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MEASURING DUKE STORAGE RING LATTICE USING TUNE BASED TECHNIQUE*

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Abstract

The Duke electron storage ring is a dedicated driver for oscillator Free-Electron Lasers (FELs). A 34 m long straight section of the storage ring is used to host up to four FEL wigglers in several different configurations. A total of six wigglers, two planar OK-4 wigglers and four helical OK-5 wigglers, are available for FEL research. The storage ring magnetic lattice has to be designed with great flexibility to enable the storage ring operation with different FEL wigglers, at various wiggler settings, and for different electron beam energies. Since 2012, the storage ring has demonstrated all designed characteristics in terms of lattice flexibility and tuning. This work is aimed at gaining better understanding of the real storage ring lattice by performing a series of measurements of the beta-functions along the storage ring. Unlike the LOCO technique, the β-functions in the quadrupoles are directly measured with good accuracy using a tune measurement system. We will describe our experimental design and techniques, and measurement procedures. We will also report our preliminary results for the lattice characterization.

INTRODUCTION

The Duke electron storage ring is a dedicated driver for oscillator Free-Electron Lasers (FELs). This facility consists of three accelerators, a linac pre-injector (0.16 GeV), a booster injector (0.16 – 1.2 GeV), and an electron storage ring (0.24 – 1.2 GeV). In the south part of the storage ring, a 34 m long straight section is used to host up to four FEL wigglers in several different configurations. Two planar OK-4 wigglers and four helical OK-5 wigglers, are available for FEL research. To enable the storage ring operation with different FEL wigglers at various wiggler settings, and for different electron beam energies, the storage ring magnetic lattice has to be designed with great flexibility. The storage ring with a number of new wiggler configurations has demonstrated all designed characteristics in terms of lattice flexibility and tuning since 2012 [1]. This work is aimed at gaining better understanding of the real storage ring lattice by performing a series of measurements of the β-functions along the storage ring. This technique is different from the LOCO technique, β-functions in the quadrupoles are measured directly with good accuracy measurement using transverse feedback system [2, 3]. We will introduce β measurement method and measurement system, discuss tune changes related with beam current decay, influence of quadrupole hysteresis on β measurements, describe our experimental design and preliminary measurement results for the lattice characterization.

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MEASUREMENT METHOD AND SYSTEM

In a storage ring that quadrupole strength change can be controlled independently, β functions at the location of the quadrupole can be measured directly. A change in the quadrupole strength will cause a tune change proportional to the β-function at the quadrupole, we can measure β-functions by measuring the tune changes [4]. The relation between β-function and the changes in tune is given by:

$$\Delta\nu_{x,y} = \frac{1}{4\pi}\int_{quad}(\Delta K_1)_{x,y}\,\beta_{x,y}\,ds$$

$$\text{or}\ \left\langle\beta_{x,y}\right\rangle = \frac{4\pi\Delta\nu_{x,y}}{(\Delta K_1)_{x,y}L_{eff}}$$

where ν is the measured betatron tune, K_1 is the quadrupole strength, L_{eff} is the effective length of the quadrupole, and the measured $\langle\beta\rangle$ is the average β at the location of the quadrupole.

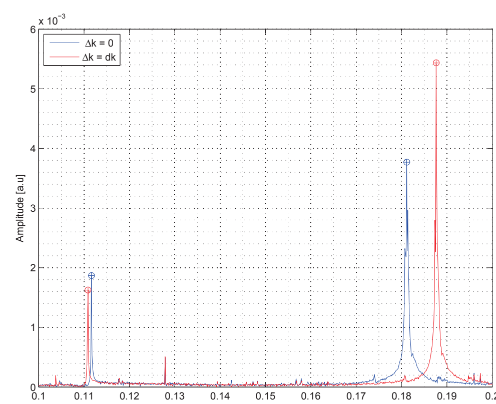

Figure 1: Tune signals measured with a network analyzer system, with a 638 MeV beam. The blue line is the nominal tune, the red line is the tune signal after a quadrupole is changed by $\triangle K_1$. The fractional nominal tune is [0.11, 0.18], the left peaks show the horizontal tune ν_x and the right peaks show the vertical tune ν_y.

