Nd-Fe-B MAGNETS UNDER ELECTRON IRRADIATION WITH THE ENERGY OF 23 MeV

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Four Nd-Fe-B magnets underwent irradiation under 23 MeV electron beam. Nd-Fe-B magnets were magnetized to the technical saturation in the magnetic field of 3.5 T before electron treatment. Two Nd-Fe-B samples (1 and 2) were exposed to the direct electron beam with the energy of 23 MeV. Sample 2 was shielded by tungsten converter. The thickness of the tungsten converter was 4.72 mm. The absorbed dose for the samples was 16 GRad. Sample 3 was subjected to bremsstrahlung of electron irradiation with the energy of 23 MeV. Sample 4 was used as a reference sample for calibration and control measurements. While magnetic flux of sample under direct electron beam of 23 MeV was changed significantly, sample 2 showed the change of magnetic flux to a less degree. Magnetic performance of sample 3 corresponded closely to the initial state.

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INTRODUCTION

High performance rare-earth permanent magnets have wide application in the various magnetic systems of electron accelerators. However, potential exposure of rare-earth permanent magnets to the radiation fields induces magnetic degradation and damage of magnetic materials [1]. It was shown that Sm-Co magnets are preferred choice in some high-temperature applications due to strong resistance to radiation-induced demagnetization effects [2]. Despite the good magnetic performance of Sm-Co magnets under 23 MeV [4] in comparison with Nd-Fe-B magnets following irradiating at a twice lower energy of 10 MeV [3, 5], the high radiation activity of the former greatly hampers their practical use in the actual compact electron accelerators [4]. High-temperature grades of Nd-Fe-B magnets are typically doped with Cobalt, which affects the radiation activity of magnetic samples also. Moreover, Nd-Fe-B magnets with identical stoichiometric compositions from different producers show various remanence loses [2].

The purpose of this paper is to study the demagnetization behaviour of Nd-Fe-B magnets protected by a barrier and exposed to an electron beam with the energy of 23 MeV. We investigate how Tungsten barrier can keep magnetic performance under irradiation.

1. EXPERIMENTAL DETAILS

Four Nd-Fe-B magnets produced by PLP technology [6, 7] with dimensions of 30×40×12 mm were used in the study. The density of the magnets was 7.35…7.4 g/cm^3. All four magnets were covered with a thin coating of nickel to reduce oxidation of the magnetic material. The coercitivity, remanence and Curie temperature of these magnets are Br=1.2 T, Hcj=1190 kA/m, Tc=320°C. Each magnet had a unique identification namely sample 1, 2, 3, and 4. Samples were magnetized at the field of 3.5 T to the technical saturation. The temperature of the samples during irradiation was kept constant at about T=40°C by the cooling system.

Irradiation of sample 1 and sample 2 was performed at the EPOS linear technological accelerator. The electron beam of 23 MeV is used for irradiating the magnets [8].

A vertically unfolded electron beam was brought out horizontally from the accelerator into the air through a titanium foil [9]. Then, the electron beam was scattered on the Al foil and reached the surface of the magnets at the distance of 1.35 m from the accelerator exit. The orientation of the magnets was chosen to provide electron irradiation of 30×40 mm plane (south pole). The deviation of electron flux within magnet’s surface was lower 10%.

W-convertor with the thickness of 4.72 mm was installed adjacent to sample 2 and exposed to the electron beam.

Sample 3 was placed outside the electron beam at the distance of 300 mm from the irradiation area.

Space of irradiation around magnetic samples, dimensions 130×560×20 mm, was filled with the light-weighted material (density 3.5 g/cm^3) yielding a 75% loss of electron energy. Hence, magnetic samples were exposed to the γ-ray Bremsstrahlung with an intensity of 50 times more than Bremsstrahlung produced by electrons emerging at the samples.

Samples 1, 2 and 3 were irradiated within 192 hours. The absorbed dose generated by electrons was 16 GRad (the fluence for the absorbed dose 1.4×10^{17} cm^{-2}).

Sample 4 was not irradiated and used as a reference sample for calibration and control measurements.

