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# INFLUENCES OF HARMONIC CAVITIES ON THE SINGLE-BUNCH INSTABILITIES IN ELECTRON STORAGE RINGS

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*Abstract*

Single-bunch instabilities usually determine the bunch performance at high charges as well as the highest single-bunch currents in storage rings. It has been demonstrated that the passive harmonic cavities, which have been widely used in electron storage rings of the third-generation synchrotron light sources, can generally make the beam more stable. However, the influences of the harmonic cavities on the single-bunch instabilities are still not fully understood. We hereby present our study of both longitudinal and transverse single-bunch instabilities when using different settings of the harmonic cavities.

## INTRODUCTION

Harmonic cavities have been used to lengthen the bunches in the storage rings of many existing ring-based synchrotron light sources [1,2]. The increase of the Touschek lifetime due to the implementation of the harmonic cavities has been carefully studied and demonstrated in the operations of many machines [3–5]. Some studies show that the harmonic cavities help cure the longitudinal coupled-bunch instabilities [6–8]. Moreover, there are also some studies indicating that the harmonic cavities help stabilize the transverse coupled-bunch instabilities [9].

The newly proposed ultra-low emittance rings are usually more sensitive to the collective beam instabilities, while the total impedance of the rings tends to be higher since the the much narrower vacuum chambers will be used. Therefore, people pointed out that it would be essential for the ultra-low emittance rings to implement the harmonic cavities to lengthen the bunches.

However, almost all of the existing harmonic cavities work in the 'passive' mode, meaning that no external RF power source will be used, the voltage in the harmonic cavities is induced only by the charged particle beam. In the operation mode with passive harmonic cavities, the voltage and phase of the RF field in the harmonic cavities would be determined mainly by charged particle beams. Therefore, it's non-trivial to optimize the settings of the passive harmonic cavities for different operation modes due to the lack of knobs. We are also considering to propose the active harmonic cavities in the HEPS storage ring for keeping the flexibility to optimize the settings of the harmonic cavities in different operation modes. Nevertheless, we need to understand better the influences of the harmonic cavities on the singe-bunch instabilities first.

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In the longitudinal direction, microwave instability is usually dominant. Studies of the microwave instability in both cases without and with ideal lengthening harmonic cavities have been reported for different machines. It would be interesting to carry out more studies between these two conditions. In the transverse direction, both the Transverse Mode-Coupling Instability (TMCI) and the head-tail instability could be the limiting factors. There hasn't been a universal explanation of the influences of the harmonic cavities on both the above mentioned transverse single-bunch instabilities. We hereby would like to carry out simulation studies of the above mentioned single-bunch instabilities. Our work will help understand the influences of the settings of the harmonic cavities. Hereby, we use the lattice and the impedance model loosely based on HEPS, the key parameters of which are listed in Table 1.

Table 1: Key Lattice Parameters Used in the Studies, which are Loosely Based on the HEPS

| **Parameters** | **Symbols** | **Values and Units** |
|---|---|---|
| Circumference | C | 1360.4 m |
| Beam Energy | $E_0$ | 6 GeV |
| Total Current | $I_0$ | 200 mA |
| Vertical Tune | $\nu_y$ | 106.16 |
| Momentum Compaction Factor | $\alpha_c$ | 1.28e-5 |
| Natural Energy Spread | $\delta_p/p$ | 1.14e-3 |
| Average Radiation Energy Loss per Turn | U0 | 2.81 MeV |
| Harmonic Number of the Primary RF | $h_1$ | 756 |
| Frequency of the Primary RF | $f_0$ | 166.60 MHz |

The impedance model, consisting of most of the typical components, is shown in Figure 1. The simulations are mainly carried out by the `elegant` [10] and Pelegant [11] codes. Therefore, the convension used in Figure 1 is the same as the definition in `elegant`.

