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EFFECT OF PHASE MODULATION ON THE TRANSVERSE BEAM SIZE AND EMITTANCE OF THE HLS-II RING*

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Abstract

In this paper, the radio-frequency (RF) phase modulation method is exploited to investigate the variations in the transverse beam size and emittance at Hefei Light Source (HLS-II). Meanwhile, a certain quantitative analysis was performed on the stability and practicability of the beam transverse profile measurement systems. The experiments show that the RF phase modulation method can effectively explore the robustness and stability of beam transverse profile measurement systems over the range of 20.0–22.5 kHz, which is close to the first-harmonic of the synchrotron frequency. It is concluded that when the modulation amplitude of the external phase perturbation is less than 0.04 rad, this optical system can be capable of maintaining reliable and stable working status. This is also useful for analyzing the influence of RF phase noise on the subsequent beam measurement and diagnostics, which including the deterioration of beam quality, emittance blowup, beam jitter, and beam loss.

INTRODUCTION

In the synchrotron radiation (SR) storage ring light sources, it is crucial to real-time high-accuracy monitor the variations of the transverse beam size and emittance. With this in mind, HLS-II is equipped with two transverse beam profile measurement systems as that of the synchrotron light imaging system and interferometric system to precisely measure the beam size, emittance, and energy spread on the basis of the actual measurement requirement [1, 2]. In previous machine experiments, a RF phase modulation method is developed to improve beam lifetime and explore longitudinal beam characteristics in the HLS-II storage ring. However, we found that the transverse beam size and emittance are affected by the parametric resonances resulting from the introduced phase perturbation [3, 4]. Therefore, it is necessary to deeply research and elaborate the variations of beam transverse profile and beam emittance subjected to the external RF phase modulation. It has considerable physical and engineering guiding significance in the operation, commissioning, and beam manipulation of the HLS-II storage ring and our future Hefei Advanced Light Facility (HALF) [5]. Considering that the preliminary machine measurement are carried out in the single-bunch operation mode, we mainly focused on investigating the stability and feasibility of the beam transverse profile measurement systems by use of the changes on the transverse beam size and emittance. Furthermore, the dependence curve of the beam energy spread as a function of the RF phase modulation frequency is further analyzed under different modulation amplitudes.

THE MEASUREMENT PRINCIPLE

As for the HLS-II storage ring, it is noted that the interferometer and imaging system are installed on the dedicated diagnostic beamlines B7 and B8, respectively. Correspondingly, the underlying equations for the transverse beam emittance and energy spread can be separately expressed as

$$\begin{cases} \varepsilon_x = \dfrac{\sigma_{x,\mathrm{B7}}^2\eta_{x,\mathrm{B8}}^2-\sigma_{x,\mathrm{B8}}^2\eta_{x,\mathrm{B7}}^2}{\beta_{x,\mathrm{B7}}\eta_{x,\mathrm{B8}}^2-\beta_{x,\mathrm{B8}}\eta_{x,\mathrm{B7}}^2} \\ \delta = \left(\dfrac{\sigma_{x,\mathrm{B8}}^2\beta_{x,\mathrm{B7}}-\sigma_{x,\mathrm{B7}}^2\beta_{x,\mathrm{B8}}}{\beta_{x,\mathrm{B7}}\eta_{x,\mathrm{B8}}^2-\beta_{x,\mathrm{B8}}\eta_{x,\mathrm{B7}}^2}\right)^{1/2} \end{cases} \tag{1}$$

Where the subscripts B7 and B8 represent the parameters at the light source points respectively, ε_x for the horizontal beam emittance, δ for the beam energy spread, η_x for the dispersion function in the horizontal direction, σ_x for the horizontal beam size, and β_x for the beta function in the horizontal plane, x. Similarly, the vertical beam emittance can be obtained by

$$\varepsilon_y = \sigma_y^2/\beta_y \tag{2}$$

Here, σ_y and β_y indicate the beam size and beta function in the vertical direction y, respectively. To the best of our knowledge, the applied external RF phase modulation will bring about the obvious parametric resonances in the case that the modulation frequency is close to an integral multiple of the synchrotron oscillation frequency. In the case that the modulation frequency of the RF system approaches to a single harmonic of the synchrotron frequency, which corresponding to the standard Hamiltonian equation related to the charged particle motion can be described by [3, 4]

$$\langle H_1\rangle_t = (\omega_s-\omega_m)\,J - \frac{\omega_s J^2}{16} - \frac{\omega_s a_m}{2}(2J)^{\frac{1}{2}}\cos\psi - \omega_s \tag{3}$$

