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Improving Touschek lifetime and synchrotron frequency spread by passive harmonic cavity in the storage ring of SSRF

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Abstract Beam lifetime of a synchrotron is dominated by Touschek scattering. In the beamline Phase II project of Shanghai synchrotron radiation facility, a passive third harmonic cavity is to be installed for bunch lengthening and instability suppressing. In this paper, the beam dynamics of the cavity is investigated. The parameters of passive operation are optimized to cancel the slope of RF voltage and lengthen the bunches. The Touschek lifetime increases are estimated for optimum and non-optimum voltage flattening. A tolerance of the operation is studied in case that there is a shift on detuning angle. The effect caused by reduction in harmonic voltage generated by lengthened bunch distribution is also estimated using iteration method. An increase in synchrotron frequency spread due to nonlinearity of the voltage giving to the bunch is found by using tracking simulation. This spread can help in damping coupled bunch instability through Landau damping.

Keywords Landau damping · Passive harmonic cavity · SSRF

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1 Introduction

Shanghai synchrotron radiation facility (SSRF) has a low emittance of 3.9 nm-rad [1]. Its beam lifetime is dominated by the Touschek scattering effect caused by the momentum deviation transferred from elastic collisions of electrons in the bunch at higher bunch charge [2]. Higher harmonic cavity is an effective method to increase the beam lifetime without affecting the brightness [3–5]. It can suppress coupled bunch instabilities [6–8] and single bunch instabilities through increased synchrotron frequency spread [9]. One can operate a higher harmonic cavity in active or passive mode. An active mode needs external RF power supplies. In passive operation, a harmonic cavity voltage is induced by the beam itself, and hence, there is no need of an external RF power source, being compact and economic. The passive cavities are widely used in third-generation light sources [10–12]. Therefore, in Phase II project of SSRF, we have planned to install a passive third harmonic cavity to the storage ring. In this paper, longitudinal beam dynamics with passive cavity is reviewed including with investigation on the lifetime improvement, factor and tolerance of bunch lengthening. Due to passive operation, the fields excited in the harmonic cavity depend on the bunch distribution. The influence of lengthening bunch on the lifetime improvement is also discussed. In the last session, an increase in synchrotron frequency spread is studied using tracking codes for synchrotron motion.

2 Longitudinal beam dynamics with passive cavity

The total voltage seen by the beam can be defined by [13]

$$V(\tau) = V_{\rm rf}\sin(\varphi_s - \omega_{\rm rf}\tau) - 2I_bFR_s\cos\psi_h\cos(\psi_h - n\omega_{\rm rf}\tau), \tag{1}$$

where τ is the relative time deviation, $V_{\rm rf}$ is the main RF voltage, φ_s is the synchronous phase of the main RF cavity, $\omega_{\rm rf}$ is the angular frequency, I_b is beam current, R_s is the shunt impedance, ψ_h is detuning angle of the harmonic cavity, n is the harmonic number, and F is the bunch form factor given by

$$F = \exp[-(n\omega_{\rm rf}\sigma_\tau)^2], \tag{2}$$

where σ_τ is the RMS bunch length; according to Eq. (1), the phase of harmonic voltage and the amplitude are related to detuning angle. To optimize bunch lengthening, the following conditions should be satisfied:

$$\sin\varphi_s = \frac{n^2}{n^2-1}\frac{U_0}{V_{\rm rf}}, \tag{3}$$

$$\tan\psi h = -n\cot\varphi_s, \tag{4}$$

$$R_s = \frac{V_{\rm rf}\sin\varphi_s}{2I_bFn^2\cos^2\psi h}. \tag{5}$$

Parameters of the SSRF storage ring are given in Table 1. From Eqs. (3)–(5), passive operation parameters for optimum bunch lengthening can be calculated as $R_{\rm s} = 21.32\ \mathrm{M\Omega}$ and $\psi_{\rm h} = 96.86°$.