## HIGHER HARMONIC CAVITY

As mentioned in Table 1, we propose to use 166.60 MHz as the frequency of the primary RF cavities. The third harmonic cavity ($\approx$ 500 MHz) is chosen to provide bunch lengthening in our studies. If we consider using the active harmonic cavity, meaning that both the voltage and phase of the harmonic cavity can be adjusted freely, we can reach the

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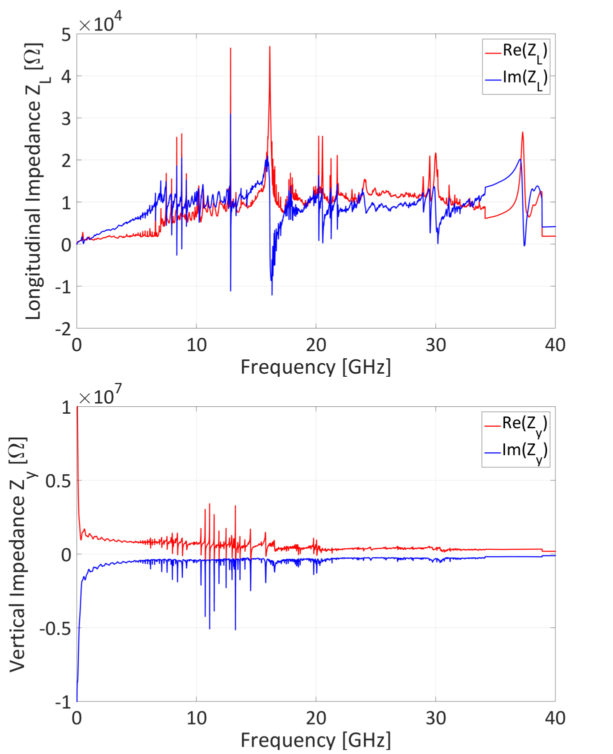


Figure 1: Impedance model used in the studies. The upper and lower subfigures correspond to the longitudinal and vertical impedance spectrum, respectively.

following ideal-flat potential condition [12]:

$$\sin\phi_s = \frac{V_{HC}}{V_{RF}}\sin\phi_{HC} + \frac{U_0}{eV_{RF}} \quad (1)$$

$$\cos\phi_s = \frac{V_{HC}}{V_{RF}} h \cos\phi_{HC} \quad (2)$$

$$\sin\phi_s = \frac{V_{HC}}{V_{RF}} h^2 \sin\phi_{HC} \quad (3)$$

where, $V_{RF}$ and $V_{HC}$ are the peak voltage of the primary RF cavities and the peak voltage of the harmonic cavities, respectively; $\phi_s$ and $\phi_{HC}$ are respectively the synchronous phases of the primary RF cavities and the harmonic cavities; $U_0$ represents the average radiation energy loss per turn; $h = h_{HC}/h_1$ is the harmonic index.

However, besides the cases without harmonic cavity and with harmonic cavity under the ideal-flat potential condition, there are more settings in between, corresponding to different bunch lengthening conditions, different bunch distributions, etc. By adjusting the voltage of the harmonic cavities, we could get two typical conditions. When the voltage of the harmonic cavities is smaller than the value under the ideal-flat potential condition, the bunch lengthening is not as significant. This case is one of the typical settings of the harmonic cavities, marked as the 'HC set1' in the following text. Keep increasing the voltage of the harmonic cavity to higher than the case of the ideal-flat potential condition, there will be one unstable fix point in the middle of the RF bucket, in between of the two stable fix points. The bunch distribution will have 'double-hump' shape, as marked by the 'HC set4'.

Besides the above mentioned two typical settings, it's also interesting to study the dynamics near the ideal-flat potential condition. By adjusting the phase of the harmonic cavity to ±0.5°, we manage to get the two typical settings which correspond to the two different distorted distributions towards the head (HC set2) and the tail (HC set3) of the bunch, respectively.

The Hamiltonian tori of the above mentioned conditions are shown in Figure 2, while the corresponding bunch distributions are shown in Figure 3.

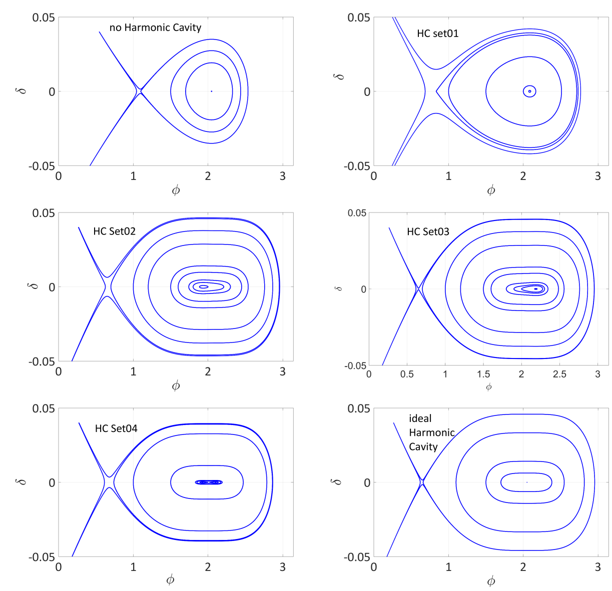


Figure 2: Harmiltonian tori at different settings of the harmonic cavity.