In Eq. (3), it is worth pointing out that the systematic Hamiltonian formalism is an invariant. ω_s denotes the synchrotron oscillation angular frequency, which is equal to $\omega_s = 2\pi f_s$, where f_s represents the synchrotron frequency. Whereas ω_m denotes the modulation angular frequency of the external RF noise that is equivalent to $\omega_m = 2\pi f_m$, in which f_m represents the modulation frequency, and a_m represents the phase

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error modulation amplitude. It is noted that J and ψ denotes the action-angle coordinates. In terms of the aforementioned theoretical Eq. (3) and in combination with the characteristic parameters of the HLS-II storage ring, we simulated the particle motion trajectories at different modulation amplitudes for the case of the RF modulation frequency approaching to the synchrotron frequency, as shown in Fig. 1.

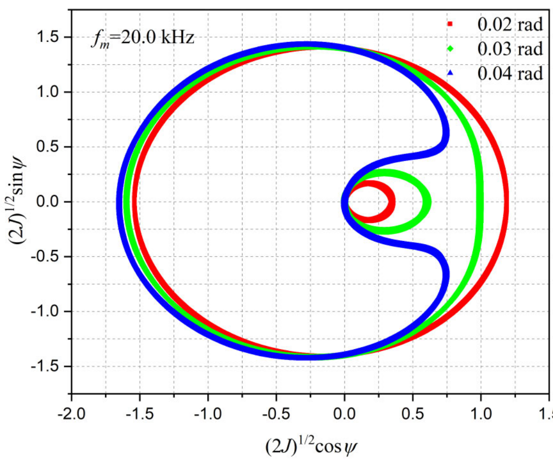

Figure 1: The particle trajectories under different RF phase modulation amplitudes (f_s = 21.3 kHz and f_m = 20.0 kHz).

In Fig. 1, the red square, green diamond, and blue triangle stand for the Hamiltonian tori with the modulation amplitudes of 0.02, 0.03, and 0.04 rad, respectively. For the sake of simplicity and convenience, it is mentioned that the simulated Hamiltonian torus in phase space is chosen to be the modulation frequency of 20.0 kHz. It can be clearly seen that the introduction of the phase noise has a great impact on the charged particle motion trajectory and bunch volume. The main reason is attributed to the parametric resonance effect and the beam dilution theory. It should be emphasized that this method can give rise to the deterioration of beam emittance in the case of improving beam lifetime and suppressing beam instability. As a consequence, we aim to investigate the variations of beam characteristic parameters which including transverse beam size, emittance and energy spread related to phase modulation. There is no doubted that this has outstanding importance on machine research and beam dynamics analysis at the HLS-II storage ring.

EXPERIMENTAL SETUP AND RESULTS

According to the above-mentioned theoretical analysis, in which the experimental arrangement is distinctly depicted in Fig. 2.

As shown in Fig. 2, it can be clearly observed that the experimental measurement system is mainly composed of the RF system, the synchrotron light interferometer system, and the synchrotron light imaging system. Note that the interferometer and the imaging system are installed on the source points B7 and B8, respectively. The interferometer system is divided into horizontal and vertical interferometer, which are employed for measuring the horizontal and vertical beam size, respectively. In comparison, the imaging system is relatively simple and compact, which is the most direct universal beam profile measurement method. It should be pointed out that the optical attenuator is being taken to modulate the light intensity to avoid the damage to CCD camera. With regard to the polarizer, whose role is to extract the polarization component of the SR light. In addition, it is emphasized that the band-pass filter is utilized for selecting the spectrum of the SR light and reducing the influence of chromatic aberration. To do that we can real-time monitor the beam size and emittance using the two beam transverse profile measurement systems.

