Письма в ЭЧАЯ. 2016. Т. 13, № 7(205). С. 1269–1274

ФИЗИКА И ТЕХНИКА УСКОРИТЕЛЕЙ

THE PROTOTYPE OF NEW VARIABLE-PERIOD UNDULATOR FOR NOVOSIBIRSK FREE-ELECTRON LASER

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To improve the parameters of the second stage Novosibirsk free-electron laser, we plan to replace the existing electromagnetic undulator by permanent-magnet variable-period undulator (VPU). The VPUs have several advantages compared to conventional undulators, which include wider radiation wavelength tuning range and an option to increase the number of poles. Both these advantages will be realized in the new undulator under development at the Budker INP. There are some technical problems, which have to be solved before this idea can be implemented in practice. To check the solution of these problems, we designed and manufactured a small undulator prototype, which has just several periods. In this paper, the results of mechanical and magnetic measurements of this undulator prototype are presented and compared with simulations.

Для улучшения параметров второй очереди новосибирского лазера на свободных электронах планируется поменять существующий электромагнитный ондулятор на ондулятор с переменным периодом (ОПП). По сравнению с обычными ондуляторами ОПП имеют ряд преимуществ, среди которых более широкий диапазон перестройки длины волны и возможность изменять число полюсов. Оба этих преимущества будут реализованы в новом ондуляторе, разработка которого в настоящее время ведется в ИЯФ им. Г. И. Будкера СО РАН. Для реализации идеи ОПП необходимо решить ряд технических задач. Чтобы проверить работоспособность возможных способов решения этих задач, был сконструирован и изготовлен небольшой прототип ондулятора, состоящий всего из нескольких полюсов. В статье представлены результаты механических и магнитных измерений данного прототипа, а также проведено их сравнение с результатами компьютерного моделирования.

PACS: 41.60.Cr

INTRODUCTION

The VPU for the NovoFEL under development at the Budker INP has a remarkable feature, which is the possibility to change the number of periods. The new undulator will replace the electromagnetic one used in the second stage FEL. The old undulator has a period $\lambda_u = 120$ mm and the field amplitude B_0 varying from 0 to 0.13 T. It is installed on the bypass of the second horizontal track [1]. The tuning range of the existing FEL is 35–80 μm. Application of the VPU will allow shifting the short wavelength boundary to 15 μm [2].

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Basic undulator parameters

Parameter	Limit
Undulator period λ_u, mm	48–96
Radiation wavelength, μm	15–70
Number of periods	40–80
Filed amplitude on the undulator axis, kGs	0.94–1.9
Deflection parameter	0.42–1.79

The available free length for the undulator is 4 m. Electron energy at the second stage FEL is 22 MeV. One can find the most important parameters of the VPU in the Table.

1. UNDULATOR GEOMETRY

To ensure low diffraction losses at maximum radiation wavelength, the diameter of the circle inscribed into the aperture of undulator was chosen to be 50 mm. As the field amplitude B decreases exponentially with growth of g/λ_u, where g is the undulator gap, one can obtain the limitation that λ_u should not be smaller than g, so we have chosen minimum λ_u to be 48 mm [2].

Each undulator block consists of one permanent magnet and two iron plates. The permanent magnets are made of NdFeB. In simulations, we used a permanent magnet with a remanence of 1.3 T. We optimized the dimensions of the magnets and iron plates to obtain a maximum field amplitude at minimum period.

The transverse cross sections of the iron plate and permanent magnet with final dimensions are presented in Fig. 1. The longitudinal sizes (thicknesses) are 20 mm for the magnets and 2 mm for the iron plates.

The opposite plates of two blocks are adjacent in the longitudinal direction form one pole. Each couple of the right and left blocks at the top is combined in one unit, which can move as a whole (see Fig. 2). Each couple of the right and left blocks at the bottom also forms a similar movable unit.

The top and bottom units are not connected. Blocks in one unit are tilted relative to each other, therefore the free aperture is a rhomb. This configuration provides field amplitude growth with distance from the central axis in all directions. As a result, this undulator will focus the electron beam both horizontally and vertically. This feature is important be-

