MODELING AND DESIGN OF THE VARIABLE PERIOD AND POLE NUMBER UNDULATOR FOR THE SECOND STAGE OF THE NOVOSIBIRSK FEL*

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Abstract

The concept of the permanent magnet variable period undulator (VPU) has been proposed just several years ago and there are few examples of its implementation yet. The VPUs have several advantages compared to conventional undulators. One of them is wider radiation wavelength tunability range and another one is an option to increase the number of poles for shorter periods. Both these advantages will be realized in VPU which is being developed now at Budker INP. In this paper, we present the 2-D and 3-D magnetic field simulation results and discuss the design features of this VPU.

INTRODUCTION

Tuning of the radiation wavelength is one of the basic FEL advantages which differs them from conventional lasers. Wide tunability range is desirable for many applications. Therefore its increasing is important goal of the FEL design optimization. As the wavelength in FEL depends on several parameters it can be tuned several ways. Each of them has its own advantages and disadvantages. But from the point of view of the maximum tunability range the best way of wavelength tuning is based on the varying of the undulator period.

The concept of the variable period undulator (VPU) has been proposed just recently [1] and it has very few implementations yet. There are several types of the VPU design. One of them proposed in [2] is similar to conventional hybrid undulator in which the iron poles are divided in two halves. This type of VPU is composed from separate magnet blocks which can move freely along longitudinal axis. Each block includes one permanent magnet and two iron plates. At fixed positions of the outer blocks the inner blocks distribute evenly in longitudinal direction due to the repulsive forces and the period of this distribution can be adjusted by moving of the outer blocks. This design allows to change number of blocks so, that at fixed space allocated for undulator one can have larger number of periods for shorter wavelength.

The variable period undulator for the NovoFEL is being developed now at Budker INP. It will replace electromagnetic undulator of the second stage FEL which is installed on the bypass of the second horizontal track [3]. The tunability range of the existing FEL is 35 - 80 microns. Application of VPU will allow to shift the short wavelength boundary to 15 microns (see simulation results below). By now design of the VPU magnetic block has been already developed and small prototype which has only six blocks is being manufactured now. In this paper we discuss undulator design and its magnetic field properties.

UNDULATOR GEOMETRY AND FIELD SIMULATION RESULTS

To find the optimal undulator geometry and investigate the magnetic field properties 2-D and 3-D simulations were carried out. For 2-D simulations we used code FEMM [4] which runs quite fast therefore we could calculate magnetic field for the total number of undulator periods (about 50). The final 3-D geometry is presented in Fig. 1. It was simulated by CST Studio [5].

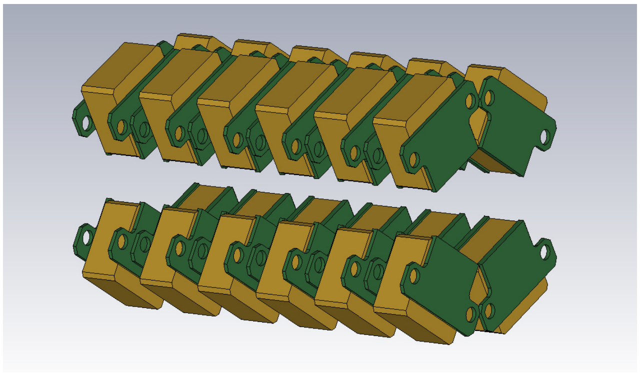

Figure 1: Undulator geometry used in 3-D simulations. Yellow blocks – permanent magnets, green plates – iron poles.

The undulator transverse aperture was chosen to be 50 mm. This value cannot be significantly reduced because of electron and optical beam losses. The minimal undulator period 48 mm is limited by the aperture. For the smaller periods the undulator deflection parameter and consequently the FEL gain become too small (see Fig. 6,8).

Each undulator block consists of one permanent magnet and two iron plates. The opposite plates of two blocks adjacent in longitudinal direction form one pole. Two blocks at the top as well as two blocks at the bottom are combined in one unit which moves as a whole. Top and bottom units are not connected. The blocks in one unit are tilted with respect to each other. This configuration provides the growth of the field amplitude with the distance from the central axis in all directions. As the

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result this undulator will focus electron beam horizontally as well as vertically.

