MAGNETIC FIELD LOSSES IN $Nd-Fe-B$ MAGNETS UNDER $10\,MeV$ ELECTRON IRRADIATION

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Reversible changes in magnetic properties of $Nd-Fe-B$ magnets under electron beam with the energy of $10\,MeV$ and bremsstrahlung irradiation were investigated. It was shown that direct electron beam irradiation resulted in the decrease of magnetic flux and substantial alteration in the magnetic pattern on the surface of the samples. Increasing the radiation dose in 10 times did not lead to a linear reduction of magnetic flux. Bremsstrahlung also did not produce any significant drop in magnetic performance. Re-magnetization after the irradiation allowed to restore the initial magnetic properties of $Nd-Fe-B$ magnets.

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1. INTRODUCTION

Rare-earth permanent magnets are widely used in the self-powered compact devices [1,2]. Now, $Nd-Fe-B$ magnets are the essential part of technological electron accelerators with energy up to $10\,MeV$. Magnets have many practical applications as focusing beam systems and energy beam measuring devices [3,4]. However, the stability of magnetic performance can be influenced by the direct electron beam and bremsstrahlung irradiation [5]. In this paper, we present the study of magnetic performance stability of $Nd-Fe-B$ magnets under electron and bremsstrahlung irradiation. $Nd-Fe-B$ magnets were manufactured using PLP technology [6,7]. KUT-1 technological accelerator [8] with the energy of $10\,MeV$ was used as the source of the electron beam. The density of magnetic samples obtained with PLP technology was $7.35...7.4\,g/cm^3$. The magnets had geometrical dimensions of $30\times40\times12\,mm^3$. The surface of the samples was covered with a thin layer of nickel to prevent corrosion. During the irradiation, the samples were cooled with water at a temperature of no more than $40°C$. Pulsed magnetic field of $3.5\,T$ was used for samples magnetization.

2. EXPERIMENTAL SETUP

The direct irradiation experiments were carried out with three magnets designates as M1, M4 and M5. All samples were located behind output foil of the accelerator. Continued water cooling was used to prevent samples from heating. The side ($30\times40\,mm^2$) of South magnetic pole (S. pole) was chosen for the direct electron irradiation. The heterogeneity of beam density was less than 10%. The M2 sample underwent bremsstrahlung radiation generated by electron bombardment of M1 sample. In view of this, M2 sample was placed beyond electron beam. The distance between M1 and M2 samples was $1\,cm$. The M2 sample was also water-cooled. The non-irradiated M3 sample was used for reference measurements of induced activity and magnetic flux stability. M1, M2 and M4 samples were exposed to continue irradiation within $20\,hours$. The absorbed dose of M1 and S4 samples was $16\,Grad$. M5 sample was irradiated within $20\,hours$ sessions with 24 hours breaks. The total absorbed dose for M5 sample was $160\,Grad$. The γ-spectra of each irradiated sample were collected within $24\,hours$ after the end of irradiation. CANBERRA GC1818 spectrometer with high-purity Ge semiconductor detector was utilized. As a result of $^{148}Nd(\gamma,n)^{147}Nd$ reaction with the threshold of $7.3\,MeV$, the unstable ^{174}Nd isotope with 10.98 days half-life was revealed. The ^{174}Nd isotope attributes to 91.136, 319.406, 439.835, $530.913\,keV$. However, ^{174}Nd isotope did not considerably change the activity of the samples in comparison with non-irradiated one. Thus, negligible induced activity enables to use $Nd-Fe-B$ magnets at the technological electron accelerators.

3. MAGNETIC MEASUREMENTS

Magnetic measurements were performed by the seven (7) Hall probes assembly [9]. Hall probes were fixed in the copper matrix to temperature compensation. The distance between Hall probes was $6\,mm$. The normal component of the magnetization was measured. The relative accuracy was not less than 0.01%.

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Magnetic samples were moved parallel to the surface of the copper matrix. The distance between magnets and copper matrix was 3.05 *mm*. The steps of measurements along the direction of travel varied from 3 to 5 *mm*. The accuracy of travel was 1 μm. Initial reference point was fixed by the supporting system. The magnetic field distribution (magnetic flux) was scanned from the both sides of the magnet ($30 \times 40\,mm^2$). Fig.1 shows the North pole (N. pole) magnetic scans for M1 sample before irradiation.

