ION INSTABILITY STUDY FOR THE ILC 3 KILOMETER DAMPING RING

Guoxing Xia
Max Planck Institute for Physics, 80805, Munich, Germany

Abstract

The ILC GDE is currently pushing the cost reduction for all subsystems of the ILC project for the Technical Design Phase 1 (TDR). A short damping ring with circumference of 3.2 km (Strawman Baseline 2009 or SB2009) was developed for this purpose. Based on this lattice, we performed a weak-strong simulation study of the fast ion instability in the electron damping ring for various beam fill patterns and vacuum pressures. The simulation results are given in this paper.

INTRODUCTION

The residual gases in the vacuum chamber of an accelerator generally account for the formation of the ion cloud. When the electron beam in a storage ring collides with the residual gases (H_2, H_2O, CO, N_2, CO_2, CH_4, etc.), the low velocity positively charged ion are produced and trapped in the beam potential. If the number of ions reaches a certain threshold, they will disturb the motion of beam. This two-stream instability due to ions has long been recognized as a potential limitation in the machines like electron and antiproton storage rings. They may result in beam emittance growth, tune shifts and spread, and the beam lifetime reduction etc [1].

Generally speaking, there are two kinds of ion effects. One is called conventional ion trapping instability and the other is called fast ion instability. For the former case, the ions are accumulated over many turns in the storage ring and trapped by the beam potential all the time. This instability can be partially cured by intentionally leaving some empty RF buckets (gaps) in the beam fill pattern after the bunch train. These gaps will make the ions over-focused and eventually lost to the vacuum chamber wall.

However, modern storage rings feature an extremely small beam emittance (in nanometer scale) and many bunches (a few hundreds to thousands bunches) operation. The bunch spacing is therefore very short (a few nanoseconds), effect of single-passage ion instability so called fast ion instability (FII) is dominant [2, 3]. In this case, the ions are generated from a single passage of the bunch train and the ion density increases linearly along the bunch index. The number of ions produced by a single long bunch train is large enough to disturb the beam motion significantly. In the gap at the end of the bunch train the ions are lost, and there are only insignificant amount of ions left when the bunch train returns on its next revolution. This phenomenon has already been observed in many electron storage rings and ring-based light sources, e.g., ALS, PLS, TRISTAN-AR, ELETTRA, ATF, SSRF, SOLEIL, etc. [4-8].

The International Linear Collider (ILC) will be the next generation lepton collider beyond the LHC. It will give us more insights about our Universe. To meet the luminosity requirement, many ultra-low emittance electron and positron bunches are needed for collision. For the electron damping ring, many bunches (a few thousands) with short bunch spacing will circulate in the ring for a few damping times to achieve an ultra-low emittance. In this case, the fast ion instability is appreciable and it has been recognised as one of the highest priority issues for the R&D of the ILC damping ring.

In 2009, The ILC GDE pushed the cost reduction for all subsystems of the project for the Technical Design Phase (TDR). A short damping ring with circumference of 3.2 km (Strawman Baseline 2009 or SB2009) was therefore developed for this purpose [9]. Since there are 1305~2610 bunches filled in the ring and the bunch spacing is very short (3 ns), the number of ions produced by a long bunch train will be significant, which may produce a strong perturbation to the beam motion. The main beam parameters for SB2009 damping ring are listed in Table 1. Based on this lattice, we performed a simulation study of the fast ion instability in the electron damping ring for various beam fill patterns and vacuum pressures. The simulation results are given in this paper.

Table 1: Beam Parameters for ILC SB2009 Damping ring

Energy (GeV)	5.0
Circumference (m)	3238
Harmonic number	7021
Bunch number	2610-1305
Bunch spacing (buckets)	2-4
Number of particles/bunch	2×10^{10}
Damping time τ_x (ms)	24
Emittance ε_x (nm)	0.66
Emittance ε_y (pm)	2
Momentum compaction α	1.5×10^{-4}
Synchrotron tune	0.059
Energy spread	1.2×10^{-3}
Bunch length (mm)	6
RF frequency (MHz)	650
RF voltage (MV)	7.5

SIMULATION METHOD

We employ a weak-strong code to simulate the interactions between the electrons and ions in the damping ring [10]. In our simulation, the beam is rigid and regarded to be a Gaussian distribution in the transverse plane and the ions are regarded as the macro-particles. Only the barycentre motion of the beam is taken into account. The number of ions is increased with respect to the number of bunches in the bunch train. The ion line density per bunch is given by $\lambda_{ion} = N_0\sigma_{ion}n_{gas}$, here N_0 is the bunch population, σ_{ion} is the ionization cross section of gas and n_{gas} is the gas density (the gas density is proportional to the gas pressure in vacuum pipe). In the simulation, the first bunch in the bunch train produces the ions and it does not interact with the ions. The following bunches interact with the ions produced by their preceding bunches. After one turn interaction, we assume that the ions are cleared away from the beam vicinity (either by clearing gap or clearing electrodes). The new ions will be produced by the beam in the second turn. In our simulation, one arc section of SB 2009 lattice (SB2009 damping ring is a racetrack structure, we use only one arc section to save CPU time in calculation) is used in which the beta function and dispersion function vary in different locations along the ring. In these interaction points (each element in the lattice corresponds to an interaction point), we artificially enhance the number of ions by taking into account the real vacuum pressure of the ring. The adjacent beam-ion interaction points are connected through the linear transfer matrix. The beam parameters used here are taken from Table 1.