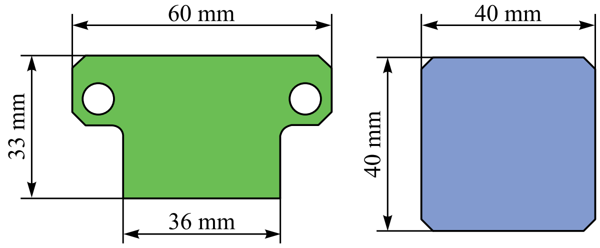

Fig. 1. Transverse cross sections of the iron plate and permanent magnet

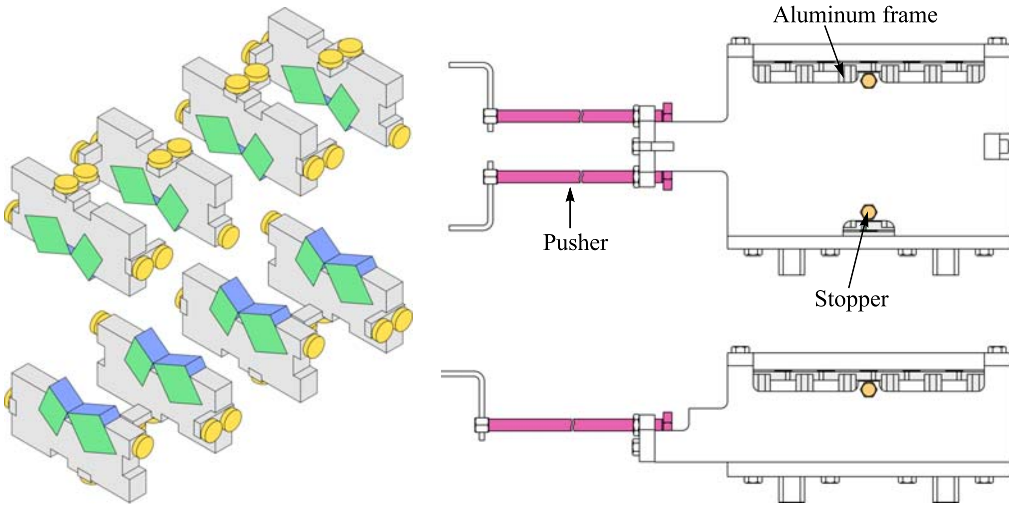

Fig. 2. Sketches of undulator units (left) and VPU prototypes (right)

cause of the low (22 MeV) electron energy and, consequently, strong focusing by the undulator field.

Each unit has a set of bearings that provide low friction to avoid significant undulator period tapering [2].

2. PROTOTYPE MECHANICAL DESIGN

Two prototypes of the VPU were manufactured in order to examine magnetic and mechanical undulator properties. Carcasses of undulators are made of aluminum and allow installing up to 8 units in a row. One prototype has both upper and lower arrays of units and the other has just upper array and a metal plate in the horizontal symmetry plane that provides proper boundary conditions for magnetic field. One can see sketches of prototypes in Fig. 2. The first one is suitable for magnetic measurements and the second one is convenient to conduct mechanical measurements. Both prototypes have pusher screws in one side and stoppers in the middle, which allows changing the number of units and undulator period. There are deepenings in the inner side of the frames for bearings.

As was said before, each undulator unit consists of two permanent magnets, four iron plates, aluminum frame, and a set of bearings. Bearings positions are optimized to avoid tilts of the unit.

3. MAGNETIC MEASUREMENTS

To check results of three-dimensional computer simulations of the field in the undulator, several mechanical and magnetic measurements were performed.

One can measure the value of magnetic field produced by a single undulator unit at a given point with the help of the Hall probe. So one can compare magnetization of different units with the value used in simulations.

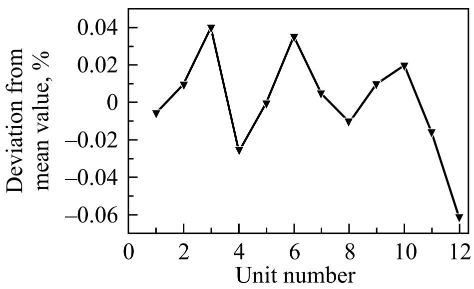

Fig. 3. Variation of unit's field measured at given point

The mean value of longitudinal magnetic field measured by the Hall probe at 90-mm distance from unit is 97.8 Gs, while the magnetic field calculated in CST Studio software [3] for this configuration is 97.3 Gs. It means that magnetizations of manufactured magnets are very close to project value 1.3 T. One can see deviation from the mean value of magnetization for all units in Fig. 3.

Moreover, the distribution of magnetic field in the prototype was measured, Fig. 4. As the prototype contains only a few units, its field distribution does not have regular part at all. To characterize the field properties, we used the field oscillation amplitude in the middle of undulator. It was obtained by fitting of the cosine function with its third harmonic to the measured data. This value does not have to coincide with the field amplitude in the regular part, but nevertheless the agreement with simulations is quite good. One can see the dependence of measured vertical field amplitude on the undulator period in Fig. 4 and compare it with the results of simulations.

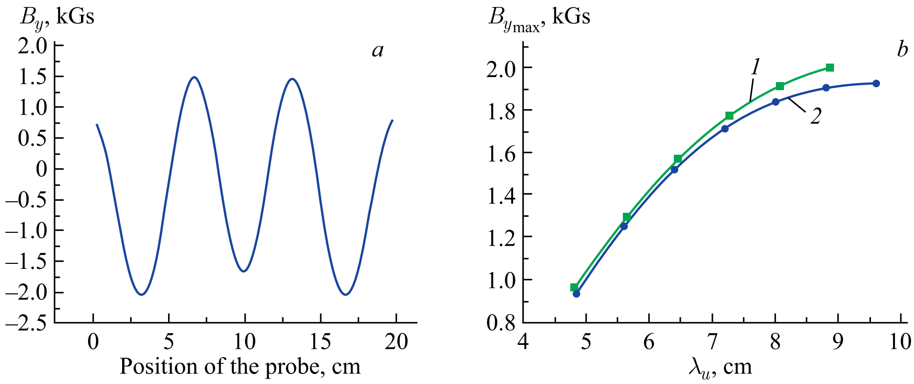

Fig. 4 (color online). Measured field distribution on the prototype axis (plot *a*, $\lambda_u = 6.46$ cm). Magnetic field amplitude (plot *b*, green line (*1*) — measured data, blue line (*2*) — data from computer model)