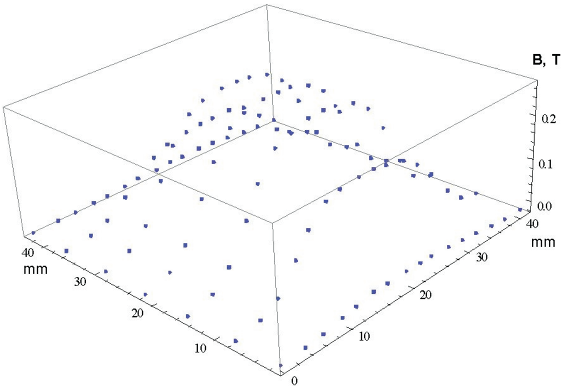

Fig.1. *Magnetic field scans for M1 sample (N. pole)*

Scanned data were used for the three-dimension square interpolation. The area of simulation was limited by the out-to-out Hall probes positions in the copper matrix and scanning area. Fig.2 demonstrates the simulation for the M1 sample utilizing data shown in Fig.1.

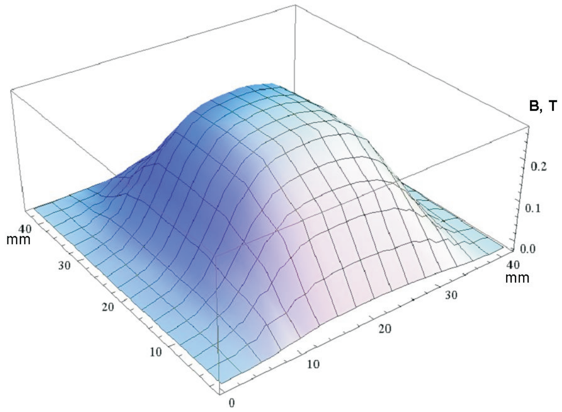

Fig.2. *Simulation of magnetic flux for M1 sample (N. pole)*

The magnetic field around the sample can be described by the integral Bx component in a plane 3.05 *mm* of the surface of the block. The integral Bx component of magnetic flux measured at the N. pole side of non-irradiated samples is shown in Table. It was revealed, that integral Bx component of magnetic fluxes at both sides of the non-irradiated samples showed good agreement within the accuracy of measurements.

Integral value of magnetic flux of the samples

Name	Integral Bx component Name (N. pole) , arb. units
M1	175.763
M2	179.556
M3	175.452
M4	174.275
M5	176.357

The carried out examinations accuracy of recurring of integral Bx component for the same sample, related to a binding to boundaries of the sample of a measuring system, give repeatability at level of 0.5%.

4. RESULTS AFTER ELECTRON IRRADIATION

The simulation of magnetic field distribution for the sample after electron irradiation is shown in Figs.3-8. The simulation of the magnetic field distribution of M1 for S. pole is depicted in Fig.4. The corresponding integral Bx component of M1 sample for S. pole was -160.2. It can be seen that integral Bx component for M1 equals to 162.356 for N. pole. As it can be seen in Figs.3 and 4, the magnetic field distribution of both N. and S. poles are in a good agreement after electron irradiation, within the accuracy of measurements.

Simulated magnetic field distribution for M4 sample (N. pole) after irradiation is shown in Fig.5. It was revealed that integral Bx component (N. pole) for M4 sample after irradiation dropped to 151.122. The shape of the simulated magnetic field distribution of S. pole for M4 sample is close to the pattern in the Fig.5. The integral Bx component of S. pole for M4 sample is about -151.509.

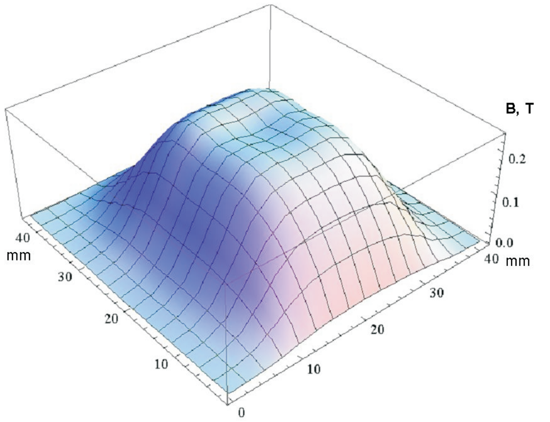

Fig.3. *The simulation of magnetic field distribution for M1 sample (N. pole) after irradiation (accumulated dose 16 Grad)*