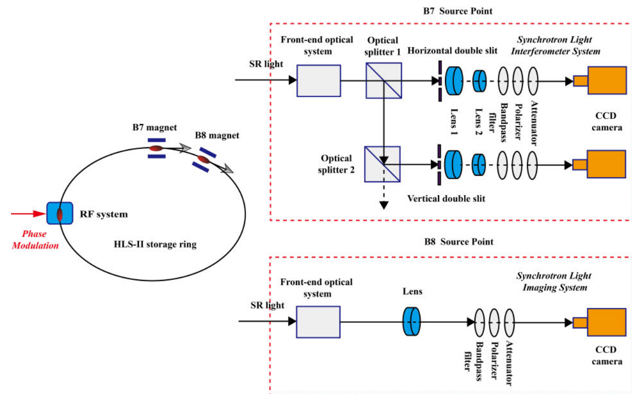

Figure 2: Schematic diagram of the experimental measurement system.

In Fig. 2, it is especially mentioned that the RF phase modulation method is developed for investigating and analyzing the changes of beam size and emittance. It is well-known that the introduction of phase noise into RF system can obviously affect the beam performance in the HLS-II storage ring. Consequently, we are devoted to explore the stability, measurement accuracy and applicability of the beam transverse profile measurement system in view of the external RF phase disturbance. The measured results are shown in Figs. 3 and 4, respectively.

As plotted in Fig. 3, (a) and (b) indicate the dependence curves of the horizontal beam size and emittance with modulation frequency, respectively. Nevertheless, Fig. 4, (a) and (b) separately reveal the variations of beam size and emittance in vertical direction as increasing the modulation frequency. Here, the blue square, green circle, and magenta triangle signify the changes of the transverse beam size and emittance with the increase of the RF phase modulation frequency at the modulation amplitudes of 0.02, 0.03 and 0.04 rad. It is apparent that the measured values have obvious discrepancy when increasing the modulation amplitude in vicinity of the synchrotron frequency 20.0–22.5 kHz. This is mainly originated from the parametric resonance effect caused by the external RF phase noise, of which can manipulate bunch electron density and simultaneously bring perturbation to the beam. It is directly observed that when the modulation amplitude is increased to 0.04 rad, which results in the beam transverse profile measurement systems

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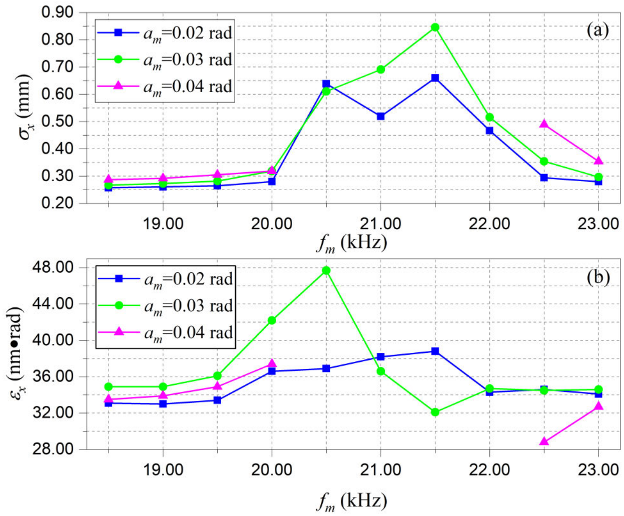

Figure 3: The change cure of the horizontal beam size and emittance versus the modulation frequency.

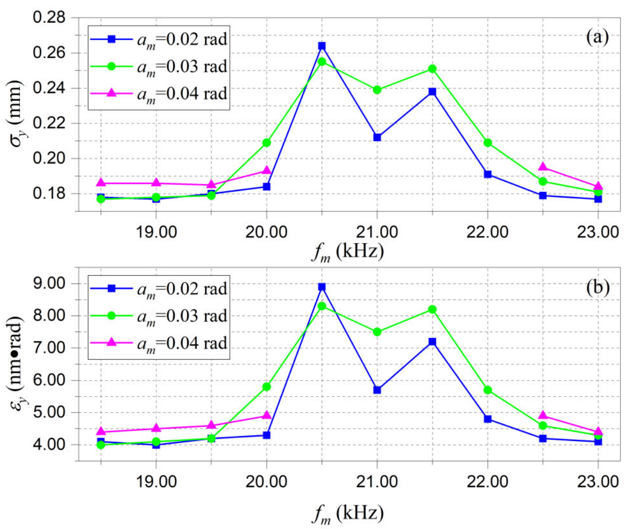

Figure 4: The change cure of the vertical beam size and emittance with respect to the modulation frequency.

can no longer accurately measure the beam size and emittance as a result of the violent bunch jitter and oscillation. Additionally, it will bring about these systems to fail to maintain the stable operation state. Therefore, in order to ensure the measurement reliability and feasibility of the beam transverse profile measurement systems, the tolerance level of the experimental system associated with the external RF phase noise should be avoided no more than 0.04 rad.

