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Tracking simulations for the HLS-Ⅱ with a passive harmonic cavity in the symmetric and asymmetric fill patterns*

FAN Hao(樊浩) WU Cong-Feng(吴丛凤)1) WANG Lin(王琳)

National Synchrotron Radiation Laboratory (NSRL), University of Science and Technology of China, Hefei 230029, China

Abstract: A simulation code that executes the tracking of longitudinal oscillations of the bunches for the double rf system of the Hefei Light Source Ⅱ Project (HLS-Ⅱ) is presented to estimate the mean beam lifetime and the Robinson instabilities. The tracking results show that the mean beam lifetime is in agreement with the analytical results and the system is stable when we tune the harmonic cavity in the optimum lengthening conditions. Moreover, the simulated results of the asymmetric fill pattern show that some bunches are compressed only with a 7% gap (3 gaps), which will lead to the reduction in the mean bunch lengthening and potential beam lifetime. It is demonstrated that HLS-Ⅱ with a passive higher harmonic cavity is not suitable for operating in an asymmetric fill pattern.

Key words: tracking code, fill pattern, Robinson instabilities, harmonic cavity

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1 Introduction

Because a higher harmonic cavity can improve beam lifetime without affecting the energy acceptance and has the potential of the Landau damping of coherent instabilities, it has been successfully installed and operated in several light source facilities. The analytical study of applying a passive harmonic cavity to improve the beam lifetime has been performed for the HLS-Ⅱ [1]. However, the analytical model only works in the case of a symmetric storage ring fill pattern and does not account for the transient effects of the double rf system. Moreover, the harmonic cavity must be tuned to the Robinson unstable side of the rf harmonic to achieve bunch lengthening and may be used to vary the synchrotron oscillation frequency, possibly exciting the ac and dc Robinson instabilities [2]. A multibunch single particle tracking code has therefore been developed at NSRL, which computes the longitudinal beam motion by taking into account the synchrotron radiation, the beam loading of the harmonic cavity, and the Robinson instability, simultaneously.

In this paper, the voltage in a passive harmonic cavity and difference equations for the synchrotron motion are respectively reviewed for a tracking code to investigate the effects of a passive HHC on beam lifetime improvement factor and Robinson instabilities for HLS-Ⅱ. Especially, we explore the status of the HLS-Ⅱ with a passive harmonic cavity operating in the asymmetric fill pattern.

2 Multibunch single particle model for tracking code

2.1 The voltage in a passive harmonic cavity

The wake field of the bunch is the only source of the voltage in a passive harmonic cavity. The tracking code models each bunch as a single macroparticle of charge q. We assume that the cavity-beam energy exchange occurs at a single point in the ring [3]. When a charge q crosses the cavity, the induced voltage ν_m of each mode depends on the angular frequency ω_m,

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1) E-mail: cfwu@ustc.edu.cn

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the shunt impedance R_{sm} and the quality factor Q_m of that mode is given by

$$\nu_m = -2k_m q, \tag{1}$$

where $k_m = \dfrac{\omega_m R_m}{2Q_m}$ is the loss factor and m labels the cavity mode number. In order to take into account the bunch length, assuming a Gaussian distribution, the induced voltage is corrected by a factor F [4].

$$\Phi(z) = -2k_m qF, \tag{2}$$

where the factor $F = \mathrm{e}^{[-(\omega_m\sigma)^2]}$, σ is the RMS bunch duration. In the storage ring, particle bunches pass periodically through the cavity and we have to consider the cumulative build up of induced fields. If the only fundamental (m=0) mode is considered in this paper, the turn-by-turn harmonic voltage induced by the bunch is found from the iterative equation.

$$\nu_{i+1} = \nu_i \mathrm{e}^{\left[\left(\mathrm{j}\omega_0 - \frac{1}{\tau_0}\right)\Delta t\right]} - 2k_0 q_{i+1} F, \tag{3}$$

where $\tau_0 = \dfrac{2Q_0}{\omega_0}$ is the cavity filling time, i labels the macroparticles (bunches) number and Δt is the difference in arrival time of the current (t) and previous ($t-1$) turn for the bunch i (t labels the turn number).

