EUROTeV-Report-2007-013

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Guoxing Xia[1], Eckhard Elsen[1]

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1 Introduction

Ion effects can be divided into two categories, one is traditional ion trapping instability, and the other is fast ion instability (FII). The former occurs mainly in storage rings when bunches are uniformly filled. The collisional ionization of residual gas by the beam particles in the vacuum chamber leads to an accumulations of molecular-like ions. In general, if some conditions are satisfied, the beam potential will trap a large amount of ions. These ions mutually couple to the motion of beam particles and lead to a beam instability in the ring due to trapped ions. In the ILC damping ring, the beam emittances are extremely small (0.5 nm in horizontal direction and 2 pm in vertical direction), the bunch number is large (2800~5600), and the bunch spacing is short (2~6 ns). Consequently, ions from a single train may play an important role for the beam motion. We have to consider the FII and try some remedies to cure this instability.

The draft version of the Reference Design Report (RDR) of the ILC was released in the ILC Beijing meeting in this February [1]. This is a starting point for us to estimate the beam collective instability. In this note the ion related instability is emphasized.

Figure 1 is the configuration of ILC damping ring. It consists of 6 identical arc sections and 6 straight sections. Each arc section is made from a basic TME cell. Two long straight sections accommodate the injection and extraction kickers, respectively. Damping wigglers are put in four short straight sections. RF cavities are located before two wiggler sections. The beam parameters of this ring are listed in Table 1.

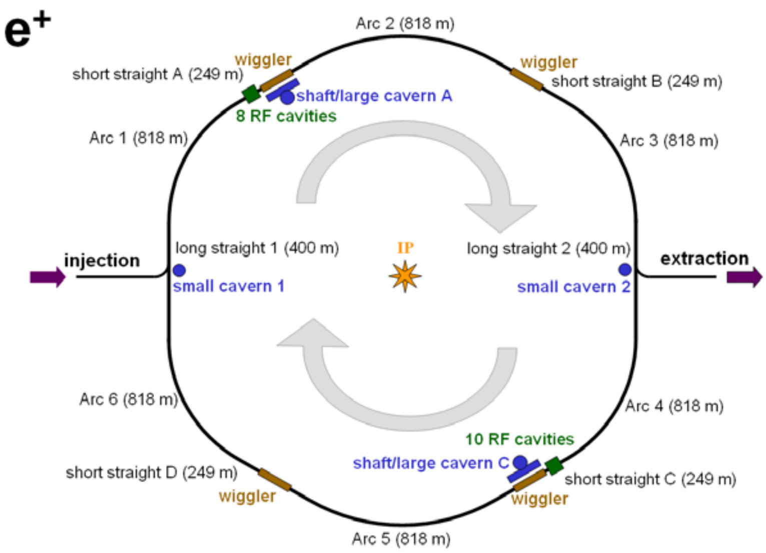

Fig.1: Configuration of the ILC damping ring.

Table 1: Parameters of ILC damping ring.

Parameters	Value
Energy [GeV]	5.0
Circumference [km]	6.695
Nominal # of bunches	2625
Nominal bunch population	2.0×10^{10}
Maximum # of bunches	5534
Bunch population at max # of bunches	1.0×10^{10}
Average current [A]	0.40
Energy loss per turn [MeV]	8.7
Beam power [MW]	3.5
Nominal bunch current [mA]	0.14
RF frequency [MHz]	650
Total RF voltage [MV]	24
RF bucket height [%]	1.5
Injected beam emittance, A_x+A_y [m.rad]	0.09
Equilibrium γεx [μm.rad]	5.0
Chromaticity,Ξ_x/Ξ_y	-63/-62
Partition numbers, $Jx/Jy/J_E$	0.9998/1.0000/2.0002
Harmonic number h	14,516
Synchrotron tune ν_s	0.067
Momentum compaction factor α_c	4.2×10^{-4}
Tunes ν_x/ν_y	52.40/49.31
Bunch length [mm]	9.0
Momentum spread σ_p/p	1.28×10^{-3}
Transverse damping time τ_x [ms]	25.7
Longitudinal damping time [ms]	12.9

