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PRELIMINARY STUDIES OF ION EFFECTS IN ILC DAMPING RINGS

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Ion effects are potentially detrimental to the performance of the damping rings for the International Linear Collider (ILC). In this paper, the ion effects in ILC damping rings are briefly reviewed. The fast beam-ion instability (FBII) is studied in the linear regime. The growth time and the tune shifts at bunch train end due to FBII are analytically calculated and compared for two variants of the ILC damping ring designs (OCS and TESLA) and discussed as a function of the vacuum pressure. Finally, some simulation results are also given.

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Abstract

Ion effects are potentially detrimental to the performance of the damping rings for the International Linear Collider (ILC). In this paper, the ion effects in ILC damping rings are briefly reviewed. The fast beam-ion instability (FBII) is studied in the linear regime. The growth time and the tune shifts at bunch train end due to FBII are analytically calculated and compared for two variants of the ILC damping ring designs (OCS and TESLA) and discussed as a function of the vacuum pressure. Finally, some simulation results are also given.

INTRODUCTION

Ions are regarded as one of the potential emittance limitations in electron storage rings where ions are generated by beam-gas multi-collisions. When ions are trapped in the potential well of beam bunches, the interaction between ions and electrons will lead to beam size blow-up, emittance growth and betatron tune shifts. If the ion density is large enough, the beam lifetime will reduce considerably. In order to alleviate ion effects, most electron storage rings are designed to include a gap in the bunch train to over-focus the produced ions. The gap will make ions unstable and oscillate with large amplitude. In this case, the interaction between ions and electrons are non-linear and the ions will less affect the beam stability.

In order to achieve high luminosity, ILC damping rings operate in a new regime with high current, long bunch train and very small transverse beam emittances. In this case, ions generated within a bunch or a single bunch train can have serious effects. Similarly, in the transport line and the ILC main linacs, where the vacuum pressure is relatively high, the ion effects are still prominent. This single passage ion effects is called "fast beam-ion instability" (FBII). The analytic theory of FBII was first proposed by T.Raubenheimer and G.V.Stupakov, [1,2]. This FBII phenomenon has been observed in some experiments [3,4]. The growth time of this effect is too quick to be cured by present feedback systems. In this paper, we will discuss the fast beam ion instability in ILC damping rings and their related impact on the ring performance. Some simulation results on FBII are also presented.

FAST BEAM-ION INSTABILITY

There are a few damping ring designs for the ILC. The circumference varies from 3 km to 17 km and the bunch spacing varies from 4 ns to 20 ns. After careful considerations, the ILC damping ring community finally chose a baseline and an alternative design for damping rings [5]. The baseline uses one 6 km ring as electron ring and two identical 6 km rings as positron rings. The alternative one uses the 17 km dogbone damping ring design. One of the main beam dynamics issue concerning electron damping ring is FBII.

According to the linear theory, the growth rate of FBII strongly depends on the number of bunches, the transverse beam sizes and the residual gas pressure. It is given by [1]

$$\tau_c^{-1}(s^{-1}) = 5p[Torr]\frac{N_b^{3/2} n_b^2 r_e r_p^{1/2} L_{sep}^{1/2} c}{\gamma \sigma_y^{3/2}\left(\sigma_x+\sigma_y\right)^{3/2} A^{1/2}\omega_\beta} \quad (1)$$

here p is the partial residual gas pressure which leads to instability, N_b is the number of particles per bunch, n_b is the bunch number, r_e and r_p are the classical radius of electron and proton respectively, L_{sep} is bunch spacing, c is the speed of light, γ is the beam relativistic energy factor, $\sigma_{x,y}$ are the horizontal and vertical rms beam sizes, A is the atomic mass number of the residual gas molecules, $\omega_\beta \approx 1/\beta_y$. We assumed an ionization cross section of 2Mb for CO^+ ions at beam energy of 5 GeV.

