NONLINEAR DYNAMICS IN THE DUKE STORAGE RING WITH FEL WIGGLERS *

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Abstract

Single particle dynamics in the storage ring can be significantly influenced by strong nonlinearities from long and strong-field insertion devices. This paper reports our preliminary results on the dynamics impact of the 24 m long OK5 FEL in the Duke ring. Initial studies are performed using an intermediate lattice with two OK5 wigglers. The dynamic aperture is computed using a recently developed symplectic wiggler integrator and the frequency map technique, NAFF. We have observed significant dynamic aperture reduction due to OK5 wigglers at lower beam energies. We also report our preliminary findings on the means to improve beam dynamics with wigglers.

1 INTRODUCTION

The Duke storage ring is designed as a dedicated driver for Free Electron Lasers (FELs). The first operational FEL on the Duke ring is the 8-meter long OK4 FEL with two planar wigglers [1], originally designed for the VEPP-3 storage ring at Budker Institute of Nuclear Physics (BINP), Russia. Since 1998, the OK4 FEL has demonstrated broad tuneability from 2.1 μm to 194 nm. Operating in both continuous-wave (CW) and giant pulse modes, the OK4 FEL has been used in medical, biological, chemical, and surface science research. Operating in a two-bunch mode, the OK4 FEL, via Compton scattering, also serves as a driver for a linearly polarized monochromatic gamma source in a wide energy range from 0.7 MeV to 58 MeV.

The capabilities of the OK4 FEL are limited in two main areas: (1) the relatively small gain limits the shortest lasing wavelength; (2) the strong on-axis synchrotron radiation from the linearly polarized wigglers causes significant mirror damage. To overcome these limitations, a next generation FEL, a variably polarized 24-meter long OK5 FEL system, has been specially designed to increase the FEL gain, to reduce the on-axis radiation, and to match the high quality of the electron beam in the storage ring.

The OK5 FEL system [2] consists of four 4-meter long wigglers and three bunchers. Each wiggler is comprised of two electro-magnetic pole-tip arrays, one vertical and one horizontal, shifted for a quarter of the wiggler period with respect to each other. By controlling the horizontal and vertical magnetic fields independently via two power suppliers, the OK5 wigglers can be configured to produce radiation with various polarizations, from linear and elliptical polarizations to left and right circular polarizations.

The overall performance of the Duke storage ring depends critically on the dynamic aperture. A large momentum dynamic aperture helps increase the beam lifetime and extends the no-loss mode of gamma-ray operation to higher energies. A large transverse dynamic aperture is essential for injection, especially for the future top-off injection with a booster ring while operating the OK5 FEL. At a low beam energy, the dynamic aperture can be significantly altered by OK5 wigglers with strong nonlinearities. The dynamics impact of OK5 wigglers is the main focus of this paper.

2 OK5 FEL LATTICES

The Duke FEL storage ring is a race-track structure comprised of two compact 180-degree arcs and two 34.21 m long straight sections. One of the two straights is dedicated to driving FEL light sources. This straight section lattice is designed with bilateral symmetry to host the present OK4 FEL. To achieve the additional flexibility required for the OK5 FEL operation, the new straight section lattice [3] has been redesigned using a combination of quad doublets and triplets. Each triplet cell includes a quadrupole triplet (QF-QD-QF), a buncher, and an OK5 wiggler. The three triplet quads are individually powered to provide compensations for linear focusing changes due to varying OK5 settings. Two quad doublets are used to match the β-functions between the arc and OK5 lattice. A comparison of OK5 and OK4 wiggler parameters is shown in Table 1.

Table 1: Comparison of OK4 and OK5 wiggler parameters.

	OK4 FEL	OK5 FEL
Total wiggler length [m]	6.7	16.16
No. of wigglers	2	4
No. of periods per wiggler	33.5	33
Wiggler periods [cm]	10	12
Wiggler gap [mm]	22.6	40×40
Peak magnetic field [kGs]	5.3	3.0
Max. wiggler $K = \frac{e B_0}{k_w m_e c^2}$	4.9	3.4

The exact length of the triplet cell is chosen to be 6.71625 m, exactly a sixteenth of the ring circumference, in order to produce gamma-rays. When operated with 8 equally spaced bunches, the maximum number of collision points are five: three at the center of the defocusing quad in the triplet and two in the matching sections. Each triplet employs four sets of horizontal and vertical orbit correctors to individually control collision points in the quads.

