Effective improvement of beam lifetime based on radiofrequency phase modulation at the HLS-II storage ring

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Abstract A radiofrequency (RF) phase modulation method is applied to the Hefei Light Source II storage ring to deeply investigate its longitudinal beam characteristics and improve the beam lifetime. A theoretical analytical model and corresponding experimental measurements of single bunch length and island phenomena are examined. From a series of online machine experiments, we demonstrate that the suitable phase modulation amplitude is 0.02 rad, corresponding to an optimum modulation frequency ranging from 19.6 to 20.7 kHz of the RF system. Furthermore, the overall beam lifetime can be increased by a factor of 2.38 as a result of the beam dilution effect.

Keywords Phase modulation · Amplitude · Beam lifetime · Longitudinal beam characteristics · Beam dilution · Island

1 Introduction

It is well known that the longitudinal beam dynamics associated with synchrotron motion play a particularly important role in synchrotron radiation (SR) light sources [1, 2]. To the best of our knowledge, the evolution of particle motion is closely related to the perturbation induced by radiofrequency (RF) phase and amplitude noise, power supply ripple, mechanical vibration, environmental disturbance, and wakefields. In the past few decades, a number of researchers have devoted efforts to the development and application of RF modulation techniques [3-5]. For example, in an early study, Senichev et al. verified a dramatic enhancement in the beam lifetime by conducting the modulation experiment from the first to the fourth harmonic in the ASTRID-II storage ring [6]. Hereafter, Sakanaka et al. [7] also demonstrated that, by using the phase modulation technique, the Touschek lifetime can be effectively improved in the High Energy Accelerator Research Organization Photon Factory (KEK-PF). It was found that the beam lifetime was significantly increased in the case where the modulation frequency was close to twice the synchrotron frequency. Moreover, related studies of longitudinal beam dynamics were also performed to improve the beam stability and quality by means of this phase modulation approach [8]. To date, a number of online systematic measurements and corresponding theoretical analyses have been conducted at other SR light sources to investigate the longitudinal beam dynamics associated with beam performance based on an RF modulation method [9–12].

Indeed, a better understanding of the relevant features of the longitudinal beam behaviors is of considerable interest and useful in improving beam lifetime [6, 7], enhancing beam quality and stability [8], and conducting beam manipulation [9, 10]. In addition, it can be employed to suppress the longitudinal coupled-bunch beam instability [10, 11] caused by the higher-order modes excited in the RF cavity and to study the nonlinear phenomena of the resonance islands [12, 13]. It is of particular importance for the design, construction, operation, and commissioning



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requirements of our future diffraction-limited storage ring light source, namely the Hefei Advanced Light Facility (HALF) [14, 15], and other circular accelerators. In view of these attractive potential benefits, a range of classic theoretical analytical models and detailed experimental studies has been developed to deeply study longitudinal beam dynamics by virtue of the RF phase or voltage modulation. Moreover, it was discovered that the aforementioned method has the outstanding advantages of being simple, low-cost, highly flexible, easy to operate, and broadly applicable compared with higher harmonic cavities (HHCs) [16–18]. Consequently, this study aims to increase the beam lifetime and research the fundamental longitudinal beam bunch behaviors of the Hefei Light Source II (HLS-II) ring [19, 20] with the help of the RF modulation technique. In this work, an RF phase modulation (RFPM) method is introduced into the HLS-II ring to elongate the beam lifetime and simultaneously investigate the longitudinal beam dynamic characteristics. It mainly focuses on elaborating and discussing the bunch-lengthening effect, particle redistribution, beam dilution mechanism, and longitudinal profile of a single bunch in the presence of RFPM.

This paper is systematically organized as follows. In Sect. 2, a suitable RFPM theoretical analytical model is proposed to explore the longitudinal beam behaviors in phase space based on first-order parametric resonance. Subsequently, in Sect. 3, a series of related online experimental measurements are performed using a streak camera to observe longitudinal beam bunch characteristics with RFPM amplitude and frequency in the vicinity of a single harmonic of the synchrotron oscillation frequency. Moreover, we analyze and discuss the measured results based on the well-established RFPM model and in combination with the current machine operating status. Finally, brief conclusions are given in Sect. 4.