In passive operation, the resonant frequency of harmonic cavity should be detuned as Eq. (6):

$$\tan\psi_h = 2Q(\delta f/f_r), \tag{6}$$

where $\delta f = f_r - 3\,f_{\rm rf}$ is detuning frequency, with f_r being the resonant frequency of the cavity and $f_{\rm rf}$ being the main RF frequency, and Q is the quality factor, which is very high for a superconducting cavity. When $\delta f \approx f_r/Q$, the induced voltage can be given by [14]

$$V_h \approx I_b(R_s/Q)(f_r/\delta f), \tag{7}$$

Table 1 Parameters of the SSRF storage ring

Parameters	Value
Energy (GeV)	3.5
Circumference (m)	432
Beam current (mA)	300
RF frequency (MHz)	500
Harmonic number	720
Momentum compaction	0.00042
Energy spread	0.00098
Radiation loss (MeV)	1.44
Main RF voltage (MV)	4.8
Nominal bunch length (mm)	3.8

so that the flattened RF potential at the synchrotron phase is established and thus the bunch is lengthened. For $R_s/Q = 180\ \Omega$, $\delta f = 53.43$ kHz is needed to gain the voltage of 1.52 MV.

3 Bunch lengthening and the lifetime improvement

To investigate how much the bunch can be lengthened, the longitudinal charge density distribution of the bunch is determined from Gaussian energy distribution in the potential well. The longitudinal density distribution is given by [13]

$$\rho(z) = \rho_0\mathrm{Exp}[\Phi(z)/(a\sigma_e)^2], \tag{8}$$

where ρ_0 is a normalization constant, $\Phi(z)$ is the potential defined by line integral of the voltage in Eq. (1) [13], α is momentum compaction, and σ_e is the energy spread. The RF potential is calculated from integral of the RF voltage. Touschek loss rate is proportional to probability for scattering beyond the RF acceptance and the square of the volume charge density in the bunch. The change in volume density can be simply calculated from the longitudinal density distribution in Eq. (8). The scattering probability is inversely proportional to the square of the RF acceptance, $\delta_{\rm rf}$. Therefore, an improvement factor defined by a ratio of the lifetimes with and without harmonic voltage can be calculated by Eq. (9) [13].

$$R = \frac{\delta_{\rm hc}^2}{\delta_{\rm rf}^2}\frac{\int dz\rho_{\rm rf}^2(z)}{\int dz\rho_{\rm hc}^2(z)}, \tag{9}$$

The lifetime improvement factor in Eq. (9) depends significantly on the distribution of the particles. According to Eq. (1), particle distribution in passive operation is mainly corresponding to beam current, shunt impedance, and detuning angle. When shunt impedance and detuning angle satisfy the flat voltage condition, the potential well becomes flatten and bunch distribution becomes broader. The Touschek lifetime consequently improves by a factor of 3.77, when the shunt impedance is fixed by the beam intensity of 300 mA, as shown in Fig. 1. A change in beam current can greatly perturb the bunch lengthening since amplitude of harmonic voltage changes. Below 300 mA of beam intensity case, the lifetime improvement decreases rapidly; while over 300 mA of beam intensity, it rises until a peak valve of 4.47, where it begins to drop sharply.

In Eqs. (2)–(4), the only parameter that depends on the beam current is the shunt impedance. The easiest way to achieve the desired bunch lengthening effect with fluctuated beam intensity is to install a variable resistor on the harmonic cavity and adjust the proper shunt impedance by

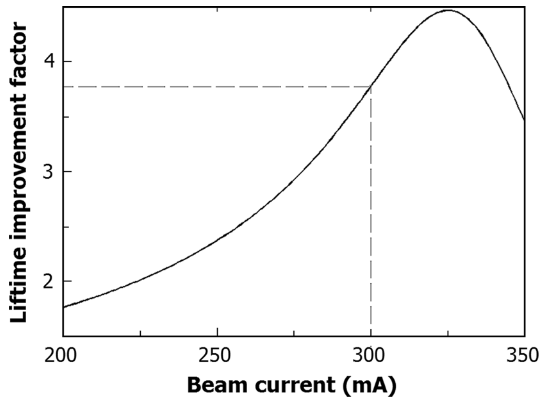

Fig. 1 Lifetime improvement factor versus beam current for the SSRF storage ring

observing the intensity of the electron bunches. When the shunt impedance is not adjustable, one can only adjust the detuning angle instead. From Eq. (1), the detuning angle is related to both amplitude and phase of harmonic RF voltage. As shown in Fig. 2a, the detuning angle shift affects the particle distribution. When the detuning angle is slightly tuned from 96.86° of the flattened potential condition, the distribution becomes broader and transforms to two bunch-lets. This condition, known as overstretch condition, can improve the Touschek lifetime until reaching the maximum factor of 4.16 at detuning angle of 97.22° as shows in Fig. 2b. When detuning angle is tuned further, there is a significant distortion on the particle distribution, leading to a drop on the improvement factor.

