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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Magnetic flux loss of the permanent magnets used for the wigglers of FELs by the irradiation with high-energy electrons or X-rays

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Abstract

Study was made on the irradiation effects of the permanent magnets used for the wigglers of FELs with high-energy electrons and X-rays. Four kinds of Nd–Fe-B and one kind of Sm-Co samples were irradiated with 17 MeV electron beams or ^{60}Co γ-rays. The magnetic flux loss of one kind of Nd-Fe-B samples irradiated with electrons at doses below 2.1×10^{-3} C cm^{-2} increased with the irradiation dose. For the electron irradiation at doses of about 1.4×10^{-3} C cm^{-2}, magnetic flux loss was apparent for two kinds of Nd-Fe B samples. So flux loss was observed for γ-rays at absorbed doses higher than that of the electrons. The influence of the irradiation of electrons on the magnets of a wiggler in FEL experiments is discussed.

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1. Introduction

In the experiments of a free-electron laser (FEL) permanent magnets as components of a wiggler are irradiated with high-energy electrons and Bremsstrahlung X-rays, especially in the initial beam conditioning and in the beam positioning with screen monitors. Because extremely high accuracy is required for the strength of magnetic fields on the path of an electron beam in the wiggler, the modification of the field strength would be a serious problem. However, so far, investigations regarding the irradiation effects of such magnets with electrons and X-rays have been very few.

Rare-earth permanent magnets of Nd-Fe-B or Sm-Co are being used for most of the wigglers of FELs. The effects of irradiation with high-energy electrons or photons on the magnetic flux of such magnets were investigated with ^{60}Co γ-rays [1,2] and with a mixed beam of electrons and X-rays [3]. In our previous work [4], Nd-Fe-B and Sm-CO magnets were irradiated with electron beams at an energy of 17 MeV or with ^{60}Co γ-rays, in which magnetic flux loss was observed for the Nd-Fe-B

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magnet irradiated with an electron beam: In the experiments only one kind of samples were used for Nd-Fe-B and Sm-Co, respectively. The mechanism of the magnetic flux loss and the dependence of the flux loss on the physical properties of the samples are not known. In order to evaluate the influence of radiation on the strength of magnetic fields in a wiggler, irradiation experiments should be performed for various kinds of magnets.

The present work investigated the irradiation effects for the wiggler magnets. The samples of several kinds of Nd-Fe-B or Sm-Co magnets were irradiated with high-energy electron beams of a linear accelerator (linac) or with ^{60}Co γ-rays.

2. Experimental

2.1. Samples of permanent magnets

The physical properties of Nd-Fe-B and Sm-Co magnets used in the present experiments are listed in Table 1. The samples N-l. N-2. N-3 and S-l are cylindrical disks 2 mm long with a diameter of 10 mm. The sample N-4 is a rectangular stick of 2 x 2 x 10 mm^3. The direction of magnetization is parallel to the cylinder axis for the former sample and is vertical to the direction of the length of the sample for the latter.

Magnetic flux loss of Nd-Fe-B and Sm-Co magnets is observed when the temperature of the sample becomes nearly or above 100-C. The samples of N-2 and N-4 arc temperature resistant compared with those of N-l and N-3. respectively. Furthermore, Sm-Co is more resistant than Nd-Fe-B.

Table 1
Physical properties of the magnet samples

Number	Materials	Trade names	Remanent magnetic flux density (T)	Coercive force (kA m^{-1})
N-l	Nd–Fe–B	N33H	1.18	1420
N-2	Nd-Fe-B	N34UH	1.19	1990
N-3	Nd-Fe-B	35H	1.25	1353
N-4	Nd–Fe–B	32EH	1.11	2387
S-l	Sm-Co	R26HS	1.05	2120

N-l. N-2. S-l: manufactured by Shin-Etsu Chemical Co.
N-3. N-4: manufactured by Sumitomo Special Metals Co.

2.2. Irradiation with electron beams or γ-rays

The electron beams generated by the L-band linac at The Institute of Scientific and Industrial Research (ISIR), Osaka University [5] were used for the irradiation experiments. The experimental setup for irradiation is schematically shown in Fig. 1. The conditions for the experiments are almost the same as those of the previous experiments [4]. An electron beam at an energy of 30 MeV is focused on a vacuum window. The distance between the window and the samples is 600mm. Seven 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 samples and their holder are placed in an aluminum chamber. in which water flows at a fixed temperature of 20 °C. The water directly contacts the samples. The sample is taken out from the chamber within 30min after the irradiation. At the front surface of the sample the energy of the electrons is estimated to be 17 MeV. The energy is high enough for the electrons to penetrate through the sample. A macropulse of the electron beam with a length of 1.5 μs is repeated at a frequency of 60 Hz. The average current of the incident beam at the sample is about 200nA cm^{-2}. The error in the irradiation dose of the electron beam is estimated to be $\pm$ 3%. The absorbed dose is evaluated with

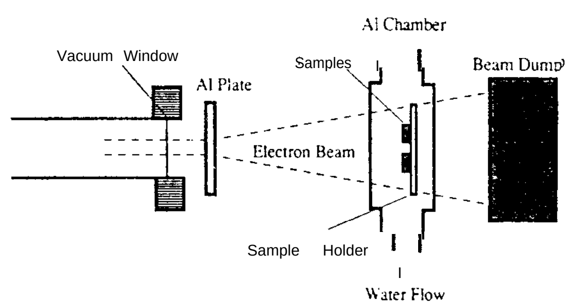

Fig. 1. Experimental setup for the electron-beam irradiation.

a celium dosimeter. The rise in temperature in the sample in the steady state during the irradiation can be calculated from the thermal diffusivity of the sample and is below 0.2°C.

