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Helical wigglers for the OK-5 storage ring VUV FEL at Duke ☆

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Abstract

In this paper, we present the design and parameters of electromagnetic wigglers with controllable polarization for the VUV OK-5/Duke storage ring FEL. The OK-5 FEL, the first distributed optical klystron, is comprised of four wigglers and three matching sections with individually controlled quadrupoles and bunchers. The geometry and the relative strength of horizontal and vertical fields determine the polarization of the radiation from the OK-5 wigglers. We compare the predicted and measured quality of the wiggler fields. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The OK-5 FEL will replace the OK-4 FEL at the Duke storage ring, which successfully operated in a the wide spectrum region from the near IR to the deep UV [1]. The OK-5 FEL will be a first implementation of distributed optical klystron [2] with reasonably high gain in the UV and the VUV ranges of spectrum [3]. Detailed description of the OK-5/Duke storage ring FEL is presented elsewhere [4,5]. The main components of the OK-5 FEL are four electromagnetic wigglers (EM) with controllable polarization. The main advantages of the helical wigglers are the increase of the gain (almost by a factor of two at fixed period and wavelength) and the absence of high harmonics of radiation on its axis. The later feature provides for substantial reduction of the downstream mirror heating and degradation. The control of the polarization in the OK-4 FEL is critical for a number of experiments under consideration. First, we plan to use the OK-5/Duke SR FEL for effective generation of the beams of mono-energetic polarized γ-rays [4] in the scheme similar to that used with the OK-4 FEL [6]. The nuclear physics experiments with polarized targets require switchable circular and linear polarization of γ-rays [7,8]. Second, we plan to use left-and-right circular polarization in the 150–250 nm range for

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studies of the dichroizm of biological objects for increasing the contrast of the their images. Third, we plan to conduct the experiment on the parity violation in atomic transitions 1S–2S in atomic hydrogen [9].

In Section 2, we describe the design and parameters of the helical EM wigglers. Section 3 is dedicated to the description of the 3D magnetic filed and its model. In Section 4, we compare the predicted and the measured magnetic fields as well as the current status of the devices. We conclude with the discussion of our plans.

2. Design and parameters of the OK-5 wigglers

The magnetic system of the OK-5 FEL will extend for 24.2 m and will occupy most of the 34-m South straight section (SS) of the Duke storage ring [10]. The OK-5 FEL is comprised of four EM wigglers separated by three 2.68 m long midsections [4]. The length of the segment (the wiggler + midsection) is equal to $\frac{1}{8}$ of the ring circumference. This configuration provides for effective generation of γ-rays using 8 e-bunches and three collision points [4].

Each helical wiggler is composed of two planar wigglers shifted with respect to each other on a quarter of the wiggler period. Fig. 1 shows the regular part of the wiggler with the top quarter taken off. The main wiggler parameters are presented at Table 1. Each component of the field is independently controllable by the coil current in vertical and horizontal arrays. Each coil consists of four bent water-cooled copper busses, which surround the poles in "snake-like" fashion, similar to the OK-4 wiggler design [11,12]. The coils are connected at the end of the wiggler. Two layers make one complete turn around each pole. The 4-m quarter-yokes of the wiggler are made from soft magnetic steel on high precision milling machine. The pole tips are made independently and pinned to the yokes. The final accuracy of the assembly is about 20 μm.

The requirement for switching the helicity of radiation leads to violation of the helical symmetry of the wiggler design. As the result, the additional steps should be taken to compensate asymmetry of the magnetic field. Special design of the wiggler terminations is also required to provide for the adiabatic entrance of particles into the regular part of the wiggler.

3. Description of the 3D magnetic field

When the steel is not saturated, the magnetic field of the wiggler can be presented as direct superposition of the fields produced by horizontal and vertical arrays. In the vacuum the field can be described by scalar potential: $\vec{B} = \nabla\psi$, where

$$\psi(x, y, z) = A_x\,\psi_0(x, y, z) + A_y\,\psi_0\left(y, x, z - \frac{\lambda_{\rm w}}{4}\right). \tag{1}$$

Periodic part of the potential can be expanded into series

$$\psi_0(x, y, z) = \sum_{q=0}^{\infty} f_q(x, y)\cos(qk_{\rm w}z) \tag{2}$$

with condition forced by Laplace equation $\Delta\psi_0 = 0$:

$$\frac{\partial^2 f_q}{\partial x^2} + \frac{\partial^2 f_q}{\partial y^2} - q^2k_w^2 f_q = 0. \tag{3}$$