2 Theoretical modeling and analysis

With the aim of achieving long beam lifetime, the RFPM technique is implemented in the HLS-II storage ring. We can also study the longitudinal beam characteristics to further analyze the machine performance. It should be emphasized that this RFPM tool is mainly based on the primary RF system, which is installed between beamline7 (B7) and beamline8 (B8). Accordingly, the prominent characteristic parameters of the RF cavity system are exhibited in Table 1. The main RF frequency is 204.030 MHz, the revolution frequency is 4.534 MHz, and the harmonic number is 45, corresponding to 45 filling buckets. The synchrotron frequency is measured to be 20.0–21.5 kHz, which is relevant to the actual RF cavity

Table 1	Basic	parameters	of the	RF s	ystem a	t the	HLS-II ring
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Parameter	Value
Beam energy, E (GeV)	0.8
Circumference, C (m)	66.13
Beam lifetime, τ (h)	7–8
Natural rms bunch length, σ_{τ} (ps)	\sim 50
Revolution frequency, f_{rev} (MHz)	4.534
Harmonic number, h	45
Main RF frequency, $f_{\rm rf}$ (MHz)	204.030
Synchrotron frequency, f_s (kHz)	20.0-21.5
Synchronous phase, $\phi_{\rm s}$ (°)	172
Main cavity gap voltage, V_c (kV)	122
Main cavity shunt impedance, $R_{\rm sh}$ (M Ω)	3.3
Main cavity unloaded quality factor, Q_0	28,300
Main cavity coupling coefficient, β	2.02

gap voltage and the synchronous phase. In addition, the cavity shunt impedance, unloaded quality factor, and coupling coefficient are 3.3 M Ω , 28,300, and 2.02, respectively.

In view of the standard Hamiltonian equation for the longitudinal beam dynamics in the presence of phase modulation, a simple compact RFPM model is developed to analyze the beam bunch behavior and research the beam performance of the HLS-II synchrotron storage ring. Considering that the frequency of the RFPM is close to the first harmonic of the synchrotron frequency, the complete perturbed Hamiltonian for a particle motion in phase-space coordinates (δ, ϕ) can be derived as [1, 2]

$$H(\delta, \phi) = \frac{\omega_{s} \delta^{2}}{2} + \omega_{s} \tan \phi_{s0} [\sin \phi \cos(a_{m} \sin \omega_{m} t) + \cos \phi \sin(a_{m} \sin \omega_{m} t)]$$
(1)
$$- \omega_{s} \cos \phi \cos(a_{m} \sin \omega_{m} t) + \omega_{s} \sin \phi \sin(a_{m} \sin \omega_{m} t) - \omega_{s} \phi \tan \phi_{s0}.$$

In Eq. (1), $a_{\rm m}$ represents the modulation amplitude, $\omega_{\rm m}$ the modulation angular frequency, and $\omega_{\rm s}$ the angular frequency of the synchrotron particle. Note that the phase $\phi_{\rm s0}$ is related to the synchronous angle $\phi_{\rm s}$ by satisfying $\phi_{\rm s0} = \pi - \phi_{\rm s}$. The variables δ and ϕ represent the energy deviation and phase of particle motion, respectively. To further investigate the longitudinal beam dynamics of Eq. (1), the action-angle variables $(\tilde{J}, \tilde{\psi})$ are introduced for coordinate transformation. It is worth pointing out that $\phi = \sqrt{2\tilde{J}}\cos\tilde{\psi}$ and $\delta = -\sqrt{2\tilde{J}}\sin\tilde{\psi}$. Consequently, the new Hamiltonian is given by

$$H(\tilde{J}, \tilde{\psi}) = \omega_{s} \tilde{J} \sin^{2} \tilde{\psi} - \omega_{s} \sqrt{2} \tilde{J} \tan \phi_{s0} \cos \tilde{\psi},$$