The irradiation with y-rays was made by using a ^{60}Co irradiation facility at ISIR. Samples are placed in air atmosphere at a temperature of about 20°C during the irradiation. The absorbed dose is evaluated with a celium dosimeter.

2.3. Measurement of the magnetic flux of the sample

For the samples N-l. N-2 and S-l. the magnetic flus is measured by using an open coil. The sample is moved through a 200 turn coil along the axis of the coil. the induced voltage being integrated. By this method the total magnetic flux of the sample is evaluated. The magnetic flus of the samples of N-3 and N-4 is measured with a Hall element. being set at a distance of 3.4 mm apart from the surface. The intensities measured for both sides of the sample are averaged.

The magnetic flux loss is obtained by subtracting the loss for the reference sample which is not irradiated. The error in the measurement is estimated to be below ± 0.1%.

3. Experimental results and discussion

The dose dependence of the magnetic flux loss of the samples of N-l irradiated with electron beams or y-rays is shown in Fig. 2, in which some data of the previous esperiments [4] are also plotted. One data point was obtained from one sample. In the case of electron beams at doses below 2.1 x 10^{-3} C cm’ the flux loss increases with the irradiation dose, as shown in this figure. The results of the measurement of the flux loss after the irradiation with electron beams or y-rays for all the samples are shown in Table 2. In these results the flux loss is apparent for the samples of N-l and N-3 irradiated with electron beams. During the irradiation with electron beams the temperature is fixed at 20°C. Therefore, the flux loss is not attributed to the temperature elevation in the bulk of the sample. Previously, local heating along the orbit of a charged particle was considered to be one of the possible causes of the flux loss [6]. In the present results the flux loss due to the electron-beam irradiation is not apparent for temperature resistant samples of N-2, N-4 and S-l, which suggests that the flux loss is a kind of thermal effect such as local heating.

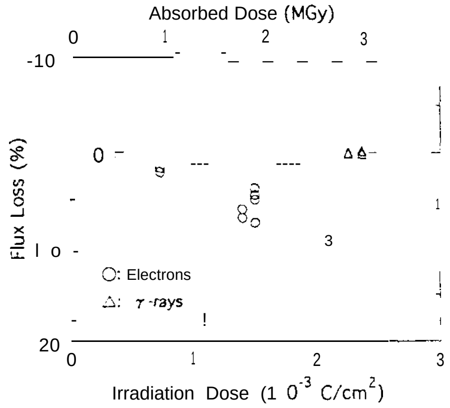

Fig. 2. Magnetic flux loss of the Nd–Fe–B samples of N-l irradiated with 17 MeV electron beams or ^{60}Co γ-rays: some of the previous data [4] are also plotted in the figure.

Table 2
Magnetic flux loss of the magnet samples irradiated with 17 MeV electron beams or ^{60}Co y-rays: an Irradiation dose of electrons of 1.4 C cm^2 corresponds to an absorbed dose of 1.7 MGy

Sample number	irradiation dose (C cm' for e: MGy for γ)	magnetic flux loss (%)
Irradiation with electron beams		
N-1	1.4–1.5 × 10^{-3}	5.6
N-2	1.4 × 10^{-3}	0.4
s-3	1.3–1.4 × 10^{-3}	0.8
N-4	1.4x 10^{-3}	0.2
S-l	1.-lx 10^{-3}	– 0.1
Irradiation with γ-rays		
s-1	2.8–2.9	0.1
N-3	1.9	0.0
N-4	2.9	0.0
S-l	2.8	0.2

In the present experiments magnetic flux loss was not observed for y-ray irradiation at absorbed doses higher than that in the case of electrons. This fact shows that the absorbed dose is not the main cause of the flux loss in the case of electron beams. For investigating the effects of γ-rays a higher dose is required.

At ISIR, far-infrared FEL experiments are being performed. The material of the wiggler magnets are the same as that of N-3 shown in Table 1. In the present experiments a magnetic flux loss of the sample N-3 was 0.8% at an irradiation dose of about 1.4 x 10^{-3} C/cm^2. Assuming the limit of the permitted magnetic flux loss to be 0.5%. the acceptable dose of electron beams becomes roughly 10^{-3} C/cm^2 from the results. In our FEL experiments. the averaged current of the electron beam is 4 μA in the case for conditioning or positioning electron beams and is 50 μA for operating the FEL at a high average power. When the magnets are irradiated with a narrow electron beam it would be serious even for a relatively short period. For long-term operations of the FEL the irradiation effects of the magnets around beam monitors. screen monitors in our case. should be taken into account. It is important to adopt wiggler magnets which are resistant to irradiation. In order to evaluate the irradiation effects with Bremsstrahlung X-rays for long-term operations of FELs. irradiation experiments at higher doses are necessary.

4. Summary

After the irradiation of the samples of Nd-Fe-B and Sm-Co permanent magnets with electron beams at an energy of 17 MeV or ^{60}Co ;/-rays. the magnetic flux loss was observed for two kinds of Nd-Fe-B samples irradiated with electron beams. The flux loss was not observed for the samples of Sm-Co and the temperature-resistant samples of the Nd-Fe-B. The present results suggested that the flux loss was a kind of thermal effect. From the comparison of the results for electron beams and y-rays it was found that the main cause of the flux loss was not the absorbed dose in the magnet. The consideration about the wiggler magnets used for our FEL experiments showed that the magnetic flux loss possibly causes a serious problem.

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