We assume that the major species of the residual gas in the vacuum chamber are Carbon Monoxide (CO) and Hydrogen (H_2). Since the cross section of collision ionization for CO is about 6 times higher than that for H_2 in this beam energy regime. In addition, the heavy mass of CO makes it easier to be trapped in the beam potential. We therefore regard CO^+ ions the dominant instability source in the simulation.

SIMULATION RESULTS

For the ILC damping ring, a flat beam is circulated in the ring. The vertical beam emittance is much smaller than the horizontal one (coupling factor of ~0.4%), therefore the FII is much more significant in the vertical plane. In our simulations, the time evolution of the growth of beam dipole amplitude is simulated and recorded turn by turn. The data are recorded for 1000 turns which is around a half damping time. The vertical oscillation amplitude of the bunch centroid is half of the Courant-Synder invariant and given by

$$J_y = \left[\gamma y^2 + 2\alpha y y' + \beta y'^2\right]/2$$

where α, β and γ are the Twiss parameters of the ring determined by the ring lattice. The value of $\sqrt{J_y}$ is compared with the vertical beam size which is represented by the value of $\sqrt{\varepsilon_y}$ (here ε_y is the beam vertical emittance).

Fig. 1 shows the beam maximum vertical oscillation amplitude due to FII with respect to the number of turns for a single long bunch operation in which 1305 bunches are filled in the ring. In this figure, N_0 is the number of particles per bunch, n_b the number of bunches per train, n_{train} is the number of trains and S_b is the bunch spacing. Here we assume the CO partial pressure of 1.0 nTorr. It can be seen that the beam oscillation amplitude is above the beam size (vertical beam size is around 1.4×10^{-6} m, as depicted by a dot line in the figure). The growth time of FII is also estimated and shown in the Fig.1. We can see in this case the FII growth time is very quickly (3 turns) and it is difficult to use feedback system to cure the FII (Typical damping time of the fast bunch-by-bunch feedback damping system is 0.2 ms from the experience of KEKB [11]). Fig.2 and Fig.3 give the beam maximum oscillation amplitude with respect to the number of turns with the same beam parameters as used in Fig.1 at CO pressure of 0.1 nTorr and 0.01 nTorr, respectively. It can be seen that at CO pressure of 0.1 nTorr the growth of beam vertical amplitude is beyond the beam size and the FII growth time is around 40 turns, which is longer than that at CO pressure of 1 nTorr. At CO pressure of 0.01 nTorr, the beam vertical amplitude is below the beam size due to fewer ions produced at lower gas pressure. Appling a very fast feedback system with damping time 20 turns (~0.2 ms) in the simulation, Fig.4 shows that the growth of FII can be cured at CO pressure of 0.1 nTorr. For 2610 bunches in a single train operation, Fig. 5 gives the growth of beam maximum oscillation amplitude with respect to the number of turns at CO pressure of 0.1 nTorr. In this case, the bunch spacing is 2 RF buckets. We found that the FII growth time is 20 turns, which is half of the FII growth time shown in Fig.2. This is because more ions are produced for 2610 bunches than that for 1305 bunches at the same bunch intensity. Even when the CO pressure is 0.01 nTorr, the growth of maximum oscillation amplitude is still over the beam size, as shown in Fig.6. In order to control the growth of FII, we divide a long bunch train into many small bunch trains (minitrain), with each consisting of tens of bunches. We then simulate the FII growth for different minitrain cases. Fig. 7 depicts the growth of FII for a specific fill pattern, in which 1305 bunches are divided into 29 bunch trains, with each consisting of 45 bunches. In between the two adjacent bunch trains, 62 RF buckets ((LtrainGap = 62) are left for ions clearing. The simulation shows that at CO pressure of 0.1 nTorr, the FII growth rate is significantly reduced, compared to Fig.2. Fig.8 shows the growth of FII for another specific fill pattern, in which 2610 bunches (with bunch intensity $N_0 = 1.0\times10^{10}$) are divided into 58 bunch trains, with each consisting of 45 bunches. In between the two adjacent bunch trains, 31 RF buckets (LtrainGap =31) are left for ions clearing. The simulation shows that at CO pressure of 0.1 nTorr, the FII growth time is 145 turns, which is longer than the growth time shown in Fig.5 and it may be damped by applying a fast bunch-by-bunch feedback system.

