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BETA FUNCTION MATCHING AND TUNE COMPENSATION FOR HLS-II INSERTION DEVICES*

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Abstract

In order to increase its brightness and improve the performance, the Hefei Light Source (HLS) was completely renovated from 2010 to the end of 2014. The magnet lattice of the new storage ring consists of four double bend achromatic (DBA) cells. There are eight straight sections which can be used to install up to 6 insertion devices (IDs). Currently, five insertion devices have been installed in the storage ring. It is known that the dynamics of the electron beam motion in the storage ring would be influenced by the insertion device, depending on its physical properties. In order to keep high performance operation of the storage ring and make the insertion device transparent to the rest of the storage ring, a complex compensation scheme is developed to match the beta functions at both ends of a ID and perform transverse tune compensation. This scheme has been integrated into the EPICS based control system of the HLS-II. The result indicates that the scheme is very effective to compensate the impact of the insertion devices.

INTRODUCTION

The Hefei light source (HLS) at the National Synchrotron Radiation Laboratory (NSRL) was overhauled to increase its brightness and improve the performance. This major upgrade was started in 2010 and finished at the end of 2014. The new light source, named HLS-II, is comprised of an 800 MeV linac, a beam transfer line and an 800 MeV electron storage ring. Some critical parameters of the HLS-II storage ring are listed in Table 1.

Table 1: Main Parameters of the HLS-II Storage Ring [1]

Name	Value
Beam energy (MeV)	800
Circumference (m)	66.13
Magnet lattice	DBA
Beam emittance (nm·rad)	38
ν_x/ν_y	4.414/3.346
Number of IDs installed	5

Four fold double bend achromatic (DBA) cells are adopted as the magnet lattice of the HLS-II storage ring. The storage ring has two types of straight sections, four 4-meter long and four 2-meter long straight sections. One 4-meter long straight section is used to install the injection devices, and one 2-meter long straight section is used to hold the RF cavity. The rest straight sections can be used to install up to 6 insertion devices (IDs) . At present time, five insertion devices have been installed in the storage ring and providing strong narrow band synchrotron radiation for various user experiments. It is known that an insertion device would have strong impact on the optical parameters of the storage ring, depending on the physical properties of the insertion device. In order to keep high performance operation of the storage ring and make the insertion device transparent to other parts of the storage ring, a complex compensation scheme is developed to match the beta functions at both ends of the ID and perform compensation for the transverse tune. This scheme has been implemented in the EPICS based control system of the HLS-II storage ring. The impact of the IDs is automatically compensated by the control system according to the gap between the top and bottom magnetic poles.

As one example, this paper reports the compensation results of one of the HLS-II insertion devices. It first illustrates the fitting for the scheme, and then a beam based calibration of the scheme is reported. The tune shift and orbit distortion after the compensation are also presented in this paper.

REVISIT OF THE COMPACT OF AN UNDULATOR ON THE STORAGE RING OPTICS

Considering a horizontal undulator, the magnetic field is given by [2]

$$B_y = B_0 \cosh k_{\mathrm{w}} y \cos k_{\mathrm{w}} z, \tag{1}$$

where $k_{\mathrm{w}} = 2\pi/\lambda_{\mathrm{w}}$ is the wave number of the undulator, B_0 is the peak value of the magnetic field. The vector potential of the undulator is

$$\vec{A_x} = -\frac{B_0}{k_{\mathrm{w}}} \cosh k_{\mathrm{w}} y \sin k_{\mathrm{w}} z. \tag{2}$$

And the normalized vector potential is

$$\begin{aligned} a_x &= \frac{eA_x}{P_0} = -\frac{eB_0}{\gamma\beta mck_{\mathrm{w}}} \cosh k_{\mathrm{w}} y \sin k_{\mathrm{w}} z \\ &= -\frac{K_{\mathrm{w}}}{\gamma\beta} \cosh k_{\mathrm{w}} y \sin k_{\mathrm{w}} z, \end{aligned} \tag{3}$$

where $K_{\mathrm{w}} = \frac{eB_0}{mck_{\mathrm{w}}} = \frac{eB_0\lambda_{\mathrm{w}}}{2\pi mc}$ is the undulator strength parameter.

