MEASUREMENT OF PERMANENT MAGNET MATERIAL DEMAGNETIZATION DUE TO IRRADIATION BY HIGH ENERGY ELECTRONS [*]

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Abstract

Demagnetization of NdFeB permanent magnet (PM) samples delivered by the Stanford Magnets Company, has been measured as a function of radiation dose induced by high energy electrons. The 5GeV electron beam from 12GeV Cornell Synchrotron was used as a radiation source. Calorimetric technique was employed for radiation dose measurement.

Experimental data demonstrated strong correlation between susceptibility to demagnetization induced by radiation and temperature. The correlation was described by an exponential function with two parameters acquired from the data fitting.

The obtained results will be used for evaluation of ERL IDs performance degradation rate under expected operation conditions. Experimental setup, measurement technique, results, analysis and conclusions are described.

INTRODUCTION

Magnetization loss of PM material caused by radiation is a great concern in the insertion device (ID) design. The strength of the ID magnetic field and, consequently, x-rays intensity and spectrum depend on the ID gap. Smaller ID gap results in stronger magnetic field, higher x-ray intensity and wider operation spectrum. All these make ID operation more efficient. However, the smaller gap increases the risk of ID radiation damage. The number of high energy electrons scattered from the electron beam and absorbed in PM material and resulting radiation dose increase rapidly when the gap size is decreased. The radiation causing PM demagnetization leads to ID performance degradation, [1]. The accurate knowledge of the PM material radiation resistivity would help greatly in optimizing ID performance while taking into account the ID's required life time and operation condition.

The measurements of dependence of radiation-induced demagnetization on radiation dose for several PM materials are described in references [2], [3], [4]. The data indicate that the demagnetization depends not only on radiation dose, but also on PM material intrinsic coercive force, sample dimensions, magnetic environment, heat treatment prior to irradiation, sample temperature at the moment of irradiation and many other factors. The complicity of the problem is well illustrated in reference [5]. The variety of factors affecting demagnetization as well as a wide spread of radiation characteristics among studied PM materials suggest that the data published to date can be used only as a general guideline. To evaluate specific ID design, one should test specific PM material in conditions close to what are expected in operation. This was the main motivation for the experiments described below.

PM MATERIAL AND THE TESTED SAMPLES PROPERTIES

In the radiation test two grades of NdFeB PM material, $N40$ and $N40SH$ from "Stanford Magnets Company", were used. These grades have different intrinsic coercive forces (see Table 1) and quite different dependencies of magnetization loss on temperature (see demagnetization curves on website *http://www.maurermagnetic.ch*).

Table 1: Characteristics of the tested NdFeB (Stanford Magnets Company) PM materials

$Grade$	$\frac{Br}{(KGs)}$	$\frac{Hc}{(KOe)}$	$\frac{Hci}{(KOe)}$	$\frac{(BH)max}{(MGOe)}$
$N40$	12.5-12.8	$\geq$ 11.6	$\geq$ 12	38-41
$N40SH$	12.4-12.8	$\geq$ 11.8	$\geq$ 20	38-41

Table 2: The tested samples properties

Sample	Dimension $W \times H \times L[in]$	Direction of mag.	Demag. tmp. ^0C
$N40, V$	$1.0 \times 0.5 \times 0.125$	0.500	62
$N40, H$	$1.0 \times 0.5 \times 0.125$	0.125	115
$N40SH, V$	$1.0 \times 0.5 \times 0.25$	0.500	129
$N40SH, H$	$1.0 \times 0.5 \times 0.25$	0.250	150

The tested samples were rectangular blocks with dimensions summarized in Table 2. Note $N40SH$ blocks were twice as long as $N40$ and the samples had two directions of magnetization. "V" type were magnetized in $0.5in$, "vertical", direction and "H" type were magnetized in the shortest, "horizontal", directions. To increase reliability of the measurement, two identical samples of each type were tested.

Column "Demag. tmp." in the Table 2 shows the temperature at which the tested samples should permanently lose magnetization. It was obtained from from 3-D magnetic field modeling and demagnetization curves at different temperature (see *http://www.maurermagnetic.ch*).