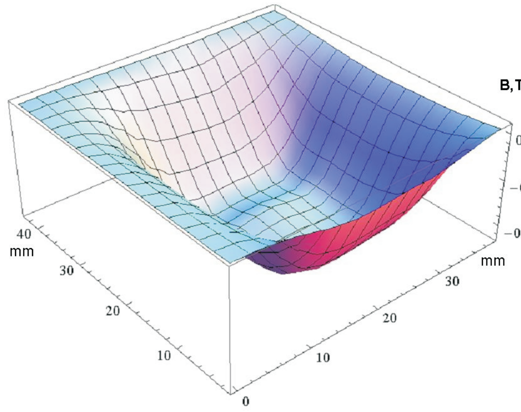

Fig.4. *Simulated magnetic field distribution for M1 sample (S. pole) after irradiation*

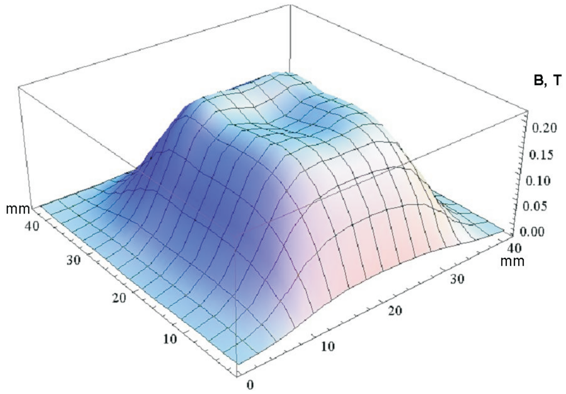

Fig.5. *The simulation of magnetic field distribution for M4 sample (N. pole) after irradiation (accumulated dose 16 Grad)*

Whereas direct electron irradiation substantially modified the magnetic pattern of the samples, bremsstrahlung irradiation hardly changed the magnetic field distribution (see Fig.6) and integral Bx component of 178.526 (see also Table).

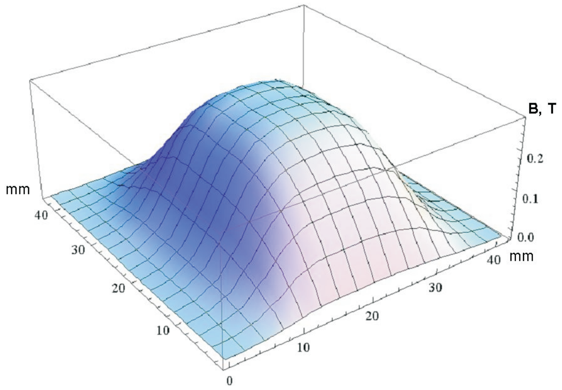

Fig.6. *Simulated magnetic field distribution N. pole of M2 sample*

Predictably, the most transformation of magnetic field distribution was found for M5 sample with the highest accumulated dose of 160 *Grad* (Fig.7). The integral Bx component was reduced to 126.556. It should be noted that integral Bx component was not proportional to the accumulated dose.

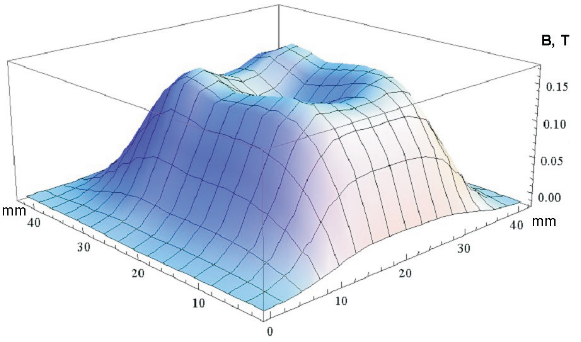

Fig.7. *Magnetic field distribution for M5 sample (N. pole) after irradiation (accumulated dose 160 Grad)*

5. EFFECTS OF ACTION OF AN EXTERIOR MAGNETIC FIELD

The full recovery of magnetic properties was indicated for M1 and M4 samples after re-magnetization. Figs.8-10 shows the simulated magnetic field distribution of M1 and M5 samples after re-magnetization. After irradiation (see Fig.3) and re-magnetization (Fig.8) of M1 sample, the pattern of N. pole magnetic field distribution was slightly changed and almost coincided with the initial state (see Fig.1). The integral Bx component was about 175.224, which is in good agreement with the initial value.

