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Central RF frequency measurement of the HLS-II storage ring*

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Abstract: Central RF frequency is a key parameter of storage rings. This paper presents the measurement of central RF frequency of the HLS-II storage ring with the sextupole modulation method. Firstly, the basis of central RF frequency measurement of the electron storage ring is briefly introduced. Then, the error sources and the optimized measurement method for the HLS-II storage ring are discussed. The workflow of a self-compiled Matlab script used in central RF frequency measurement is also described. Finally, the results achieved by using two data processing methods to cross-check each other are shown. The measured value of the central RF frequency demonstrates that the circumference deviation of the HLS-II storage ring is less than 1 mm.

Keywords: HLS-II storage ring, circumference, central RF frequency, sextupole modulation

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1 Introduction

The upgraded Hefei Light Source (HLS-II) at the National Synchrotron Radiation Laboratory (NSRL) in Hefei, China, is a storage-ring-based light source which provides scientific users with high brightness photons with an energy range from vacuum ultraviolet to far infrared. It has been running well since commissioning was completed in late 2014 [1]. The upgrade of the 800 MeV storage ring is the major part of the upgrade project. On the one hand, the lattice was replaced by DBA (double bend achromatic) cells [2], which not only significantly decreases the beam emittance but also increases the number of straight sections for insertion devices. On the other hand, a series of subsystems, such as the RF system, power supply system and corresponding instrumentation, have been redeveloped and rebuilt in order to improve the machine stability and reliability. The main parameters of the HLS-II storage ring are shown in Table 1.

The central RF frequency is a direct measure of the circumference of the storage ring. The central RF frequency can be used to estimate the deviation of the ring circumference from the design value after the ring installation. In addition, the evolution of the circumference induced by various effects such as tide needs to be tracked over the long term using the beam position measurement, but the average radical beam position should be calibrated by the central RF frequency measurement [3].

Moreover, the beam passing off-center through the quadrupole can “sense” the coexistence of the dipole and quadrupole fields in a separated function lattice, which changes the distribution between the horizontal partition number and the longitudinal partition number. By increasing the RF frequency, which in essence increases the horizontal partition number, the emittance of the storage ring can be further reduced [4]. However, this adjustment is limited by the instability of the longitudinal motion since the longitudinal partition number is reduced at the same time. Therefore, the adjustable range of the RF frequency in this case must be investigated by comparing the current RF frequency with the central RF frequency.

Table 1. Main parameters of HLS-II storage ring.

parameter	value
energy	800 MeV
circumference	66.13 m
beam current	300 mA
DBA cells	4
RF frequency	204.030 MHz
harmonic number	45
tune	0.44/0.36
emittance	36 nm·rad

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2 Basis of the central RF frequency measurement

The beam orbit in the storage ring is defined by the arrangement of the bending magnets. The quadrupoles for focusing and sextupoles for chromaticity and nonlinearity correction are distributed along the orbit and aligned to make sure that the beam orbit passes the magnetic centers. The orbit which passes on average through the center of the quadrupoles and sextupoles is called the central orbit and the length of the central orbit is the circumference of the ring. Therefore, the RF frequency corresponding to the central orbit is called the central RF frequency. Using the relation between the RF frequency and the length of the beam orbit for relativistic particles, the central RF frequency $f_{\mathrm{RF}}^{\mathrm{C}}$ is defined as

$$f_{\mathrm{RF}}^{\mathrm{C}}=h\frac{c}{C_{\mathrm{C}}}, \tag{1}$$

where h is the harmonic number, C_{C} is the length of the central orbit and c is the speed of light. However, magnet alignment errors cannot be avoided in the practical installation of the machine. There is always a slight difference between the actual circumference and the design value of the storage ring.

