Effects of electron-beam and \( \gamma \)-ray irradiation on the magnetic flux of Nd–Fe–B and Sm–Co permanent magnets

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Abstract

The effects of irradiation with 17 MeV electron beams and \(^{60}\)Co \( \gamma \)-rays on the magnetic flux of Nd-Fe-B and Sm-Co permanent magnets have been studied. At an electron dose of \( 2.1 \times 10^{-3} \) C/cm\(^2\) (at an absorbed dose of 2.6 MGy), the magnetic flux loss of Nd-Fe-B is 9\%, while the flux loss of Sm-Co is below 0.4\% at a dose of \( 1.4 \times 10^{-3} \) C/cm\(^2\). After remagnetization of the irradiated Nd-Fe-B sample the magnetic flux almost recovers to the strength before irradiation. For \( \gamma \)-ray irradiation of Nd-Fe-B and Sm-Co at an absorbed dose of 2.8 MGy, the flux loss is below 0.5\%. Irradiation by \( \gamma \)-rays is considered to be equivalent to that of electrons at energies below 0.8 MeV. The difference between the results for electron-beam and \( \gamma \)-ray irradiation of Nd-Fe-B is discussed.

1. Introduction

In the facilities of high-energy particle accelerators, devices with permanent magnets are used under irradiation. Usually, the material of the magnets is Sm-Co or Nd-Fe-B. Previous work on the irradiation effects for such permanent magnets has been performed with high-energy neutrons [1], protons [2,3], deuterons [4] and \(^{60}\)Co \( \gamma \)-rays [4,5]. Electrons have been used for irradiation along with bremsstrahlung photons to investigate the effects of mixed irradiation [6]. In most cases loss of magnetic flux due to the irradiation has been observed. It has been suggested that the flux loss cannot be attributed to the structural change of the material of the magnet due to radiation damage [1–4]. Local heating along the orbit of the charged particles penetrating through the magnets is considered to be one possible cause of the flux loss [3]. However, the mechanism of the flux loss due to irradiation is not understood. Irradiation experiments with high-energy electron beams are expected to offer important information about the irradiation effects because electron beams have some special characteristics distinct from ions, neutrons and \( \gamma \)-rays. For a certain absorbed dose the amount of radiation damage induced by electron-beam irradiation is very small compared with that for ions or neutrons. As compared with \( \gamma \)-ray irradiation, parameters of electron-beam irradiation can be changed more widely.

The insertion devices of electron storage rings and the undulators of free-electron lasers (FELs) consist of many permanent magnets which form periodically alternating magnetic fields. These magnets are directly irradiated with high-energy electrons in such special cases where they are installed in a vacuum vessel in order to make the undulator gap narrow. Because high accuracy is required in the magnetic fields of the undulator, typically 0.5\% modulation of the strength of the magnetic field cannot be permitted. From this fact irradiation experiments with electron beams are necessary.

The present work has been carried out to investigate the effects of electron-beam irradiation on the magnetic flux of permanent magnets.

2. Experimental

2.1. Samples of permanent magnets

Samples of Nd-Fe-B and Sm-Co permanent magnets have been manufactured by Shin-Etsu Chemical Corp. The sample is a cylindrical disk 2 mm long with a diameter of 10 mm. The direction of magnetization is parallel to the cylinder axis. The main properties of the samples are listed in Table 1.

2.2. Irradiation with electron beams

Electron beams generated from the L-band rf linear accelerator at The Institute of Scientific and Industrial Research, Osaka University, 8-1 Mihogaoka, Ibaraki, Osaka 567, Japan
Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>Nd-Fe-B</th>
<th>Sm-Co</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trace names</td>
<td>Nd₂Fe₁₅B</td>
<td>Sm₁Co₁₇</td>
</tr>
<tr>
<td>Permeance coeff.</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Curie temperature</td>
<td>355</td>
<td>820</td>
</tr>
<tr>
<td>Thermal diffusivity[kcal/(m h°C)]</td>
<td>5.3</td>
<td>20</td>
</tr>
<tr>
<td>Rem. magnetic flux density[T]</td>
<td>1.18</td>
<td>1.05</td>
</tr>
<tr>
<td>Coercive force[kA/m]</td>
<td>1420</td>
<td>2120</td>
</tr>
</tbody>
</table>