2. RADIATION MEASUREMENTS

After the irradiation, samples were held for 16 days to become safe for radioactivity measurements. CANBERRA GC1818 spectrometer equipped with a high-sensitivity germanium semiconducting detector was used to record the gamma-ray spectrum of the magnetic samples. The relative efficiency and ^{60}Co line energy resolution of the detector are 18% and 1.8 keV accordingly. CANBERRADSA 1000 digital spectrum analyzer with in-built high voltage source was used as the acquisition and analysis system.

The efficiency calibration of the spectrometer was carried out by standard etalons including ^{133}Ba, ^{137}Cs, ^{241}Am, ^{22}Na, ^{60}Co, and ^{152}Eu. Absolute efficiency curves were described by Campbell function [10].

Fig. 1 shows the example of the absolute efficiency versus energy obtained by the etalon source of ^{152}Eu at the distance of 10 cm from the detector window.

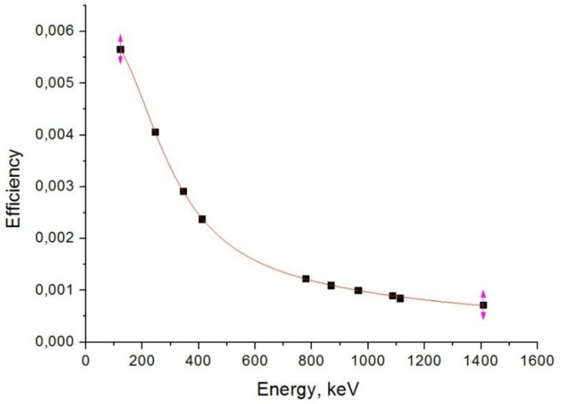

Fig. 1. The absolute efficiency versus energy (etalon source of ^{152}Eu at the distance of 10 cm from detector window)

Activity measurements were performed in the low-background conditions. The low-background conditions were achieved by passive cylindrical shield combining Pb layer (~10 cm), Cd layer (5 mm), and Cu layer (5 mm). Measured γ-spectrums were processed by WinSpectrum [11].

Spectrums of samples 1, 2, and 3 after irradiation are shown in Figs. 2, 3, and 4 correspondingly. The exposition of measurements was 10 min.

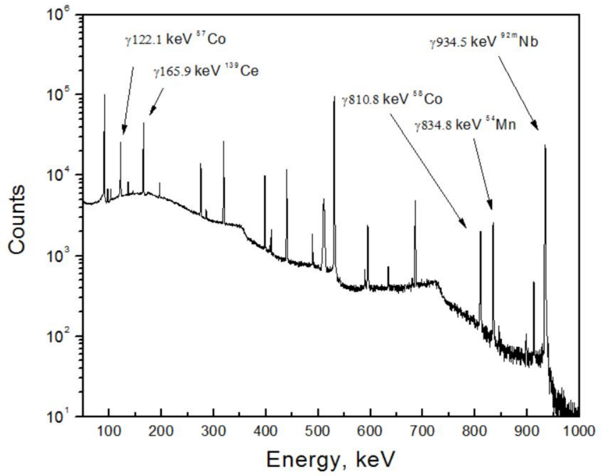

Fig. 2. Induced gamma-activity spectrum of sample 1 (exposition – 10 min). Almost all unmarked peaks correspond to ^{147}Nd isotope

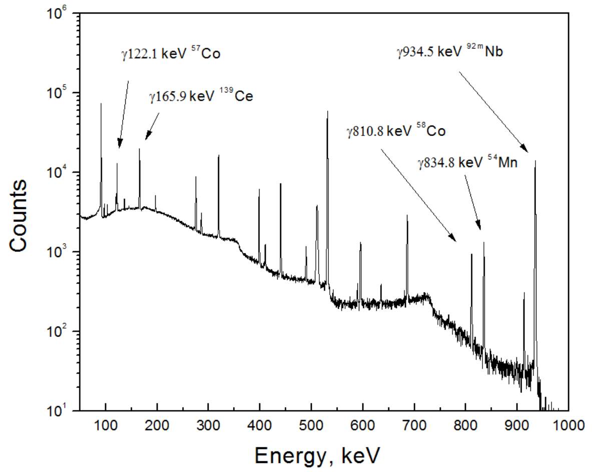

Fig. 3. Induced gamma-activity spectrum of sample 2 (exposition – 10 min). Almost all unmarked peaks correspond to ^{147}Nd isotope

