LONG-TERM STABILITY OF Nd-Fe-B MAGNET FOR ELECTROSTATIC ACCELERATOR X-RAY SUPPRESSION SYSTEM

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Measurements of the magnetic field of a permanent magnet made using the rare earth alloy Nd-Fe-B were compared at an interval of 18 years. The 2025 data indicate that the magnet's metrological characteristics remained within the limits determined in the 2007 studies. Diffusion of Fe-Al-Nb with grain formation on the magnet surface was identified. The surface segregation time was 18 years. The grain composition was determined.

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INTRODUCTION

Permanent magnets made of rare earth metal alloys are important components of electrical devices and systems [1]. One of the main requirements for a magnetic field is its temporal stability. It is determined by the aging of the magnet over time under the influence of various factors harmful to it.

In [2], the magnetic field of an unirradiated sample of a Sm-Co alloy magnet was measured after 5 years of experiments. It was shown that the magnetic field remained unchanged.

In [3], it was concluded that for a sample of an Nd-Fe-B magnet exposed to bremsstrahlung radiation, no significant change in the field was observed.

Currently, to reduce X-ray radiation from the accelerating tube (AT) of the Sokol electrostatic accelerator (ESA) at the Institute of Applied Physics of the National Academy of Sciences of Ukraine, a magnetic system consisting of permanent magnets [4–7] has been used for 18 years (Fig. 1).

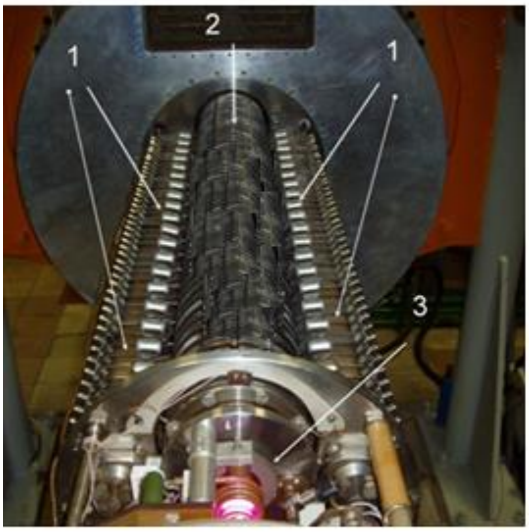

Fig. 1. Location of the radiation suppression system magnets on the high-voltage structure of the AF: 1 – magnets; 2 – AT; 3 – ion source

The purpose of this study is to evaluate the aging of reference magnets that are not installed on the ESA and have been stored under normal conditions. This will allow us to determine the degree of influence of harmful factors on the aging of magnets installed on the ESA AT.

LONG-TERM MAGNETIC STABILITY OF REFERENCE (UNIRRADIATED) MAGNETS

The reason for the aging of magnets is a change in the domain structure of the material, which tends to establish a stable thermodynamic equilibrium over time. The main factors affecting aging are radiation (irradiation with gamma quanta, neutrons, etc.), temperature, and chemical exposure (aggressive environments).

The magnets of the Sokol radiation suppression system are made of Nd-Fe-B (neodymium-iron-boron, ТУУ 21174514.001-96) produced by Polus-N Scientific and Production Company (Kharkiv, Ukraine). The cylindrical magnets (length 30 mm, diameter 16 mm) are manufactured using PLP technology. Typical density is 7.35...7.4 g/cm^3. A layer of Ni was used as a protective coating, with a layer of Zn on the ends. The thickness of the layers is 0.2 mm. Residual magnetization B_r = 1.2 T.

The percentage composition of the magnet was measured using a ProSpector 3 Elvatech portable X-ray fluorescence analyzer. The results are presented in Table 1.

Table 1
Magnet composition (%, 2025)

Nd	Fe	B	Nb	Cu	Al
15	80.23	1	1.83	1.0	0.9

The reference magnets were stored under conditions close to normal (closed room, relative humidity 40...60%, ambient temperature 18...20 °C, Earth's magnetic field induction 50 µT).

The magnetic induction profiles $B(z) = B_x$ were measured at a distance X_0 from the plane $X=X_0$ (Fig. 2).

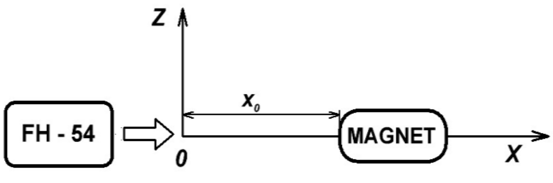

Fig. 2. Experimental setup: X_0= 75 mm, Z =0…120 mm

The measurements were performed using a FH-54 Gauss-Teslameter. The magnetic field induction profiles are shown in Fig. 3.

