Calculations of operating schemes for a passive harmonic cavity in HLS-Ⅱ *

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Abstract: A passive higher harmonic cavity (HHC) will be used in the Hefei Light Source II Project (HLS-Ⅱ) to lengthen the bunch and consequently increase the beam lifetime dominated by Touschek scattering. The effects of constant voltage and constant detuning have been calculated and compared over the operating current from 0.4 to 0.2 A on the bunch lengthening for the passive normal conducting harmonic cavity system in HLS-Ⅱ. The results show that the bunch shape has less change and the lifetime improvement factors are not less than 2.7 over the beam currents for the constant voltage case. The constant voltage operating scheme may be applied to our machine.

Key words: harmonic cavity, lifetime improvement, bunch length, operating scheme

PACS: 29.27.Bd **DOI:** 10.1088/1674-1137/36/9/018

1 Introduction

The beam lifetime dominated by Touschek scattering is one of the most important aspects of a synchrotron radiation light source. Lengthening the bunch is considered to be an effective method to reduce the longitudinal charge density and consequently increase the lifetime. The bunch length can be increased by varying the main RF voltage. However, a reduction in the RF voltage implies a reduction in the RF acceptance [1]. A particularly attractive option for stretching the bunch is to use a passive HHC. A harmonic cavity RF system is widely used because it improves the beam lifetime without affecting the energy acceptance and it has the potential of Landau damping of coherent instabilities such as longitudinal coupled-bunch instabilities [2, 3]. For a passive HHC, the harmonic voltage is induced by the beam itself and thus the external RF resource is not required.

In this paper, the longitudinal beam dynamics and conditions for optimum bunch lengthening in the presence of a passive HHC are reviewed. The synchronous phase and the HHC tuning angle to reach optimum flattening are presented as crucial parameters for the machine. The Touschek lifetime improvement factor and optimum bunch length are calculated in the next section. It is particularly critical to choose a suitable operating scheme for a double RF system. We explore the effects of an adjusted HHC in the constant voltage scheme and the constant detuning scheme on the bunch lengthening in HLS-Ⅱ. The discussion and conclusion are presented in the last section.

2 Longitudinal beam dynamics with passive HHC

We start with a brief review of the longitudinal beam dynamics in the presence of a passive HHC to gain an insight into the double RF system. For the passive HHC, the total RF voltage seen by the beam in the storage ring is defined by [4]

$$V(z) = V_{\rm RF}\sin\left(\frac{\omega_{\rm RF}}{c}z+\phi_{\rm s}\right) -2I_{\rm DC}FR_{\rm s}\cos(\psi_{\rm h})\cos\left(\frac{\omega_{\rm RF}}{c}z-\psi_{\rm h}\right), \quad (1)$$

where F, $R_{\rm s}$ and $\psi_{\rm h}$ are the form factor, shunt impedance and tuning angle of the HHC respectively,

Received 16 December 2011

* Supported by National Natural Science Foundation of China (10675116) and Major State Basic Research Development Programme of China (2011CB808301)

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and ϕ_s is the synchronous phase of the RF cavity. The RF potential formed by the total voltages is given by

$$\Phi(z)=\frac{\alpha}{E_0T_0c}\int_0^z[eVz-U_0]\mathrm{d}z'. \tag{2}$$

According to the conditions [5], the minimum shunt impedance to obtain the optimum bunch length is given by

$$R_s=\frac{1}{2I_{DC}F}\frac{(n^2-1)(eV_{RF})^2-(nU_0)^2}{n^2eU_0}. \tag{3}$$

Then the synchronous phase and the HHC tuning angle at these conditions are given by

$$\phi_s = \arcsin\left(\frac{n^2}{n^2-1}\frac{U_0}{eV_{RF}}\right), \tag{4}$$

$$\psi_h = \arccos\left(\sqrt{\frac{U_0}{2I_{DC}FR_s(n^2-1)}}\right). \tag{5}$$

According to the above equation, the voltage of a passive HHC is a function of the beam current and tuning angle. The phase of the passive HHC is also related to the tuning angle. Thus the optimum lengthening conditions will be obtained at only a single beam current by adjusting the tuners, thus changing the tuning angel [4].

