NEW STORAGE RING LATTICE FOR THE DUKE FEL WIGGLER SWITCHYARD SYSTEM

H. Hao*, J. Li, Y. K. Wu
FEL Laboratory, Triangle Universities Nuclear Laboratory, and Department of Physics, Duke University, Durham, NC 27708-0319, USA

Abstract

The Duke storage ring is a dedicated driver for the OK-4 FEL and OK-5 FEL, and for the state-of-the-art Compton gamma-ray source, High Intensity Gamma-Ray Source (HIGS). To produce FEL lasing below 190 nm and gamma-ray beams above 100 MeV, the FEL system needs to be upgraded to increase the FEL gain by adding two more helical OK-5 wigglers to form a four-wiggler FEL. To preserve the linear polarization capability of the gamma-ray beam produced by the planar OK-4 FEL, a wiggler switchyard system is under development which will enable the switch between two planar OK-4 wigglers and two helical OK-5 wigglers in the middle of the FEL straight. In this work, we present the new magnetic lattice designed for the operation of the wiggler switchyard system. This new lattice is developed with great flexibility for the operation with different numbers of FEL wigglers, variable betatron tunes, and adjustable electron beam sizes at the collision point for the HIGS. In addition, the new lattice is developed for the operation in a wide range of energies, from 240 MeV to 1.2 GeV, with proper nonlinear dynamics compensations in order to realize a large dynamic aperture.

INTRODUCTION

The Duke storage ring (DSR) is a dedicated driver for storage ring free-electron laser (FEL) and the high performance Compton backscattering based γ-ray source, the High Intensity Gamma-Ray Source (HIGS) at Duke University. With a 54 m long optical cavity, the optical klystrons, OK-4 and OK-5, can lase from about 190 nm to 1060 nm. By colliding this visible/UV FEL with the circulating electron beam at several hundred MeV, the DSR can produce a high flux, nearly monochromatic γ-ray beam with the γ-ray energy varying from 1 MeV to 100 MeV. With a wide energy coverage, and an intensity higher than 10^{10} g/s around 10 MeV, the HIGS is a premier γ-ray facility for nuclear physics research [1].

To operate the HIGS with the γ-ray energy above 100 MeV, which could create new scientific opportunities at the HIGS, a high power FEL lasing below 190 nm is required. Two helical OK-5 wigglers are being installed to increase the FEL gain to achieve this. In order to preserve the capability of producing linearly polarized photons using OK-4 wigglers, a wiggler switchyard system will be used. This system enables a switch between two planar OK-4 wigglers and two helical OK-5 wigglers in the middle of the Duke storage ring south straight section (SSS) within several days [2][3]. To operate with new wiggler configurations enabled by this wiggler switchyard system, a redesign of the SSS lattice is required. A series of lattices have been designed for all six wiggler configurations of the upgraded Duke storage ring. In this paper, we will use the configuration of two OK-5 as an example to introduce the design of these lattices.

CONSIDERATIONS FOR THE LATTICE

The original lattice of the Duke storage ring, in terms of both linear and nonlinear beam dynamics, is a set of well-designed magnetic optics as demonstrated in its successful use in powering the Duke FEL and the HIGS [4]. As this switchyard upgrade is a partial upgrade — the hardware only in the SSS will be reconfigured and upgraded, it is convenient to keep the lattice outside the SSS unchanged and only redesign the SSS lattice. Using this design, most characteristics of the linear beam dynamics of the original lattice, i.e., the global tune and the injection scheme, can be preserved, which will help reduce the design and commissioning efforts. Moreover, as there are no sextupole and higher order multipoles in SSS, this design can also keep the leading order nonlinear terms in the storage ring Hamiltonian unchanged for on-momentum particles in the lattice with all wigglers turned off (the 0-lattice).