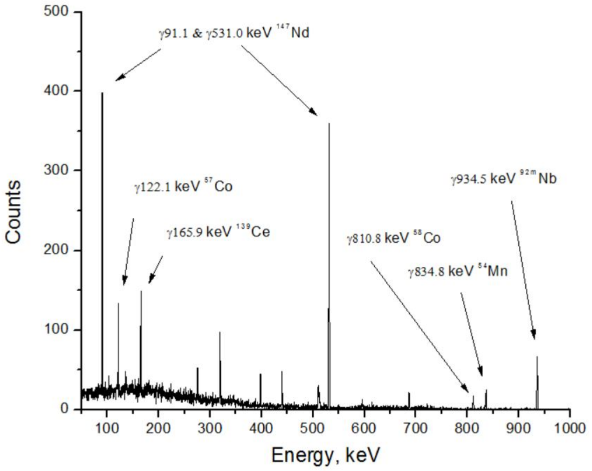

Fig. 4. Induced gamma-activity spectrum of sample 3 (exposition – 10 min)

It can be seen that γ-spectrums of sample 1 and 2 are very similar with a bit smaller activation of sample 2. The activation of sample 3 was considerably lower. It was characterized by the lines of the same isotopes as for samples 1 and 2.

3. MAGNETIC MEASUREMENTS AFTER IRRADIATION

The normal component of magnetic field intensity for each of the four Nd-Fe-B magnets was measured with seven Hall probes supported on the non-magnetic bar [12]. The magnetic sample was moved across the bar. The distance between Hall probes was about 6 mm. The starting point of the sample positioned to the bar was fixed by the stopper system. The sample was moved parallel to the surface of the bar. The distance between sample and bar was 3.05 mm. The step between points of measurements along the sample's surface was from 2 to 5 mm. The accuracy of the sample positioning was about 1 micron.

The measurements of magnetic field intensity on the south pole was performed by 180-degree rotation of the sample along long axis after Hall probe scanning of north pole side. The relative error of the normal component of magnetic field intensity was about 0.01%.

Integral of the normal component of magnetic field intensity by scanned area $I=\int B_{norm}ds$ was calculated to estimate the magnetic field of the samples in arbitrary units. Repetitive scans and calculated I – parameter for each magnetic sample showed little variation with the infinitesimal error of 0.5%.

The area of interpolation was limited by the out-to-out distance of Hall probes liner and scanning points along the samples' surface accurately fixed by a coordinate system.

The scanned data of magnetic field intensity for the south pole of sample 4 before irradiation is shown in Fig. 5.

The interpolation of scanned sample 4 gives the distribution of the magnetic field (Fig. 6).

Integrals of normal component of magnetic field intensity by scanned area of un-irradiated samples north pole) revealed very similar values of I_1 = 176.4; I_2 = 177.9; I_3 = 178.1, and I_4 = 175.4. Additionally, the I

parameters of south pole side are in very good agreement with north pole ones within the accuracy limits.

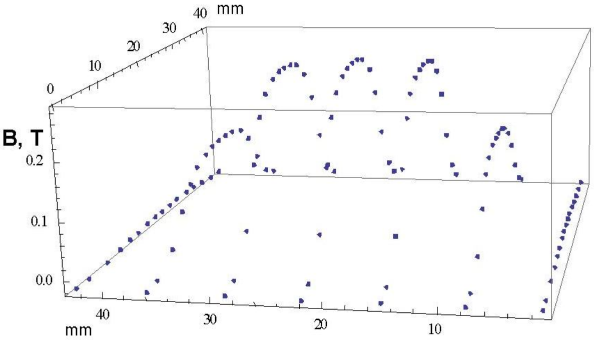

Fig. 5. Scanned data of magnetic field intensity of sample 4 (south pole)

