DIRECT AND HIGH RESOLUTION BETA-FUNCTION MEASUREMENTS FOR STORAGE RING LATTICE CHARACTERIZATION

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Abstract

Betatron functions are a set of commonly used merits to characterize the lattice performance of a circular accelerator. The betatron functions in many accelerators can be computed using a lattice model trained or calibrated using a set of closed orbit responses, which is exemplified by the widely used Linear Optics from Closed Orbit (LOCO) technique. However, for some accelerators, like Duke storage ring with quad-sextupole combined function magnets, LOCO cannot be employed in any straight forward manner. In this case, direct measurements for betatron function are required. One way to determine betatron functions at the location of quadrupoles for a circular accelerator is to use the relationship between the quadrupole strength variations and the corresponding betatron tune change. In this paper, we present a set of carefully developed techniques to measure the betatron functions at the location of quadrupoles, which allow us to achieve extremely high resolution. Measurement errors will be discussed, and the detailed measurement technique will be present. Finally, the experimental results of betatron function measurements in the Duke storage ring with statistical error on the order of 1% will be presented.

INTRODUCTION

Beta functions are a set of merits to characterize the lattice performance of a circular accelerator. A throughout understanding of the linear optics in a storage ring is critical to achieve maximum performance, since it determines the dynamic aperture, energy aperture and beam lifetime. Precise understanding and correction of normal and skew gradient errors can be used to minimize horizontal and vertical beam sizes. Correction of the gradient errors can restore the designed periodicity of a storage ring, decrease the negative effects of nonlinear resonances and increase the beam lifetime. Beta functions in many circular accelerators can be computed using a lattice model trained or calibrated using a set of closed orbit responses, which is exemplified by the widely used LOCO technique [1]. It can also be derived from the turn-by-turn (TBT) BPMs data points using proper analyze techniques. Another technique for direct average beta function measurement at the location of a quadrupole is to vary quadrupole strength (QV) and measure the corresponding betatron tunes.

In the Duke storage ring, LOCO can not be applied in any straight forward manner, which is likely due to the employment of combined quadru-sextupoles magnets in the arc sections. Therefore, direct measure technique needs to be employed to characterize the Duke storage ring lattice. The turn-by-turn facilities are not readily available in the Duke storage ring, so we decide the measure the beta-functions using the QV technique, since all the quadrupole magnets in the Duke storage ring can be adjusted independently. The average beta-function at the quadrupole magnet can be obtained by changing the quadrupole and measure betatron tunes:

$$\beta_0\,(s) = \frac{2}{\Delta KL}\frac{\cos(2\pi\nu_0) - \cos(2\pi\nu)}{\sin(2\pi\nu_0)} \qquad (1)$$

where β is the average beta-function, ΔK is the quadrupole strength variation, L is the effective length of this quadrupole, and ν_0 and ν are the fractional betatron tunes before and after the quadrupole variation.

In this paper, we will discuss about the measurement errors, and present a set of carefully developed techniques to achieve extremely high resolution beta-function measurement at the location of quadrupoles. The preliminary experimental results of beta-function measurements in the Duke storage ring with static error on the level of 1% will be presented.

TUNE MEASUREMENT AND BEAM CURRENT DEPENDENCY

To measure the fractional betatron tune is to measure the transverse oscillating frequency of this oscillation system. Hence, the basic approach is to excite the beam and measure its response. In the Duke Storage ring, a tune measurement system based on the transverse feedback (TFB) system is employed [2]. Since the beam is excited with white noise, it takes quite a short time to measure a betatron tune. A tune measurement with a typical resolution of 3.6×10^{-5} and scanning range of [-0.072, 0.215] takes about 12 seconds. Since the frequency side band spacing is typically 100 Hz which corresponds to tune fluctuation of about 3.6×10^{-5} and the tune spread in electron beam is expected to be on the level of 10^{-3} to 10^{-2}, there are multi points in the tune response area of a betatron tune measurement. To improve the accuracy of tune measurement, Gaussian or Lorentzian fitting methods can be applied to the measurement result. An example of tune measurement with the TFB system is shown in Fig. 1.

