COMPENSATION SCHEMES FOR OPERATION OF FEL WIGGLERS ON DUKE STORAGE RING*

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Abstract

The Duke Free-electron laser is the photon driver for the High Intensity Gamma-ray Source (HIGS). To extend the capabilities of the FEL and HIGS to higher photon energy regions, an FEL wiggler switchyard system was developed in the recent years. This system was installed and commissioned in 2012. The FEL wiggler switchyard is used to change between two planar OK-4 wigglers and two helical OK-5 wigglers in the middle of the FEL straight section in a short period of time (a few days). With a total number of six electromagnetic wigglers, the Duke FEL can be operated in a number of wiggler configurations and with a wide range of magnetic fields. The operation of uncompensated FEL wigglers can cause significant changes to the electron beam closed orbit and magnetic lattice. To maintain sufficiently large dynamic aperture for efficient injection and good beam lifetime, a set of complex compensation schemes, including wiggler magnetic field and lattice compensation, have been developed for the operation of the FEL wigglers. This paper reports the overall architecture and performance of the FEL wiggler compensation schemes and their implementation in the accelerator control system using the feed-forward mechanism.

INTRODUCTION

The High Intensity Gamma-ray Source (HIGS) at Triangle University Nuclear Laboratory (TUNL) is driven by an electron storage ring and storage ring based oscillator free-electron lasers (FELs) [1]. The gamma-ray photons are generated by colliding high energy electrons with intense FEL photons trapped inside the oscillator cavity by two concave mirrors separated by 54 meters, half of the storage ring circumference. The oscillator FEL is installed in one of the two 34-meter long straight sections. It was comprised of two helical OK-5 wigglers in the upstream and downstream ends, and two planar OK-4 wigglers in the middle of the FEL straight section. Selectively energizing these wigglers, HIGS was successfully operated to provide 1 to 60 MeV circularly or linearly polarized gamma-ray beams for user experiments, and demonstrated the capability of generating 100 MeV gamma-ray beam with considerable flux [2]. To increase the gamma-ray flux in the high energy region and extend the capabilities of the FEL and HIGS to even higher photon energies, an FEL wiggler switchyard system was developed in the recent years. This system was installed and commissioned in 2012 [3].

The FEL wiggler switchyard is used to change between two planar OK-4 wigglers and two helical OK-5 wigglers in the middle of the FEL straight section in a short period of time (a few days). With a total number of six electromagnetic wigglers, the Duke FEL can be operated in a number of wiggler configurations and with a wide range of magnetic fields as shown in Fig. 1.

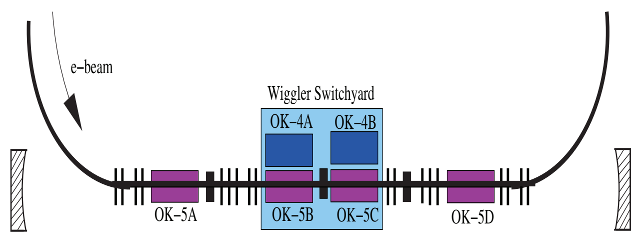

Figure 1: The schematic of the Duke FEL with the wiggler switchyard.

The operation of uncompensated FEL wigglers can significantly impact the closed orbit of the electron beam and storage ring magnetic lattice. To minimize these effects, a set of complex compensation schemes, including magnetic field and lattice compensation, have been developed [4] and implemented in the storage ring control system.

LATTICE COMPENSATION AND TUNE KNOBS

Since the Duke FEL can be operated with various wiggler configurations, it needs a different scheme to compensate the magnetic lattice for each wiggler configuration. Nine families of quadrupoles (a total number of 18 individual quadrupoles) in the FEL straight section are used for beta function matching and tune compensation.

These quadrupoles are also used to build a tune knob, a critical tool for operating the storage ring in a transparent manner while preserving good performance of the magnetic optics. Due to the impact of wigglers, the coefficients of the tune knob change with the wiggler configurations and wiggler fields. The total change of the quadrupole strength needed for lattice compensation and tune knob is given by a polynomial function up to 6th order of the scaled wiggler strength $\widetilde{K}_\text{w}$ [4],

$$\begin{aligned}\Delta K &= f(\nu_x, \nu_y, \widetilde{K}_\text{w}) \\ &= \sum_{m=0}^{6} a_m \widetilde{K}_\text{w}^m +\end{aligned}$$