With this triplet design, the OK5 lattice is very flexible to allow a wide range of β-functions at the center of wigglers. In fact, β_x and β_y can be tuned from 4 m to 10 m in arbitrary combinations. By adjusting quads in the FEL straight, the betatron beating due to changing OK5 settings can be fully compensated, resulting in small residual tune changes ($max(d\nu_{x,y}) < 0.007$). A typical OK5 triplet lat-

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tice is shown in Fig. 1, resulting in a set of vertical OK5 wiggler arrays energized.

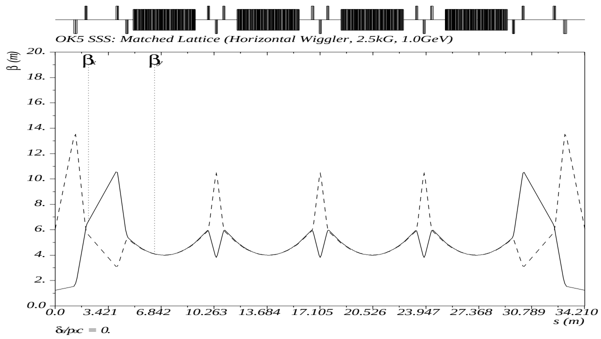

Figure 1: Dispersion-free OK5 FEL lattice at 1 GeV. Powered as horizontal wigglers, the maximum field in the OK5 is 2.5 KGs. The solid and dashed lines are β_x and β_y respectively. At the center of the wiggler, $\beta_x = \beta_y = 4$ m.

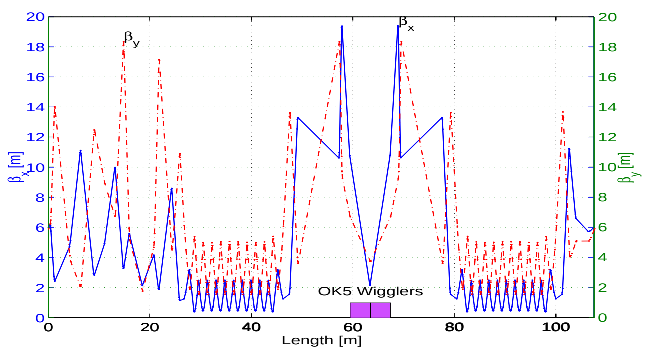

Figure 2: β-functions for the Duke ring with two OK5 wigglers located at the center of the FEL straight ($\beta_x = 2.14$, $\beta_y = 3.75$ m). The beam energy is 300 MeV and OK5 wigglers are circularly polarized with a peak field of 1.8 kG for each wiggler array. The solid and dashed lines are β_x and β_y respectively.

The long OK5 wigglers are expected to significantly alter the beam dynamics in the ring. To minimize dynamics risk associated with OK5 wigglers, an incremental upgrade plan has been developed with its first phase to test two OK5 wigglers. One of possible scenarios is to install two OK5 wigglers in the present location of OK4 wigglers in an intermediate lattice. To cover a range of gamma-ray energies and polarizations, three operation modes of this lattice have been investigated:

1. a 1 GeV lattice for the production of 100 MeV circularly polarized gamma beams;
2. a 300 MeV lattice for the production of 2 MeV circularly polarized gamma beams;
3. a 300 MeV lattice for the production of 2 MeV linearly polarized gamma beams;

The ring beta functions for the above mode 2 operation is shown in Fig. 2. The circularly polarized OK5 wigglers are described by a field model in the following section.

3 WIGGLER MODEL

The circularly polarized field of OK5 wigglers is expressed as the superposition of two sets of linearly polarized wiggler fields generated by two independent wiggler arrays. For example, the horizontally polarized light is generated by the vertical wiggle array. Its field is described by a set of wiggler harmonics with the mid-plane symmetry as follows:

$$\begin{aligned}
B_y &= -\sum_{m,n} C_{mn}\,\cos(k_{xl}x)\cosh(k_{ym}y)\cos(k_{zn}z+\theta_{zn}),\\
B_x &= \sum_{m,n} C_{mn}\frac{k_{xl}}{k_{ym}}\,\sin(k_{xl}x)\sinh(k_{ym}y)\cos(k_{zn}z+\theta_{zn}),\\
B_z &= \sum_{m,n} C_{mn}\frac{k_{zn}}{k_{ym}}\,\cos(k_{xl}x)\sinh(k_{ym}y)\sin(k_{zn}z+\theta_{zn}),\\
\vec{B}_{\rm H} &= (B_x, B_y, B_z),
\end{aligned}$$

