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THE STUDY OF SINGLE-BUNCH INSTABILITIES IN THE RAMPING PROCESS IN THE HEPS BOOSTER*

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Abstract

The booster of High Energy Photon Source (HEPS) is proposed to ramp the beam energy from 500 MeV to 6 GeV, and to deliver the required charge to the storage ring. However, the transverse single-bunch instability may limit the reachable bunch charge in the booster. The study of the transverse single-bunch instability has been carried out for the HEPS booster at both 500 MeV and 6 GeV to double check whether the required single-bunch charge can be achieved. Furthermore, the energy ramping process was recently included in the study. We concentrate in the analyses of the simulation results with the consideration of energy ramping process in this paper.

INTRODUCTION

High Energy Photon Source (HEPS) [1] is a 6 GeV storage ring based synchrotron light source which is under design. The on-axis swap-out injection scheme is presently chosen as the baseline. One of the challenges for the booster when implementing the swap-out injection scheme is the collective instabilities in the booster, mainly because this scheme requires full-charge bunches from the injector. The requirement of the full-charge bunches is especially difficult if the high single-bunch charge is needed in the storage ring.

For the storage ring of HEPS, two operation modes, named "high-brightness mode" (680 bunches, 200 mA) and "high-bunch-charge mode" (63 bunches, 200 mA), are currently proposed. Therefore, about 14.4 nC/bunch is needed in the above mentioned high-bunch-charge mode (200 mA, 63 bunches). If we assume that the injection efficiency from the HEPS booster to the storage ring can reach about 90%, and no particle loss will happen in the energy ramping process, about 16 nC/bunch is expected to be ramped in the booster. However, our previous studies [2, 3] show that the capture and ramping such a high-charge bunch in the HEPS booster is extremely challenging, especially at the injection energy (500 MeV) of the booster. Therefore, a "high-energy accumulation" scheme was proposed to avoid the request of ramping a high-charge bunch directly from low energy. More detailed information about the proposal of "high-energy accumulation" scheme can be found in [4].

Even though the "high-energy accumulation" scheme can relax the requirement of single-bunch charge for the HEPS booster, systematic studies of the collective instabilities in the booster are still necessary. The previous studies showed that the no particle loss or increase of energy spread appear at both 500 MeV and 6 GeV in the booster, even when the single-bunch charge achieves as high as 25 nC [2], where four continuous bunches from the LINAC were injected into the same bucket of the booster. However, we would like to carry out more systematic studies of the microwave instability with consideration of energy ramping. Moreover, for studying the effects of the transverse impedance under more realistic conditions, we would also like to include the energy ramping process in our tracking simulations of the transverse single-bunch instability. `elegant` code [5] and its parallel version `Pelegant` code [6] are used in our studies.

The rest of the paper will be organized as follows: Firstly, we present the basic information of the conditions of our calculations, such as, the main parameters of the lattice, the energy ramping curve, the impedance model. Afterwards, we present the tracking simulations of longitudinal and transverse single-bunch instabilities under the above mentioned conditions, respectively. Discussions will be given at the end of this paper.

LATTICE AND BASIC INFORMATION

There have been several versions of the lattices for the HEPS booster. In this section, we present the main parameters of the baseline lattice in the preliminary design stage, the corresponding impedance model, and the energy ramping curve. The information presented in this section will be the conditions used in the rest of the paper.

Lattice Parameters

Table 1 gives the main parameters of the booster lattice. More information can be found in [7].

Ramping Curve

The period of one booster ramping cycle is designed as 1 s. In the present design, the peak RF voltage ramps from 2 MV to 8 MV linearly in 400 ms in each cycle. To preserve the capability of multi-bunch operation in the booster, a 200 ms flat bottom and a 200 ms flat top are proposed for injecting bunches into the booster at 500 MeV and extracting the bunches at 6 GeV, respectively. The above mentioned ramping curve of the peak RF voltage is shown by the blue curve in Figure 1. The corresponding energy ramping process is expressed by the Lorentz factor variation curve in red color in the same figure. However, for the single-bunch operation mode of the booster, we believe that the bunch energy can be ramped immediately after injected into the