In the undulator, the Hamiltonian for the electron motion is given by [2]

$$H \backsimeq \frac{(p_x - a_x)^2 + p_y^2}{2(1+\delta)}, \tag{4}$$

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where $\delta = \frac{p-p_0}{p_0}$ is the relative momentum deviation, p_0 is momentum of the synchronous particle, p_x and p_y are the transverse momenta of an electron. The total impact of the undulator can be estimated using the averaged Hamiltonian, which is given by

$$< H >= \frac{P_x^2 + P_y^2}{2(1+\delta)} + \frac{< a_x^2 >}{2(1+\delta)}, \tag{5}$$

For an ultra-relativistic electron with $\beta \approx 1$, one have

$$\begin{aligned} < a_x^2 > &= \frac{K_\mathrm{w}^2}{2\gamma^2}(\cosh k_\mathrm{w} y)^2 \simeq \frac{K_\mathrm{w}^2}{2\gamma^2}(1 + \frac{1}{2}(k_\mathrm{w} y)^2 + \cdots)^2 \\ &= \frac{K_\mathrm{w}^2}{2\gamma^2}(1 + k_\mathrm{w}^2 y^2 + \cdots). \end{aligned} \tag{6}$$

Only keeping the linear focusing term, Eq. (5) yields

$$H_1 = \frac{1}{4(1+\delta)} \frac{K_\mathrm{w}^2}{\gamma^2} k_\mathrm{w}^2 y^2. \tag{7}$$

Hence, the minimum tune shift of an on-momentum electron is

$$\Delta\nu_y = \frac{1}{8\pi}(\frac{K_\mathrm{w} k_\mathrm{w}}{\gamma})^2 \cdot \bar{\beta}_\mathrm{w} \cdot L_\mathrm{w}, \tag{8}$$

where $\bar{\beta}_\mathrm{w}$ is the averaged vertical beta function, L_w is the length of the undulator. Equation (8) indicates that for a given undulator, the tune shift is proportional to the square of the wiggler parameter K_w, i.e. B_0^2.

THE COMPENSATION SCHEME

In this section, we illustrate the compensation scheme for one of the installed insertion devices, WIG. Some of its main parameters are listed in Table 2 [1].

Table 2: Parameters of WIG in HLS-II

Length (m)	1.72
Period	0.156
Number of period	10
Max magnetic field (T)	1.39
Gap (mm)	30-155

WIG is installed in the middle of a 2-meter long straight section as shown in Fig. 1. This figure shows one cell of the HLS-II storage ring. As shown in the figure, there are two quadrupole doublets (WQD, WQF) symmetrically installed at both near ends of WIG. Two dipoles and another two quadrupole doublets (QD, QF) are symmetrically installed at both far ends of WIG.

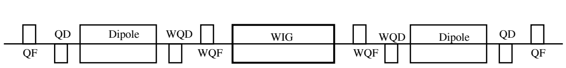

Figure 1: Magnet lattice around WIG.

In order to minimize the impact of the insertion device with different gap on the optical parameters beyond this straight section, a compensation scheme is needed to keep the twiss parameters unchanged at both ends of the straight section, and the phase advance constant. This scheme is fitted using MAD [3] in two steps. In the first step, only WQD and WQF are used to match the twiss parameters at both ends of the WIG straight section. Since these quadrupoles at the near ends can not provide enough phase advance to compensate all the tune shift, this step is used to find a closest solution for the compensation. In step two, other quadrupoles, QD and QF, at the far ends are used to compensate the residual tune shift.

The K1 values used to compensate the tune shift and match the beta function are plotted in Fig. 2 as a function of B_0^2. The K1 values of all the quadrupoles in use change smoothly as the B_0 increase or decrease. The residual tune shift is negligible, as shown in Fig. 3. These facts indicate that this scheme is effective for the compensation.

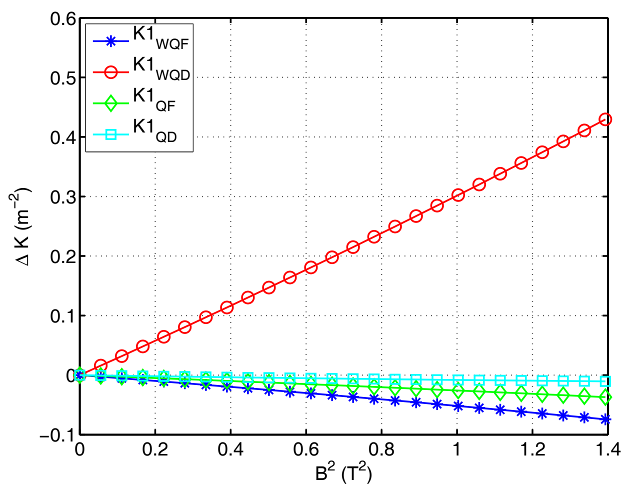

Figure 2: K1 values for compensating tune shift and matching beta function for WIG.

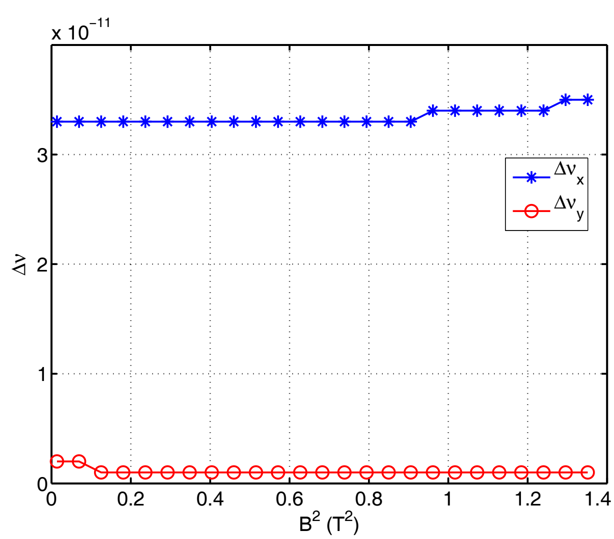

Figure 3: Residual tune shift after compensation.

