STUDIES ON COLLECTIVE INSTABILITIES IN HEPS *

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Abstract

The High Energy Photon Source (HEPS) is a new designed photon source at beam energy of 6 GeV. Due to the small beam size and increased coupling impedance with the restricted beam pipe aperture, the collective effects may bring new challenges to the physical design of the machine. The collective instabilities are estimated for different operational mode. The critical instability issues are also identified for each mode.

INTRODUCTION

HEPS is a low emittance photon source designed at beam energy of 6 GeV with emittance of 59.4 pm.rad. Extensive efforts have been made on the lattice design and the relevant studies [1]. Interaction of an intense charged particle beam with the vacuum chamber surroundings may lead to collective instabilities under certain conditions. The vacuum components are designed with the criteria of minimizing the impedance to avoid the beam instability or reduce the HOM heating.

In HEPS, two operational modes with different filling patterns are considered. One is high brightness mode with 648 bunches, followed by 10% of gap. The other one is the timing mode, with 60 bunches uniformly distributed in the ring. A novel on-axis longitudinal injection scheme based on two active RF systems was proposed [2, 3]. This scheme has a short bunch of 3 mm during the injection process, and the bunch will be lengthened to about 3 cm by harmonic RF cavities after injection. The injection process will take 200 ms for each cycle of 2 minutes. So different operational modes need to be studies. The main parameters used in this study are listed in Table 1.

Table 1: HEPS Lattice Parameters

Parameters	Values
Energy E_0	6 GeV
Beam current I_0	200 mA
Circumference	1295.6 m
Natural emittance ε_{x0}	59.4 pm.rad
Working point ν_x/ν_y	116.16/41.12
Synchrotron tune ν_s	0.0022/0.00021
Bunch number, n_b	648/60
Natural bunch length, σ_{l0}	3.0/30 mm
Beta functions at ID sect. (H/V)	9/3.2 m
Synchrotron damping, $\tau_x/\tau_y/\tau_z$	19/26/16 ms
RMS energy spread	7.97×10^{-4}
Momentum compaction	3.74×10^{-5}

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In this paper, the possible collective instabilities that may affect the beam quality are investigated for different operational conditions. The intensity thresholds or growth rates of the instabilities are given, and the possible remedies are discussed.

IMPEDANCE BUDGET

The longitudinal and transverse impedance models are developed for various components of the main ring [4]. The impedance contributions of different elements are shown in Fig. 1 and Fig. 2. The broadband effective impedance is calculated for bunch length of 3 mm and 30 mm separately. The results are listed in Table 2. $Z_{||}/n$ is the longitudinal effective impedance, and k_y is the transverse kick factor.

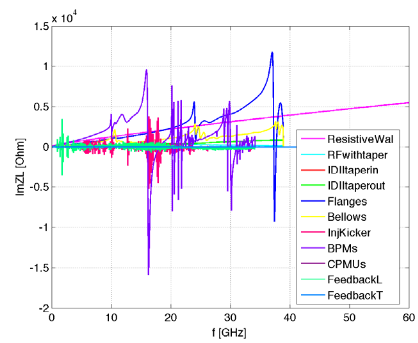

Figure 1: The longitudinal impedance of various components in the main ring.

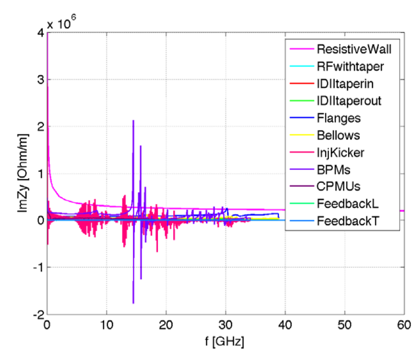

Figure 2: The transverse impedance of various components in the main ring.

Table 2: Impedance Budget for Different Beam Conditions

Beam condition	$Z_{\|\|}/n$ [mΩ]	k_y [kV/pC/m]
Injection (σ_{l0}=3mm)	109.0	23.6
Operation (σ_{l0}=30mm)	172.4	5.3

With the design parameter, the analytical theories show a primary estimation on the impedance threshold, which gives us a rough idea of how much should we control the

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impedance of the whole machine. The impedance thresholds at different operational cases are shown in Table 3.

