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VARIABLE-PERIOD VARIABLE-POLE NUMBER HYBRID UNDULATOR DESIGN FOR NOVOSIBIRSK THz FEL

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Abstract

The undulator developed for the first FEL of Novosibirsk FEL facility employs variable-period structure based on the hybrid undulator scheme with poles splinted into halves. The design was adapted to deliver optimal performance, estimations were made based on results of three-dimensional field simulations. According to the modeling results, the undulator will not only widen significantly the first FEL tuning range moving the long-wavelength border of the first harmonic from 200 µm to 450 µm but also provide wider aperture and increase efficiency at shorter wavelengths.

INTRODUCTION

Undulators are magnetic devices designed to provide intensive interaction of a monochromatic electromagnetic wave with a relativistic electron beam (see [1]). They are used in both spontaneous and stimulated emission modes. FELs are based on the second one but in both cases, it needs to provide the ability to tune the wavelength of the radiation. The undulator radiation properties depend on the parameters of an electron beam and field distribution in an undulator, but mainly first radiation harmonic properties are determined by following three parameters: electron energy, undulator period, and undulator field amplitude. One way to tune the wavelength is to vary the electron energy. This approach was implemented successfully [2,3] in the first hard x-ray FEL LCLS. Field amplitude variation is the most common way of wavelength tuning. In permanent magnet undulators, it is frequently realized due to change in the gap between the upper and lower halves of undulator [4]. Alternatively, an undulator period may be varied to shift radiation wavelength, some advantages of this approach in comparison with other techniques of radiation tuning are described in [5], where a bellows-like scheme was proposed. A design of electromagnetic variable-period undulators for storage rings was developed in [6]. Recently, a Halbach structure based on an arrangement of rotating cylindrical permanent magnets was proposed, the period of such an undulator may be varied by tuning magnetization rotation angle between adjacent cylinders[7].

A concept of hybrid undulator with freely moving poles was proposed in [8], and a similar helical device was constructed and commissioned at KAERI [9]. Following this concept, a planar undulator with a variable period and a variable pole number was designed for the second FEL of the Novosibirsk FEL facility [10–13]. Results of modeling in [14] show that the new undulator will widen the radiation wavelength tuning range and the gain variation will be smaller within this range in comparison with existing electromagnetic (EM) undulator and hypothetical optimal variable gap undulator. A prototype of this device has been manufactured; details of tests of its properties can be found in [15].

In this paper authors describe a new permanent magnet variable-period undulator (VPU) that was designed to upgrade the first (terahertz) FEL of the Novosibirsk FEL facility. In order to shift the long-wave limit of the tuning range from 200 µm to 400 µm and beyond, the aperture of the vacuum chamber in the new undulator will be increased, which will reduce the diffraction losses at the ends of the insertion device section. The enlarged gap undulator will be installed on the first track of the energy recovery linac. It will replace the existing two 4-meter long undulators and phase shifter between them. Both old undulators are planar electromagnetic devices with a period of 12 cm, a gap of 8 cm, and the undulator deflecting parameter K varying from zero to 1.1, see Table 1.

Table 1: Basic Undulator Parameters

Parameter	Former EM undulators	VPU
Period, cm	12	10 – 16
Gap (Inner Diameter), cm	8	14
Number of Periods	2 * 32	50 – 80
Radiation Wavelength, µm	90 – 240	82 – 450
Deflection Parameter	0 – 1.1	0.45 – 1.9
Full Length, cm	800	860

DESIGN

Focusing of electron beam due to the undulator field is strong at low electron beam energies (10.5 to 13.3 MeV for the first stage FEL). A concave pole is a common solution to redistribute focusing between the transverse directions. Moreover, it weakens the field dependence on the distance from the undulator axis, which is useful in the case of large aperture. Both the magnet and pole profiles will be segments enveloping the vacuum pipe with different outer diameters; the dimensions are shown in Figure 1.

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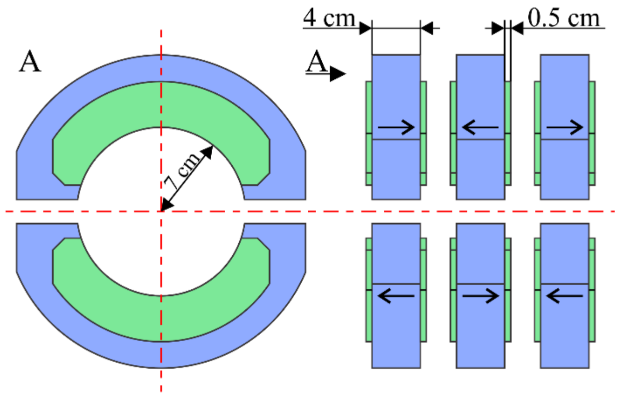

Figure 1: Magnetic design of the undulator. Blue parts are permanent magnets (magnetization is shown with arrows), green parts are iron poles.

