Summary of Radiation Damage Studies on Rare Earth Permanent Magnets

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With the proposed use of permanent magnets for both the NLC and VLHC the issue flux loss due to radiation damage needs to be fully understood. There exist many papers on the subject. There are many difficulties in drawing conclusions from all of these data. First there is the difference methods of dosimetry, second different types of magnets and magnetic arrangements, and third different manufactures of magnet material. This paper provides a summary of the existing literature on the subject.

1. Introduction

Rare Earth Permanent Magnets (REPM) have been widely used in accelerators since the early 1980s. Wigglers, Undulators and Quadrupoles have been used in light source and damping rings. Currently there are proposals for permanent magnet quadrupoles for use in the NLC [1] and the VLHC [2]. The advantages of permanent magnets are zero operating costs and reduce capital costs by eliminating power supplies can cables. The main disadvantage is the loss of strength of the magnets due to radiation damage.

2. Literature

There have been many studies and papers published regarding radiation damage. Roger Carr and Andy Ringwall [3] of SLAC have collected a list of such papers. These can be found at: `http://www-project.slac.stanford.edu/lc/local/notes/dr/Wiggler/wiggler_rad.html` These papers are concerned with radiation damage in Rare Earth Permanent (REP) magnets, both Samarium Cobalt and Neodymium Boron Iron. There is a wide variety of sources from the US, Europe and Japan. Most of these studies were instigated by accidental exposure of magnets to beam. Some of the papers are systematic studies of radiation exposure to magnetic material. Some report on dosimetry and other on exposures to magnets in accelerators.

3. Magnet Manufacturing

All REPM magnets are made by first milling the material to a very fine powered. The particle size is on the order of microns. The proper proportions of material are mixed and water is added to make slurry. The slurry is then pressed either in a die or isostatically. During the pressing process a magnetic field is applied either parallel or perpendicular to the pressing direction. The field aligns the grains of material and defines the easy axis. The magnetic material is then sintered in a kiln and ground to the proper dimensions. The material and the processing steps all have an effect of the properties of the final magnets.

4. Measurements

Brown et al., [4] from Los Alamos and Coninckx et al. [5] at CERN did some measurements of Samarium Cobalt magnets in the early 1980's. One of the first observations was that all magnet material was not the same. Different manufactures showed different rates of demagnetization. Coninckx's group was able

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to reverse the magnetization on a sample from Vacomax after the exposure of over 10^{10} rads. Figure 1 shows demagnetization for various samples of Sm. Cobalt as reported by Coninckx. Similar results using different manufactures were reported by Brown. Coninckx used secondary spray from a target at the SPS while Brown used neutrons with energy of 0.1 to 30 MeV. The change in field observed by Brown was lower than the change observed by Coninckx. It was suggested by Coninckx that there were changes in the crystallographic structure of the material.

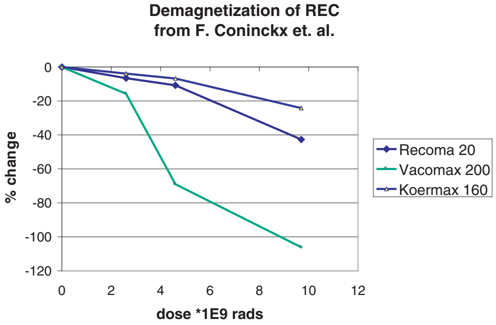

Figure 1: Demagnetization for various samples of Sm. Cobalt.

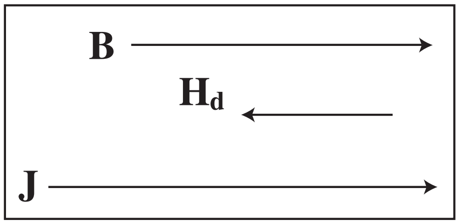

Figure 2: Fields inside permanent magnet material.

Brown also measured the change in magnetization as a function of the length versus diameter (L/D) of different samples. He made the observation that small L/D had a higher flux loss. As stated in the paper “it should be realized that the samples with the smallest L/D ratio have the highest demagnetizing field and…the highest decay rate.”

Brown also observed the replacing Neodymium (Nd A = 60) with Dysprosium (Dy A = 66) increases coercivity and resistance to radiation induced demagnetization.

Luna et al. Luna:1989 irradiated both Samarium Cobalt and Neodymiun Iron magnet with ^{60}Co and 85 MeV electrons. For 1.4 10^9 rads of ^{60}Co they observed no loss in field for either Samrium or Neodymium. For direct electron radiation they did observe a 1.5% decrease in remanence for Neodymium. In their paper they published a table of known results for different experiments.

5. Theory

Once permanent magnets are removed from the magnetizing field free poles are established and a field potential −Hd exists between the free poles [7]. The magnitude of Hd is dependent on the geometry of the magnet and $B = J -$ Hd (see Figure 2). Hence there is always a demagnetizing field present in permanent magnets.

O-P Kähkönen et al. [11] theorized that knock on particles would raise the temperature in a local area of the lattice above the Curie point and if there was a sufficient demagnetizing field present then the spins can flip and a new domain can be created with a field direction opposite to the rest of the magnet. This can have a cascading effect since there is now a larger demagnetizing field present. Starting from Laplace’s equation for heat flow and using a Greens function they give the temperature required to heat a sphere of radius R as

$$T_1 = T_o + (T_c - T_o)\left(2\pi R^2/3d^2e^{-1}\right)^{3/2} \tag{1}$$

where d^3 is the volume of one atom. The energy of the knock on atom is then

$$E = 3/2kB(T_1 - T_o). \tag{2}$$

If a sufficient number of domains are flipped then there will be a measurable loss in magnetic field. The parameterization they give is

$$\Delta M/M = 2V_{\text{grain}}/V_{\text{sample}}P\,Np \tag{3}$$

where $P = n\sigma L$ (L the sample thickness) and Np is the number of incident particles. The amount of demagnetization depends on the grain size of the material and how the material was manufactured. This

Table I Summary of Radiation Damage from Luna et al.

