65 MEV NEUTRON IRRADIATION OF ND-FE-B PERMANENT MAGNETS

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Abstract

Rare-earth permanent magnets, while having high intrinsic qualities, are known to be highly sensitive to irradiation. Of the numerous studies carried out, most neutron irradiation experiments used reactors neutrons with a wide, but mainly low, energy spectrum. In this paper we report on an experiment carried out on NdFeB magnets with monoenergetic 65 MeV neutrons at the Takasaki Advanced Radiation Research Institute of the Japan Atomic Energy Agency.

INTRODUCTION

Rare-earth permanent magnets (REPMs) are playing a major role in accelerators where their high intrinsic properties allow for compact and flexible designs at no operating cost (no power nor cooling required), of beam transport systems [1] and light sources (the so-called insertion devices) [2]. Unfortunately, REPMs are highly sensitive to direct and scattered radiations which cause demagnetization [3]: the lifetime of these magnetic devices becomes, therefore, a major issue. As a matter of fact, even a small change in remanence in part of a magnetic element can generate higher multipoles field (thus affects the beam trajectory and/or envelope) or degrades the performance of an insertion device (critical for free electron lasers, FEL). Among REPMs, $Nd_2Fe_{14}B$, the material of choice for its high remanence ($B_{r\ max} > 1.4$ [T]), is also known to be more sensitive to radiation than the brittle and less performant SmCo magnets, Sm_2Co_{17} ($1.02<B_r<1.09$) being more radiation resistant than $SmCo_5$ ($0.75<B_r<0.95$).

Although no effect has been observed so far, radiation damage is an important issue for SPring-8, as well as for its future compact 8 GeV X-FEL source [4]. Both use in-vacuum undulators [5] where the magnets are within a few millimetres from the beam, therefore exposed to a direct hit by the electrons. In such high-energy facilities, the subsequent shower consists of a (minimum) mixture of electrons/positrons, fast photo neutrons and hard photons, whose energy spectra depend on the energy of the lost particle. For the γ and hard component of synchrotron radiation, the dose could reach the kGy/A.h [6]. For neutrons, the fluence could reach 8.1×10^{-3} n/cm^2/primary electron (for an 8 GeV electron hitting the RF-finger Cu block placed before the in-vacuum undulator) [7]. Knowing the damage threshold of a given magnetic material for a given particle dose or fluence and energy is therefore of crucial importance.

Numerous studies have been carried out to clarify the demagnetization mechanism or to test magnetic materials for a particular application under specific conditions of irradiation (particle, temperature, etc.) or magnetic arrangement (permeance P_c, direction of magnetization with respect to the beam, etc.) [3]. It was shown that the higher the permeance or the intrinsic coercivity, the higher the radiation resistance of a given sample is. The direction of the magnetization with respect to the incoming beam also proved to be important for protons [8] and electrons [9]: magnets with their magnetization perpendicular to the incoming beam are less sensitive than those with their magnetization parallel to it. The effect of irradiation was also shown not to depend on the accumulated dose but on the nature and energy of the incident particle, which defines the interaction process in the material, and the nature of the shower.

While there have been many neutron irradiation experiments so far, most were carried out at reactors, were neutrons have a wide, but mainly low, energy spectrum, in other words far from what can be expected in an accelerator. A few were done at spallation sources, with a high energy tail but a peak at low energy (1~15 MeV). For NdFeB magnets, fluences ranged up to 10^{18} n/cm^2 (Fig. 1). Only one experiment was made with monoenergetic neutrons, but, again, at a relatively "low" energy (14 MeV) and for a fluence up to 36 10^{12} n/cm^2 [11]. Our objective was therefore to study the effect of mono and highly energetic neutrons, and check the effect of the direction of magnetization with respect to the neutron beam. Irradiation was carried out at the AVF cyclotron in the Takasaki Ion Accelerators for Advanced Radiation Application (TIARA) facility of the Japan Atomic Energy Agency (JAEA) [12].

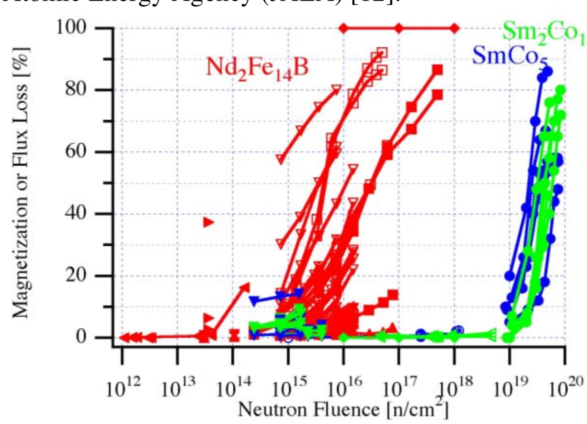

Figure 1: Flux or remanence loss as a function of the neutron fluence [10].