4. MECHANICAL MEASUREMENTS AND COMPARISON WITH SIMULATIONS

Attraction force between upper and lower units placed in the magnetic field H can be described by Maxwell's stress tensor [4]. The vertical force can be found as integral of stress tensor over horizontal symmetry plane between two units. Using magnetic field distribution from simulations, one can find the vertical attraction force and compare it to the measured one.

One can see scheme of the experiment in Fig. 5. Lower unit was fixed and upper unit could be moved only vertically. The measured force is 60.42 N and the weight of the unit is 9.92 N, thus, attraction force is 50.5 N.

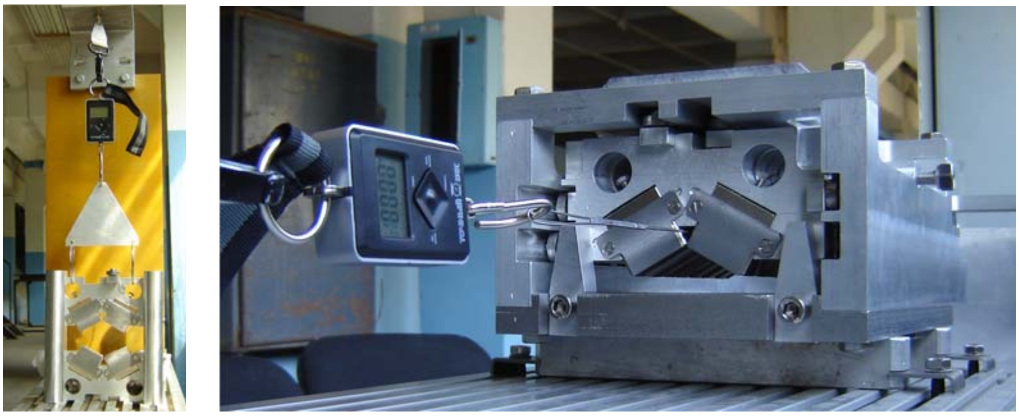

Fig. 5. Measurement of the vertical attraction force (left), measurement of longitudinal repulsive force (right)

The force obtained from numerical calculation of simulated field is 50.85 N. Claimed error of the dynamometer is 0.1 N, measuring distance between units could also add error.

The repulsive force acting between undulator units, significant characteristic for VPU, was carefully measured as well. The prototype construction allows one to fix position of the first and the last units. In order to avoid errors related with displacement of inner units, it was decided to measure longitudinal repulsive force using only three units: two fixed at the ends and one that we can move in the middle, as shown in Fig. 5.

As the period of undulator changes, the restoring longitudinal force changes too. Figure 6 shows the dependence of three-unit system rigidity (repulsive force normalized on shift) on the undulator period. The results of simulations differ from the measured values on short periods, where the error of measuring force is higher.

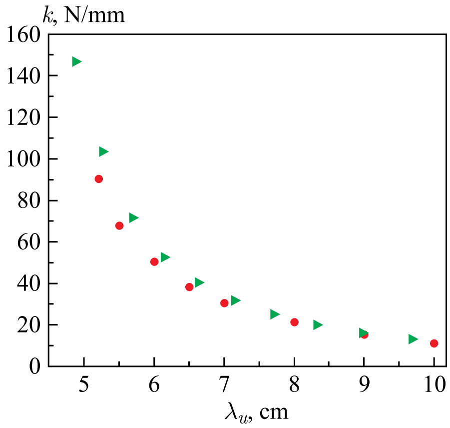

Fig. 6. Dependence of three-unit system rigidity on the undulator period (triangles — data from simulations, circles — measured data)

CONCLUSIONS

Results of measurements obtained at VPU prototypes are in good agreement with simulations. It confirms the feasibility of our VPU design. Valuable experience, which was obtained during the prototype assembly, will be used for the full-scale undulator that is being designed and manufactured at the Budker INP now.

This work was supported by the Russian Science Foundation (project No. 14-12-00480).

REFERENCES

1. *Kulipanov G. N. et al.* // IEEE Trans. Terahertz Science and Tech. 2015. V. 5, No. 5. P. 798.
2. *Davidyuk I. V. et al.* // Proc. of FEL, Basel, Switzerland, 2014. P. 66.
3. CST Studio Website. https://www.cst.com/Products/CSTEMS.
4. *Landau L. D., Lifshitz E. M.* The Classical Theory of Fields. Amsterdam: Elsevier Sci., 1980.