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PHYSICS AND TECHNIQUE OF ACCELERATORS

Magnetization Measurement and Sorting of Permanent Magnets for the NovoFEL Variable-Period Undulator

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Abstract—A new variable-period undulator for the Novosibirsk free electron laser facility (FEL) is being developed at the Budker Institute of Nuclear Physics. The undulator has an enlarged aperture, so it uses permanent magnets with a nonstandard shape. In this article, the design of the measuring stand is described and preliminary results of measurements of the parameters of the magnet are presented.

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INTRODUCTION

The Novosibirsk free electron laser (FEL) is a unique source of coherent radiation with a total wavelength tuning range of 8–340 μm [1]. This source includes three FELs, the undulators of which are installed on different tracks of the multiturn accelerator–recuperator. The first of these FELs operates in the terahertz region of the spectrum 90–340 μm. In its spectral range, this FEL has the highest average radiation power in the world. It was put into operation in 2003 and has since been successfully used for research in various fields of science, including physics, chemistry, and biology.

At present, an electromagnetic undulator consisting of two sections is installed in the first FEL. A similar undulator was previously used in the second FEL, but in the summer of 2021 it was replaced by an undulator based on permanent magnets with a variable period (VPR) [2]. As a result of this replacement, the wavelength tuning range of the second FEL was increased from 35–80 to 15–120 μm. The successful launch of the second FEL demonstrated the operability of the new undulator design and confirmed the feasibility of installing a VPR on the first FEL. Work on the creation of such an undulator for the first FEL is currently being carried out at the Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Sciences [3]. The new undulator will make it possible to expand the wavelength tuning range of this FEL to the long wavelength region.

An increase in the wavelength will lead to an increase in the size of the light beam in the FEL, so the new undulator must have a sufficiently large aperture. At the same time, to preserve the short-wavelength limit of the tuning range, the minimum period of the undulator should be sufficiently small. Since the required minimum period (10 cm) in the new undulator turned out to be less than its minimum allowable aperture (14 cm), the geometry of the undulator was optimized in order to obtain a sufficiently large amplitude of the magnetic field on the axis. Based on the results of this optimization, the shape of the magnets was chosen in the form of a turned letter *C* with rather large dimensions: height of 120 mm (outer border radius 130 mm), width of 240 mm, and thickness of 40 mm (see Fig. 1).

The weight of one magnet is 6.25 kg. The main magnetization component is directed perpendicular to the large flat face of the magnet. In the process of manufacturing magnets, magnetization errors inevitably appear, which can manifest themselves both in the form of a spread in the value of the main (longitudinal) component and in the appearance of additional transverse components. To control the quality of the magnets, a measuring bench was assembled, which makes it possible to find all three magnetization components with the required accuracy.

DESIGN OF THE MEASURING STAND

The standard method for measuring magnetization is based on the use of Helmholtz coils. In this method, using an integrating voltmeter, the integral of the EMF induced in the coil is measured when the magnet is removed or rotated by 180°. The value of the measured integral is proportional to the projection of the total magnetic moment onto the axis of the coils [4, 5].

The method of measuring the magnetization with the extraction of the magnet from the coil was already successfully used by us earlier for sorting the VPR

