Measurement of radiation-induced demagnetization of NdFeB permanent magnet material for ERL undulators*.

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Abstract.

The note describes measurement of NdFeB permanent magnet (PM) material demagnetization induced by high-energy electron radiation. In experiments we compared N40 and N40SH grades from Stanford Magnets Company, which have different intrinsic coercive forces. Dimensions of the tested PM blocks were close to those that will be used for ERL undulator construction. It was found that depending on direction of magnetization, N40SH grade PM blocks are suffered 1% demagnetization when irradiated with 2.5Mrad or with 11.3Mrad dose from 5GeV electron beam.

Setup, measurement technique, results and analysis are presented.

Introduction.

The radiation-induced demagnetization of PM materials is an issue of great concern in insertion device design. ID field strength and, as a result, ID spectrum and radiation intensity depend on the ID gap. Decreasing the ID gap results in a stronger field, a wider operating spectrum, and a higher radiation intensity. On the other hand, a gap reduction increases risk of ID damage due to demagnetization by irradiation by high energy electrons scattered from the beam. An example of this kind of ID damage has been well documented in reference / 1 /. Thus, knowing how radiation-induced demagnetization depends on radiation dose, one can more efficiently optimize IDs and the environment where they operate.

In references / 2, 3, 4 / are described measurements of dependence of radiation-induced demagnetization on radiation dose for some PM materials. Data obtained there indicates that the demagnetization depends not only on radiation dose, but also on many other factors such as PM material intrinsic coercive force, sample dimensions, magnetic environment, heat treatment prior to irradiation, sample temperature at the moment of irradiation and so on.

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The large variety of factors affecting demagnetization as well as a wide spread of radiation characteristics among PM materials suggest that the data found in references can only be used for strategic guidance. To get numbers, which can be used for reliable evaluation of the specific ID design, one should test PM material in conditions close to what are expected in operation. This was a main motivation for the experiments described below.

Some properties of tested PM materials.

In the radiation test were used two grades of NdFeB PM material, N40 and N40SH, from "Stanford Magnets Company". They have different intrinsic coercive forces, 12 and 20 KOe, see Table 1, which result in quite different demagnetization characteristics depicted in Fig. 1.

Grade	Br (KGs)	Hc (KOe)	Hci (KOe)	(BH)max (MGOe)	Curie Temp. (°C)	Max. Op. Temp (°C)
N40	12.5-12.8	>11.6	>12	38-41	310	80
N40SH	12.4-12.8	>11.8	>20	38-41	340	150

Table 1. Some characteristics of N40 and N40SH grades of NdFeB magnetic material used in test.

