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Abstract

Many materials and electronics need to be tested for the radiation environment expected at linear colliders (LC) where the accelerator and detectors will be subjected to large fluences of hadrons, leptons and γ's over their life[1]. Examples are NdFeB magnets considered for the damping rings and final focus, electronic and electro-optical devices to be utilized in detector readout and accelerator controls and CCDs required for the vertex detector. Effects of γ's on many materials have been presented[2] and our understanding of the situation for rare earth permanent magnets at PAC2003[3]. Here we give first measurements of the fast neutron, stepped doses at the UC Davis McClellan Nuclear Reactor Center (UCD MNRC) together with the induced radioactivities. Damage appears to be proportional to the distances between the operating point and H_{ci}.

INTRODUCTION

This work is a continuation of work reported recently at NSREC[2] and PAC'03[3, 4]. It has the general goals of improving efficiencies of systems such as LCs over their lifetimes and providing us a predictive understanding of radiation damage mechanisms based on more controlled and systematic experiments. Here we provide first results for a study[1] of the effects of fast neutrons on $Nd_{2-x}Fe_{14}B$ blocks where x represents substitution of other rare-earths such as Dy, Pr or Tb. Previous studies[5] have shown these substitutions improve H_{ci} with a high linear correlation of 0.96 as well as radiation resistance (RR) with a correlation of 0.87 and thus, a good correlation of 0.78 between RR and H_{ci}. While temperature was controlled, neither T_s, the stabilization T, nor the effective operating point or load-line were specified although the magnets were in an essentially open circuit configuration. Such questions were addressed in [3] where a new type of two-pole, offset quadrupole was proposed to test the interplay between the H_{ci} of an unloaded block and its loaded, operating point in magnetic circuits which can vary quite dramatically - even over a single PM block in a magnetic multipole[6].

The UCD MNRC has a number of areas for irradiating samples with neutron fluxes up to $4.5 \cdot 10^{13}$ n/cm^{2}s. We used a specialized area that allows irradiation with 1 MeV equivalent neutrons with fluxes up to $4.2 \cdot 10^{10}$ n/cm^{2}s while suppressing thermal neutrons and γs by large factors where we irradiated individual blocks and magnets as just described [3]. Below, we describe our specific use of the reactor, the measurements and our first results.

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LOGISTICAL AND OTHER PROBLEMS

In reviewing experiments in this area, some common characteristics emerge that explain both the difficulty and the lack of many systematic, carefully controlled experiments [3]. In fairness, even a brief consideration by anyone wanting to carry out such a program leads one to conclude they probably shouldn't attempt it because there are too many questionable and hard to control circumstances such as the difficulty of handling and measuring the PM test materials even when they are not radioactive. Among other things, this implies that a considerable number of people must be involved in their handling before any data point is ever added to a graph. At each step there is ample opportunity to damage the blocks or change their magnetic properties in ways totally unrelated to radiation damage e.g. most frisking detectors or monitors have steel components that can easily lead to chipped or broken blocks.

While there are many problems, there are also many potential uses. We discussed the importance of this work for accelerators[1, 2, 3] but there are opportunities in materials research such as defect and domain manipulation e.g. there is evidence that so-called "damage" improves $|M|$ after remagnetization.

CHOICE OF PM BLOCKS & MAGNETS[3]

Among others, we used isolated (open circuit) Shin-Etsu blocks of N50M and N34Z in Fig. 1 for a wide variation in characteristics. In magnets, PM dipoles should be less susceptible to damage followed by undulators, wigglers, and quadrupoles due to variations in $\vec{M}$ over different block types *and* especially variations in $\vec{H}_{ext}$[6].

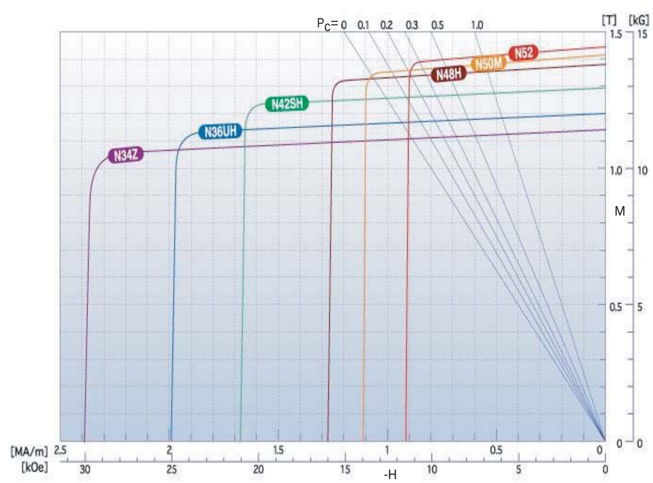

Figure 1: Demagnetization curves explaining block choice.