The RF frequency differing from the central RF frequency leads to two effects. The first effect is that the beam will “sense”the coexistence of dipole and quadrupole fields at the location of the quadrupole magnets. The distribution of the damping partition numbers in three degrees of freedom can be modified according to Robinson’s criterion [5]. Therefore, the central RF frequency can be derived by the relation between the RF frequency and either damping partition numbers or other dependent parameters [6]. However, the accuracy of this method is seriously limited due to the strong collective effects induced by the high beam current. These methods will not be considered yet, until the instability issues in the HLS-II storage ring have been systematically studied.

The second effect is that the beam will also “sense”extra quadrupole fields at the location of the sextupoles. The method based on this effect is referred to as the direct measurement of central RF frequency and is a standard method which is both simple and reliable [7].

If the current RF frequency differs from the central RF frequency, the relative momentum deviation δ is

$$\delta=-\frac{1}{\alpha}\frac{\Delta f_{\mathrm{RF}}}{f_{\mathrm{RF}}^{\mathrm{C}}}, \tag{2}$$

where α is the momentum compact factor and Δf_{RF} is the deviation of current RF frequency from the central RF frequency. Then the off-momentum particles will “sense”an extra focusing force introduced by sextupole fields in the dispersion section. Consequently, the tune shift is

$$\Delta \upsilon_{x,y}=\delta\xi_{x,y}, \tag{3}$$

where $\xi_{x,y}$ is the corrected chromaticity. The corrected chromaticity is relative to the sextupole setting which is

$$\xi_{x,y}=-\frac{1}{4\pi}\oint\beta_{x,y}[K_{x,y}(s)-S(s)\eta(s)]\mathrm{d}s, \tag{4}$$

where S is the sextupole strength, $\beta_{x,y}$ is the beta function, η is the dispersion function, $K_{x,y}$ is the quadrupole strengths and the subscripts represent the two transverse directions.

From Eqs. (2), (3) and (4), it is clear that the tune will not vary with the different sextupole settings if Δf_{RF} is equal to zero. Therefore, the measurement of central RF frequency of a storage ring is to find out the RF frequency point at which the chromaticity curves cross, or in other words, to find out the frequency point at which the tune does not rely on the sextupole strength. The methods to find out this RF frequency point can be classified into two categories: RF shaking and sextupole modulation [8]. In the RF shaking method, the RF frequency is repeatedly swept as a predefined function for the different chromaticity settings. Then the frequency at the crossing point of the different chromaticity curves is viewed as the central RF frequency. Opposite to the RF shaking method, the sextupole modulation method is to sweep repeatedly the strength of the sextupoles at different RF frequencies. Although the two methods to obtain the data differ, there is no essential distinction between the results.

3 Error source analysis and measurement optimization

In practice, the central RF frequency achieved by direct measurement is a measure of the length of the central orbit in the sextupoles. The quadrupoles in the storage ring are not involved. Thus the accuracy of central RF frequency measurement is limited by the alignment errors between sextupoles and quadrupoles. This effect defines the intrinsic resolution of the measurement of the central RF frequency. Figure 1 shows the adjacent quadrupoles and sextupoles in a DBA cell of the HLS-II storage ring. Note that the four magnets are installed on the same support as a unit. Adjacent sextupoles and quadrupoles are aligned with respect to each other with an accuracy lower than 0.08 mm [9]. The HLS-II storage ring uses two sextupole families (denoted as S_3 and S_4, each family with 8 identical sextupoles) in the dispersion sections to correct the chromaticity [10]. Eq. 4 then becomes

$$\xi_x=\xi_x^{\mathrm{nat}}+\frac{2}{\pi}(s_3\eta_3\beta_{x3}l_3+s_4\eta_4\beta_{x4}l_4), \tag{5}$$

$$\xi_y = \xi_y^{\mathrm{nat}} + \frac{2}{\pi}(s_3\eta_3\beta_{y3}l_3 + s_4\eta_4\beta_{y4}l_4), \tag{6}$$

where ξ_x^{nat} and ξ_y^{nat} are the natural chromaticity in two directions, which are sextupole-independent, s_3 and l_3 are respectively the strength and length of the magnets in S_3, while s_4 and l_4 are respectively the strength and length of the magnets in S_4. The different chromaticity parameters can be obtained by modifying the strength of either S_3 or S_4. In order to further reduce the effect of alignment errors between magnets, measurements were independently performed using S_3 and S_4 as references respectively. In addition, the measurements in the two transverse directions lead to two independent results. Therefore, there are four independent measured results which can be used to cross-check with each other.