where, C_{mn} are the amplitudes of wiggler harmonics, $k_{ym}^2 = k_{xl}^2 + k_{zn}^2$, $k_{zn} = n\,k_w$, $k_w = 2\pi/\lambda_w$, and θ_{zn} are the relative phases of wiggler harmonics. The magnetic field of a vertically polarized wiggler generated by the horizontal wiggler array, $\vec{B}_{\rm V}(x,y,z)$, can be expressed in the similar manner by interchanging the arguments x and y in the above expression. When the iron saturation is not significant, the general wiggler field in a variably polarized OK5 wiggler can be expressed as the sum of the two linearly polarized fields:

$$\vec{B}(x,y,z) \;=\; a\,\vec{B}_{\rm H}(x,y,z) + b\,\vec{B}_{\rm V}(x,y,z+\frac{\lambda_u}{4}),$$

where $-1 \le a \le 1$ and $-1 \le b \le 1$. For example, to produce circularly polarized radiation, $a = b = 1$.

Table 2: A set of normalized horizontal wiggler harmonics for dynamics simulation.

Modes	$C_{m,n}$	k_x/k_w	k_y/k_w	k_z/k_w
1	1.025	1.0592	1.4567	1
2	-0.0094	4.1272	4.2466	1
3	-0.0156	2.9555	4.2113	3

To compute the OK5 wiggler field, a 2D/3D magnet design code, Mermaid [4], has been used extensively. The numerically calculated 3D fields on a transverse grid are stored using 128 wiggler harmonics. An analytic wiggler model with three dominant harmonics are obtained by fitting the model with the calculated field on a cylindrical surface inside the wiggler (see Table 2).

4 DYNAMICS WITH TWO WIGGLERS

As found in the previous studies, long wigglers can have a significant influence on the single particle dynamics in the Duke ring [5]. The most significant dynamics impact is expected at the lowest e-beam energy with the strongest effective nonlinearity of wigglers. The dynamics studies are performed using a recently developed symplectic wiggler integrator [6] and the frequency map analysis method, NAFF, of J. Laskar [7]. Fig. 3 and Fig. 4 show the computed dynamic apertures for a bare lattice without OK5 wigglers and a 300 MeV lattice with circularly polarized OK5 wigglers to produce 2 MeV gamma beams. In Fig. 3, the large footprint of the bare lattice (the left plots) in both configuration and tune spaces is reduced to a much smaller footprint when two OK5 wigglers are turned on (the right plots). The reduction in the momentum aperture, from (-2.7%, 3.8%) to (-2.8%, 3.1%), will reduce the beam lifetime when OK5 wigglers are turned on. Significant transverse dynamic aperture reduction is observed in Fig. 4 for on-momentum particles. This can have significant impact on the injection efficiency, which is critical for our future top-off injection with a booster ring.

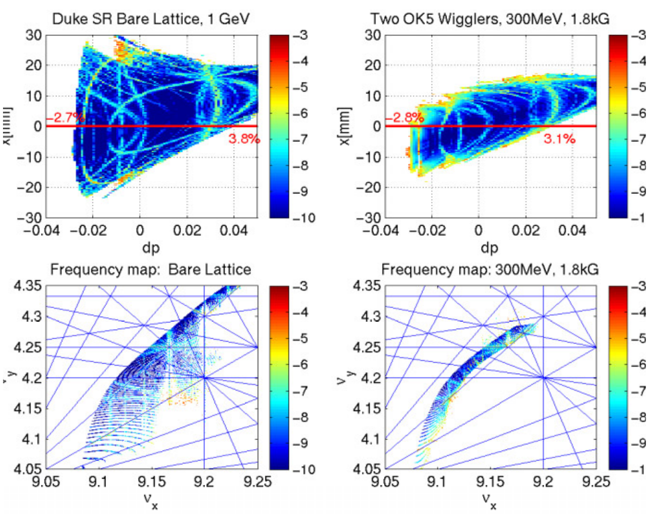

Figure 3: Horizontal and momentum aperture comparison at the center of the arc, $\beta_x = 2.48$, $\beta_y = 1.56$ m. On the left, a Duke ring lattice without wigglers; on the right, a Duke ring lattice with two OK5 wigglers energized.