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EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUE

For irradiation, four PM blocks were stacked in assembly depicted in Fig. 1. Two ”H” and two ”V” blocks were separated by $1in$ copper spacers. The spacers were used to reduce reciprocal influence of magnetic field of the adjacent blocks.

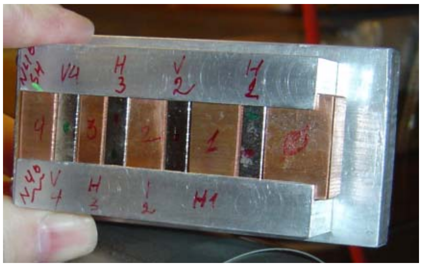

Figure 1: PM block assembly.

The assembly was attached to a straight section of the East transfer beam line connecting 12GeV Synchrotron with Cornell Electron Storage Ring. For irradiation, the 5GeV electron beam coming from the synchrotron was steered with bending magnet to the PM assembly location. Immediate response to beam radiation was an increase in temperature of assembly. This temperature variation was used for radiation dose measurement.

Radiation Dose Measurement Technique

One example of the temperature record during the irradiation cycle is depicted in Fig. 2. It shows a $\sim 5^0C$ temperature rise during period when electron beam was directed to the assembly location, (period 1), and cooling down process, (period 2), with electron beam turned off. The temperature rise is the result of radiation. Noting that the accumulated radiation dose is, in fact, the amount of energy deposited in unit of mass, one can easily find it from the assembly temperature variation.

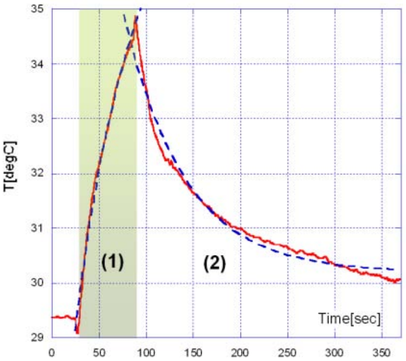

Figure 2: PM assembly temperature variation during irradiation cycle. Shaded area indicates period with electron beam turned on. Cooling occurs during period 2, with electron beam turned off. Dashed line shows fitting according to Eq. 1.

Dependence of the assembly temperature on time, $T(t)$, can be described by the equation:

$$\frac{dT}{dt} = \frac{Q}{C} - \frac{T - T_0}{\tau} \tag{1}$$

Where Q is the rate of energy deposition per unit of mass, i.e., radiation dose rate, C - material specific heat capacity, τ - cooling time constant, T_0 - the ambient temperature. Specific heat capacities for the NdFeB blocks and cooper spacers are 0.44 and 0.39 $J/g/{}^0C$. Because they differ by only 10%, one can use averaged number 0.41 $J/g/{}^0C$.

A fit of the observed temperature variation to solution of Eq. 1 (see dashed line in Fig. 2), yields cooling time $\tau = 64.5 \pm 0.97 sec$ and $Q/C = 0.131 \pm 0.001^0C/sec$. For given specific heat capacities, the energy deposition rate or the radiation dose rate, will be $Q = 0.054J/g/sec = 5.4 \times 10^3 rad/sec$. $60sec$ of irradiation time, see period 1 in Fig. 2, yield accumulated radiation dose:

$$D = 5.4 \times 10^3[rad/sec] \times 60[sec] = 0.324[Mrad] \tag{2}$$

To avoid demagnetization by temperature, the temperature rise during irradiation was purposely kept low by controlling electron beam intensity and irradiation time. To accumulate desired dose, irradiation cycles were repeated.

The Measurement Sequence

First, the magnetic moment of each PM block was measured with Helmholtz coil apparatus. Then blocks were assembled in structure shown in Fig. 1, assembly was moved to CESR tunnel and attached to East transfer line. After irradiation, assembly was retrieved from the tunnel and taken apart, the magnetic moment of each PM block was measured again. Radiation dose was calculated from the assembly temperature variation during irradiation as described above.

RESULT AND DATA ANALYSIS

The main experimental results are presented in Fig. 3 and in Table 3. Fig. 3 shows the dependence of the PM blocks magnetization loss on accumulated radiation dose. Table 3 show the radiation doses caused 1% of magnetization loss for each type of the tested PM block obtained from the linear fit of the data shown in Fig. 3.

