COLLECTIVE EFFECTS IN THE BEPCII SINGLE-RING SCHEME

Q. Qin, Institute of High Energy Physics, Beijing, 100039, P.R. China

1 INTRODUCTION

BEPCII, the upgrade project of the current BEPC, will have two options to enhance its luminosity. One choice is to apply the pretzel orbits in the present ring, and another is to build an additional storage ring for higher luminosity. In this paper, the beam collective effects in the single-ring scheme are mainly focused, since either the single bunch or the beam current is big. Some main parameters of the storage ring for the BEPCII single-ring scheme are listed in Table 1.

Table 1 Main parameters of BEPCII storage ring

Beam energy	1.55 GeV
Circumference	240.4 m
Beam current	288*2 mA
Bunch number/beam	6*3
Bunch current	16 mA
Particle number/bunch	8.02×10^{10}
Bunch length	1.0 cm
Natural bunch length	0.88 cm
RF frequency	501.317 MHz
RF voltage	3 MV
Emittance (H/V)	300/8.6 nm·rad
Bunch spacing	2.392 m
Natural energy spread	4.37×10^{-4}
Momentum compaction	0.035
Coupling impedance	0.2 Ω
Design luminosity	3.8×10^{32} cm^{-2}s^{-1}

2 SINGLE BUNCH INSTABILITIES

2.1 Bunch Lengthening

Similar to the present BEPC, bunch lengthening is the dominant single bunch collective effect, which limits the reduction of β_y^* and finally influences the enhancement of luminosity.

Bunch lengthening happens in the regime of potential well distortion at low bunch current. Above the threshold current, longitudinal microwave instability causes bunch lengthening too, along with the potential well distortion. In the single ring of the BEPCII, we try to control the bunch current below the microwave instability threshold via limiting the longitudinal coupling impedance. In the light of Keil-Shnell criterion[1], the limit of longitudinal effective impedance is

$$\left|\frac{Z_{//}}{n}\right|_{eff} \le 0.41\Omega \qquad (1)$$

if the design bunch current is considered the threshold current of microwave instability. The impedance budget shown in Table 1 leaves a margin to the result in eq. (1).

Several methods are adopted to estimate the bunch lengthening in the single ring scheme of the BEPCII. First, in the potential well distortion regime, the bunch length σ_l can be got from[2]

$$\left(\frac{\sigma_l}{\sigma_{l0}}\right)^3 - \left(\frac{\sigma_l}{\sigma_{l0}}\right) + I_b \frac{e\alpha_p \operatorname{Im}[(Z_{//}/n\}_{eff}]}{\sqrt{2\pi}E\nu_{s0}^2}\left(\frac{R}{\sigma_{l0}}\right)^3 = 0\,, \quad (2)$$

where σ_{l0} is the natural bunch length, I_b the bunch current, e the electron charge, α_p the momentum compaction, R the average radius of storage ring, E the beam energy and ν_{s0} the synchrotron tune. With eq. (2), one can get the bunch length will be 0.95 cm at I_b =16 mA and V_{rf} =3 MV.

The second way to estimate the bunch length is to get the longitudinal effective impedance from the impedance model with formula of[3]

$$\left|\frac{Z_{//}}{n}\right|_{eff} = \frac{\int \left|\frac{Z_{//}}{n}\right| h_m^2 dn}{\int h_m^2 dn}\,, \qquad (3)$$

where the spectral density h_m can be the Hermite mode

$$h_m(\omega_0 n\sigma_t) = \frac{1}{\Gamma(m+1/2)}(\omega_0 n\sigma_t)^{2m} e^{-(\omega_0 n\sigma_t)^2}\,, \quad (4)$$

ω_0 the angular revolutionary frequency, $n = \omega/\omega_0$ and σ_t the bunch length in unit of time. In the single-ring case, the longitudinal effective impedance is 0.26 Ω. Fig. 1 is the longitudinal impedance spectrum.