In the HIGS, to have an efficient interaction between the FEL beam and the electron beam for either FEL production or γ-ray production, the electron beam should be matched with the FEL beam. For the FEL operation with two wigglers in the middle of the SSS, the optimum $\beta_{x,y}$ in the SSS center should be 4 m to 6 m. For the routine operation, a 4.5 m β-function is used to coincide with the Rayleigh range of the FEL cavity. In the design of the new SSS lattice, β_x is kept at 4.5 m. To create room for the longer OK-5 wigglers, two pairs of doublets at the middle of the SSS must be relocated outward by about 20 cm. As this change is not significant, it is possible to have the new lattice similar to the original one, i.e., the characteristics of the β-function and focusing/defocusing sequence of quadrupoles could be similar to the original lattice.

The HIGS operation requires to switch the use of different wigglers[5] in several minutes and without significant beam loss. For example, during a nuclear physics experiment, one or two planar OK-4 wigglers in the middle of the SSS will be turned off and one or two helical OK-5 wigglers on the side will then be turned on. To enable the transition among different wiggler configurations, we need to design a 0-lattice shared by all six SSS configurations for

* haohao@fel.duke.edu

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the new SSS lattice. From this 0-lattice, one SSS configuration can be ramped to another one with proper wiggler compensation.

LATTICE FOR THE TWO OK-5 WIGGLERS

The OK-5 wiggler is a 30-period, 4.08-m-long electromagnet helical wiggler used for producing the circularly polarized FEL and γ-ray beam with the maximum wiggler parameter $K_{\rm w} = 3.53$. It can be operated at different strength for FEL operation from 190 nm to 1050 nm. To produce gamma-rays at different energies, the strength of the wiggler and energy of the electron beam will be varied. The SSS lattice should be designed for a wide range of wiggler settings and beam energies. Theoretically, the linear lattice perturbation caused by a wiggler is related to the square of the energy normalized wiggler strength, $(K_{\rm w}/E_0)^2$, where E_0 is the electron energy. Thus we can write the change of the quadrupole strength necessary for wiggler compensation as $\Delta K_{1,\rm cmps}(k)$ where $k = (K_{\rm w}/10/E_0[\rm GeV])^2$ is chosen for practical reasons. The design of the wiggler compensation scheme then becomes a task of finding $\Delta K_1(k)$ for all 18 quadrupoles under a set of lattice constraints including certain betatron phase advances in the SSS and certain values of β-functions at some locations. While it is known that $\Delta K_{1,\rm cmps}(k)$ cannot be explicitly solved for a general case. But based on the understanding that $\Delta K_{1,\rm cmps}(k)$ should be a well-behaved function which varies smoothly with k, we can use a low order polynomial of k to approximate $\Delta K_{1,\rm cmps}(k)$,

$$\begin{aligned} K_1 &= K_{1,0} + \Delta K_{1,\rm cmps}(k) \\ &= K_{1,0} + a_1 k + a_2 k^2 + a_3 k^3 + a_4 k^4 + a_5 k^5 + a_6 k^6, \end{aligned} \quad (1)$$

where $K_{1,0}$ is the quadrupole strength for 0-lattice, $a_{1,2,\cdots}$ are coefficients for different orders of k.

For the lattices with two OK-5 wigglers, we use 6th order polynomials to represent the functions $\Delta K_{1,\rm cmps}(k)$ for all 18 quadrupoles. Figure 1 shows the SSS lattices with different values of k from 0 to 0.7 GeV^{-2}. It is clear that the β-functions at two ends of the SSS are nearly the same for different wiggler strengths, indicating that with the wiggler compensation lattice variations due to the change of the wiggler setting can be limited mostly to the regions inside the SSS. The β-function represented by thick black and red lines in Figure 1 is the beta-function of the 0-lattice, $k = 0$ GeV^{-2}. Starting from this 0-lattice, we can see that the SSS lattices for non-zero wiggler strength, shown in thin black and red lines, vary smoothly with the increase of the strength of OK-5 wigglers until $k = 0.7$ GeV^{-2}, without a discontinuity. Meanwhile, the phase advance of the SSS is kept fixed, $\mu_x = 1.302 \times 2\pi$ rad and $\mu_y = 1.030 \times 2\pi$ rad, which corresponds to the fixed storage ring tunes of $\nu_x = 9.111$ and $\nu_y = 4.180$. From Figure 1, it can be seen that inside the SSS the maximum $\beta_{x,y}$ are 10.2 m and 18.0 m, respectively. These values are reasonably good for an efficient injection and a good beam lifetime. $\beta_{x,y}$ at the SSS center are kept to be 4.5 m for different values of k, which is optimal for the FEL and γ-ray operation. An interesting observation of the β-functions is that in the middle of the SSS $\beta_x \approx \beta_y$, this is the result of a nearly equivalent amount of focusing in x and y directions provided by the helical OK-5 wigglers.

