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STUDIES OF COUPLED-BUNCH INSTABILITIES IN THE HEPS BOOSTER*

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Abstract

The High Energy Photon Source (HEPS), which is a 6 GeV diffraction-limited storage ring (DLSR)-based synchrotron light source, is under construction in Beijing, China. HEPS consists of a Linac, a booster synchrotron, and a storage ring. The HEPS booster is proposed to operate in multi-bunch mode. And the 5-cell PETRA-type cavity, which is rich in high-order modes (HOMs), is chosen to be used in HEPS booster. For the related coupled-bunch instabilities (CBIs), comprehensive studies are performed. In this paper, we present the studies of CBIs both at the two fixed energy points (500 MeV and 6 GeV) and with the consideration of the energy ramping process in the HEPS booster. HOM measurements and preliminary Monte-Carlo analyses were carried out to estimate the possibility for the growth.

INTRODUCTION

The High energy photon source (HEPS) [1], which is going to be the first 4th generation synchrotron light source in China, is under construction in Beijing. The accelerator complex of HEPS consists of a 500 MeV Linac, a booster for ramping the beam energy to 6 GeV, and a 6 GeV storage ring. The commissioning of Linac started on 9 March. The installation of the booster was completed, and the booster commissioning is expected to start in this year. The installation of the storage ring is ongoing.

There is a so-called "high-bunch charge mode" (63 bunches, 200 mA) proposed as one of the baseline operation modes of the HEPS storage ring. The corresponding single-bunch charge is approximately 14.4 nC [2]. Furthermore, the on-axis swap-out injection scheme was proposed as the baseline injection scheme for the HEPS storage ring, indicating that the booster needed to provide the full-charge bunches to the storage ring. Therefore, the collective beam instabilities in the booster needed to be studied carefully. We carried out comprehensive studies on the single-bunch instabilities in the HEPS booster in the design stage [3, 4], indicating that TMCI was a key limiting factor to the single-bunch charge in the HEPS booster, especially at the low energy stage. To avoid capturing and accelerating single bunches with high charge from low energy, the so-called "on-axis swap-out with booster high energy accumulation" scheme was proposed in HEPS. The booster was used as a high energy accumulator ring, which can merge the accelerated bunches and the reinjected bunches (from the storage ring) to accumulate single-bunch charge.

Furthermore, the coupled-bunch instabilities were also needed to be studied to ensure the designed beam current in the HEPS booster can be achieved. The main sources which may drive CBIs were the transverse resistive-wall (RW) impedance and the high-order modes (HOMs) from the RF cavities. In the HEPS booster, 6 PETRA-type 5-cell normal-conducting cavities were planned to be used. Based on the previous experiences, the 5-cell cavity is fruitful of HOMs and lack of tuning measures, which might be annoying.

In this paper, we presented the studies of the CBIs in the HEPS booster. The v3.1 lattice of the HEPS booster was used. The main lattice parameters and RF parameters used in the computations were listed in Table 1.

Table 1: Main Lattice Parameters of the HEPS Booster

Parameters	Symbols	Values at 500 MeV	Values at 6 GeV
Circumference	C	454.0665 m	
Beam Energy	E_0	500 MeV	6 GeV
Maximum Beam Current	I_{tot}	12 mA	15 mA
Betatron Tunes	ν_x/ν_y	21.15 / 11.21	
Momentum Compaction Factor	α_c	2.259e-3	
Horizontal Damping Time	τ_x	8.09 s	4.68 ms
Vertical Damping Time	τ_y	8.09 s	4.68 ms
Longitudinal Damping Time	τ_δ	4.05 s	2.34 ms
Energy Loss per Turn	U_0	187 eV	3.88 MeV
RF Frequency	f_0	499.8 MHz	
Harmonic Number	h	757	
RF Voltage	V_{RF}	2 MV	8 MV
Beta Functions at RF Cavities	β_x/β_y	13.71 m / 15.00 m	

The rest of the paper was organized as follows: Firstly, the information of the impedance used in the study was pre-

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sented. Then, the CBI thresholds at 500 MeV and 6 GeV, which was obtained by analytic computations, were presented. Simulations were carried out with the consideration of energy ramping process. The simulations results were then presented. Finally, the conclusions and discussions were given.

CBI THRESHOLDS AT FIXED ENERGIES

As mentioned above, the HEPS booster acts also as a high-energy accumulator ring for the purpose of accumulating single-bunch charge. This fact causes the maximum currents corresponding to 500 MeV and 6 GeV, which was approximately 12 mA and 15 mA, to be different in the HEPS booster. The difference was considered in the following analytic computations of the impedance thresholds determined by CBIs.

