RADIATION DAMAGE IN MAGNETS FOR UNDULATORS AT LOW TEMPERATURE

T. Bizen, X. Maréchal, T. Seike, JASRI/SPring-8, Hyogo, Japan
H. Kitamura, T. Hara, T. Tanaka, RIKEN/SPring-8, Hyogo, Japan
Y. Asano, JAERI/SPring-8, Hyogo, Japan
D. E. Kim, H. S. Lee, PAL, Pohang, Korea

Abstract

The resistance to radiation-induced demagnetization of sintered $Nd_2Fe_{14}B$ permanent magnets, used in insertion devices, increases with the coercivity. By exploiting the negative temperature dependence of the coercivity and the remanence, both can be increased by lowering the magnet temperature. In this experiment, $Nd_2Fe_{14}B$ and $Pr_2Fe_{14}B$ magnets for cryogenic undulators were irradiated with 2.5 GeV electrons at low temperature and the magnetic field loss was measured. The resistance to radiation increased greatly at low temperature.

INTRODUCTION

The properties of sintered $Nd_2Fe_{14}B$ permanent magnets are highly desirable for insertion devices: thanks to their high intrinsic coercivity and high maximum magnetic energy product [(BH)max] small and thin magnets can be used. However, the radiation sensitivity of the magnets is of concern when they are used in a strong radiation environment.

Many reports indicate that the resistance to radiation depends on the coercivity [1,2,3,4,5]. While the coercivity increases with the addition of dysprosium (Dy) [6], the saturated magnetization or remanence decreases because the magnetic moment orientation of Dy is opposite to that of Fe. This implies that higher remanence magnets cannot be used in a strong radiation environment.

Another specific property of $Nd_2Fe_{14}B$ magnets is the negative temperature dependence of the remanence and the coercivity: both increase as the magnet temperature decreases [7]. One of the concepts of the cryogenic undulator, advocated by T. Hara et al [8], is to take advantage of this property in the permanent magnet undulator technology to improve drastically the performance of the magnetic field and the coercivity. The enhancement of coercivity at low temperature, as well as by the addition of Dy, is expected to strengthen the resistance to radiation damage.

Only few experiments of radiation-induced demagnetization were made at low temperature. O. –P. Kähkönen et al. reported that 20 MeV proton irradiation induced flux loss of NdFeB magnets was remarkably smaller at 15K [9,4]. However, using NdFeB magnets at very low temperature is impractical because NdFeB magnets lose remanence around 140K due to spin reorientation [10].

The objective of this experiment was to test the effects of high-energy electron irradiations on the magnets at the cryogenic undulator operating temperature.

EXPERIMENTAL PROCEDURE

Samples

Two types of sample magnets were manufactured by NEOMAX Co., Ltd. The dimensions of the samples are $44 \times 8 \times 12$ mm^3 for $Nd_2Fe_{14}B$ magnets (NEOMAX-50BH) and $46 \times 8 \times 12$ mm^3 for $Pr_2Fe_{14}B$ magnets (NEOMAX-53CR). The magnet surface was coated with 5 μm TiN to protect against corrosion and to reduce out gassing in vacuum. No treatments (annealing, etc.) were applied to the samples after magnetization.

Cryostat

A cryostat was made to lower the temperature of the sample magnet down to 77 K. A schematic diagram is shown in Fig.1. The magnet holder was clamped with low thermal conductive polyimide washers and supported by stainless steel tubes in a flange. The sample magnet was cooled using a pulse tube cooler (15W at 77K). The sample holder and the heat transfer copper parts from the cold head are connected by 0.2 mm thick copper plates to compensate for the thermal contraction. The sample holder temperature was controlled using a micro ceramic heater and a thermocouple. The magnet temperature was monitored by a 4-wired resistance thermometer. These components were assembled in an aluminium vacuum chamber. The chamber was evacuated to an effective thermal insulation pressure of 10^{-4} Pa by a turbo-molecular pump.

Irradiation

Irradiation was performed using the linac of the Pohang Accelerator Laboratory. The electron beam parameters are listed in Table 1. The structure of the sample and the target is shown in Fig.2. The electron beam was injected into a 40 mm thick copper block after passing through a 0.2 mm thick stainless steel vacuum window. The beam position was monitored and adjusted with a CCD camera and a fluorescent plate in front of the copper block. The electron intensity was measured with a current monitor.