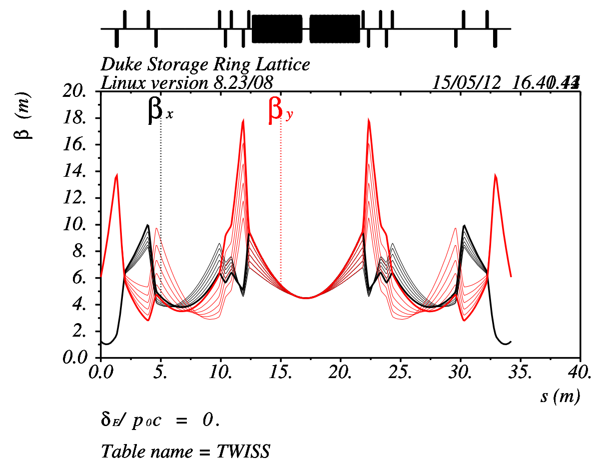

Figure 1: SSS Lattices of different OK-5 wiggler strength for two OK-5 wigglers configuration. The energy normalized wiggler strength k varies from 0 GeV^{-2} to 0.7 GeV^{-2}. Black lines represent β_x, and red lines represent β_y.

The coefficients in the Eq. (1) are extracted by fitting the discrete K_1 data which are obtained from the designs of SSS lattices with different wiggler settings using the lattice design code MAD-8.23 [6]. It is worth investigating differences between the lattices with fitted K_1 values (from Eq. (1)) and those lattices with K_1 values directly obtained using MAD. These differences are shown in Fig. 2. From Figure 2(a), we can see the maximum relative β-beating outside the SSS due to the wiggler compensation schemes is on the order of 0.1%, much smaller than the allowed amount of β-beating for the operation of a typical storage ring. Figure 2(b) shows the storage ring tunes difference between these two sets of lattices. From this Figure, we can see differences for ν_x and ν_y are small, on the order of 10^{-4} and 10^{-3}, respectively, which can be easily compensated by using the tune knobs introduced in the next Section.

TUNE KNOBS FOR TWO OK-5 WIGGLERS CONFIGURATION

A storage ring needs a set of tune knobs to provide lattice flexibilities for storage ring commissioning and operation. In principle, the tune knobs should provide means to return the global tunes (ν_x, ν_y) to the desired values and have a possibly small impact on beam dynamics. For the new SSS switchyard lattice in the Duke storage ring, a set of tune knobs is designed with the capability of varying the storage ring tunes $\nu_{x,y}$ by ± 0.1. Meanwhile, variation of

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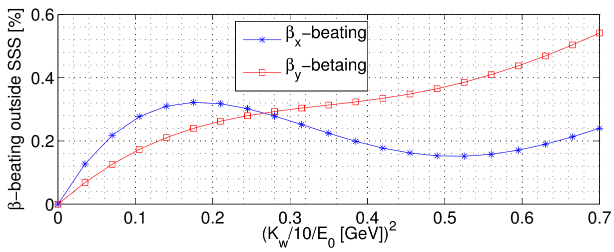
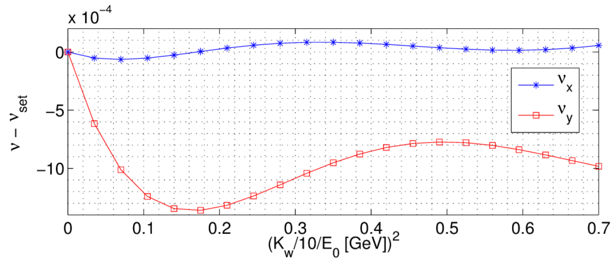


(a) Beta-beating outside the SSS.



