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Measurement of optics for the SSRF storage ring in commissioning*

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Abstract The Shanghai Synchrotron Radiation Facility (SSRF) is a low emittance third-generation synchrotron radiation light source. Some optics parameters of the storage ring were measured when commissioning. This report presents the common methods for measuring some optics parameters of the storage ring, including the betatron tune, beta function, chromaticity, natural chromaticity and dispersion. The results and analysis of measurement for the optics parameters are given here, which are indispensable for the orbit correction of the accelerator and the nonlinear optimization.

Key words betatron tune, beta function, chromaticity, natural chromaticity, dispersion

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1 Introduction

SSRF is a third-generation synchrotron radiation light source, whose stability of the performance is very strict. Some optics parameters, such as betatron tune, beta function, chromaticity, natural chromaticity and dispersion were measured when the storage ring was in commissioning from December 21$^{\mathrm{th}}$, 2007. Some measured results in different commissioning stages provide an advantage as basis for the performance of real storage ring close to the design.

2 Measurement methods

2.1 Method to measure betatron tunes

Betatron tune is defined as the number of betatron oscillations per revolution. The betatron tune is divided into the integer part and the fractional part for measurement. The integer part of the betatron tune is the number of oscillation periods around the ring induced by exciting a single steering corrector. A method to measure the fractional part of the betatron tune is Fast Fourier Transform (FFT)[1, 2]: that means to excite the transverse beam motion induced by a kicker and to detect the transverse beam position over a number of successive turns, the detected signal is computed via a Fourier transformation, and finally, the frequency is analyzed by a spectrum analyzer. The fractional parts are the frequencies with the highest amplitude peak of the FFT spectra[3, 4]. The betatron tune measured with this method might be a little different from the real betatron tune because of the nonlinear factor and variance between beams and so on.

2.2 Method to measure betatron function

Betatron function is called β function. A common method is to detect the shift of the betatron tune as the strength of an individual quadrupole magnet is varied. The average β function of the corresponding quadrupole magnet could be calculated as follows[2)

$$\beta_{x,y} = \pm\frac{2}{\Delta\left(|K|l\right)}\left\{\cot\left(2\pi Q_{x,y}\right)\left[1-\cos\left(2\pi\Delta Q_{x,y}\right)\right]+\sin\left(2\pi\Delta Q_{x,y}\right)\right\}, \tag{1}$$

where $\Delta Q_{x,y}$ is the horizontal or vertical tune shift, l is the effective length of the quadrupole magnet, and

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$\Delta(|K|l)$ is the change of quadrupole integrated gradient. The $\pm$ sign refers to the horizontal and the vertical planes, respectively. For a small tune movement, far from the integer or half integer resonance, the β function can be simplified:

$$\beta_{x,y} \approx \pm 4\pi \frac{\Delta Q_{x,y}}{\Delta(|K|l)} . \quad (2)$$

This method must ensure that the applied change in quadrupole strength does not alter the beam orbit. If the orbit is changed, part of the measured tune shift could be caused by the closed-orbit variation at the sextupole magnets elsewhere in the accelerator. The orbit should first be corrected by the correctors before the new betatron tune value is measured, if the change of quadrupole strength has a strong effect on the orbit.

2.3 Method to measure chromaticity

In a storage ring, the dependence of the betatron tunes on beam energy is referred to as chromaticity, which is denoted as ξ. This report only takes linear chromaticity into account.

$$\frac{\Delta p}{p} = -\frac{1}{\alpha - \gamma^{-2}} \cdot \frac{\Delta f}{f} , \quad (3)$$

$$\frac{\Delta Q}{Q} = \xi \frac{\Delta p}{p} . \quad (4)$$

We can get the method to measure the chromaticity from Eqs. (3) and (4). The chromaticity is given by:

$$\xi = (\gamma^{-2} - \alpha) \frac{\Delta Q/Q}{\Delta f/f} . \quad (5)$$

Where γ is the relativistic factor, and α is the momentum compaction factor.