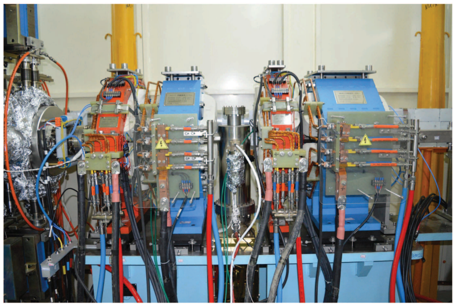

Fig. 1. (color online) Adjacent quadrupoles and sextupoles in a DBA cell of the HLS-II storage ring (blue: quadrupole pair; red: sextupoles in family S_3 and family S_4).

The measurement of central RF frequency also demands a stable machine condition. The different chromaticity curves are obtained by measuring the tune shift with RF frequency at different sextupole strength settings; this is called RF shaking. Frequent RF frequency changing, however, may affect the stability of the machine and lead to beam loss or even crash the measurement. Moreover, the time interval for the rebuilding of the RF field in the RF cavity extends the measurement time, which increases the probability of instability occurring. In order to obtain stable and reliable results, the sextupole modulation method, which is faster and more robust than the RF shaking method, was adopted for the central RF frequency measurement of the HLS-II storage ring.

Since the central RF frequency point is obtained by fitting the measured tune shift, another factor which affects the measurement precision is the fitting error. The HLS-II storage ring is equipped with a swept-frequency excitation based tune measurement system. The tune resolution is determined by the swept range. Resolution of 0.0001 can be achieved in the swept range from 2.1 MHz to 4.1 MHz. If the changing amount of the tune is less than or approximately equal to the resolution of the tune measurement system, the fitting error of data will seriously affect the measurement accuracy. However, a large amount of tune shift may lead the working point to travel across the resonance lines. In addition, as a practical consideration, the adjustable range of the RF system is limited by the nonlinear chromaticity effect and the RF system stability. Therefore, each tune shift needs to be predefined roughly with a balance between the resolution consideration and validity consideration. Using Eqs. (2), (3), (5) and (6), the proper RF frequency and sextupole strength for a predefined tune shift can be estimated.

The measurement is performed using a Matlab script under the EPICS (Experimental Physics and Industrial Control System) framework. The data interactions are based on the MCA (Matlab Channel Access) toolbox [11] which provides interfacing between Matlab and EPICS. A flow diagram of the measurement is shown in Fig. 2. The script consists of two levels of loops to perform the measurement with the sextupole modulation method. The outer loop is the data setting and reading of RF frequency and the inner loop is the data setting and reading of sextupole strengths of either S_3 or S_4. When the measurement begins, Matlab first connects the channels of the sextupole familiy S_3 or S_4, the tune measurement system and the RF system through the MCA. After this is done, the initial values of the sextupole strength, the tunes in the two transverse directions and the RF frequency are read into the Matlab workspace. Then the first RF frequency data is written into the RF system channel. After the machine condition is stable, the predefined sextupole strength data is written into the sextupole channel one by one for sextupole modulation. The tune data in two directions corresponding to each sextupole strength data are read into the Matlab workspace.