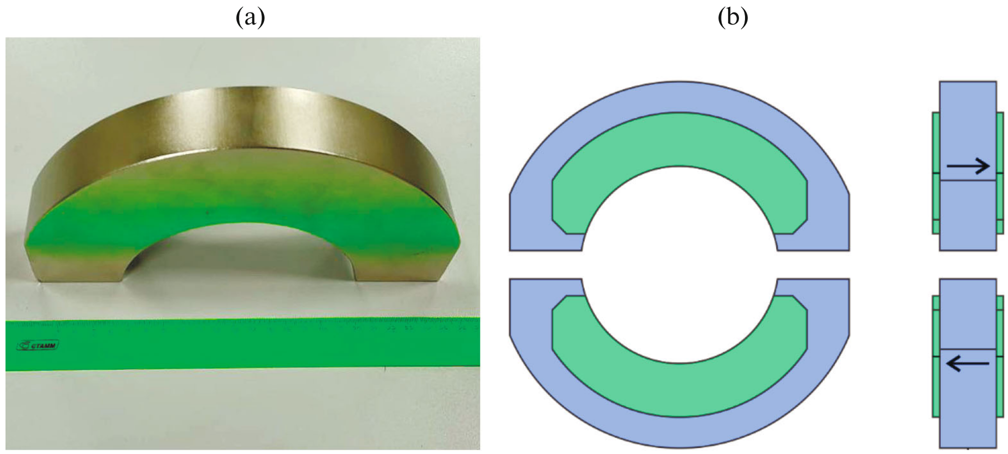

Fig. 1. (a) Photograph of the magnet and (b) diagram of one half-cycle of the undulator (front and side views). Permanent magnets are blue and iron poles are green. The arrows show the direction of the magnetization of the magnets.

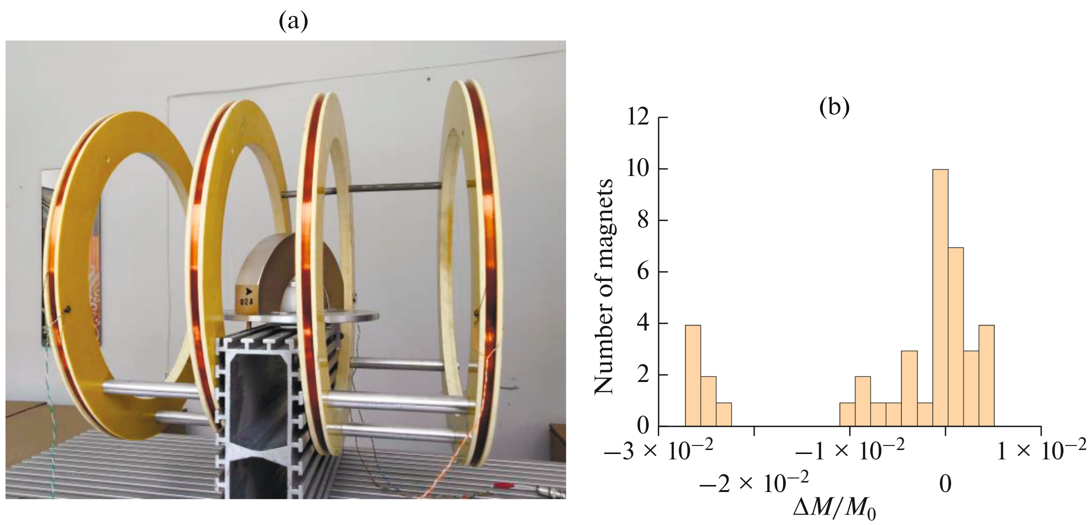

Fig. 2. (a) Photograph of the measuring stand with the installed magnet; (b) histogram of relative deviations of the measured values of the main magnetization component for 40 magnets.

magnets of the second FEL [6]. The use of this method for new magnets is complicated by the fact that the magnets have a large mass and size, so it was decided to use a variation of this method with a magnet rotated by 180°.

To carry out a correct measurement, the magnet in its initial position must be completely placed in the region of uniformity of the magnetic field of the coils. To reduce the dimensions of the measuring stand while maintaining the size of the homogeneity region, instead of Helmholtz coils, it is advisable to use Baker coils [7], which are four coaxial coils of the same diameter, and the number of turns in the outer coils is greater than in the inner coils. For all initial positions of the magnet that are used for measurements, the magnet is entirely in the region of uniformity, within which the relative deviation of the coil field does not exceed 2×10^{-3}, ensuring sufficient accuracy of the measured magnetization values.

Based on the dimensions of the coils obtained as a result of the optimization, a measuring stand was designed (Fig. 2a).