The threshold on longitudinal broadband impedance is estimated by the Boussard or Keil-Schnell criteria [5, 6]. The threshold is considerably low due to the small momentum compaction factor along with the small energy spread. The threshold on the transverse broadband impedance is determined by the transverse mode coupling instability [7]. The transverse effect is also critical since a small beam pipe aperture is adopted. We can see that both longitudinal and transverse broadband impedance exceeds the analytical threshold. The longitudinal and transverse single bunch effects are critical for both injection and operation beam. The TMCI can be stronger for the operation beam.

Table 3: Analytical Impedance Threshold

Operational mode	$(Z_{\parallel}/n)_{th}$ [mΩ]	k_y [kV/pC/m]
Injection (n_b=648)	17.0	17.4
Injection (n_b=60)	1.6	1.6
Operation (n_b=648)	169.7	1.7
Operation (n_b=60)	15.7	0.15

The threshold on narrowband impedance is given by the longitudinal and transverse coupled bunch instability. A conservative assumption is that the bunch spectrum overlaps the resonant frequency and the instability growth rate less than the synchrotron radiation damping. This gives the limit on the shunt impedance of the HOMs. For the longitudinal case, the impedance thresholds for injection and operation are

$$\frac{f}{\mathrm{GHz}}\frac{\mathrm{Re}Z_{\parallel}}{\mathrm{k\Omega}}e^{-(2\pi f\sigma_t)^2} < \begin{cases} 222.0 \text{ (injection)} \\ 21.2 \text{ (operation)} \end{cases}. \quad (1)$$

So that, the longitudinal coupled bunch instability is more critical during operation since the synchrotron tune is smaller. However, as the bunch is lengthened during operation, this can be especially restricted to the low frequency resonances. For the transverse case, the impedance should satisfy the following equation for both cases

$$\frac{\mathrm{Re}Z_{\perp}}{\mathrm{M\Omega/m}}e^{-(2\pi f\sigma_t)^2} < 2.0. \quad (2)$$

SINGLE BUNCH EFFECTS

Microwave Instability

The microwave instability will rarely induce beam losses, but may increase the energy spread and deform the beam distribution. With the impedance model obtained, the average threshold current for the longitudinal microwave instability according to the analytical theory is about 0.05 mA during injection and 0.3mA during operation. The threshold currents are all bellow the design value. However, the analytical criterion is often believed to be too passive. The simulation studies [8] showed the microwave instability threshod is between 0.8 and 0.9 mA for the injection mode, and between 2.1 and 2.3 mA in the operation mode. Moreover, in high-energy light sources, it is quite common that the timing mode operates beyond the microwave instability threshold and users are insensitive to the turbulent longitudinal phase space.

Coherent Synchrotron Radiation

The coherent synchrotron radiation (CSR) is generated when a beam passes through the bending magnets. It can induce microwave instability with high bunch intensity. With the linear theory, the beam becomes unstable when [9],

$$I_b > \frac{3\sqrt{2}\alpha_p\gamma\sigma_e^2 I_A\sigma_z}{\pi^{3/2}h}. \quad (3)$$

where α_p is the momentum compaction, γ the relativistic energy, σ_e the relative energy spread, and I_A=17045A. The instability threshold given by the above equation is 0.5 mA during injection and 5.0 mA during operation. The beam instability due to the CSR effect during injection needs to be studied by simulations. Moreover, the CSR wake generated from the insertion devices should also be considered.

Transverse Mode Coupling Instability

The transverse mode coupling instability is estimated with Eigen mode analysis. The analysis gives the dependences of the head-tail mode frequencies on the bunch current, as shown in Fig.3. The Eigen mode analysis shows the threshold bunch current is around 0.3 mA during injection and 0.1 mA during operation with zero chromaticity. The results are consistent well with the numerical simulations. Both analyses show that the design beam current is above the instability threshold. Since the bunch will be further lengthened by the longitudinal impedance, the transverse instability threshold should be higher. Besides, according to the experience in the existing machines, a positive chromaticity can help to further increase the instability threshold.

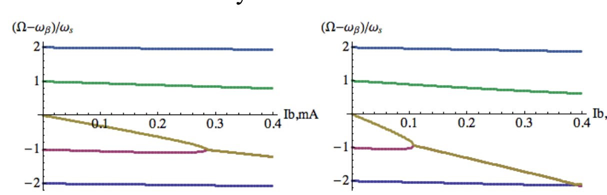

Figure 3: Dependences of the head-tail mode frequencies on the bunch current (left: injection case, right: operation case).