When the detuning angle is below the flattened potential condition, there will be much less shifting effect on distribution than that in overstretch condition. The distribution is narrower than that with flattened potential condition and even turns to be shortened when the detuning is <90°. As a result, the lifetime improvement factor decreases.

From Fig. 2b, the decrease in improvement factor is sensitivity to the detuning angle. The distortion of particle distribution caused by detuning shift can greatly disturb the lengthening effect of the harmonic cavity. From Eq. (6), it is estimated that to maintain the lifetime improvement to be more than 80% of that in flattened potential case, the detuning frequency should be 47.21–57.44 kHz.

Regarding the stable beam intensity in top-up mode operation of SSRF, small fluctuation of beam current can be handled by varying detuning frequency. Thus, this issue is far from our concern. On the other hand, the effect of lengthened bunch distribution on passive operation is the one we are interested and will be discussed in next section.

4 Investigation on lengthened bunch effects

The influence of the bunch shape on the excitation of the fields in the harmonic cavity is taken into account by the bunch form factor in Eq. (2). From previous calculation, the effect of lengthened bunch was neglected. The bunch form factor was estimated as an original short bunch even when the bunch was much lengthened. In this section, the influence of lengthened bunch distribution on the lengthening effect is investigated.

To acquire the efficient bunch distribution after the bunch was lengthened, the self-consistent method was used. We started the calculation to obtain an initial bunch distribution as we did in Sections II and III using the form factor in Eq. (2). Assuming that the distribution is in Gaussian form, the RMS bunch length could be calculated from full width half maximum of the distribution divided by the factor of 2.3548. By substituting the calculated RMS bunch length to Eq. (2), the new harmonic voltage and the new potential could be found. Then, we achieved the new longitudinal distribution. A new form factor from this longitudinal distribution was used to re-calculate the parameters again. Within 10 times of iteration, the parameters converged and saturated. The form factor and

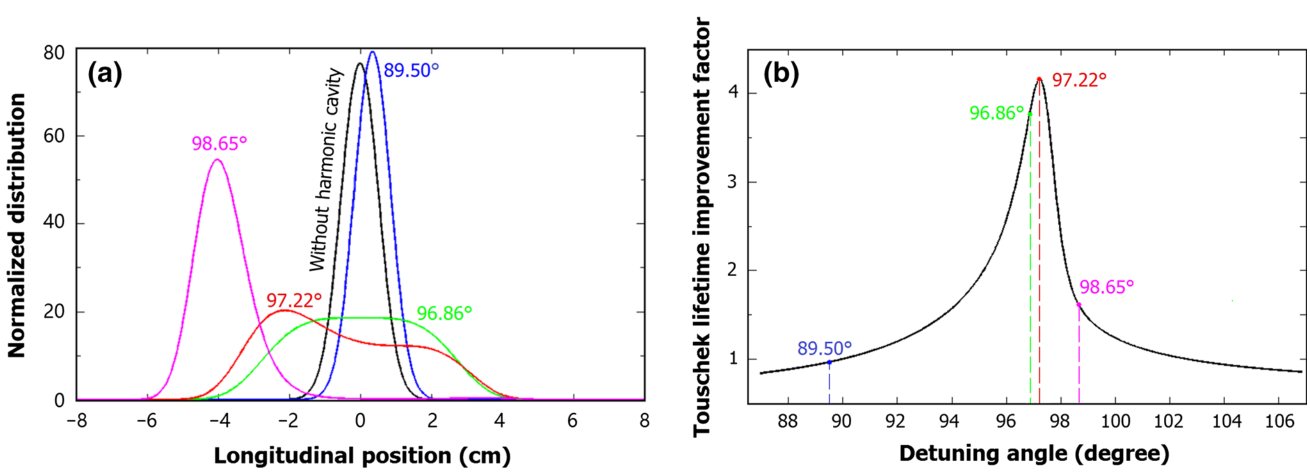

Fig. 2 (Color online) The bunch distribution (**a**) and lifetime improvement factor (**b**) at different detuning angles

Touschek lifetime improvement factor resulted from the iteration method in flattened potential case are shown in Fig. 3. The high value of form factor which is close to 1 indicates the shorter bunch, and the lower value refers to broader bunch.