Research (ISIR) in Osaka University [7] have been used for irradiation experiments. The experimental setup for the irradiation is shown schematically in Fig. 1. An electron beam at an energy of 20 MeV is focused on a vacuum window. The distance between the window and the samples is 600 mm. Four samples mounted on a sample holder are irradiated at the same time. In order to irradiate the samples uniformly, an aluminum plate 2 mm thick is placed in front of the window as a beam expander. The cross-sectional distribution of the beam at the samples has been measured by moving a wire monitor across the beam. This measurement shows that the distribution of the irradiation dose on the samples is within 3%. The samples and their holder are placed in a glass cell through which water flows at a fixed temperature of 20°C. The water directly contacts with the samples. The sample is taken from the glass cell within 30 min after the irradiation: the length of time for the irradiation is 1-3 h. At the front surface of the sample the energy of incidence of the electron beam is estimated to be 17 MeV. The energy is high enough for the electrons to penetrate through the sample. The average current of the incident beam at the samples is about 200 nA/cm². The error in the dose of electron-beam irradiation is estimated to be ±5%. The absorbed dose has been evaluated with a Celium dosimeter. The error in this evaluation is estimated to be ±4%. The temperature rise in the sample in the steady state during the irradiation, calculated from the thermal diffusivity, is below 0.2°C.

During the irradiation nuclear reactions are induced by high-energy X-rays in the sample. The possibility for a nucleus in a sample to transform in the present irradiation experiments is estimated to be below 10⁻⁹. This is too small for the nuclear transformation to cause demagnetization due to the structural change in the sample.

2.3. Irradiation with y-rays

Irradiation with y-rays was performed with a 60Co irradiation facility at ISIR, Osaka University. Samples were placed about 100 mm from a y-ray source in air atmosphere and irradiated at a temperature of about 20°C. The temperature rise in the sample during irradiation is negligible. The absorbed dose rate and the absorbed dose are 6.1 kGy/h and 2.8 MGy, respectively. The length of time for the irradiation is 459 h. These have been evaluated with a Celium dosimeter. The error in the evaluation is estimated to be within ±10%. The main cause of the error is the error in determining the distance between the y-source and the samples.

2.4. Measurement of the magnetic flux of the sample and remagnetization

The magnetic flux of the sample is measured using an open coil. The sample is moved through a 200 turn coil on the axis of the coil, the induced voltage being integrated. By this method the total magnetic flux of the sample is evaluated. The measurement is made at a fixed tempera-

![Fig. 1. Experimental setup for the electron-beam irradiation](image-url)
The influence of electron-beam irradiation on the flux of the Nd-Fe-B magnets in undulators is briefly discussed. As mentioned before, even a flux loss of 0.5% is not permitted for such devices. The present results show that a 0.5% loss occurs at an electron dose of about $2 \times 10^{-4} \text{C/cm}^2$. In the FEL experiments performed at ISIR in Osaka University [8] the flux loss may not be ignored. In the start-up conditions, electron beams would reach the undulator magnets through vacuum pipes, having a current of a few tens of microamperes. Assuming that the electron beam concentrates on a 1 cm$^2$ area of an undulator magnet, 0.5% loss might occur at about 10 s. Actually, the irradiation would not be so localized but it should be considered a problem in long-term experiments.