The ion coherent angular frequency ω_i is given by

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

Taking into account the ion coherent angular frequency spread, the linear theory gives the coupled bunch motion in the bunch train like $y \sim \exp(t/\tau_e)$, and then the growth time is given by

$$\tau_e^{-1}[s^{-1}] = \frac{1}{\tau_c}\frac{c}{2\sqrt{2}l_{train}\left(\Delta\omega_i\right)_{rms}} \quad (3)$$

here $(\Delta\omega_i)_{rms}$ is the rms spread of ion coherent angular frequency, l_{train} is the bunch train length and $l_{train} = n_b L_{sep}$.

If the ions are trapped in the beam, they give rise to additional focusing. The ion induced coherent tune shift is given by

$$\Delta Q_{x,y;coh} = \frac{\beta_{x,y} r_e \lambda_{ion} C}{\gamma 4\pi\sigma_{x,y}\left(\sigma_x+\sigma_y\right)} \quad (4)$$

here C is the circumference of ring, β_x, β_y are the horizontal and vertical beta functions, respectively. The ion line density λ_{ion} at the end of bunch train is given by

$$\lambda_{ion}[m^{-1}] = \sigma_{ion} n_b N_b p / k_b T \quad (5)$$

where σ_{ion} is the ionization cross section, k_b is the Boltzmann Constant, T = 300K is the gas temperature.

Using the parameters of OCS and TESLA damping rings, the FBII growth time is analytically calculated. Fig.1 and Fig.2 describe the growth time of FBII in OCS and TESLA damping ring, respectively. In addition, the 10% ion angular frequency spread is taken into account. It can be seen that in case of 10% ion angular frequency spread the growth time of FBII is three orders of magnitude larger than that of without ion angular frequency spread. Table 1 lists the ILC damping ring parameters. The ion line density and related tune shifts at the bunch train end are also listed in Table 1. Here only a single long bunch train is used in both damping rings. We can see that the tune shift due to ions is large at gas pressure of 1 nTorr, so the lower vacuum gas pressure is critical to alleviate the ion effects in the damping ring.

Table 1: Parameters of the ILC damping rings and results from analytic theory.

Lattice	OCS	TESLA
Circumference [m]	6114	17000
Energy [GeV]	5.066	5.0
Harmonic number	13256	28200
Horizontal tune	50.84	76.31
Vertical tune	40.80	41.18
Transverse damping time [ms]	22.2	27.9
Natural emittance [nm]	0.559	0.504
Bunch length [mm]	6.0	6.0
Natural energy spread [10^{-3}]	1.29	1.29
Particles per bunch [10^{10}]	2.0	2.0
Bunch spacing [ns]	6.154	20.12
Bunches per train	47	2820
Gaps per train	8.25	0
Number of bunch trains	60	1
Average current [mA]	443	159
Mean horizontal beta function [m]	25.6	120
Mean vertical beta function [m]	31	121
Analytical results		
For partial pressure of CO [nTorr]	1.0	1.0
Ion line density at train end [m^{-1}]	3.6E5	3.6E5
Coh. vert. tune shift at train end	0.188	1.001
Coh. hori. tune shift at train end	0.014	0.042

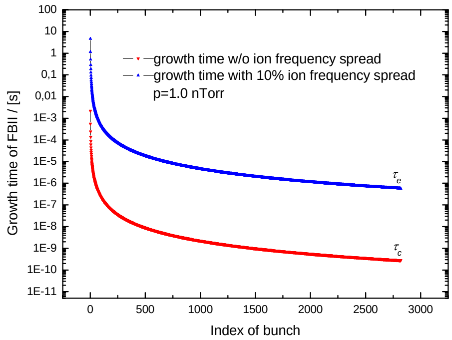

Figure 1: The growth time of FBII at OCS damping ring, 10% of ion angular frequency spread is considered.