The permanent magnets are supposed to be made of NdFeB. In simulations we used permanent magnet with magnetization value 1.3T. Dimensions of the magnets and iron plates were optimized to obtain the maximal field amplitude at minimal period.

Transverse cross-sections of the iron plate and permanent magnet with final dimensions are presented in Fig. 2.

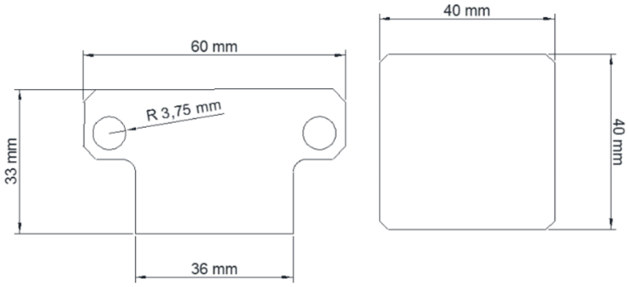

Figure 2: Transverse cross-sections of the iron plate (left) and permanent magnet (right).

Full 3-D simulations of the undulator regular part were used to obtain the dependences of the basic undulator parameters on the period. The results are presented below. Dependences of the field amplitude and K parameter on the period are shown in Fig. 3 and 4. It is seen that variation of the period in VPU does not lead to the so significant change of the field amplitude as variation of the gap does in variable gap undulators (VGU).

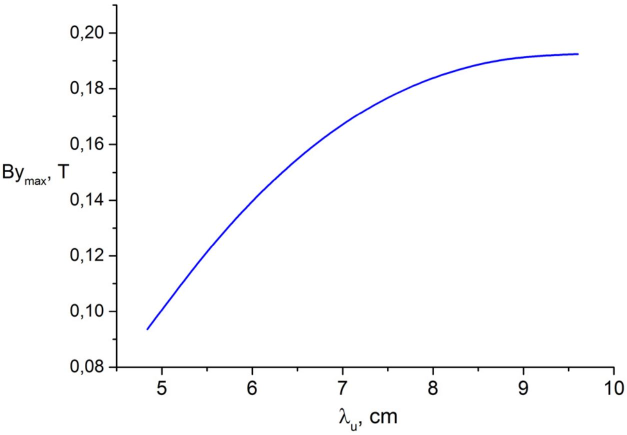

Figure 3: Dependence of the field amplitude on the undulator period.

In Fig.5 one can see the normalized amplitude of the third harmonic. In VPU it cannot be minimized for all periods but for our FEL application its value is small enough in the whole range.

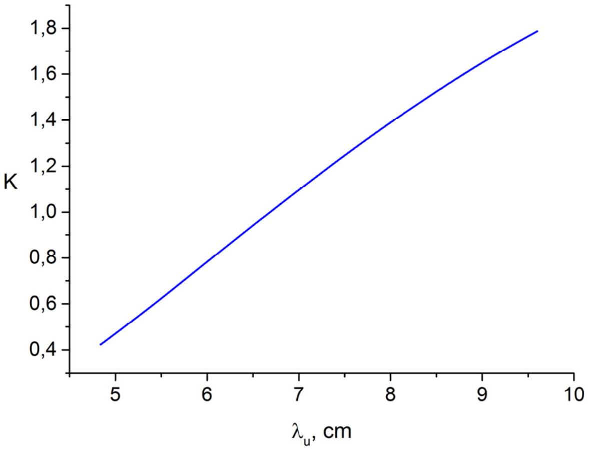

Figure 4: Undulator deflection parameter.

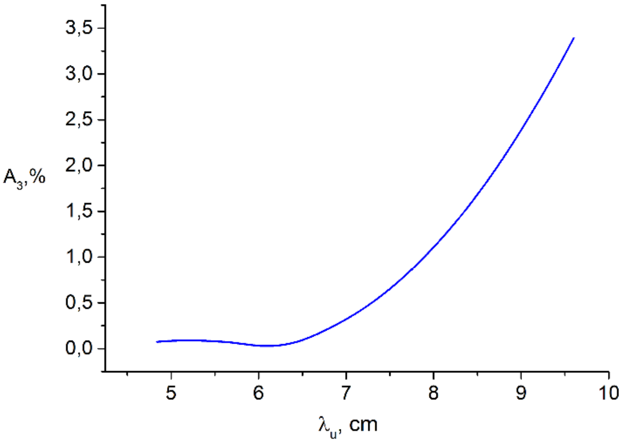

Figure 5: The third harmonic of the undulator magnetic field normalized to the first harmonic amplitude.

