Analytic modeling of instabilities driven by higher-order modes in the HLS Ⅱ RF system with a higher-harmonic cavity *

ZHAO Yu-Ning(赵宇宁) LI Wei-Min(李为民) WU Cong-Feng(吴丛凤)[1)] WANG Lin(王琳)

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

Abstract: The utility of a passive fourth-harmonic cavity plays a key role in suppressing longitudinal beam instabilities in the electron storage ring and lengthens the bunch by a factor of 2.6 for the phase Ⅱ project of the Hefei Light Source (HLS Ⅱ). Meanwhile, instabilities driven by higher-order modes (HOM) may limit the performance of the higher-harmonic cavity. In this paper, the parasitic coupled-bunch instability, which is driven by narrow band parasitic modes, and the microwave instability, which is driven by broadband HOM, are both modeled analytically. The analytic modeling results are in good agreement with those of our previous simulation study and indicate that the passive fourth-harmonic cavity suppresses parasitic coupled-bunch instabilities and microwave instability. The modeling suggests that a fourth-harmonic cavity may be successfully used at the HLS Ⅱ.

Key words: parasitic coupled-bunch instability, microwave instability, higher-harmonic cavity, analytic modeling, higher-order mode

PACS: 29.20.D-, 29.27.Bd **DOI:** 10.1088/1674-1137/37/8/087005

1 Introduction

In the phase Ⅱ project of the Hefei Light Source, one passive fourth-harmonic cavity will be added to the storage ring. It can help increase the beam lifetime dominated by large-angle intrabeam (Touschek) scattering without diminishing the transverse beam brightness.

We have already studied some side effects induced by the application of this 816 MHz passive fourth-harmonic cavity such as Robinson instabilities and some other unstable behavior. Analytic modeling and simulations have been used in our research. The two methods complement each other from different perspectives in which the analytic model describes the mechanism of instability, while the energy spread in simulations shows the severity. Both indicate that tuning in the harmonic cavity strongly suppresses longitudinal beam instabilities and extends the Touschek lifetime.

In this paper, we consider the effect of higher-order modes upon the longitudinal beam instability by analytic modelings. Parasitic coupled-bunch instabilities and the microwave instability are included in our research. The parasitic coupled-bunch instability is driven by narrow-band parasitic modes and the microwave instability is driven by broadband higher-order modes (HOM). In the modeling of the parasitic coupled-bunch instability, we run the algorithm with a typical parasitic mode where the HOM resonant angular frequency equals 1000 MHz. For the microwave instability, broadband impedances with the range from 0.125 Ω to 32 Ω are modeled and analytic predictions of microwave instability are given by the Boussard criterion. Compared to our previous studies, the analytic modeling results agree well with the simulations. Both parasitic coupled-bunch instabilities and the microwave instability are suppressed by the use of the higher-harmonic cavity. When the higher-harmonic cavity is tuned for optimal bunch lengthening, the parasitic coupled-bunch instability is strongly suppressed. Microwave instability may occur and become more severe with the increase of the broadband impedance and we figure out the broadband impedance range in which the microwave instability is not expected.

2 Parasitic coupled-bunch instability modeling

The parasitic coupled-bunch instability and the microwave instability can be driven by a higher-order mode. When $Q_3 > \frac{\omega_3 T_0}{8\pi}$ the HOM impedance may be excited by a single rotation sideband to cause the parasitic coupled-bunch instability [1], where Q_3 is the HOM quality factor, ω_3 is the HOM resonant angular frequency and T_0 is the recirculation time. The worst-case happens when the resonant frequency of the damped HOM is an inte-

Received 8 October 2012

∗ Supported by National Natural Science Foundation of China (10979045, 11175180, 11175182)

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

gral multiple of the revolution frequency. We consider an HOM resonant angular frequency ω_3=1000 MHz that equals 220 times of the revolution frequency, with an HOM resonant impedance R_3=10 kΩ. For this case, the coupled-bunch growth rate is given by

$$|\Delta\Omega_{\rm CB}|=\frac{eI\alpha\omega_3 R_3 F_3^2}{2ET_0\omega_R}. \tag{1}$$

Table 1. The machine parameters for the HLS Ⅱ.

parameter	value
beam energy/GeV	0.8
beam revolution frequency/MHz	4.533
number of bunches	45
synchronous voltage/kV	16.73
natural relative energy spread	0.00047
fundamental rf angular frequency/MHz	204
fundamental cavity shunt impedance/MΩ	3.3
fundamental quality factor	28000
fundamental cavity coupling coefficient	2
harmonic-cavity harmonic number	4
harmonic-cavity shunt impedance/MΩ	2.5
harmonic-cavity quality factor	18000
harmonic-cavity coupling coefficient	0
momentum compaction	0.02
fundamental rf peak voltage/kV	250
harmonic frequency/MHz	816
radiation-damping time constant/ms	10
HOM quality factor	3000