At the minimum period λu_{min}, the undulator is a conventional hybrid device with magnets made of NdFeB and poles of low carbon steel. All poles are split into halves, and so the undulator is an array of detachable blocks. Each undulator block has a length of half a minimal undulator period and consists of a magnet embraced by the pole halves and the aluminum frame, as shown in Figure 2. The upper and lower blocks are connected, distances between each pair of upper and lower blocks may be adjusted with help of screws for fine filed tuning (instead of shimming); the whole structure is placed on a carriage that can move freely along undulator axis on two guide rails. Adjacent magnets in a row always have alternating longitudinal magnetizations, and hence they experience repulsion from each other. Due to the strong repulsion force and the low-friction slide guides, the undulator period can be changed by shifting the end blocks, which alters the full undulator length. There will be mechanical pushers that can be operated from the control room. A similar system was described and depicted in [14].

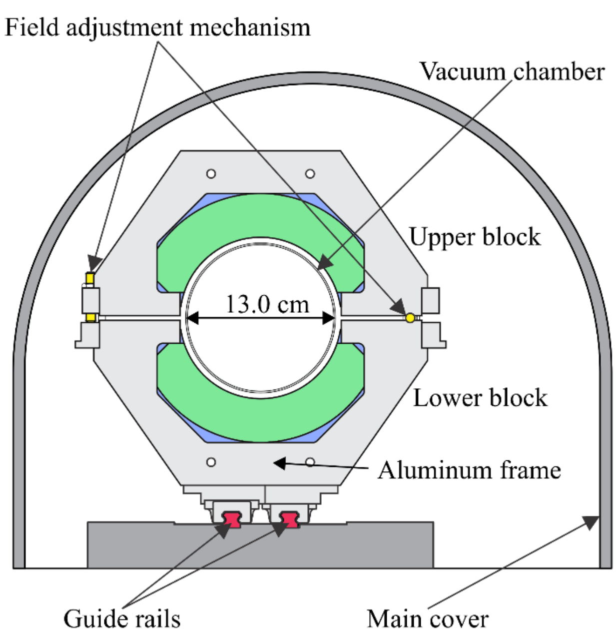

Figure 2: Front view of the undulator.

The undulator will be equipped with a supplementary external device intended for insertion of additional blocks into the undulator. This device slides the two fringe undulator blocks apart so that a period can be placed in the created space. If the desired undulator period is less than the maximum one, it will be possible to add some periods to use the entire space between the pushers.

Beamline Upgrade

The rest of the beamline will also be upgraded. New quadrupole lenses with an enlarged aperture will be installed. The optical resonator will be shortened, which will reduce the radiation beam size at the mirrors. The available space for the new undulator will shrink from 9 m to L_u = 8.6 m, but the desired long-wave edge wavelength λ_{max} will increase two-fold. An eigenmode of the two-mirror optical resonator is Gaussian beam (see, e.g., [16]). To minimize the eigenmode transverse widths at the undulator terminations, one must choose Rayleigh length of the eigenmode to be $L_u/2$. Then the r.m.s (by intensity) size of the Gaussian radiation beam at the undulator terminations is $\sqrt{\lambda L_u/4\pi}$. After doubling the wavelength this width will grow by a factor of $\sqrt{2}$, and thus the aperture should be enlarged too, to avoid significant losses at the undulator edges [17]. The outer vacuum chamber diameter was set to 14 cm, which will enable generation of longwave radiation.

Tolerance Considerations

The main disadvantage of such VPU scheme (with poles moving freely in the longitudinal direction) is some unevenness of their arrangement, which can change significantly the phase shift between the electron transverse velocity and the radiation field. Possible influence of such errors on the radiation spectrum was considered in [14], and a period adjustment procedure was proposed.

Magnetic measurements of the VPU developed for the second FEL of Novosibirsk FEL facility indicated that differences in magnetizations of the magnets in the blocks of undulator affect field regularity in the undulator insignificantly in comparison with blocks position errors. Therefore, shimming was not considered so far. However, magnets will be carefully measured and sorted and installed in blocks to compensate each other's imperfections. Blocks in undulator can be rearranged during magnetic measurements stage to optimize trajectory straightness and minimize phase errors.

MODELLING RESULTS

The dimensions of the magnets and poles were optimized in 3D magnetic field distribution modelings made with help of CST EM Studio. The minimum undulator period was determined in a compromise between a shorter radiation wavelength and a reasonable value of the deflecting parameter. Dependences of the on-axis magnetic field amplitude and the deflecting parameter on the undulator period are shown in Figure 3. The deflecting parameter K was calculated with due account for all field harmonics.