The parameters of HLS-Ⅱ are shown in Table 1. When our machine is operated in a typical current of 300 mA, the synchronous phase and the HHC tuning angle at optimum lengthening conditions are separately 3.0702 rad and 1.5529 rad. The RF potentials of the main RF system and double RF system are shown in Fig. 1. The potential is flattened in the phase-stable area by HHC.

Table 1. The nominal parameters of HLS-Ⅱ.

V_{RF}	main RF voltage/kV	250
V_{hRF}	main RF voltage/kV	62.35
ϕ_s	synchrotron phase (single RF system)/rad	3.0746
f_{RF}	RF frequency/MHz	204
I_{DC}	DC beam current/mA	300
U_0	energy lost per turn/keV	16.73
E_0	nominal energy/MeV	800
C	circumference/m	66.1308
α	momentum compaction	−0.02
σ_ε	energy spread	0.00047
σ_ι	nominal rms bunch length/mm	15
n	harmonic	4
Q	quality factor	20000, 18000

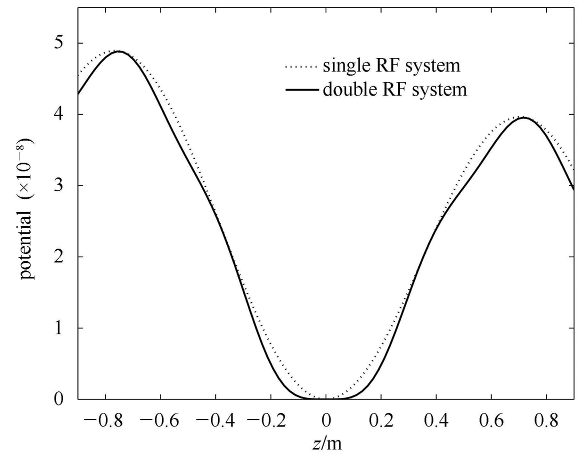

Fig. 1. Potentials of the main and double RF system.

3 Bunch length and Touschek beam lifetime improvement factor

The longitudinal density distribution of the bunch is determined from the energy distribution in the potential well formed by the total RF voltage. Near the bunch center, the restoring force of the RF voltage is approximately linear. Given a Gaussian energy spread, the resulting longitudinal distribution is also Gaussian. The density distribution is given by [4]

$$\rho(z)=\rho_0\mathrm{e}^{-\frac{\Phi(z)}{\alpha^2\alpha_z^2}}. \tag{6}$$

Figure 2 presents the calculated bunch density distributions for the main RF system and the double RF system respectively. The peak charge density of the bunch is greatly reduced and the bunch length is increased qualitatively by the HHC. The stretched bunch length is given by [6]

$$\sigma_\iota=\sqrt{\frac{\int\rho_0\exp\left(-\frac{\Phi(z)}{\alpha^2\sigma_\varepsilon^2}\right)z^2\mathrm{d}z}{\int\rho_0\exp\left(-\frac{\Phi(z)}{\alpha^2\sigma_\varepsilon^2}\right)\mathrm{d}z}}. \tag{7}$$

The ratio of the double RF system and the main RF system lifetime is defined as the Touschek lifetime improvement factor given by [7]

$$R=\frac{\Phi_{hmax}}{\Phi_{max}}\frac{\int\rho^2(z)\mathrm{d}z}{\int\rho_{hc}^2(z)\mathrm{d}z}, \tag{8}$$

where Φ_{hmax} and Φ_{max} are respectively the maximum potentials in the phase-stable area with and without harmonic voltage shown in Fig. 1.

