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Author(s): D. B. Barlow, LANSCE-1
R. H. Kraus, P-21
M. J. Borden, LANSCE-2

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Radiation Hardness Measurements of New Permanent Magnet Materials for High-Intensity Linac Applications

David B. Barlow*, Robert H. Kraus and Michael J. Borden

Abstract

This is the final report of a two-year, Laboratory Directed Research and Development (LDRD) project at Los Alamos National Laboratory (LANL). The radiation resistance of samples of high-strength samarium cobalt permanent-magnet material has been studied. Samples of commercially available material were obtained from four different manufacturers. The remanent field of the samples was measured before and after the samples were irradiated with neutrons produced at the beam stop of the Los Alamos Neutron Science Center (LANSCE) proton accelerator.

Background and Research Objectives

High (magnetic) strength, rare-earth permanent-magnet material can be used in many compact magnets for steering and focusing high-energy particle beams. Such permanent magnet assemblies result in a considerable savings in space over comparable electromagnets in areas where space is often at a premium. In addition, permanent magnets offer a level of reliability that far surpasses that of electromagnets in applications where reliability is critical. However, the magnetic strength of rare-earth permanent-magnet material has proven to be sensitive to radiation damage in accelerator environments. Several studies of the effects of radiation on the magnetic strength of rare-earth permanent-magnet material have been performed at Los Alamos National Laboratory (LANL) as well as at other institutions around the world.¹⁻⁹ These studies indicate that the rate at which magnet material loses its magnetic strength is anomalously large compared to the expected rate of material damage. It has been shown that the rate of radiation damage is increased by applying an external field parallel to the sample's direction of magnetization (Fig. 1), or by raising the temperature. Furthermore it has been shown that after a moderate exposure, the magnetic strength can be completely restored by remagnetizing the sample, indicating that no metallurgical damage has occurred.

* Principal Investigator, E-mail: dbarlow@lanl.gov

It has been proposed that high-energy particle irradiation, e.g., neutrons or protons, causes a loss of magnetization through a mechanism where a single high-energy particle interaction can cause an entire magnetic domain, containing several million atoms, to reverse its direction of magnetization. External magnetic fields applied parallel to the direction of magnetization or elevated temperatures increase the rate of radiation damage by making it easier to reverse a domain's direction of magnetization. The details of this process are not well understood but it has been shown to depend on the differences in the microstructure of the material. In particular, the grain size and thickness of the grain boundary appear to play an important role in determining the radiation resistance.

Of the many parameters used to characterize permanent magnet material, the two most important are the coercivity (resistance to demagnetization) and the remanence (residual magnetic field). The combination of high coercivity and high remanence leads to high strength permanent magnet material. Of these two parameters, it is the remanence that suffers most from exposure to radiation. Of the most common types of rare-earth permanent magnet material, neodymium iron boron (NdFeB) and samarium cobalt (SmCo), it is the latter that shows the greatest resistance to radiation damage. Although possessing similar coercivity and remanence, SmCo typically has an order of magnitude more resistance to radiation damage than NdFeB. Measurements made at LANL have shown that at an exposure of $\sim 2 \times 10^{16}$ neutrons per cm^2 , samples of SmCo have lost 1 to 2% of their original remanence whereas samples of NdFeB have lost 20 to 50% of theirs, as shown in Fig. 2. There are several other high-strength permanent-magnet materials under development and available in small quantities, e. g., praseodymium iron boron (PrFeB) and samarium iron (SmFe). However the radiation resistance of these materials is not expected to approach that of SmCo. Hence the objective of this project is to characterize the radiation resistance of commercially available SmCo in an accelerator radiation environment.

Importance to LANL's Science and Technology Base and National R&D Needs

Permanent magnet assemblies are being used in place of conventional electromagnets in a number of accelerators where the assemblies are exposed to low intensity radiation doses. However several new accelerator projects, e. g., Accelerator Production of Tritium and the National Spallation Neutron Source, are being designed at LANL where the use of permanent magnet assemblies would be advantageous in areas where they would be exposed to high-intensity radiation doses. The first step in studying

the feasibility of using permanent magnet assemblies in such high radiation environments is to determine the radiation resistance of a selection of commercially available permanent-magnet materials.

