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RESEARCH OF PHYSICAL PROCESSES IN PERMANENT MAGNETS UNDER THE ACTION OF ELECTRONS, NEUTRONS, AND GAMMA QUANTUM

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A review of works was conducted in which the interaction of electrons, neutrons and gamma quanta from the material of permanent magnets used in electron accelerators was studied. The main conclusions of the review indicate that in order to establish the mechanisms of demagnetization of alloys, it is necessary to carry out detailed studies of changes in the structure of materials after irradiation.

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INTRODUCTION

One of the main ideas in the creation and implementation of modern accelerator projects is energy saving. This can be achieved using the latest technologies in the field of superconducting accelerating structures (SRF) and permanent magnets based on rare earth alloys. The advantages of superconducting structures are significantly reduced energy losses in the process of particle acceleration, as well as substantial energy return of the accelerated beam to replenish the energy that feeds the accelerating structures (Energy Recovery Mode (ERL) technology [1]. Dipole magnets and quadrupoles based on permanent magnets, which are the basis of the magnetic structure of all accelerators, do not require power sources and will be the basis of energy saving both in large colliders [2–6] and small technological accelerators [7, 8]. A vivid example of the implementation of all these ideas is the accelerator complex in Cornell, where the CBETA installation [9–13] was built and launched. It is a prototype for the world's first multi-turn ERL accelerator using superconducting accelerator structures. The magnetic system of this installation is mainly built on dipoles and quadrupoles made on the basis of permanent magnets, and the HF the system is established on superconducting accelerating structures.

The importance of the CBETA project lies in the fact that it implements several concepts of energy saving in the design of accelerators. These energy saving concepts are already becoming a standard in the development of projects of large accelerator complexes [14, 15].

The goal of the CBETA project was to test new technologies that could be used for the future Electron-Ion Collider EIC [16], the next major US particle accelerator to be built at BNL in ten years. The ERL Linac technology will be used in the project to cool a beam of protons and heavy ions.

In addition to the options mentioned above, permanent magnets are widely used to generate radiation in free-electron lasers and undulators, which are the basis for obtaining hard radiation in synchrotron radiation sources.

Thus, the creation of future accelerator projects aimed at studying the change in the characteristics of magnetic materials under the influence of both the particles accelerated in the accelerator and the secondary radiation that occurs when the accelerator beam interacts with the materials are of high importance. For an electronic accelerator, these are primarily electrons, gamma quanta and neutrons.

INTERACTION OF BEAMS WITH PERMANENT MAGNETS

A lot of works are devoted to the study of the interaction of beams of different particles (references to these works can be found in a number of reviews [17–24].

The results of the interaction of electron beams with an energy of 6 GeV in the PETRA III synchrotron radiation source with permanent magnets in undulators are presented in works [25, 26]. It was established that over time the magnetic field in the undulators decreases, which leads to a change in the radiation spectrum and the trajectory of the beam. The results of field reduction along the length of various undulators in the installation are presented in Fig. 1.

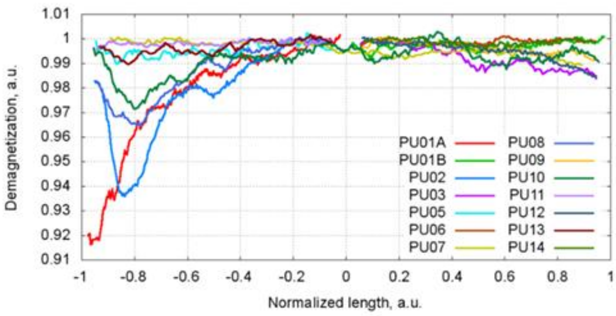

Fig. 1. Reduction of the magnetic field of undulators PETRA III rings [26]

It was also shown that the reduction of the magnetic flux is directly related to the radiation dose, which is directly proportional to the operation time of the installation. This indicates that the primary basis of changes is the scattered electron beam. Fig. 2 shows the field changes in one of the undulators with time after installation in the installation.

The works [25, 26] do not establish the mechanism of degradation of magnetic material characteristics and contain only a recommendation to improve beam dynamics, which can reduce beam losses on devices.