Natural chromaticity derives from the energy dependence of the quadrupole focusing, which is the chromaticity of a ring without sextupole magnets. It could be obtained by detecting the variation of the betatron tune with the change of the dipole field strength, thus the natural chromaticity is given by:

$$\xi^{\mathrm{nat}}_{x,y} \approx \frac{\Delta Q_{x,y}}{\Delta B/B} . \quad (6)$$

The horizontal and the vertical natural chromaticities are commonly minus, which might affect the instability of the head-tail beam and so on. Some methods to correct the natural chromaticity are needed.

2.4 Method to measure dispersion

In a storage ring, the orbit deviation due to an energy offset is given by the periodic dispersion function $\eta(s)$. Usually the dispersion function is inferred from the orbit change induced by a shift of the frequency, it is measured as follows:

$$\eta(s) = (\gamma^{-2} - \alpha) \frac{\Delta x(s)}{\Delta f/f} , \quad (7)$$

where γ is the relativistic factor, and α is the momentum compaction factor. It must be ensured that the frequency can be changed without beam loss.

3 The result and analysis for the measurement

3.1 The result of measurement for beta tune

The storage ring was put in commissioning in a 3 GeV non-dispersive mode on March 31$^{\text{th}}$, 2008. The designed horizontal and vertical beta tunes were 22.22/11.32, respectively. The orbit distortion that is essentially a betatron oscillation was induced by changing the current of a horizontal or a vertical steering corrector. The integer part of the horizontal or the vertical tune could be gotten by counting the number of oscillation periods around the ring. Fig. 1 shows the integer part of the beta tune. The results of integer part for the horizontal and vertical tunes are 22/11, which are identical with the designed values.

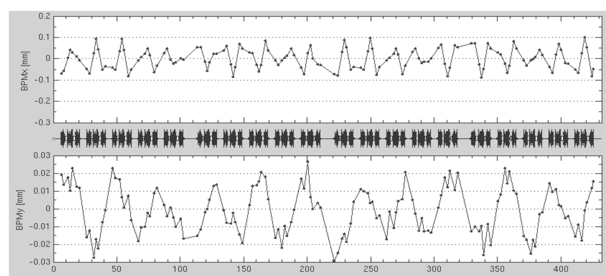

Fig. 1. The horizontal (top) and the vertical (bottom) integer parts of the beta tune.

The numerical values of Fig. 2 and Fig. 3 are the results of measurement for the fractional parts of beta tune. Some other peaks appear on the spectrum analyzer because of transverse coupling and other uncertain factors. Because the highest peak is not always the beta tune, it needs a range to judge. In Fig. 3, the webbing of horizontal beta tune is caused by minus corrected chromaticity.

The horizontal fractional part of beta tune could be gotten by using a kicker and the method of FFT, while the vertical fractional part could be observed by a strip-line. Fig. 2 shows the fractional part of beta tune (non-dispersive mode); Fig. 3 shows the fractional part of beta tune (dispersive mode) when the designed horizontal and vertical beta tunes of the storage ring were 22.22/11.29, respectively.

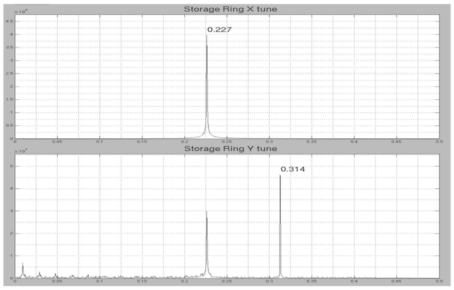

Fig. 2. The horizontal (top) and vertical (bottom) fractional parts of beta tune (non-dispersive mode).

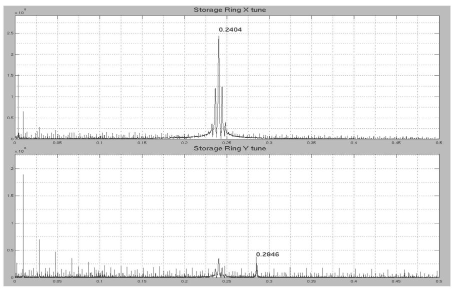

Fig. 3. The horizontal (up) and vertical (down) fractional parts of beta tune (dispersive mode).

3.2 The results of measurement for beta functions

The beta functions of a super period for storage ring were measured on March 15th, 2008. The beta functions could be measured based on Eq. (2). Because it must be ensured that the applied change in quadrupole strength does not alter the beam orbit, the quadrupole strength can't change too much. The results of measurement can easily be gotten by using BetaMeas GUI tool[5].