Applying the HLS-Ⅱ parameters shown in Table 1 to the above equations, the bunch length is obtained at about 39 mm and the Touschek beam lifetime

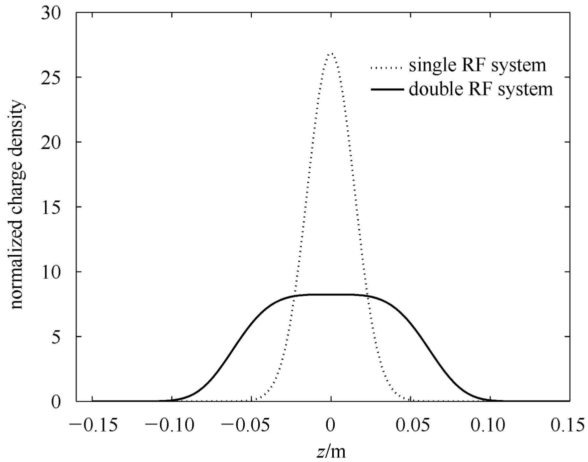

Fig. 2. The normalized charge density of the main and double RF system.

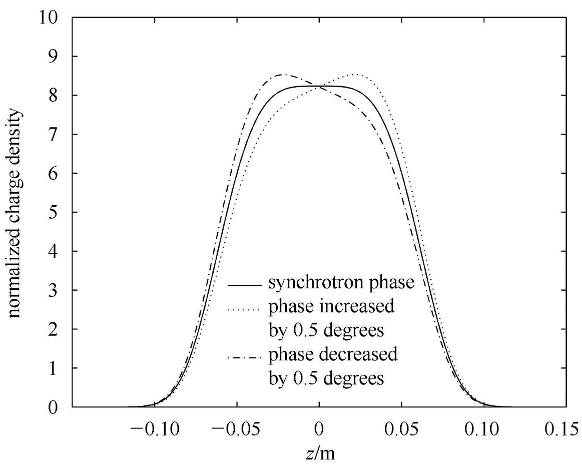

Fig. 3. The bunch shapes with phase shift.

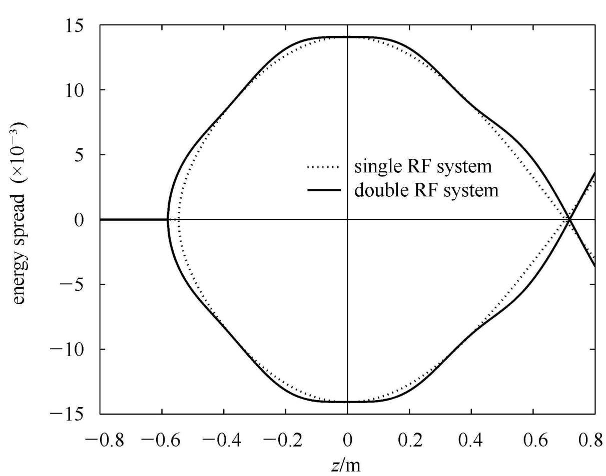

Fig. 4. RF buckets of the main and double RF system.

improvement factor is approximately equal to 2.75.

Figure 3 illustrates that the bunch shape is sensitive to the phase shift especially near the optimum conditions. Fig. 4 shows the separatrices in longitudinal phase space. Relative to the single RF system, the RF acceptance of the double RF system is changed slightly. Both acceptances are large enough for their scenarios.

4 Operating schemes

For a double RF system, it is particularly critical to choose a suitable operating scheme. According to the parameters of HLS-Ⅱ listed in Table 1, two operating schemes are analyzed respectively and compared with each other.

The first scheme is to keep a constant detuning. The tuning plunger of HHC is fixed to produce a fixed amount of detuning. Fig. 5 is a contour plot of the lifetime improvement factor as a function of HHC detuning and beam current, which are the two main factors affecting the beam lifetime improvement factor. The blue line shown in Fig. 6 is a plot of the lifetime improvement factor as a function of beam current for a fixed detuning of 1268.9 kHz. It shows that the maximum factor can be achieved in one beam current for a fixed amount of detuning. The second scheme is to detune the HHC to keep a constant cell voltage over the beam current. Fig. 7 shows a contour of the lifetime improvement factor as a function of the HHC voltage and beam current. The green line shown in Fig. 6 is a plot of the lifetime improvement factor for a fixed voltage of 62.35 kV. It is noted that the fixed detuning of 1268.9 kHz and the fixed voltage of 62.35 kV used here are from the optimum conditions [5] at the typical beam current of 300 mA for HLS-Ⅱ.