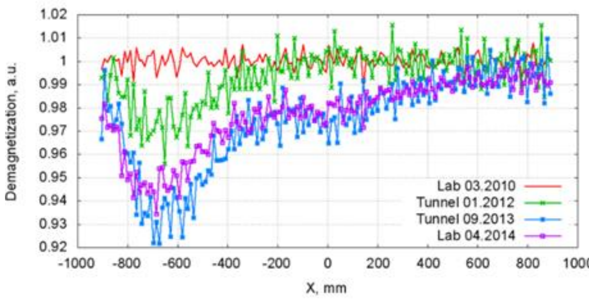

Fig. 2. Degradation of undulator magnets over time [26]

In works [19, 27, 28], on the basis of experimental studies of the interaction of an electron beam with an energy of 2 GeV with different configurations of the magnetic system of undulators made of different magnetic materials, a method was found to reduce the effect of the degradation of the magnetic field of the material on the magnitude of the undulator field. Fig. 3 shows the dependence of the degree of demagnetization of the undulator system on the number of electrons falling on it [19] for three magnetic configurations.

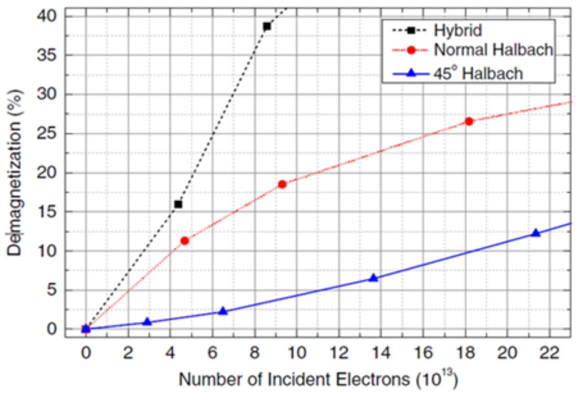

Fig. 3. Dependence of the amount of demagnetization on the number of incident electrons [19]

This dependence was associated with the features of the magnetic circuit in the structure of the undulator.

The influence of the composition of secondary radiation on the demagnetization of magnet materials was demonstrated by placing copper and tantalum blocks in front of the prototype of the magnetic undulator system [27, 28] (Fig. 4). The spectrum and intensity of bremsstrahlung radiation and neutrons depends on the charge of the atomic nucleus of the target, and therefore the amount of demagnetization was greatest when using a tantalum block.

Although there are numerous publications regarding the change in the magnetic field of undulators on various installations beside the last one cited [27, 28], it is impossible to obtain information about the mechanisms of magnetization change under the influence of electron beam irradiation from them.

Some data can be obtained from the analysis of works studying the interaction of certain types of secondary particles that appear as a result of the interaction of electrons with magnet materials.

Thus, special attention should be paid to the results obtained during the interaction of electrons with the basic Sm-Co and Nd-Fe-B alloys at significantly lower electron energies. The works [29–35] used electron beams with energies of 83, 17, 10, and 23 MeV, and also studied the effects of the interaction of the bremsstrahlung radiation of these beams with alloys.