It is known that betatron tune shifts with the decay of beam current as a result of lattice change due to wake field in the storage ring [3]. Thus, in a betatron function measurement, the nominal betatron tune changes systematically as a

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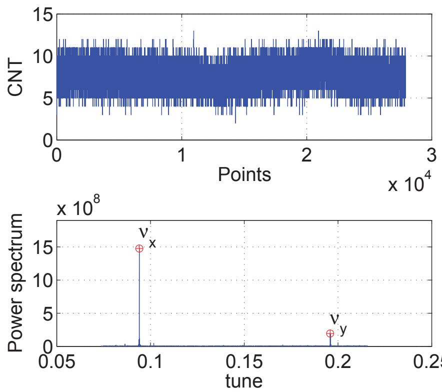

Figure 1: An illustration for tune signal measured with transverse feedback system.

result of beam current decay, which is superimposed to the tune change introducing error to measure beta-function. To indicate this effect on the betatron function measurements and calibrate this effect, betatron tunes are measured with beam current decay from about 4.6 mA to 2.4 mA in the 638 MeV lattice. The measured result and linear fit are shown in Fig. 2. It shows that the tune dependency on beam current is more significant in vertical than horizontal in this lattice, the fitted beam current-tune slope are -1.4×10^{-4} in horizontal and -4.1×10^{-4} in vertical.

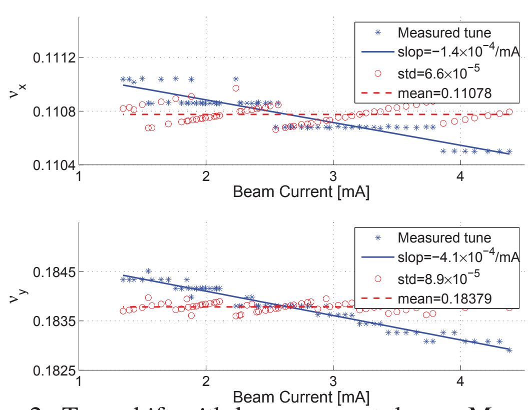

Figure 2: Tune shift with beam current decay. Measured in a 638 MeV lattice. Blue stars are measured tune and red circles are subtracted with fitting line.

ERROR ANALYSIS AND OPTIMIZE ΔK

To perform an high resolution beta-function measurement in a quadrupole, the error terms should be well understood. According to the formula of beta-function measurement Eq. 1, the static error in this measurement can be roughly estimated using

$$\frac{\sigma\beta}{\beta} = \sqrt{2\left(\frac{\sigma K}{\Delta K}\right)^2 + (2 + 4\pi\Delta\nu \cot(2\pi\nu))\left(\frac{\sigma\nu}{\Delta\nu}\right)^2} \quad (2)$$

where σk is determined by the power supply, $\sigma\nu$ is determined by the tune measurement accuracy, beam orbit stability, energy spread, surrounding environment effect and so on. In fact, $\sigma\nu$ was obtained in the measurement of tune shift with beam current decay, which suggested the tune fluctuation to be 6.6×10^{-5} in horizontal and 8.9×10^{-5} in vertical.

Thus, the static error of a measurement can be roughly estimated by the amount of quadrupole variation using a rough model. Using the linear approach of Eq. 1, we can obtain the expression of the quadrupole strength variation:

$$\Delta K = \frac{\sqrt{2(\sigma K)^2 + (2 + 4\pi\Delta\nu \cot(2\pi\nu))(4\pi\sigma\nu/(\beta L))^2}}{(\delta\beta/\beta)} \quad (3)$$

In other word, the quadrupole variation in a measurement can be optimized to perform a high resolution beta function measurement, if the power supplies of magnets and betatron tune measurement system are well studied, as well as a model close to the real machine is obtained.

Therefore, the amount of quadrupole variation ΔK is optimized for beta-function measurement at each quadrupole using the above formula to retrain the static error to the level of 1%. The optimized ΔK are shown in Fig. 3. In this optimization, some restrictions are used, such as the minimum and maximum tuning range of magnet (determined by the quadrupole power supply), the minimum tune gap (set to $\nu_y - \nu_x \geq 0.05$) and so on.

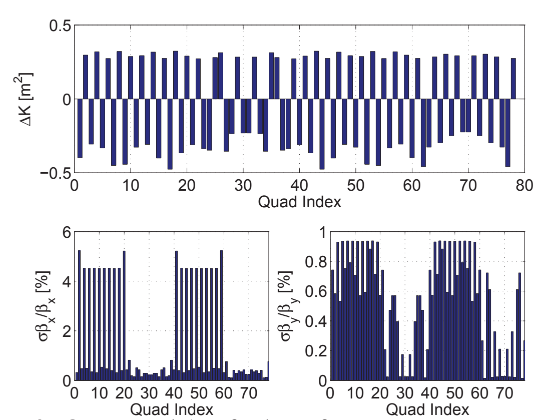

Figure 3: Optimized ΔK for beta-function measurement at each quadrupole and estimated horizontal and vertical beta-function measurement resolution. Most of their static errors are within the level of 1%.

