ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAF014

STUDIES OF THE SINGLE-BUNCH INSTABILITIES IN THE BOOSTER OF HEPS*

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Abstract

High Energy Photon Source (HEPS), which is proposed in China, is an ultra-low emittance storage ring based synchrotron light source. Because of the requirement of the relatively high single-bunch charge, the booster may suffer from the single-bunch instabilities. A preliminary impedance model has been developed for the studies of collective instabilities in the booster. Based on this impedance model, the longitudinal and transverse single-bunch instabilities have been studied.

INTRODUCTION

HEPS is proposed to be a 6 GeV, quasi diffraction limited storage ring based synchrotron light source. The dynamic aperture, on the order of millimeter, has been achieved after substantial optimizations [1]. The swap-out injection has been chosen as the baseline scheme for the HEPS storage ring. However, to use the swap-out injection scheme, the single bunch with full required charges needs to be injected into the storage ring at one time. This requirement leads to dramatic increase of the difficulty for the injector design. If no special consideration is made, the bunch with full required charges needs to be accelerated in the booster, which can be a big challenge to the booster. Moreover, it's nontrivial to generate and accelerate such a high charge bunch in the electron gun and linac, too.

To reduce the requirement of single-bunch charge in the booster, a novel scheme [2] has been proposed for HEPS. In this scheme, the bunch in the storage ring, which needs to be refreshed, will be extracted and reinject into the booster instead of being dumped. The reinjected bunch will merge with the existed bunch in the same bucket of booster. The replenishment of the bunch charge happens in the booster at the extraction energy. Then, this refreshed bunch will be injected into the storage ring. By applying this scheme, the requirement for the booster can be reduced since no full bunch charge is required at the low energy of the booster. Nevertheless, the requirement of the single-bunch charge in booster is still substantially higher than the cases in the third generation synchrotron light sources. This fact motivates careful studies of the single-bunch instabilities in HEPS booster.

Since the optimization of the booster lattice is still ongoing, a preliminary design of the booster lattice is used to study the important single-bunch instabilities. The main parameters of this lattice are listed in Table 1. More information about the booster lattice design can be found in [3].

Table 1: Key lattice Parameters of the Booster Used in the Studies

Parameters	Symbols	Values and Units
Circumference	C	453.47 m
Beam Energy	E_0	500 MeV / 6 GeV
Betatron Tunes	ν_x/ν_y	16.40 / 10.73
Momentum Compaction Factor	α_c	4.2e-3
Horizontal Radiation Damping Time	τ_x	7.76 s / 4.56 ms
Vertical Radiation Damping Time	τ_y	7.77 s / 4.51 ms
Longitudinal Radiation Damping Time	τ_δ	3.84 s / 2.24 ms
Radiation Energy Loss per Turn	U_0	195.1 eV / 4.02 MeV
Repetition Rate	f_{rep}	1 Hz
RF Frequency	f_0	499.8 MHz
Harmonic Number	h	756

In order to study the collective beam instabilities in the booster, we've carried out careful calculations of the total impedance. The impedance of most of the critical components, such as the RF cavities, the flanges, the bellows, BPMs, and kickers, have been calculated via either analytic formulae or by simulations. The resistive-wall impedance was calculated by the analytical formulae under the assumptions of round stainless-steel vacuum chambers with 15 mm inner radius along the whole ring. The longitudinal and vertical total impedance used in the this paper are shown in Figure 1-(a) and Figure 1-(b), respectively.

To reduce the required sing-bunch charge to the electron gun and the linac, we propose to take advantage of the RF frequency of 2998 MHz in linac and the 499.8 MHz RF in the booster. 4 bunches in the contineous 4 RF periods of the linac are proposed to be injected into the same RF bucket of the booster. Because of the synchrotron motion, adiabatic damping in the energy ramping process, and the synchrotron radiation damping, the initial bunches in the same RF bucket of the booster will finally merge together. By applying this scheme, the requirements of single-bunch charge to the gun and the linac are both reduced 4 times. Here we assume that each bunch is in Gaussian distribution with σ_t = 5 ps and

* Work supported by National Natural Science Foundation of China (No. 11775239), NKPSTRD (2016YFA0402001), and Key Research Program of Frontier Sciences CAS (QYZDJ-SSW-SLH001)
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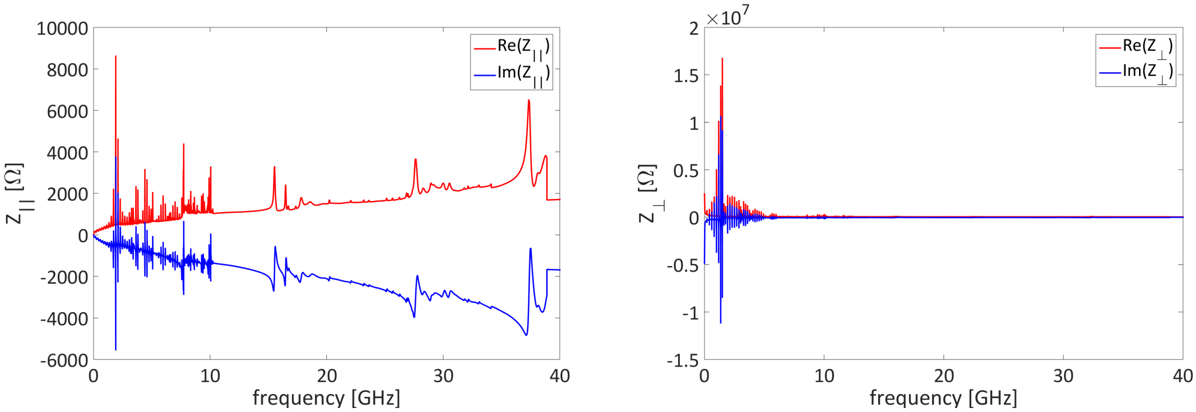