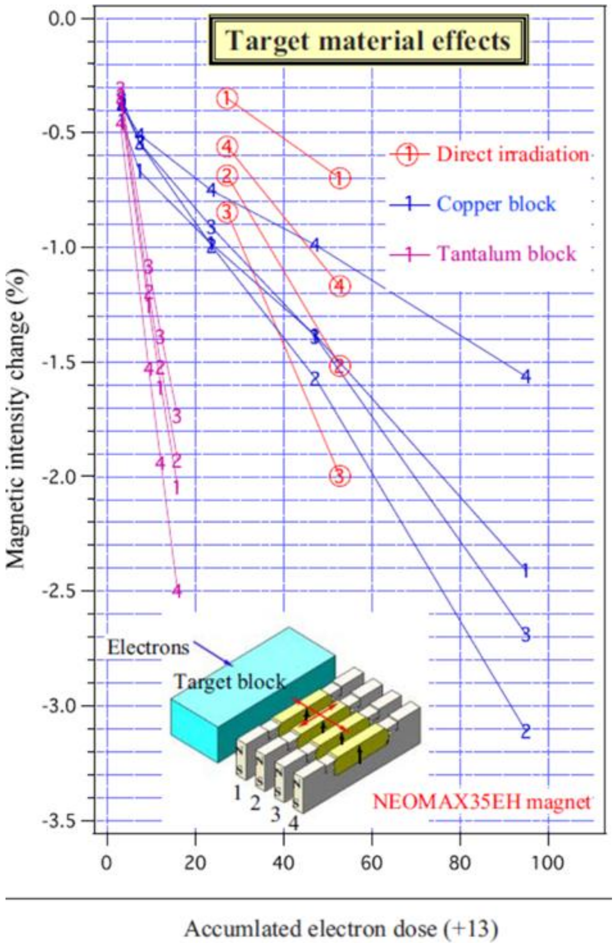

Fig. 4. Dependence of the amount of demagnetization on the number of incident electrons and the material of the target [27, 28]

The main results of the research are follows: the magnetic field of Sm-Co samples at significant doses of irradiation with direct electron beams practically does not change, but Nd-Fe-B samples show significantly decrease the magnitude of the magnetic field.

Irradiation of samples with a stream of gamma quanta from a Cobalt-60 source and bremsstrahlung radiation of an electron beam practically does not change the distribution of the magnetic field of the samples.

Nd-Fe-B samples restore the magnitude of the field they had before irradiation after re-magnetization.

It should be noted that one of the important physical parameters, which is significantly different in these alloys, is a much higher Curie temperature for alloys of the Sm-Co system.

In experiments at low electron energies, there is largely no contribution to the field change effect by photoneutrons, which are generated in small quantities at these energies.

The main results of the influence of neutrons on the magnetic characteristics of Nd-Fe-B and Sm-Co alloys are presented in works [36–38].

For Nd-Fe-B alloys and the fluence of fast neutron radiation at the level of $2 \cdot 10^{13}$ n/cm^2 and thermal neutron irradiation up to a full fluence of $2.94 \cdot 10^{12}$ n/cm^2, no difference in magnetization was recorded in the irradiated magnet samples of more than 0.5%.

The magnetic properties of the Sm-Co samples were not affected by irradiation up to a fluence of 10^{18} n/cm^2.

The decrease of magnetic flux in irradiated Nd-Fe-B samples at a dose of 10^{15} n/cm^2 was revealed after repeated magnetization and repeated measurements. Magnetic recovery was found to be 100% for samples irradiated up to 10^{16} n/cm^2, indicating that irradiation did not cause changes in the microstructure of the material.

The recovery rates were 97.5 and 95% for samples irradiated with a flux of 10^{17} and 10^{18} n/cm^2, indicating some damage of the microstructure of Nd-Fe-B magnets might occurred.

Magnetic recovery after remagnetization suggests that radiation damage is mostly due to a thermal effect rather than an irreversible change in the microstructure.

It can be considered that some confirmation of such conclusions is provided by the results of work [39], where the dependence of demagnetization on the neutron flux dose in Nd-Fe-B alloys was measured at temperatures of 426 and 350 K. The initial loss of residual magnetization occurs almost twice as fast for irradiation at 426 than at 350 K.

Hence, the contribution of neutrons to the field change during the interaction of electrons with permanent magnets is very small.

It should be noted that it is very difficult to generalize when analyzing the publications of the original works, for example, works [40–43] that summarize the results of studies over the demagnetization of alloys under the influence of various particles. This is caused by the fact that all these works were carried out in different conditions, with different materials, and the goals of the works were also different. Therefore, even in general works, it is difficult to come to unequivocal conclusions regarding the mechanism of change in the magnetization of materials under the influence of radiation.

Kahkonen et al. [44] proposed a theoretical model that describes the influence of a high-energy particle inside a magnetic material (Nd-Fe-B). Part of the energy of the incoming particle is transferred to the atom and its energy is used in the crystal lattice to increase the temperature. If this temperature exceeds the Curie temperature, the demagnetizing force will create a reverse domain that immediately grows to the size of the grain.

Bizen et al. [45] summarizes some previous models. Authors propose two mechanisms of radiation damage to permanent magnets. The first: "broad unstable region" (Fig. 5) is the release of energy in a wide region caused by low energy particles (gamma rays, electrons and neutrons). Reverse domains nucleate at grain boundaries. This is similar to heat-induced demagnetization and can be mitigated using the same techniques.