2 Evaluation of ion effects in the ILC damping ring

According to the ion trapping theory [2,3], the ions are trapped by the beam potential if their mass A (in units of the proton mass) is larger than a critical mass

$$A_{crit} = \frac{Q_i N_b r_p L_{sep}}{2\sigma_y\left(\sigma_x + \sigma_y\right)} \tag{1}$$

where Q_i is the charge of the ion (in units of the electron charge), r_p is the classical proton radius, $\sigma_{x,y}$ are the horizontal and vertical rms beam sizes respectively. For the ILC damping ring, the beam emittance and energy spread are changing with respect to the damping time as following

$$\varepsilon_x(t) = \varepsilon_{x,0}e^{-2t/\tau_x} + \left(1 - e^{-2t/\tau_x}\right)\varepsilon_{x,\infty} \tag{2}$$

$$\varepsilon_y(t) = \varepsilon_{y,0}e^{-2t/\tau_y} + \left(1 - e^{-2t/\tau_y}\right)\varepsilon_{y,\infty} \tag{3}$$

$$\sigma_\delta(t) = \sigma_{\delta,0}e^{-t/\tau_\delta} + \left(1 - e^{-t/\tau_\delta}\right)\sigma_{\delta,\infty}$$

(4) where t is the time elapsed after the bunch injection; $\tau_x, \tau_y, \tau_\delta$ are the transverse and longitudinal damping times; $\varepsilon_x(t), \varepsilon_y(t)$ are the horizontal and vertical emittance respectively with $\varepsilon_{x,0}, \varepsilon_{y,0}$ the initial and $\varepsilon_{x,\infty}(t), \varepsilon_{y,\infty}(t)$ the equilibrium horizontal and vertical emittance respectively; σ_δ is the rms energy spread, $\sigma_{\delta,0}, \sigma_{\delta,\infty}$ are the initial and equilibrium energy spread.
The beam sizes can be written as

$$\sigma_x(t) = \sqrt{\varepsilon_x(t)\beta_x + \eta_x^2\sigma_\delta^2(t)} \quad (5)$$

$$\sigma_y(t) = \sqrt{\varepsilon_y(t)\beta_y + \eta_y^2\sigma_\delta^2(t)} \quad (6)$$

where $\beta_{x,y}$ and $\eta_{x,y}$ are the betatron and dispersion functions in horizontal and vertical planes, respectively. In general, $\eta_y \approx 0$, hence the vertical beam size is $\sigma_y(t) = \sqrt{\varepsilon_y(t)\beta_y}$.

Fig. 2 shows the beam emittance variation with respect to the damping time in mode 1 described below. It can be seen that at least 5 damping times are needed to achieve the required extraction equilibrium emittance. The equilibrium horizontal and vertical emittances are 0.5nm and 2pm respectively. Since the beam size varies in the ring due to radiation damping, the critical mass is a function of time during the storage The two curves in Fig. 3 show the predicted critical ion mass (in units of proton mass) with respect to the storage time in OCS6 damping ring [4]. An average beta function $\beta_x \approx \beta_y = 30$ m is assumed here. We investigate two modes, both assuming one long bunch train. For mode 1 we use a train with bunch intensity 2.0×10^{10}, a number of bunches of 2625 and a bunch spacing of 6ns; for mode 2, the bunch intensity is 1.0×10^{10}, the number of bunches is 5534 and the bunch spacing is 3 ns. We can see during the first 2 damping times, the beam size is comparatively large and even the lightest gas species are trapped in the beam potential (in the vacuum chamber, the main gas species are H_2, CH_4, H_2O, CO, N_2 and CO_2 etc.). After 3 damping times the critical mass increases. This is because the different ions species become over-focused in the inter-bunch gaps and get lost at different storage times. Fig.3 shows hydrogen ions are lost after 1.7 damping times in mode 1 and 2.8 damping times in mode 2. Carbon monoxide ions are over-focused after 3.7 damping times in mode 1 and always trapped in mode 2.