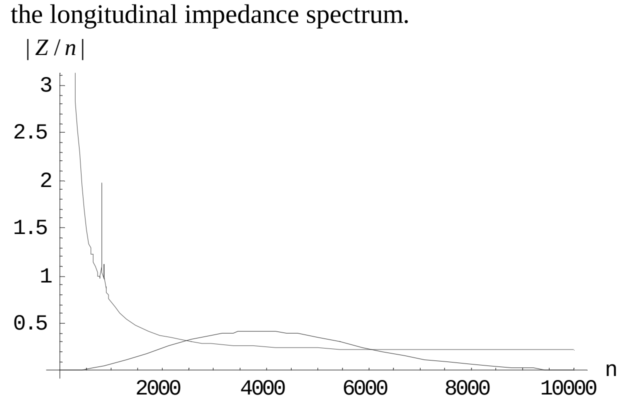

Fig. 1 BEPCII storage ring longitudinal impedance spectrum (parabolic line represents h_m)

With the effective impedance, we estimated the bunch lengthening and the energy spread widening as shown in Fig. 2. The threshold bunch current is I_b =18.2 mA.

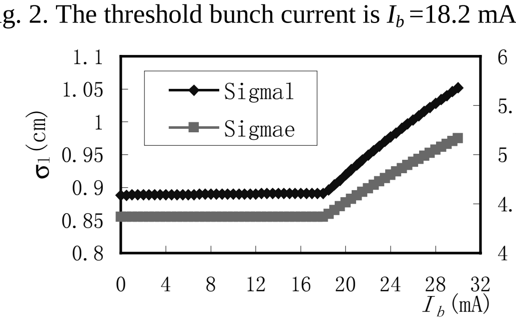

Fig. 2 Bunch lengthening and energy spread widening.

The broadband impedance can be estimated from the total loss factor, which is 6.0 V/pC for the BEPCII storage ring. A resonator with Q = 1 at the beam pipe cut-off frequency and k = 6.0 V/pC is generated to model the broadband impedance. With eqs. (3) and (4), we can get the effective longitudinal impedance is $|Z_{//}/n|_{eff}$ = 0.17 Ω. Thus, the threshold bunch current of the microwave instability is I_{th} = 18.5 mA at V_{rf} = 3 MV.

Several estimations show that the bunch length can be controlled less than 1 cm, provided that the longitudinal impedance is as small as 0.2 Ω.

2.2 Transverse Mode Coupling Instability

The transverse mode coupling instability (TMCI) limits the single bunch current in big electron storage ring, such as LEP and PEP. It happens when two head-tail modes (m = 0 and –1) have the same coherent frequencies, or degenerate at the threshold bunch current[2]. In small ring, like BEPCII, it has very little effect on the beam, since the threshold bunch current of TMCI will be $I_b \approx 4$ A.

3 COUPLED BUNCH INSTABILITY

High Q structures, such as RF cavities and resistive-wall beam pipes can generate coupled bunch instabilities. Since the beam currents in the BEPCII storage ring are large, this effect has to be carefully treated.

3.1 Effects from RF HOMs

The longitudinal and transverse coupled bunch modes can be expressed as[4]

$$\omega_p^{//} = (pM + \mu + a\nu_s)\omega_0 \qquad (5)$$

and

$$\omega_p^{\perp} = (pM + \mu + a\nu_\beta)\omega_0 , \qquad (6)$$

respectively, where a and μ are mode numbers, M the bunch number, p = 0, ±1, …, etc., ν_s and ν_β the fractional parts of the longitudinal and transverse oscillation tunes. Due to the narrowband impedance, the frequencies of these modes will be shifted.

Since bunches are filled fractionally due to the bunch train pattern in the BEPCII, we here estimate the up bound of growth rates of the dangerous modes with a symmetric filling of 102 bunches, which has a uniform bunch spacing of the smallest bunch spacing in a train and 16 mA/bunch. The lower bound comes from the case of 6 bunches symmetrically filled around the ring with 16 mA per bunch. A medium case with 6 symmetrically filled bunches and 48 mA/bunch is considered. In the estimation, KEKB superconducting RF cavity is adopted[5]. Table 2 and 3 list the main longitudinal and transverse HOMs of KEKB superonducting RF cavity. With these HOMs, we obtain the dangerous instability modes and their growth times as well for the above three cases, shown in Table 4.