+ $\omega_{s} \tan \phi_{s0} \sin \left[\sqrt{2} \tilde{J} \cos \tilde{\psi} + a_{m} \sin \omega_{m} t \right],$
- $\omega_{s} \cos \left[\sqrt{2} \tilde{J} \cos \tilde{\psi} + a_{m} \sin \omega_{m} t \right].$ (2)

In the favorable combination of the *n*-order Bessel functions J_n and physical derivation, the simplified Hamiltonian can be further approximated by

$$H(\tilde{J},\tilde{\psi}) = \omega_{s}\tilde{J}\left(1 - \frac{1}{2}\cos 2\tilde{\psi}\right) - \omega_{s} - \frac{\omega_{s}\tilde{J}^{2}}{16},$$

$$- 2\omega_{s}\sum_{n=1}^{\infty} (-1)^{n}J_{2n}(\sqrt{2\tilde{J}})\cos(2n\tilde{\psi}),$$

$$+ \omega_{s}a_{m}J_{1}(\sqrt{2\tilde{J}})\sin\left(\omega_{m}t - \tilde{\psi}\right),$$

(3)

It is apparent from Eq. (3) that this perturbed Hamiltonian formulation is dependent on the time variable t. By applying the generating function F_2 , the resultant time-averaged Hamiltonian is obtained in such a way as to clearly describe the particle movement trajectory in the resonance rotating frame.

$$F_2(J,\psi) = \left(\tilde{\psi} - \omega_{\rm m}t - \frac{\pi}{2}\right)J \tag{4}$$

$$J = \frac{\partial F_2}{\partial \psi} = \tilde{J}, \psi = \frac{\partial F_2}{\partial J} = \tilde{\psi} - \omega_{\rm m} t - \frac{\pi}{2}$$
(5)

$$\langle H_1 \rangle_t = (\omega_s - \omega_m)J - \frac{\omega_s J^2}{16} - \frac{\omega_s a_m}{2} (2J)^{\frac{1}{2}} \cos \psi - \omega_s$$
(6)

Typically, the completed parametric resonant Hamiltonian is an invariant related to the value of the modulation amplitude and frequency. This indicates that the trajectory of the particle motion is along the constant Hamiltonian torus. With $\frac{\partial J}{\partial t} = 0$ and $\frac{\partial \psi}{\partial t} = 0$, the fixed points of the system are obtained, which can be characterized for the resonance islands. In terms of the abovementioned RFPM theoretical model, Eq. (6), we simulate the single-particle trajectories versus different modulation amplitudes, as shown in Fig. 1. The formation and annihilation mechanisms and processes of the resonance islands are also explored. The simulation parameters are set as follows: The synchrotron frequency f_s is 21.3 kHz, the phase angle ϕ_s of a synchrotron particle is 172°, and the original bifurcation frequency f_{bif} is computed as 20.6 kHz [1, 3].

Figure 1a, b shows the Hamiltonian tori in phase space with respect to different modulation amplitudes corresponding to modulation frequencies of 19.7 kHz and 20.5 kHz, respectively. The green squares, blue circles, and red triangles indicate amplitudes of the applied external RFPM of 0.02, 0.03, and 0.04 rad, respectively. It can be clearly seen that the motion trajectories of the charged particles vary with the modulation amplitude. It is interesting to observe that the phase-space torus of the constant Hamiltonian changes from an ellipse-like to a crescent-like shape. To the best of our knowledge, the difference in particle trajectory mainly originates from the coherent perturbation of the parametric resonance caused by the driving RF phase error noise. As shown in Fig. 1a, when the modulation frequency is slightly far from the synchrotron frequency, there is one unstable fixed point (UFP) and two stable fixed points (SFP1 and SFP2), as described by the violet dots in this picture. Consequently, the particle motion in the phase space is manipulated and gradually forms stable islands owing to the influence of the UFP and SFPs. It is evident that the beam dilution effect [21, 22] and bunch-splitting phenomenon gradually strengthen with increasing modulation amplitude of the RF system. This implies that the effectiveness of the parametric resonance generated by the RF phase amplitude modulation occupies the dominant contribution part. On the other hand, when the modulation frequency is very close to the bifurcation frequency, the inner stable fixed point SFP2 moves out and the UFP moves in, as indicated by the black arrows in Fig. 1b. In this case, the SFP2 and UFP collide and therefore gradually disappear together. Finally, only the outer SFP1 can be observed as the RFPM amplitude increases. Here, it should be emphasized that the collapse of the isolated resonance islands and the shrinkage of the central stable bunch region are attributed to the overlapping parametric resonances. As a result, particle diffusion and redistribution are mainly driven by the corresponding overlapping resonance islands.

