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CHARACTERIZING BETATRON TUNE KNOBS AT DUKE STORAGE RING *

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Abstract

A good control of the electron beam betatron tune is critical for the operation of a storage ring. As the driver for Duke free-electron lasers (FELs) and the High Intensity Gamma-ray Source (HIGS), the Duke storage ring is operated in a wide energy range (0.3 GeV – 1.2 GeV), with several different electromagnetic wiggler configurations. This creates the challenge of controlling the betatron tune in a global manner. As the the first step, the feedforward tune compensation schemes were designed and implemented to the real-time computer control system to compensate the tune change caused by the wiggler field. To further increase the flexibility of the operation, a set of tune knob schemes are designed for various wiggler configurations. The β function changes caused by these knobs are constrained within the south straight section where the tune knob is located, minimizing the impact on the electron beam dynamics (i.e. injection and lifetime). The tune and β function measurements show a good agreement with the calculation. In addition, it is found that some tune knob schemes are effective for new wiggler configurations that are not originally designed for.

INTRODUCTION

In the operation of a storage ring based light source, it is necessary to have a good control of the storage ring lattice, i.e. the ability to vary the betatron tunes in a desired way. This type of control is usually realized using the tune knob, a scheme to vary a set of quadrupoles simultaneously in a way such that the global tunes can be changed as needed. As the driver for Duke free-electron lasers (FELs) and the High Intensity Gamma-ray Source (HIGS) [1] [2], the Duke storage ring is operated in a wide energy range from 0.3 GeV to 1.2 GeV, with several different electromagnetic wiggler configurations. The vasitility of the Duke storage ring opeation creates the challenge of designing a set of betatron tune knobs to work with different lattice configurations. As part of the wiggler switchyard upgrade project in 2012, a set of tune knobs were designed on top of the lattices with wiggler focusing compensations [3]. The knobs were implemented into the EPICS control system in a feedforward manner [4]. The tune knobs have been used for the HIGS γ-ray operation since 2012. In this paper, we report the quantitative investigation of effectiveness of these tune knobs and document a set of calibrations to improve the usefulness of the tune knobs.

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DESIGN OF THE TUNE KNOB

A tune knob is realized by changing the the strength of a set of quadrupoles in the storage ring. To minimize the impact on the beam dynamics of the Duke storage ring, e.g. the injection, the β fucntion changes introduced by the quadrupole variations are constrained within the 34-meter-long south straight section (SSS). The lattice at two ends are required to match with the arc lattice when the quadrupoles are varied. To preserve the beam dynamics, the symmetry of the lattice also should be preserved whenever possible.

For the HIGS γ-ray operation, the electron beam energy, FEL wiggler strength and configuration are varied in a wide range to produce high-flux γ-ray photon beams for a variety of nuclear physics experiments. To cover such wide range of operation, a number of tune knobs are designed for 6 commonly used wiggler configurations, with the wiggler strength varying from zero to its maximum setting. The horizontal (or vertical) tune knobs are designed to control tune only in one direction, with a minimum impact on the tunes in the other direction. The complete tune knob to change both ν_x and ν_y is realized by simply adding together the two independent knobs in the two directions. Numerical computation shows that this design could simultaneously control tunes (ν_x, ν_y) in both directions.

CALIBRATION OF THE TUNE KNOBS

The calibration of tune knobs requires a large number of tune measurements. A transverse feedback (TFB) based tune measurement technique was used to reduce the tune measurement time [5]. In the measurement, the electron beam is excited by a pseudo white noise signal with a finite bandwidth which covers the frequency range of betatron tunes. The turn-by-turn BPM signal of the transverse orbit motion is recorded by the TFB. By using the fast Fourier transform (FFT), the betatron tune can be identified. Compared to the conventional network analyzer based method that we also use, the TFB based tune measurement technique reduces the measurement time by a factor of 3, with an improved tune resolution. In the operation of Duke storage ring, the tune variation cannot reach the maximum designed tune knob values of ± 0.1 due to the betatron tune resonances. One of the resonances is the horizontal integer resonance $\nu_x = 9$; another one is the difference resonance $\nu_x - \nu_y = 5$. In our measurements, the tune knob variation is limited within ± 0.05, which is more than adequate to cover the tune variation for HIGS operation.