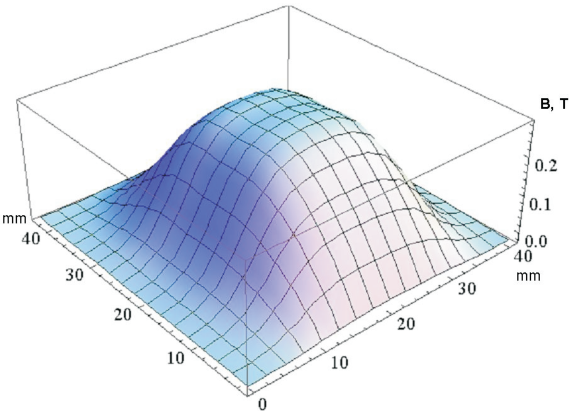

Fig.8. *Magnetic field distribution N. pole of M1 sample after irradiation and re-magnetization.*

The same effect was indicated for M5 sample (see Figs.9 and 10). The integral Bx component of M5 sample after re-magnetization recovered to the initial value of 174.894 (N. pole) and −176.78 (S. pole).

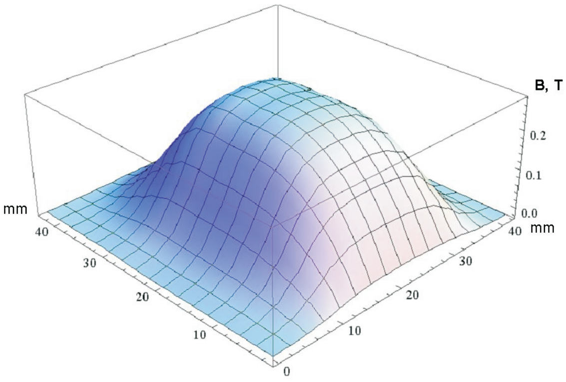

Fig.9. *Magnetic field distribution N. pole of M5 sample after irradiation and re-magnetization*

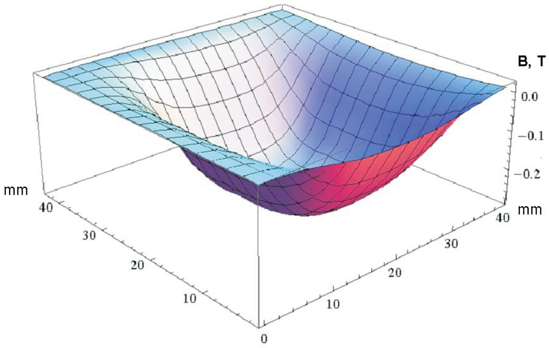

Fig.10. *Magnetic field distribution S. pole of M5 sample after irradiation and re-magnetization*

6. SUMMARY

The direct electron irradiation of the Nd-Fe-B magnets let to the substantial change in magnetic field distribution of the samples. There was no direct correlation between the decrease of magnetic properties and the accumulated dose within the range of 16...160 *Grad*. Re-magnetization of the samples after irradiation resulted in the full recovery of magnetic properties. Within the interval of the used radiation absorption doses of the electron beam, no dependence of this effect on the dose was observed. Within the indicated doses, there was no significant change in the activity of the samples due to the formation of unstable isotopes in the material of magnets, which makes it possible to simplify the use of finished products on technological accelerators with energy of up to 10 MeV.

References

1. David J. McLaughlin, Kenneth R. Hogstrom, Robert L. Carver, John P. Gibbons, Polad M. Shikhaliev, Kenneth L. Matthews II, Taylor Clarke, Alexander Henderson, and Edison P. Liang. Permanent-magnet energy spectrometer for electron beams from radio-therapy accelerators // *Medical Physics.* 2015, v.42, N9, p.5517-5529.