3 Experimental results and discussion

3.1 RFPM measurement system

According to the above RFPM theoretical model, the preliminary beam dynamic experiments at HLS-II are performed in the context of external phase modulation. The experimental arrangement is displayed in Fig. 2.

As shown in Fig. 2, the experimental measurement system is mainly composed of a double-RF cavity system, a timing sequence control system, a front-end optical system, an optical power control system, a streak camera (OPTOSCOPE: SCMU-ST), and a data acquisition and processing system. It is noted that the double-RF dynamical system is composed of an HHC and a main RF cavity. This RFPM scheme is based on the primary RF cavity system, a photograph of which is shown in Fig. 3. Here, the timing sequence control system is used to precisely control



Fig. 1 (Color online) Tori of the time-independent Hamiltonian at different modulation amplitudes



Fig. 2 (Color online) RFPM experimental setup

the triggering and timing of streak scanning. Moreover, the front-end optical system is employed to improve the quality of the radiation light beam. The role of the optical power control system is to effectively modulate the light intensity incident onto the streak camera, thereby preventing damage to the photocathode from excessive input optical power.

In our experiment, first, the signal source (Agilent: E8257D) of the main RF system is appropriately adjusted to induce the external phase modulation. The modulated signal from the signal source travels through the high-power solid-state amplifier to increase the RF signal power and then feeds back into the primary RF cavity. Subsequently, we can observe longitudinal beam behaviors intuitively and in real time, including the bunch length, longitudinal distribution, and beam dilution process, by means of the streak camera mounted on B8. A personal

computer is simultaneously employed to acquire and process the experimental data. We can also monitor the change in other beam characteristic parameters of the HLS-II ring resulting from the RFPM in the control center.

3.2 Longitudinal beam behaviors

Based on the experimental device described above, we roughly probe the applicable modulation amplitude range of the RF dynamical system on the HLS-II ring. Correspondingly, the measured results of the characteristic feature of bunch evolution under different modulation amplitudes are obtained, as shown in Figs. 4 and 5. In the specific experiments, the trigger frequency of a streak camera is chosen to be 102 MHz operating in dual-axis scanning mode, which corresponds to a horizontal streak speed of 100 ps/mm and a vertical streak speed of 50 ns/



Fig. 3 (Color online) Photograph of the main RF cavity system



Fig. 4 (Color online) Observation of longitudinal beam behaviors at different modulation amplitudes with 19.7 kHz modulation frequency

mm. The threshold of the beam current is set to 11.00–13.00 mA in top-off mode. Additionally, it is noted that the passive HHC is switched on and has little impact on bunch lengthening and longitudinal distribution in the single-bunch operation mode.

Figures 4 and 5 show the detailed evolutions of the longitudinal beam distribution and bunch profile with modulation frequencies of 19.7 kHz and 20.5 kHz, respectively. In these figures, (a), (b), and (c) show the variation in longitudinal beam characteristic features for modulation amplitudes of 0.02, 0.03, and 0.04 rad, respectively. In Fig. 4, it is evident that the bunch-length-ening and island phenomena become increasingly obvious with increasing RFPM amplitude when the modulation frequency f_m is far from the bifurcation frequency. This can



Fig. 5 (Color online) Observation of longitudinal beam behaviors at different modulation amplitudes with 20.5 kHz modulation frequency

cause a significant beam dilution effect. Moreover, in Fig. 5, in which the modulation frequency $f_{\rm m}$ approaches the bifurcation frequency, notable bunch lengthening is observed, whereas the island phenomenon is not visible or observable as a result of the relative equilibrium particle distribution. From the online experimental measurements, we can roughly acquire 0.02 rad of the acceptable modulation amplitude, and the maximum value for the RFPM amplitude is obtained as 1.00 rad; otherwise, it will lead to beam loss.