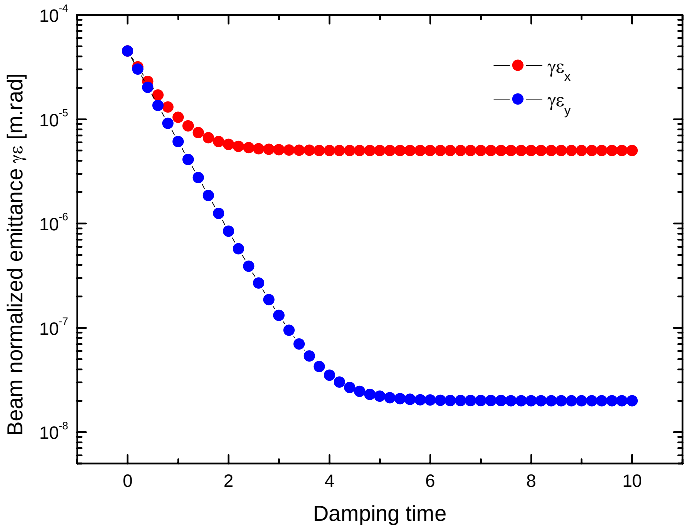

Fig.2: Beam emittance variation with respect to damping time in mode 1.

The ions are produced by collisional ionization as the beam circulates around the ring. We assume the ionization cross section for CO molecules is about 2 Mbarn in the beam energy of 5 GeV [5]. Therefore the ion line density λ_{ion} at the end of bunch train is given by

$$\lambda_{ion}[m^{-1}] = \sigma_{ion} n_b N_b p / k_b T \approx 6.4 N_b n_b p \,[\text{Torr}] \quad (7)$$

where σ_{ion} is the ionization cross section, k_b is the Boltzmann Constant, T = 300 K is the gas temperature, p is the gas pressure, n_b is the bunch number. Actually even if the ions are trapped from turn to turn, the ion accumulation can not continue forever. There are at least two mechanisms which limit the ion build up and make it reach an equilibrium density. One is the ion density cannot exceed the average beam density [6], namely, $\lambda_{ion} \le N_b n_b / C$

($\approx 7.8\times10^{9}\,\mathrm{m}^{-1}$ for OCS6 damping ring). The other boundary is the residual gas density, $\lambda_{ion} \leq 2\pi\sigma_x\sigma_y p/(kT)$ ($\approx 1.0\times10^{6}\,\mathrm{m}^{-1}$ at extraction). Fig. 4 shows the line density of trapped ions for a uniform bunch pattern as a function of the number of bunches, for mode 1 and mode 2 respectively (the partial pressure of CO assumed is 1 nTorr). In this model the ion line density increases linearly with the number of bunches. However it is still below the average beam density and residual gas density.

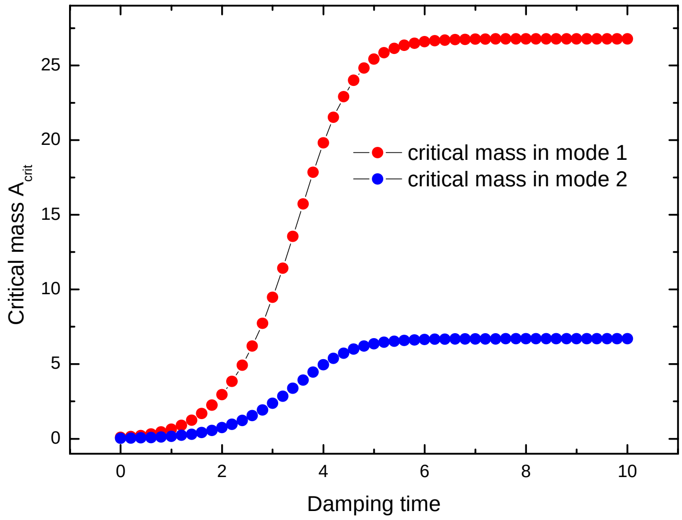

Fig.3: Critical ion mass in units of proton mass with respect to damping time for a uniform bunch pattern (mode 1: the bunch intensity is 2.0×10^{10}, # of bunches is 2625 and bunch spacing is 6ns; for mode 2, the bunch intensity is 1.0×10^{10} and # of bunches is 5534 and bunch spacing is 3ns). One long bunch train is assumed here.