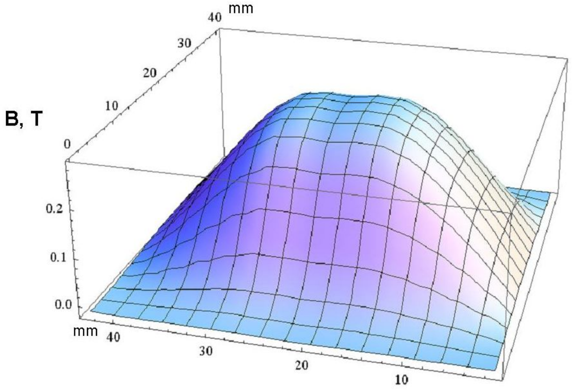

Fig. 6. The distribution of magnetic field intensity sample 4 (South pole)

The result obtained by integration and interpolation of sample 1 following irradiation of a direct electron beam of 23 MeV revealed dramatic flux loss. Magnetic field distribution of sample 1 after irradiation is presented in Fig. 7. I parameter of sample 1 after irradiation dropped to $I_1 = 74.69$.

Similar behaviour was observed in sample 2 after irradiation (Fig. 8). I parameter of irradiated sample 2 decreased to $I_2 = 107.37$. However, no significant change in magnetic flux was measured and calculated for sample 3 following irradiation (Fig. 9). The I parameter of irradiated sample 3 estimated to be $I_3 = 176.56$.

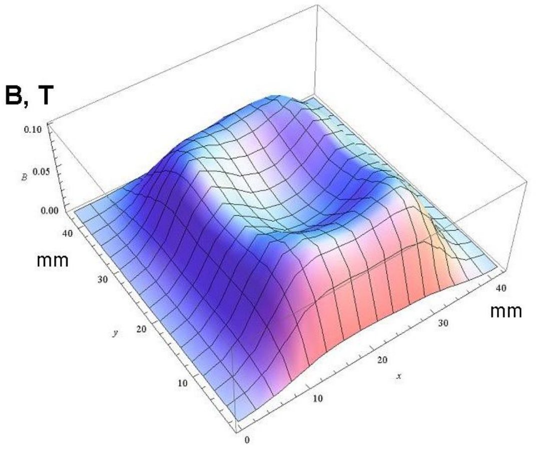

Fig. 7. The distribution of magnetic field intensity sample 1 after irradiation

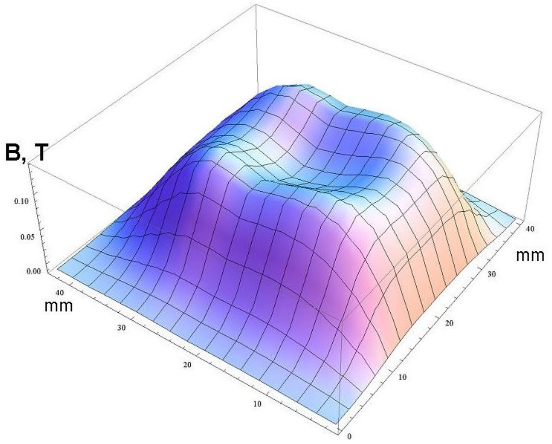

Fig. 8. The distribution of magnetic field intensity sample 2 after irradiation

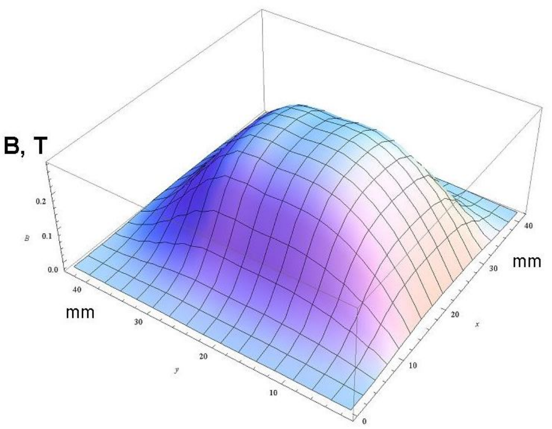

Fig. 9. The distribution of magnetic field intensity sample 3 after irradiation

Similar data for south pole surfaces were measured within accuracy limits for all samples after irradiation.

4. REPEATED MAGNETIC MEASUREMENTS AND REMAGNETIZATION

Repeated magnetic measurements were performed in 3 years and 8 months after irradiation experiments.