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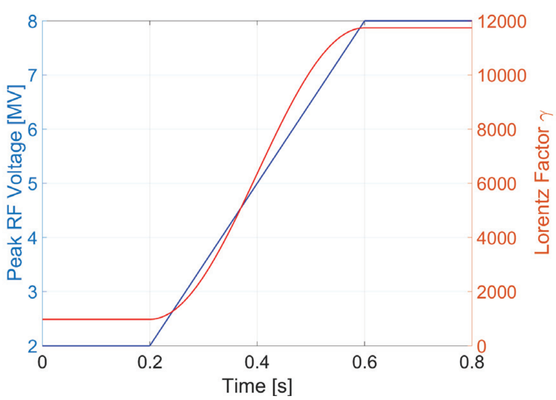
Table 1: Main Lattice Parameters

Parameters	Symbols	Values and Units
Circumference	C	454.0665 m
Beam Energy	E_0	500 MeV / 6 GeV
Betatron Tunes	ν_x/ν_y	17.15 / 11.21
Chromaticity	C_x/C_y	+1 / +1
Momentum Compaction Factor	α_c	3.68e-3
Horizontal Damping Time	τ_x	7.8 s / 4.5 ms
Vertical Damping Time	τ_y	7.8 s / 4.5 ms
Longitudinal Damping Time	τ_δ	3.9 s / 2.3 ms
Energy Loss per Turn	U_0	193.9 eV / 4.02 MeV
Repetition Rate	f_{rep}	1 Hz
RF Frequency	f_0	499.8 MHz
Harmonic Number	h	757

booster at 500 MeV. It's not necessary to always store the single bunch in the booster at 500 MeV in the operation.



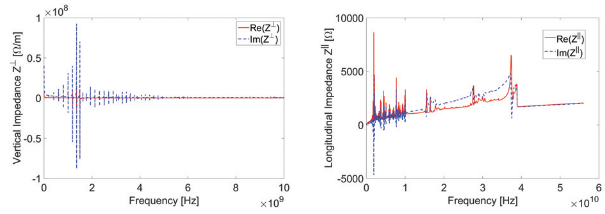
(a)

Figure 1: Ramping curves of the peak RF voltage (in blue color) and the corresponding Lorentz factor (in red color) γ.

Impedance Model

The impedance model we used in the studies of collective instabilities is still very preliminary, including only 6 key contributions. However, we believe that it's a good starting point. The total vertical and longitudinal impedance spectrum are shown in Figure 2 (a) and (b), respectively. In our tracking simulations, the beam-impedance interactions are computed in frequency domain. Update of the impedance model for the HEPS booster is still on-going.

Here we assume that the initial bunch is a single bunch from the LINAC in Gaussian distribution. The horizontal and vertical emittance of the initial bunch are identical (40 nm). The initial bunch length and energy spread are about 5 ps and 0.5%, respectively. The above mentioned



(a) (b)

Figure 2: Vertical (a) and longitudinal (b) impedance used in the tracking simulations.

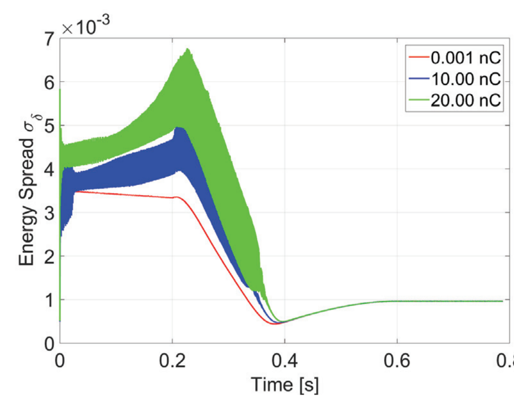
parameters of the initial bunch were mainly from our LINAC colleagues. The resulting initial bunch is mismatched in the longitudinal phase space at injection.

TRACKING SIMULATIONS WITH ENERGY RAMPING

Some beam parameters, such as the synchrotron frequency and radiation damping time, usually vary during the ramping process. Due to the varying frequencies of the modes, it becomes more difficult to build up the mode coupling and growth of the head-tail modes. On the other hand, the growing energy corresponds to the stronger synchrotron radiation damping, which helps stabilize the beam oscillations in all the three directions (horizontal, vertical, and longitudinal). Therefore, we believe that the bunch should get stabler as the energy ramping, in general.

Longitudinal Single-Bunch Effect

To study the longitudinal single-bunch effect influenced by the longitudinal impedance in the energy ramping process, we used the full ramping curve shown in Figure 1 in the tracking simulations. Figure 3 show the variations of energy spread, which is the sign of microwave instability, along the energy ramping process.



(a)

Figure 3: Variation of energy spread in the ramping process.

