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## Magnetoelastic effects in $\text{Nd}_2\text{Fe}_{14}\text{B}$ permanent magnets for undulator systems

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Received March 2, 2026

Revised March 31, 2026

Accepted April 1, 2026

The effects of uniaxial compression up to 70 MPa on the stray field of  $\text{NdFeB}$  permanent magnets for undulator systems were experimentally studied. Spatially distributed alteration of magnetic flux density was registered with three dimensional Hall mapping. Observed difference was established to be a result of magnetoelastic Villari effect as opposed to being limited by sample motion during the experiment. Relative change in magnetic flux density reached  $\sim 10^{-2}$ . Presented results are important to determine allowable mechanical loads on permanent magnets during precision undulator design to achieve stable field distribution in the gap.

**Keywords:**  $\text{NdFeB}$ , Villari effect, permanent magnet undulator, stray field.

DOI: 10.61011/TPL.2026.07.63829.20665

The magnetoelastic effect, also known as the Villari effect, is a phenomenon of variation in the magnetic properties of a ferromagnetic material under the action of mechanical stresses of various nature (compression, tension, bending, torsion, etc.). The magnetoelastic effect is by its nature the inverse of magnetostriction and has potential for application in magnetic straintronics — a sector of micro- and nanoelectronics industry, where mechanical strains are used to control magnetic properties and convert the energy [1,2].

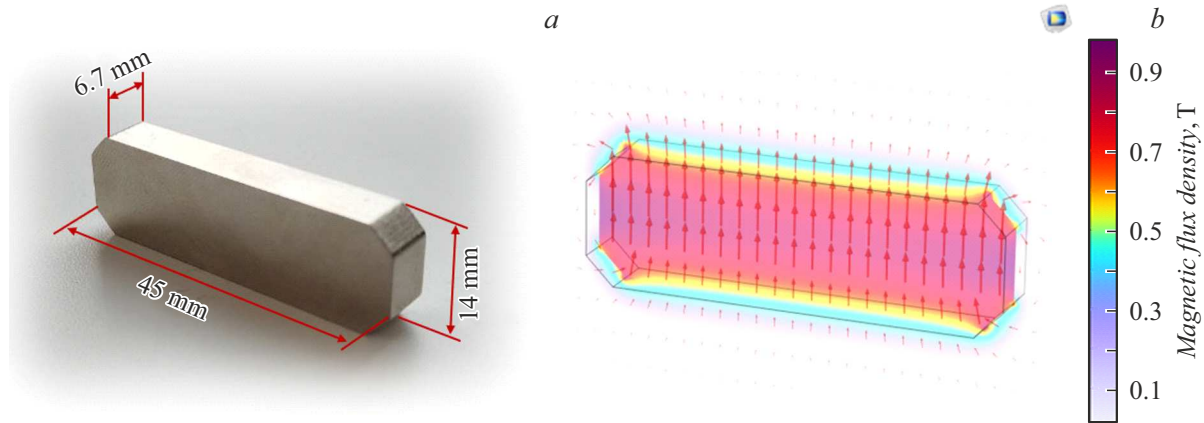
On the other hand, accounting for the magnetoelastic effects is crucial in technical systems and devices, in which, on the contrary, stable magnetic properties are required. Such devices include undulators — an insertion device for generating coherent synchrotron radiation, which has a periodic structure of dipole magnets (permanent or superconducting), and electrons passing through the periodic magnetic structure are forced to move with acceleration and thus radiate energy [3,4]. Some of the most common insertion devices for generating coherent synchrotron radiation are permanent magnet undulators, which use magnetized blocks of permanent magnets ( $\text{NdFeB}$ ,  $\text{SmCo}$ , etc.) as a source of magnetic field. The key challenge in manufacturing precision permanent magnet undulators lies in high demands placed on the precision of the magnetic assembly and the stability of the permanent magnet properties to achieve the required spatial distribution of magnetic induction in the working gap of the device. Errors in distribution of magnetic induction in the working gap of the undulator affect the trajectory of the electron beam and reduce the radiation intensity at a given frequency. The angular deviation of the electron beam is defined by the first integral of the magnetic field along the direction of its movement, the orbital displacement of the electron beam is determined by the second integral of the magnetic field,

and the quality of the radiation can be estimated by the root-mean-square error of the magnetic field induction in the amplitude value or phase error.