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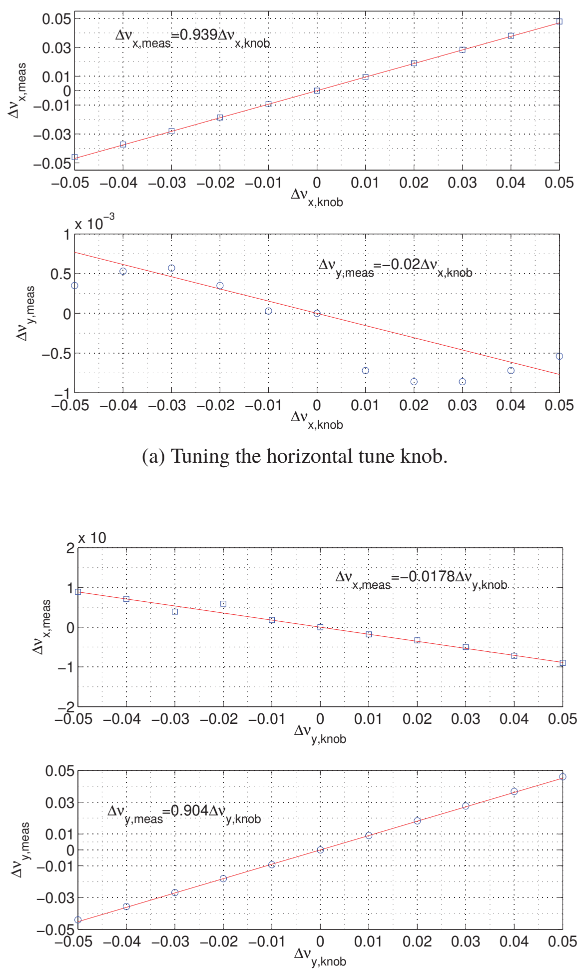

(a) Tuning the horizontal tune knob.

(b) Tuning the vertical tune knob.

Figure 1: Measured horizontal and vertical tune variations by varying the tune knobs.

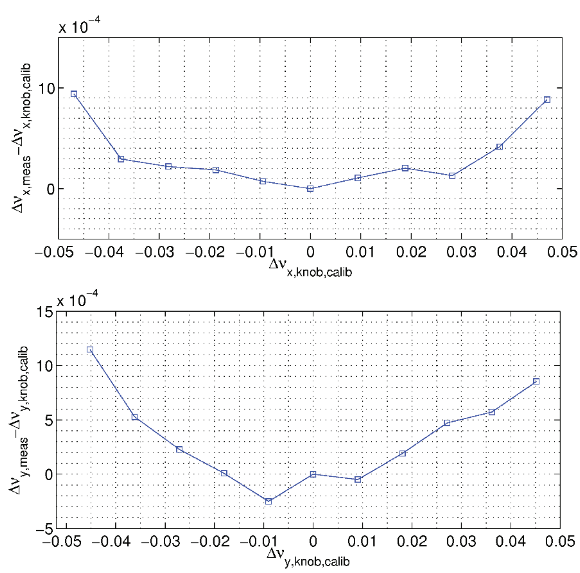

Figure 2: The residual tune variations after applying the tune knob calibrations.

Calibration of Nominal Lattice Tune Knobs

The tune knobs are first calibrated for the nominal storage ring lattice with zero wiggler strength. Figure 1 shows the measured tune changes as a function of tune knob settings in the storage ring. It can be seen that the relationship between measured tunes $\Delta\nu_{x,y,\mathrm{meas}}$ and their corresponding tune knobs settings $\Delta\nu_{x,y,\mathrm{knob}}$ is close to linear, with the fitting results of $\nu_{x,\mathrm{meas}} = 0.939\,\nu_{x,\mathrm{knob}}$ and $\nu_{y,\mathrm{meas}} = 0.904\,\nu_{y,\mathrm{knob}}$. Relatively, the measured tune changes are 6.1% and 9.6% less than the knob settings in horizontal and vertical directions, respectively. The tune "leakage" from the tune knobs in one direction to the other is also shown in Figure 1. The tune leakage from one direction to the other is small, at the level of about 2% of the tune knob. One main reason that the fitting coefficients are not unity (0.939 horizontally and 0.904 vertically) is that the real lattice is different from the designed one. According to [6], the measured rms beta-beating are 5% to 6% in both directions, respectively. Another source of discrepancy is the hysteresis effect of the quadrupole magnets. The relationship between the driving current and magnetic field of quadrupoles in the Duke storage ring are determined using the up branch of the hysteresis curve. For the quadrupoles with a decreasing strength in the tune knob, the magnetic field does not change as expected, introducing a discrepancy in the focusing strength change, which leads to a small inconsistency in the global tune change.

Based on the above measurement results, the tune knob calibration can be realized using the fitted slopes: $\nu_{x,\mathrm{knob,calib}} = \nu_{x,\mathrm{knob}}/0.939$ and $\nu_{y,\mathrm{knob,calib}} = \nu_{y,\mathrm{knob}}/0.904$. Figure 2 shows the tune differences between the measured tune variations and the calibrated tune knobs. We can see the maximum residual tune variations using calibrated tune knobs are significantly reduced, to about 10^{-3} in both horizontal and vertical directions, which corresponds to a relatively difference of about 2%. This amount of discrepancy is comparable with the tune reproducibility of the same lattice operated at different times.

In addition to measuring the tunes in x or y direction separately, two-dimensional tune scan measurements in both x and y directions were also conducted. Figure 3 shows the differences between the measured tune variations and the calibrated tune knobs in two-dimensional plane, where the calibration is based upon the one dimensional results above. In the blank area at the bottom-right corner of the plots, the tunes cannot be measured due to the resonance $\nu_x - \nu_y = 5$. The residual tune variations with the calibrated tune knobs are smaller than 3×10^{-3} in the entire plane, showing a good agreement between the measured and the calibrated tune knobs.