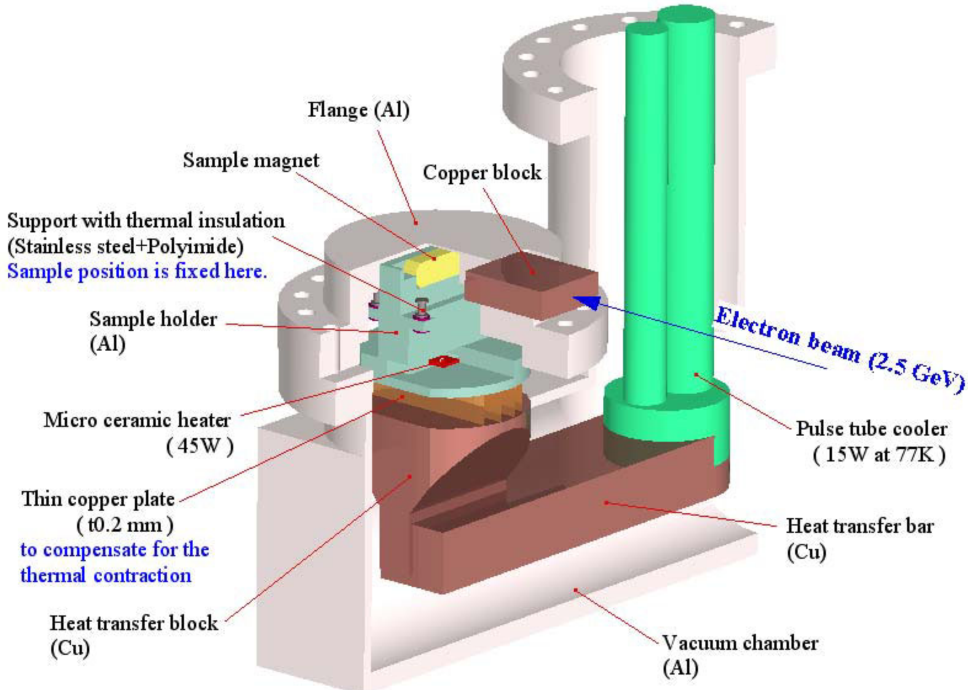

Figure 1: Schematic diagram of the cryostat.

Table 1: Electron beam parameters of the linac

Beam energy	2.5 GeV
Average beam current	600 mA
Operation frequency	10 Hz
Macro pulse length	1 nsec

Measurement system

The hall-probe was placed in a small copper holder with a thermistor and a resistance heater to keep the probe temperature constant within ±0.02K. The hall-probe was set to measure the vertical magnetic field of the sample above the upper surface of the flange in air. A water cooled aluminium plate was placed above the probe to keep the temperature of the scanning area constant during the scan. The probe was moved by XY positioning tables to map the distribution of the magnetic field, 4 mm above the top surface of the magnet. During irradiation the hall-probe was placed into a lead radiation shield cover. Before each measurement the stability of the sensor sensitivity was checked using reference permanent magnets located in the shield cover. The positioning table was remote controlled, so the measurements were performed continuously without accessing the samples and the measurement machine. The digital multi-meter used to measure the output voltage from the hall-probe and the current supply for driving the hall-probe were placed in a constant temperature box to reduce the drift due to the long time measurement time.

EXPERIMENTAL RESULTS AND DISCUSSION

NEOMAX-50BH ($Nd_2Fe_{14}B$)

Figure 3. shows the radiation-induced demagnetization curves of NEOMAX-50BH. The resistance to radiation at 145K increases remarkably compared to irradiations at 300K. Radiation-induced demagnetization depends on coercivity. Hara et al. reported that the coercivity of this sample is 3060 kA/m at 145K, and 1116 kA/m at 300K [8]. This result suggests that the large increase of the coercivity at lower temperature improved the resistance to radiation.