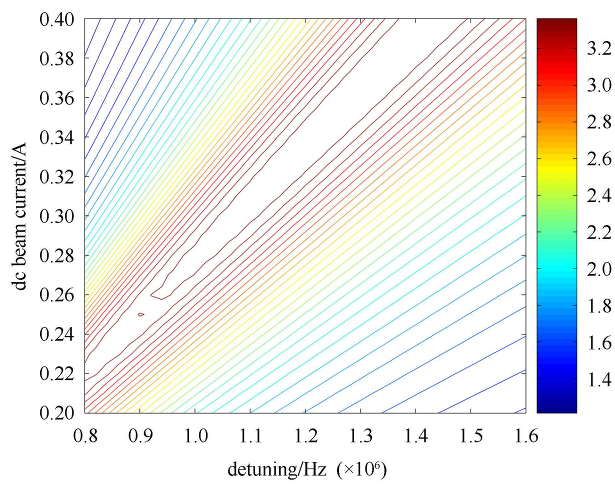

Fig. 5. Contour plot of the lifetime improvement as a function of beam current and detuning.

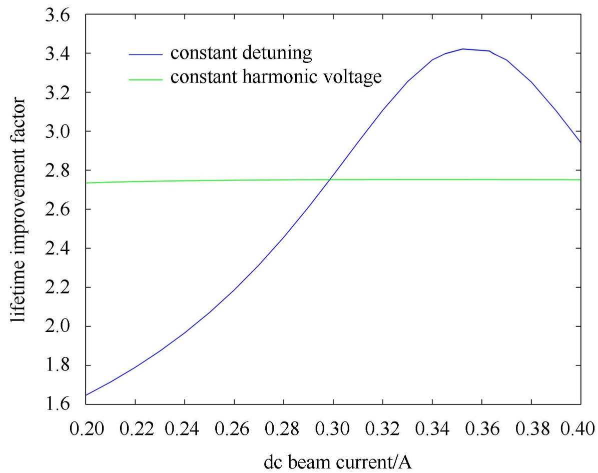

Fig. 6. Plots of the lifetime improvement as a function of beam current for constant detuning (blue line) and constant voltage (green line) schemes.

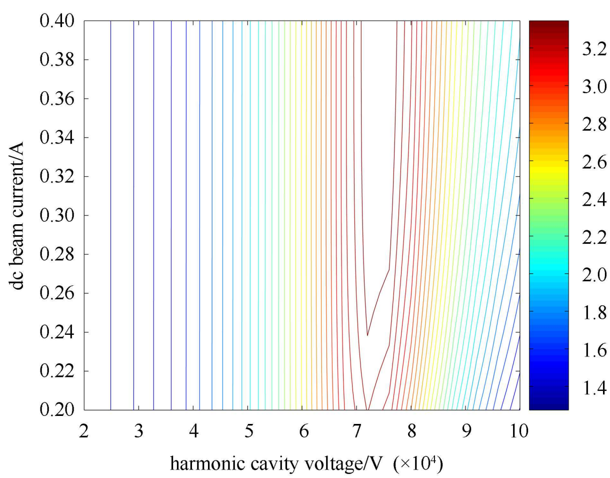

Fig. 7. Contour plot of the lifetime improvement as a function of beam current and voltage.

For the operating scheme of constant detuning, because the tuning plunger of HHC is fixed, it simplifies the operation of HHC, avoids using the RF feedback systems and consequently reduces the cost. However, the bunch can't be lengthened effectively when the beam current is too low or too high. As indicated in Fig. 6, the lifetime improvement factors over the operating currents reveals the trend of big fluctuations. The factor reaches a maximum at a current of 0.35 mA. For the constant voltage scheme, the lifetime improvement factor remains stable over the beam current. Fig. 8 and Fig. 9 show the evolution of the bunch density distribution over the beam current for the double RF system. For the case of constant detuning, the bunch phase has less change. The bunch is stretched as the beam current increases from 0.2 to 0.3 A. The bunch forms two bunchlets within the RF bucket with a further increase in beam current, which is the overstretched condition. For the case of constant voltage, the bunch phase slips forward and behind the synchronous phase below and above the current where the maximum bunch length occurs. Fortunately, the phase slip occurs slowly and the bunch shape has less change. In addition, the detuning as a similar linear function of the operating beam current is shown in Fig. 10.