As RFPM is a transient, changing, and unstable process, it inevitably gives rise to a certain measurement error during the experiment. In addition, external environmental perturbations including ground shaking, machine vibration, and temperature also affect the measurement uncertainty of the system. In general, this RFPM method is shown to be capable of effectively elongating the beam bunch and controlling the charge density based on experimental observation and verification.

To clearly and intuitively observe and analyze the effectiveness of the modulation amplitude on the longitudinal beam bunch distribution and beam dilution, the following longitudinal bunch profiles with respect to different modulation amplitudes are depicted in Fig. 6.

As shown in Fig. 6, the violet, red, green, and blue curves reveal the various longitudinal bunch distributions and profiles in the case of RFPM off and modulation amplitudes of 0.02, 0.03, and 0.04 rad, respectively. In Fig. 6a, where the modulation frequency is 19.7 kHz, it is apparent that the bunch length and particle distribution vary with increasing RFPM amplitude. The effects of bunch lengthening and beam dilution become increasingly obvious when the modulation amplitude increases. This is



Fig. 6 (Color online) Longitudinal bunch distributions and profiles versus different modulation amplitudes ($\mathbf{a} f_m = 19.7 \text{ kHz}$, $\mathbf{b} f_m = 20.5 \text{ kHz}$)

accompanied by the appearance of resonance islands that move around the center of the bunch. Accordingly, it can be clearly observed that the island phenomena are increasingly significant as the modulation amplitude is increased. Here, the outer resonance islands and the central position of the bunch are also provided to illustrate the effects of longitudinal particle distribution and bunch stretching due to RFPM, as marked by the black arrows in Fig. 6a.

As a comparison and reference, we also make further observations and investigations on the changes in the longitudinal bunch distribution and profile when the modulation frequency is close to the bifurcation frequency. The measured results are shown in Fig. 6b. The violet curve indicates the natural bunch length and distribution without applying the RFPM technique. The red, green, and blue curves express the diverse longitudinal bunch distributions and bunch profiles for modulation amplitudes of 0.02, 0.03, and 0.04 rad, respectively, with 20.5 kHz modulation frequency. The effects of beam dilution and bunch lengthening are quite pronounced relative to Fig. 6a. However, the resonance island phenomenon is not obvious. The reason for this is that overlapping parametric resonance occurs. In this case, it will give rise to uniform distribution of charged particles inside the single bunch, which therefore suffers from a decrease in electron bunch density. The bunch lengthening and beam dilution effects are relatively distinct compared to the case of no external RFPM.

As shown in Fig. 6a, b, the measured curves are not very smooth, with a degree of fluctuation and jitter. The main reason for this is that quality damage could occur when the photocathode of the streak camera is worked for too long, eventually resulting in a measurement error of the longitudinal beam distribution and bunch profile. Moreover, this transient and continuous change in the longitudinal bunch behaviors caused by RFPM also leads to measurement uncertainty. Besides, the inherent jitter of the bunch itself and the beam instability existing in the operation of the machine also affect the measurement accuracy. In a follow-up study, the streak camera measurement system and RFPM parameters are further optimized to improve the measurement accuracy of the entire experimental system.

3.3 Effect of beam dilution

In the following, to better understand the beam dilution mechanism, the longitudinal bunch distribution and bunch lengthening when the modulation frequency is close to the synchrotron frequency are explored and observed in more detail, as shown in Fig. 7.