Sample	Alloy	Type of Irradiation	Maximum Dose Grad	Remanence loss %	Hc kOe	Hci kOe
CERN 1983 [6]						
RECOMA 20	REC$_{o5}$	400 GeV protons	9.70	-42.70	8.8	30.0
VACOMAX 200	SmCo$_5$		10.400	-106.10	8.9-9.5	12.5-19.0
KOERMAX 60	SmCo$_5$		11.400	-24.20		
Krupp WIDIA	Sm$_2$Co$_{17}$		10.500	-2.60		
TRIUMPH 1985 [8]						
HICOREX 90B	SmCo$_5$	500MeV protons	3.02	-13.50	8.2	>1.5
HICOREX 96B	(SmPr) Co$_5$		1.53	-6.50	8.8	1.5
CRUCORE 18	SmCo$_5$		5.81	-1.64	8.4	16.0
CRUCORE 26	Sm$_2$Co$_{17}$		5.94	-0.30	9.6	10.0
NeIGT 27	Nd-Fe-B		0.003	55.40		17.0
LANL 1986 [9]						
CRUMAX 282	Nd-Fe-B	Gamma	48.8Mrad	-0.00	10.8	28.2
NeIGT 27	Nd-Fe-B		48.8 Mrad	-0.00		
			Max fluence x 10^8 n/cm$_2$			
LANL 1982 [10]						
HICOREX 90B	SmCo$_5$	800 Mev protons to produce neutrons	1.10	-1.88	8.2	>1.5
HICOREX 96B	(SmPr) Co$_5$		1.20	-2.21	8.8	1.5
LANL 1986 Omega west reactor [9]						
CRUMAX	Nd-Fe-B	Reactor neutrons	2.50	-79.10	10.8	28.2
NeIGT 27H	Nd-Fe-B		2.50	-86080		17.0
HICOREX 94B	Nd$_2$Fe$_{14}$B		3.80	-14.00		
INCOR 18	Sm$_2$Co$_{17}$		2.60	-0.00		
INCOR 22HE	Sm$_2$Co$_{17}$		2.60	-0.20		

explains the differences between REPM made by different manufactures. If the grain size is different due to the manufacturing process then the changes in the remanence will vary.

6. Observations

Finer milling of the material would produce a smaller grain size. This explains the different demagnetization curves for different manufactures. Magnetic material in the presence of an external demagnetizing field would experience more radiation damage than the same material with no demagnetizing field. A defect in most studies is the irradiation of free bricks instead of magnets in a circuit. Free bricks will be more susceptible to demagnetizing fields than bricks in a magnetic circuit. While it is not good practice, it is possible to design a magnet with internal demagnetizing fields. In magnet designs keeping the load line far away from the knee of the demagnetization curve is an important consideration. Magnet material with a large coercivity is desirable for use in permanent magnets. This will help to keep demagnetizing fields as low as possible.

7. Tests

To test Kähkönen theory two magnets with a known load line one with high coercivity material and another with lower coercivity material should be built and irradiated until a noticeable change in the field is observed. The lower coercivity magnet should show loss in field with less radiation than the higher coercivity magnet. The magnets should then be disassembled and the magnetic material re magnetized.

The field after re-magnetization should be the same as the original field. Similar magnets should also be built and not irradiated to measure the effects of aging in the magnetic system. The manufacture of the magnetic material should be carefully controlled at all steps to ensure uniform and small grain size.

8. Conclusion

The model of Kähkönen with a dependence of demagnetization on grain size can explain the different rates of demagnetization as seen by many experiments. The idea of local heating exceeding the Curie temperature and allowing for flipping of the magnetic domains also explains why Dy is better than Nd for radiation hardness. A heavier element will resist flipping direction. For any radiation damage study to be meaningful it should be done on complete magnet with a known load line. Testing of individual bricks will not necessarily indicate how magnet will perform in a given situation. In addition the temperature rise caused by radiation should be minimized so that heating of the material does not fake a radiation induced signal.

References

[1] Next Linear Collider, TO Raubenheimer, "Overview of the X Band R&D Program," submitted to this conference and "Progress in the Next Linear Collider Design," SLAC-PUB-8672, October 2000

[2] Very Large Hadron Collider design guide `http://www.vlhc.org/`

[3] Carr and Ringwall, `http://www-project.slac.stanford.edu/lc/local/notes/dr/Wiggler/wiggler_rad.html`.

[4] RD Brown and JR Cost, *IEEE Trans on Magnetics* **25** No. 4, July 1989, 3117.

[5] F Coninckx, et al., CERN/SPS 83-1 TIS-RP/IR/83-07.

[6] HB Luna, *Nuclear Instruments and Methods in Physics research* **A285**(1989), 349.

[7] From RJ Parker, PMG-88, Magnetic Materials Producers Association `http://www.mmpa.org/`.

[8] EW Blackmore, *IEEE Trans Nucl Sci* **NS-32**(1985).

[9] JR Cost, Los Alamos National Lab Report LA-UR 87-1455 (1987).

[10] RD Brown, Los Alamos National Lab Report, LA-9437-MS (1982).

[11] O-P Kähkönen, *J Phys Condensed Matter* **4**(1992), 1007.