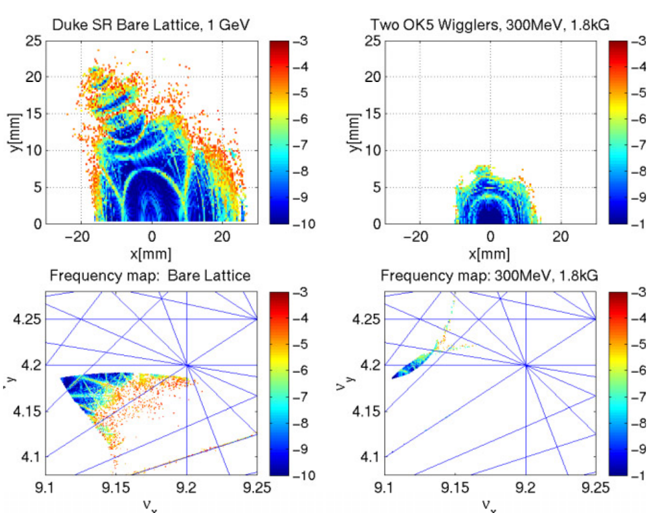

Figure 4: Horizontal and vertical aperture comparison for on-momentum particles at the center of the arc. On the left, a Duke ring lattice without wigglers; on the right, a Duke ring lattice with two OK5 wigglers energized.

The dynamics impact of two OK5 wigglers for three operational modes is summarized in Table 3. At 1 GeV, a small reduction in the transverse dynamic aperture is not expected to have any direct impact on the ring performance. However, at 300 MeV in both linearly and circularly polarized modes, momentum and transverse apertures are significantly reduced. Most notably, the vertical aperture is reduced by about a factor of four. Some preliminary studies have been performed in search of possible field compensation solutions. One study assumes that OK5 wigglers were comprised of two ideal wiggler arrays with infinite poles (no field roll-off). The computed dynamic aperture for this scenario is shown as the last row of Table 3. In this case, both the momentum aperture and vertical aperture are restored to the similar values as the bare lattice. Therefore, it seems possible to recover some of the lost aperture by certain field compensation schemes built into OK5 wigglers. Several wiggler pole-tip modifications have been designed and their impacts on dynamics will be carefully investigated.

Table 3: Computed dynamic apertures with or without OK5 wigglers.

Duke Ring Lattice	Energy Aper. [%]	Hori. Aper. [mm]	Vert. Aper. [mm]
Bare Lattice	(-2.7,3.8)	(-15, 24.9)	13.5
1 GeV, circular	(-2.7,3.8)	(-12.6,17.7)	8.86
0.3 GeV, circular	(-2.8, 3.1)	(-9.9, 13.5)	6.5
0.3 GeV, linear	(-2.7, 2.7)	(-11.7, 17.4)	7.25
0.3 GeV, ideal wig	(-2.8, 3.7)	(-10.5, 14.7)	13.75

5 SUMMARY

In this paper, we have reported our preliminary findings on the Duke ring dynamics with two OK5 wigglers. Significant dynamics aperture reduction has been observed due to the strong nonlinearities of the long wigglers. In the near future, we plan to study the dynamics impact of four OK5 wigglers in its final lattice configuration. In particular, we would like to investigate possible wiggler field compensation schemes and optimal lattice designs to improve the Duke ring dynamics with the OK5 FEL.

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6 REFERENCES

[1] I. B. Drobyazko and *et al.*, Nucl. Instr. and Mech. A 282 (1989), 424–430.

[2] V. N. Litvinenko and *et al.*, Nucl. Instr. Methods, v. A475, pp. 407–416 (2001).

[3] Y. K. Wu and *et al.*, Nucl. Instr. Methods, v. A475, pp. 253–259 (2001).

[4] A. N. Dubrovin, "MERMAID, the 2D/3D code for magnetic design," Novosibirsk, Russia.

[5] Y. Wu and *et al.*, Nucl. Instr. and Mech. A 341 (1994), 363–366.

[6] Y. K. Wu and *et al.*, Proc. of PAC2001, Chicago, p. 459 (2001).

[7] J. Laskar, Physica (Amsterdam), 67D, p. 257–281 (1993).