MEASUREMENT RESULT

With properly designed procedure of the measurement for 78 quadrupoles, the lattice characterization for the Duke storage ring is repeated 5 times in a same day. Each set of beta-function measurements is carried out after normalizing the storage ring magnets, and all the five sets of measurements took a total of about 12 hours. The measured

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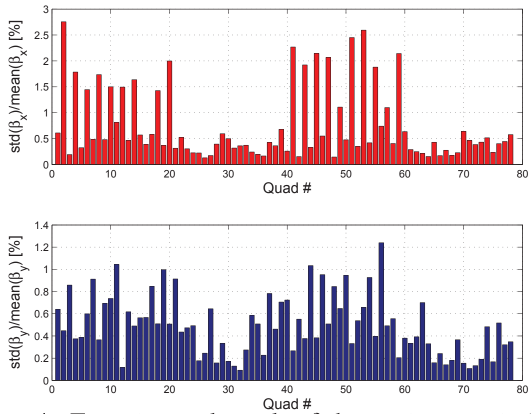

Figure 4: Experimental result of the static error in beta-function measurements.

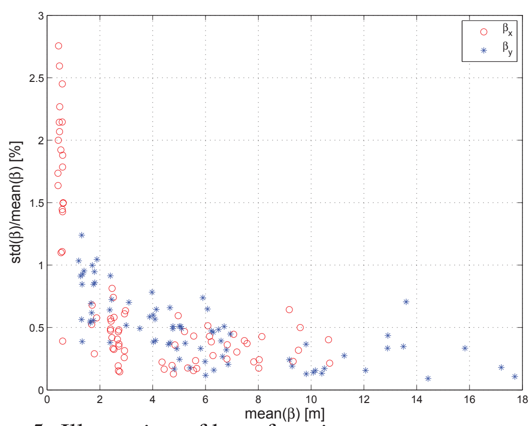

Figure 5: Illustration of beta-function measurement resolution and the average beta-function value.

betatron tunes are calibrated with the beam current, and beta-functions are calculated. The standard deviation of measured beta-function at each quadrupole is obtained with the five or four reliable measurements and these standard deviations are compared with the mean values as shown in Fig. 4 and Fig. 5.

The beta-function measurement resolutions are typically a few centimeters, and most of the beta-functions are measured with a relative resolution within the level of 1%. The root mean square (rms) of the total relative measurement errors is 1.1% in horizontal and 0.5% in vertical, which agrees with the estimation very well. It also shows high resolution beta-function measurements at the locations of large beta-functions in both horizontal and vertical are achievable, and static error at the locations of small beta-functions are relatively large. Therefore, large error bars are shown in the horizontal measurements at arc defocusing quadrupoles, where β_x are as small as 0.35 m. In these measurement, the tune shifts are typically very small due to the limited quadrupole

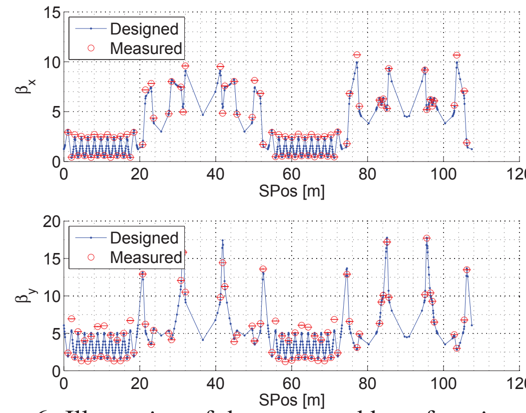

Figure 6: Illustration of the measured beta-functions with comparison to the designed lattice.

variation range and small horizontal beta-functions, therefore, the tune measurement fluctuation dominates the beta-function measurement static error.

The measured beta-functions are shown in Fig. 6 with comparison to the designed lattice. It shows that the measured beta-functions match the designed lattice well in general. However, the measured vertical beta-functions show significant wiggling in the arc sections, which are obviously different from the designed lattice. These differences predict lattice discrepancy from the designed.

SUMMARY AND DISCUSSION

In this paper, we discussed the static error in beta-function measurement and optimized the ΔK to perform a reasonable high resolution measurement. With the optimized ΔK, five sets of beta-functions measurements for the 78 quadrupoles in the Duke storage ring were carried out. The measurement result shows the rms of horizontal static error is about 1.1%, while it is about 0.5% in vertical, which are as expected. Therefore, this work experimentally proved that the resolution of betatron function measurement can be predicted, and high resolution beta-function measurements can be performed with proper designed scheme and technique. Further lattice compensation work will be performed based on these measurements.

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