Firstly, the transverse impedance threshold can be computed by

$$(\beta_\perp Z_\perp)^{\text{threshold}} = \frac{1}{f_0} \cdot \frac{2E_{\text{total}}}{eI_{\text{total}}\tau_\perp} \quad (1)$$

where $\beta_\perp$ represents the transverse beta function at the positions where the transverse impedance $Z_\perp$ locates. f_0 is the revolution frequency. E_{total} and I_{total} represent the total energy and total current of the beam, respectively. $\tau_\perp$ is the transverse damping time. In our computations, only synchrotron radiation damping was considered. It is worth to point out that in the computations, we assumed that the RF cavities are located at the center of the straight section. The obtained thresholds of the transverse impedance determined by the transverse CBI are listed in Table 2.

Table 2: Main Lattice Parameters of the HEPS Booster

$\mathbf{Z_{x,y}^{threshold}}$	**Horizontal**	**Vertical**	**Units**
at 500 MeV	1.14e-3	1.04e-3	M/m
at 6 GeV	18.88	17.25	M/m

Similarly as the computations in the transverse direction, the longitudinal impedance threshold can also be obtained at both 500 MeV and 6 GeV energies via the analytic equation Eq.(2).

$$Z_\parallel^{\text{threshold}} = \frac{1}{f_{\parallel\text{HOM}}} \cdot \frac{2E_{\text{total}}Q_s}{eI_{\text{total}}\eta\tau_\parallel} \quad (2)$$

where $Z_\parallel^{\text{threshold}}$ stands for the threshold of the longitudinal impedance. $f_{\parallel\text{HOM}}$ is the resonant frequency of the longitudinal HOM. E_{total} and I_{total} represent the total energy and total current of the beam, respectively. $\tau_\parallel$ is the longitudinal damping time. Q_s is the synchrotron tune. η is the phase slip factor. The threshold of longitudinal impedance was computed by Eq. (2). The spectra of the impedance threshold at 500 MeV and 6 GeV are shown in Fig. 1.

It is worth to point out that the red and green lines are the threshold of longitudinal impedance computed by Eq. (2). From these two lines, one can find that the threshold of longitudinal impedance decreases monotonically as the resonant frequency of the longitudinal HOM increases. Moreover, the

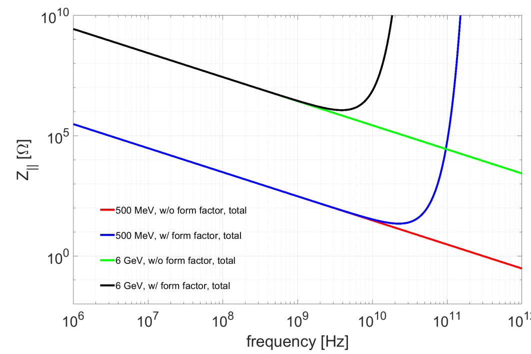

Figure 1: Threshold of longitudinal impedance at 500 MeV and 6 GeV.

higher threshold can be obtained for the higher beam energy. More interestingly, one can find that the blue curve and the black curve, which were obtained with the consideration of the form factor (FF = exp $(-(2\pi f t)^2)$) of the bunch, shows higher longitudinal impedance threshold above certain resonant frequencies.

The aforementioned computations of the impedance thresholds can be used to give constraints to the related hardware design, for instance, the RF cavity. The first priority is to make the narrow band impedance of the hardware below the impedance thresholds (as shown in Table 2 and Fig. 1 for transverse and longitudinal, respectively). However, if the impedance is higher than threshold, one needs to evaluate the growth rate and look for other mitigation methods.

Take the transverse resistive-wall impedance as an example, it may drive the transverse resistive-wall instability (TRWI), which is mainly determined by the zero-frequency resonance. The chamber is made of stainless steel with a thickness of 0.7mm to mitigate its influence to the magnetic field due to the eddy current effect. The transverse impedance is calculated based on the resistive-wall impedance theory of multilayer beam pipe developed in [5]. The growth rates for the different transverse oscillation modes are calculated based on the analytical theories at both injection (500 MeV) and extraction energy (6 GeV), as shown in Fig. 2. The most dangerous mode has a growth time of approximately 3 ms and 26 ms at injection and extraction energy, respectively. The instability at injection energy is much faster than the synchrotron radiation damping, therefore, further damping from the bunch-by-bunch feedback is required if there is a long duration of flattop before energy ramping. In addition, the energy ramping is expected to bring extra damping of the instability. The instability should be safe at the extraction energy, considering the stronger synchrotron radiation damping as well as that the beam is more robust at higher beam energy.