Tolerance Requirements

In the considered type of VPU design longitudinal positions of the magnetic blocks in the regular part of undulator are not fixed mechanically and in principal may have some essential errors. This fact is often used as an argument against feasibility of the VPU concept. Therefore this problem has to be investigated.

There are two types of position errors – random deviation from regular positions and systematic change of the distance between adjacent blocks which leads to slow linear tapering of undulator period. The last one is most dangerous. This type of errors can appear due to friction forces or due to the tilt of undulator from horizontal plane.

To find acceptable spread of longitudinal positions for our undulator we made 2-D simulations of undulator with 50 periods for both types of errors. The linear tapering for systematic error simulations was 10 µm per period. Undulator performance was characterized by spectrum of spontaneous emission at zero angle. The results are presented in Fig. 6.

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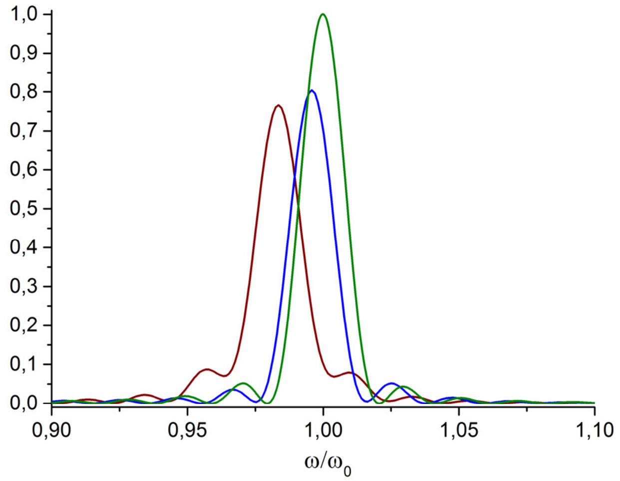

Figure 6: Spectrums of spontaneous emission. Green one – ideal undulator, blue – random block shift with amplitude 1.5 mm, red – systematic 5μm block shift.

It seen that acceptable random spread is more than 1 mm while systematic shift should not exceed several microns which at first sight does not look very realistic. But 3-D calculations showed that restoring force acting on one unit at 5 microns shift is 0.2 N. The weight of one unit block is less than 1 kg and vertical magnetic force acting on the unit is about 40 N. Therefore to avoid the problem with systematic shift one has to provide the value of the friction coefficient less than $4\cdot10^{-3}$ and the value of the tilt angle less than 0.02 which looks feasible.

Terminations Field Correction

In the regular part of undulator electron beam has to move along the central axis. This condition is required to provide overlap of electron beam with the optical cavity mode as well as to avoid betatron oscillations induced by strong undulator focusing. The standard way to provide this condition consists in decreasing of the strength of two magnets at undulator entrance. By proper choice of the decreasing coefficients one can easily compensate the first and the second field integrals at given undulator period. Varying of the period in principle can lead to violation of this compensation but according to our undulator simulations for the considered range of periods (from 4.8 to 9.6 cm) this violation is not very significant.

Undulator Focusing

Electron beam in Novosibirsk FEL has low energy therefore undulator focusing plays significant role. As it was mentioned earlier the undulator geometry provides focusing in both vertical and horizontal directions. In Fig. 7 one can see the dependence of the matched horizontal and vertical β - functions on the undulator period.