This method of β-function measurement is based on tune measurements. The basic approach to measure the betatron tune of the electron beam is to excite the beam and measure its response. Two sets of tune measurement systems are

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available in the Duke storage ring. One is a tune measurement system based on a network analyzer, this kind of betatron tune measurement system works in this way: a network analyzer generates an RF drive signal and send it to a short stripline kicker to excite the electron beam; the beam motion is detected using synchrotron radiation from a dipole magnet; and then, the detected motion signal is compared with the drive signal. To improve the accuracy, the bandwidth of the sweep signal needs to be reasonably narrow, which, however, leads to longer measurement time. A tune measurement with a resolution of 1×10^{-4} and tune scan range of [0.1, 0.2] takes about 30 seconds. Figure 1 shown an example of measured tunes using the network analyzer.

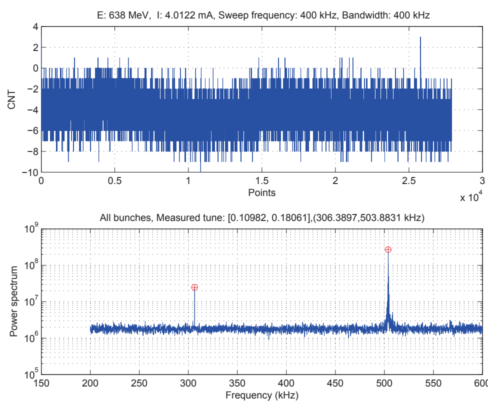

Figure 2: Upper plot shows a measured time-domain signal with TFB system, lower plot is the signal after FFT. The left peak is ν_x and the right peak is ν_y.

Another tune measurement system is a based on transverse feedback (TFB). In this system, a broadband signal is generated by integrated Gigasample processor (iGp) and applied to the electron beam through a transverse feedback kicker; the beam response in time is recorded; Fast Fourier Transform (FFT) is then applied to the time-domain beam signal to find out the betatron tune of the beam. Since the beam is excited once, the measurement takes less time. A tune measurement with a resolution of 3.5×10^{-5} and tune scan range of [−0.072, 0.215] takes about 12 seconds. Figure 2 is an example tune measurement with the TFB system. In this system, kicking the beam and recording beam response takes only a few seconds, most of the time are spent on transferring data from the iGp to local computer and analyzing data. The measurement speed could be further improved by a factor of 5~10 with more efficient memory management and data transfer strategy.

BEAM CURRENT DECAY AND HYSTERESIS

During the process of measuring β-function, beam current decays due to elastic electron-gas collisions (Coulomb scattering), inelastic electron-gas collisions (bremsstrahlung scattering), and intrabeam electron-electron collisions. It is known that betatron tune shifts with beam current decay [5]. To find out how much this effect influences the β measurements, we measured betatron tunes with beam current as it decays from 4.4 mA to 1.3 mA. The measured tunes and linear fit are shown in Fig. 3. The fitted *tune slope* is about -1.75×10^{-4}/mA in horizontal and -4.95×10^{-4}/mA in vertical, which means the current dependency of tune is more significant in the vertical direction. In the measurement of β using the TFB system, beam current decay between two tune measurements is typically on the level of 10^{-2} mA.

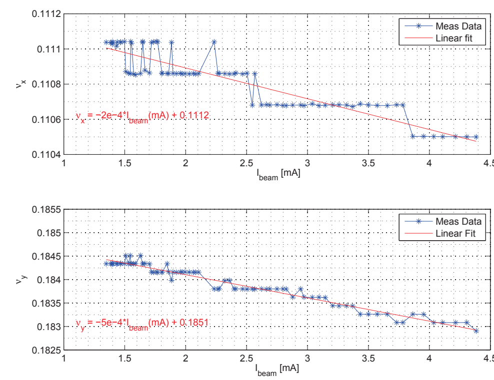

Figure 3: Tune shift with beam current decay. The beam current naturally decays from 4.4 mA to about 1.3 mA. The magnitude of the tune slope in the vertical is larger than the horizontal.

Understanding and controlling the quadrupole hysteresis effect is critical forβ-function measurement. Like many storage rings, the nominal operation of the Duke ring is along the up branch of the magnetic field hysteresis curve, and the quadrupole field was measured and calibrated along this branch. Therefore, the reliable β-function measurement should also be carried out along the up branch of the hysteresis curve. However, it is important to investigate the impact of hysteresis for the β-function measurement when the field changes are made both along the up- and down-branches of the hysteresis curve.