Through the Figure 3, we can find that the energy spread increase a bit as the single-bunch charge increases in the first 0.2 s, corresponding to the flat bottom in the ramping curve.

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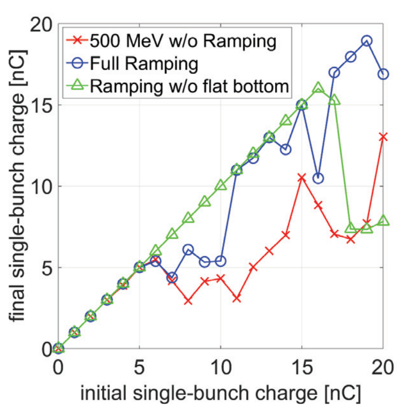
This indicates the influence of longitudinal impedance. However, since 0.2 s is much shorter than the damping time at 500 MeV beam energy, the bunch hasn't reached the equilibrium state before the energy ramping starts. As the energy ramps, the increase of energy spread disappears, indicating the high threshold current of the microwave instability at 6 GeV in the booster.

Transverse Single-Bunch Effect

The previous studies indicated that the transverse single-bunch instability at 500 MeV energy limited the highest single-bunch charge in the booster. Here, we would like to consider the energy ramping process in the simulations.

To figure out the threshold current with the consideration of energy ramping, we carry out particle tracking using the ramping curve shown in Figure 1. However, as implied above, the flat bottom of the ramping curve is for keeping the capability of multi-bunch operation in the booster. It's not necessary for a single bunch to stay at 500 MeV for 200 ms. We therefore consider two extreme situations, corresponding to the situations that the single bunch stays at 500 MeV for the full flat bottom (200 ms) before ramping (blue curve in Figure 4), or the energy of the bunch ramps immediately after injected into the booster at 500 MeV (green curve in Figure 4), respectively. The result without ramping is shown as the red curve in Figure 4 for comparison.

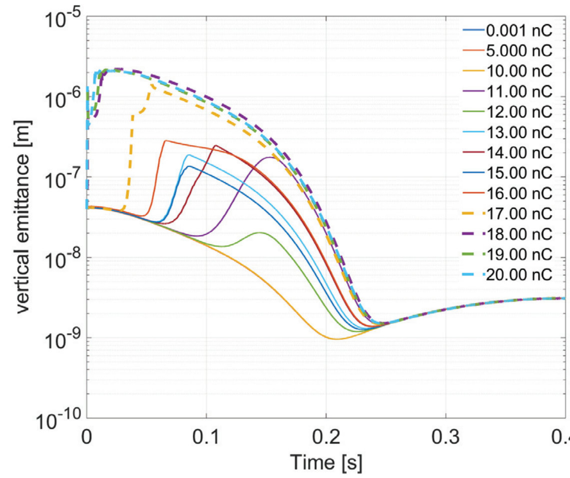


(a)

Figure 4: Comparison of the single-bunch charge threshold under the conditions with and without the consideration of energy ramping.

The fact, that the green curve indicates higher threshold current than the red curve in Figure 4, demonstrates our understanding that the threshold current would be higher when considering energy ramping. However, the blue curve seems quite similar to the red one. The main reason is that the flat bottom has 200 ms, corresponding to more than 132,000 turns, which is longer than the time needed to build up the transverse single-bunch instability at 500 MeV.

The evolution of bunch vertical emittance in the ramping process is shown in Figure 5, in which the dashed curves indicate the situations with particle loss while the solid curves



(a)

Figure 5: Vertical emittance vs. time under the condition that the bunch energy ramps immediately after injected at 500 MeV, corresponding to the green curve in Figure 4. The dashed curves represent the situations with particle loss, while the solid curves are the cases without particle loss.

are without particle loss. What Figure 5 reminds us is to pay more attention to the implementation of physical aperture along the ring. Otherwise, there might be a risk to underestimate the impedance effect.

DISCUSSION

The requirement of relatively high single-bunch charge to the HEPS booster motivated us to carry out systematic studies of the impedance and collective instabilities for the HEPS booster. In the previous studies, we first developed a preliminary impedance model as a starting point, and carried out studies of both longitudinal and transverse single-bunch instabilities in the booster at 500 MeV and 6 GeV, respectively.

Here in this paper, we mainly present the studies of the single-bunch instabilities with the consideration of energy ramping process. The stabilization effect because of energy ramping was observed, implying that we don't need to be scared too much by the strong instability at 500 MeV in the booster. Energy ramping helps stabilize the beam anyway.

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