

# PERMANENT MAGNETS FOR RADIATION DAMAGE STUDIES

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## Abstract

Permanent magnetic (PM) devices have many current and potential applications based on advantages in size, cost and simplicity but they suffer from uncertainties related to environmental and damage effects. One missing ingredient is a magnet designed to explicate demagnetization effects as a function of the principal magnetic characteristics of the device, the material, the blocks and their fab procedures – all of which need to be independently varied while minimizing the induced radioactivity from testing. We describe such a magnet and the measurements on it and its blocks and discuss the parameters of most interest as well as the constraints that motivate this choice.

## INTRODUCTION

In the next linear collider (NLC), PM devices such as solenoids, multipoles, undulators and wigglers could have important uses if the limits of their stability to differing high radiation environments could be established. This work is part of a broader proposal[1] to determine the types and levels of radiation to be expected and the susceptibility of PM material to radiation damage from these. A major goal is to obtain a general interpretation applicable to any PM device. For this, we have developed an unconventional magnet that is simple and easy to test and modify.

We discuss the magnet, defined as more than one PM block, that can't be used for conventional applications but allows a good comparison between the key ingredients thought to be important in radiation damage mechanisms by simply changing the magnet gap or the block material or its characteristics such as intrinsic coercivity  $H_{ci}$ .

## PROBLEM DESCRIPTION/SITUATION

Demagnetization and especially radiation damage has been of interest in our field for over twenty years[2, 3, 4, 5, 6, 7] with a broad array of approaches. A physically realistic but qualitative picture has the Curie temperature  $T_c$  being exceeded in some volume followed by remagnetization in the local, residual field at that location. This implies a natural hierarchy in terms of nominal  $T_c$  values:  $\text{Sm}_2\text{Co}_{17}(800^\circ) > \text{SmCo}_5(700^\circ) > \text{Nd}_{2-x}\text{Fe}_{14}\text{B}(300^\circ)$  where  $x$  represents substitution of other rare-earths such as Dy, Pr or Tb that are known to improve  $H_{ci}$ . Tests are open-circuit yet assume fixed load-lines and permeances. Conclusions are mostly empirical with curious omissions e.g. no discussion of characteristics such as stabilization temperatures  $T_s$ , tests with thermal neutrons nor any post radiation activation analyses[8].

Initially, Brown et al. [2] looked at SmCo but did not measure or control the temperature. Later, Brown and Cost[3] observed that higher Dy or Tb contents resulted in higher  $H_{ci}$  in NdFeB (with very high linear correlation 0.96) as well as greater radiation resistance (RR) with high correlation (0.87) and thus, a good correlation between RR and  $H_{ci}$  (0.78). They controlled temperature but didn't specify  $T_s$ . They suggested a radiation induced, nucleation of domain reversals from processes that exceed the domain nucleation energy barrier.

Zeller[4] argued, from the known loss of magnetization with temperature or  $P_c$ , that the dominant mechanism was loss of coercivity as opposed to loss of remanence based on macroscopic Pandira simulations. Varying  $H_c$  and then  $B_r$ , he obtained shapes consistent with his field scans and argued that NdFeB demagnetizes worse than other alloys based on its lighter elements B and O gaining significantly greater recoil energy from knock-on collisions.

Kahkonen et al.[5] proposed this as well and appeared to verify it with 20 MeV protons. They indicated, without comment, that the demagnetization had a  $\cos\theta$  dependence if  $\theta$  is the angle between  $\vec{M}$  and the particle velocity  $\vec{v}$ . This implies that the particle's path is unaffected by the B field and is understood by remembering that the material is crystalline. They noted their model was premature but this was the first quantitative attempt that suggested tests.

Okuda et al.[6] used electrons and  $\text{Co}^{60}$   $\gamma$ 's and showed that  $\text{Sm}_2\text{Co}_{17}$  was better in all respects except the  $B_r$  ratio of 1.12 for the samples tested. Nearly complete remagnetization after irradiation suggested little structural change consistent with Ref's [2, 3].