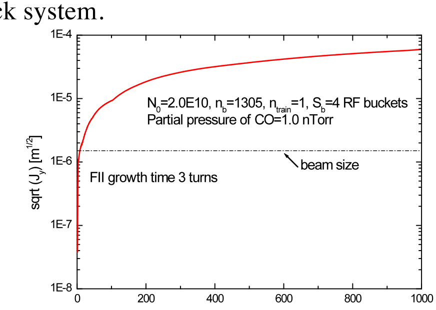

Figure 1: Beam oscillation amplitude *vs*. number of turns for 1305 bunches in a single train at 1.0 nTorr CO.

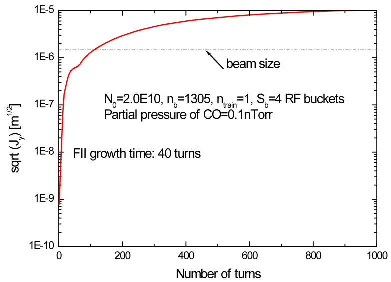

Figure 2: Beam oscillation amplitude *vs*. number of turns for 1305 bunches in a single train at 0.1 nTorr CO.

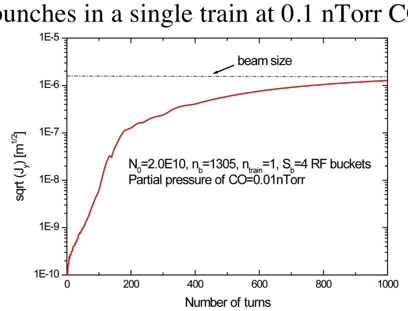

Figure 3: Beam oscillation amplitude *vs*. number of turns for 1305 bunches in a single train at 0.01 nTorr CO.

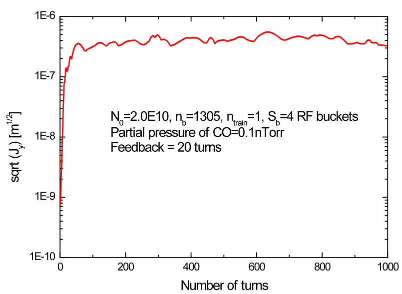

Figure 4: Beam oscillation amplitude *vs*. number of turns for 1305 bunches in a single train at 0.1 nTorr CO, with a feedback damping of 20 turns.

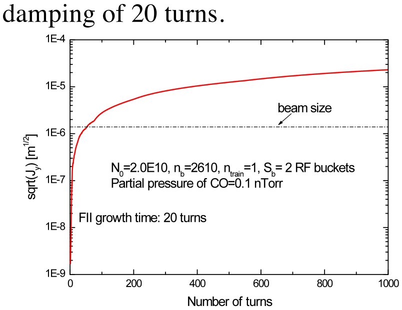

Figure 5: Beam oscillation amplitude *vs*. number of turns for 2610 bunches in a single train at 0.1 nTorr CO.

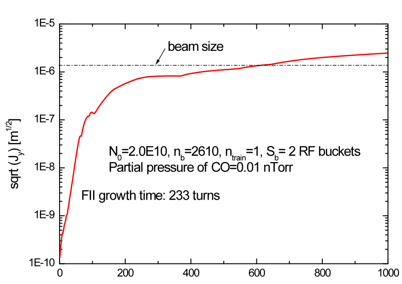

Figure 6: Beam oscillation amplitude *vs*. number of turns for 2610 bunches in a single train at 0.01 nTorr CO.

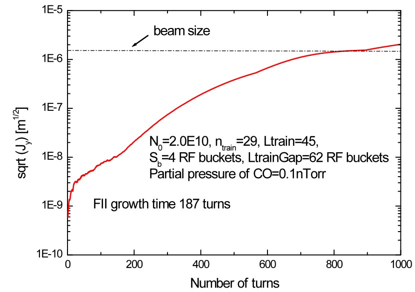

Figure 7: Beam oscillation amplitude *vs*. number of turns for 29 bunch trains, with each consisting 45 bunches at 0.1 nTorr CO.

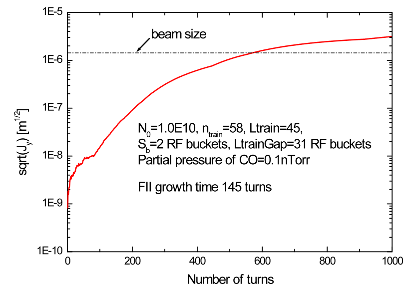

Figure 8: Beam oscillation amplitude *vs*. number of turns for 58 bunch trains, with each consisting 45 bunches at 0.1 nTorr CO.

CONCLUSION

The fast ion instability based on the ILC SB2009 damping ring lattice has been simulated by using a weak-strong code. Simulation shows that the beam vertical oscillation amplitude grows beyond the beam size for a single long train operation at the CO pressure larger than 0.1 nTorr. For a very low vacuum pressure, e.g. CO pressure of 0.01 nTorr, the beam oscillation amplitude is within the beam size level for 1305 bunch operation. Besides, a feedback system with damping time tens of revolution turns may control the FII growth in the ring. If the long bunch train is divided into several mini-trains with empty RF buckets in between as clearing gaps, the growth rate of FII will be reduced significantly.

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