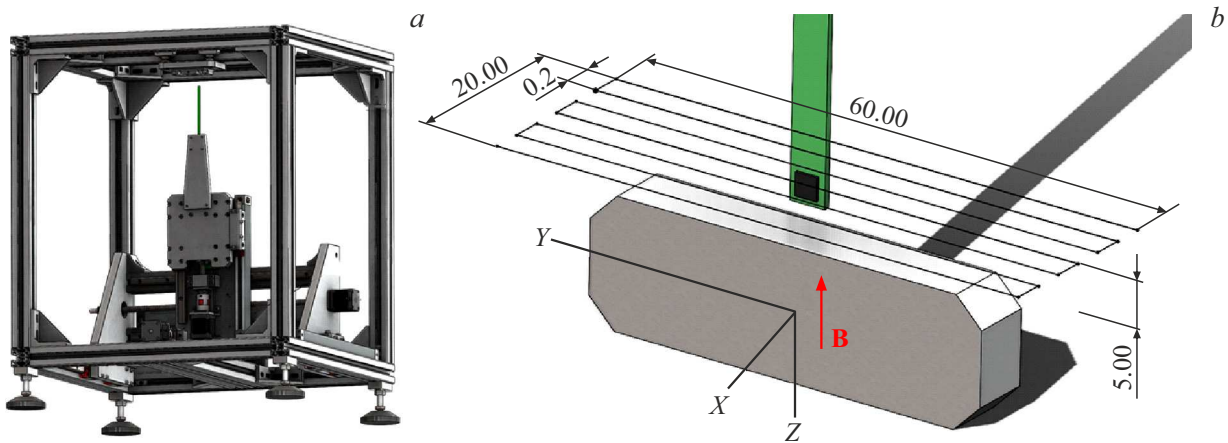
There are various technical solutions and algorithms for undulator tuning, which are associated both with the creation of precision mechanical systems for moving magnetic elements [5,6], and with the arrangement of blocks of permanent magnets of the magnetic assembly in a certain sequence [7]. From the appropriate literature we see that there are virtually no works that systematically study phenomena associated with the influence of mechanical effects on the magnetic properties of permanent magnets [8–10], in particular those used in modern undulators with permanent magnets. This problem is relevant because magnetic properties of a permanent magnet in a free and mechanically clamped state in an undulator assembly may differ, especially in the case of hidden mechanical defects and non-uniform magnetization of the permanent magnet block.

Given this, it was required to evaluate the influence of uniaxial mechanical compression on residual magnetic induction  $B_r$   $\text{Nd}_2\text{Fe}_{14}\text{B}$  ( $\text{NdFeB}$ ), which is one of the main magnetic characteristics of permanent magnets. The change in residual magnetic induction was assessed by measuring the spatial distribution of magnetic field induction at a given distance from the permanent magnet. The samples of permanent  $\text{NdFeB}$  magnets were studied with standard dimensions corresponding to the magnetic elements used in U27 undulators (ESRF, Grenoble, France) [11] with a period of  $\lambda_U = 27$  mm — one of the common types of insertion devices used in modern third and fourth generation synchrotron radiation sources. The material of permanent magnet corresponds to N38EH grade.

The authors developed a setup for three-dimensional mapping of magnetic fields, consisting of an AST144SH Hall sensor on a three-axis suspension. The suspension allows



**Figure 1.** The magnet sample under study. *a* — photo of the sample, *b* — distribution of magnetic induction in the plane of the sample, illustrating the direction of magnetization.



**Figure 2.** Experimental setup for measuring magnetic field. *a* — digital model of the experimental setup, *b* — trajectory of the Hall sensor during the experiment.