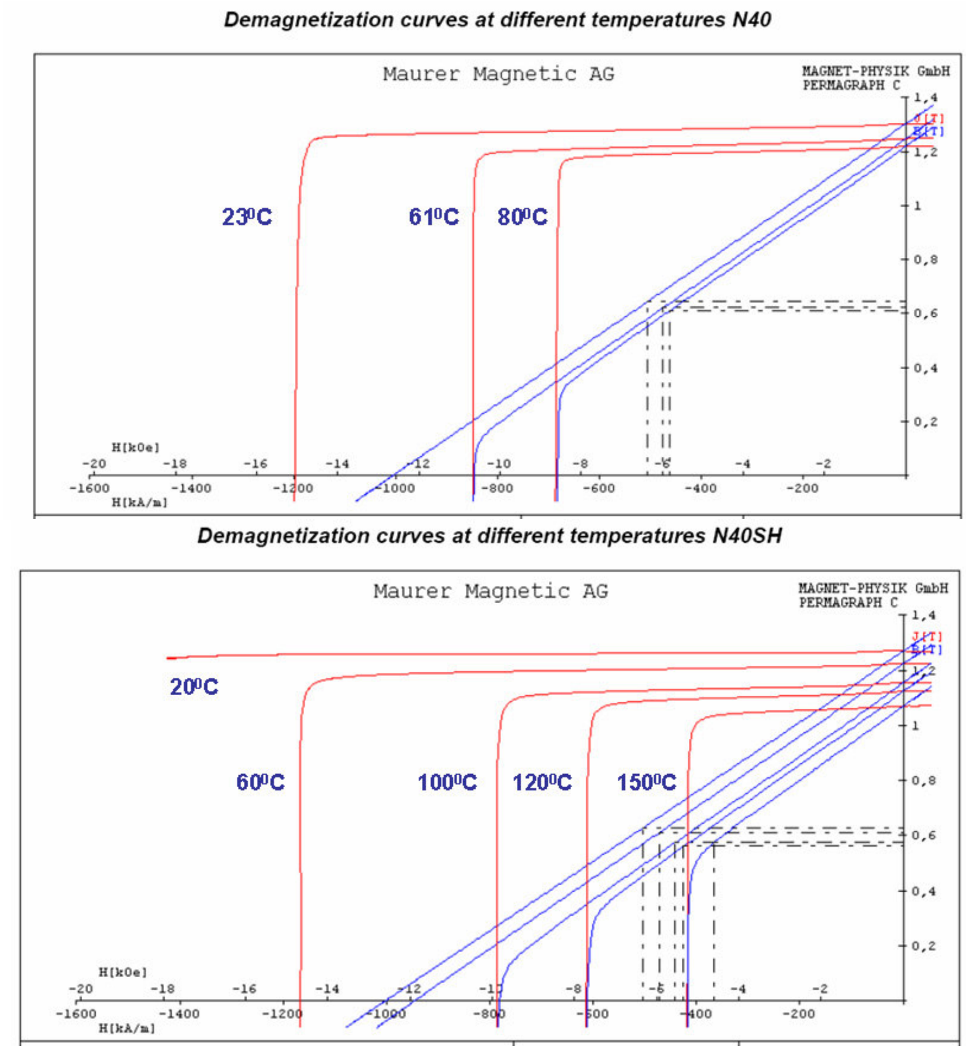

Figure 1. Demagnetization curves at different temperatures for N40 (upper plot) and N40SH (lower). Data was copied from website: www.maurermagnetic.ch

These are demagnetization curves for N40 and N40SH for different temperatures. They show intrinsic magnetic field (blue curves) and magnetization (red curves) as functions of magnetic field induction. Negative induction means that it is applied in the direction opposite to magnetization. Knees in curves indicate points where PM material becomes permanently demagnetized. The data clearly show superiority of N40SH grade. For a given temperature, N40SH is more resistant against demagnetizing field than N40; for a given demagnetizing field, N40SH can survive much higher temperature without permanent demagnetization.

In the experiments we used N40 PM rectangular blocks with dimensions 1.0x0.5x0.125" and N40SH blocks with dimensions 1.0x0.5x0.250". One of N40 PM blocks is shown in Fig. 3a. There were two types of block magnetization. "V" type blocks were magnetized in 0.5" direction. "H" type blocks were magnetized in 0.125"(N40) and in 0.25"(N40SH) directions. Magnetic field geometry for both "H" and "V" type blocks are shown on upper plots in Fig.2. Here the line directions and the line density indicate the magnetic field direction and strength. Comparing these two plots one can see that inside of “H” blocks magnetic field is much weaker than inside of “V” blocks. This difference is quantitatively shown on the lower plot of Fig.2. This plot shows magnetic field in direction of magnetization for “H” and “V” blocks as a function of y at x=0.

