilities (see description below) 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 is in the second year of a three year program 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 initial study in this program concerns radiation damage due to neutrons in samples of NdFeB permanent magnet materials using the MNRC facilities.

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

Neutrons from photonuclear reactions are an important source of radiation damage to permanent magnets at LC in beam tunnels and damping ring enclosures. The radiation doses have been estimated in the 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 $1.9 \times 10^{14}$ cm$^{-2}$ for 10 years of operation. The magnets themselves are likely to see much higher neutron fluences, especially in other locations, such as the damping rings.

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). The rate of reduction with fluence depended on the magnet operating point during irradiation, the intrinsic coercivity of the material and the manufacturer of the material. 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 planned 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 [3]. 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 the baseline LC design.

High doses of gammas and electrons are also present in these locations, of course, but the associated radiation damage is expected to be much less than from the neutrons. 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) using $^{60}$Co gammas with no observable effects up to 1 MGy, as expected [4].

Existing measurements of the radiation environment in the SLAC damping rings should provide an estimate of the neutron fluences in the LC damping ring magnets. The existence of significant neutron fluences have been demonstrated along the beam line in the SLC electron damping ring and their sources have been studied [7]. Fermilab is also estimating beam loss distributions and particle fluxes for LC collimation systems which will help specify the requirements elsewhere.

The considerations above lead 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 $^{10}$B in the material with its 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.

We do not propose to test SmCo samples in this program. There is already a proof of principle for the use of SmCo in the SLC and evidence from Ito et al. [3] that the material is considerably more radiation-hard than NdFeB. Further, SmCo presents a severe handling and disposal problem due to the copious production of the long-lived radioactive isotopes $^{153}$Sm and $^{60}$Co by thermal neutrons. We also note that SmCo damage has been studied in the SLAC damping rings by the SLAC people in this proposal.
The latter part of this project will involve testing electronic and electro-optical devices and materials for LC accelerator and detector applications [5] using neutrons at MNRC or at CNL or 63 MeV protons in the CNL radiation test beam.

**Current Research Progress**

As mentioned earlier, this project is in the second year of a three year program funded by the US Department of Energy under LCRD contract DE-FG02-03ER41280. We briefly summarize the progress in this section. More detailed information has been presented at conferences and is available on the web [7][8]. Some results of our current work will be given at PAC2005 [9].

Test assemblies of NdFeB magnet blocks with iron flux returns have been fabricated that fit into the MNRC reactor test chambers and provide a broad variation in operating points over the different constituent blocks. A conceptual diagram showing how the magnet is constructed from NdFeB magnet blocks and iron flux returns is shown in Fig. 1. The actual assemblies have thinner flux returns than indicated in the diagram. The configuration is an asymmetric quadrupole magnet with simple two-pole geometry and a gap which can be varied through choice of flux return blocks. Typical block dimensions are in the range 6-9 mm. The gap can be chosen in the range 2-7 mm. In the case shown, the load-line of the lowest block is far into the first B-H quadrant (from the field of the adjacent, larger block and circuit) and is nearly the same throughout the block while its matching partner at the top has material that is clearly in the second quadrant as does the larger block. As the gap is decreased, the difference increases - making the upper one more susceptible to damage. The magnetizations of individual blocks were measured using a Helmholtz coil facility in the SLAC Magnetic Measurements Group. Field scans were made using a special Hall probe fixture. Details of the design of the magnet test assemblies and results of field measurements are given in the report by Spencer and Volk [7].

![Figure 1: Schematic diagram of magnet test structure showing magnetization vectors.](image)

An initial irradiation of a magnet assembly was performed directly downstream of a hydrogen target in a SLAC beam line, achieving a dose of 10 kGy of gammas and 1 kGy of 1 MeV equivalent neutrons (stated as tissue equivalent dose to simplify comparisons). The two most significant radioactive isotopes were $^7$Be and $^{51}$Cr from the B and Fe with the latter 20 times stronger but still less than one $\mu$Ci. The next strongest after these was down another factor of 4 from the $^7$Be. Half lives are of order one to two weeks. There was no evidence of radiation from the Nd derived isotopes nor from any substitution elements such as Dy, Pr or Tb.

Magnet structures using blocks manufactured by Sumitomo and isolated (open circuit) Shin-
Etsu blocks of N50M and N34Z were used, among others, for irradiation at MNRC as they provide a wide variation in magnetization characteristics. They have been subjected to a continuing series of irradiations using 1 MeV-equivalent neutrons in the NIF facility at the MNRC reactor.