EXPERIMENTAL SET-UP

Magnets

Since radiation resistance is known to strongly depend on the magnet properties, four different types of NdFeB permanent magnets representing a wide range of characteristics (a 1.6 factor in energy product, and more than a factor 2 in coercivity) have been studied:

Neomax™ 27VH, 32AH, 35EH and 44H, Neomax™ 35EH being the material used in the SPring-8 in-vacuum undulators. Table 1 gives the remanent field B_r, minimum intrinsic coercivity H_{cJ} and energy product $(BH)_{max}$ of each magnet. The samples were 8x8x8 mm^3 in size and coated with 5μm TiN to protect them from corrosion and oxidation. The permeance is 3.1 [13], or 2.2 [14] when averaged over the magnet, the effect of the neighbouring magnets being negligible (within a few tenth percent).

Table 1: Magnet characteristics [15].

Name Neomax™	B_r [T]	H_{cJ} min [kA/m]	$(BH)_{max}$ [kJ/m^3]
27VH	1.02 ~ 1.10	2864	199 ~ 231
32AH	1.12 ~ 1.2	2626	246 ~ 279
35EH	1.17 ~ 1.25	1989	262 ~ 295
44H	1.3 ~ 1.36	1273	326 ~ 358

Sample set-up

Each magnet was clamped on an individual holder. The five samples where then mounted on two water cooled aluminium frames to keep the magnet temperature constant during irradiation and insure that demagnetization would not be caused by thermal heating of the sample (Fig. 2). The magnet temperature kept at 25ºC during the whole irradiation. The effect of the direction of magnetization with respect to the neutron beam was also studied. The four samples closest to the neutron source (27VH, 32AH, 35EH and 44H) had their magnetization parallel to the direction of the neutron beam. For the far off one (35EH), it was perpendicular.

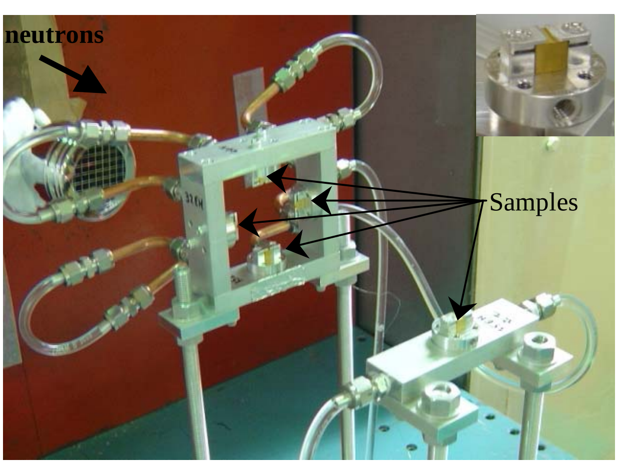

Figure 2: Experimental Set-up: The magnets are mounted on a water-cooled aluminium frame. The neutron port is on the upper left side of the picture. Inset (top right): An individual magnet in its holder.

Neutron Source

The experiment was carried out on the TIARA LC beamline. The 65 MeV protons of the AVF cyclotron hit a 5 mm lithium target to produce 65 MeV neutrons (Fig. 3). With a proton a current of 1.6p μA, the typical neutron flux was ~ 2.5 10^4 n/cm^2/s in our experiment.

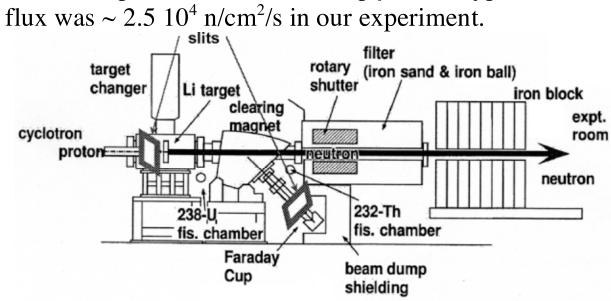

Figure 3: The TIARA neutron spallation source.

Irradiation and Magnetic Measurement

The magnets were irradiated for a total of ~ 26 hours, in steps ranging from 2 to 6 hours. After each irradiation, the magnet samples were left to "cool down" to an activation level safe for handling (typically 30 minutes). Then, they were taken to a separate room for magnetic measurement. The magnets were set on an aluminium water-cooled holder (room temperature), allowing for the magnet temperature to stabilize in order to avoid any thermal artefact (magnet temperature: 25ºC). The same water channel was used to regulate the temperature of the copper casing holding the hall probe. Each magnet was set in the copper holder, and the magnetic field was measured. The repeatability error over one hundred measurements of the same magnet was less than 0.1%.