In Fig. 4 and Fig. 5, the blue and red lines denote the horizontal and vertical beta functions, respectively; the green stars and purple triangles denote the horizontal and vertical measured values at the locations of the quadrupole magnets, respectively. The measured beta function is the mean value inside the individual quadrupole. LOCO has been used in SSRF to find bad BPMs, to calibrate BPM gains, to find quadrupole gradient errors and to restore the lattice periodicity. Before LOCO, beta functions have been measured using BetaMeas GUI tool, the horizontal and the vertical mean errors between the measured and the designed values are 11.51%/8.57%, respectively, as shown in Fig. 4. After LOCO, beta functions have been measured again, the mean errors can reduce to 5.19%/6.05%, respectively, as shown in Fig. 5. The veracity of the measured beta tune may bring error between the measured and the real values.

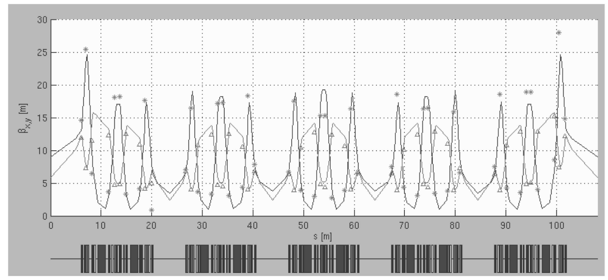

Fig. 4. The beta functions for a super period (before LOCO).

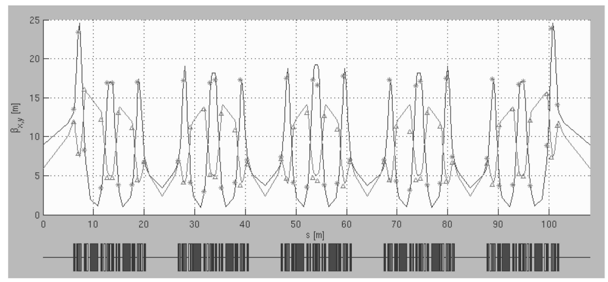

Fig. 5. The beta functions for a super period (after LOCO).

3.3 The result of measurement for chromaticity

The current of dipole magnet is 601.748 A when the deflexed angle is 9° based on the excitation curve calibration for the SSRF magnet system. The relationship between the dipole strength and the current is almost linear, shown as:

$$\frac{\Delta B}{B}=\frac{\Delta I}{I}\,. \tag{8}$$

Using Eq. (8), Eq. (6) can be transformed as follows:

$$\xi^{\mathrm{nat}}_{x,y}\approx\frac{\Delta Q_{x,y}}{\Delta I/I}\,. \tag{9}$$

Figure 6 shows the results of the variation of the betatron tunes with the change of the dipole field strength which alters from 599.2442 A to 600.6442 A (each time it increases 0.2 A).

In Fig. 6, the red slope is the horizontal natural chromaticity; the blue slope is the vertical natural chromaticity. The horizontal and the vertical natural chromaticities are −50.7126/−14.7131, respectively, which are different from the designed natural chromaticities: −55.64/−17.94. The error between the measured value and the designed one may be caused by the precision of measurement for beta tune and the big change of the dipole current.

The excursion of beta tune caused by the chromaticity can be reduced if the total chromaticity is nearly zero. In SSRF, two groups of sextupole magnet

(SD/SF) are used to correct the chromaticity, which are located in the dispersive region. The SF is located in the place where the horizontal beta function is big; and the SD is located in the place where the vertical beta function is big. The energy acceptance and dynamical aperture are very small because of nonlinear influence, if there are only sextupole magnets to correct the chromaticity. The correct technique of syntonic wave is used to enlarge the energy acceptance and dynamical aperture.

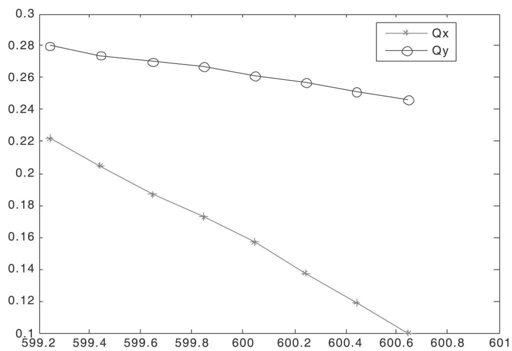

Fig. 6. The beta tune as a function of a relative variation in the main dipole current.