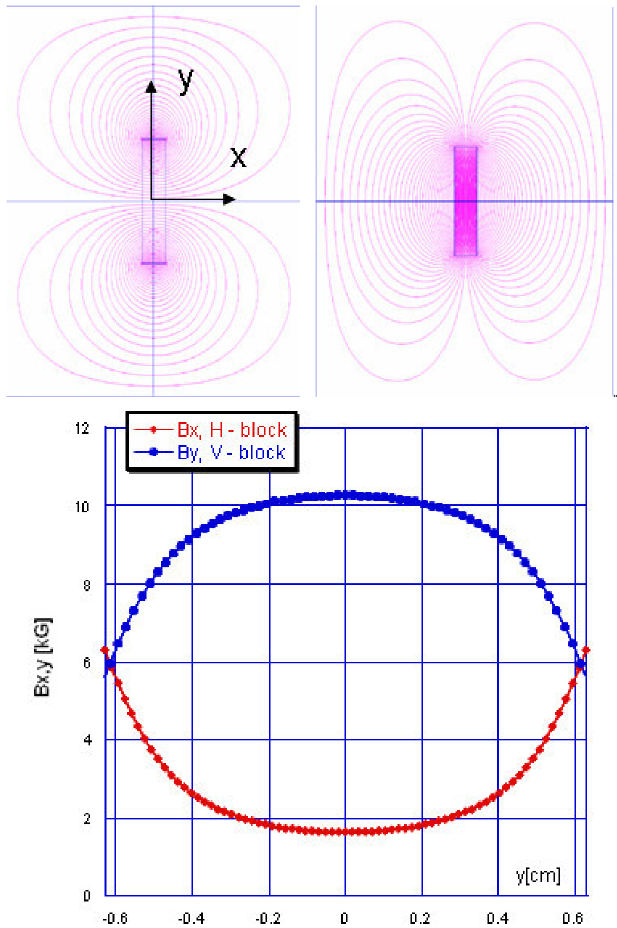

Fig. 2. Magnetic field lines, two upper plots; magnetic field strength in the direction of magnetization versus vertical position for “H” and “V” type blocks, lower plot. Calculations have been made for NdFeB 1.0x0.5x0.125” blocks of N40 grade.

The lower plot indicates that “H” blocks have 1.8kG minimum magnetic field in the center region while “V” blocks have minimum field of 6.0kG close to edges. From demagnetization curves, presented in Fig.1 (upper plot), one can expect that “H” blocks will be permanently demagnetized at temperature above 50^0C and “V” blocks at temperature above 100^0C. This difference in demagnetization temperatures is due solely to geometrical factor which in turn causes different demagnetizing intrinsic fields.

Blocks made of N40SH grade, having stronger intrinsic coercive forces, should demonstrate a higher demagnetization temperature. The aforementioned geometrical factor will likewise apply to the N 40SH material, with “V” type blocks more stable against temperature-induced demagnetization than “H” type.

Irradiation setup and radiation dose measurement.

For irradiation four PM blocks, two of “V” and two of “H” type, were assembled in structure shown on Fig. 3 (b). In order to reduce reciprocal influence of magnetic field of one block on another, blocks were separated by ~1” long cooper spacers.

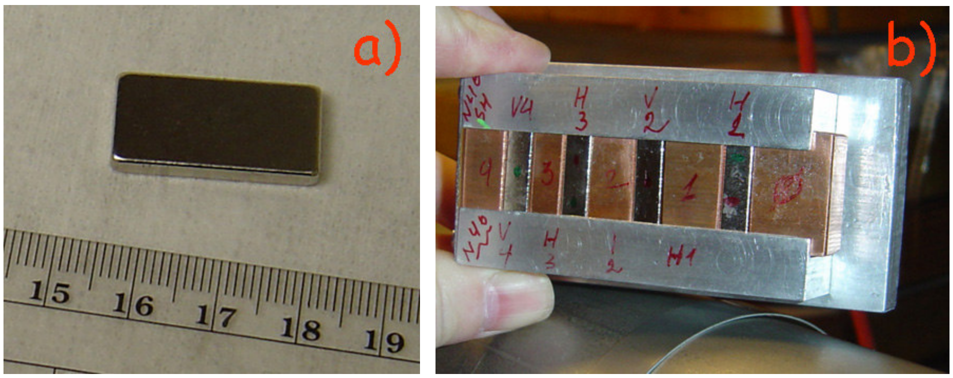

Fig. 3. Single N40 PM block (a) and N40SH PM blocks assembly (b) used in radiation experiment.

Then assembly was attached to a long straight section of the East transfer beam line connecting 12GeV Synchrotron with Cornell Electron Storage Ring (CESR), see Fig.4.