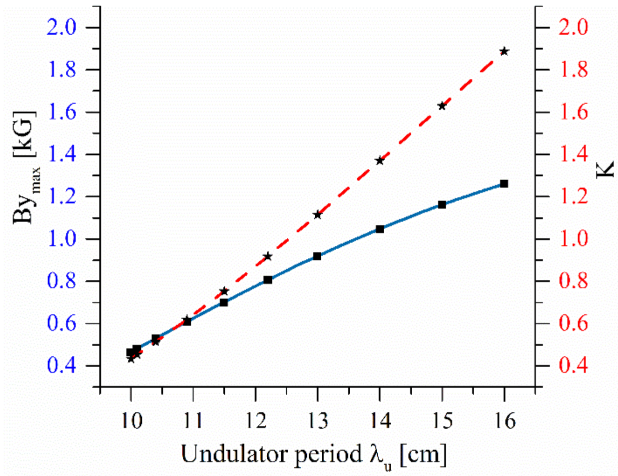

Figure 3: On-axis field amplitude (solid blue line with squares, left vertical axis) and deflection parameter K (dashed red line with stars, right vertical axis) vs. undulator period.

Increase in the undulator period is accompanied by a growth of amplitudes of higher odd field harmonics, however, higher field harmonics are strongly suppressed due to the large undulator gap, so normalized third harmonic amplitude does not exceed 0.3%. The circular pole profile helped to make the field amplitude gradient almost equal for both transverse directions. The undulator thus focuses electron beam in horizontal plane as well. At such a low electrons energy, vertical and horizontal beta functions of an electron beam remain constant along the undulator if initial conditions were matched to minimize average beta function in the undulator [18]. Dependences of the matched beta functions in the undulator on its period are shown in Figure 4.

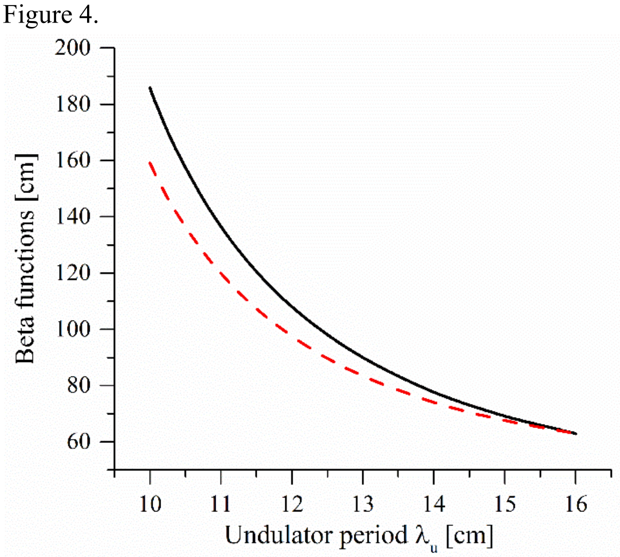

Figure 4: Vertical (dashed) and horizontal (solid) matched beta functions vs. undulator period.

Besides, redistribution of transverse gradients of magnetic field, particularly diminution of the vertical gradient, make the variation in field amplitude between pole tip and undulator axis lower. It worth noting that the arc geometry used to increase the field on axis is useful for fixed gap only.

Undulator Terminations

The terminations field correction was conducted in several steps. Arc-shaped shields made of soft magnetic steel will be placed at the ends of the undulator to prevent electrons deviations in the field of terminating blocks. In order to weak terminating field peaks thus minimizing first two integrals of the field along the undulator, poles of first two blocks at both ends will be made of aluminum. Moreover, magnets of end blocks will be demagnetized up to 0.3 of their initial magnetization by heating. Aluminum gaskets will be placed after the first two blocks to prevent changing distance between them and the regular part of the undulator. This will make the field integrals minimization scheme independent of the undulator period. Implementation of mentioned above techniques will reduce first and second field integrals along the undulator to tolerable values that can be compensated with the help of dipole correctors in the ends of the undulator.

CONCLUSION

Incorporation of developed undulator will help to upgrade the terahertz FEL of Novosibirsk FEL facility due to advantages of variable-period undulator scheme. Due to the device design based on permanent magnets, the period-to-gap ratio can be made smaller for the minimum period, thus, this scheme allows smaller undulator period for short wavelength radiation and a wider aperture for the long part of the tuning range. Wavelength tuning is accompanied by smaller field amplitude variation for variable-period undulators with free moving blocks, therefor gain length and radiated power vary less across the tuning range. Moreover, this scheme has a remarkable feature of a larger number of periods for the short-wave part of the tuning range, which increases the gain. Besides, permanent magnets need no power supplies and are relatively cheap.