It is noted that the resolution of the beam transverse profile measurement systems are also affected by the depth of field effect and the curvature error. Besides, the installation error of the optical system and environmental disturbances also give rise to the measurement error. However, the error caused by these external factors to the optical measurement system is approximately several micrometers, which is much lower than the sudden variation in the beam size being attributed to RF phase noise. In summary, the simple and flexible RF phase modulation method in the sense that is capable of roughly and intuitively providing the useful guidance for accelerator operation and commissioning.

In addition, we also further measured the change in beam energy spread under the case of the external RF phase modulation in the experiment accordingly, as shown in Fig. 5.

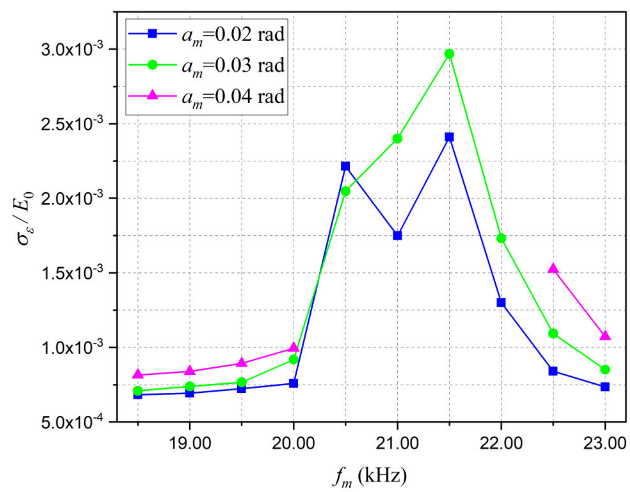

Figure 5: The beam energy spread variation curve via the modulation frequency at different modulation amplitudes.

From Fig. 5, it is evident that there is a severe variation on beam energy spread under the condition of the phase modulation ranging from 20.0 to 22.5 kHz. This means that this RF phase modulation approach has a great impact on beam performance. In the future research work, we will attempt to further expand the application scenarios based on this phase modulation method, of which including improving beam performance, analyzing RF noise, and studying the beam instability of the HLS-II storage ring.

CONCLUSION

In general, it is desirable to explore and discuss the stability, feasibility and practicability of the beam transverse profile measurement systems on the HLS-II storage ring by means of the RF phase modulation method. It has demonstrated that these beam transverse profile measurement systems can be effective of maintaining measurement reliability in the case of the modulation amplitude of the external phase noise is less than 0.04 rad within the range of 20.0–22.5 kHz. At the same time, this phase modulation approach is of great significance to the operation, machine research and beam diagnosis of the HLS-II storage ring. Furthermore, it can provide feasible suggestions and ideas for researching the physical phenomena such as emittance dilution, beam jitter, and beam loss in the synchrotron storage ring light sources.

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REFERENCES

[1] K. Tang *et al.*, "Transverse beam size measurement system using visible synchrotron radiation at HLS II", *Chinese Phys. C*, vol. 40, no. 9, p. 097002, 2016. `doi:10.1088/1674-1137/40/9/097002`

[2] C. Cheng *et al.*, "Beam size and position measurement based on logarithm processing algorithm in HLS II", *Chinese Phys. C*, vol. 40, no. 4, p. 047004, 2016. `doi:10.1088/1674-1137/40/4/047004`

[3] H. Huang *et al.*, "Experimental determination of the Hamiltonian for synchrotron motion with rf phase modulation", *Phys. Rev. E*, vol. 48, no. 6, pp. 4678–4688, 1993. `doi:10.1103/PhysRevE.48.4678`

[4] N. P. Abreu *et al.*, "Longitudinal dynamics with rf phase modulation in the Brazilian electron storage ring", *Phys. Rev. ST Accel. Beams*, vol. 9, no. 12, pp. 124401, 2006. `doi:10.1103/PhysRevSTAB.9.124401`

[5] P. Yang *et al.*, "Design of a hybrid ten-bend-achromat lattice for a diffraction-limited storage ring light source", *Nucl. Instrum. Meth. A*, vol. 943, p. 162506, 2019. `doi:10.1016/j.nima.2019.162506`