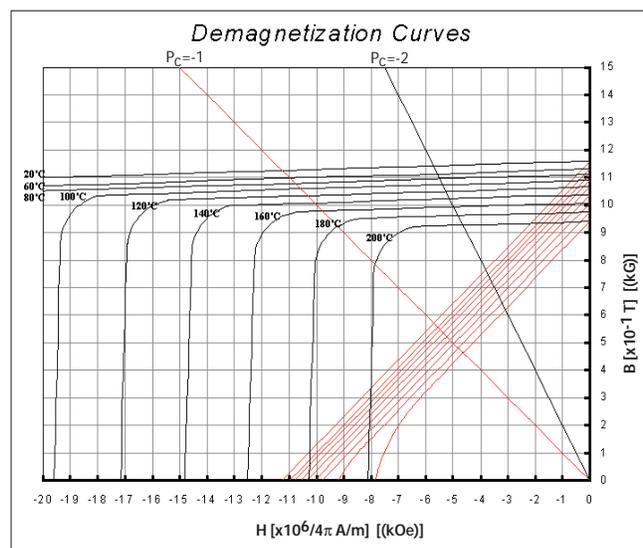


Figure 1: Shin-Etsu N34Z material indicating reversible, thermal behavior up to 200°C for permeances  $|P_c| > 0.5$ .

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Most recently, Ito et al.[7] used 200 MeV protons to test consensus on the effects of  $H_{ci}$  and  $P_c$  on RR and that “flux loss cannot be attributable to structural change” but that mechanisms are not fully understood. For samples with the same  $P_c=0.5$ ,  $Sm_2Co_{17}$  was better than the best Nd sample in all respects except for the  $B_r$  ratio of 1.07 even when the Nd had double the coercivity  $H_{ci}$ . Their Nd materials were similar to ours such as shown in Fig. 1.

### Nomenclature and Conclusions

People have consistently tried to explain RR in terms of a few “simple” properties of a block and its material such as  $P_c \equiv B/H$ . This is a signed quantity that is not unique in sign or magnitude for many block operating conditions[9]. Similarly, neither it nor the load line it describes is ever unique, even for unloaded, open circuit blocks or magnet assemblies. Still, models[5] assume that every demagnetization is followed by a remagnetization in the opposite direction due to self fields.

While several experiments appear to provide consensus, there are discrepancies. For example, it is interesting to compare *all* available charged hadron data for NdFeB. This includes 106 MeV deuterons and several proton energies from 20-500 MeV[2, 4, 5, 7]. For comparable values of  $H_{ci}$  and  $P_c$ , one finds the damage hierarchy:  $p > d > n > e > \gamma$ . Similarly, high energy protons are worse than low[7] - at least  $p(200 \text{ MeV}) > p(20 \text{ MeV})$  where the authors note “the reason is not clear” and “more detailed studies are needed”. We agree[10].

There is another serious discrepancy. If one assumes that radiation and ionization loss promotes nucleation of reversed domains[3], one might expect electrons to cause more damage than ions if only radiative losses from bremsstrahlung were relevant:

$$\sigma_i^{rad} \sim \alpha Z^2 (z_i r_i)^2 \ni r_i = r_e \left[ \frac{m_e c^2}{m_i c^2} \right] \text{ [cm}^2/\text{nucleus]}. \quad (1)$$

Clearly, ionization and atomic excitation dominate for ions and much of the electron data as well since  $E_e < E_c$  - the critical electron energy for the material. Thus, over these energies, one can use the Bethe Bloch equation. This gives  $p(\text{LowE}) > p(\text{HiE})$  but also  $d(106 \text{ MeV}) > p(200 \text{ MeV})$ . The maximum energy of knock-on electrons goes as  $2m_e c^2 (\beta\gamma)^2$  reaching  $\approx 1.4 \text{ MeV}$  for 500 MeV protons. This model is inconsistent with the data but consistent with no structural damage.

The model where the primary cause is recoil of Boron atoms from Coulomb scattering is intriguing because B is much less prevalent and has a much lower Coulomb cross section than the other components  $\propto (Z_A z_i / T_R)^2$  where  $T_R$  is the reduced kinetic energy. However, it has a larger “Curie radius” that can be comparable to or larger than the grain size. However, if we extend this model to other incident channels, we expect  $\sigma(p) > \sigma(n)$  from the larger Coulomb size but the damage is much greater for protons[3, 7] than expected. Nonetheless, from the maximum energy transfer, we expect:  $d > p > n > e > \gamma$

at *fixed* energy and comparable conditions as well as  $p(\text{HiE}) > p(\text{LowE})$ . Thus, we have some simple but distinct models where only the latter gives any qualitative agreement. All suggest a much higher limit on truly irremedial radiation damage that should be tested - especially with thermal neutrons that can produce structural changes from reactions such as  $B^{10}(n, \alpha)Li^7$ .