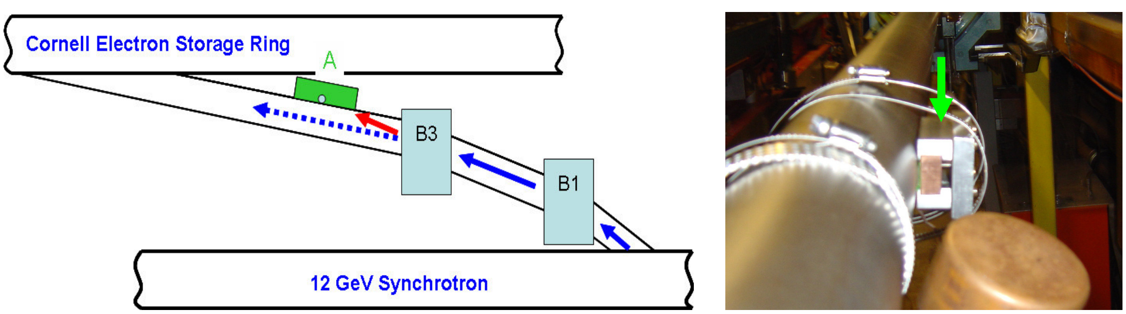

Fig. 4. East transfer beam line schematic view (left) and PM blocks assembly attached to the beam line straight section (right).

For irradiation 5GeV electron beam coming from 12GeV synchrotron was steered with banding magnet “B3” to the assembly location. Immediate response to beam radiation was the rise in assembly temperature and signal from radiation monitors positioned nearby. For assembly temperature monitoring were used two attached thermocouple sensors.

The radiation dose was determined through the analysis of assembly temperature variation during irradiation cycle. One example of the temperature record is presented in

Fig. 5. which shows a 5^0C temperature rise caused by radiation (period 1), and then cooling down (period 2).

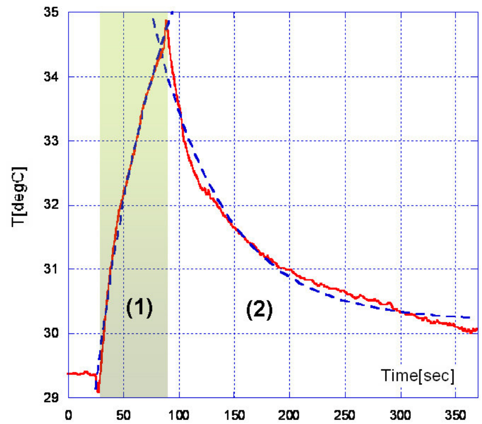

Fig. 5. Example of the assembly temperature change during irradiation cycle (solid line). Dashed line shows fitting according to expression (2) and (3), see text. Period 1 (shaded area) shows the time when electron beam was on. Here the temperature rise is due to irradiation. Cooling occurs in period 2, with electron beam off.

Noting that the accumulated radiation dose is, in fact, the amount of energy absorbed per unit mass, the dose can be found as follows:
Equation for the temperature rise during irradiation:

$$\frac{dT}{dt} = \frac{Q}{C} - \frac{(T - T_0)}{\tau} \qquad (1)$$

Where T is the assembly temperature, τ - cooling time constant, C - material specific heat capacity, Q is the rate of energy absorption per unit mass, i.e., radiation dose rate. Specific heat capacities for the cooper spacers and NdFeB PM blocks are given in Table 2.

Material	Density [g/cm3]	Heat Capacity [J/g-°C]
Cooper	8.9	0.39
NdFeB*	7.5-7.8	0.44

Table 2. Material properties, * see web-site http://www.matweb.com/.