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BEAM BASED CALIBRATION OF THE B FIELD

In order to minimize the error between the magnetic model and the real magnetic field seen by the electron beam, the magnetic field of WIG is calibrated using the compensation scheme illustrated in section with the electron beam in the storage ring. The calibration procedure is as the following:

- Open the gap of WIG to maximum and measure both the transverse tunes;
- Close the gap of WIG to a smaller value;
- Using the compensation scheme to minimize the tune shifts, record the gap value and B_0 used for the compensation;
- Repeat above two steps until get to the minimum gap;
- Fit B_0 as a function of gap values of WIG;
- Modify the compensation scheme using the gap values.

The measured data are shown in Fig. 4. The B_0 values are fit into 3rd order polynomial of the gap value for ease of integrating the compensation scheme into the control system.

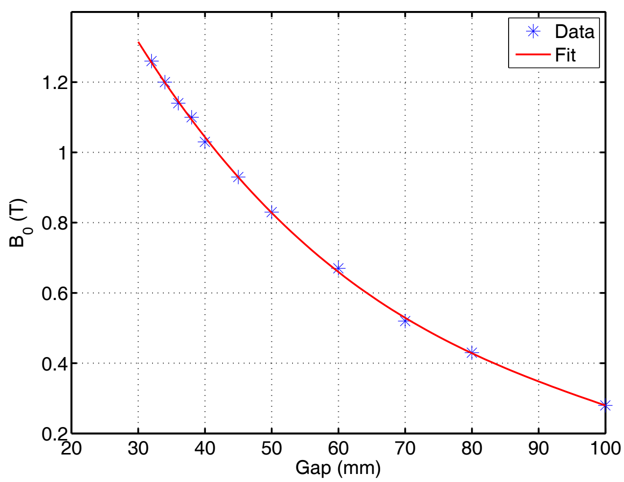

Figure 4: Measured B_0 as a function of the magnet pole gap of WIG.

COMPENSATION RESULTS

The compensation is performed using the scheme discussed in section . The tune shift measured at different gaps is plotted in Fig. 5. The results indicate that the vertical tune shift is negligible, the maximum horizontal tune shift is 0.003. This tune shift is durable for stable operation of the storage ring. The maximum RMS orbit distortion caused by the WIG is 60 µm, which can be easily corrected by the orbit feedback (see Fig. 6).

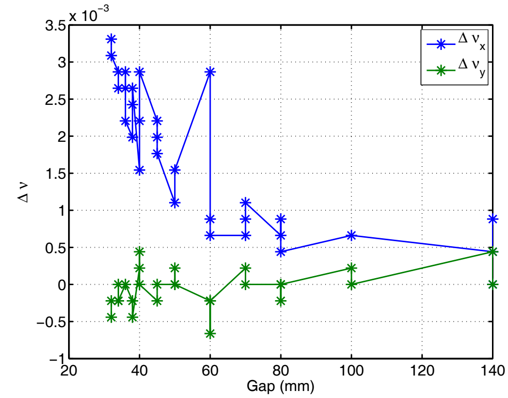

Figure 5: Residual tune shift after compensation.

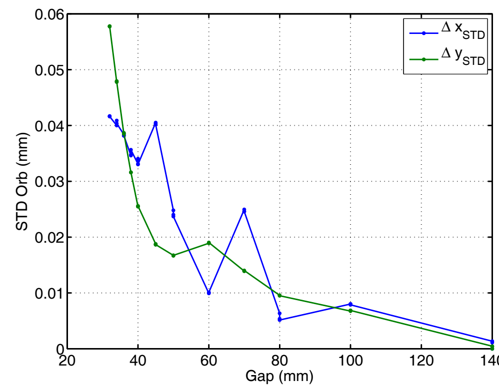

Figure 6: Residual orbit distortion caused by WIG.

SUMMARY AND ACKNOWLEDGMENT

The compensation scheme of WIG is fitted using the MAD program. This scheme adopts four quadrupole doublets to keep the twiss parameters unchanged at both ends of the holding straight section and the phase advance constant in the section. Beam based calibration is performed to minimize the error between the theoretical model and the real magnetic field of the WIG. Although there is still a small amount of residual tune shifts after the compensation, it does not significantly impact the stable operation of the storage ring. Further optimization will be performed in order to eliminate this effect .

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[2] Lee S Y, Accelerator Physics, 2004:479-482.

[3] http://madx.web.cern.ch/madx/.