### MAGNET DESCRIPTION

Under certain qualifying caveats, conventional PM dipoles should be less susceptible followed by undulators, wigglers, and quadrupoles due to variations in  $\vec{M}$  of the blocks *and* variations in  $\vec{H}_{ext}$  i.e. their differing load lines throughout each type of block and magnet[9]. This is clear from Fig. 2 and explains our choice of an asymmetric quadrupole magnet with simple dipole geometry – shown here for a large gap magnet  $G \geq l_x, l_y, l_z$  of the PM blocks.

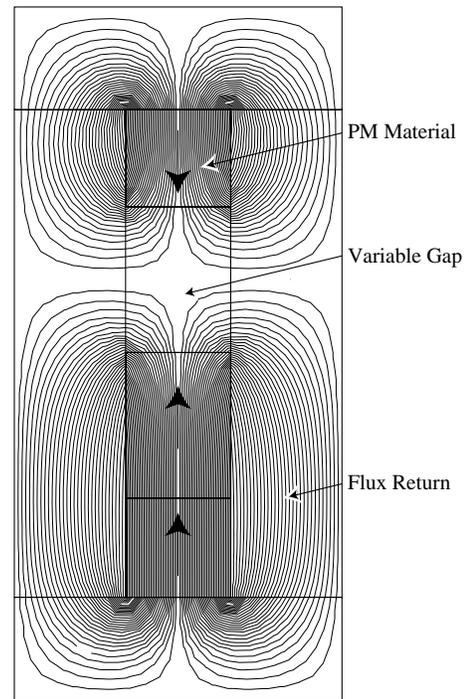


Figure 2: Schematic layout showing magnetization vectors.

In this case, 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. Going further, some material can be driven past the knee (Fig. 1),  $H_{cb}$  and  $H_{ci}$  where “irreversible” but not unremediable effects, with or without radiation, are expected. Most of this depends on the magnetic circuit rather than the block dimensions or even the material. This is one reason we measured the block magnetizations several times after initial assembly and disassembly. Clearly, the closed circuit material is too bulky in Fig.3 but this suggests a typical setup.

## MAGNETIC MEASUREMENTS

For magnets such as shown in Fig. 2, we have made and measured several variants. For activation analysis,  $G=2,3,5$  & 7 mm with block sizes  $l_z=9$  mm,  $l_x=5.9$  and  $l_y=6.8,9$  mm. The finished OD, for a pneumatic rabbit, is 9 x 9 x 30 mm. Some field scans along z are shown in Fig. 3 for the 2(M1) and 7(M3) cases. The effective magnetic length ( $\int B_y dz$ )/ $B_y^{peak}$  of M3 is  $L_z \approx 9$  mm.

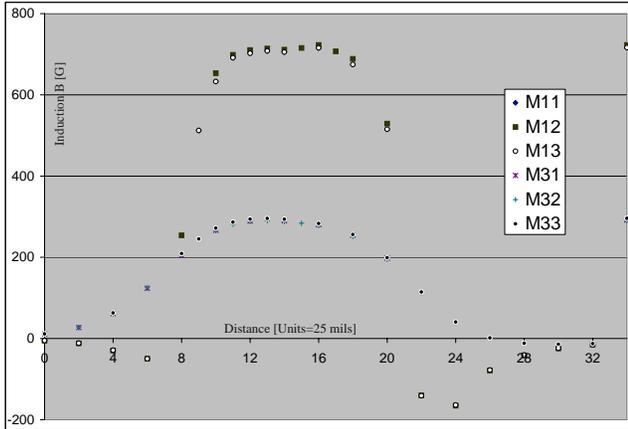


Figure 3: Typical mid-plane scans for the 2 and 7 mm gaps.

The peak field for each scan is shown at position 34 ( $34 \times 25 = 0.85$ in) and in Table 1 as Mid as well as along the top and bottom poles for the same probe orientation.

Table 1: Some Peak Field Values

Gap[mm]	Top	Mid [kG]	Bot
2 (M1)	1.185	$0.7211 \pm 0.0041$	+0.722
3 (Ref)	2.880	$0.6788 \pm 0.0024$	-1.557
5 (M2)	3.976	$0.5109 \pm 0.0025$	-2.880
7 (M3)	4.344	$0.2932 \pm 0.0026$	-3.262

Table 2 gives some block measurements. The larger blocks are now at top and bottom (Fig. 2). Easy axis angle errors are large but repeatability is good for such small blocks.