Here, I is the ring current, α is the momentum compaction, E is the ring energy, $\omega_{\rm R}$ is the calculated frequency of collective dipole oscillations and F_3 is the bunch form factor at frequency ω_3, given by

$$F_3=\exp(-\omega_3^2\sigma_{\rm t}^2/2). \tag{2}$$

$\sigma_{\rm t}$ is the bunch length. If $|\Delta\Omega_{\rm CB}|-\tau_{\rm L}^{-1}>|\Delta\Omega|_{\rm thresh}$, we consider that Landau damping is not sufficient to prevent the parasitic coupled-bunch instability. $\tau_{\rm L}^{-1}$ is the radiation damping rate and $|\Delta\Omega|_{\rm thresh}$ is the dipole Laudau damping rate [2, 3]. The parameters we use are shown in Table 1. The modeling results of the parasitic coupled-bunch instability for a given ring current and harmonic cavity tuning angle are shown in Fig. 1. For a tuning angle with the range from −83.40° to −89.80° the parasitic coupled-bunch instability is predicted to occur before optimal bunch lengthening is obtained. The results are in good agreement with those from our previous simulations in which an optimal bunch lengthening curve described by parameters of tuning angle and current is obtained and along this curve, the natural relative energy spread is not predicted [4]. Our simulation also shows that the energy spread exceeds its natural value by 10%–30% before optimal bunch lengthening is obtained. Therefore, the parasitic coupled-bunch instability is strongly suppressed when the higher-harmonic cavity is tuned for optimal bunch lengthening and we conservatively estimate that at least 10% is suppressed in the value of the relative energy spread.

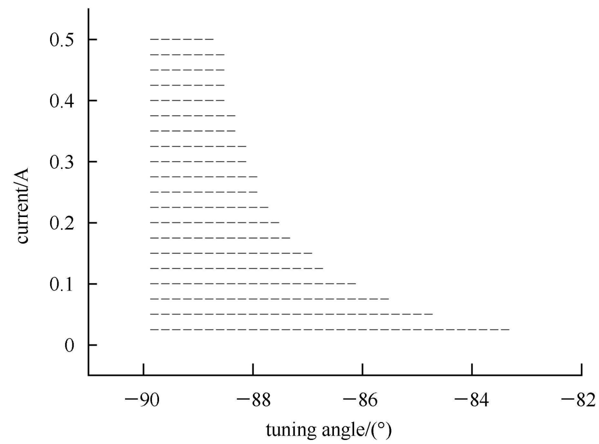

Fig. 1. Instability modeling for passive operation at the HLS, in which the worst-case parasitic coupled-bunch instability is considered. Horizontal line: the parasitic coupled-bunch instability.

3 Microwave instability modeling

Microwave instability can be considered when $Q_3<\frac{\omega_3 T_0}{8\pi}$. For a HOM characterized by ω_3, R_3 and Q_3, the Boussard criterion [5] gives an approximate threshold ring current of microwave instability

$$I_{\rm threshold}=\frac{\omega_{\rm g}}{\sqrt{2\pi}}\frac{E}{e}T_0|\alpha|\left(\frac{\sigma_E}{E}\right)^2 \times\frac{\left[1+Q_3^2\left(\omega_3\sigma_{\rm t}-\frac{1}{\omega_3\sigma_{\rm t}}\right)^2\right]^{\frac{1}{2}}}{R_3}, \tag{3}$$

$\omega_{\rm g}$ is the fundamental rf angular frequency and $\frac{\sigma_E}{E}$ is the natural relative energy spread.

In our modeling, we compute the bunch length without considering any potential-well distortion from the broadband HOM. So the bunch length $\sigma_{\rm t}$ obeys $\sigma_{\rm t}^2=\langle\tau^2\rangle-\langle\tau\rangle^2\approx\langle\tau^2\rangle$, where

$$\langle\tau^n\rangle=\frac{\int\tau^{\rm n}\exp[-U(\tau)/2U_0]{\rm d}\tau}{\int\exp[-U(\tau)/2U_0]{\rm d}\tau}. \tag{4}$$

$U(\tau)$ is the Taylor expansion of the synchrotron potential and $U_0=\alpha^2(\sigma_E/E)^2/2$.

At the HLS Ⅱ, the microwave instability may driven by the reduced longitudinal broadband impedance $|Z_p/p|$ of the vacuum chamber. And only in the long-bunch regime ($\omega_3\sigma_{\rm t}>1$), microwave instability can be suppressed by lengthening the bunch with a higher-harmonic