Because they differ by only 10%, we can use averaged number 0.41 [J/g-°C] without introducing a large error. Solving equation (1), one can find expression for the temperature rise during irradiation period:

$$T(t) = T_0 + \tau \frac{Q}{C} [1 - \exp(-t/\tau)] \qquad (2)$$

and the temperature decay during cooling period:

$$T(t) = T_0 + \Delta T \cdot \exp(-t/\tau) \qquad (3)$$

A fit of the temperature during cooling (period 2 in Fig. 4) to expression (3) gives cooling time constant:

$$\tau = 64.5 \pm 0.97\,\sec$$

Putting it in expression (2) and then fitting the temperature rise during irradiation (period 1) to this expression, one can find:

$$Q/C = 0.131 \pm 0.001\ {}^{0}C/\sec$$

For C = 0.41 [J/g-°C], the radiation dose rate will be:

$$Q = 0.054\ J/g/\sec = 5.4 krad/\sec$$

For a total of 60sec of irradiation (period 1), the accumulated radiation dose is:

$$D = 0.054[J/g/\sec]\cdot 60[\sec] = 3.24[J/g] = 324\ krad$$

It should be mentioned that to avoid magnetic material demagnetization by elevated temperature, the temperature rise during irradiation was purposely kept low by controlling electron beam intensity and irradiation time. Therefore, to accumulate desired dose, it was necessary to repeat cycles. For example, Fig. 6 shows the assembly temperature during irradiation on Nov 15 2006. Here one can see 11 cycles with total dose of 3.2Mrad.

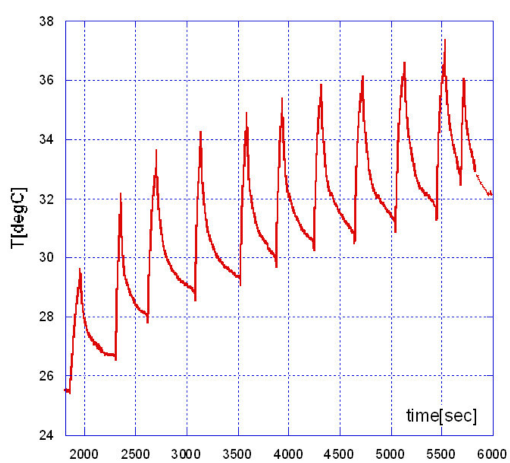

Fig. 6. Assembly temperature variation during irradiation on Nov. 15 2006. The total dose accumulated by assembly is 3.2Mrad.

Measurement procedure.

The following procedure was used to measure dependence of PM block demagnetization on irradiation dose. First, the magnetic moment of each PM block was measured with Helmholtz coil apparatus. Then blocks were assembled in structure shown in Fig. 3b, and the assembly was moved to CESR tunnel and attached to East transfer line. After irradiation, we waited a couple of days to allow residual radiation of the assembly to decay to a safe level. Assembly was then retrieved from the tunnel, taken apart, and magnetic moments of the PM blocks were measured again. Radiation dose was calculated from the temperature variation during irradiation as described above. If the change in magnetic moments was too small, the sequence was repeated.

The measurements presented in this paper have been made in October-November of 2006 during CESR operation for CHESS. All irradiations have been done in parasitic mode without disturbing CESR operation.

Experimental Results.

Experimental results are summarized in Fig.7 and Table 3. Fig.7 shows measured dependence of PM blocks demagnetization on accumulated radiation dose. Table 3 gives the linear fit result of the data shown in Fig.7.

As shown in Fig.7, "H" block of N40 grade is most sensitive to radiation. A linear fit indicated that only 0.076 Mrad will cause 1% demagnetization. "V" blocks of the same material grade are less sensitive. For 1% demagnetization they require 0.851 Mrad, i.e., 11 times more. Blocks made of N40SH grade are much more stable. A 2.5Mrad dose is required for 1% demagnetization of "H" block, and 11.3Mrad for "V" block. At a qualitative level, this is very similar to what one can expect from demagnetization induced by temperature (see discussion at the end of "Some properties of tested PM materials" section).