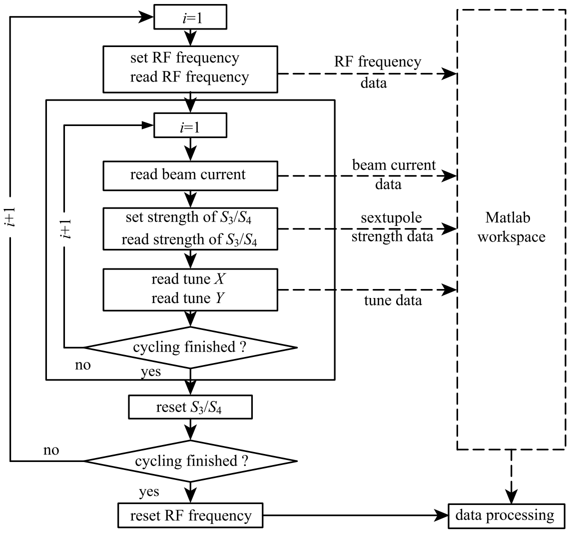

Fig. 2. (color online) Flow diagram of the central RF frequency measurement with the S_3/S_4 modulation method.

When this modulation is done, the next RF frequency data is written and the sextupole modulation repeats till the measurement is finished. The time interval between two data setting events is 30 s to make sure that the stable machine parameters are recorded into the Matlab workspace. In order to monitor whether any beam loss occurred or not, the beam current is sampled after every inner loop is completed during the measurement. When the measurement is done, a preprocessing of the data is immediately made to investigate the validity of the measured data. In this process, the beam current changes and the working point movement during the measurement can be observed, as well as the linearity of tune shift with sextupole strength and RF frequency.

4 Results and discussion

The measurements were started at the beam current of 3.62 mA. The collective effects has a relatively small impact on the measurements in this mode. The RF frequency and strength of S_3 (or S_4) were respectively swept 5 times as a predefined function. The sampled beam current data are shown in Fig. 3. There was no significant beam loss when the measurements were performed. The traveling of the working point during the measurement is shown in Fig. 4 (with the resonance lines up to fifth order). The maximum of the working point movement approaches 0.02 in both directions. Each working point is still far from the dominant resonance lines.

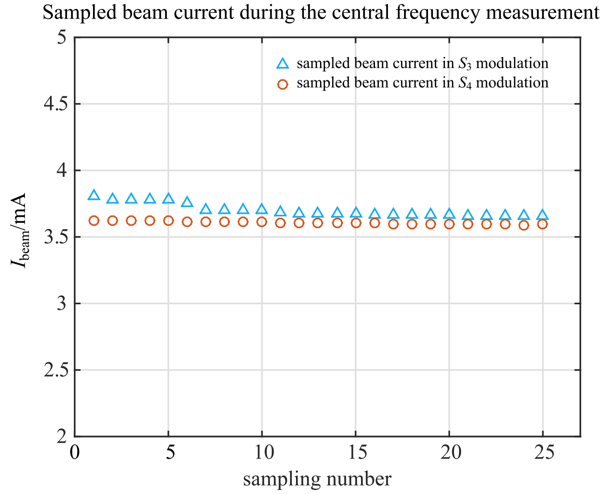

Fig. 3. (color online) Sampled beam current during the central RF frequency measurement.

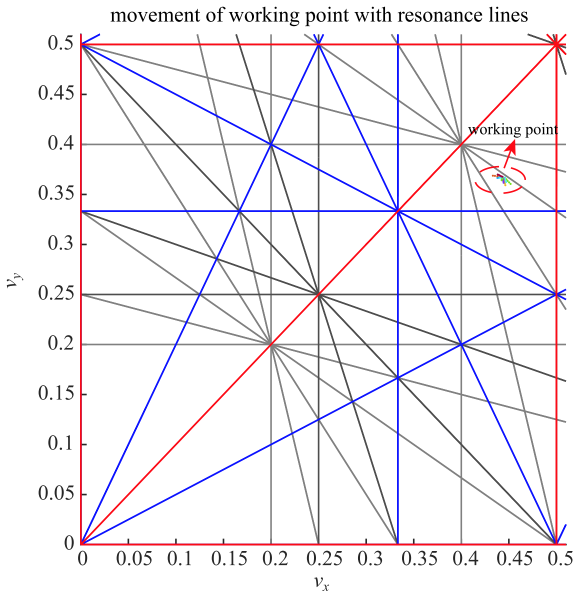

Fig. 4. (color online) Working point movement during the central RF frequency measurement (with the resonance lines up to fifth order).