Figure 4a shows the distribution of a lengthened bunch, together with the bunch distribution calculated using the original bunch in flattened potential condition. Because the harmonic voltage corresponds to the form factor related to the bunch shape, an increase in bunch length can limit the bunch lengthening effect through a decrease of voltage of harmonic RF. The peak harmonic voltage generated by lengthened bunch distribution drops to 1.41 MV, and hence, the degraded lengthening efficiency and the reduced lifetime improvement factor from 3.77 to 3.05. To reach the flattened potential distribution, the harmonic voltage amplitude of 1.74 MV is needed to compensate the reduced harmonic voltage due to the lengthened bunch.

As discussed in previous section, increasing shunt impedance is the simplest method to provide desired harmonic voltage without affecting the detuning angle. By increasing shunt impedance to 24.51 MΩ, the overstretch distribution can be obtained from original short bunch calculation. After the bunch lengthening reaches saturation, the broad distribution in flattened potential condition is shown in Fig. 4b. At a fixed shunt impedance, the harmonic voltage can be controlled only by adjusting detuning angle through resonant frequency of the cavity. With shunt impedance of 21.32 MΩ from previous flattened potential condition, the desired harmonic voltage can be reached by increasing detuning angle to 97.89°. In this case, the bunch distribution is distorted and shifted due to detuning angle deviation. Therefore, the broad distribution from flattened potential cannot be achieved in this situation.

At fixed shunt impedance, the more bunch distribution is lengthened, the more distortion of bunch distribution appears. This effect causes a limitation on the lifetime

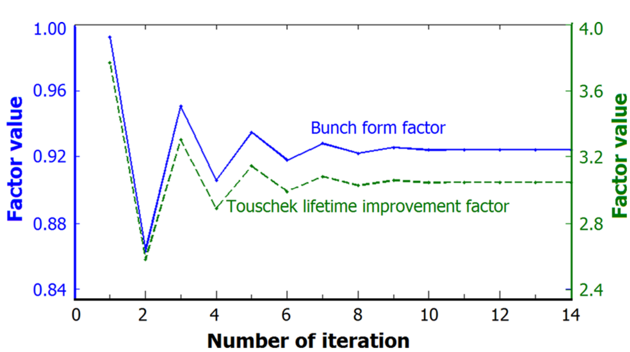

Fig. 3 (Color online) The bunch from factor and Touschek lifetime improvement factor calculated by iteration method for flattened potential case

improvement especially when it reaches high value. Figure 5 shows the Touschek lifetime improvement factors of the original and lengthened bunches. At detuning angle of 97.66°, the improvement factor from lengthened bunch iterative method is maximized at 3.81, which is still 8.5% <4.16 from the original bunch.

5 Synchrotron frequency spread investigation

A nonlinear acceleration field from third harmonic cavity gives a large spread in synchrotron frequency. To investigate an increase in synchrotron frequency spread, the distribution in the (φ, ε) phase space was generated by tracking. The bunch was considered as a macro-particle, and difference equations of longitudinal motion were developed corresponding to the voltage and the phase in the main and harmonic cavities [15]. Difference equations for the synchrotron oscillations of each bunch can be expressed as

$$\varepsilon_{i+1} = \varepsilon_i + V_{\mathrm{rf}}(\varphi_i) - U_0 - 2\frac{T_0}{\tau_\varepsilon}\varepsilon_i, \tag{10}$$

$$\varphi_{i+1} = \varphi_i + \frac{\alpha T_0}{E_0}\varepsilon_i, \tag{11}$$

where ε_i is the relative beam energy deviation for the ith turn of calculation, φ_i is the bunch phase with respect to the nominal synchronous phase, T_0 is the revolution period, and E_0 is the beam energy. Synchrotron frequency of each particle can be estimated from Fourier transform of the phase oscillation of all particles in the bunch using tracking method by neglecting radiation damping in the last term of Eq. (10). In this part, the specific effect of lengthen bunch is neglected but it can be considered as an imperfection of harmonic voltage. As shown in Fig. 6, for the SSRF storage ring, the synchrotron frequency shifts in downwards direction, and the synchrotron frequency spread increases with the harmonic voltage. The largest spread occurs at flat voltage condition. These results agree with analytical method reported earlier [16].

