Lattice and Dynamic Aperture of the Duke FEL Storage Ring*

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Abstract

A low emittance lattice of the Duke FEL (Free Electron Laser) storage ring dedicated to drive UV-VUV FELs is presented. The second order geometrical aberration is compensated to increase the dynamic aperture. The 6-D dynamic aperture study has been performed on this lattice using symplectic tracking codes, which demonstrates a large energy aperture. The influences of higher-order multipoles (HMs), RMS errors and 6.8-m OK-4 undulator on dynamic aperture are studied. The transverse dynamic aperture is mainly limited by HMs in the straight section quadrupoles.

For future FEL operations, we have designed a new straight section lattice for a 26-m long FEL undulator. The dynamic aperture for this lattice is discussed.

I. New Lattice Design

The original design of the FEL storage ring in Stanford [1] had problems with the sextupole saturation from closely placed dipole magnets and asymmetric dipole fields due to parabolic endpieces needed to create sextupole moments. We have eliminated these problems in the new lattice design by removing sextupole magnets and dipole endpieces. To create sextupole moments we have used combined function magnets: asymmetrically excited quadrupoles and dipoles with thin steel shims installed in the center of the magnets [2,3].

The Duke storage ring [4] has a racetrack configuration with two identical arcs and two long straight sections. Each arc is made up of ten FODO cells. The north straight section provides space for injection, RF cavity and 3.64-m NIST undulator; the south straight section is flexible to contain undulators with a maximum length of 26-m. The storage ring layout is shown in Figure 1 and the lattice parameters are given in Table 1.

Table 1. Duke storage ring lattice parameters.

Circumference [m]	107.46
Number of dipoles and quadrupoles	40, 64
Number of FODO cells	20
Length of straight section, and arc [m]	34.21, 19.52
Momentum compaction	0.0086
Operation energy [GeV]	0.25 - 1.0
RF frequency [MHz] (RF voltage 850 kV)	178.547
Energy Acceptance (limited by RF)	$\pm 3.0\%$
Horizontal emittance [mm-mrad]	0.018
Nominal tunes, ν_x and ν_y	9.1107, 4.1796
Natural chromaticities, C_x and C_y	-10.0, -9.78
Maximum FEL undulator length [m]	26.0

To minimize the second-order geometric aberrations due to strong sextupole moments, we design arc cells with a structure similar to the second-order achromat. The phase advance per cell is chosen as $\Delta\Psi_x = (3/10)\,2\pi$ and $\Delta\Psi_y = (1/10)\,2\pi$. The last two cells are modified to match (η_x, η_x') functions to zero in the straight sections. Finally, we redistribute sextupole moments in the modified cells to cancel horizontal second-order geometric aberrations and minimize the cross-talk aberrations of the two transverse planes [3].

II. Dynamic Aperture of Duke Storage Ring

The tracking codes used for dynamic aperture study are Tracy [5] and Despot [6], which employ fourth-order symplectic integrators for magnets. To study the influence of undulators, a second-order symplectic integrator is added to both codes.

