COLLECTIVE EFFECTS STUDY FOR BEPCII

J.Q. Wang, Z.Y. Guo, Q. Qin, J. Xing, IHEP, Beijing, P.R. China

Abstract

BEPCII is the upgrade project of Beijing Electron Positron Collider (BEPC). It is a double ring machine with beam current near 1A in each storage ring. This paper focuses on the single beam instabilities due to the intensive beams. The bunch lengthening and the coupled bunch instabilities are investigated. The photon electron cloud instability (ECI) in the positron ring and ion effects in the electron ring are studied analytically as well as with simulation. The beam lifetime is also estimated.

1 INTRODUCTION

BEPCII is an upgrade project of BEPC aiming at the luminosity of 1×10^{33}cm^{-2}s^{-1} at 1.89 GeV [1]. It consists of 2 rings with electron and position circulating in each separate storage ring while colliding at the common interaction point. The two rings are accommodated in the existing BEPC tunnel. The main parameters of BEPCII are listed in Table 1.

Table 1: The main parameters of BEPCII

	Symbol	Parameters
Energy (GeV)	E	1.89
Circumference (m)	C	237.5
RF frequency (MHz)	f_{rf}	499.8
Beta function at IP (cm)	β_x*/β_y*	100/1.5
Bunch number	n_b	93
Bunch current (mA)	I_b	9.8
Mom.. compaction factor	α_p	0.024
Tune	$\nu_x/\nu_y/\nu_s$	6.6/7.6/0.034
Energy spread (10^{-4})	σ_{e0}	5.16
Bunch length (cm)	σ_{l0}/σ_l	1.3/1.5
Damping time (ms)	$\tau_x/\tau_y/\tau_z$	25/25/12.5
Luminosity (cm^{-2}s^{-1})	L_0	1×10^{33}

Since the single beam current in BEPCII gets to 910mA with the single bunch current of 9.8 mA, both the single and multi-bunch effects will influence the performance of the beam and finally the luminosity of BEPCII. In the following sections the single and multi-bunch collective effects, the ion effect in the electron ring and the ECI in the positron ring are discussed. The beam lifetime and the average luminosity are also estimated.

2 SINGLE BUNCH EFFECTS

The single bunch collective effects include bunch lengthening and transverse mode coupling instability.

2.1Bunch lengthening

In BEPCII, to achieve the high luminosity, the micro-β scheme is adopted. To avoid the degradation of the luminosity by the hourglass effect, it is required that the bunch length be well controlled to around 1.5cm. However, bunch lengthens due to the potential well distortion and the microwave instability. Normally, the design bunch current should be under the threshold of microwave instability. Thus a strict impedance budget [2] has been made to control the longitudinal broadband impedance. With the main impedance generating elements being taken into account, $(Z/n)_0$ is estimated as about 0.2Ω. To estimate the bunch lengthening, the longitudinal effective impedance is got from the broadband impedance model such as the Heifets-Bane model [3] based on the impedance budget Then $|Z_{//}/n|_{eff}$ =0.24Ω. The bunch lengthening is shown in Fig. 1. The threshold bunch current for the microwave instability is around 37mA, which is about 4 times of the design current. Above the microwave instability threshold, the energy spread of the beam increases associated with bunch lengthening.

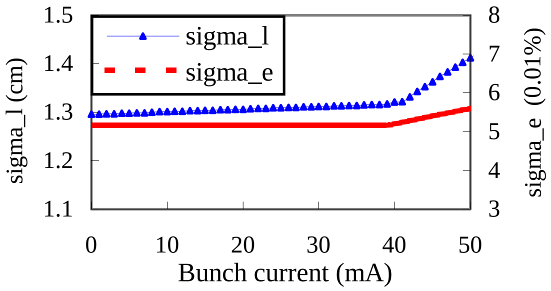

Figure 1: Bunch lengthening versus bunch current.

We have also calculated the wake potential of a Gaussian bunch with σ_l =1mm and take it as the wake function of the storage ring. Then the computer code developed by K.Oide and K.Yokoya [4], which includes both the potential well distortion and the microwave instability, is used to calculate the bunch length versus the bunch current. The result consists with the above estimation. At the bunch current of 9.8mA, the bunch lengthens by about 5%.

2.2Transverse mode-coupling instability (TMCI)

The transverse broadband impedance can be derived from the longitudinal one. Then the threshold bunch current of the TMCI is estimated as I_b =0.87A which is much higher than the design current, so it has very little effect on the beam.

3 COUPLED BUNCH INSTABILITY

The coupled bunch instabilities may arise from the high-Q resonant structures, such as the RF cavities and the resistive-wall impedance of the beam pipe at low frequencies. They are one of the main concerns due to the high beam current with multi-bunches.