$$\Delta t = \frac{\phi_{i,t} - \phi_{i,t-1}}{\omega_0} + T_{\mathrm{b}}, \tag{4}$$

where ϕ is the bunch phase with respect to the nominal synchronous phase and T_{b} is the number of buckets between the bunches multiplied by the rf period [2]. Based on the fundamental theorem of beam loading, half of this voltage acts back on the bunch itself [5]. The effective harmonic voltage can be written as

$$V_{i,t} = \nu_{i,t} - (-k_0 q_i F). \tag{5}$$

2.2 The difference equations of the synchrotron motion

The purpose of this paper is mainly to investigate the effects of a passive harmonic cavity on a bunch train, and further explore the Robinson instabilities of the double rf system and the status of the asymmetric fill pattern. So, we assume that the beam loading in the main rf cavity is well compensated to maintain a constant voltage by adjusting the tuning angle and the generator voltage. The difference equations of the longitudinal motion can be expressed as [2]

$$\begin{aligned} \varepsilon_{i+1,t} &= (1-2\lambda_{\mathrm{rad}})\varepsilon_{i,t} + \frac{1}{E_0}[eV_{\mathrm{rf}}\sin(\phi_{i,t}+\phi_{\mathrm{s0}}) \\ &\quad + eV_{i,t} - U_0], \end{aligned} \tag{6}$$

$$\phi_{i+1,t} = \phi_{i,t} + 2\pi\alpha h\varepsilon_{i,t}, \tag{7}$$

where ε is the relative beam energy deviation, λ_{rad} is the radiation damping rate, ϕ_{s0} is the nominal synchronous phase and U_0 is the radiation loss per turn.

3 The simulation results in the symmetric fill pattern

Based on the difference equations of the synchrotron motion with a passive harmonic cavity, we can track the bunch motions of an arbitrary number of turns by virtue of our tracking code. In this part, the simulation results of the symmetric fill pattern (no bunch gap in the filling) are presented and compared with the calculated results by the analytical study [2]. The parameters used in our tracking code for the HLS-Ⅱ are shown in Table 1.

For a passive harmonic cavity, the voltage of the harmonic cavity is induced by the beam itself and also has an influence on the synchrotron phase. If the double rf system is stable, the harmonic voltage

Table 1. The nominal HLS-Ⅱ parameters.

V_{rf}	main rf voltage	250 kV
ϕ_{s0}	nominal synchrotron phase	3.0746 rad
f_{rf}	rf frequency	204 Mhz
I_{dc}	dc beam current	300 mA
h	harmonic number	45
U_0	energy lost per turn	16.73 keV
E_0	nominal energy	800 MeV
C	circumference	66.1308 m
α	momentum compaction	−0.02
σ_ε	energy spread	0.00047
n	harmonic	4
Q	quality factor	20000, 18000
λ_{rad}	radiation damping rate	4.172e-5

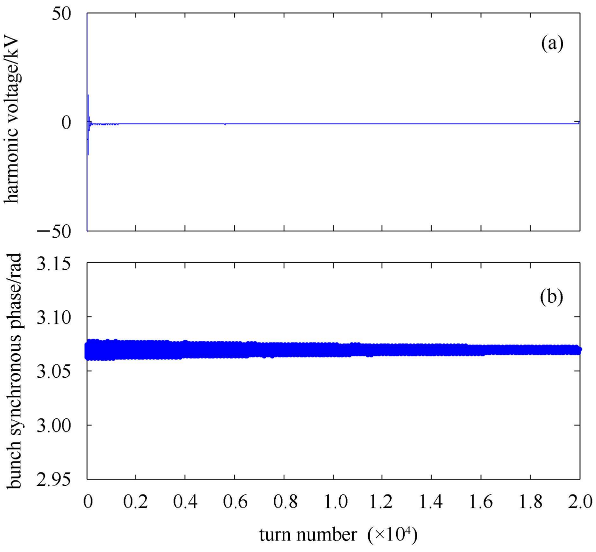

Fig. 1. The turn-by-turn harmonic voltages and the turn-by-turn bunch phases.

and the synchrotron phase will reach the steady-state value at each bunch of the bunch train. The convergence of the turn-by-turn harmonic voltages and the turn-by-turn bunch phases are displayed in Fig. 1. Fig. 2(a) and (b) shows that the harmonic voltage and the bunch synchronous phase nearly respectively converge to a single steady value for all 45 bunches in the symmetric fill pattern.