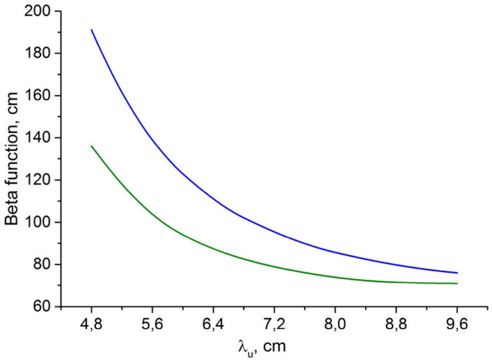

Figure 7: Dependence of the matched horizontal (blue) and vertical (green) β - functions on the undulator period.

FEL Tunability Range

According to the simulation results the developed undulator allows to increase the wavelength tunability range of the Novosibirsk FEL. As it is well known the lasing in FEL oscillator is possible when the FEL gain increases the round trip radiation losses in optical cavity. In Fig. 8 one can see the gain and losses [6] of the second stage Novosibirsk FEL for different wavelengths and for different types of undulators. The gain was calculated for the following electron beam parameters: energy – 22 MeV, energy spread – 0.5 %, peak current – 40 A. Gain calculation for the VPU case takes into account increasing of the number of periods for shorter wavelengths. Together with VPU plot one plot for the VGU with comparable tuning range and one plot for the currently installed EM undulator are presented. Advantage of the VPU becomes evident from comparison these plots.

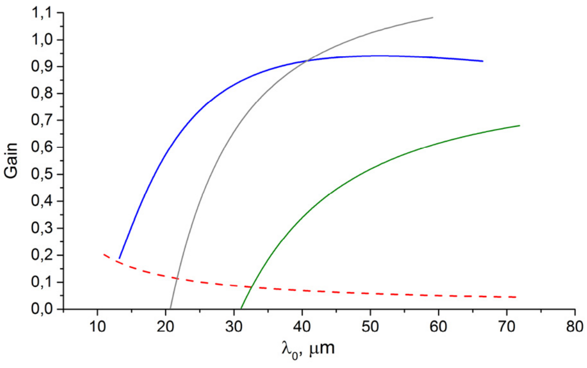

Figure 8: The FEL gain (blue – VPU, gray – VGU, green – electromagnetic undulator) and optical cavity losses (red dashed) for different radiation wavelengths.

MECHANICAL DESIGN

The undulator mechanical design is presented in Fig 9.

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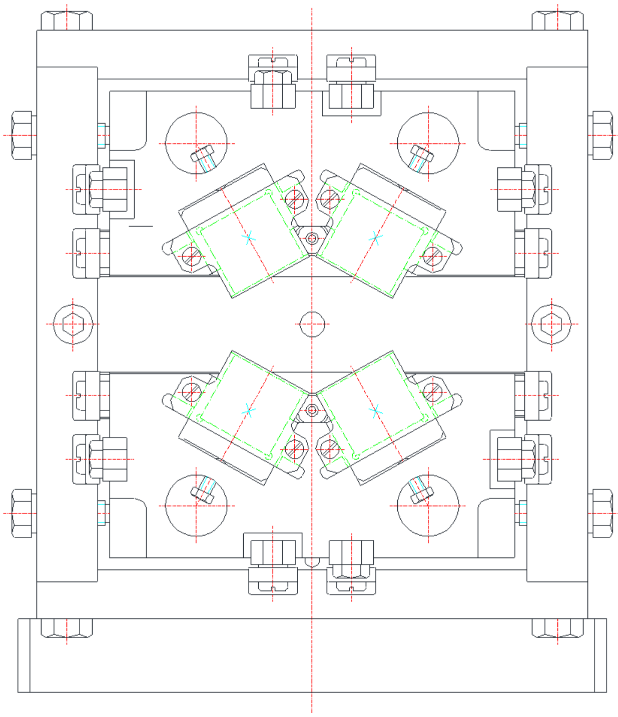

Figure 9: Undulator mechanical design.

To provide small friction coefficient the units, which contain magnet blocks are placed on the bearings. In present design the number of periods is changed manually but the period itself can be varied remotely by special mechanism.

CONCLUSION

The variable period undulator developed for the Novosibirsk FEL provides a wavelength tuning range about 13 – 76 µm while the tuning range of existing FEL based on electromagnetic undulator is only 37 – 80 µm. Thus the proposed undulator replacement will essentially reduce the short wavelength limit that will make Novosibirsk FEL more powerful research instrument.

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