3.1 Coupled bunch instability by SCC HOMs

We take the parameters of the KEKB superconducting cavity (SCC) [5] to estimate the growth rate of the symmetric filling pattern with 99 equally spaced bunches and each bunch has currents of 9.8mA as the up bound of the growth rates. The three fastest growing instability modes and their rising times are calculated as shown in Table 2. From the data, longitudinal feedback system is necessary.

Table 2: Fastest Growing Modes of Instability.

	Growth time (ms)		Growth time (ms)	
Long.	a = 1	τ1 =6.3	a = 2	τ1 =121.6
		τ2 =6.5		τ2 =124.7
		τ3 =6.7		τ3 =128.4
Tran.	a = 0	τ1 =26.6	a = 1	τ1 =1076
		τ2 =29.0		τ2 =1165
		τ3 =30.0		τ3 =1229

3.2 Resistive-wall instability

The growth rate of this instability is calculated by assuming that bunches are uniformly spaced with equal population of particles, and the material of the beam pipe in the arc of the BEPCII storage ring is aluminium, and in the straight section is stainless steel. Fig. 2 shows the growth rate as a function of the betatron tune. At the working points ν_x/ν_y = 6.6/7.6, the most unstable mode is m = 91 with a growth time of 4.3ms, so this should be damped with bunch-to-bunch feedback system.

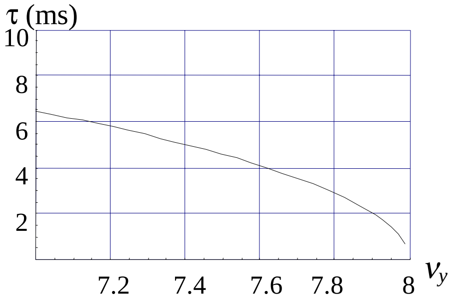

Figure 2: Growth time vs. transverse tune.

4 ION EFFECTS

4.1 Ion trapping

If a clearing gap is kept with 5% of the total buckets unfilled, i.e. with one bunch train of 93 bunches, the ion trapping condition [6] can be avoided.

4.2 Fast Beam-Ion Instability

Though the clearing gap removes the ions, due to the high beam intensity, ions accumulated during a single passage of bunch train can cause transient instability which is similar to the multi-bunch beam break-up in a linac and called "fast beam-ion instability" (FBII). [7]. Since the vertical emittance is much smaller than the horizontal one, the FBII is much more serious in the vertical plane. With linear treatment the instability rise time τ_c is [7],

$$\frac{1}{\tau_c} = \frac{4 d_{gas} \sigma_{ion} \beta_y N_b^{3/2} n_b^{2} r_e r_p^{1/2} L_{sep}^{1/2} c}{3\sqrt{3}\gamma \sigma_y^{3/2} (\sigma_x + \sigma_y)^{3/2} A^{1/2}} \qquad (1)$$

where $d_{gas}=p/k_B T=5.1\times10^{13}$ m^{-3} is the density of residue gas. σ_{ion}=2M barn the ionization cross section, N_b the particle number in a bunch, r_e and r_p the classical radius of electron and proton respectively. L_{sep} the bunch space, σ_x and σ_y the horizontal and vertical beam size respectively. A the ion mass in unit of proton mass.

However ion motion decoheres because the vertical ion frequency depends on the horizontal position. Further, the existence of various ion species and the variation of the beam size around the ring introduce spread in the effective ion frequency, which damps the instability. If all of these effects are taken into account, the instability growth becomes purely exponential with [8]

$$\frac{1}{\tau_e} = \frac{1}{\tau_c} \frac{c}{2\sqrt{2} l_{train} (\Delta \tilde{\omega}_i)_{rms}} \qquad (2)$$

where $\Delta \tilde{\omega}_i$ denotes the rms variation of the angular ion frequency as the function of the azimuthal position around the ring, l_{train} the length of bunch train. The coherent angular ion frequency is,

$$\omega_i = \left(\frac{4 N_b r_p c^2}{3 A L_{sep} \sigma_y (\sigma_x + \sigma_y)} \right)^{1/2} . \qquad (3)$$

For the BEPCII parameters, it can be calculated as $\omega_i=2.\times10^7$ s^{-1} and $\Delta \tilde{\omega}_i$ =1.38×10^7 s^{-1}. Then the growth time of instability is τ_e=3ms which is shorter than the radiation damping time. Therefore FBII should be damped with the feedback system.

5 ELECTRON CLOUD INSTABILITY

In the positron storage ring, the photon electrons generated by synchrotron light hitting the chamber wall and the secondary emission due to multipacting in the presence of the electric field of positron beam can accumulate in the beam pipe during multi-bunch operation with close spacing, giving rise to an 'electron cloud' (EC). The EC can link together the motion of subsequent bunches and induce a coupled bunch instability. It also leads to the beam-size blow-up and luminosity degradation, which was observed in the two positron rings of KEKB [9] and PEPII [10]. Here ECI is estimated analytically referring to [11] and simulations are being done.