The f_q can be expanded into Tailor series for further studies:

$$f_q(x, y) = \sum_{m,n=0}^{\infty} b_{m,n,q}x^m y^n. \tag{4}$$

We used design with the plane symmetry, which provides for $\psi_0(x, y, z) = -\psi_0(x, -y, z)$, and therefore $b_{m,2l,q} = 0$. According to Eq. (3), coefficients $b_{m,n,q}$ obey the relations

$$(m+2)(m+1)\,b_{m+2,n,q} + (n+2)(n+1)\,b_{m,n+2,q} = q^2\,k_w^2\,b_{m,n,q}.$$

The yokes and poles have both plane and left–right symmetry (see Fig. 2). The left–right symmetry of the field is slightly violated by asymmetric coil. The additional symmetry in the design provides for:

$$\psi_0(x, y, z) = -\psi_0\left(-x, y, \frac{\lambda_w}{2} - z\right).$$

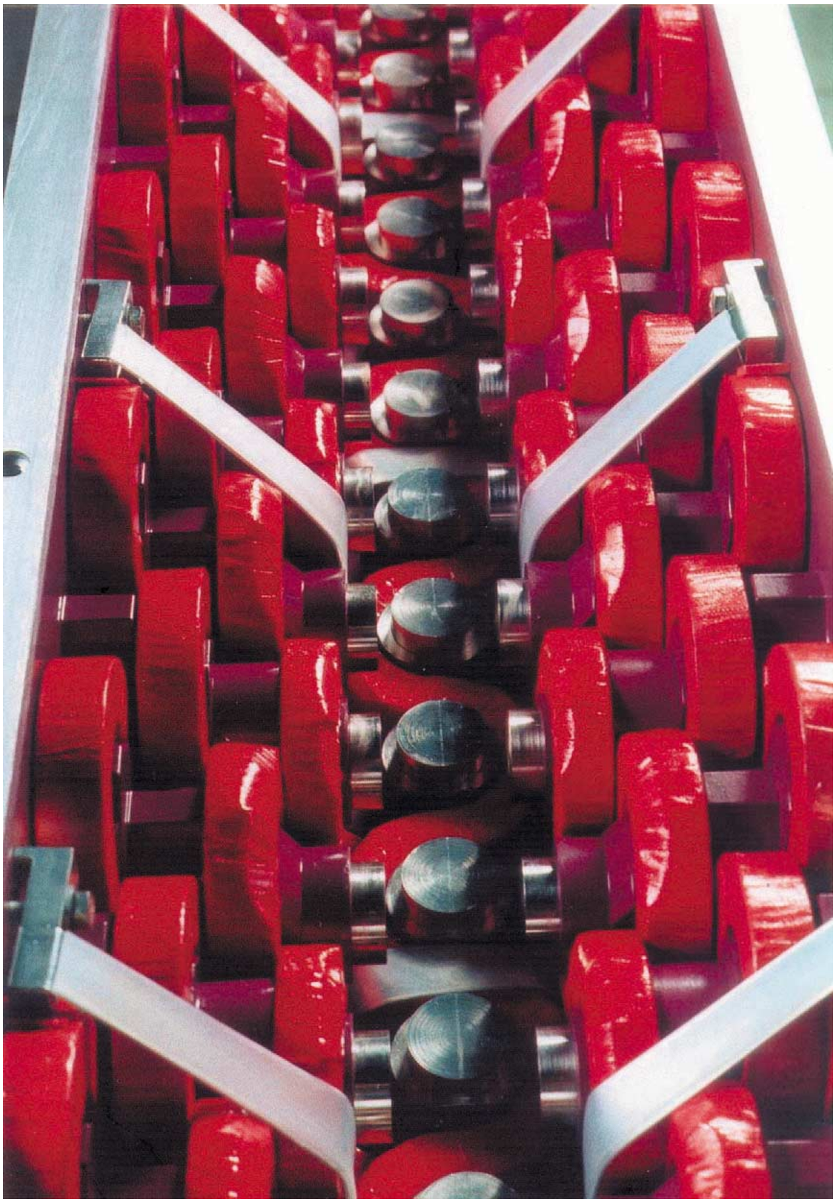

Fig. 1. Regular part of the wiggler.