Calibrating Tune Knobs for Lattice with Wigglers

To improve the effectiveness of the tune knobs with the wigglers, the tune knob calibration for the lattice with OK4-A wiggler turned on was performed. The calibration is based

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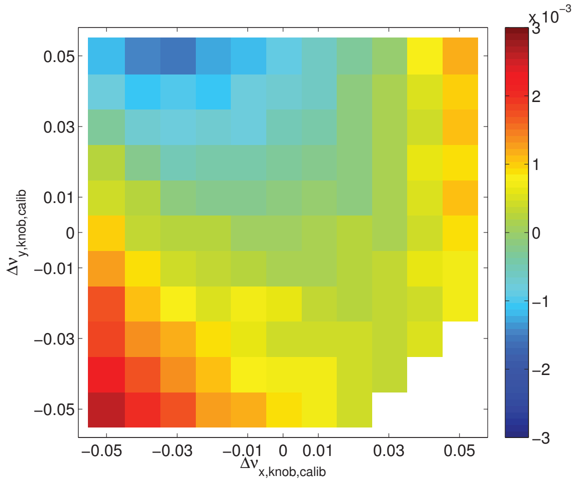
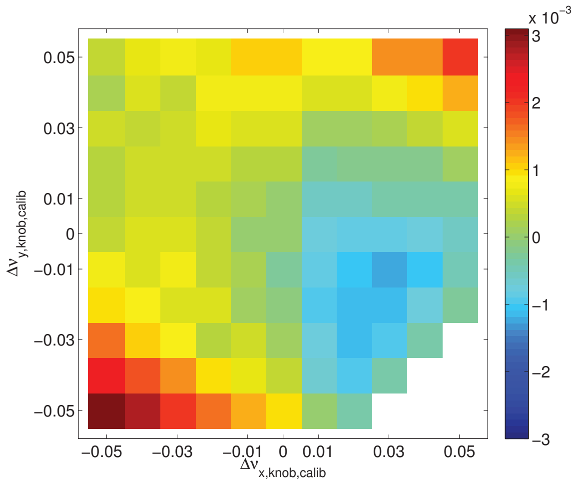


(a) Residual horizontal tune variation.



(b) Residual vertical tune variation.

Figure 3: Residual tune variations by varying the horizontal and vertical tune knobs simultaneously.

upon the lattice with the wiggler focusing compensation scheme. The additional focusing of the wiggler is compensated by a set of quadrupoles in south straight section [3]. Figure 4 shows the tune calibration results for the OK4-A wiggler at its highest current setting of 3000 A, where the wiggler magnet has already started to saturate. The maximum residual tune variation in horizontal and vertical directions are a few times of 10^{-3}, comparable to the results for the lattice with all wiggler turned off. These results demonstrate that the calibrated tune knobs are as effective in controlling of the betatron tunes in the presence of strong wigglers.

SUMMARY

The tune knob is an important tool for a flexible operation of a storage ring. In this paper, the Duke storage ring tune knobs are calibrated for nominal lattice with all wigglers turned off and for a lattice with the OK4-A wiggler operating at its maximum strength. The results show that the calibrated

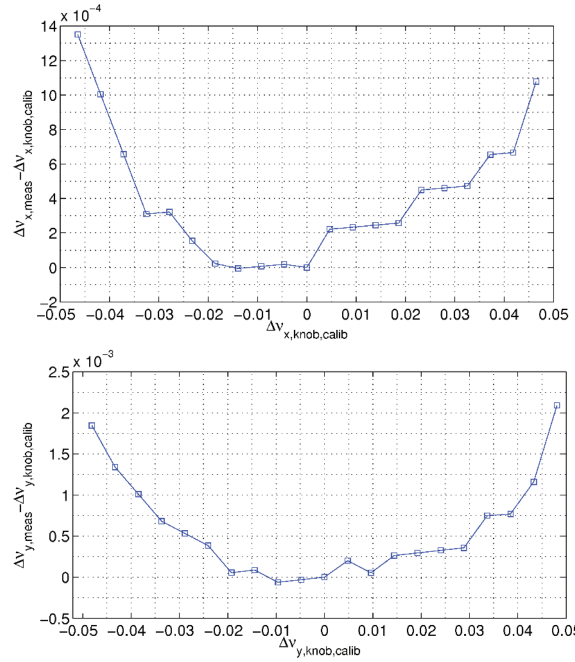


Figure 4: Residual tune variations with calibrated tune knobs for the lattice with the OK4-A wiggler set to 3 kA (its maximum setting).

tune knobs agree with the designed one within a few times of 10^{-3} for a maximum tune change of ± 0.05. These tune knobs have been an effective tool for tuning the Duke storage ring lattices for variety of operation modes., including FEL research and γ-ray production. In the future, the calibration for the other wiggler configurations will be conducted, and the coefficients will be implemented into the EPICS control system.

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