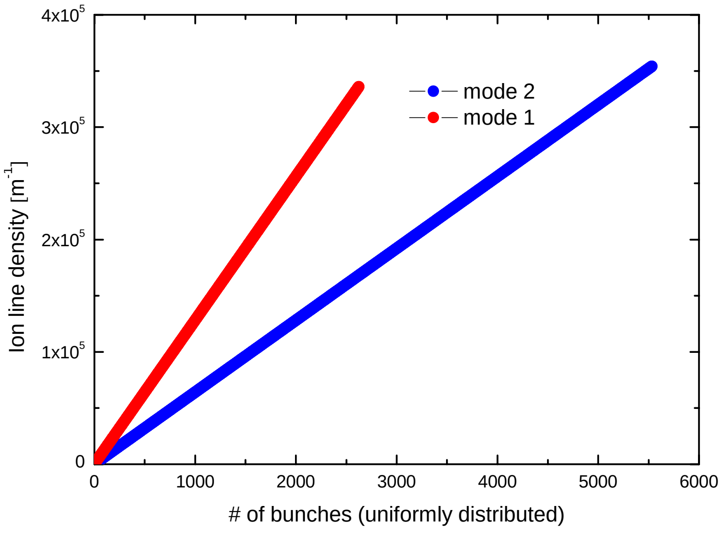

Fig.4: Line density of trapped ions for a uniform bunch pattern as a function of the number of bunches, for mode 1 and mode 2 respectively (Partial pressure of CO is 1 nTorr).

If the ions are trapped in the beam, they give rise to additional focusing. The ion induced coherent tune shift is given by [7]

$$\Delta Q_{x,y;coh} = \frac{\beta_{x,y} r_e \lambda_{ion} C}{\gamma 4\pi\sigma_{x,y}\left(\sigma_x + \sigma_y\right)} \tag{8}$$

here, C is the circumference of the ring, β_x, β_y are the horizontal and vertical beta functions, respectively. For a single long bunch train, the ion induced coherent tune shifts at the bunch train end are 0.29 and 0.32 in mode 1 and mode 2 respectively.

When these ions are trapped by the beam, they oscillate in the beam potential well. The ion frequency is [8]

$$f_{i;x,y} = \frac{c}{2\pi}\left(\frac{4N_b r_p}{3AL_{sep}\sigma_{x,y}\left(\sigma_x+\sigma_y\right)}\right)^{1/2} \tag{9}$$

The horizontal and vertical ion frequencies for CO are depicted in Fig.5. It can be seen that the vertical ion frequency is about one order of magnitude larger than that of the horizontal one.