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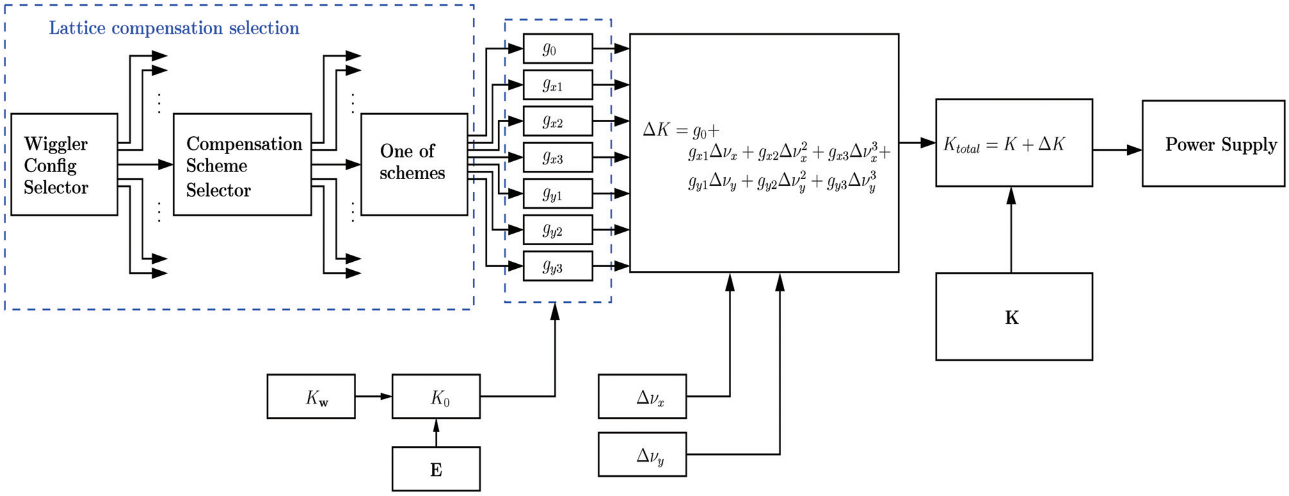

Figure 2: The block diagram of the lattice compensation and tune knob schemes of the Duke FEL storage ring. These schemes are realized using EPICS records resided in an Input-Output Controller (IOC).

$$\sum_{n=1}^{3}\left(\sum_{m=0}^{6} b_{nm}\widetilde{K}_{\rm w}^{m}\Delta\nu_x^n + \sum_{m=0}^{6} c_{nm}\widetilde{K}_{\rm w}^{m}\Delta\nu_y^n\right)$$
$$= g_0\left(\widetilde{K}_{\rm w}\right) + \sum_{n=1}^{3}\left[g_{xn}\left(\widetilde{K}_{\rm w}\right)\Delta\nu_x^n + g_{yn}(\widetilde{K}_{\rm w})\Delta\nu_y^n\right], \quad (1)$$

where

$$\widetilde{K}_{\rm w} = \left(\frac{K_{\rm w}}{10E[\rm GeV]}\right)^2 = \left(\frac{0.934\lambda_{\rm w}[\rm cm]B_0[\rm T]}{10E[\rm GeV]}\right)^2. \quad (2)$$

In these expressions, B_0 and $\lambda_{\rm w}$ are the nominal magnetic field and period of the wiggler, respectively, E is the energy of electrons, $\Delta\nu_{x,y}$ are the tune knob adjustments, the polynomial coefficients a_m, b_{nm} and c_{nm} are determined using a large number of designed lattices for each wiggler configuration with varying wiggler strengths and tune knob settings. g_0, g_{xn} and g_{yn} are used to calculate feed-forward tables with $\widetilde{K}_{\rm w}$ as the variable. There are seven feed-forward tables for each quadrupole in every wiggler configuration. The quadrupole strength can be changed smoothly using these tables for varying wiggler and tune knob settings.

These lattice compensation and tune knob schemes are implemented in the EPICS database of the storage ring control system as shown in Fig. 2 and 3. The wiggler configuration selector (WCS) defines a particular wiggler configuration of the FEL using a set of *MBBO* and *DFANOUT* records. The compensation scheme selector (CSS) , which is realized using a set of *DFANOUT* and *AO* records, is used to select a proper compensation scheme — a set of feed-forward tables for quadrupoles according to WCS. The feed-forward tables are pre-loaded into the EPICS Input-Output Controller (IOC) using break-point table (*BPT*) records. When the wiggler configuration, the wiggler setting, or a tune knob setting is changed, these *BPT* records will calculate a set of coefficients g_0, g_x, and g_y. A subroutine record then calculates the quadrupole strength change ΔK using these coefficients according to Eq. 1. ΔK is then added to the nominal value K of a particular quadrupole magnet, which leads to resetting the corresponding quadrupole power supply.

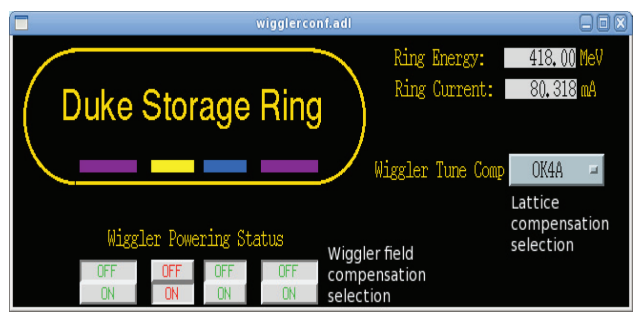

Figure 3: Control panel of selecting Lattice and wiggler field compensation schemes for the Duke FEL operation.

The control schemes for wiggler compensation and tune knob have been brought into operation since June 2012, and served as critical tools for the light source commissioning and operation.