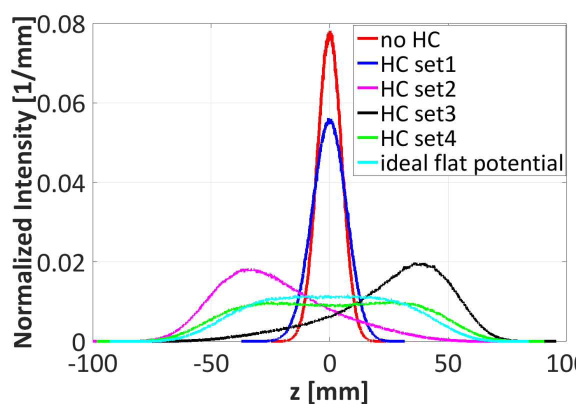


Figure 3: Equilibrium bunch distributions at different settings of the harmonic cavities without considering the beam coupled impedance.

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## MICROWAVE INSTABILITY

Microwave instability is a kind of very important longitudinal single-bunch instability which can induce the bunch turbulent in the longitudinal phase space and the increase of the energy spread of a bunch. It has been demonstrated that the bunch lengthening effect because of the implementation of the harmonic cavities manages to increase the microwave instability threshold. Implementing the above mentioned different settings of the harmonic cavities, we get the variation of the bunch length and the energy spread in different cases, as shown in Figure 4. The situation without harmonic cavities is also simulated to be used for comparison.

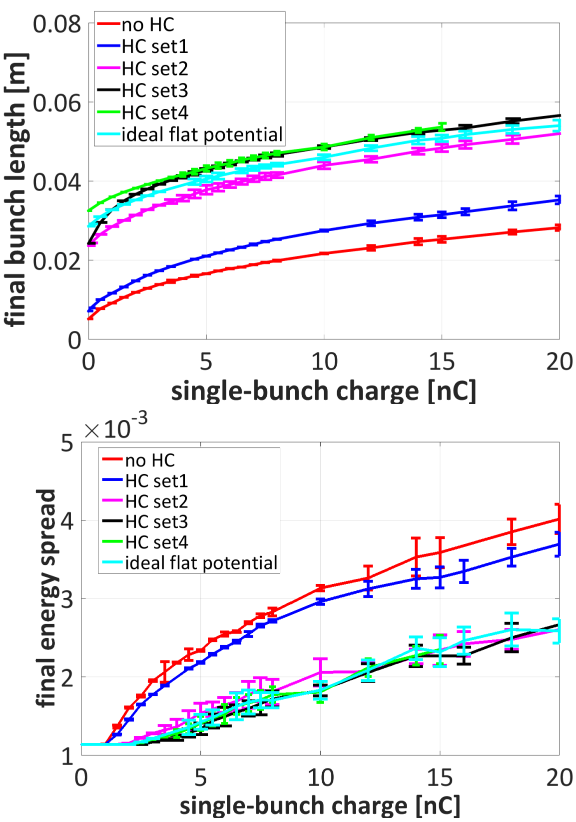


Figure 4: Bunch length and energy spread with the increasing single-bunch charge. The different curves are obtained using different settings of the higher harmonic cavity.

As we can see from the upper plot in Figure 4, the bunch length in the case without harmonic cavity is about 6 mm at zero current. The bunch length in the 'HC set1' is very closed to the case without harmonic cavities since the voltage in the harmonic cavities is much smaller than the ideal-flat potential condition. For the cases 'HC set2', 'HC set3', and 'HC set4', the bunch lengths are closer to the ideal-flat potential condition. We notice that the bunch is always longer when the bunch has a 'double-hump' in the 'HC set4' than the values in the ideal-flat potential condition. The 'HC set3' is more interesting since it has shorter bunch length than the ideal flat potential case at zero current. However, the bunch lengthening is faster than the ideal-flat potential condition case when increasing the single-bunch charges. This fact is mainly because the bunch distorts towards the tail of the bunch without considering the impedance effects. However, if we consider the beam impedance interactions, we can find that some particles losing energy and therefore moving towards the head of the bunch. when we keep increasing the single-bunch charge under the 'HC set3' condition, we can observe the bunch getting flatter first when we consider the potential-well distortion effect. The final bunch distributions (the bunch distributions at the 50000th turn) at different single-bunch charges under the conditions without harmonic cavity, HC set3, and with ideal-flat potential condition, are shown in the Figure 5.