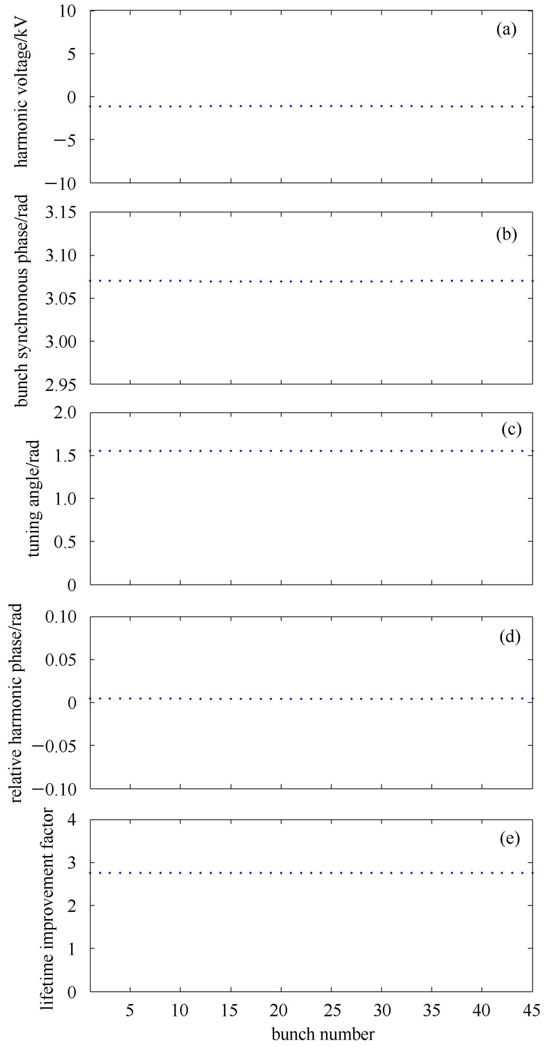

Fig. 2. Steady-state distributions of the harmonic voltage (a), the bunch synchronous phase (b), the harmonic cavity tuning angle (c), the relative harmonic phase (d) and the lifetime improvement factor (e) along the bunch train.

The tuning angle can be varied by moving the tuner in or out to adjust the harmonic voltage met by the bunch and is generally given by [6]

$$\tan\psi_{\rm h} = 2Q\left(\frac{\omega_r - nW_r}{\omega_r}\right). \tag{8}$$

In our tracking code, the harmonic cavity tuning angle at each bunch is the phase of the vector ν_i, as shown in Fig. 2(c). Fig. 2(d) shows the steady-state values of the relative harmonic phase angle $\phi_{\rm h}$ along the bunch train. $\phi_{\rm h}$ is related to the tuning angle $\psi_{\rm h}$ by

$$\phi_{\rm h} = -\frac{1}{n}\left(\psi_{\rm h} - \frac{\pi}{2}\right). \tag{9}$$

According to these simulated quantities, the calculated lifetime improvement factor along the bunch train is shown in Fig. 2(e).

Figure 2 indicates that the steady-state values of the harmonic voltage, the bunch synchronous phase, the tuning angle, the relative harmonic phase, and the lifetime improvement factor barely vary along the bunch train. The arithmetic mean values of these quantities for all bunches are listed in Table 2 and are almost equal to the data given by the analytical study, which proves that the tracking code model is reliable.

Table 2. The tracking code and analytical study results.

	tracking code(a.m.)	analytical study
harmonic voltage/kV	−1.1155	1.1153
bunch synchronous phase/rad	3.0701	3.0702
tuning angle/rad	1.5529	1.5529
relative harmonic phase/rad	0.3972	0.3972
lifetime improvement factor	2.7605	2.7521

4 Ac and dc Robinson instabilities

The harmonic cavity must be tuned to the Robinson unstable side of the rf harmonic to achieve bunch lengthening and may be used to vary the synchrotron oscillation frequency, possibly exciting the ac and the dc Robinson instabilities. The ac and the dc Robinson instabilities in the presence of a harmonic cavity have been discussed elsewhere [2, 7]. There are two examples of ac and dc Robinson instabilities for the HLS-Ⅱ in the symmetric fill pattern.

The ac Robinson instability occurs when the damping rate of the Robinson mode becomes negative, corresponding to growth. This type of instability displays exponential growth of an oscillation at a finite frequency. With a passive harmonic cavity, the ac Robinson instability can be excited when the growth contribution from the harmonic cavity exceeds the damping contribution from the fundamental rf cavity. Shown in Fig. 3(a) is an example of an ac Robinson instability with the passive harmonic cavity tuned to 819.989 MHz.

The dc Robinson instability occurs when the Robinson oscillation frequency approaches zero. It is also called the equilibrium phase instability because the restoring force for low-frequency oscillations disappears. It is always a fast instability rather than a growing oscillation. Shown in Fig. 3(b) is an example of a dc Robinson instability with the passive harmonic cavity tuned to 816.045 MHz.