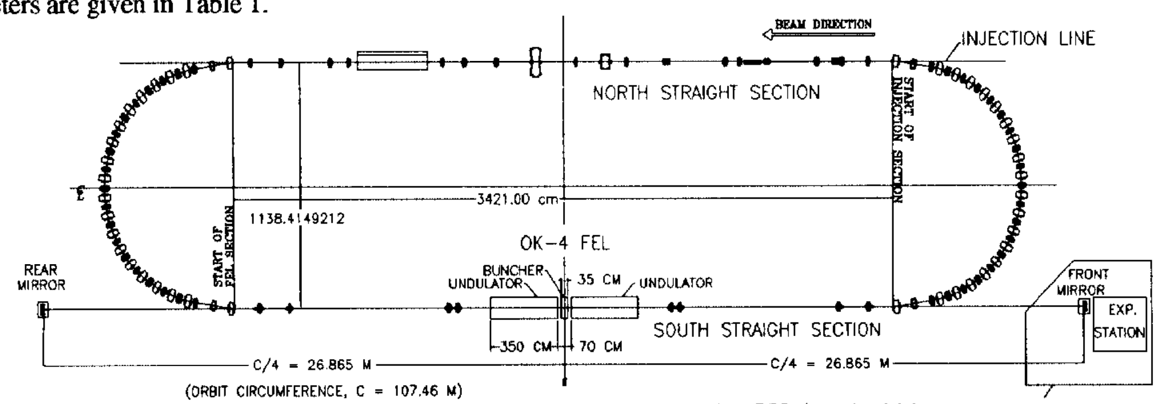

Figure 1. Layout of Duke FEL storage ring with OK-4 optical klystron.

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A. Influence of higher-order multipoles (HMs) and RMS errors

HM strengths are extracted from magnetic measurement data [2,3]. The strong HMs in straight section quadrupoles ($K_5/K_1 = -1.576\times10^4\,\mathrm{m}^{-4}$ and $K_9/K_1 = -2.62\times10^{10}\,\mathrm{m}^{-8}$) caused by imperfect design are used in the tracking codes. Much weaker HM moments in arc quadrupoles are neglected.

Reasonable RMS errors are assumed in our simulations: $dB/B = 0.0005$ in dipoles, $dK_1/K_1 = 0.001$ in quadrupoles and $dK_2/K_2 = 0.01$ in sextupole strengths; transverse position errors $dX = dY = 0.1\,\mathrm{mm}$ and longitudinal rotation errors $dT = 0.5\,\mathrm{mrad}$ in all magnets. All beam position monitors (BPMs) have RMS displacement errors of 0.2 mm. The closed orbit is corrected by 51 horizontal and 31 vertical correctors. A statistical study has been done using eight different seeds to generate RMS errors [3].

In Figure 2, we have shown that the transverse aperture is mainly limited by the HMs in straight section quadrupoles. RMS errors do not significantly reduce the aperture.

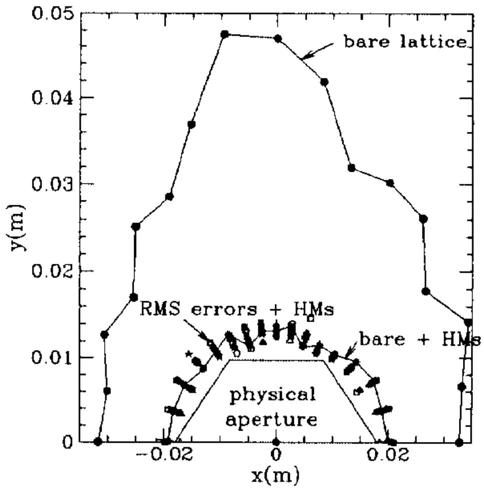

Figure 2. Comparison of Transverse dynamic apertures for two kinds of lattices: (1) Lattice with RMS errors and HMs; (2) Lattice with only HMs. In these calculations, radiation is turned on, particles are tracked for 1000 turns and apertures are plotted after the septum magnet. (The same as in Figure 3.)

B. Energy aperture of lattice

High efficiency FELs and long Touchek life time require a large energy aperture. By performing a tracking study on the bare lattice (containing only dipole, quadrupole and sextupole components), we find that the energy aperture is $\pm3.0\%$, only limited by RF voltage of 850 kV (at this voltage, the RF system has an energy acceptance $\pm3.1\%$). Using an advanced RF system with peak voltage of 3.4 MV, $\pm5.0\%$ energy aperture is achievable according to the tracking study [3].

The energy dependence of transverse aperture is plotted in Figure 3 for a realistic lattice with HMs and RMS errors described in section II.A. At the largest energy deviations $\pm3.0\%$, the transverse apertures are comparable to the physical aperture.