The undulator is now under manufacture. With an obvious size scaling of a permanent magnet structure, one can also use a similar geometry for incertion devices for shorter wavelength FELs.

REFERENCES

[1] E. Levichev and N. Vinokurov, "Undulators and Other Insertion Devices," *Rev. Accel. Sci. Technol.*, vol. 03, no. 01, pp. 203–220, Jan. 2010. doi:10.1142/S1793626810000403

[2] E. Gluskin *et al.*, "Optimization of the design for the LCLS undulator line," *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.*, vol. 475, no. 1–3, pp. 323–327, Dec. 2001. doi:10.1016/S0168-9002(01)01612-6

[3] E. Trakhtenberg, V. Tcheskidov, I. Vasserman, N. Vinokurov, M. Erdmann and J. Pfluger, "Undulator for the LCLS project—from the prototype to the full-scale manufacturing," *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.*, vol. 543, no. 1, pp. 42–46, May 2005. doi:10.1016/j.nima.2005.01.110

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[4] A. S. Artamonov *et al.*, "The first experiments with an optical klystron installed on the VEPP-3 storage ring," *Nucl. Instruments Methods*, vol. 177, no. 1, pp. 247–252, Nov. 1980. doi:10.1016/0029-554X(80)90557-1

[5] R. Tatchyn, "A universal classification of optimal undulator types and parameters for arbitrary storage ring environments," *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.*, vol. 275, no. 2, pp. 430–434, Feb. 1989. doi:10.1016/0168-9002(89)90720-1

[6] G. K. Shenoy, J. W. Lewellen, D. Shu, N. A. Vinokurov, "Variable-period undulators as synchrotron radiation sources," *J. Synchrotron Radiat.*, vol. 10, no. 3, pp. 205-213, May 2003. doi:10.1107/S0909049502023257

[7] P. Vagin, A. Schöps, and M. Tischer, "Variable Period Undulator with Tunable Polarization," *Synchrotron Radiat. News*, vol. 31, no. 3, pp. 48–52, May 2018. doi:10.1080/08940886.2018.1460178

[8] N. A. Vinokurov, O. A. Shevchenko, and V. G. Tcheskidov, "Variable-period permanent magnet undulators," *Phys. Rev. Spec. Top. - Accel. Beams*, vol. 14, no. 4, p. 040701, Apr. 2011. doi:10.1103/PhysRevSTAB.14.040701

[9] J. Mun *et al.*, "Variable-period permanent-magnet helical undulator," *Phys. Rev. Spec. Top. - Accel. Beams*, vol. 17, no. 8, p. 080701, Aug. 2014. doi:10.1103/PhysRevSTAB.17.080701

[10] G. N. Kulipanov *et al.*, "Novosibirsk Free Electron Laser—Facility Description and Recent Experiments," *IEEE Trans.* TERAHERTZ *Sci. Technol.*, vol. 5, no. 5, 2015. doi:10.1109/TTHZ.2015.2453121

[11] O. A. Shevchenko *et al.,* "Current status of the Novosibirsk infrared FEL and the third stage lasing," *Phys. Part. Nucl. Lett.*, vol. 13, no. 7, pp. 1002–1005, Dec. 2016. doi:10.1134/S1547477116070451

[12] O. A. Shevchenko *et al.*, "The Novosibirsk Free Electron Laser – Unique Source of Terahertz and Infrared Coherent Radiation," *Phys. Procedia*, vol. 84, pp. 13–18, Jan. 2016. doi:10.1016/j.phpro.2016.11.004

[13] B. A. Knyazev *et al.*, "Novosibirsk Free Electron Laser as a User Facility," *Phys. Procedia*, vol. 84, pp. 27–34, Jan. 2016. doi:10.1016/j.phpro.2016.11.006

[14] I. 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*, vol. 19, no. 2, p. 020701, Feb. 2016. doi:10.1103/PhysRevAccelBeams.19.020701

[15] I. V. Davidyuk, O. A. Shevchenko, V. G. Tcheskidov, and N. A. Vinokurov, "Results of test of prototype of variable period undulator," *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.*, vol. 871, pp. 77–82, Nov. 2017. doi:10.1016/j.nima.2017.07.060

[16] A. Yariv, *Quantum electronics*, 3rd Edition John Wiley & Sons, 1989.

[17] V. V Kubarev, B. Z. Persov, N. A. Vinokurov, and A. V Davidov, "Optical resonator of powerful free-electron laser," *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.*, vol. 528, no. 1–2, pp. 199–202, Aug. 2004. doi:10.1016/j.nima.2004.04.046

[18] H. P. Freund and T. M. Antonsen, *Principles of Free Electron Lasers*. Cham: Springer International Publishing, 2018. doi:10.1007/978-3-319-7510