PETRA-type 5-cell normal-conducting cavities are chosen by the HEPS booster. Commercial products without dedicated design of the HOM suppression are used. Therefore, there are some HOMs exceeding the aforementioned impedance threshold. the growth rates of the fastest modes

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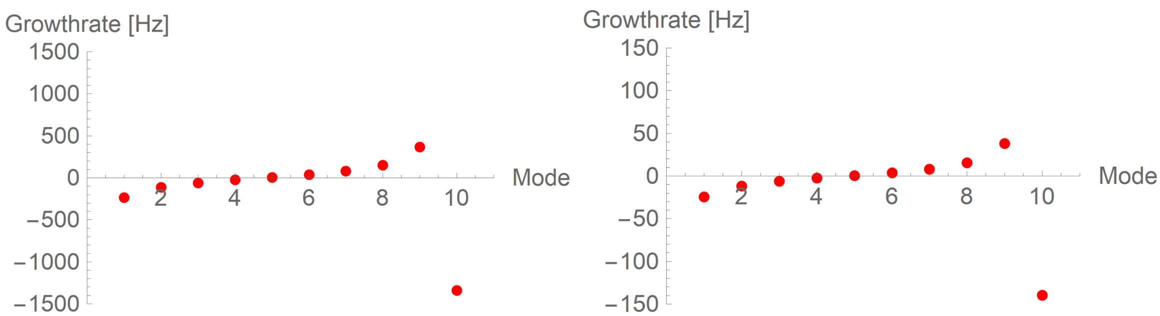

Figure 2: The growth rates of the TRWI at 500 MeV (left) and 6 GeV (right), respectively.

in both transverse direction and longitudinal direction were then computed and shown in Table 3.

Table 3: Growth Rates of the Fastest Modes of LCBI and TCBI at the injection energy (500 MeV) and the extraction energy (6 GeV)

$Z_{x,y}^{threshold}$	Longitudinal	Transverse	Units
at 500 MeV	0.40	0.17	ms
at 6 GeV	2.09	1.61	ms

SIMULATIONS WITH RAMPING

It can be clearly seen from Table 3 that the growth of longitudinal CBI at 500 MeV and 6 GeV are both very fast if the resonant frequency of the most dangerous HOM overlaps with the beam. To check whether the energy ramping process can stabilize the beam, we carried out multi-particle tracking simulations using `elegant` and its parallel version `Pelegant`. The comparison between the total transmission rate without and with considerations of energy ramping is shown in Fig. 3, from which, we can find that the ramping doesn't affect much on the particle loss.

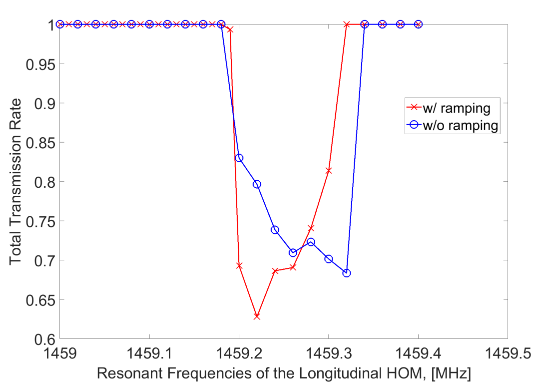

Figure 3: Total transmission rate with (red curve with cross marks) and without (blue curve with circle marks) consideration of the energy ramping process.

It's worth to point out that the overlap between the HOM impedance and the beam spectrum is not always the case. By controlling the positions of the plug-in tuners and temperature of the cooling water, the resonant frequencies of HOMs can be varied differently. Therefore, Monte-Carlo analyses can be done to estimate the possibility of the instability. We collaborated with the colleagues in RF group to do cold test of a PETRA-type 5-cell cavity. The cumulative distribution function (CDF) of the 7 most dangerous longitudinal HOMs are obtained and shown in Fig. 4. From this result, we can find that the M5 and M3 are the two most dangerous longitudinal HOMs. Anyway, the bunch-by-bunch feedback system is chosen to stabilize the LCBI.

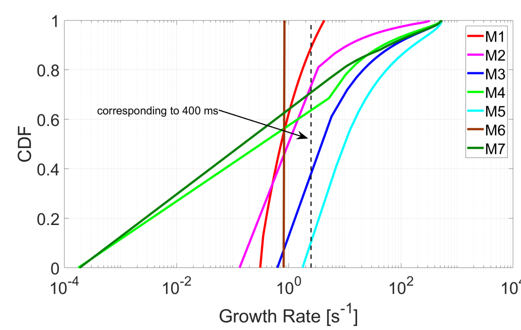

Figure 4: The cumulative distribution function of the 7 most dangerous longitudinal HOMs.

CONCLUSIONS AND DISCUSSIONS

In this paper, the studies of the coupled bunch instabilities in the HEPS booster were presented. The CBI thresholds were computed at both the injection energy (500 MeV) and the extraction energy (6 GeV). Furthermore, the multi-particle tracking simulations were carried with the consideration of energy ramping. At the end, the preliminary Monte-Carlo analyses are presented.

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