RESULTS

The change in magnetic field as a function of the neutron fluence is shown in Fig.3: The difference in fluence between the samples comes from the difference in distance from source to sample (~ 20 cm). No demagnetization was observed within the realm of experimental errors up to a fluence of 2.4 10^9 n/cm^2 for the foremost magnet (magnetization parallel to the neutron beam), and up to 2.2 10^9 n/cm^2 for the far off one (magnetization perpendicular to the neutron beam).

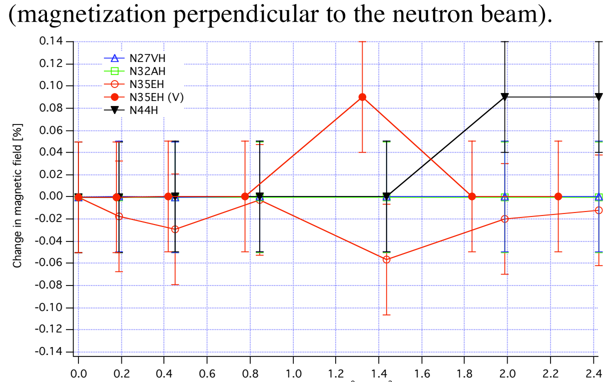

Figure 3: Change in magnetic field as a function of the neutron fluence. (V) indicates the far off vertical magnet.

DISCUSSION

Neutrons demagnetization experiments on REPMs cover a wide range of sources, materials and experimental conditions making any direct comparison difficult [10].

This is especially true for reactors, where the neutron spectrum characteristics are usually not given. As such, experiments with a well-defined neutron spectrum, or with mono-energetic neutrons offer a valuable benchmark. The experiment by Kawakubo et al. [16] with 14 MeV neutrons was the only one done so far. The magnets tested (also from Neomax with a coercivity ranging from 880 to 2400 kA/m, P_c = 1.2) showed flux losses from 37 to 1% respectively at a fluence of 3.64 10^{13} n/cm^2. For N44H, also studied here, the loss was 6.4% at 3.64 10^{13} n/cm^2.

Other results for NdFeB on sources with known characteristics, include a study on magnet N38H (B_r ~ 1.2 T, H_{cJ} =1353 kA/m, P_c ~ 0.3) with a ^{252}Cf source (peak at 1 MeV) showing a loss from ~2 10^{13} n/cm^2 [17]. A study on a spalliation source (peak at 15 MeV), but on magnets of unknown characteristics (P_c ~ 0.5), gave a high loss (17%) from 1.6 10^{13} n/cm^2 [18]. The results by Chen et al [19] demonstrate the importance of temperature control during irradiation experiments on REPMs, especially at high neutron flux: the local temperature can rise above the Curie temperature if the neutron flux is too high. In such a case, losses due to the rise in temperature can be mistaken for "true" radiation damage losses. Finally, on the low energy side, it should be noted that no effect has been observed so far for thermal neutrons.

Explanations for the demagnetization process have been proposed by several authors. The loss of magnetization is not related to the amount of physical damage (displacement, ionization or transmutation) in the magnet. Charged particles (electrons, protons, ions) exchange energy with the lattice through Coulomb interaction, raising the temperature locally (thermal spike): when the conditions are right (opposite field, low P_c, low Curie Temperature or low coercivity, etc.), a local domain can be flipped over, decreasing the magnetization locally. Neutrons, like photons, do not interact directly: it is the primary knock-on atom kicked out by the high-energy neutrons, which will cause the thermal spike [20]. For neutrons, the energy of the knock-on atom can reach a few MeV or more, the lighter boron atom being the more energetic knock-on [21]. Since the energy of the knock-on is proportional to the energy of the incident neutron (mono-energetic case), and considering the results by Kawakubo [16] and those obtained here, one can expect that a minimum fluence in the 10^{11}~10^{12} n/cm^2 range is necessary to observe any effect, especially with high P_c or high coercivity magnets.

SUMMARY

We were able to confirm that neutrons with an energy up to 65 MeV do not affect NdFeB magnets with a coercivity > 1273 kA/m for fluences up to 2.4 10^9 n/cm^2 and permeance larger than 2.2. Moreover, no difference was observed between magnets with the direction of their magnetization parallel/perpendicular to the irradiation beam. Further experiments with high energy monochromatic neutrons are necessary. Since for mono-energetic neutrons, the energy of the knock-on atom (which will generate the thermal spike) is only proportional to the energy of the incident neutron energy, fluences higher than 10^{11} are necessary, especially with high P_c magnets, to generate any damage.

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