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Irradiation effects of a 10 MeV neutron beam on a Nd–Fe–B permanent magnet

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ABSTRACT

The effects of irradiation of a Nd–Fe–B permanent magnet by fast neutrons was investigated. The decrease in measured magnetic flux density at the center of the magnets were 0.6%, 6.9%, 25.2% and 47.3% after continuous irradiation of 1.1 kGy, 3.7 kGy, 5.6 kGy and 7.4 kGy, respectively. On the other hand, the decrease due to non-continuous irradiation, in which the magnet was first irradiated at 3.7 kGy, then irradiated again at 3.7 kGy nine months later, was 14% smaller than that of continuous irradiation, even for the same total dose. The temperature coefficient of the magnetization did not change with irradiation. Some radioactive materials, such as ^{147}Nd, ^{151}Pm, and ^{54}Mn, were detected in the magnet after irradiation.

1. Introduction

Nd–Fe–B permanent magnets have special characteristics concerning compactness, such that they require no power supply and no cooling system. These magnet materials are characterized by a high remanent flux density of 1.2–1.5 T, and an energy product of up to 400 kJ/m^3. Therefore, many kinds of applications in the accelerator field such as magnetic focusing equipment [1], ECR ion sources [2], insertion devices for synchrotron radiation [3] and cyclotrons for AMS [4] have been reported.

At NIRS (National Institute of Radiological Sciences), a compact cyclotron has been studied for use in the production of positron emitter radioisotopes at low operational cost. Here, Nd–Fe–B permanent magnets will be employed as the main-magnets of the cyclotron. In this case, a quantity of high-energy neutrons are supposed to come from internal RI-production targets, extraction devices, beam shutters and so on. Thus, demagnetization of the permanent magnets due to high-energy beam irradiation must be studied.

Several studies concerning the demagnetization of Nd–Fe–B permanent magnets with irradiation have been reported, as listed in Table 1 [5–9]. It seems that demagnetization strongly depends on the kind of radiation. Alderman et al. carried out X ray, ^{60}Co gamma ray, ^{252}Cf thermal and fast neutron irradiation experiments, and reported that only fast neutron irradiation damaged the magnetization [10]. In the present work, we focused on demagnetization with fast neutron irradiation with a central energy of 10 MeV. The temperature dependences of the magnetization and the residual activities in the magnets were also investigated to study the applicability of Nd–Fe–B permanent magnets for a cyclotron.

A Nd–Fe–B permanent magnet, NEOMAX-39SH, was used in the experiment. The main specifications of the magnet are listed in Table 2. A sample from the permanent magnet was formed into a rectangular shape of 25 mm × 25 mm and 5 mm thickness, and the direction of magnetization was parallel to the short axis.

2. Experimental setup

2.1. Irradiation system

A fast neutron flux for irradiating the magnet was produced by a method involving a deuteron-Be reaction system, which was equipped in one of the vertical beam lines at the NIRS-cyclotron facility [11]. During the reaction, the measured gamma ray dose was less than 5% of the total dose [12]. Therefore, the gamma ray dose was too small to induce any demagnetization in the sample

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Table 1
Typical references of demagnetization of Nd–Fe–B permanent magnets with irradiation.

Kind of radiation	Energy or source	Demagnetization (%)	Dose (kGy)	Ref.
Gamma-ray	^{60}Co	0.5	2800	[6]
Electron	20 MeV	9	2600	[6]
Electron	85 MeV	14	4500	[9]
Proton	500 MeV	50	40	[8]
Proton	200 MeV	20	2000	[7]
Neutron	Reactor	50	3.2×10^{16} n/cm^2	[5]

Table 2
Main specifications of the Nd–Fe–B permanent magnet.

Material code	NEOMAX-39SH
Max BH products (kJ m^{-3})	319
Remanence B_r (T)	1.29
Coercivity H_{CB} (kA m^{-1})	1003
Coercivity H_{CJ} (kA m^{-1})	1671
Temp. coeff. of B_r (%)	−0.11

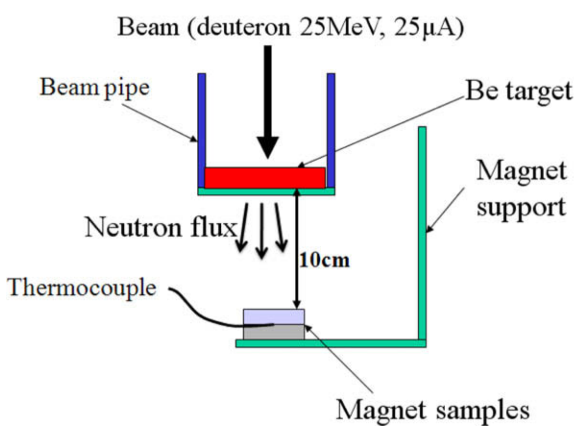

Fig. 1. Schematic view of the sample magnets and irradiation system. Two samples were set in a pile. The magnetization direction was parallel to the beam direction.

magnet. A neutron flux, having a central energy of about 10 MeV was produced by a 25 MeV deuteron beam on a water cooled Be target of 3 mm thickness. Usually, the neutron flux is used for biological experiments, and a sample is irradiated at 2 m downstream from a Be target. At that position, a neutron dose rate of 0.154 Gy/min was measured using an ion chamber when the incident deuteron beam current was 25 μA.

