SIMULATION STUDY OF FAST ION INSTABILITY IN THE ILC DAMPING RING

Guoxing Xia, Eckhard Elsen
Deutsches Elektronen-Synchrotron DESY, 22607, Hamburg, Germany

Abstract

The so-called fast ion instability (FII) potentially constitutes a performance limitation for the electron damping ring of the International Linear Collider (ILC). Based on the latest baseline lattice of the ILC damping ring, the fast ion instability is simulated using a weak-strong code. Various fill patterns are examined to mitigate the onset of the instability. Feedback mechanisms are also explored. The growth time of the fast ion instability is estimated for various vacuum pressures on the basis of the simulation results.

INTRODUCTION

The so-called fast ion instability is still one of the very high priority issues for the R&D of the damping rings for the International Linear Collider (ILC) [1]. The accumulated ions coming from collisional ionization between beam particles and residual gas molecules in the vacuum chamber will cause two beam instabilities and lead to beam size blow up, beam emittance growth, tune shift and tune spread [2, 3]. It potentially has adverse effects for the low emittance ring performance like the ILC electron damping rings. In order to see which parameter set will trigger this instability, in this paper the fast ion instability is simulated using a weak-strong code based on the latest baseline lattice of the ILC damping ring. The beam oscillation amplitude in various fill patterns and different gas pressures are investigated in details and the corresponding growth time is also estimated from the simulation results. This paper is structured as follows. In section 2, the simulation principle is briefly introduced. Section 3 presents the detailed simulation results for various fill patterns. Finally, a short summary is given in section 4.

SIMULATION METHOD

A code has been developed to simulate the beam centroid oscillation due to FII. The weak-strong model is employed in this code [4]. 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 macro-particles, which are ionized by the previous electron bunch. In order to save computation time, we assume there is limited number of ionization points in the damping ring. The ion motion is non-relativistic without longitudinal drift. The ion distribution is the same as its 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 upon it can be calculated by applying the Bassetti-Erskine formula [5]

$$F(x,y) = -2N_0 r_e m_e c^2 f(x,y) \qquad (1)$$

where N_0 is the number of particles per bunch, r_e is the classical radius of electron, m_e is the electron mass, c is the speed of light. (x,y) are the horizontal and vertical position with respect to the bunch centre. $f(x,y)$ is a function composed by complex error function w as follows

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

in which the complex error function is give by

$$w(z) = e^{-z^2}\left[1+\frac{2i}{\sqrt{\pi}}\int_0^z e^{t^2}\,dt\right] \qquad (3)$$

Therefore, 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

$$\Delta y_e' + i\Delta x_e' = \frac{2N_0 r_e}{\gamma}\sum_i f(x_{ie}, y_{ie}) \qquad (4)$$

and the kick to an ion with mass M_A is given by

$$\Delta y_i' + i\Delta x_i' = -2N_0 r_e c\frac{m_e}{M_A} f(x_{ie}, y_{ie}) \qquad (5)$$

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

SIMULATION RESULTS

The number of ions that are generated by an electron bunch with the particle population of N_0 is given by $n_i[m^{-1}] = 0.045N_0 p$ [Pa]. For the CO partial pressure of 1 nTorr, the ion line density are 62m^{-1}, 93m^{-1} and 124m^{-1}, for the typical fill pattern case *A*, *B* and *C* as listed in Table 1 [6], respectively.

Since the vertical beam emittance is smaller than the horizontal one, the FII is much serious in the vertical plane. In our simulations, the time evolution of the growth of dipole amplitude of the beam is simulated and recorded turn by turn. The vertical amplitude of bunch centroid is half of the Courant-Synder invariant, which is given by

$$J_y = \frac{1}{2}\left[\frac{\left(1+\alpha^2\right)}{\beta}y^2 + 2\alpha y y' + \beta y'^2\right] \qquad (7)$$

where α and β are the Twiss parameters. We compare $\sqrt{J_y}$ with the vertical beam size, which is represented by the value of $\sqrt{\varepsilon_y}$ (here, ε_y is the vertical emittance of the beam). Both of these quantities are in units of $\mathrm{m}^{1/2}$.