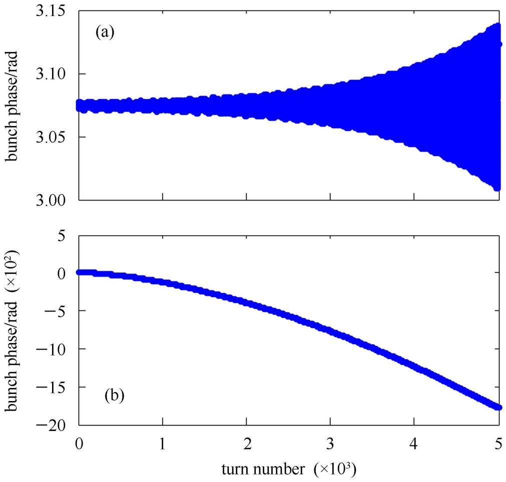

Fig. 3. Simulation results of the ac (a) and the dc (b) Robinson instabilities.

The harmonic cavity of HLS-Ⅱ is operated in the optimum lengthening conditions [1] for each bunch to improve the mean beam lifetime optimally. Fortunately, the tracking result shows that the system is stable. As shown in Fig. 2(b), the bunch synchronous phases converge to a steady value for all bunches.

Tuning in a passive harmonic cavity can aggravate or suppress the Robinson instability. It is significant that there is a sufficient tuning range to lengthen the bunch over the beam current, which will be addressed in the future.

5 The simulation results in the asymmetric fill pattern

The asymmetric fill pattern is necessary for one class of synchrotron light experiment [2]. Moreover, the gap in the bunch train has been presented to suppress the electron cloud instability [8]. In this section, we track the synchrotron motions of bunches in the asymmetric fill pattern for HLS-Ⅱ with a passive harmonic cavity.

Assuming the HLS-Ⅱ operating with a 7% gap (3 gaps) in the fill pattern, Fig. 4 indicates that there are large variations in the harmonic voltage and the bunch synchronous phase. The harmonic voltage and the synchrotron phase will converge the different steady-state values along the bunch train as shown in Fig. 5(a) and (b). Fig. 5(c) and (d) show the steady-

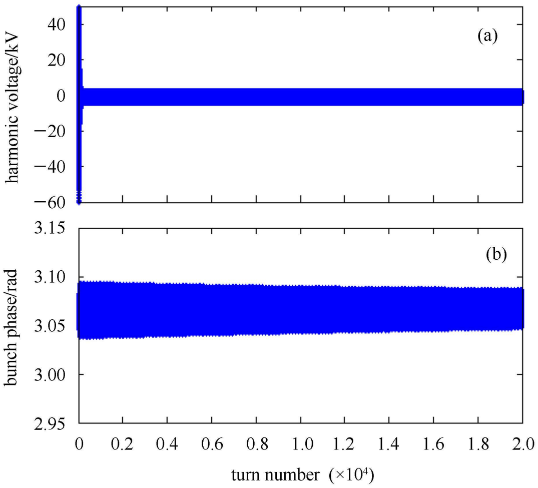

Fig. 4. The turn-by-turn harmonic voltages and the turn-by-turn bunch phases (7% gaps).