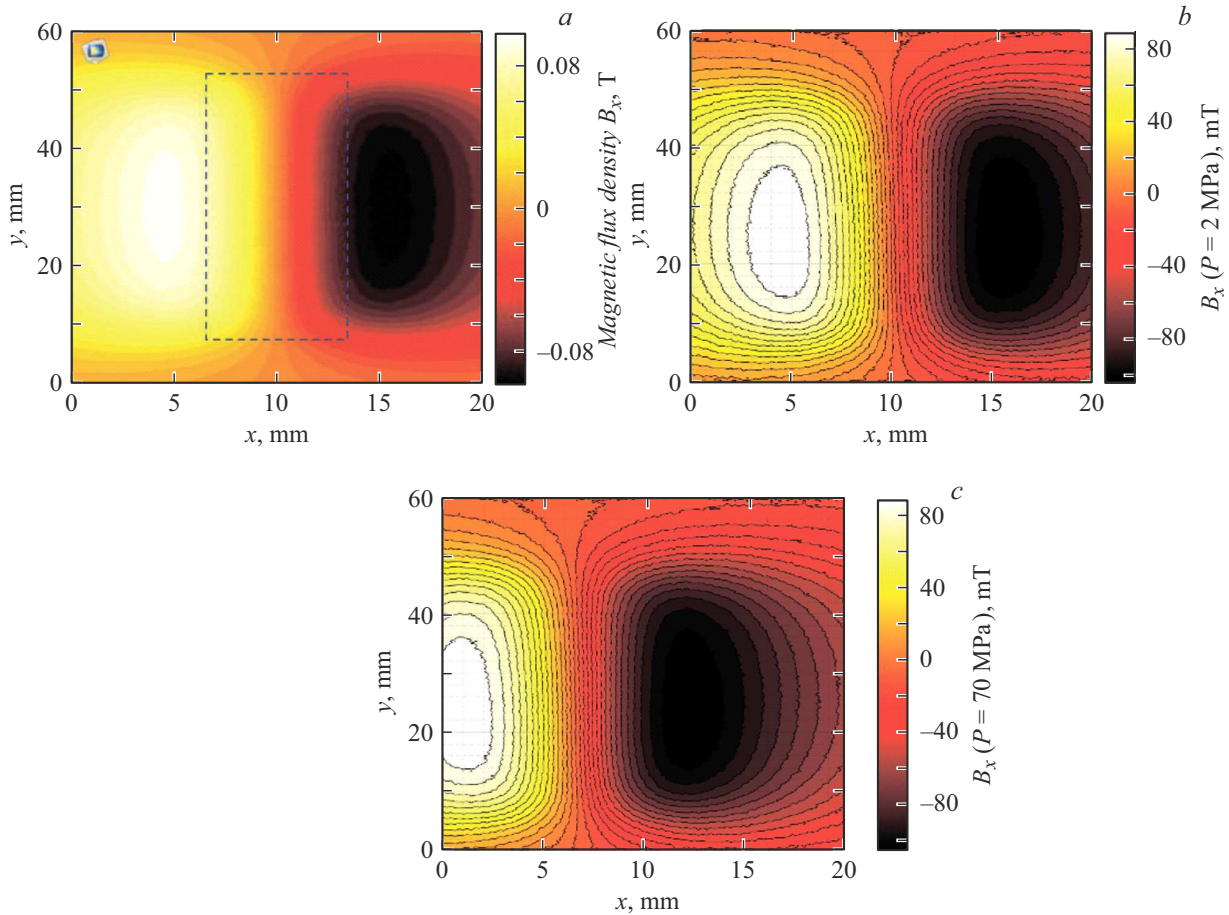
the sensor to be moved in space along any trajectory in accordance with a given program. A set of linear encoders in the setup monitors the sensor's movements. The signal from these encoders acts as a trigger for reading the sensor data. In this way, scanning of a three-dimensional region of space with high ( $4\mu\text{m}$ ) spatial resolution and collection of data on the distribution of magnetic induction around the sample are carried out automatically. To uniaxially compress a sample with a given force, a vice made of a material with low magnetic susceptibility, calibrated using a force sensor, was developed and manufactured. The mechanism allows creating a force of up to 40–45 kN, which for the selected sample corresponds to a mechanical stress of 70 MPa.

During the experiment, a sample of NdFeB undulator magnet (Fig. 1, *a*) magnetized as shown in Fig. 1, *b* was investigated. The sample was compressed in the magnetic field measuring setup (Fig. 2, *a*) with a slight force of 2 MPa in the direction of *X* axis. The Hall sensor measured  $B_x$  component of the magnetic induction vector  $\mathbf{B}$  and moved along a zigzag trajectory (Fig. 2, *b*) with a step between passes of  $200\mu\text{m}$ . A total of 100 passes were

performed; thus, a two-dimensional rectangular area of size  $20 \times 60\text{ mm}$ , located at a distance of 5 mm above the end of the magnet, was scanned. During each pass, voltage was measured from the Hall sensor at 15,000 points located every  $4\mu\text{m}$ . Inaccuracies in the movement system resulted in the number of measured points in different passes differing by a small amount with an error of within 5 points per pass. After this, a load of 70 MPa was applied to the magnet and the experiment was repeated.