(b) Tune deviations.

Figure 2: Beta-beating outside the SSS and the tune deviation using the fitted K_1 formula for the two OK-5 lattice with a varying wiggler strength k from 0 to 0.7 GeV^{-2}.

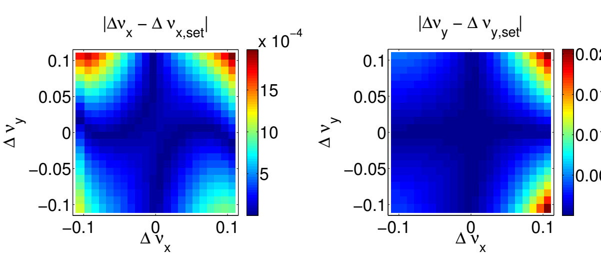


Figure 3: Tune deviations due to lattice tuning.

β-functions caused by the tune knob should be limited to the region inside the SSS.

Once the 0-lattice is determined, the additional quadrupole strength for the tune knob is a function of the tune deviations $\Delta\nu_{x,y}$ and the wiggler strength k, $\Delta K_{1,\mathrm{knob}} = \Delta K_{1,\mathrm{knob}}(k, \Delta\nu_x, \Delta\nu_y)$. As the tune knob is expected to be a small perturbation to the storage ring lattice, we can approximate the focusing change, $\Delta K_{1,\mathrm{knob}}$, using a low order polynomial of $\Delta\nu_{x,y}$. To make the fitting formula simpler, we make an assumption that there is no coupling between the x and y directions for a small tuning range, so that the crossing terms involving both $\Delta\nu_x$ and $\Delta\nu_y$ will not appear in the polynomial. Then the fitting formula for the quadrupole strength, taking into account of both wiggler compensation and tune variations can be written as

$$\begin{aligned} K_1 &= K_{1,0} + \Delta K_{1,\mathrm{cmps}} + \Delta K_{1,\mathrm{knob},x} + \Delta K_{1,\mathrm{knob},y} \\ &= K_{1,0} + a_1 k + a_2 k^2 + \cdots \\ &\quad + b_1(k) \times \Delta\nu_x + b_2(k) \times (\Delta\nu_x)^2 + \cdots \\ &\quad + c_1(k) \times \Delta\nu_y + b_2(k) \times (\Delta\nu_y)^2 + \cdots, \end{aligned} \quad (2)$$

where tune knob coefficients $b_{1,2}(k)$ and $c_{1,2}(k)$ are functions of wiggler strength k. Like $\Delta K_{1,\mathrm{cmps}}(k)$, these coefficients should also be well-defined functions of k and be able to be represented using low order polynomials of k. The coefficients in Eq. (2) can be obtained by fitting the quadrupole strength data obtained form the designs of lattices with tune changes. For the two OK-5 wigglers configuration lattice, we use 3rd order polynomials of $\Delta\nu_{x,y}$ for $\Delta K_{1,\mathrm{knob},x,y}$, and 6th order polynomials of the wiggler strength k as the coefficients in $\Delta K_{1,\mathrm{knob},x,y}$. Figure 3 shows the effectiveness of the tune knob for the two OK-5 wiggler configuration lattice for a tuning range $\Delta\nu_{x,y}$ from -0.1 to $+0.1$. We can see that, for most part of the desired tuning region, the absolute tune differences between the calculated values using Eq. (2) and the desired values $\Delta\nu_{\mathrm{set}}$ are smaller than 10^{-3}, which is quite adequate for operation.

CONCLUSIONS

The newly installed SSS switchyard system for the Duke storage ring can significantly improve the flexibility and capability of the HIGS. This switchyard system requires a redesign of the SSS lattice. In this paper, we introduce a design of the SSS lattice for the operation of the two OK-5 wigglers in the middle of the SSS. The wiggler compensation for the lattice can be realized with a small perturbation outside the SSS, and a set of effective tune knobs have also been developed with a wide tuning range.

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