Table 1: Measured Vertical Tunes by Changing the E07 Defocusing Quadrupole Strength in Four Loops

Loop	**Vertical Tune ν_y**			
ΔK_1	0	-0.27716	0	0.27716
1	0.18724	0.20158	0.18886	0.17487
2	0.18849	0.20176	0.18903	0.17523
3	0.18867	0.20175	0.18903	0.17541
4	0.18867	0.20176	0.18903	0.17541

To study this effect, betatron tunes are measured by changing quadrupole strength in a closed loop of $[0, \triangle K_1, 0, -\triangle K_1]$. This local loop is repeated 4 times. The measured vertical betatron tunes based upon different parts of the loop are shown in Table 1. Average β of the

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quadrupole can be calculated with each two nearby measured betatron tunes. The measured β-functions at different segments of the loop is compared to the $1st$ measurement which is considered to be true measurement of the β-function. The relative difference of the measured vertical β-functions at E07 defocusing quadrupole is shown in Fig. 4. It shows that the β-functions in the subsegment measurements are always smaller than the $1st$ measure.

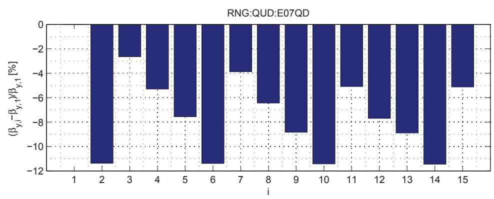

Figure 4: β_i is calculated with the ith and $(i+1)th$ measured tunes. β_1 is calculated with the $1st$ and $2nd$ measured tunes in the $1st$ loop. In each loop, betatron tunes are measured at 0, $\triangle K_1$, 0 and $-\triangle K_1$.

SOURCES OF MEASUREMENT ERRORS

In the measurements of β-function, quadrupole strength change $\triangle K_1$ should be neither too small nor too large. A small $\triangle K_1$ can lead to less accurate measurement of the β due to a small tune change compared to tune measurement errors. A large $\triangle K_1$, however, leads to a large tune change, which may cause beam loss by bring the tune close to a strong resonance; it will also introduce more hysteresis effect. In our measurements, $\triangle K_1$ for each quadrupole is optimized with a typical value of 10^{-2} of the quadrupole strength. To reduce the residual field, the quadrupole setting is returned by completing a 'local normalization' loop. To minimize the influence on global tune change, β are measured at focusing and defocusing quadrupoles alternately. To improve lattice consistency, the storage ring is normalized and lattice is restored after a certain number of measurements.

The β-functions were measured for 78 quadrupoles on the Duke storage ring, with a 638 MeV electron beam. All the measurements were taken with a beam current of 3 mA $\sim$ 4.5 mA. The designed, measured and simulated vertical β-functions are shown in Fig. 5. Simulated βs are calculated with simulated experiment in the designed lattice with the same $\triangle K_1$ change for each quadrupole. The RMS difference between the measured and simulated β-function is 16% in the vertical direction.

One of the most difficult challenges for characterizing and calibrating the Duke storage ring lattice is the use of all combined function quadru-sextupoles in the arcs [6]. With these complex magnetic elements, the closed beam orbit in the arc is not unknown in advance. Furthermore, the electron beam orbit is directly coupled to the focusing strength of quadrupoles. This has been a major difficulty to use the LOCO [7] method to calibrate the Duke storage ring. The direct beta-function measurement technique described in this work does not depend on the beam orbit, therefore, will provide an alternative and effective way to characterize the Duke storage ring magnetic optics.

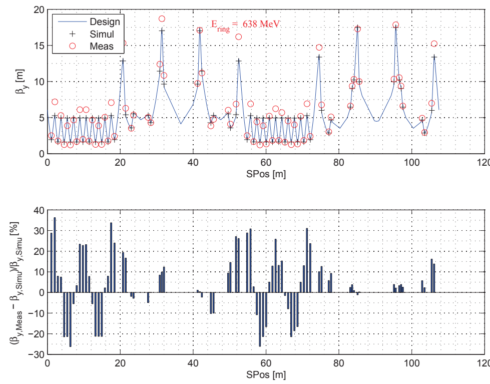

Figure 5: β-functions are measured for 78 quadrupole magnets around the ring, the measured β are compared with simulated ones, with RMS difference about 16%. Most of these differences are from the east and west arcs.

SUMMARY

In this project, a fast β-function measurement technique is developed using the transverse feedback system. The tune resolution is increased by 3 times while the measurement time is reduced to 1/3 compared with the technique using the network analyzer. Two factors that influence β-function measurements are discussed: tune change due to beam current decay and hysteresis of the quadrupole. There are other factors which influence beta-function measurement, including quadrupole focusing strength calibration, temperature change of the ring, β-function change due to accumulated hysteresis effect, and beam orbit change and so on. With directly measured beta-functions of the Duke storage ring, we will develop a lattice compensation technique using the SVD algorithm.

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