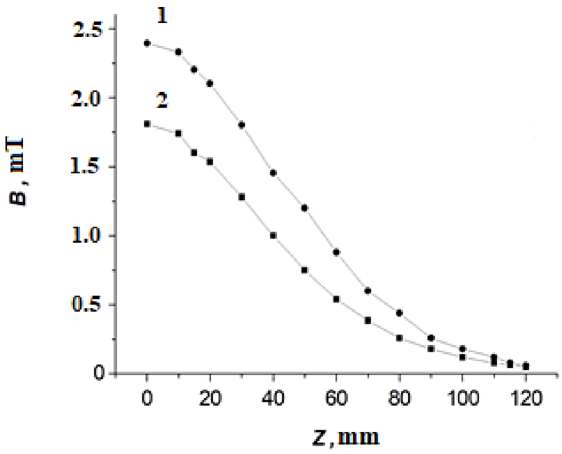

Fig. 3. Magnetic induction profiles of reference magnets: 1 – measurements in 2007; 2 – measurements in 2025

The magnet aging coefficient at point Z=0, X=0 is:

$\beta_s = (\Delta B/B) = (2.394 - 1.81)/2.394) = 24\%.$ (1)

Measurements were taken for a group of $N = 10$ magnets, resulting in the average magnetic field induction value:

$$B = \frac{1}{N}\sum_{1}^{N} B_n .$$

After the magnets were manufactured (2007), the magnetic induction at their ends (magnetic charge density):

$$B_{n0} = 0.7\,T,$$

after 18 years (2025):

$$B_n = 0.557\,T .$$

Thus, for the ends of the magnets:

$$\beta_c = \frac{B_{n0} - B_n}{B_{n0}} = 23\,\%,$$

which corresponds to (1) with an accuracy of the experimental error.

The change in magnetic induction $\beta_c = (\Delta B/B)\times 100\%$, caused by magnetic aging during the time τ, can be estimated by the following expression [8, 9]:

$$\beta_c = A \cdot \ln(\tau/\tau_0) \times 100\%, \quad (2)$$

where the aging coefficient A is determined experimentally by magnetic aging at a single operating point during the time $\tau = \tau_A$.

As a rule, for permanent rare-earth magnets of various types, in practice (τ= 1 year) is taken $\beta_c \sim 1 \ldots 2\%$.

In our case, the estimate is:

$$\beta_c \approx 18 \text{ years} \times 1.5\% = 27\%, \quad (3)$$

which is in good agreement with (1).

From (1) and (2), assuming $\tau_0 = 1$ year, $\tau_A =$ 18 years, we obtain $A = 0.086$, and for this Nd-Fe-B magnet (1) will take the form:

$$\beta_c = 0.086 \cdot \ln(\tau) \times 100\%. \quad (4)$$

Next, the results obtained are compared with magnetic measurements on the “Sokol” electronic control system. This will allow us to determine the influence of harmful factors (radiation, chemically aggressive environment, temperature) on the stability of the magnets.

DIFFUSION OF Fe-Al-Nb GRAINS TO THE SURFACE OF THE MAGNET. THE EFFECT OF TEMPORARY SEGREGATION OF Nd-Fe-B MAGNET GRAINS

Over 18 years of storage, a layer of black grains more than 3 mm thick has accumulated on the ends of the reference magnets (Fig. 4). At the same time, no defects associated with the emergence of grain components on the surface of the magnet have been observed. The diameter of the grains, measured using an MBS-10 optical microscope, was 0.01 mm.

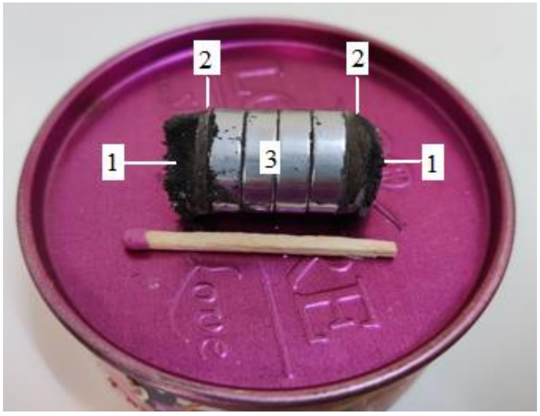

Fig. 4. Grains on the surface of the magnet: 1 – grains; 2 – Zn coating; 3 – Ni coating

The results of measuring the percentage composition of the grains are presented in Table 2. Neodymium (Ne), the main driver of magnetic force (residual magnetization B_r), is not included in the composition of the grains. The composition of the grains may indicate a decrease in mechanical strength (Fe, Al), corrosion resistance, moisture resistance (Al), and stability of magnetic characteristics (Nb).

The qualitative composition generally corresponds to the content of the components of magnet scrap [10].

Table 2

Composition of grains on the magnet (%, 2025)

Fe	Al	Nb
95.3	2.2	2.44

CONCLUSIONS

1. Magnetic aging of reference magnets 18 years after manufacture is approximately 20% (1).
2. An analytical expression for the change in magnetic induction caused by aging (4) has been obtained, which is in good agreement with the experimental results.
3. In the future, it is necessary to determine the aging of magnets after 2 years (a series of aging of permanent magnets: 7, 17, 20 years).
4. Temporary segregation of magnet components was detected, followed by the formation of grains on the surface of the magnet (see Fig. 4, Table 2).

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ДОВГОТРИВАЛА СТАБІЛЬНІСТЬ МАГНІТУ Nd-Fe-B ДЛЯ СИСТЕМИ СУПРЕСІЇ РЕНТГЕНІВСЬКОГО ВИПРОМІНЮВАННЯ В ЕЛЕКТРОСТАТИЧНОМУ ПРИСКОРЮВАЧІ

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Проведено порівняння вимірювань магнітного поля постійного магніту, виготовленого з рідкісноземельного сплаву Nd-Fe-B, з інтервалом у 18 років. Дані 2025 року свідчать, що метрологічні характеристики магніту залишилися в межах, визначених у дослідженнях 2007 року. Виявлено дифузію Fe-Al-Nb з утворенням зерен на поверхні магніту. Час поверхневої сегрегації становив 18 років. Визначено склад зерен.