The irradiation takes place inside the reactor vessel but outside the core inside a shielded container which provides attenuation of thermal neutrons and significantly reduces gamma ray exposure. Magnets are attached to a hexagonal structure inside the container. The container is rotated during irradiation to insure uniform neutron doses. Various forms of dosimetry were provided. The irradiations have been relatively short 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. Gamma ray spectroscopy was performed on samples after irradiation to characterize the radiation and to evaluate the effect of doping the material by the manufacturer with other rare earth substitutions.

The results of the irradiation at SLAC and the initial series of irradiations at MNRC were presented at EPAC04 [8]. The results of the first three MNRC runs are shown in Table 1. Details of the blocks and the numbering scheme are given in [7]. The larger blocks are now at top (#7) and bottom (#5). Easy axis strength errors are small and repeatable even for the small blocks. Fig. 2 shows the magnetization loss of the blocks vs. run number. Run 1 corresponds to no radiation (corresponding to Table 1). Run 2 was the irradiation in End Station A at SLAC. The remaining runs were at MNRC with $9.7 \times 10^{12}$ n/cm$^2$ for Run 3 and $1.9 \times 10^{13}$ n/cm$^2$ each for Runs 4 and 5. The total 1 MeV-Si equivalent neutron dose delivered at MNRC was 35 Gy.

<table>
<thead>
<tr>
<th>Block</th>
<th>$M_x$ (G)</th>
<th>$M_y$ (T) ± (G)</th>
<th>$M_z$ (G)</th>
<th>$\delta M_y / \delta D$ (G/Gy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#7 (top)</td>
<td>167</td>
<td>1.0904 ± 7</td>
<td>483</td>
<td>-1.6</td>
</tr>
<tr>
<td>#3 (mid)</td>
<td>-414</td>
<td>1.0950 ± 5</td>
<td>343</td>
<td>-1.2</td>
</tr>
<tr>
<td>#5 (bot)</td>
<td>-444</td>
<td>1.0727 ± 7</td>
<td>283</td>
<td>-0.7</td>
</tr>
<tr>
<td>N34Z1</td>
<td>-382</td>
<td>1.1102 ± 2</td>
<td>-382</td>
<td>-0.4</td>
</tr>
<tr>
<td>N50M1</td>
<td>-144</td>
<td>1.3717 ± 1</td>
<td>-2.8</td>
<td>-1.4</td>
</tr>
</tbody>
</table>

The results are consistent with 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 and the variation of the damage with dose is roughly twice as great for #7 as for #5. We have also investigated the effects on magnet radiation resistance and induced radioactivity due to the presence of additional rare-earth components such as Tb (as revealed by the gamma spectra) [8].

In the last year, we had encountered some delays in this program due to changes in personnel at MNRC and the shutdown at SLAC but our irradiations at MNRC are now progressing well. We have constructed a portable magnet measuring stand which uses stepping motor micropositioners controlled by a laptop computer running LabVIEW to automate the Hall probe measurements. New magnet blocks using materials from Hitachi (HS36, HS48) and a new magnet structure with three more blocks in a higher field configuration have been added to the series of tests. Results from the current work will be presented at PAC05 in Knoxville in May [9].
Facilities, Equipment and Other Resources

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).

The MNRC reactor has a number of areas for irradiating samples with neutron fluxes up to $4.5 \times 10^{13}$ $n/cm^2s$. A specialized area (NIF) allows irradiation with 1 MeV-equivalent neutrons in a flux of $4.2 \times 10^{10}$ $n/cm^2s$ while suppressing thermal neutrons and gammas by large factors. Other areas allow irradiating very large objects at lower fluxes.

The CNL radiation test beam consists of protons of up to 63.3 MeV kinetic energy spread over a rather uniform beam spot 7 cm in diameter. A typical central flux is $4.2 \times 10^9$ protons/cm²s (0.56 kRad/s (Si)). A secondary emission monitor calibrated with a Faraday cup is used to measure the beam fluence to an accuracy of better than 5%. The beam profile has been established by a variety of means, showing the dose to have fallen by only 2% at a radius of 2 cm. The facility can also produce a neutron beam with a flat energy spectrum extending to 70 MeV kinetic energy. We have used the CNL proton facility for a wide variety of tests on electronic devices and detector components.

References