This is clear from Fig. 2 of [3] and especially Fig. 4 of [6] and explains our design of an asymmetric quadrupole with simple dipole geometry – shown in [3] for a large gap $G \geq l_x, l_y, l_z$ of the included PM blocks. Four magnets with gaps G=2,3,5 & 7 mm were made with one small and two large blocks with l_z=9 mm, l_x=5.9 and l_y=6.8,9 mm. All blocks were Nickel coated $Nd_2Fe_{14}B$.

The load-line of the lowest block goes well into the first B-H quadrant (from the field of the adjacent block and circuit) and is nearly the same throughout the block while its matching partner at the top has material that is in the second quadrant as does the smaller block adjacent to the lower 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. Much of this depends on the magnetic circuit more than the block dimensions or the material. This is one reason we measured the block magnetizations several times after first assembly and disassembly. Clearly, the iron closing the circuit is too bulky in [3] so this was made much thinner than the enclosed blocks.

RADIATION MEASUREMENTS

UC Davis has two facilities[1] that could be invaluable in providing the missing information on hadron damage. The MNRC provides a number of areas for irradiating samples with neutron fluxes up to 4.5 x 10^{13} n/cm^{2}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 x 10^9 protons/cm^{2}s (0.56 kRad/s (Si)). The laboratory can also produce deuteron and neutron (60 MeV) beams. Thus, both facilities are of great interest. Here, we used the MNRC 1 MeV equivalent neutron facility NIF as well as their Ge detector based γ-spectroscopy setup.

Radiation Monitoring

Several methods were used to control and monitor the radiation dose and temperatures that the various PM blocks and magnets were subjected. First, a low power level of 350 kW was set for the MNRC reactor to control heating, dose rate and uniformity of dose. The containment vessel was rotated with a five-sided holder to keep the magnets well isolated from one another and provide dose uniformity. The first run was for 23 minutes and contained an unused neutron/photon dosimeter pair consisting of a PIN diode for the neutron dosimetry that is orders of magnitude more sensitive to neutrons than gammas and MOSFET photon dosimeters where the reverse situation obtains[7]. In addition to these detectors that were measured before and after each run, two sulphur tablets were included whose radioactivity was measured to determine average fluence for each run. Table 1 shows the results for our first three runs.

Magnetic Measurements

For individual blocks and our kinds of magnets, we made a special Hall probe fixture to do field scans in combination with Helmholtz magnetization measurements. Some typical magnetization measurements and field scans along z were given in Fig. 3 and Tables 1–2 of [3]. Table 1 and Fig. 2 give our measurements for the blocks irradiated here. The larger blocks are now at top(#7) and bottom(#5) (Fig. 2). Easy axis strength errors are small and repeatable even for the small blocks. Damage $\delta\mathbf{M}_y/\delta\mathbf{D}$ is in G/Gy.

Table 1: Initial magnetizations for irradiated blocks.

Block #	$\mathbf{M}_x$[G]	$\mathbf{M}_y$[T]±[G]	$\mathbf{M}_z$[G]	$\delta\mathbf{M}_y/\delta\mathbf{D}$
7 (top)	167	1.0904±7	483	-1.6
3 (mid)	-414	1.0950±5	343	-1.2
5 (bot)	-444	1.0727±7	283	-0.7
N34Z1	-382	1.1102±2	-382	-0.4
N50M1	-144	1.3717±1	-2.8	-1.4

Figure 2 implies that fast neutron damage is proportional to dose but depends on the disposition of the effective load lines relative to the nonlinear part of the hysteresis curve. The two biggest blocks bracket the smaller one and the variation of the damage with dose is twice as bad for #7 as for #5. We note that Run 1 is with no irradiation (Table 1), Run 2 saw an irradiation in End Station A at SLAC, Run 3 saw $9.7{\cdot}10^{12}$ n/cm^2, and Runs 4 and 5, $1.9{\cdot}10^{13}$ n/cm^2 each at MNRC for a total of 35 Gy of 1 MeV-Si equivalent there with $|\delta\mathbf{M}_y/\delta\mathbf{D}| \leq$ 1.6 G/Gy. Stepped doses are continuing.

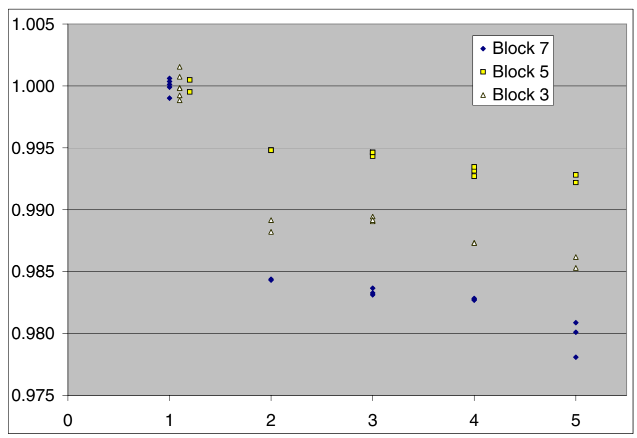

Figure 2: Magnetization loss versus radiation run number.