The calculation of up bounds tells us the effect of HOMs in longitudinal is stronger than that in transverse. For the dangerous modes, feedback systems are needed.

Table 2 Main longitudinal HOMs of KEKB SRF cavity

f (MHz)	Mode	R/Q (Ω)	Q
783	LBP-TM01	0.12	132
834	LBP-TM01	0.34	72
1018	TM011	6.6	106
1027	TM020	6.4	95
1065	SBP-TM01	1.6	76
1076	LBP-TM01	3.2	65
1134	LBP-TM01	1.7	54

Table 3 Main transverse HOMs of KEKB SRF cavity

f (MHz)	Mode	R/Q (Ω/m)	Q
609	LBP-TE11	1.9	92
648	LBP-TE11	40.19	120
688	LBP-TE11	170.4	145
705	TM110	227.3	94
825	SBP-TE11	6.16	60
888	SBP-TE11	3.52	97

Table 4 Fastest growth times of instability modes

	Up bound	Medium case	Lower bound
Long.	3.03 ms	108 ms	352 ms
Trans.	11.76 ms	106 ms	318 ms

3.2 Transverse resistive wall instability

The real part of the resistive wall impedance excites this instability[6]. The growth rate of the instability with the rigid particle model is given by

$$\tau^{-1} = -\frac{e\beta_\perp \omega_0 I_b}{4\pi E}\sum_{p=-\infty}^{\infty}\mathrm{Re}[Z_{rw}(\omega_{p,n,\nu_\beta})] , \qquad (7)$$

where

$$\omega_{p,\mu,\nu_\beta} = (pM + \mu + \nu_\beta)\omega_0 , \qquad (8)$$

$\beta_\perp$ the averaged beta function over the ring, Re[Z_{rw}] the real part of the resistive wall impedance and other variables have the same meanings as previous ones. Since the above equations are valid for symmetrical filling, we still estimate the up and lower bounds of the instability modes. Here, we compare the vacuum chambers with different kinds of material, listed in Table 5.

Table 5 Fastest growth times for various vacuum chamber

Vac. Chamber	Cu	Al	Al+SS
Up bound (M =102, I_b=16mA)	14.9 ms	11.6 ms	4.02 ms
Lower bound (M = 6, I_b =16mA)	302 ms	220 ms	76.2 ms

At the nominal tune, ν_x/ν_y = 6.58/7.64, the shortest growth time comes from 70% Al and 30% SS chamber. It can still be damped with feedback system.

4 ION EFFECTS

4.1 Ion trapping

Ion trapping, happened in electron machines, leads to the increase of local gas pressure and beam emittance enlargement through the space charge effect. Strong ion trapping causes the dramatic decrease of beam lifetime. Partially filling bunches in the RF buckets and installing cleaning electrode are possible methods to eliminate the ion trapping.

The criterion of ion trapping for beam with gap is[7]

$$\left|\cos(\omega_i l_{train}/c) - \frac{1}{2}\omega_i T_g \sin(\omega_i l_{train}/c)\right| \le 1, \quad (9)$$

where l_{train} is the length of bunch train, c the speed of light, T_g the gap of bunch trains in time, and ω_i the ion angular frequency, which can be expressed as

$$\omega_i = \left(\frac{2QN_b r_p c^2}{AL_{sep}\sigma_y(\sigma_x+\sigma_y)}\right)^{1/2}. \quad (10)$$

Here, Q is the charge of ion in unit of electron, r_p the classical proton radius, A the ion mass in unit of proton mass, L_{sep} the bunch spacing in a train, N_b the population of particle per bunch and $\sigma_{x,y}$ the bunch transverse sizes.