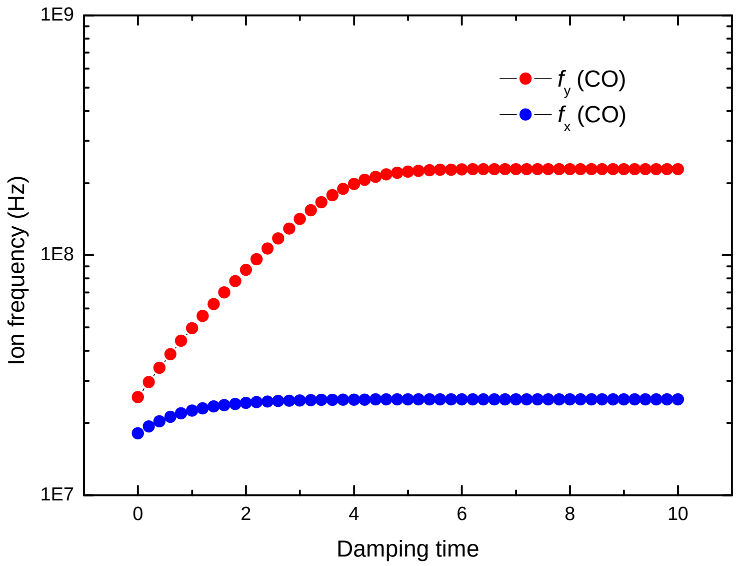

Fig.5: Horizontal and vertical ion oscillation frequencies of CO in mode 1.

The ion cloud and beam particles oscillate with respect to each other and cause conventional trapped ion instability in the storage rings. In general, an ion-clearing gap after the bunch train makes the ions unstable and over-focused by the beam potential. Beam shaking and clearing electrodes constitute other methods to cure this kind of instability.

3 Fast Ion Instability in ILC Damping Ring

In low emittance and high intensity storage rings, fast ion instability is potentially detrimental to the machine performance [6-9]. For the ILC damping ring, the beam emittance is extremely low, the bunch number is large and the bunch spacing is small. The number of ions accumulated from one single train is large enough to make the beam unstable.

According to the linear theory, the growth rate of FII strongly depends on the bunch intensity, number of bunches, the transverse beam sizes and the residual gas pressure. It can be estimated as [6]

$$\tau_c^{-1}(s^{-1}) = 5p[Torr]\frac{N_b^{3/2}n_b^2 r_e r_p^{1/2} L_{sep}^{1/2} c}{\gamma\sigma_y^{3/2}\left(\sigma_x+\sigma_y\right)^{3/2} A^{1/2}\omega_\beta} \tag{10}$$

where p is the partial residual gas pressure which causes 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, 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, $\omega_\beta \approx 1/\beta_y$ is the vertical betatron frequency.

The ion coherent angular frequency ω_i is given by

$$\omega_i = \left(\frac{4N_b r_p c^2}{3AL_{sep}\sigma_y(\sigma_x + \sigma_y)} \right)^{1/2} \tag{11}$$

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

$$\tau_e^{-1}[s^{-1}] = \frac{1}{\tau_c} \frac{c}{2\sqrt{2} l_{train} (\Delta\omega_i)_{rms}} \tag{12}$$

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

Using the parameters of the ILC damping ring in Table 1, the FII growth time is analytically calculated. One long bunch train is assumed here to see how fast this instability grows. Fig.6 and Fig.7 describe the growth time of FII with respect to the number of bunches in mode 1 and mode 2, respectively. In addition, simulation shows that the ion angular frequency spread is about 30% in baseline damping ring lattice [10]. It can be seen that in case of 30% ion angular frequency spread the growth time of FII is three orders of magnitude larger than that of without ion angular frequency spread. Here we assume a partial CO vacuum pressure of 1 nTorr. From these analytical results we can see at bunch train end, the growth time of FII is extremely fast in both cases (mode 1 and mode 2). The FII growth time for the 2625th bunch is 4.6×10^{-3} μs in mode 1 and for the 5534th bunch is 4.1×10^{-3} μs in mode 2. If 30% of ion angular frequency spread is used in calculation, the FII growth time for the 2625th bunch is 7.4 μs in mode 1 and for the 5534th bunch is 7.0 μs in mode 2. This growth time can potentially be controlled by up-to-date bunch by bunch feedback system [11].