Scientific Approach and Accomplishments

A majority of the studies in the past have been done at reactors where the energy spectrum of fission neutrons is considerably lower than what might be expected in a typical accelerator environment. For this experiment the exposures were done at the Los Alamos Spallation Radiation Damage Effects Facility (LASREF) at the Los Alamos Neutron Science Center (LANSCE).¹⁰ LASREF produces neutrons with a fission energy spectrum with the addition of a high energy tail, which is more typical of the energy spectrum one expects from a high-energy proton accelerator. LASREF consists of an iron insert in the shielding above the LANSCE beam stop. The insert has a number of tubes through which samples can be lowered to a point close to the beam stop. At the bottom of the tubes the samples are exposed to a neutron flux of up to 5×10^{13} n/cm²-s.

Samples of commercially available high-strength samarium cobalt (grade 26 Sm₂Co₁₇) were obtained from four different manufacturers: Shin-Etsu, Vacuumschmelze, Ugi Mag, and Electron Energy Corp. All the samples were energized by the supplier before shipment. A low speed diamond saw was used to section the samples into smaller samples measuring approximately 5 mm by 5 mm by 10 mm, with the direction of magnetization parallel to the long dimension. Each sample was hermetically sealed, by electron beam welding, in a separate nonmagnetic cylindrical container small enough to fit the inside diameter of the sample tubes.

The magnetic moment of each sample was measured after it was welded into its container by recording the peak integral voltage as it was passed through the center of an annular measurement coil. The remanence is proportional to the magnetic moment of the sample. Four containers containing samples of the four different materials were then strung together and lowered down a sample tube. A thermocouple was attached to the uppermost sample of each string to provide continuous monitoring of the temperature.

Five sample strings were assembled and lowered down the sample tubes. The sample strings were removed at different times to give neutron fluences ranging from 4.4×10^{16} n/cm² to 4.6×10^{18} n/cm². The neutron fluences were determined knowing the integrated proton beam at the beam stop for each sample string, and from prior

measurements of the neutron flux and energy spectrum.¹¹ A typical energy spectrum is shown in Fig. 3.

Active cooling of the iron insert maintained the temperature of four of the five sample strings below 40° C at all times. The exception was the sample string exposed to 9.1×10^{17} n/cm² which briefly recorded a peak temperature of 95° C. A temperature of 95° C by itself would not have an irreversible effect on the magnetic properties of the samples but it may have increased the rate of radiation damage during the time the samples were at this temperature.

After the sample strings were removed they were kept in storage for about 10 months to allow the short-lived activation products to decay to a level where the remanence of the samples could be remeasured with less exposure to personnel. After this time the magnetic moment of each sample was remeasured using the same procedure as before. The change in remanence vs the neutron fluences is shown in Fig. 4. The average error in the measurement of the change in remanence was about 0.4%.

A control sample was used to check for systematic errors due to drifts in the calibration of the measurement setup. The control sample was not exposed to radiation and was measured whenever measurements were made. The measurement of the magnetic moment of the control sample varied by less than $\pm 0.2\%$ from measurement to measurement. Given these errors about all one can conclude is that all four samples performed about the same and that they lost about 0.5% of their remanence when exposed to a neutron flux of 4.6×10^{18} n/cm². This is a considerable improvement in the radiation resistance over the samples of magnet material measured by Cost and Brown ten years ago, depicted in Figs. 1 and 2.

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Fig. 1. Fractional loss of remanence for SmCo from two different manufacturers with and without a 5.5 kG external magnetic field applied parallel to the direction of magnetization. Measured by J. Cost and R. Brown.

Fig. 2. Fractional loss of remanence for SmCo and NdFeB rare-earth magnet material from different manufacturers as measured by J. Cost and R. Brown.

Fig. 3. Typical differential neutron energy spectrum from the results of D. Davidson et al.

Fig. 4. Fractional loss in remanance vs the neutron fluence for the four different magnet materials. For clarity the uncertainty of the measurements is not shown. However the average uncertainty in the measurement of the change in remanance is 0.4%.