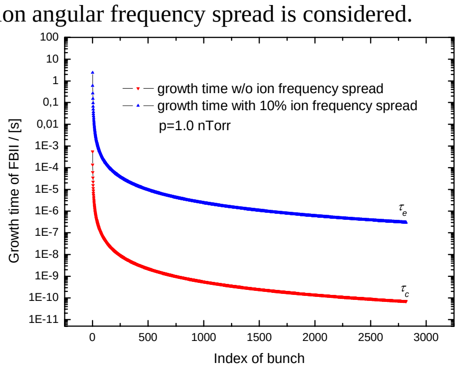

Figure 2: The growth time of FBII at TESLA damping ring, 10% of ion angular frequency spread is considered.

SIMULATION STUDY

Simulation model

A code has been developed to simulate the beam centroid oscillation due to FBII. The weak-strong model is employed in this code [6]. The electron bunch is treated as the rigid Gaussian bunch and only its center-of-mass movement is taken into account. The ions are treated as marco-particles which are ionized by the previous electron bunch. In order to save CPU time, we assume there are a few ionization points in the damping rings. The ion motion is non-relativistic without longitudinal drift. The ion distribution is the same as the parent electron bunch and their initial momentum are thermal motion at 300K. Ions are assumed to move freely in the bunch interval. The linear lattice transformation for electron bunches is adopted except for the beam-ion interaction.

For an ion with electron charge +e in the field of the Gaussian bunch, the Coulomb force acting on it can be calculated by applying the Bassetti-Erskine formula [7]

$$F(x,y) = -2N_b r_e m_e c^2 f(x,y) \tag{6}$$

where m_e is the electron mass, (x,y) are the horizontal and vertical position with respect to the bunch centre, and $f(x,y)$ is a function composed by complex error function w as

$$f(x,y) = -\frac{\sqrt{\pi}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\left[w\left(\frac{x+iy}{\sqrt{2(\sigma_x{}^2-\sigma_y{}^2)}}\right)\right. \tag{7}$$
$$\left.-\exp\left(-\frac{x^2}{2\sigma_x{}^2}-\frac{y^2}{2\sigma_y{}^2}\right)w\left(\frac{\frac{x\sigma_y}{\sigma_x}+i\frac{y\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x{}^2-\sigma_y{}^2)}}\right)\right]$$

in which the complex error function is given by

$$w(z) = e^{-z^2}\left[1+\frac{2i}{\sqrt{\pi}}\int_0^z e^{t^2}\,dt\right] \tag{8}$$

hence, we can write the kick to the rigid electron bunch by an ion with distance of (x_{ie}, y_{ie}) and sum together for all of the ions as follows

$$\Delta y_e' + i\Delta x_e' = \frac{2N_b r_e}{\gamma}\sum_i f(x_{ie}, y_{ie}) \tag{9}$$

and the kick to an ion with mass M_A is

$$\Delta y_i' + i\Delta x_i' = -2N_b r_e c\frac{m_e}{M_A} f(x_{ie}, y_{ie}) \tag{10}$$

where $(\Delta x_e', \Delta y_e')$ and $(\Delta x_i', \Delta y_i')$ are the transverse angle kick to the center of mass of electron bunch and ions respectively.

Simulation results

The FBII effect is simulated for the OCS and TESLA damping rings, respectively. The parameters used come from Table 1. All electron bunches were initially set to zero displacement. In addition, no feedback and other damping mechanism are considered. In order to speed up the simulations, we used a reduced bunch train of 282 (instead of nominal 2820) bunches, with the bunch charge and bunch separation increased by a factor of 10. We used the average beta functions and beam sizes in the wiggler sections in both lattices [8]. The following figures are some preliminary results of vertical beam oscillation amplitude and bunch maximum offset in units of vertical beam size with respect to number of turns in different gas pressure. The last bunch (the 282th bunch) is recorded.

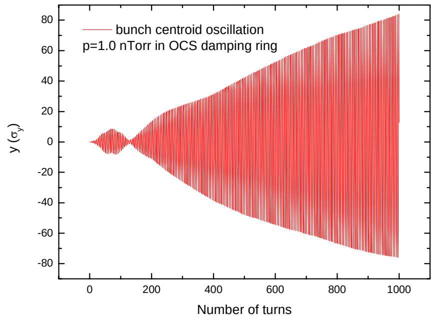

Figure 3: Oscillation of vertical beam centroid *vs.* number of turns in OCS damping ring (p=1.0nTorr).