Fig. 5 shows the measurement results in the S_3 modulation. The top figure shows the horizontal chromaticity curves at different strengths of S_3. As mentioned above, the frequency at the crossing point of the different chromaticity curves can be viewed as the central RF frequency. Due to the existence of the various error sources, the different chromaticity curves do not cross at a same point. The vertical dashed line indicates the average frequency of all the crossing points. The average frequency with corresponding rms value of the crossing points is 204.027005±0.000762 MHz. The bottom figure of Fig. 5 shows the vertical chromaticity curves at different strengths of S_3. The obtained central RF frequency is 204.027546±0.000148 MHz. Similarly, the measurement results in the S_4 modulation are shown in Fig. 6. The central RF frequency is 204.027322±0.000119 MHz taking the horizontal plane as reference, and the central RF frequency is 204.027342±0.000030 MHz taking the vertical plane as reference.

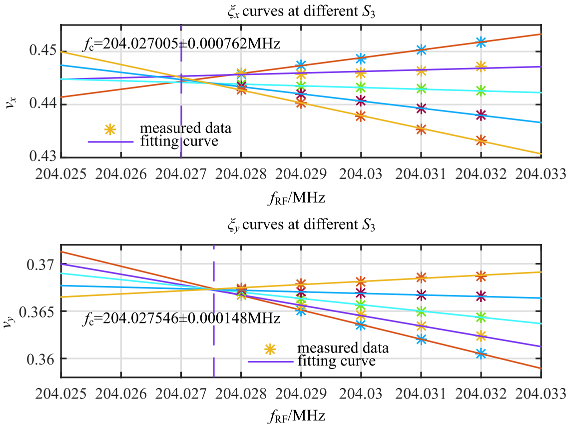

Fig. 5. (color online) Chromaticity curves at different strengths of S_3.

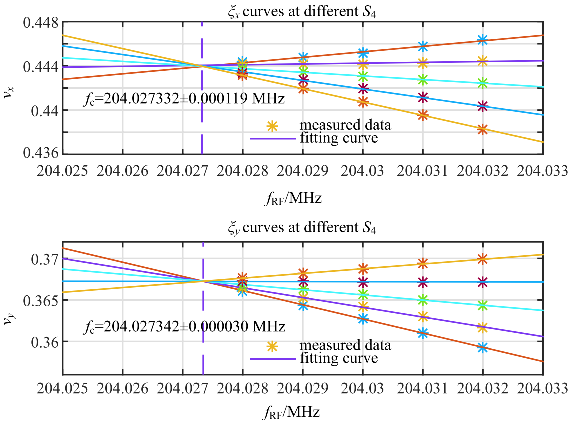

Fig. 6. (color online) Chromaticity curves at different strengths of S_4.

The chromaticity curves are obtained by fitting the tune shift with RF frequency. If the amount of tune shift with the RF frequency is smaller than the resolution of the tune measurement system, the fitting error would be significant in finding the precise central RF frequency point. To compensate this, the existing data are processed using another method. As mentioned above, the central RF frequency can also be obtained by finding the frequency point at which the dependence of tune on the strength of the sextupole vanishes. To do this, a coefficient is defined to measure the dependence of the tune on the strength of the sextupole. From Eq. 5 and 6 we can see that the tune changes linearly with the strength of a single sextupole family, either S_3 or S_4. Thus the dependence coefficient can be obtained by linear fitting of the tune with the strength of the sextupole. In the top figure of Fig. 7, the dependence coefficient of the horizontal tune as a function of RF frequency in S_3 modulation is shown. The star indicates the point at which the dependence coefficient is equal to zero. The obtained central RF frequency is 204.027095 MHz. Taking the vertical plane as reference, the result is 204.027543 MHz, which is shown in the bottom figure of Fig. 7. Similarly, the top and bottom figures of Fig. 8 show respectively the dependence coefficients in two transverse directions as a function of RF frequency in S_4 modulation. The obtained results are respectively 204.027320 MHz and 204.027343 MHz.