As depicted in Fig. 7, we select longitudinal bunch distribution images at equal intervals of 0.20 kHz captured by the streak camera. It is clear that the longitudinal distribution, bunch length, and oscillation amplitude vary with the modulation frequency f_m . It is found that the island phenomena are gradually produced notably as f_m approaches the bifurcation frequency of 20.6 kHz. In contrast, the resonance islands gradually disappear when f_m is larger than the bifurcation frequency. Correspondingly, the influence of particle diffusion gradually increases and subsequently decreases over the range of 19.5–20.9 kHz.

3.4 Improvement in beam lifetime

The beam lifetime [23–25] is related to quantum fluctuations, intrabeam Coulomb scattering, vacuum pressure in the beam pipe, and Touschek scattering. For low-energy SR storage ring light sources such as HLS-II, the beam lifetime is mainly determined by the Touschek lifetime and the vacuum lifetime. In the actual experimental



measurement process, it is emphasized that the vacuum condition is improved by long-term beam cleaning; therefore, the resultant ring mean vacuum pressure can be better than 3.60×10^{-8} Pa, which belongs to the ultra-high vacuum regime. Generally, the approximate composition of the residual gas molecules in the HLS-II ring is roughly monitored as 90.2% H₂, 6.02% CO, 2.1% H₂O, 1.05% CH_4 , and 0.63% others. Considering that the limiting vacuum chamber aperture is 11.5 mm, and the RF momentum acceptance is 1.02%, the vacuum lifetime is estimated to be larger than 120 h. Consequently, the influence of beam-gas scattering in the HLS-II storage ring is negligibly small. As a result, the improvement in the total beam lifetime mainly originates from the Touschek lifetime. In this regard, the lifetime due to the Touschek effect in the laboratory reference frame is characterized by [7]

$$\frac{1}{\tau_{\text{Tous}}} = -\frac{1}{N_b} \frac{\mathrm{d}N_b}{\mathrm{d}t} = \frac{r_c^2 c N_b}{8\pi\sigma_x \sigma_y \sigma_z} \frac{\lambda^3}{\gamma^2} D(\xi), \tag{7}$$

where

$$D(\xi) = \sqrt{\xi} \left[-\frac{3}{2} e^{-\xi} + \frac{\xi}{2} \int_{\xi}^{\infty} \frac{\ln u}{u} e^{-u} du + \frac{1}{2} (3\xi - \xi \ln \xi + 2) \int_{\xi}^{\infty} \frac{e^{-u}}{u} du \right].$$
(8)

In Eq. (7), it can be seen that the expression for the Touschek lifetime τ_{Tous} is a comparatively sophisticated function depending on many physical parameters. $N_{\rm b}$ denotes the number of particles in a bunch, c denotes the speed of light in a vacuum, $r_{\rm c}$ denotes the classical electron radius, γ denotes the relative energy, and σ_x , σ_y , and σ_z denote the rms beam sizes of the bunch width, height, and length, respectively. λ refers to the momentum acceptance parameter of the RF bucket such that $\lambda^{-1} = \Delta p/p_0|_{\rm rf}$. It is mentioned that $D(\xi)$ is dependent on the beam energy, energy spread, and RF parameters. The parameter ξ is defined as $\xi = \left(\frac{\Delta p_{\rm rf}}{\gamma \sigma_p}\right)^2$, in which the relative momentum spread σ_p can be described by $\frac{mc\gamma \sigma_x}{\beta_x}$, where the constants mand β_x are the electron mass and the betatron oscillation amplitude function, respectively.

It is interesting to note that the occurrence of resonance islands acts as a basin of attraction or attractor, which gives rise to bunch lengthening, increasing bunch volume, and uniformization of the electron bunch density. Thereby, it is capable of mitigating intrabeam scattering and eventually improving the Touschek lifetime. Thus, the total beam lifetime can be increased via the RFPM beam manipulation technique. Subsequently, we accurately monitor the beam lifetime variation in real time using the DCCT system [26] under the effective modulation amplitude. The measured



Fig. 8 Dependence curve of beam lifetime with respect to modulation frequency

curve as a function of modulation frequency $f_{\rm m}$ is plotted in Fig. 8.