Also, to verify the measurement results, computer modeling of the magnetic field distribution was carried out using the finite element method in COMSOL Multiphysics software. Magnetic Fields module was used for modelling, the magnet geometry was similar to the real sample geometry, the magnet material was NdFeB alloy, the material parameters were taken from COMSOL library [12], the residual magnetization value was  $B_r = 1.2\text{ T}$ . The modelling results are given in Fig. 3, *a*.

As a result of the experimental study, in each of the measurement series, approximately  $1.5 \cdot 10^6$  values of the sought field component were obtained. To compensate for

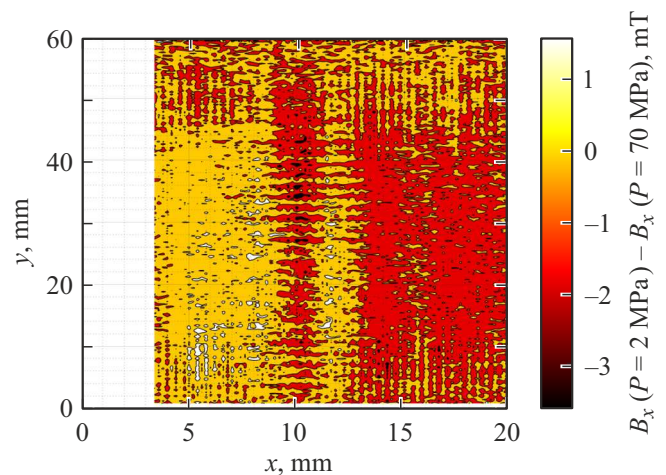


**Figure 3.** Results from studying the sample's magnetic field. *a* — spatial distribution of the magnetic induction vector component  $B_x$  obtained as a result of modeling in COMSOL Multiphysics (the dashed line shows the location of the magnet in the model); the measured distribution of the magnetic induction vector component  $B_x$ : *b* — compression force 2 MPa, *c* — compression force 70 MPa.

the variation in the number of points between passes, only the first 14,950 points of each pass were used. To reduce the sensor noise and obtain field values, a median filter was applied to the square grid cells, thinning out the grid in the direction of  $Y$  axis. Thus, two field distributions in  $20 \times 59.8$  mm region were obtained with a step of  $200 \mu\text{m}$  in each of the directions (Fig. 3, *b, c*).

It can be seen that experimental results are qualitatively consistent with the results of computer modeling shown in Fig. 3, *a*, however, in Fig. 3, *c* a shift of the magnetic field of the sample in the direction parallel to the applied load is noticeable, which significantly exceeds the characteristic values of magnetostriction and therefore can be caused by the displacement of the sample itself during loading. To eliminate the effect of the sample's possible displacements, an attempt was made to move the measured point clouds so that the symmetry planes of the measured fields coincided (by rotation and translation) (Fig. 4).

As a result, it was found that when loading the sample with a pressure of 70 MPa, changes in the field within the range of  $\pm 3$  mT were observed in the studied zone. It is noticeable that in the right part of the studied region the field induction has mainly increased, while in the left



**Figure 4.** The difference between the fields in the loaded and unloaded state.

part it has generally declined. This change may be caused by rotation of the sample around  $Y$  axis and cannot be compensated for in this experiment. It is noteworthy that in

the plane of the sample's symmetry (corresponding to the coordinate  $x = 10$  mm) an increase in the field is observed, and to the left and right a decrease is seen, which cannot be explained by any displacement of the sample. The observed result confirms that the application of external mechanical stress leads to a decrease in the magnetic induction of the stray fields from the permanent magnet due to Villari effect. Another possible explanation for the result is a change in the magnetic field because of disruption of the sample's integrity caused by compression with the formation of microcracks, however, existing studies [13,14] of the mechanical properties of NdFeB do not predict such behavior of the sample when a load of 70 MPa is slowly applied.

Thus, the developed experimental setup for three-dimensional mapping of the magnetic field of Nd<sub>2</sub>Fe<sub>14</sub>B permanent magnets under controlled mechanical loading made it possible to experimentally study the effect of uniaxial compression up to 70 MPa on the spatial distribution of magnetic induction around NdFeB magnet. It is shown that the observed changes in the magnetic field are not reduced to mechanical displacement of the sample and indicate the manifestation of magnetoelastic effects. The obtained findings are important for selecting design solutions for the implementation of permanent magnet holders and assessing the values of permissible mechanical loads in order to ensure stability and specified accuracy of creating a spatial distribution of magnetic induction in the gap of undulator systems with permanent magnets.

### Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by T. Zorina