The result obtained in the vertical plane in S_4 modulation is taken as a credible value of the central RF frequency of the HLS-II storage ring since the uncertainty is the lowest and this value is also covered by other results. Using Eq. (1), the relative deviation of the circumference from the designed value after the installation of the ring is 1.3027×10^{-5}. The circumference deviation is 8.6151×10^{-4} m.

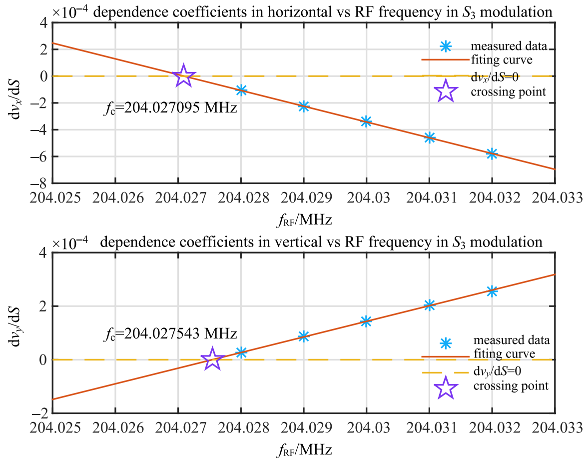

Fig. 7. (color online) The dependence coefficients of tunes on the strengths of S_3 at different RF frequencies.

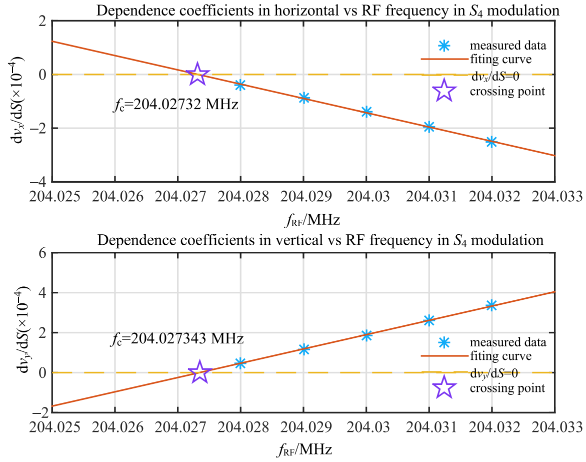

Fig. 8. (color online) The dependence coefficients of tunes on the strengths of S_4 at different RF frequencies.

5 Conclusion

During the commissioning phase of the HLS-II storage ring, the central RF frequency was measured with the sextupole modulation method. Three factors to affect the measurement accuracy were considered before measuring, in order to optimize the measurement method. These factors include the alignment error of the magnets, the machine stability during the measurement and the fitting error resulting from the limited resolution of the tune measurement system. Four independent groups of data were obtained by the measurements in two directions and using sextupole families S_3 and S_4 modulation. The amount of tune shift was optimized with the balance between the stability and resolution of the tune measurement system. The measurements were performed using a self-compiled Matlab script which works under the EPICS frame work. During the measurement, there was no significant beam loss. By processing the four groups of measured data using two methods, the results were cross-checked. The results demonstrate that the circumference deviation of the HLS-II storage ring is less than 1 mm. Moreover, the measurement result can be used for future use such as long-term circumference tracking and emittance optimization of the HLS-II storage ring.

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