Radiation Damage Studies of Materials and Electronic Devices Using Hadrons

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Summary:

This project is part of the DOE university-based advanced technology program in generic accelerator R&D relevant to a future linear collider. It is described more fully in the 2004 LCRD Accelerator Proposal, Sec. 2.9. Many 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. For example, NdFeB permanent magnets have many potential uses in the damping rings, injection and extraction lines and final focus, even though the linacs will be superconducting. This material is advantageous for its relatively low cost and its high energy product $(BH)_{\max}$, but due to its relatively low Curie temperature T_C, one needs to better understand and characterize the degradation of its magnetic properties due to radiation damage. Other possible candidates for testing in this program are electronic and electro-optical devices which will be utilized in the detector readout, possible gamma channels and accelerator control systems and CCDs which will be required for the vertex detector.

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. Electron beam losses create showers of secondary particles dominated by electrons, positrons, photons and neutrons. The neutron energy spectrum is broad but expected to be peaked near 1 MeV. This irradiation can reduce the remanence of NdFeB permanent magnets significantly. Among other factors, the rate of reduction with fluence depends on the type of magnet, its operating point during irradiation, the intrinsic coercivity (and remanence) of the material and the manufacturer of the material. Thus, we chose a range of materials with the basic goal of giving a predictive procedure that obviates the need to characterize the damage of every candidate material and application.

UC Davis has two major facilities that 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). Our initial study concerns radiation damage from fast neutrons in samples of NdFeB permanent magnet materials from different vendors using the MNRC facilities. Our measurements appear to be unique in their ranges of loading or operating points and they are complementary to existing measurements using protons.

Recent Accomplishments:

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 used 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. The magnet structure is shown in Fig. 2 undergoing a field scan using a Hall probe. The Hall probe fixture has since been automated using stepping motor micropositioners controlled by a laptop computer running LabVIEW. Accurate measurements of the effective vector magnetizations of individual blocks are made using the SLAC Magnetic Measurements Group Helmholtz coil facility shown in Fig. 3. Easy axis field component measurements are repeatable within small errors even for the small blocks. The Hall probe scans are being done to ascertain 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.

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. Magnet structures using blocks manufactured by Sumitomo and 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, as illustrated in Fig. 4 for the Shin-Etsu materials. The irradiation takes place at a location outside the core but within the reactor vessel (indicated by the arrow in Fig. 5) inside the NIF facility, a suspended shielded container which absorbs thermal neutrons and significantly attenuates the γ flux. The container is shown opened in the Fig. 5 insert. Magnets are attached to a hexagonal structure inside the container which is rotated during irradiation to insure uniform neutron doses. The irradiations have been relatively short (46 minutes) 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 dose and induced radioactivity as well as to evaluate the effects of doping the material (by the manufacturer) with other rare earth substitutions.

Fig. 6 shows the magnetization loss of Blocks 3, 5 and 7 vs. run number after the irradiation in End Station A (Run 1) and three runs at MNRC (Run 0 corresponds to the initial magnetization measurements prior to irradiation). The associated fluences for the runs at MNRC were 9.7×10^{12} n/cm^2 for Run 2 and 1.9×10^{13} n/cm^2 each for Runs 3 and 4. The total 1 MeV-Si equivalent neutron dose delivered at MNRC in this series was 35 Gy. 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 (Block 4) and the variation of the damage with dose is roughly twice as great for Block 7 as for Block 5.

Results on the demagnetization rate due to radiation dose $-\delta M_{xy}/\delta D$ (in G/Gy) are given in Table 1 after three additional doses at MNRC. In this table, $\langle M_y \rangle$ is the average over all runs of one component of $\mathbf{M}$ (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 Shin-Etsu blocks received 6 doses totaling 77.8 Gy (Si). New magnet blocks using materials from Hitachi (HS36, HS48) received 2 doses totaling 28 Gy (Si). The damage appears to be linear with dose over these ranges. Stepped doses are continuing for these and additional 3-block test structures.

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. Essentially all of the observed lines have been identified. The sources of most lines are clear e.g. n-capture on Fe^{58}, Nd^{146} 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 esp. 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. Based on known capture cross sections for Fe^{58} and Tb^{159} and relative abundances one infers a large substitution in N34Z that greatly improves its radiation resistance. Further information on the gamma spectra, material doping and the relation to radiation hardness is given in the listed publications.

Further runs in the series will continue on our enlarged sample set and also include certain electrical and fiber optic materials such Suprasil 300 based on previous studies with gammas.

Publications:

1. J. Spencer and J. Volk, “Permanent Magnets for Radiation Damage Studies,” PAC'03, Portland, May 2003, 779-781.
2. J. Allen, S. Anderson, J. Spencer, Z. Wolf, M. Boussoufi, D. Pellett and J. Volk, “Radiation Damage Studies with Hadrons on Materials and Electronics,” EPAC'04, Geneva, May 2004.
3. S. Anderson, J. Spencer, Z. Wolf, A. Baldwin, D. Pellett, M. Boussoufi and J. Volk, “Fast Neutron Damage Studies on NdFeB Materials,” PAC'05, Knoxville, May 2005.

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