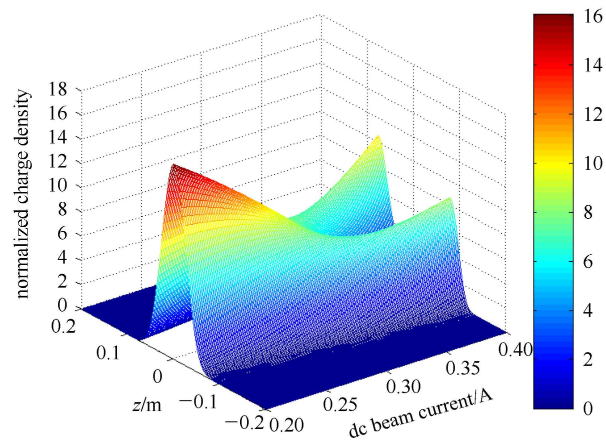

Fig. 8. Evolution of the bunch density distribution over beam current for the case of a fixed detuning of 1.2689 MHz.

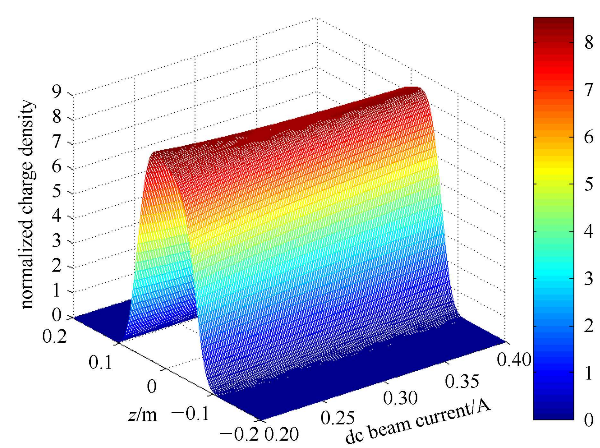

Fig. 9. Evolution of the bunch density distribution over beam current for the case of a fixed voltage of 62.35 kV.

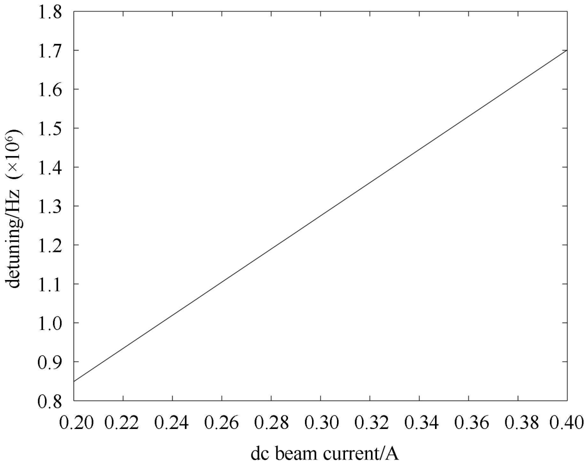

Fig. 10. Detuning over the beam current for maintaining a fixed voltage of 62.35 kV.

5 Discussion and conclusion

When the passive harmonic cavity is operated closer to the maximum bunch lengthening, the bunch synchronous phase and the bunch shape are sensitive to the beam current. Therefore, the passive HHC is operated under understretched conditions and the limitation for the minimum shunt impedance may be reduced. The results indicate that the optimum bunch length is close to 39 mm and the maximum Touschek beam lifetime improvement factor is approximately equal to 2.75.

The constant detuning scheme simplifies the operation of HHC, avoids using the RF feedback systems and consequently reduces the cost. One of the potential disadvantages of this scheme is that the bunch would be overstretched when the machine operates in a higher beam current. For the constant voltage case, the tuner system is required to maintain a fixed harmonic voltage over the range of the operating currents from 0.4 to 0.2 A. The bunch shape has less change and the lifetime improvement factor can keep a relatively large value(>2.70) over the operating currents. Therefore, the constant voltage operating scheme may be applied to our machine.

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