For the coupled bunch instability due to EC, by assuming the density of the electron being saturated, the growth time of the coupled bunch instability can be estimated as [11]

$$\tau_{\mathrm{e,CB}} \approx \frac{\gamma \omega_\beta h_x h_y L_{sep}}{2 r_{\mathrm{e}} N_b c^2} . \qquad (4)$$

Where h_x and h_y are the dimensions of the vacuum chamber, ω_β the betatron frequency. For the BEPCII parameters, $\tau_{e,CB}$=0.03ms, which is extremely too fast. Though the estimated saturated electron density may be too higher than the real case, it reflects that ECI can be one main limit to the performance of the beam. We make a comparison of the growth time of ECI between BEPCII and the two B-factories in Table 3, which suggests that in the three machines the instability growth rates are of the same order. So the feedback system with specifications similar to the B-factories should be considered in the BEPCII design.

The electron cloud can also drive a single bunch instability, which is potentially more dangerous than the coupled bunch instability for it cannot be cured by feedback system. This instability can be described as TMCI. With a two-particle model, the threshold electron density of TMCI is [11]

$$\rho_{e,thr} \approx \frac{2\gamma\nu_s}{\pi\beta_y r_e C} . \qquad (5)$$

The comparison between BEPCII and B-factories shows that the threshold of TMCI is higher in BEPCII. This may attribute to its small circumference and large beam chamber. So we can anticipate that the TMCI due to the EC may not be stronger than the two B-factories.

Table 3: ECI Parameters of BEPCII and B-factories.

	BEPCII	KEKB	PEPII
τ_{CB} (ms)	0.03	0.01	0.06
TMCI ρ_e (10^{12} m^{-3})	22.7	1	0.5

The above estimation is a very rough one. Simulations are being done to study the density of electron cloud and the growth rate of instability. In addition, a series of experiments on the emission yield of electron is being done on the BEPC. To guarantee the beam performance against ECI, precaution methods referring to those successfully adopted in PEPII and KEKB will be considered in the BEPCII design. In the arc region of the positron ring we will adopt antechamber with the inner surface of beam chamber TiN coated to reduce the primary and secondary electron yield, and in the straight section space may be reserved for winding solenoids to suppress the flow of electrons towards the beam. Besides, we are also investigating the possibility to install clearing electrodes to sweep out electrons. Primary simulations have shown that with antechamber and TiN coating, the EC density is substantially lower than the instability threshold [12]. Further simulation study is still under way. We hope that with all the above methods, the beam instability owing to the electron cloud effect will not limit the performance of BEPCII.

6 BEAM LIFETIME

The beam lifetime of colliding beams are determined by two types of beam loss mechanism. One is related to the beam-beam bremsstrahlung during beam collision, which is calculated as 6.5 hours at the peak luminosity. The other is associated with the single beam effect such as the beam-gas scattering which is about 16 hours at the vacuum pressure of 8×10^{-9} Torr, and the Touschek effect which gives the beam lifetime of 9.0 hrs, so the total beam lifetime is 2.7 hrs.

The luminosity lifetime is half of the beam lifetime, so τ_L= 1.35 hours. If the refill time is τ_f and the time for physics is τ_c, the average luminosity is

$$\langle L \rangle = \frac{\int_0^{t_c} L(t)dt}{t_c + t_f} = L_0 \tau_L \frac{1 - e^{-t_c/\tau_L}}{t_c + t_f} . \qquad (6)$$

To improve the average luminosity, top-off injection is adopted. Then the injection time is the function of beam lifetime and the data taking time. A moderate choice is that the efficiency is higher than 60% and the corresponding physics run including injection takes about 1.0 hour.

7 SUMMARY

With the impedance well controlled, the design bunch current is under the threshold of microwave instability and the bunch length is less than 1.5cm. The longitudinal coupled bunch instability due to the HOMs of RF cavity and the transverse resistive wall instability dominate the multi-bunch collective effects and a bunch-to-bunch feedback system is needed to cure the instabilities. In the electron storage ring, a gap occupying 5% of the total buckets is needed to avoid ion trapping. The FBII should be damped with the feedback system. In the positron ring, the ECI exists. Antechamber with TiN coated on the inner surface of the beam chamber is needed to reduce the electron cloud density. In addition, solenoid winding as well as clearing electrode are planned to minimize the ECI. The beam lifetime is about 2.7hours. With top-off injection, the maximum average luminosity can reach more than 60% of the peak luminosity.

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