Radioactivity Studies

While it is known that binary Sm_xCo_y compounds are more radiation resistant than those of NdFeB, they also tend to be weaker, more expensive and can become quite radioactive e.g. through the large neutron capture cross section going to Co^{60} [8] having a 5.3 year half-life. Nevertheless, they may often be the preferred choice – especially if damage is important. NASA recently awarded a contract to study radiation and thermal stability effects for SmCo in space applications.

In contrast, NdFeB is generally cheaper and stronger but less radiation resistant with radioactivity characteristics that are not as well understood esp. when doped with other rare earth substitutions. Those candidates are not generally considered from the latter standpoint. They also tend to be proprietary and changing e.g. Shin-Etsu considers N34Z to be a 5^{th} generation material that is still under development while N50M is described similarly but as 6^{th} generation. They would not disclose their compositions.

There are several characteristics of rare earths that are of interest here. One, $_{61}$Pm, has no stable isotope and only the Z,N=odd,even elements have isotopes with 100 % stable fractions e.g. $_{59}Pr^{141}$, $_{65}Tb^{159}$, $_{67}Ho^{165}$ and $_{69}Tm^{169}$. The others, with the exception of La, Eu and Lu with two apiece have many isotopes with $_{60}$Nd, $_{62}$Sm, $_{64}$Gd and $_{66}$Dy each having seven with Nd running from A=142-150.

Neodymium is typically 17-31 % by weight, Iron 66-68 % and Boron about 1 %. Still, different models[5, 9] suggest Boron is the major factor in demagnetization. It has two stable isotopes (A=10 & 11) with $_5B^{10}$ the worst because of its lighter mass and very large neutron capture cross section of 3.8 kb while $_{64}Gd^{157,155}$ has 242,61 kb and $_{66}Dy^{164}$ has 3 kb. A major difference is that we expect B^{10} can lead to permanent magnetization loss whereas the others lead to similar, stable, substitution isotopes.

Table 2 gives results for three different types of blocks from our first 43 min run in NIF taken before shipping and magnetic measurements to obtain trace elements as well as sources and levels of radioactivity. While "Ref" refers to a 3-block magnet (#3, 5 & 7 in Table 1) with a thin iron return yoke, the overall volumes of material and their geometries in the 3 samples were comparable to obtain uniformity of dose throughout their volumes. Similarly, all blocks were Ni plated. For completeness, we note that Fe has 4 stable isotopes ranging from A=54-58 with $_{26}Fe^{56}$(91.7%) while Ni has 5 ranging from A=58-64 with $_{28}Ni^{58}$(67.9%).

Table 2: Radioactive species by count rate.

Element $_ZX^A$	Decay Prob.^{a}	Energy [keV]	Block Type^b N34Z	N50M	Ref
$_{65}Tb^{160}$	0.270	298.6	47.6	26.5	-
$_{65}Tb^{160}$	0.168	879.3	28.4	15.6	-
$_{65}Tb^{160}$	0.127	966.1	22.3	12.4	-
$_{65}Tb^{160}$	0.130	1177.9	11.9	6.5	-
$_{27}Co^{60}$	1.000	1173.2	2.8	2.4	2.4
$_{27}Co^{60}$	1.000	1332.4	2.6	2.1	2.2
$_{61}Pm^{151}$	0.229	340.1	2.6	3.1	2.4
$_{60}Nd^{147}$	0.280	91.2	2.3	2.8	1.7
$_{60}Nd^{147}$	0.131	531.0	2.1	2.6	2.0
$_{61}Pm^{151}$	0.088	167.8	1.2	1.4	1.1
$_{61}Pm^{151}$	0.072	275.3	1.0	1.3	1.0
$_{61}Pm^{149}$	0.031	285.9	0.9	1.4	1.0
$_{25}Mn^{54}$	1.000	834.8	0.3	0.3	1.0
$_{26}Fe^{59}$	0.565	1099.2	0.3	0.1	0.3

^{a}Taken from [10]. ^{b}Resized blocks from Sumitomo Metals, Ltd.

Essentially all of the observed lines have been identified but a number were not tabulated to save space e.g. some Tb^{160} levels with higher rates than Co^{60} were left out because they don't affect our conclusions. 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. It follows from Table 2 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 RR.

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