Results indicate that $N40, H$ samples are most sensitive to radiation demagnetization. ”$N40, V$” blocks are less susceptible. $N40SH$ grade blocks are more stable than $N40$. Qualitatively it is similar to demagnetization induced by temperature (see the end of ”PM material and the tested samples properties” section). To make comparison between these two phenomenon easier, the column with demagnetization temperatures from Table 2 was copied to Table 3.

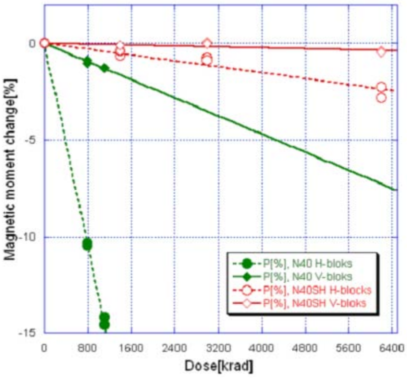

Figure 3: The measured magnetic moment change as a function of accumulated radiation dose. Solid circles and diamonds are for "H" and "V" blocks of $N40$ grade, open circles and diamonds indicate $N40SH$ "H" and "V" blocks respectively.

Table 3: Radiation doses caused 1% of magnetization loss and demagnetization temperatures.

PM Grade, Block type	Radiation dose $[Mrad]$	Demag. temp. $[^0C]$
$N40$, H	0.0765 ± 0.005	61.66
$N40$, V	0.851 ± 0.020	114.6
$N40SH$, H	2.54 ± 0.17	128.8
$N40SH$, V	11.3 ± 3.0	149.5

The obvious correlation between radiation and temperature induced demagnetizations can be explored phenomenologically. In Fig. 4 the measured radiation doses corresponding to 1% of demagnetization, $D_{1\%}$, are plotted as a function of the demagnetizing temperature, T_{dmg}. Vertical axes is in logarithmic scale. Each data point represents the tested sample. Note that the tested samples had different intrinsic coercive forces, geometry and direction of magnetization. The plot demonstrates strong linear correlation between $Log(D_{1\%})$ and T_{dmg}. A least-square fit to the function:

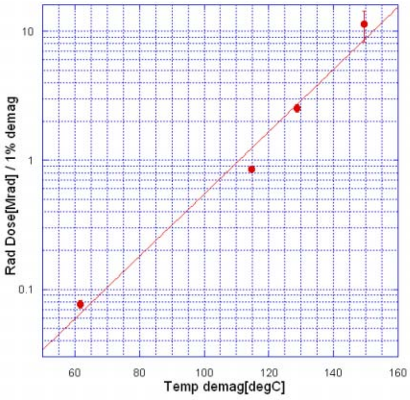

Figure 4: Radiation dose causing 1% of magnetization loss as function of demagnetization temperature.

$$Log_{10}(D_{1\%}[Mrad]) = m0 + T_{dmg}[^oC]/\overline{T} \qquad (3)$$

gives $m0 = -2.68 \pm 0.28$, $\overline{T} = 41.4 \pm 4.0$ with parameter $R = 0.991$. Using Eq. 3 one can easily find expression for the sample demagnetization, dM/M, as function of accumulated radiation dose, D, and demagnetization temperature,T_{dmg} :

$$\frac{dM}{M} = -0.01\frac{D}{D_{1\%}} = -\frac{D}{D^*} \times 10^{-T_{dmg}/\overline{T}} \qquad (4)$$

where $D^* = 0.25 \pm 0.14$, $\overline{T} = 41.4 \pm 4.0$. D is in $Mrad$, T_{dmg} is in ^0C units.

CONCLUSION

NdFeB PM samples of two different grade materials, sizes and magnetizations were irradiated by high energy electrons and their demagnetization was measured as a function of accumulated radiation dose.

The data demonstrated a strong correlation between radiation induced magnetization loss and demagnetization temperature. This correlation was described by exponent function with two parameters obtained from the data fitting.

Extending this correlation to PM assemblies, such as undulator magnets, one can first find their demagnetization temperature from 3D modeling and PM material characteristics, and then *predict* their radiation resistivity. This will be extremely helpful for ID life time estimation under given operational conditions as well as for evaluation of requirement on the residual gas density at ID location and requirement on ID radiation shielding.

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