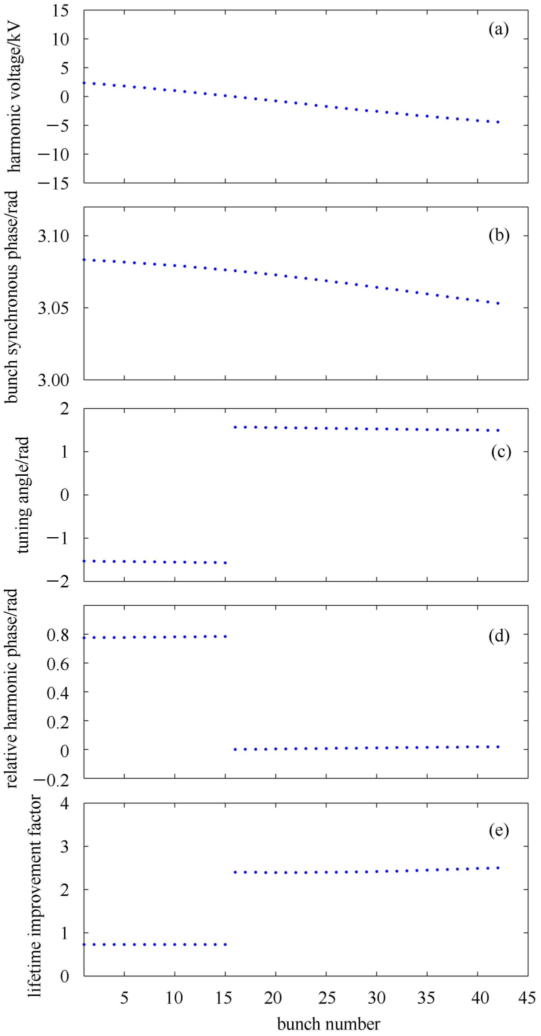

Fig. 5. Steady-state distributions of the harmonic voltage (a), the bunch synchronous phase (b), the harmonic cavity tuning angle (c), the relative harmonic phase (d) and the lifetime improvement factor (e) along the bunch train (7% gaps).

state distributions of the relative harmonic phase and harmonic tuning angle along the bunch train. These tracking results vary significantly along the bunch train, which results in a variation in the bunch lifetime along the train. The harmonic voltages met by the bunches at the head of the bunch train become positive, as shown in Fig. 5(a), which leads to shorter bunches. As shown in Fig. 5(e), the lifetime of these bunches at the head of the bunch train is not improved, but also is reduced.

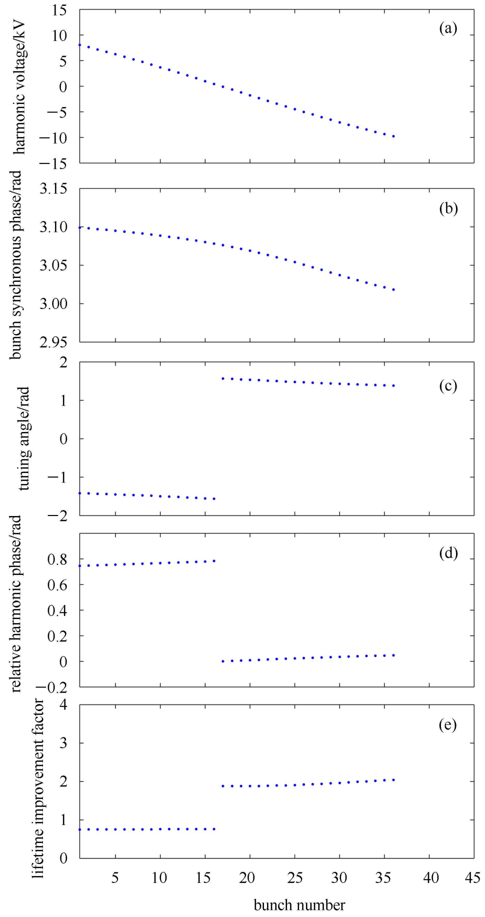

Fig. 6. Steady-state distributions of the harmonic voltage (a), the bunch synchronous phase (b), the harmonic cavity tuning angle (c), the relative harmonic phase (d) and the lifetime improvement factor (e) along the bunch train (20% gaps).

Figure 6 shows the results for the same parameters of HLS-Ⅱ but with a 20% gap in the fill pattern. Larger gaps will cause more bunches to be compressed and larger variations of the bunch synchronous phase, the harmonic cavity tuning angle and the relative harmonic phase, which result in a lower beam lifetime.

Because improving the beam lifetime is the primary goal of the harmonic system, based on the parameters of HLS-Ⅱ, the passive harmonic cavity is not suitable for operating in the asymmetric fill pattern. If all of the bunches are required to lengthen in order to maintain a higher beam lifetime, some measures (such as the feedback systems) must be taken or an active harmonic cavity used.

6 Conclusion

In this paper, we present a tracking code to firstly estimate the beam lifetime and the Robinson instabilities of the HLS-Ⅱ with a passive harmonic cavity. The results show that the harmonic voltage, the bunch synchronous phase, the harmonic tuning angle, the relative harmonic phase and lifetime improvement factor nearly respectively converge to a single steady value for all 45 bunches in the symmetric fill pattern. The tracking code and the analytical study results almost are in agreement, which proves that the tracking code model is reliable. Tuning in a passive harmonic cavity can aggravate or suppress the Robinson instability. The harmonic system is stable with the harmonic cavity operating in the optimum lengthening conditions.

The simulation results of the asymmetric fill pattern show that larger gaps will result in lowering the mean beam lifetime and some bunches are compressed only with a 7% gap (3 gaps). The asymmetric filling is not suitable for the HLS-Ⅱ unless some measures are taken or an active harmonic cavity is used.

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