The coils are wound with thin wire on frames made of textolite. The radius of the coils is 250 mm, the winding width is 10 mm, and the thickness is about 1 mm. The number of turns in the outer coils is 100; in the inner coils it is 44. The coils are connected in series and connected to a VsDC3 integrating voltmeter developed at the Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences [8]. The coil frames are fixed on an aluminum profile on which a turntable is also located. There are stops on the table that uniquely fix the position of the magnet. To measure the main magnetization component, the magnet is placed vertically, and to measure the transverse components, the magnet is placed horizontally on the table. In order to keep the center of mass of the magnet as close as possible to the center of the coils, two different tables with different heights are used in the case of vertical and horizontal orientation of the magnet. This design provides for the adjustment of the angle of rotation, which is carried out due to the fine adjustment of the limiters.

MEASUREMENT RESULTS

A photo of the stand with the magnet is shown in Fig. 2a. The position of the magnet shown in the photo was used to measure the main component of the magnetization. To measure the transverse components, the magnet was placed horizontally, the measurements of each transverse component were performed at two positions of the magnet with the main component of the magnetization directed up and down, and the result was averaged. This was done in order to eliminate the contribution to the measurement of the main component, which may arise due to the tilt of the table plane relative to the coil axis.

The magnetizations of 40 magnets were measured. For all magnets, the magnitude of the transverse components of the magnetization turned out to be within the allowable values: $\max\left|\Delta M_x/M_0\right| \le 0.4\%$, $\max\left|\Delta M_y/M_0\right| \le 1\%$. The results of measurements of the main component are presented in Fig. 2b. From the histogram shown in this figure, it can be seen that the parameters of 33 magnets satisfy all the imposed restrictions.

CONCLUSIONS

By selecting the shape of the magnets, it is possible to design undulators with nonstandard geometries optimized for specific applications. Modern technologies make it possible to manufacture magnets of arbitrary shape with a sufficiently small spread of parameters, which makes it possible to use them in undulators for FELs. Nevertheless, despite the rather high manufacturing quality, the control of the parameters of the magnets is an important step in the assembly of the undulator. To measure the parameters, depending on the chosen shape of the magnets, it may be necessary to modify the standard measurement methods or develop new ones.

The magnetization measurement method considered in this article provides an accuracy sufficient for manufacturing a new variable-period undulator for the Novosibirsk FEL. The use of this undulator will significantly expand the boundaries of possible applications of this FEL.

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REFERENCES

1. N. A. Vinokurov and O. A. Shevchenko, “Free electron lasers and their development at the Budker Institute of Nuclear Physics, SB RAS,” Phys. Usp. **61**, 435–448 (2018).
2. I. V. Davidyuk, O. A. Shevchenko, V. G. Tcheskidov, and N. A. Vinokurov, “Modeling and designing of variable-period and variable-pole-number undulator,” Phys. Rev. Accel. Beams **19**, 20701 (2016).
3. I. Davidyuk, O. A. Shevchenko, V. G. Tcheskidov, and N. A. Vinokurov, “Magnetic and mechanical design of large-aperture variable-period permanent magnet undulator,” Nucl. Instr. Methods Phys. Res., Sect. A **915**, 36–39 (2019).
4. D. Martin and M. Benz, “Magnetization changes for cobalt-rare-earth permanent magnet alloys when heated up to 650°C,” IEEE Trans. Magn. **8**, 35–41 (1972).
5. S. R. Trout, “Use of Helmholtz Coils for magnetic measurements,” IEEE Trans. Magn. **24**, 2108–2111 (1988).
6. Ya. Gorbachev, I. Davidyuk, S. Serednyakov, N. Vinokurov, V. Tcheskidov, A. Pavlenko, A. Batrakov, K. Shtro, and O. Shevchenko, “Measurements of magnetic field of variable period undulator and correction of field errors,” AIP Conf. Proc. **2299**, 020009 (2020). https://doi.org/10.1063/5.0031522
7. J. R. Barker, “New coil systems for the production of uniform magnetic fields,” J. Sci. Instrum. **26**, 273–275 (1949).
8. A. Batrakov, A. Pavlenko, D. Shickov, and P. Vagin, “Multimode digital integrators for precise magnetic measurements,” in *Proceedings of RUPAC2012 Conference, Saint-Petersburg, Russia, 2012*, pp. 617–619. https://accelconf.web.cern.ch/rupac2012/papers/weppd032.pdf.