In Fig. 8, the blue curve reveals the change in the beam lifetime at different modulation frequencies. Here, the initial beam lifetime is measured to be 2.4 h in the absence of RFPM. For the case in which the modulation frequency $f_{\rm m}$ ranges from 19.6 to 20.7 kHz in the vicinity of the synchrotron frequency, the beam lifetime tends to first increase and then gradually decrease. In this case, the optimum beam lifetime improvement factor $\tau_{\rm im}$ is 2.38. The beam lifetime of HLS-II shows the most notable improvement compared with other SR light sources, as shown in Table 2.

It is recognized that the longitudinal beam instability and oscillation are relatively small when the HLS-II storage ring operates in the single-bunch mode. As a result, the beam lifetime is significantly improved owing to the RFPM technique. In future work, we will further explore the longitudinal beam dynamic characteristics by enhancing the robustness and stability of the measurement system and optimizing the modulation parameters of the RF system in the case of the multi-bunch mode. Furthermore, it is noted that the beam energy spread can also be increased by the introduction of RFPM technology. From preliminary

Table 2 Comparison of beam lifetime improvement in different SR light sources when applying phase modulation

Facility	DELTA [11]	LNLS [2]	KEK-PF [8]	HLS-II
Beam energy	1.5 GeV	1.37 GeV	2.5 GeV	0.8 GeV
RFPM method	$f_{\rm m} \approx 2 f_{\rm s}$	$f_{\rm m} \approx 2 f_{\rm s}$	$f_{\rm m} \approx 2 f_{\rm s}$	$f_{\rm m} \approx f_{\rm s}$
$ au_{ m im}$	1.1–1.15	1.3	1.64	2.38

experimental observations, the beam energy spread can be enhanced by a factor of 1-3 within the RFPM frequency range of 19.5-20.9 kHz. In this case, it results in a slight reduction of source brightness and divergence of the light spot. At the same time, the beam instability can be suppressed to a certain extent. Consequently, it is necessary to consider the overall beam dynamics and performance in practical accelerator operation by means of the RFPM method. In summary, it is advisable to take advantage of this RFPM approach to control the beam dilution process and increase the beam lifetime considerably. Furthermore, the investigation and understanding of beam bunch behaviors in the longitudinal phase space have significant benefits for machine study and commissioning of the double-RF system. Moreover, it is of great significance in beam diagnostics, applications, and analysis of the physical phenomena of emittance dilution and energy spread blowup.

4 Conclusion

In summary, we have experimentally observed the evolutions of longitudinal beam bunch characteristics with modulation frequencies and amplitudes in the HLS-II storage ring. It is proven that this RFPM scheme can be used not only to effectively investigate the longitudinal beam behaviors but also to control the beam dilution to dramatically improve the beam lifetime. The optimization of the beam lifetime improvement can reach a factor $\tau_{\rm im}$ of 2.38 in the region of 19.6–20.7 kHz approaching the first harmonic of the synchrotron frequency. Moreover, preliminary experimental measurements and qualitative analysis are used to reveal the essential beam dilution mechanism and the evolutions of a single bunch length and profile subjected to phase modulation.

However, the increase in beam energy spread cannot be ignored by means of the RFPM method, so this is a process of trade-off and relative balance. Therefore, it is necessary to avoid the sharp deterioration in beam energy spread caused by the excessive modulation amplitude, which could affect the normal operation of the beamlines. In subsequent research work, we will further improve the experimental measurement system and choose appropriate RF modulation parameters to gain insight into the features of the longitudinal bunch characteristics and study the beam multiparameter variations in the HLS-II ring under the multi-bunch normal operation mode, for which improvements are under way.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Yun-Kun Zhao, Bao-Gen Sun, Ji-Gang Wang, and Fang-Fang Wu. The first draft of the manuscript was written by Yun-Kun Zhao and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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