Two important observations can be made from the data. First, N40SH grade is 20(!) times (if "V" blocks are compared) more resistant to radiation than N40. There is no doubt that this is due to stronger intrinsic coercive forces (Hci) (see Table 1). Second, comparing "H" and "V" blocks of the same material grade, one can see that "V" blocks can sustain more radiation than "H" type. This difference is a factor of 10 for N40 and a factor of 6 for N40SH grade blocks. Thus, the intrinsic demagnetizing magnetic induction, which due to geometry is stronger in "H" blocks, plays an important role in both radiation-induced and temperature-induced demagnetization.

Uncertainties of the results, estimated from the residuals of the linear fitting are given in Table 2. The main contribution to the uncertainties was the non-constant temperature at the moment of PM blocks magnetic moment measurement. At 0.12% NdFeB magnetization change per 1^0C, a temperature variation in Annex (the location of the magnetic measurement lab) of +/-2 ^{0}C gives an uncertainty of +-0.24% in the blocks magnetic moment.

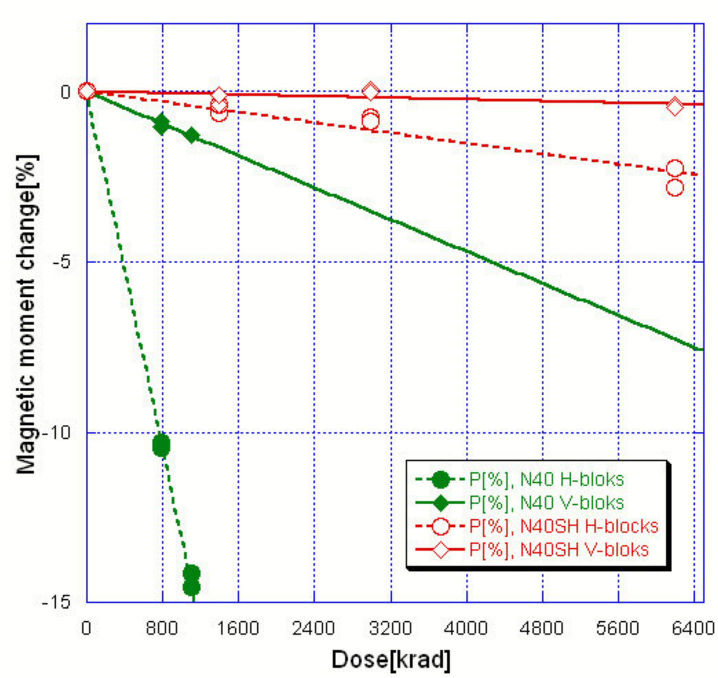

Fig. 7. The measured magnetic moment change as a function of accumulated radiation dose. Solid circles and diamonds are for “H” and “V” blocks of N40 grade, open circles and diamonds indicate N40SH “H” and “V” blocks respectively.

PM block	[Mrad] of radiation dose causing 1% of demagnetization
N40 “H” type	0.0765 ± 0.005
N40 “V” type	0.851 ± 0.020
N40SH “H” type	2.54 ± 0.17
N40SH “V” type	11.3 ± 3.0

Table 3. Result of the linear fitting of data presented in Fig. 7.

It should be mentioned that the method used for radiation dose measurement gives the dose averaged over the block volume. The measured PM block magnetic moment is also given by material magnetization averaged over the block. Assuming linear dependence of demagnetization on irradiation dose, one can find that the ratio between magnetic moment change and radiation dose obtained as described above will give the right number for demagnetization versus irradiation at scale smaller than PM block size.

Conclusion

We developed and realized a simple method for measurement of the dependence of radiation-induced demagnetization on the radiation dose. NdFeB PM blocks of a similar size and grade to what will be used for ERL undulator construction, have been irradiated in a controllable way and their magnetization loss was measured as a function of the irradiation dose.

Because the main source of the ID irradiation in ERL will be high energy electrons scattered on residual gas, PM material characteristics obtained in the measurements allow us to estimate the degradation rate of the ID performance as function of the vacuum conditions. This, in turn, will help us to evaluate requirement on ERL vacuum system and on shielding system protecting IDs from radiation.

Results of the measurements are in a reasonable agreement with data reported in reference /2/.

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