Since the harmonic cavity is tuned above the RF beam harmonic, Robinson instability can be excited. The growth rate has been studied concerning on this instability. For small amplitude oscillation, the synchrotron frequency is [17]

$$\frac{\omega_s(\tau)}{\omega_{s0}} = \frac{\pi}{2}\sqrt{\frac{n^2-1}{6}}\frac{\omega_{\mathrm{rf}}\tau}{K(1/\sqrt{2})}\sqrt{\frac{\cos\varphi_s}{\cos\varphi_{s0}}}, \tag{12}$$

where ω_{s0} is the synchrotron frequency at zero amplitude when there is no higher harmonic voltage and $K(2^{-1/2}) = 1.854$ is the complete elliptic integral for the first kind which is defined as

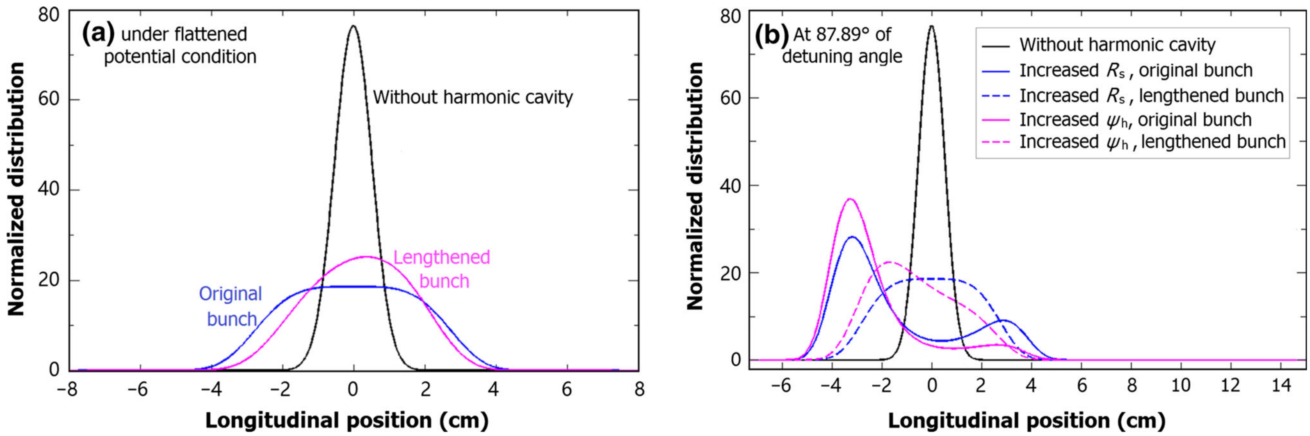

Fig. 4 (Color online) The bunch distributions under the flattened potential condition (**a**) and 87.89° detuning angle (**b**)

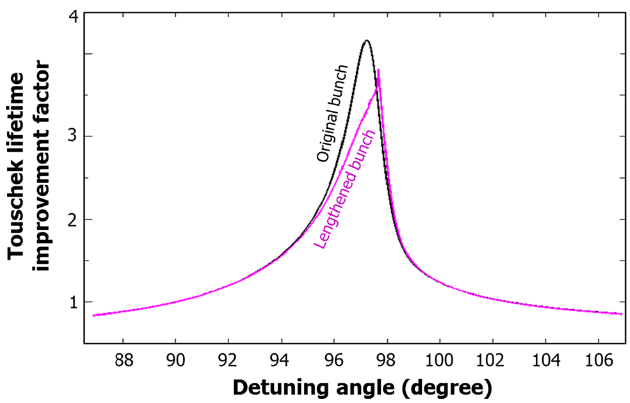

Fig. 5 (Color online) The lifetime improvement factors before and after using iteration method with lengthened bunch