WIGGLER FIELD COMPENSATION

The residual magnetic fields of the wigglers produce significant closed orbit distortion, which degrades the performance of the storage ring, and inversely affect the performance of the FEL lasing and gamma-ray production. To minimize these effects, a field compensation scheme has been developed using beam based measurements. In this scheme, either the build-in correctors at the two ends of the wigglers (OK-5 wigglers) or orbit correctors located just outside of the wigglers (OK-4 wigglers) are used for the compensation. The compensation for each wiggler is

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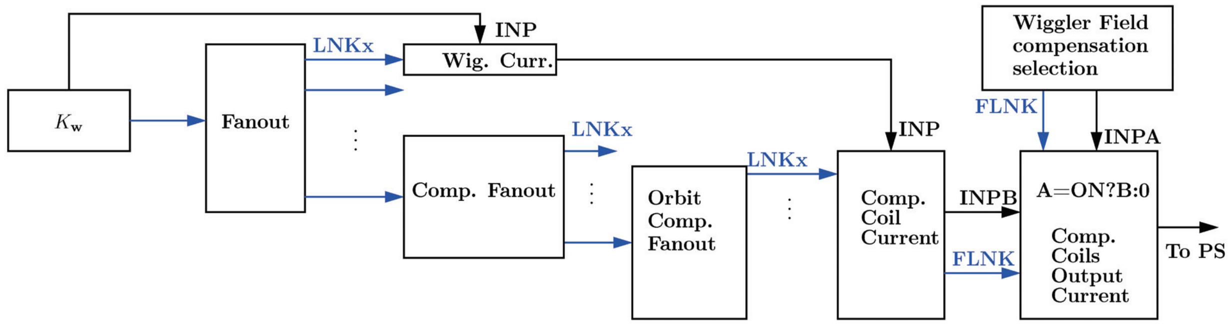

Figure 4: The block diagram of the wiggler field compensation scheme. This scheme is realized using EPICS records resided in an IOC.

individually measured with other wigglers disconnected. The compensation currents of the correctors are acquired by varying the corrector strength to minimize the orbit distortion outside the wiggler around the storage ring. The corrector strengths measured as a function of the wiggler current are used to build feed-forward tables. These tables are integrated into the control system to automatically compensate the wiggler field effects as part of the control for the wiggler setting.

The orbit compensation scheme is illustrated in Fig. 4. The wiggler field compensation selection (WFCS), an EPICS *BO* record for each wiggler, is used to control whether the wiggler needs to be compensated or not. When the setting of a particular wiggler is changed, a record corresponding to each corrector will calculate the current for compensating the orbit distortion induced by the related wiggler. If the WFCS is set for this wiggler, the calculated compensation current is sent to the corresponding corrector power supply, otherwise no compensation current will be applied.

Figure 5 shows the measured result of the field compensation for the downstream OK-4 wiggler, OK-4B. Since the OK-4 wiggler only has the vertical field, it only affects the horizontal orbit. The compensation can bring the horizontal leakage orbit RMS in the FEL straight section to below 0.2 mm without any significant vertical orbit change in the full working range of the wiggler (0-3 kA of current) for a 474 MeV electron beam.

The wiggler field compensation has been successfully used in the light source operation since September 2012. It has greatly enhanced the performance of the Duke FEL and HIGS.

SUMMARY

The lattice and wiggler field compensation schemes have been developed and implemented successfully to meet the operation requirements for all existing configurations of the Duke FEL. The tune knob has been found to be a very useful tool for both light source operation and machine studies. The feed-forward wriggler compensation has significantly enhanced our ability to establish FEL lasing with multiple wigglers. The authors would like to thank all the scientists, engineers and light source operators for their technical and operational support.

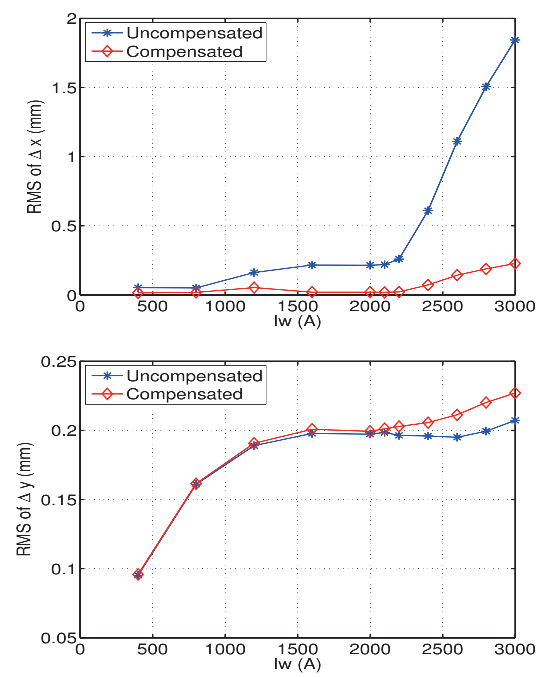

Figure 5: The RMS orbit leakage in the FEL straight section with or without compensation for one of the Ok-4 wigglers. Upper: the horizontal orbit; Lower: the vertical orbit.

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