4. Summary

The effects of irradiation with a 17 MeV electron beam and $^{60}$Co y-rays on the magnetic flux of Nd-Fe-B and Sm-Co permanent magnets have been investigated. At an electron dose of $2.1 \times 10^{-3} \text{C/cm}^2$ (at an absorbed dose of 2.6 MGy) the magnetic flux loss of Nd-Fe-B was 9%. The flux loss of Sm-Co was below 0.4% at a dose of $1.4 \times 10^{-3} \text{C/cm}^2$. At an absorbed y-ray dose of 2.8 MGy the flux loss for Nd-Fe-B and Sm-Co was below 0.5%. After remagnetization of the Nd-Fe-B samples demagnetized after the electron-beam irradiation, the magnetic flux almost recovered to the strength before irradiation.

Acknowledgements

The authors would like to thank T. Yamamoto and S. Suemine for their help with the irradiation experiments. They are also indebted to H. Yoneda for the measurement of the magnetic flux.

References

3. Results and discussion

The dose dependence of the flux loss of the Nd-Fe-B and the Sm-Co samples irradiated with electrons is shown in Fig. 2. One data point has been derived for each sample. The absorbed dose for the sample evaluated from the measurement with a Cesium dosimeter is also indicated in this figure. The flux loss of Nd-Fe-B increases with the dose. At an irradiation dose of electrons of $2.1 \times 10^{-3}$ C/cm$^2$ (at an absorbed dose of 2.6 MGy) the flux loss of Nd-Fe-B is 9%. The flux loss of Sm-Co is below 0.4% at a dose of $1.4 \times 10^{-3}$ C/cm$^2$. Such insensitivity of Sm-Co to radiation compared with Nd-Fe-B has been found in previous work [4,6]. The results for the remagnetization of the Nd-Fe-B sample demagnetized after electron-beam irradiation are shown in Table 2. For all samples the magnetic flux has almost recovered to the strength before irradiation.

The results for the irradiation with $^{60}$Co y-rays are shown in Table 3. The flux loss for Nd-Fe-B and Sm-Co due to the y-ray irradiation is below 0.5%, while the loss for Nd-Fe-B due to the electron-beam irradiation at nearly the same absorbed dose is 9%, as shown in Fig. 2.

Previous results for the irradiation experiments with ionizing radiation and even with neutrons have shown that the cause of the loss is not the structural change of the material due to radiation damage. The present results for remagnetization also agree with the previous results. Moreover, for the present experimental conditions the flux loss cannot be attributed to the temperature rise in the sample during the irradiation.

The most important information offered from the present data concerning the mechanism of the flux loss is the difference between the effects of the electron-beam and the y-ray irradiation. The effects of irradiation with y-rays are due to the irradiation of the secondary electrons emitted by the y-rays in the sample. In the present results for Nd-Fe-B, at nearly the same absorbed doses considerable flux loss can be seen only for electron-beam irradiation and not for y-rays. This shows that the flux loss does not depend only upon the total absorbed dose. The main differences between the irradiation of electron beams and y-rays are in the energies of the electrons contributing to the effects, their direction of travel and the absorbed dose rates. For y-ray irradiation the energy and the direction of movement of the secondary electron are broadly distributed. The maximum energy of a secondary electron is about 0.8 MeV. The investigation for determining the parameters most effective for magnetic flux loss in irradiation experiments will be made in the near future.

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**Table 2**

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Irradiation dose (C/cm$^2$)</th>
<th>Magnetic flux after irradiation (%)</th>
<th>Magnetic flux after remagnetization (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$7.2 \times 10^{-4}$</td>
<td>97.9</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>$7.2 \times 10^{-4}$</td>
<td>98.3</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>$2.1 \times 10^{-3}$</td>
<td>91.5</td>
<td>99.5</td>
</tr>
<tr>
<td>4</td>
<td>$2.1 \times 10^{-3}$</td>
<td>90.6</td>
<td>99.5</td>
</tr>
</tbody>
</table>

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**Table 3**

<table>
<thead>
<tr>
<th>Number</th>
<th>Material</th>
<th>Flux loss after irradiation (%)</th>
<th>Flux loss for the unirradiated sample (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nd-Fe-B</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>2</td>
<td>Nd-Fe-B</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>Sm-Co</td>
<td>0.0</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>Sm-Co</td>
<td>0.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>