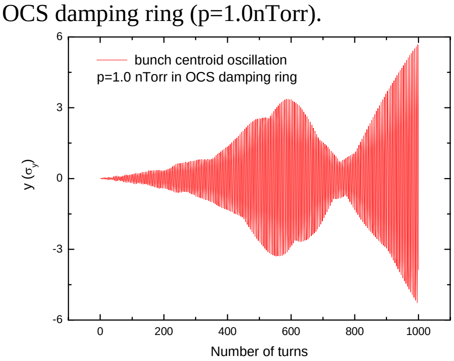

Figure 4: Oscillation of vertical beam centroid *vs.* number of turns in OCS damping ring (p=0.1nTorr).

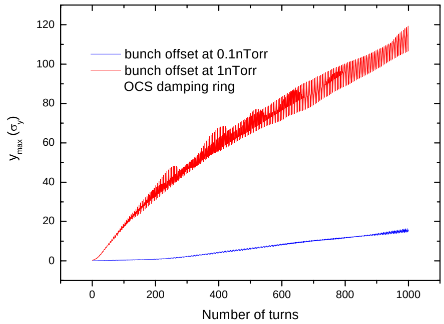

Figure 5: Bunch maximum offset *vs.* number of turns in OCS damping ring (p=1.0nTorr and 0.1nTorr).

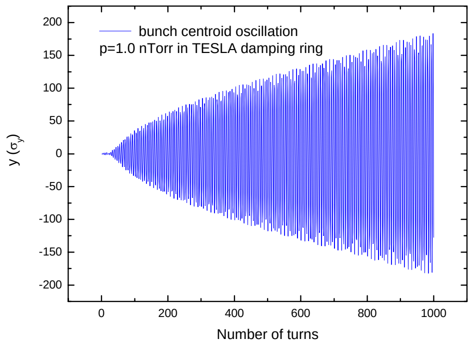

Figure 6: Oscillation of vertical beam centroid *vs.* number of turns in TESLA damping ring (p=1.0nTorr).

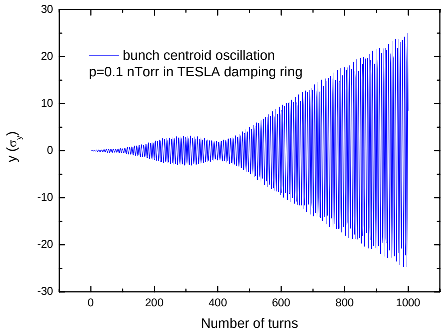

Figure 7: Oscillation of vertical beam centroid *vs.* number of turns in TESLA damping ring (p=0.1nTorr).

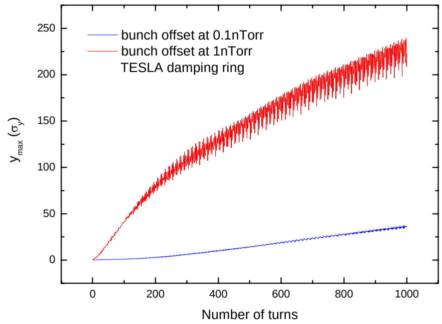

Figure 8: Bunch maximum offset *vs.* number of turns in TESLA damping ring (p=1.0nTorr and 0.1nTorr).

SUMMARY

From the above results, we can see that the tune shift at bunch train end is very large at 1nTorr. However, it is closely related to the ion density and the local beam sizes. We can use the gap between bunch trains to make the ion density and tune shift less. The growth time of FBII at bunch train end is quicker than the present feedback response time. If there is 10% ion angular frequency spread, the growth time of FBII will be increased by three orders of magnitude, which might be cured by the fast bunch-by-bunch feedback system. The bunch vertical oscillation becomes larger with respect to the number of turns. Therefore, a better vacuum pressure is necessary to mitigate the effects of FBII

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