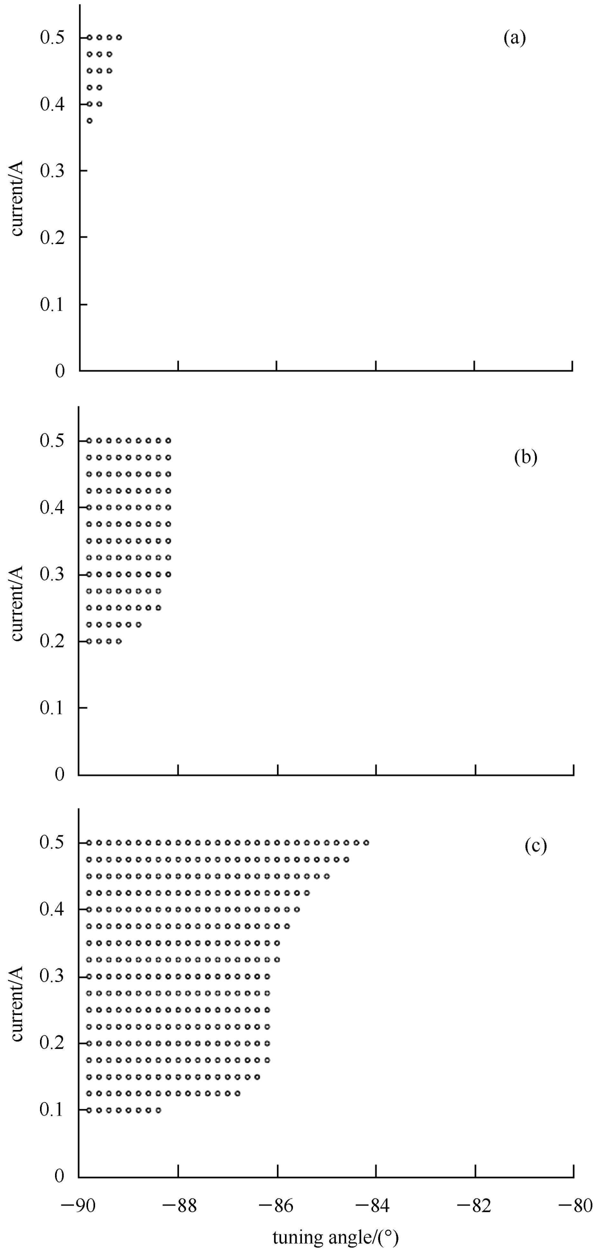

Fig. 2. Instability modeling for passive operation at the HLS Ⅱ with an HOM representing a broadband impedance $|Z_p/p|$. (a) $|Z_p/p|=4\ \Omega$, ∘: microwave instability. (b) $|Z_p/p|=8\ \Omega$, ∘: microwave instability. (c) $|Z_p/p|=16\ \Omega$, ∘: microwave instability.

cavity, because the additional bunch lengthening increases the microwave instability threshold. Therefore, we conservatively let the broadband impedance be modeled by an HOM with the smallest possible mode frequency $\omega_3=\omega_c=c/b=3183$ MHz. Here, ω_c is the cutoff angular frequency, c is the speed of light and b=30 mm is the average radius of a round vacuum chamber that approximates the HLS Ⅱ vacuum chamber's 20 mm half height and 40 mm half width. The quality factor $Q_3=1$, while $|Z_p/p|=1\ \Omega$ the HOM resonant impedance is $R_3=351.1\ \Omega$. Broadband impedances with $0.125\ \Omega\leqslant|Z_p/p|\leqslant 32\ \Omega$ are modeled and each modeling considers an impedance twice as large as the previous one. The modeling results of the microwave instability for a given ring current and harmonic cavity tuning angle are shown in Fig. 2.

In our analytic modeling, we discover no microwave instability for the broadband impedance $|Z_p/p|\leqslant 2\ \Omega$ with currents up to 500 mA. Modeling results shown in Fig. 2 predict that if the broadband impedance $|Z_p/p|>2\ \Omega$, the microwave instability may occur and become more severe with the increasing broadband impedance. When the broadband impedance reaches 32 Ω, nearly the whole range will be dotted with microwave instability. Therefore, we would prevent the microwave instability throughout our operating current 100–500 mA by decreasing the broadband impedance. We also find that the microwave instability happens first at high ring currents and it has been confirmed by simulations in our previous studies.

4 Conclusion and discussion

We have studied the parasitic coupled-bunch instability and the microwave instability with a higher-harmonic cavity using analytic modeling and their occurrence is approximately described by the analytic predictions. When the higher-harmonic cavity is tuned for optimal bunch lengthening, the parasitic coupled-bunch instability can be strongly suppressed. Compared with simulation results, at least 10% is suppressed in the value of the relative energy spread. Tuning in the higher harmonic cavity can lengthen the bunch and this additional bunch lengthening increases the microwave instability threshold, so that it suppresses the microwave instability which does not occur until the ring operates with some high currents. In our modeling, if the broadband impedance $|Z_p/p|\leqslant 2\ \Omega$, the bunches with currents up to 500 mA will not suffer from microwave instability.

References

1 Chao A W. Physics of Collective Beam Instabilities in High Energy Accelerators. New York: Wiley, 1993. 117–126

2 Bosch R A, Kleman K J, Bisognano J J et al. Phys. Rev. ST Accel. Beams, 2001, **4**: 074401

3 Bosch R A. Phys. Rev. ST Accel. Beams, 2005, **8**: 084401

4 WU C F, WANG L, LI W M, ZHAO Y N et al. Preliminary Study of The Higher-Harmonic Cavity for HLS-II. Proceedings of IPAC'10. Kyoto, Japan. 2010

5 Boussard D. CERN Laboratory Report, 1975, No. LabII-rf-Int.-75-2