In Eq. (5), the momentum compaction factor α is the designed value: 4.2704e-4; the speed of electron is nearly the velocity of light. Eq. (5) can be transformed as follows:

$$\xi = -4.2704\mathrm{e}-4\frac{\Delta Q/Q}{\Delta f/f}\,. \tag{10}$$

Linear chromaticity is the linear relationship between the frequency and the beta tune in a small region near the central frequency, so it must get the central frequency before correcting the chromaticity. Measuring the chromaticity for different sextupole strengths determines the 'central frequency'. This is the rf frequency for which the orbit on average passes through the center of all sextupoles. The relationship for different sextupole excitation patterns between the beta tune and the rf frequency is shown in Fig. 7.

In Fig. 7, the change of rf frequency is based on 499.679050 MHz (X-axis); the Y-axis is the horizontal fractional beta tune. The intersection of the four lines is 180 Hz, so the central frequency is 499.679230 MHz.

The optimized sextupole magnets are used to correct the chromaticity in the SSRF. The changes of beta tune were detected as the frequency altered around 499.679230 MHz for measuring the corrected chromaticity. The results of the measurement for the horizontal and vertical chromaticities are +0.7/+0.8, respectively, which means that the correcting method is effective.

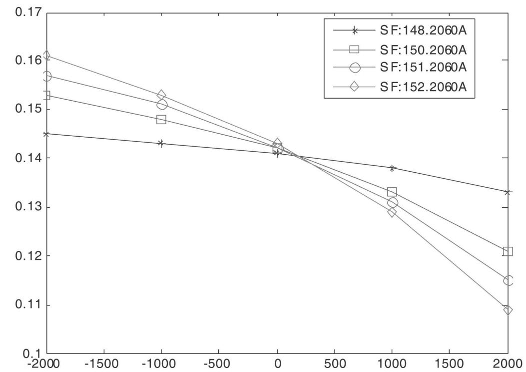

Fig. 7. Chromaticity measurements for different sextupole excitation patterns.

3.4 The result of measurement for dispersion

The frequency is reduced to 499.678730 MHz when it is the central frequency (499.679230 MHz), at the same time, the horizontal orbit change could be observed by BPM. Using Eq. (7), the momentum compaction factor α is the designed value: 4.2704e-4, then the dispersion around the whole storage ring can be obtained, shown as Fig. 8:

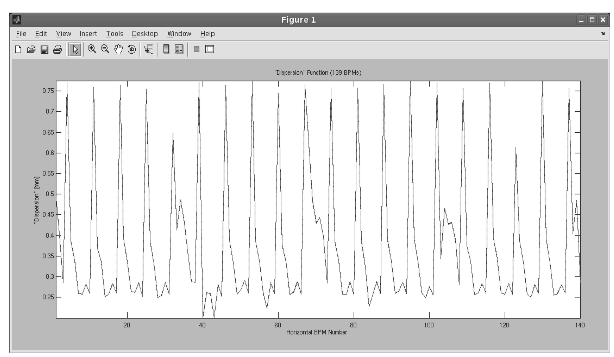

Fig. 8. Dispersion measurement around the whole storage ring when the rf frequency is reduced 500 Hz.

In Fig. 8, the horizontal axis shows the serial number of the BPM around the whole storage ring; the vertical axis shows the dispersion; the red line denotes the designed dispersion; and the blue dots denote the measured dispersion. From Fig. 8, we can see that the measured dispersion is consistent with the designed one when considering the gains of BPM.

4 Conclusions

The measurement of optics parameters for SSRF is indispensable in commissioning stage. A series of optics parameters can be measured by virtue of the methods that the report introduces and AT program and precise apparatus. The measurement process of beta function is completely automatic by the tool of BetaMeas GUI which is written by a member of SSRF. The GUI tool can be well applied to SSRF although there are some minor errors. Some other users are needed to verify the GUI tool, although it is optimized ceaselessly in commissioning. The measurement of optics parameters is very important to the orbit which needs to be corrected and optimized.

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