Table 2: Magnetization measurements for the M3 blocks

Block #	$M_x$ [G]	$M_y$ [T]	$M_z$ [G]
10 (top)	81.7	$1.1343 \pm 0.0012$	$-584.8 \pm 38.9$
2 (mid)	-411.7	$1.0627 \pm 0.0027$	$187.6 \pm 3.11$
6 (bot)	27.0	$1.1300 \pm 0.0002$	$-68.0 \pm 57.9$

## IRRADIATION PROGRAM [1]

UC Davis has two facilities[1] that could be invaluable in providing the missing information on hadron damage. The McClellan Nuclear Reactor Center (MNRC) provides a number of areas for irradiating samples with neutron fluxes up to  $4.5 \times 10^{13}$  n/cm<sup>2</sup>s. The radiation test beam at the Crocker Nuclear Laboratory (CNL) cyclotron provides protons of up to 63 MeV spread over a rather uniform beam spot 7 cm in diameter. A typical central flux is  $4.2 \times 10^9$  protons/cm<sup>2</sup>s (0.56 kRad/s (Si)). The laboratory can also produce deuteron and neutron (60 MeV) beams. Thus, both facilities are of great interest for this application.

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## REFERENCES

- [1] Maxwell Chertok, David E. Pellett(PI), James E. Spencer, James T. Volk and Zachary R. Wolf, "Radiation Damage Studies of Materials and Electronic Devices Using Hadrons", LCRD Proposal, August 2002.
- [2] R.D. Brown, E.D. Bush, Jr., and W.T. Hunter, "Radiation effects on samarium-cobalt permanent magnets", LANL Rep. LA-9437-MS, July, 1982. R.W. Blackmore, *IEEE Trans. Nucl. Sci.*, NS32(1985)3669.
- [3] R.D. Brown and J.R. Cost, "Radiation-Induced Changes in Magnetic Properties of Nd-Fe-B Permanent Magnets", *IEEE Trans. Magnetics* 25(1989)3117-3120. See also: J.R. Cost, R.D. Brown, A.L. Giorgi, J.T. Stanley, *IEEE Trans. Magnetics* 24(1988)2016.
- [4] A.F. Zeller, "Radiation Damage Mechanisms in NdFeB Magnets", 11th Int'l. Workshop on Rare-Earth Magnets, October, 1990. Also, A.F. Zeller and J.A. Nolen, 9th Int'l. Workshop on Rare-Earth Magnets, October, 1987.
- [5] O-P.Kahkonen, S.Makinen, M.Talvitie, H.Rajainmaki, M.Manninen, "Temperature Dependence of Irradiation-Induced Magnetic Flux in Nd<sub>2</sub>Fe<sub>14</sub>B Permanent Magnets", *Europhys. Lett.*, 12(1990)413. Also: O-P Kahkonen, S. Makinen, M.Talvitie, M.Manninen, "Radiation Damage in Nd-Fe-B Magnets: Temperature and Shape Effects", *J. Phys. Cond. Mat.*, 4(1992)1007.
- [6] S. Okuda, K. Ohashi, N. Kobayashi, "Effects of electron-beam and  $\gamma$ -ray irradiation on the magnetic flux of Nd-Fe-B and Sm-Co permanent magnets", *Nucl. Inst. Meth.*, B94(1994)227. For bremsstrahlung see: Henry B. Luna, Xavier K. Maruyama et al., "Bremsstrahlung Radiation Effects in Rare Earth Permanent Magnets", *Nucl. Inst. Meth.*, A285(1989)349.
- [7] Yoshifumi Ito, et al., "Magnetic flux loss in rare-earth magnets irradiated with 200 MeV protons", *Nucl. Inst. Meth.*, B183(2001)323.
- [8] This is understandable because the information on x may be proprietary and activation for trace elements may create handling problems. Still, such information suggests thermal neutrons are important: see G. Gross et al., "Experience with the SLC Permanent Magnet Multipoles", EPAC'94, London, June 1994 and Ref. [3].
- [9] M. Baltay et al., "Comparison of SmCo and NdFeB in PM Multipoles", PAC'87, Washington, D.C, March 1987.
- [10] Blackmore's data at 500 MeV[2] shows another problem because it implies  $p(200 \text{ MeV}) > p(500 \text{ MeV})$ . While cross sections decrease with energy, the energy transfer increases e.g.  $T_{ion}^{Max}(500) \approx 30 T_{ion}^{Max}(20)$  for B, Fe and Co ions while  $T_{ion}^{Max}(B) \approx 4.5 T_{ion}^{Max}(Fe, Co)$  making usual "displacement" damage hardly vary while the observed damage should.