Figure 4. shows an enlarged graph of the radiation-induced demagnetization curves of 50BH and 35CR at low temperature. The demagnetization curves of NEOMAX-35EH and NEOMAX-27VH were also superimposed on the graph for reference. Data for 35EH are taken from a previous experiment [11]. All magnets were not annealed after magnetization. The coercivity of

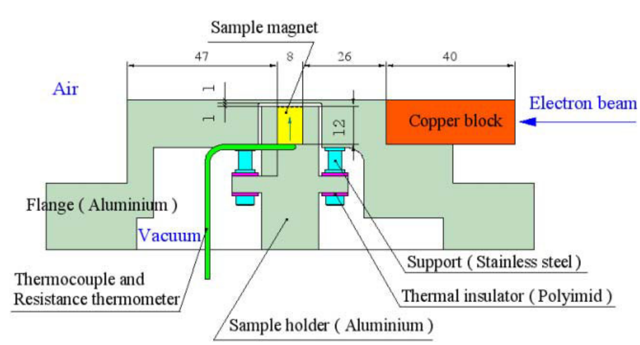

Figure2: Structure of the target

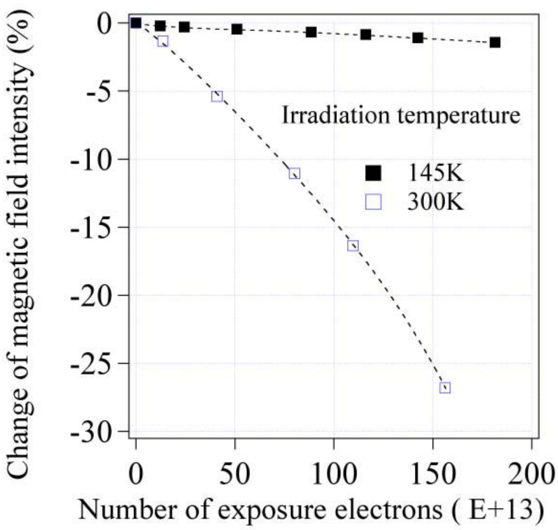

Figure3: Radiation-induced demagnetization curves of NEOMAX-50BH. The demagnetization is remarkably smaller at lower temperature.

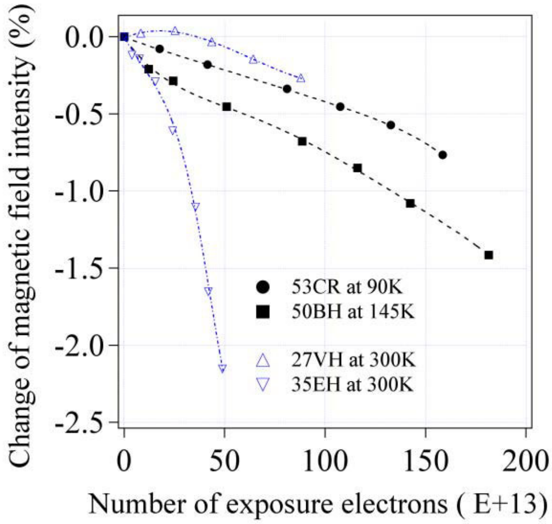

Figure4: Radiation-induced demagnetization curves of NEOMAX-50BH and NEOMAX-53CR at low temperature. NEOMAX-27VH and NEOMAX-35EH at room temperature are superimposed for reference.

50BH at 145K was almost same as that of 27VH (2864 kA/m at 293K) and superior to that of 35EH (1989 kA/m at 293K). The demagnetization curve of 50BH indicates decrease similar to 27VH when compared to 35EH. This suggests that coercivity enhancement by lowering temperature and by adding Dy show similar effect.

NEOMAX-53CR($Pr_2Fe_{14}B$)

PrFeB magnets have been developed for cryogenic devices. Both remanence and coercivity of PrFeB magnet can be increased by lowering the temperature below 77K. This wide range of available temperature is an advantage compared to NdFeB magnets.

The 53CR shows almost same the demagnetization as 27VH known as one of the high resistance magnet in NdFeB. The irradiation temperature of 90K is not the lowest temperature for operation. 53CR is expected to indicate much more resistance than 27VH since the coercivity increases below 90K.

CONCLUSIONS

The resistance to radiation of NdFeB magnet increased remarkably at lower temperature. Just like the addition of dysprosium, the enhancement of coercivity obtained at low temperature improved the resistance to radiation damage. This implies that NdFeB magnet with a high remanence and a low coercivity can be used at low temperature in a high radiation environment where previously only higher coercivity and lower remanence magnets were used

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