The second mechanism: the "quasi-thermal spike" (Fig. 6), is a localized release of energy caused by a high-energy photoneutron produced by a high-energy electron.

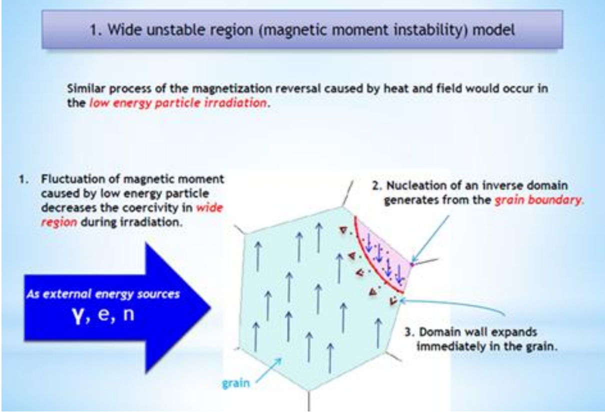

Fig. 5. Model [45]

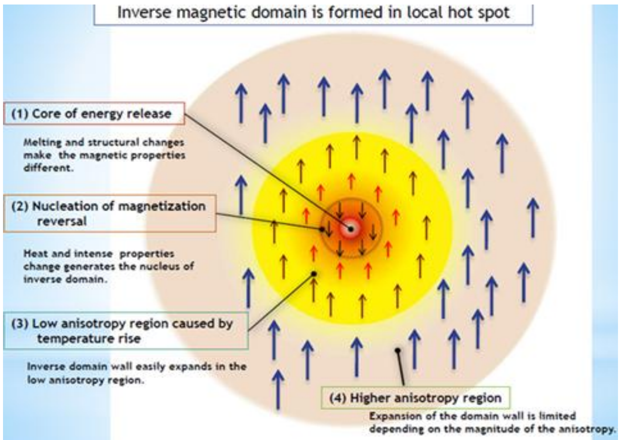

Fig. 6. Melt model [45]

In the proposed hypothesis, the authors assumed that the thermal surge would lead to a molten core with a radius of several nanometers above the Curie temperature, where the magnetization is completely lost (but the lattice structure is preserved) and the nucleation of the region of low coercivity occurs and the region of the main phase, which is not changed by the thermal surge, is preserved.

A possible mechanism of magnetization loss might be because of overheating of a small area along the electron trajectory due to electrons that are formed during ionization processes in magnet materials. This is confirmed by experiments at low electron beam energies [31–35].

Ionization losses depend little on the atomic composition of the substance, and the Curie temperature of Nd-Fe-B and Sm-Co alloys is very different.

For Nd-Fe-B alloys, the maximum working temperatures are in the range of 80…200 °C, and the Curie temperature is – 310…390 ºC. For Sm-Co alloys, the maximum working temperatures are 250…550 degrees, and the Curie temperature is in the range of 750…850 ºC. Therefore, overheating along the track in Nd-Fe-B alloys will be closer to the Curie point than for Sm-Co alloys, and these alloys will undergo stronger demagnetization.

CONCLUSIONS

It is obvious that different parameters of primary and secondary particles can contribute to the change in the magnetization of permanent magnets during electron irradiation in the interval from 8 GeV to 10 MeV in different parts of this interval. In order to establish the mechanisms of such influence, it is necessary to carry out detailed studies of changes in the structure of materials after irradiation. There are no such studies in published works.

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ДОСЛІДЖЕННЯ ФІЗИЧНИХ ПРОЦЕСІВ У ПОСТІЙНИХ МАГНІТАХ ПІД ДІЄЮ ЕЛЕКТРОНІВ, НЕЙТРОНІВ І ГАММА-КВАНТІВ

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

Проведено огляд робіт, у яких вивчалась взаємодія електронів, нейтронів і гамма-квантів з матеріалами постійних магнітів, які використовуються у прискорювачах електронів. Основні висновки огляду вказують, що для встановлення механізмів розмагнічення сплавів необхідно виконати докладні дослідження зміни структури матеріалів після опромінення.