C. Influence of a FEL undulator

The first FEL to be operated in the Duke storage ring is OK-4 optical klystron [7]. OK-4 is provided by our collaborators from the Budker Institute for Nuclear Physics at Novosibirsk in Russia [4]. We summarize the OK-4 parameters in Table 2.

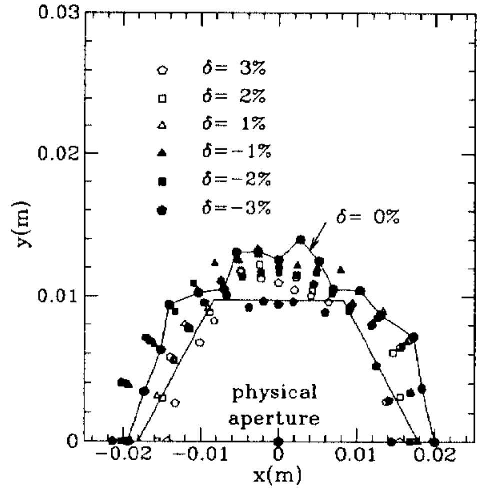

Figure 3. Dynamic apertures for electrons with seven different energies in a realistic lattice (RMS + HMs).

Table 2. OK-4 undulator parameters.

Number of undulators	2
Length of each undulator [m]	3.4
Number of periods	33.5
Undulator period and gap [cm]	10.0, 2.2
Max. magnetic field along the axis [kGs]	5.3

The magnetic filed in this planar undulator is described by the vector potential $\vec{A} = A_x\hat{x} = (B_w/k_w)\cosh(k_w y)\sin(k_w z)\hat{x}$, where $k_w = 2\pi/\lambda_w$, λ_w is the undulator period and B_w is the peak magnetic field. The normalized Hamiltonian of an undulator is $K(x,y,\delta;\overline{p_x},\overline{p_y},l;z) = -\sqrt{(1+\delta)^2 - (\overline{p_x} - eA_x/cp_0)^2 - \overline{p_y}^2}$, where l is the path length, p_0 is the design momentum and p is the momentum of the electron $p \equiv p_0(1+\delta)$; $\overline{p_x}$ and $\overline{p_y}$ are normalized canonical momenta $\overline{p_{x,y}} \equiv (p_{x,y}/p_0)$.

Averaging the Hamiltonian for one period, and expanding to the order of $\overline{p_{x,y}}^2$, we obtain

$$\langle K(x,y,\delta;\overline{p_x},\overline{p_y},l;z)\rangle = \left\{-\delta + \frac{\overline{p_x}^2+\overline{p_y}^2}{2(1+\delta)}\right\} + \frac{(\cosh(k_w y))^2}{4(1+\delta)}\left(\frac{B_w e}{cp_0 k_w}\right)^2.$$

This average Hamiltonian is implemented in Tracy and Despot using a second-order symplectic integrator.

In Figure 4, we compare the dynamic apertures for three lattices: a lattice with OK-4 undulators; a lattice with HMs and a lattice with both OK-4 and HMs. Clearly, while the dynamic aperture remains much larger than the physical aperture after the installation of OK-4, HMs reduce the aperture dramatically. Introducing OK-4 to the lattice with HMs does not further reduce the aperture. By analyzing the tracking data, we find that particle losses are caused by strong high order resonances introduced by HMs. To increase the aperture, we propose to install steel shims in straight section quadrupoles at locations of large β functions to reduce HM strengths. The improved dynamic apertures with HM strengths 0.5 and 0.1 times of the uncompensated values are also shown in Figure 4.