Takada et al. measured the neutron energy spectrum at the same beam line and position, the results are shown in Fig. 2 in Ref. [12]. The total neutron flux of 1.16×10^{11} n/(μCsr) was evaluated by integrating the numerical data of the neutron energy up to 29 MeV.

In this experiment, the magnet was set 10 cm downstream from the Be target, as shown in Fig. 1. Therefore, the neutron flux rate was estimated to be 2.90×10^{10} n/(cm^{2}s) and a dose rate of 61.6 Gy/min was estimated at the same beam current.

Since the distance between the Be target and the magnet was very close, the spatial distribution of the neutrons at the irradiation position was measured using an aluminum-activation method [13]. In this method, radioactive isotopes of ^{27}Mg were produced from the ^{27}Al(n,p) reaction by neutron irradiation on an aluminum plate. After irradiation, the aluminum plate was attached to an imaging plate to be exposed with 0.844 and 1.014 MeV photons from ^{27}Mg. This technique had an advantage that fast neutrons at more than 2.5 MeV were measured.

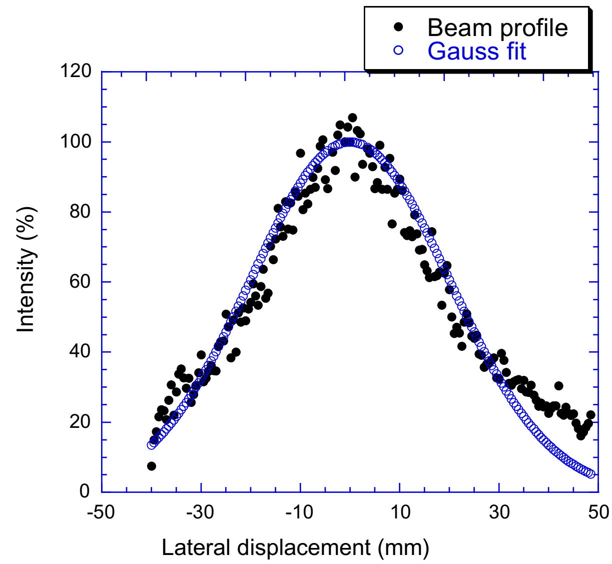

Fig. 2. Measured density distribution of the neutron flux on the irradiation position together with a Gaussian-fit.

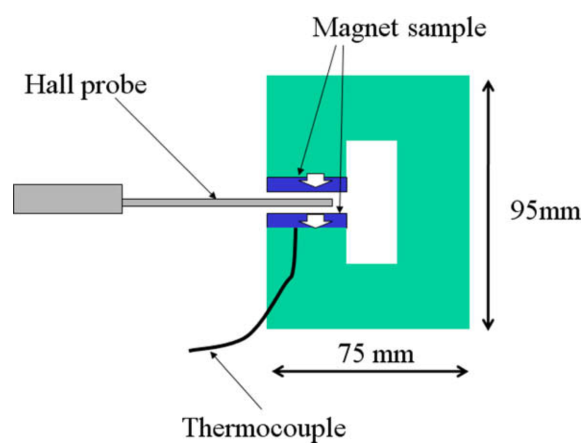

Fig. 3. Magnetic field measurement system consisting of a C-type yoke having a thickness of 25 mm. The size of the sample magnet was 25 mm × 25 mm square and 5 mm thick. Arrows indicate the direction of magnetization.

Fig. 2 shows the measured profile of the neutron flux distribution at the position of the irradiation together with a Gaussian fitted curve. The neutron flux at the magnet edge is 80% of that at the center.

2.2. Magnetic field measurement system

A simple test stand consisting of a C-type iron yoke was prepared to measure the magnetic field distribution of the magnets, as shown in Fig. 3. A pair of magnets can be easily mounted on, and then taken off from the yoke in order to measure the magnetic field strength before and after neutron irradiation.

In this layout, the magnetic flux density (B_g) in the magnet gap is given by the remanent flux density (B_r) of the permanent magnet, as follows:

$$B_g = k \cdot B_r \cdot L/(L + d) \tag{1}$$

where k is a constant determined by the structures of yoke and permanent magnets, L is the thickness of the permanent magnets (L = 5 mm × 2), and d is the gap distance (d = 5 mm). Eq. (1) is valid if the relative magnetic flux density distribution at the magnet gap