The asymmetry of the coils allows the presence of small average quadrupole and octupole fields:

$$f_0(x, y) = B_0^{(1)} xy + \frac{B_0^{(3)}}{6}\left(x^3 y - xy^3\right).$$

The magnetic field in the regular part of the wiggler was simulated with the 3D code "MERMAID" [13]. Computations were made for the half period of the wiggler with current only in the coils exciting vertical field. The wiggler pole geometry is shown in Fig. 2.

Table 1
Parameters of OK-5 wiggler

Period λ_w, cm	12
Number of regular periods	30
Wiggler length, m	4.04
Wiggler gap, cm	4×4
Maximum designed field, kGs	3
Amplitude of the fundamental harmonic (at the bus current 2 kA), kGs	2.07
Relative value of the 3d field harmonic, %	0.6

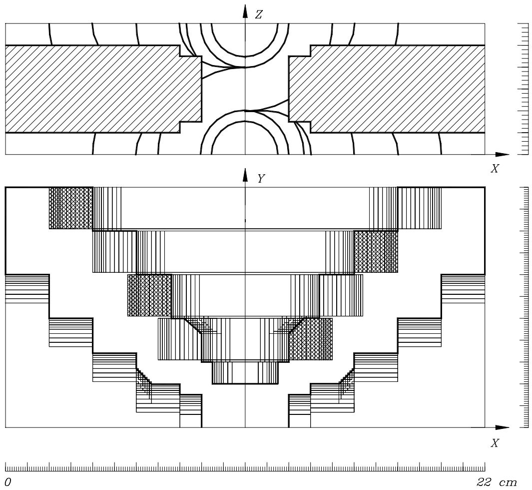

Fig. 2. 3D geometry of the wiggler half period used in MERMAID. The top fig shows a horizontal cross-section. The bottom fig shows 3D side view of the poles and coils. The dark squares show the coil cross-section. Coils are obviously asymmetric.

Because of the plane symmetry, we calculate the magnetic field only above the median plane. The boundary conditions are:

- $B_\tau = 0$ at median plane and outside boundaries.
- $B_n = 0$ at $z = 0$ and 6 cm planes.

The calculated dependencies of the amplitude of fundamental harmonic of the magnetic field on transverse coordinates x and y are shown in Fig. 3. Numerical simulations confirmed the presence of the average quadrupole and octupole terms in the regular part of the wiggler. With 2 kA current in the coils, their amplitudes were $G = 5.64$ Gs/cm

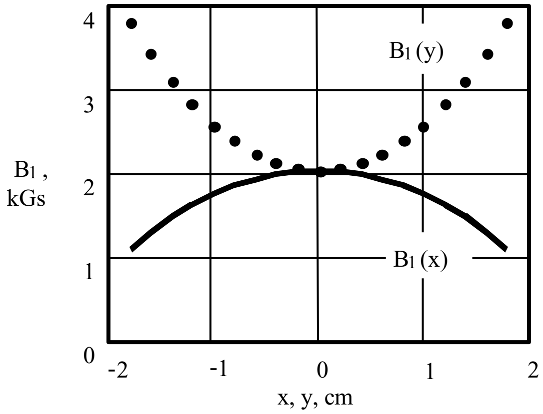

Fig. 3. Calculated dependence of fundamental harmonic of magnetic field on x and y. The current is 2 kA. The solid curve corresponds to the dependence on x at $y = 0$ and the dotted curve—on y at $x = 0$.

and $O = -2.76$ Gs/cm^3, respectively. These average terms can be compensated locally by small asymmetric cuts in the pole tips. Their integral compensation is also possible by special poles at the ends of the wigglers. We are testing both approaches.

4. Magnetic measurements

All four wigglers have been manufactured and magnetic measurements are under way. A Hall probe array with five horizontally spaced and five vertically spaced probes is employed for these measurements. These Hall probes provide accuracy of ± 0.2 Gs.

Preliminary magnetic measurements show good agreement with the calculations. Fig. 4 shows the dependence of the vertical magnetic field along wiggler axis. The central particle trajectory based on the measured field is shown in Fig. 5. The nonzero coordinate and angle of the particle at the wiggler exit will be corrected by the adjustment of the field structure in the wiggler terminations. A relatively small deviation of the trajectory in the regular part of the wiggler from the ideal indicates the good quality of manufacturing.