According to Figs. 10, 11, and 12, the results of repeated magnetic scanning suggest that magnetic field distribution and I parameter correlate well with previous measurements.

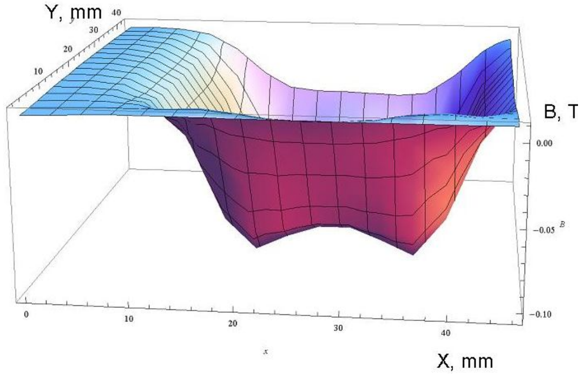

Fig. 10. The distribution of magnetic field intensity of the south pole surface of irradiated sample 1 (measurements in 3 year and 8 months)

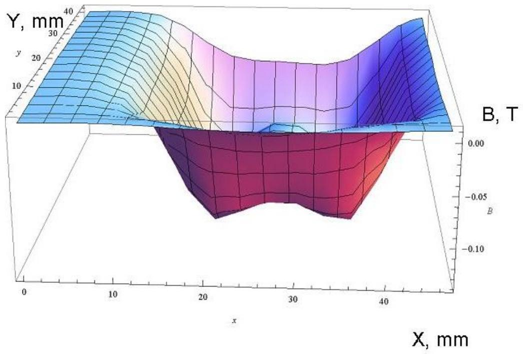

Fig. 11. The distribution of magnetic field intensity of the south pole surface of irradiated sample 2 (measurements in 3 year and 8 months)

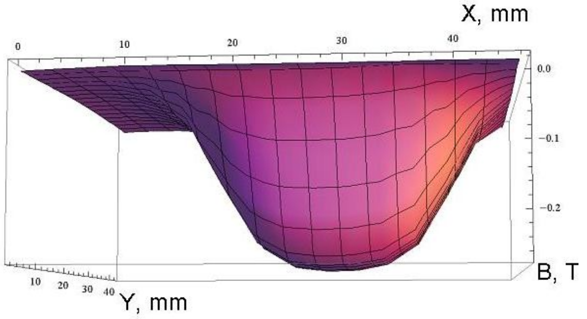

Fig. 12. The distribution of magnetic field intensity of the south pole surface of irradiated sample 3 (measurements in 3 year and 8 months)

I parameter of south pole surface of irradiated samples attributed to I_1 = -68.5403; I_2 = -95.876; I_3 = -165.099 correspondingly.

The results are shown in Figs. 10, 11, and 12 indicate a slight decrease of parameters in comparison with Figs. 7, 8, and 9 due to samples shift relatively to Hall probes positions.

Then, samples 1, 2, and 3 were remagnetized to the technical saturation in the magnetic field of 3.5 T and same polarity as before irradiation experiments. As an example, the distribution of magnetic field intensity of sample 1 following irradiating by a 23 MeV electron beam and remagnetization is depicted in Fig. 13.

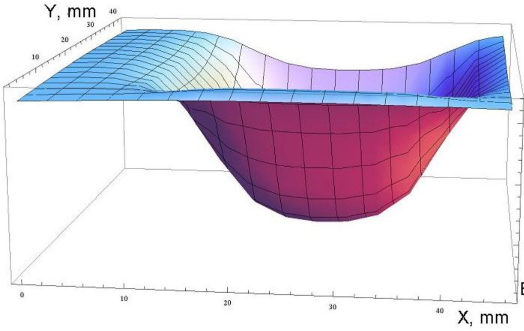

Fig. 13. The distribution of magnetic field intensity of sample 1 following irradiating by a 23 MeV electron beam and remagnetization

The same recovery of magnetic performance was observed for irradiated samples 2 and 3 after remagnetization. *I* parameters for irradiated and remagnetized samples (south pole) were about I_1 = -167.364; I_2 = -166.862; I_3 = -167.278 correspondingly. Fig. 14 depicts an example of a Y-plane scan of irradiated sample 2 after remagnetization. The measurement was performed by probe 4.