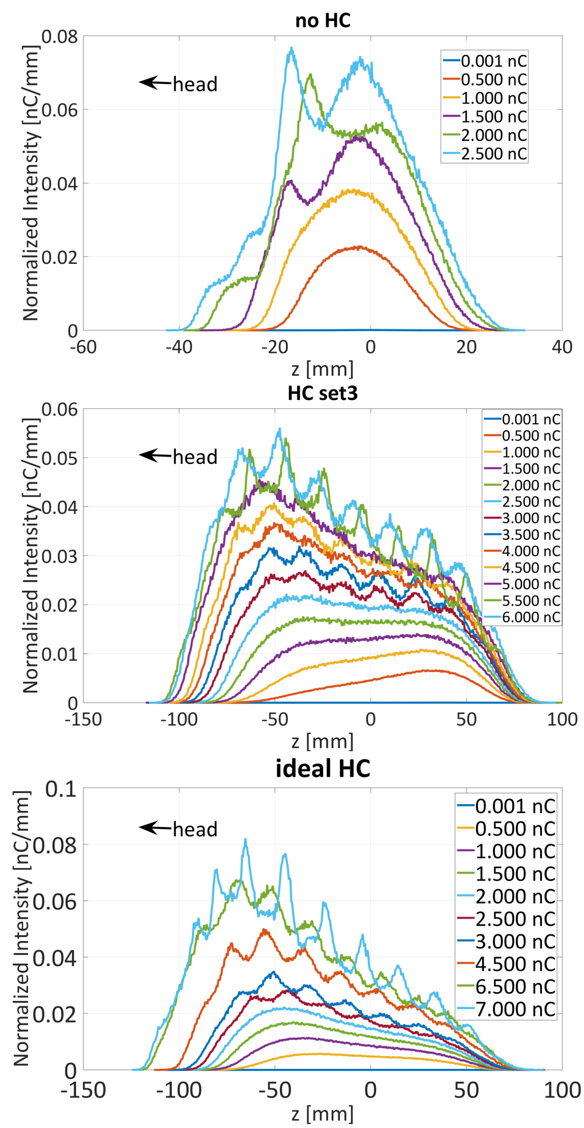


Figure 5: Bunch final distributions under different settings of the harmonic cavities at different sigle-bunch charges.

This fact makes the bunch becoming longer than the ideal flat bunch when the bunch charge is getting higher. Seeing the energy spread, we can see that the cases 'HC set2', 'HC set3', 'HC set4', as well as the ideal-flat potential case, have

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similar threshold and the growth of the energy above the threshold current is also quite the same. It seems from the results that the microwave instability threshold is not very sensitive to the settings of the harmonic cavities if the bunch lengths are similar. This fact means that we can benefit from the harmonic cavity if the bunch lengthening effect can be obtained. For the purpose of increasing the microwave instability, the ideal-flat potential condition is not necessary.

## TRANSVERSE SINGLE-BUNCH INSTABILITIES

We also carried out the studies of the transverse single-bunch instabilities under the above mentioned settings of the harmonic cavities. This problem itself is non-trivial since the influences of the harmonic cavities on the transverse single-bunch instabilities is still not very clear. Therefore, our studies would help get better understanding of this problem.

We first carried out particle tracking including the vertical short-range wake field at zero chromaticity. by observing the bunch centroid oscillation, we can distinguish whether the bunch is stable or not. The two curves in Figure 6 show the typical cases below and above the TMCI threshold current, corresponding to the stable beam motion and unstable motion, respectively. By fitting the envelope of the bunch centroid oscillation data, we manage to calculate the growth rates in different cases. The results show that the TMCI threshold current is a bit higher than the cases without harmonic cavity or HC set1. But the difference is quite small. More interesting phenomenon is that the threshold current in the non-ideal lengthening cases (HC set2, HC set3, and HC set4) are all a little bit higher than the ideal-flat potential case. This fact means that the so-called ideal-flat potential condition doesn't necessary to be better from the TMCI point of view.