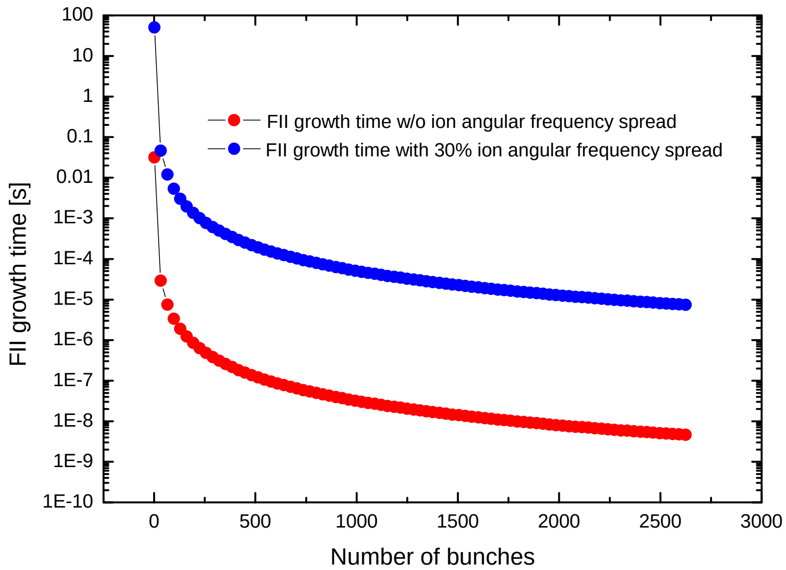

Fig.6: FII growth time as a function of bunch number in mode 1
for CO partial pressure of 1 nTorr.

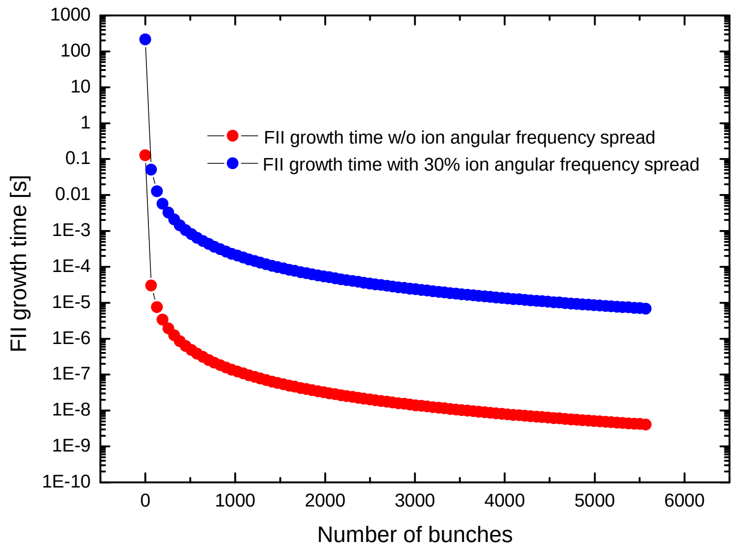

Fig.7: FII growth time as a function of bunch number in mode 2 for CO partial pressure of 1 nTorr.

Conclusion

In the ILC electron damping ring, the beam emittances are damped due to the radiation damping from wigglers and main dipoles. The beam sizes reduce as a function of time and finally reach the equilibrium state (~ after a few damping times). Therefore the ion trapping condition is also changing with respect to storage time. In mode 1 (nominal operation of ILC DR, 2625 bunches, 2×10^{10} bunch intensity and 6ns bunch spacing), the CO ions will not be trapped in the beam potential after about 4 damping times. While in mode 2 (low Q operation, 5534 bunches, $1*10^{10}$ bunch intensity and 3 ns bunch spacing), all CO ions will be trapped in the beam during whole storage time. The ion line density increases linearly with the number of bunches, so the short bunch train will eliminate the ion effects [10]. Based on the linear theory of fast ion instability, the analytical FII instability growth time is extremely fast (less than one revolution turn) when ignoring the ion frequency spread and assuming a single long bunch train. If we consider about 30% of ion frequency spread, the FII growth rate is three orders of magnitude lower. Actually the linear theory gives an over estimation about FII growth time. In real case, if this instability occurs, the nonlinear force between beam and ions will make this instability slow down and reach an equilibrium state.

Acknowledgements

This work is supported by the Commission of the European Communities under the 6^{th} Framework Programme "Structuring the European Research Area", contract number RIDS-011899.

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