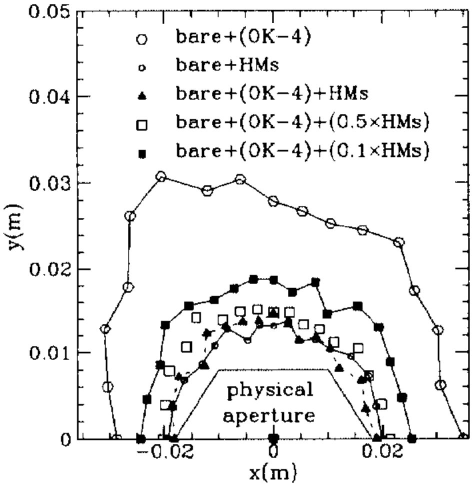

Figure 4. Influence of OK-4 on the dynamic aperture. The HMs are the main limitation of the dynamic aperture. The aperture can be enlarged by reducing the HM strengths. (The plot is made after the septum magnet, particles are tracked for 1000 turns without radiation. The same as in Figure 6).

III. Lattice Design for 26-m FEL Undulator

In order to reach shorter wavelengths (VUV and X-ray) and increase the FEL gain, we design a lattice to accommodate a 26-m FEL undulator with 10 cm period and 5.5 kGs peak magnetic field.

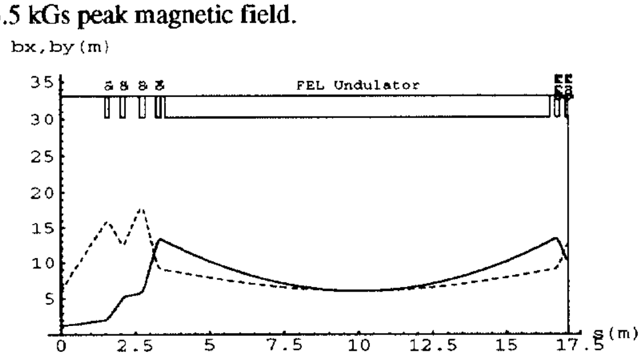

Figure 5. Beta functions in the south straight section with 26-m FEL undulator. The solid line is β_x; the dashed line is β_y.

In this design, we provide two 13-m spaces for undulators in a bilaterally symmetric structure in the south straight section. We use a triplet at the center of the section to match $\beta_x = \beta_y = 6\,\mathrm{m}$ and $\alpha_x = \alpha_y = 0$ in the middle of each undulator. Four quadrupoles are then used to match twiss parameters from the end of arc to the center of undulator. We plot the β-functions in Figure 5 for the first half of this straight section. Finally, the north straight section is used to fit the tunes to nominal values ($\nu_x = 9.1107, \nu_y = 4.1796$).

The dynamic aperture of this lattice has been computed and plotted in Figure 6. Similar to the lattice with OK-4, a large reduction of the dynamic aperture is caused by HMs.

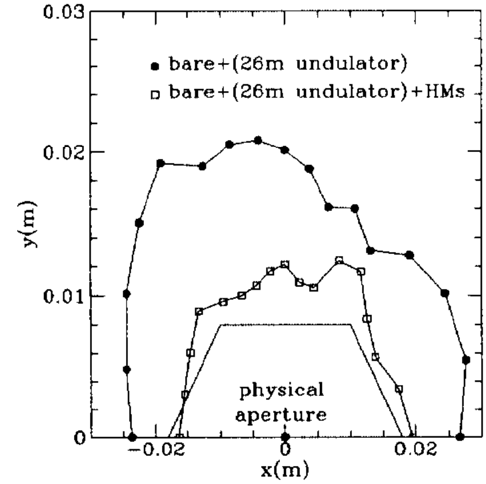

Figure 6. Dynamic aperture of the Duke storage ring with a 26-m undulator.

IV. Conclusion

In this study we find that the major limitation of dynamic aperture for the Duke FEL storage ring is higher-order multipoles in straight section quadrupoles due to an imperfect design of the magnets. The undulators (the 6.8-m OK-4 undulator or the 26-m long undulator) play a less important role in reducing the aperture. The overall dynamic aperture of a realistic lattice for the Duke storage ring is larger than the physical aperture.

V. Acknowledgments

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