2. A.M. Bovda I.S. Guk. A.N. Dovbnya, S.G. Kononenko, V.N. Lyashchenko, A.O. Mytsykov. Dipole magnet with a constant field for the accelerator "EPOS" // *Problems of Atomic Science and Technology. Ser. "Nuclear Physics Investigations".* 2015, N6(100), p.13-17.

3. F. Bodker, L.O. Baandrup et al. Permanent magnets in accelerators can save energy, space and cost // *Proceedings of IPAC2013*, Shanghai, China, p.3511-3513.

4. I.S. Guk, A.O. Mytsykov. Select of parametres of an analyzing magnet for the technological accelerator of electrons // *XIV conference on a high-energy physics, nuclear physics and accelerators.* Abstracts broshure, Kharkov, 2016, p.117.

5. A.N. Dovbnya, A.E. Tolstoy, A.M. Bovda, O.M. Utva, V.L. Uvarov, M.A. Krasnogolovets. Study on radiation resistance of permanent $Nd - Fe - B$-base magnets under continuous radiation conditions // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations".* 1999, N3(34), p.48-49.

6. Yasuhiro Une and Masato Sagawa // *J. Japan Inst. Metals.* 2012, v.76, N1, p.12-16.

7. M. Sagawa // *Proc. 21st Int. Workshop on Rare Earth Permanent Magnets and Their Applications*, Bled, Slovenia, 2010 / Ed. by S. Kobe and P.J. McGuiness, (Ljubljana: Jozef Stefan Institute, 2010), p.183.

8. M.I. Ayzatsky, V.N. Boriskin, et al. THE NSC KIPT electron linacs - R and D. // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations"* (33). 2003, N2, p.19-25.

9. I.S. Guk, A.N. Dovbnya, S.G. Kononenko, V.N. Lyashchenko, A.Yu. Mytsykov, V.P. Romas'ko, A.S. Tarasenko, V.N. Shcherbinin. Dipole magnet of the energy filter for the accelerator "EPOS" // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations"* (79), 2012, N3, p.67-69.

ИССЛЕДОВАНИЕ ВЛИЯНИЯ ОБЛУЧЕНИЯ ОБРАЗЦОВ $Nd-Fe-B$ МАГНИТОВ ЭЛЕКТРОННЫМ ПУЧКОМ С ЭНЕРГИЕЙ 10 МэВ НА ВЕЛИЧИНУ ПОЛЯ ВОКРУГ МАГНИТА

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

Экспериментально исследовано изменение магнитного поля образцов магнитов, изготовленных из $Nd-Fe-B$ сплава, при облучении их электронным пучком с энергией 10 МэВ, а также тормозным излучением такого пучка. Проведенные исследования показали, что величина и распределение поля вокруг магнитов изменяются при прямом облучении поверхности электронным пучком. Увеличение дозы облучения в 10 раз не приводит к линейному изменению наблюдаемого изменения поля образца. Под воздействием тормозного излучения электронов в образце, расположенном вне воздействия электронного пучка, существенного изменения поля не наблюдается. Повторное намагничивание образца после облучения электронным пучком позволяет восстановить первоначальную величину и распределение поля вокруг образца.

ДОСЛІДЖЕННЯ ВПЛИВУ ОПРОМІНЕННЯ ЗРАЗКІВ $Nd-Fe-B$ МАГНІТІВ ЕЛЕКТРОННИМ ПУЧКОМ З ЕНЕРГІЄЮ 10 МеВ НА ВЕЛИЧИНУ ПОЛЯ НАВКОЛО МАГНІТУ

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Експериментально досліджений розподіл магнітного поля зразків магнітів, виготовлених з $Nd-Fe-B$ сплаву, при опроміненні їх електронним пучком з енергією 10 МеВ, а також гальмівним випромінюванням такого пучка. Проведені дослідження показали, що величина і розподіл поля навколо магнітів змінюються при прямому опроміненні поверхні електронним пучком. Збільшення дози опромінення в 10 разів не приводить до лінійного зменшення поля зразка, який досліджувався. Під впливом гальмівного випромінювання електронів у зразку, розташованому поза впливом електронного пучка, істотної зміни магнітного поля не спостерігається. Повторне намагнічування зразка після опромінення електронним пучком дозволяє відновити первісну величину і розподіл поля навколо зразка.