It is easy to find that the criterion (9) is satisfied with the parameters of BEPCII storage ring for either H^+ or CO^+, which mainly compose the residual gas in the vacuum chamber, though there are big gaps among bunch trains.

With the transfer matrix method, we can also get the critical mass of ion for the BEPCII case, expressed as

$$A_c = \frac{4N_b r_p c t_1 t_2}{\sigma_y(\sigma_x+\sigma_y)(2t_1+3t_2+\sqrt{(2t_1-3t_2)^2+8t_1t_2})}, \quad (11)$$

where $t_1 = 4t_b$, $t_2 = 59t_b$ and $t_b = 1.995$ns is the bucket length. Fig. 3 gives the distribution of critical mass of trapped ion around the storage ring of BEPCII. It also tells us that any kinds of ion can be easily trapped. The cleaning electrode is perhaps the best way to curb the ion trapping.

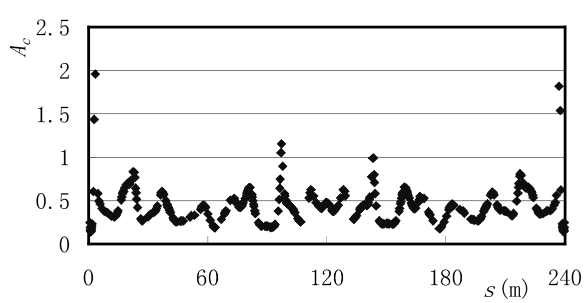

Fig. 3 Critical mass of trapped ions around the ring.

4.2 Transient ion trapping

When a bunch ionizes the residual gas, the ions left in space will also be displaced if the bunch is displaced from design orbit. Such ions execute off-centered oscillations on following bunches, amplifying the electron oscillation.

The transient ion trapping can be characterized by two parameters in vertical plane[5]:

$$\Theta = \sqrt{\frac{2zN_b m_e r_e L_{sep}}{AM_N \Sigma_y(\Sigma_x+\Sigma_y)}} \quad (12)$$

and

$$K = \frac{zn_i r_e \beta_y}{\gamma\Sigma_y(\Sigma_x+\Sigma_y)}, \quad (13)$$

where z is the ion electrovalence, N_b number of electrons per bunch, m_e and r_e the mass and radius of electron, L_{sep} the bunch spacing, A the ion mass number, M_N the mass of a nucleon, n_i the number of ions created by an electron bunch per unit length, γ the relative beam energy and $\Sigma_{x,y} = (\sigma_{ex,y}^2+\sigma_{ix,y}^2)^{1/2}$. Θ represents the phase advance of the ion oscillation between the arrival time intervals of two subsequent bunches. The coherent tune shift relates with K as $\Delta\nu_y = K\cdot R\cdot n$, where R is the radius of ring and n the bunch index.

In the BEPCII single-ring case, Θ=0.15 and K=5.7×10^{-8} if the ion of residual gas is CO^+. Even if we take the case of one bunch train with 18 successive bunches and the bunch spacing is the same as the design value, the coherent vertical tune shift would only be $\Delta\nu_y$ = 4×10^{-5}. Estimation shows the amplitude blowup factor of the unstable mode is also very small even if 18 successive bunches constitute a train. Emittance blowup has to be estimated by simulation.

4.3 Other Ion Effects

Dust effect, electrons in beam interacts with the micro ionized particles sprayed from vacuum pumps or dropped from aging chamber wall, should be rare if we deal with the vacuum pumps carefully. Photoelectron instability, happens on positron beam due to photons emitted from chamber wall hit by synchrotron radiation, will also be weak according to the experience of BEPC storage ring[8].

5 CONCLUSIONS

Bunch lengthening is still a key point, which limits the luminosity in the BEPCII single-ring scheme. The bunch length can fit the design value if the coupling impedance is controlled below 0.2 Ω. Coupled bunch instabilities due to HOMs of RF cavity and resistive wall are easy to be damped by feedback system. Ion trapping still affects the beam performance. More studies, like simulations, are needed for ion effects.

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