In the simulation, we use three typical fill patterns for the OCS8 damping ring. The basic beam parameters of the ILC OCS8 damping ring are listed in Table 2. In order to save CPU time, the optical functions of one of the octants of the ring are used. For each fill pattern, 10 bunch trains are chosen in our simulation.

Table 1: Typical fill patterns in the ILC damping ring

Fill patterns	*A*	*B*	*C*
Bunch spacing, [bucket]	2	2	4
Number of trains	117	78	58
Bunches per even-numbered minitrain	0	0	23
Gaps per even-numbered minitrain	0	0	30
Bunches per odd-numbered minitrain	45	45	22
Gaps per odd-numbered minitrain	30	90	30
DR average current, mA	405	405	401
Total number of bunches	5265	3510	2610
Bunch population [$\times 10^{10}$]	1.04	1.56	2.07

Fig. 1 shows the evolution of maximum amplitude with respect to number of turns for fill pattern case *A* without and with active feedback damping. The feedback damping time is 50 turns (~ 1ms) in our simulation (This is rather conservative considering the current technology. At present in PEP II, the feedback damping time is about 500 µs) [7]. In this Figure, N_0 denotes the number of particles per bunch, n_b the number of bunch per train, n_{train} the number of train, L_{sep} the bunch spacing in units of RF bucket, LtrainGap the gap length between two adjacent bunch trains. It can be seen that for the CO pressure of 1 nTorr, the growth of vertical amplitude is beyond the beam size. By employing the feedback system, the growth of vertical amplitude can be damped closely to the beam size. Fig. 2 gives the growth of maximum amplitude with respect to the number of turns for fill pattern case *B* without and with feedback damping. The growth of vertical amplitude is also beyond the beam size in CO pressure of 1 nTorr. Feedback can suppress the growth of instability to a certain amount. Fig. 3 shows the result in fill pattern case *C*, in which we modified the number of bunches per train in order to simplify the simulation. The conclusion is nearly the same as the above fill pattern case *A* and *B*.

Meanwhile, the mini-train effect is also studied. Fig. 4 shows the evolution of maximum amplitude with respect to number of turns for fill pattern *C* for short bunch train and long bunch train cases without feedback damping. We take 5 trains with 46 bunches per train and 10 trains with 23 bunches per train respectively (the total number of bunches is the same in both cases). It shows that the growth of vertical amplitude for long bunch train is faster than that for the short bunch train. This is because for the short trains, the gaps between bunch trains can reduce the ion density near the beam and therefore weaken the growth of FII.

Table 2: The basic parameters of ILC damping ring

Energy	5 GeV
Circumference	6476.4395 m
Harmonic number	14042
Betatron tunes	49.23, 53.34
Chromaticity	-63.7, -63.3
Momentum compaction	3.96×10^{-4}
Natural emittance	4.95 *µm*
Damping time	25 ms
RF voltage	21.2 MeV
Energy loss per turn	8.7 MeV
Momentum acceptance	1.48%
Synchrotron tune	0.06
Equilibrium bunch length	9 mm
Equilibrium energy spread	0.128%

The evolution of vertical amplitude in different gas pressures is shown in Fig. 5 for the fill pattern case *A*. It indicates the higher the gas pressure, the higher the growth of vertical amplitude. The vertical amplitude grows quickly in the beginning and then slows and finally saturates. This is also the characteristic of FII in linear theory [2]. The growth time of FII can also be estimated from the simulation results in different gas pressures and shown in Fig. 6. It indicates that the growth time of FII decreases as the gas pressure increases.

Fig. 7 gives the evolution of maximum amplitude with respect to number of turns for fill pattern case *A* in various feedback damping times for the CO pressure of 1 nTorr. It indicates that feedback damping time of over 50 turns cannot damp the instability totally. With the feedback damping time of 20 turns (~ 0.4 ms), the instability can be damped below the beam size.

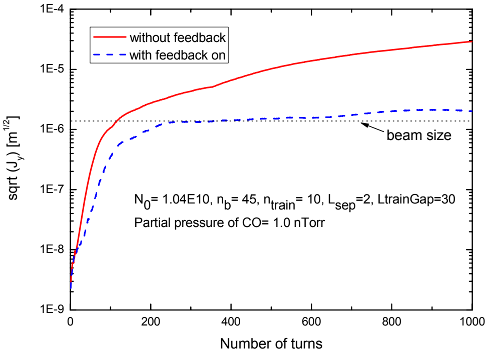

Fig. 1: Evolution of maximum amplitude with respect to number of turns for fill pattern *A* without and with feedback damping.