The other indicator of the field quality is the spectrum of spontaneous radiation. The spectrum

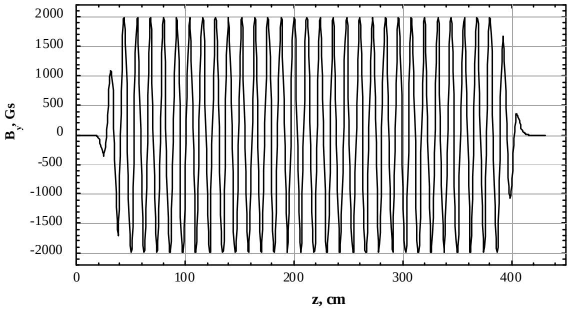

Fig. 4. Measured dependence of the vertical magnetic field along the wiggler axis.

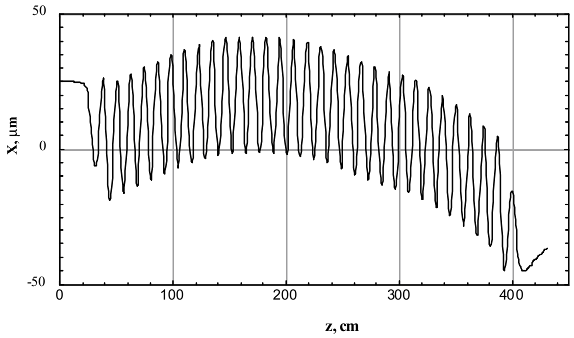

Fig. 5. Calculated trajectory of the central particle at $E = 1$ GeV.

of the radiation based on the measured magnetic field is shown in Fig. 6. The trajectory was calculated from the measured magnetic field (Fig. 4) for helical configuration. Using this trajectory, we calculated the retarded time and the value of vector potential on the wiggler axis as a function of observation time with even intervals. The time dependence of the radiated field was calculated by direct use of Lienard–Wiechert potential [14]. The radiated field was Fourier transformed into the radiation spectrum. The spectrum width corresponds to the effective number of wiggle periods $N = 30.2$, as expected.

The measured values of average gradient and octupole components are in reasonable agreement with the calculations. We are testing the pole tips, which should eliminate the average gradient and octupole completely.

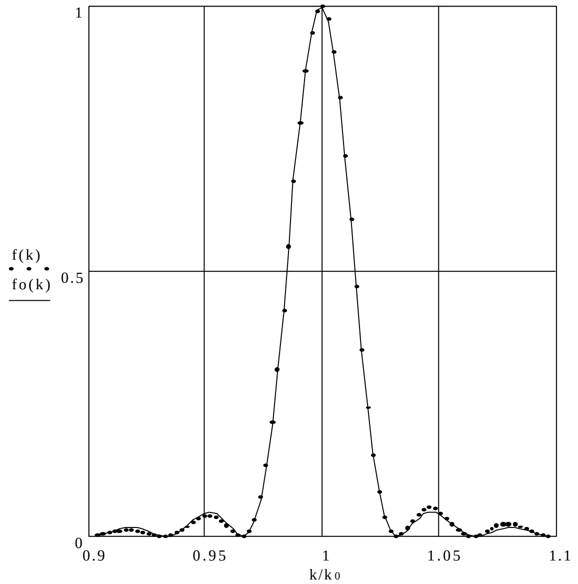

Fig. 6. Spectrum of spontaneous radiation from one wiggler. The solid curve is the $f_0 = \mathrm{sinc}(a(k-k_0))^2$ fit with $a = 1.35 \times 10^{-4}$ cm,$k_0 = 7.02 \times 10^5\,\mathrm{cm}^{-1}$.

The results of magnetic measurements will determine the choice of magnetic field structure in the wiggler terminations. We expect to complete modifications and magnetic measurements by Spring, 2001.

5. Conclusions

The wigglers for the OK-5 FEL are undergoing final adjustments to satisfy our requirements. We expect that all four wigglers will be ready by the end of the Spring 2001. The 3D simulations and preliminary magnetic measurements are in good agreement and demonstrate high quality of the regular part of magnetic field. We plan to install the wigglers and the rest of the OK-5 system into the Duke storage ring in 2001.

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