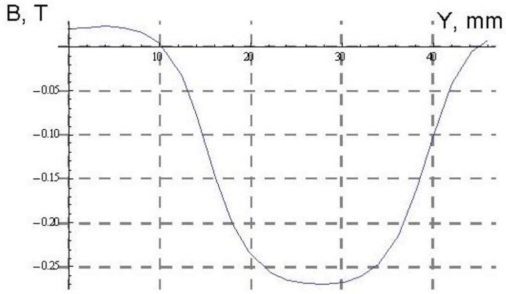

Fig. 14. Y-plane scan of irradiated sample 2 after remagnetization

It was also revealed that Y-plane scans of irradiated sample 1 and 3 after remagnetization had practically the same patterns as sample 2.

SUMMARY

The effects of irradiation with 23 MeV on magnetic field intensity and spatial distribution of Nd-Fe-B magnets were studied.

It was revealed that the magnetic performance of magnets exposed to Bremsstrahlung produced by electron beam did not undergo noticeable changes.

Despite irradiating conditions as direct electron beam, bremsstrahlung and W-converted barrier, all Nd-Fe-B magnets showed full restoration of magnetic properties after remagnetization.

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ИЗМЕНЕНИЕ МАГНИТНОГО ПОЛЯ ОБРАЗЦОВ Nd-Fe-B-МАГНИТОВ ПРИ ОБЛУЧЕНИИ ЭЛЕКТРОННЫМ ПУЧКОМ С ЭНЕРГИЕЙ 23 МэВ

В.А. Бовда, А.М. Бовда, И.С. Гук, А.Н. Довбня, В.Н. Лященко, А.О. Мыцыков, Л.В. Онищенко, С.С. Кандыбей, О.А. Репихов

Были проведены экспериментальные исследования поля четырёх образцов магнита из Nd-Fe-B-сплава, предварительно намагниченных в импульсном магнитном поле 3,5 Тл. Образцы № 1 и 2 подвергались прямому воздействию электронным пучком с энергией 23 МэВ. Перед образцом № 2 вплотную помещался конвертор из вольфрама толщиной 4,72 мм. Поглощённая доза для образцов составляла 16 Град. Образец № 3 подвергался воздействию тормозным излучением электронного пучка с энергией 23 МэВ. Образец № 4 не облучался и служил опорным эталоном для калибровки точности метода и контрольных измерений. Наблюдается существенное изменение магнитного поля образца № 1, подвергавшегося прямому воздействию электронным пучком с энергией 23 МэВ. В меньшей мере это изменение наблюдалось для образца № 2. Поле вокруг образца № 3 практически не изменилось.

ЗМІНА МАГНІТНОГО ПОЛЯ ЗРАЗКІВ Nd-Fe-B-МАГНІТІВ ПРИ ОПРОМІНЕННІ ЕЛЕКТРОННИМ ПУЧКОМ З ЕНЕРГІЄЮ 23 МеВ

В.О. Бовда, О.М. Бовда, І.С. Гук, А.М. Довбня, В.М. Лященко, А.О. Мициков, Л.В. Онищенко, С.С. Кандибей, О.О. Репіхов

Були проведені експериментальні дослідження поля чотирьох зразків магніту з Nd-Fe-B-сплаву, попередньо намагнічених в імпульсному магнітному полі 3,5 Тл. Зразки № 1 і 2 піддавалися прямій дії електронним пучком з енергією 23 МеВ. Перед зразком № 2 впритул містився конвертор з вольфраму товщиною 4,72 мм. Поглинена доза для зразків складала 16 Град. Зразок № 3 піддавався впливові гальмівного випромінювання електронним пучком з енергією 23 МеВ. Зразок № 4 не опромінювався і служив опорним еталоном для калібрування точності методу і контрольних вимірів. Спостерігається істотна зміна магнітного поля зразка № 1, що піддавався прямій дії електронним пучком з енергією 23 МеВ. У меншій мері ця зміна спостерігалася для зразка № 2. Поле навколо зразка № 3 практично не змінилося.