The simulation studies are performed including the longitudinal impedance to simulate practical longitudinal distribution. The damping effect of a positive chromaticity on TMCI is also studied. The results show that a positive vertical chromaticity of unit 2 and 3 is required for the operation and injection mode, respectively [8].

COUPLED BUNCH EFFECTS

Transverse Resistive Wall Instability

One dominant contribution to the coupled bunch instability is the resonance at zero frequency of the transverse resistive wall impedance. The growth time for the most dangerous instability mode is 0.5 ms, which is much faster than the transverse radiation damping. Therefore, transverse feedback system is needed to keep the beam stable.

Beside the feedback system, a positive chromaticity can also help to damp the instability. With nonzero chromaticity, the beam spectrum can be shifted by a frequency of $\xi\omega_0/\alpha_p$, where ξ is the chromaticity defined as $d\nu_\beta/(dp/p)$. The effect of the chromaticity can quite depend on the type of impedance and the bunch length, which can be estimated by the form factor

$$e^{-(\omega-\xi\omega_0/\alpha_p)^2\sigma_\tau^2}. \tag{4}$$

The dependence of the growth time with the chromaticity is studied. For the case with bunch length of 3 mm during injection, a positive chromaticity larger than 3.0 is needed to damp the instability without feedback. While for the case with 3 cm bunch length, a chromaticity larger than 0.5 is enough to keep the beam stable.

Instability Due to the HOMs

Another important contribution to the coupled bunch instability is the HOMs of the geometrical impedances. To keep the beam stable, the rise time of any oscillation mode should be larger than the radiation damping or the damping time of the feedback systems. Figure 4 shows the longitudinal geometrical impedance spectrum of the main ring and compared with the threshold given by Eq. (1). Figure 5 shows the transverse geometrical impedance spectrum with the threshold given by Eq. (2). The geometrical impedances are all below the instability threshold. To be noted, the HOMs of the RF cavities and harmonic RF cavities are not included here.

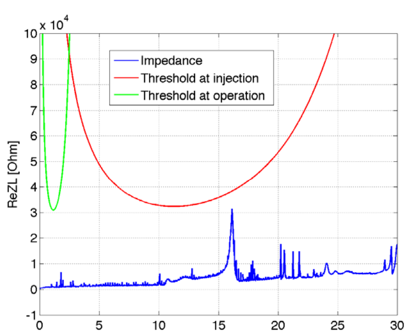

Figure 4: Longitudinal geometrical impedance spectrum and the impedance threshold determined by the radiation damping.

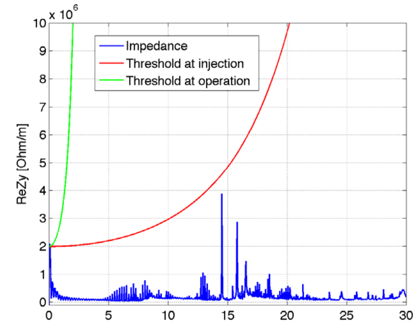

Figure 5: Transverse geometrical impedance spectrum and the impedance threshold determined by the radiation damping.

BEAM ION INSTABILITY

In an electron ring, instabilities can be excited by the ions of the residual gas accumulated in the potential well of the electron beam. The accumulation of ions within a single passage of the bunch train can induce fast beam ion instability, which may lead to beam emittance growth or beam losses.

For the high charge mode, the phase angle between adjacent bunches is $\omega_i T_b$=30, where ω_i is the ion oscillation frequency and T_b is the bunch spacing in time. Since phase angle is much larger than 1, the ions will be overfocused inside the bunch train.

For the high brightness mode, the growth time of the trailing bunch given by the analytical formula with uniform filling is around 20 ns. One damping mechanism is the ion oscillation frequency spread due to the variation of the beam size and existence of various ion species. Consider a relative ion oscillation frequency spread of 0.3, the instability growth time can be increased to 28 us, which is still much faster than the radiation damping or possible feedbacks. So multi bunch train filling and feedback system will be used to keep the beam stable. More detailed simulation studies are needed.

SUMMARY

The collective instabilities are studied with both analytical theory and numerical simulations. Two operational modes with different filling patterns are considered. The studies show that single bunch effects are critical for the high charge mode during both injection and operation. A positive chromaticity is needed in order to damp the head-tail instability, the transverse mode coupling instability, and the transverse resistive wall instability. Feedback systems are required in order to damp the coupled bunch instability and the fast beam ion instability. Moreover, a better impedance model is needed to include more impedance contributors.

ACKNOWLEDGEMENT

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