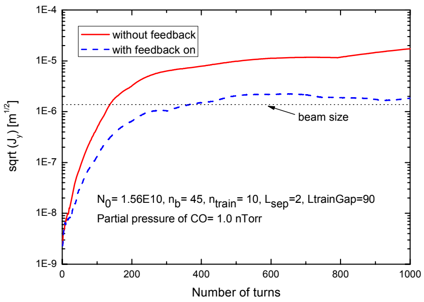

Fig. 2: Evolution of maximum amplitude with respect to number of turns for fill pattern *B* without and with feedback damping.

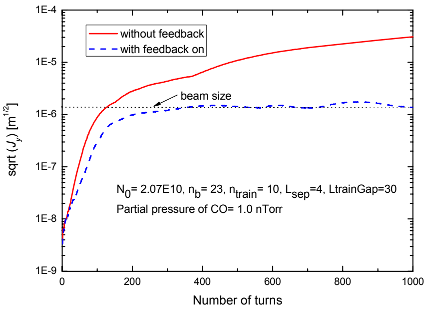

Fig. 3: Evolution of maximum amplitude with respect to number of turns for fill pattern *C* without and with feedback damping.

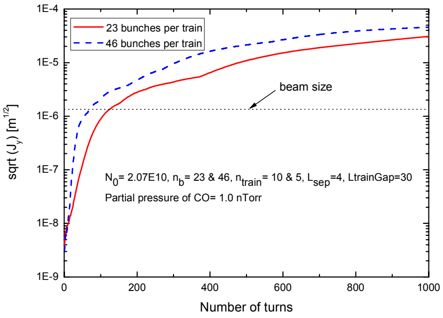

Fig. 4: Evolution of maximum amplitude with respect to number of turns for fill pattern *C* for short bunch and long bunch case without feedback damping.

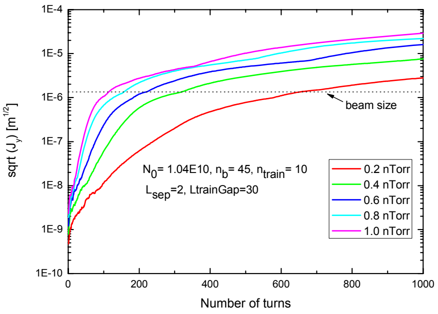

Fig. 5: Evolution of maximum amplitude with respect to number of turns for fill pattern *A* in various gas pressure of CO.

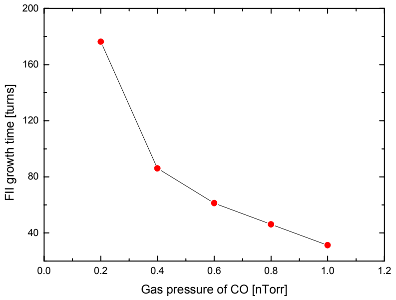

Fig. 6: FII growth time *vs*. gas pressures of CO for fill pattern *A* without feedback.

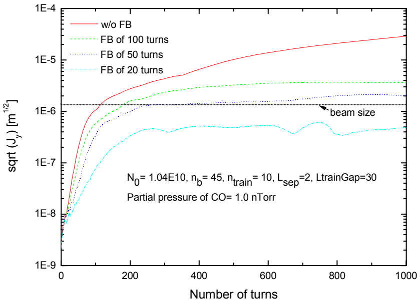

Fig. 7: Evolution of maximum amplitude with respect to number of turns for fill pattern case *A* in various feedback damping times.

SUMMARY

The simulation results show that for the current fill patterns, the fast ion instability cannot be totally damped by the fast feedback system with the damping time of 50 turns if the gas pressure of CO is larger than 1 nTorr. Therefore, better vacuum pressure less than 1 nTorr and an advanced feedback system with damping time shorter than 50 turns are crucial to alleviate FII. Comparing to one long bunch train case, the minitrain can reduce the growth of FII significantly.

ACKNOWLEDGMENTS

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

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