(a) (b)

Figure 1: (a): longitudinal total impedance; (b): the vertical total impedance.

$\sigma_\delta = 0.5\%$, cutting off at $2\sigma_t$ and $1\sigma_\delta$, respectively. The initial bunch distribution in one RF bucket of the booster is shown in Figure 2.

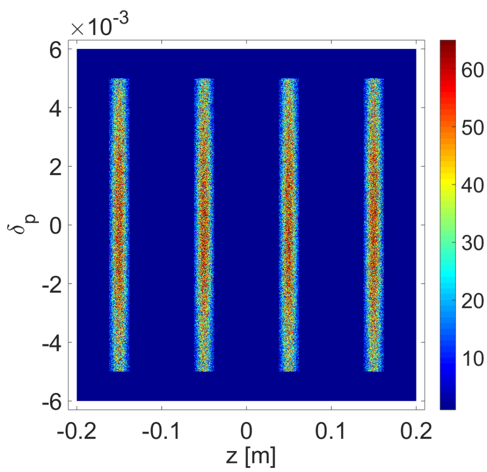

Figure 2: The longitudinal phase space distribution of the initial 4 bunches from linac in the same RF bucket of the booster.

MICROWAVE INSTABILITY

In the booster, the beam energy ramps from 500 MeV to 6 GeV. Beam parameters will change significantly during the ramping process even without consideration of the collective effects. To estimate the microwave instability, we carried out multi-particle tracking under the two extreme conditions, at the booster injection energy and the extraction energy, respectively. `elgant` [4] and its parallel version `Pelegant` [5] are used for tracking.

The particles were tracked for 50,000 turns in each case. The mean values and RMS deviations of the energy spread, calculated by the data in the last 10,000 turns, are shown in Figure 3. No increase of the final energy spread can be seen in the simulations even when the bunch charge is as high as 25 nC/bunch at 500 MeV and 32 nC/bunch at 6 GeV,

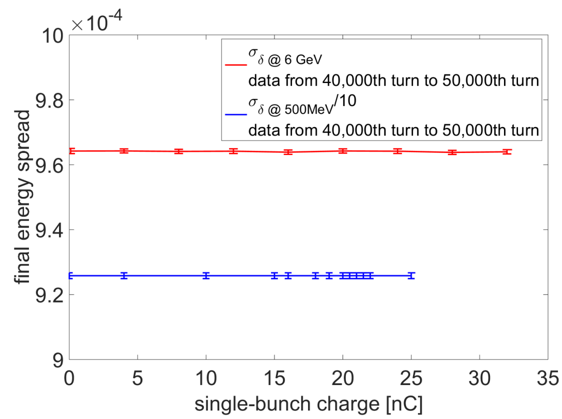

Figure 3: The final energy spread at 500 MeV and 6 GeV in the booster. To make the plot clearer, the values of σ_δ at 500 MeV have been divided by 10.

respectively. These values are already much higher than the requirement of the high-bunch-charge operation mode in the storage ring (14.4 nC/bunch).

TRANSVERSE SINGLE-BUNCH INSTABILITIES

Similarly as the above mentioned studies of the microwave instability, we also carried out the tracking studies of the transverse single-bunch instabilities under the two extreme conditions (500 MeV and 6 GeV). For each energy, the experiences suggest that one needs to set the chromaticity as a slightly positive value to avoid the very strong head-tail instability. Therefore, we carried out the studies at zero chromaticity and +1 chromaticity for both energies.

In our simulations, each bunch is tracked for 50,000 turns. One million macro-particles are used in the single bunch to make sure the good convergence. Both vertical and longitudinal impedances have been included in the tracking. By varying the single-bunch charges, we observe the vertical centroid motion and the emittance evolution of each bunch to determine whether the bunch is stable or not. If the rapid