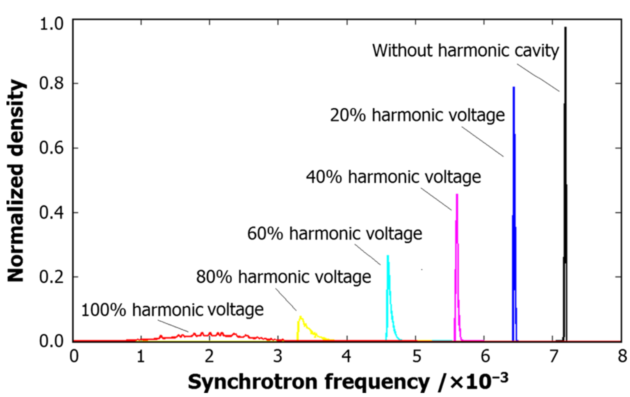

Fig. 6 (Color online) Synchrotron frequency spread for various harmonic voltages in SSRF case

$$K(t) = \int_0^{\pi/2} \frac{d\theta}{\sqrt{1 - t^2 \sin\theta}}. \tag{13}$$

RMS frequency spread can be estimated from [17]

$$\sigma_{\omega-s} = \frac{\pi\omega_{s0}}{2}\sqrt{\frac{n^2-1}{6}}\frac{\omega_{\rm rf}\sigma_\tau}{K\left(1/\sqrt{2}\right)}. \tag{14}$$

The growth rate without damping can be approximately given by [17]

$$\frac{1}{\tau} = \frac{2\eta e I_b}{E_0 T_0}\left[\frac{2\Delta}{\overline{\omega_s}} Q_{s0} R_{s0} \cos^2\psi_{\omega-s}\sin\psi_{\omega-s} \right. \\ \left. + Q_h R_h \cos^2\psi_h \sin\psi_h\right], \tag{15}$$

where the first and second terms correspond to fundamental and the third harmonic frequencies, respectively; η is the slip factor; Δ is a main RF cavity detuning frequency; Q_{s0} and R_{s0} are the quality factor and shunt impedance of main RF cavity, respectively; $\psi_{\omega\text{–}s}$ is the detuning angle of the main RF cavity; and $\bar{\omega}_s$ is the mean angular synchrotron frequency defined as [17]

$$\overline{\omega_s} = \sqrt{2/\pi}\sigma_{\omega-s}. \tag{16}$$

For SSRF storage mode, the detuning is about −2.5 to −3.8 kHz. The main RF cavity shunt impedance is 15.84 MΩ. The damping time calculated from Eq. (15) ranges 0.012–0.016 ms. It can be seen that even though the harmonic resonant frequency is tuned to the Robinson unstable side, compared to SSRF longitudinal damping time of 3.5 ms, the stability from fundamental cavity is still large enough to keep the beam stable.

From the stability criterion, the mth azimuthal mode will be stable if $1/\tau$ is close to or small than $m^{1/2}\sigma_{\omega\text{–}s}/2$ [17, 18]. From Eq. (14), the synchrotron frequency spread in flat voltage condition is about 1.40 kHz for SSRF which is able to damp an instability in the dipole azimuthal mode with the growth time, τ, longer than 1.4 ms.

6 Conclusion

Bunch lengthening induced by a third harmonic RF cavity is studied in order to increase beam lifetime of the SSRF storage ring. The detuning angle is simulated numerically to optimize the bunch lengthening. The broad potential and distribution occurred in flattened potential case lead to an increase in Touschek lifetime with the improvement factor of about 3.77. In passive operation, the beam current is an important parameter for passive operation. The change in beam current can alter the bunch lengthening effect. The shunt impedance can be adjusted to compensate the change in beam current without affecting the phase of harmonic RF, but the detuning angle becomes alternative choice for invariable shunt impedance case. The effect of detuning angle variation is investigated. The highest improvement factor reaches 4.16 when the detuning angle is tuned slightly above flattened potential condition. However, the improvement factor rapidly drops when detuning angle is tuned further. The limitation of the detuning angle and detuning frequency variation are estimated.

Because the harmonic voltage is generated by the beam current corresponding to the bunch shape through the form factor, an increase in the bunch length can cause a decrease in improvement factor. The detuning angle can be adjusted to achieve the highest improvement factor, but it cannot give flattened potential distribution due to the distortion caused by detuning angle deviation.

An effect on synchrotron frequency spread induced by third harmonic cavity in the SSRF storage ring is investigated, showing the shift and an increase in synchrotron frequency spread. This spread can help in damping longitudinal coupled bunch instability and increases stability of the beam. The instability of the beam due to Robinson unstable of the harmonic cavity is investigated, too. Although the higher harmonic cavity resonant frequency is tuned to be above the third harmonic frequency, the beam is still stable.

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