When we implement finite chromaticity, e.g. $\xi_y = +1$, the similar simulations and analyses can be done, as shown in the lower plot in Figure 7. The increase of threshold currents due to the implementation of harmonic cavities can be clearly observed. By comparing the threshold currents between zero and +1 chromaticities under different harmonic cavities setttings respectively, one can find that the remarkable increase of the threshold current at +1 chromaticity. If comparing the threshold current among different harmonic cavities settings, we can find again that the ideal flat potential condition doesn't correspond to the optimum threshold current. Our preliminary study shows the fact clearly. We need carry out more systematic theoretical and tracking studies to understand this dynamics better.

## CONCLUSION AND DISCUSSION

In this paper, we carried out some preliminary studies of the influences of the harmonic cavities on the longitudinal and transverse single-bunch instabilities. Six typical settings of the harmonic cavities (including the case without harmonic cavity) are used.

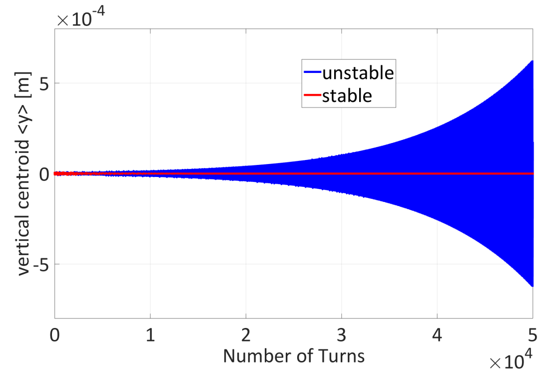


Figure 6: Beam centroid positions vs. number of turns at different single-bunch charges.

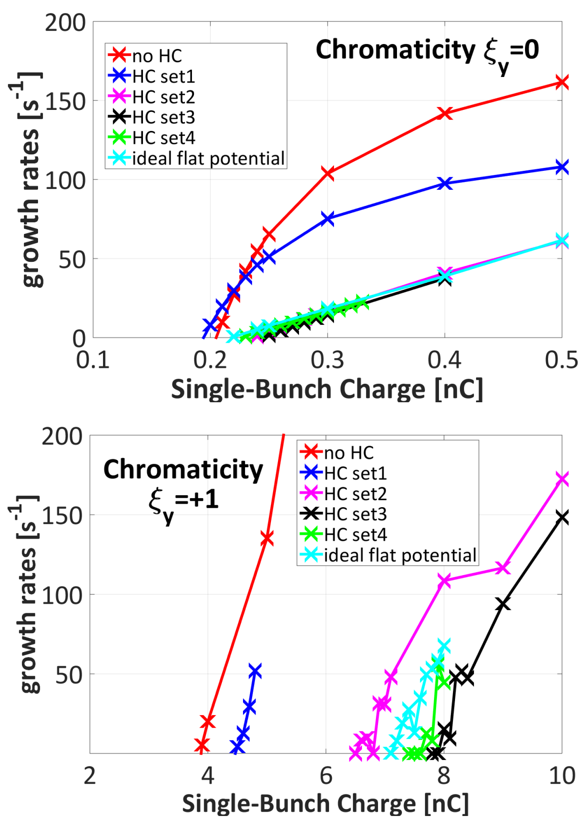


Figure 7: Growth rates at different chromaticities and different settings of the harmonic cavities.

In the longitudinal direction, the studies of the influences of the harmonic cavities settings on the microwave instability show that the longer bunch loosely corresponds to higher threshold current. when the bunch lengths in different cases are closed to the value under the ideal-flat potential condition, the microwave instability threshold current are quite similar. Therefore, there is no need to fulfill the ideal-flat potential condition for the purpose of increasing the microwave instability threshold.

The dependence of the transverse single-bunch instabilities on the settings of the harmonic cavities are a bit more complicated. The way of the harmonic cavities settings

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influence the transverse single-bunch instability threshold currents depend also on the chromaticities. Anyway, we can loosely say that the longer bunch tends to be more stable. We still need to carry out systematic studies to understand the influences of the harmonic cavities settings on the transverse single-bunch instabilities.

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