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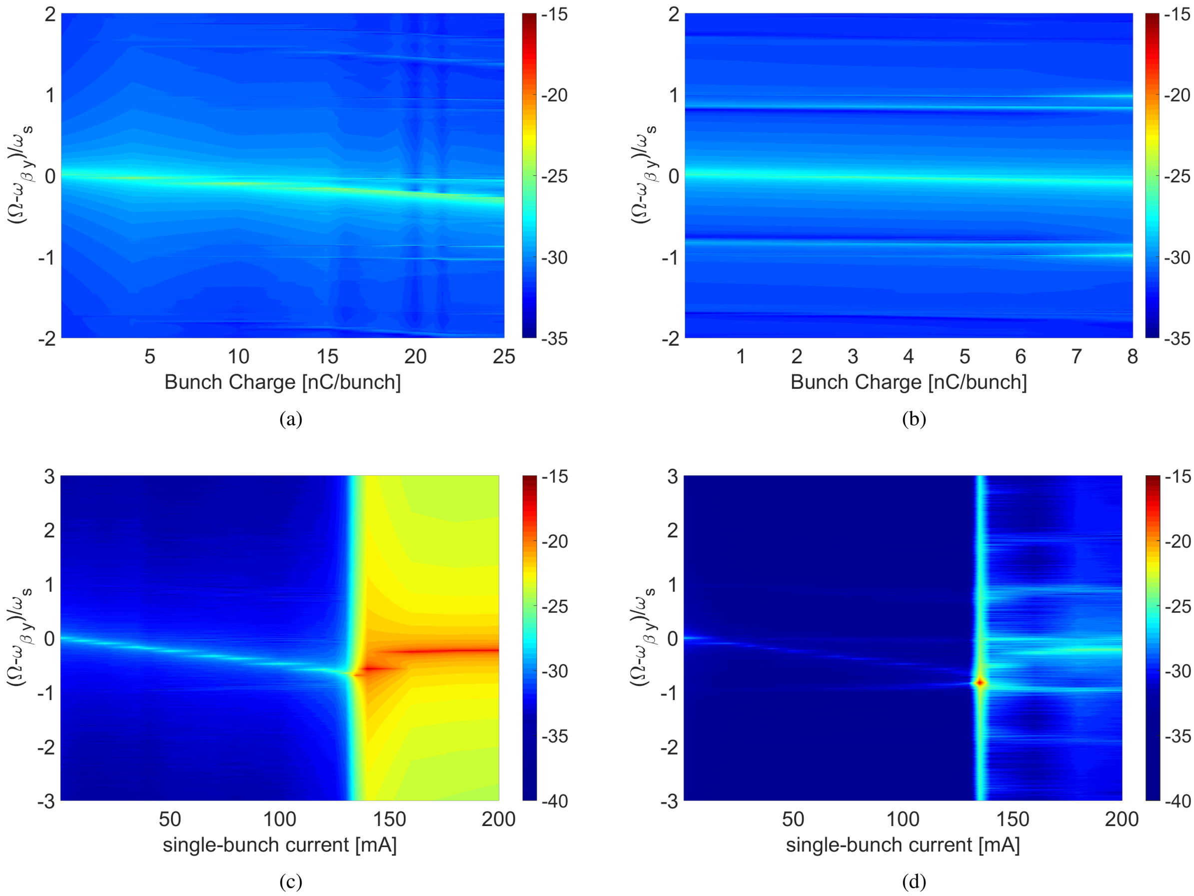

Figure 4: (a): mode analysis at 500 MeV when $\xi_y = 0$; (b): mode analysis at 500 MeV when $\xi_y = 1$; (c): mode analysis at 6 GeV when $\xi_y = 0$; (d): mode analysis at 6 GeV when $\xi_y = 1$.

growth of either the amplitude of the bunch centroid or the bunch emittance can is observed, the bunch is marked as unstable.

Besides the above mentioned method to distinguish whether the bunch is stable or not, we also carried out the mode analysis under different conditions, which are shown in Figure 4. The Figure 4-(a) and Figure 4-(b) are both the results at 500 MeV, corresponding to the zero chromaticity and +1 chromaticity, respectively. The thresholds for these two cases, which are obtained by the above mentioned method, are higher than 25 nC/bunch and 8 nC/bunch, respectively. These conclusions agree well with the Figure 4-(a) and Figure 4-(b), where neither mode coupling nor significant mode growth happens. However, the final emittance growth start to appear at about 20 nC/bunch at zero chromaticity and 6 nC/bunch at +1 chromaticity. The reasons and the influences of the emittance growth are under studied.

The Figure 4-(c) and Figure 4-(d), corresponding to zero chromaticity and +1 chromaticity, are both the results at 6 GeV. The thresholds for Figure 4-(c) is about 130 nC/bunch, while the thresholds for Figure 4-(d) is about 132 nC/bunch. In both cases, the coupling between the mode "0" and "-1" can be observed, which indicate that TMCI is the dominating effect in both cases.

CONCLUSION

We present the studies of the single-bunch instabilities in the HEPS booster. Based on the existing impedance model, no microwave instability is observed at both the injection energy and the extraction energy of the booster even up to 25 nC/bunch. The transverse single-bunch instabilities seem to limit the single-bunch charge in the booster at the injection energy. However, the threshold at +1 chromaticity at 500 MeV is about 5 nC/bunch, which should fufill the single-bunch charge requirement by the injection of the storage ring.

ACKNOWLEDGMENT

The authors would like to thank the colleagues in the Accelerator Physics Group of IHEP for the fruitful discussions. The author Haisheng Xu would like to thank the '100 Talents Program of Chinese Academy of Sciences' for supporting.

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