SIMULATION OF THE BEAM-ION INSTABILITY IN THE ELECTRON DAMPING RING OF THE INTERNATIONAL LINEAR COLLIDER*

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Abstract

Ion induced beam instability is one critical issue for the electron damping ring of the International Linear Collider (ILC) due to its ultra small emittance of 2pm. Bunch train filling pattern is proposed to mitigate the instability and bunch-by-bunch feedback is applied to suppress it. Multi-bunch train fill pattern is introduced in the electron beam to reduce the number of trapped ions. Our study shows that the ion effects can be significantly mitigated by using multiple gaps. However, the beam can still suffer from the beam-ion instability driven by the accumulated ions that cannot escape from the beam during the gaps. The effects of beam fill pattern, emittance, vacuum and various damping mechanism are studied using self-consistent program, which includes the optics of the ring.

INTRODUCTION

There are various ion effects in electron storage rings. Most of these are "conventional" effects which occur when ions are trapped by a circulating electron beam for multiple revolutions. To avoid conventional ion trapping, as in the two B-factories and most of the light sources, a long gap is introduced in the electron beam by omitting a number of successive bunches out of a train. However, the beam can still suffer from the beam-ion instability even with gaps in the train [1-4]. In the fast ion instability, individual ions last only for a single passage of the electron beam and are not trapped for multiple turns.

This paper briefly describes the beam-ion instability and tune shift due to ions in the ILC damping rings. The ion effects depend on the beam size and betatron functions. The beam emittance varies during the damping time as

$$\varepsilon(t) = \varepsilon_{eq} + (\varepsilon_i - \varepsilon_{eq})e^{-2t/\tau} \tag{1}$$

Where ε_i, ε_{eq} are respectively the injected and equilibrium emittance, and τ is the damping time. The injected emittance is 100 nm. The equilibrium horizontal and vertical emittances are 0.5 nm and 2 pm respectively. Therefore, the ion effects are a function of time.

The baseline design of ILC Damping Ring is one 6 km ring for the electron beam. This paper estimates the beam-ion instability in the 6km electron ring using a using self-consistent simulation program.

INSTABILITY DRIVEN FORCE

Both the instability growth rate and tune shift due to the ion-cloud are proportional to the ion density and inversely proportional to the beam energy. Therefore, they are proportional to the following factor

$$F = 10^5 \frac{N_b N}{E} \frac{1}{\sigma_x \sigma_y} = 10^5 \frac{q}{E} \frac{1}{\sigma_x \sigma_y}, \tag{2}$$

with the approximation of $\sigma_x >> \sigma_y$, which is satisfied for most of the light sources and damping rings. Table 1 compares the ion instability driven force for some electron rings. In the table, N_b is the total number of bunch, I is the total beam current, S_B is bunch spacing and q is the total charge of the beam. All the rings are assumed to be filled with one long bunch train and all the rings have the same vacuum. Note that the vertical emittance of ALS in normal operation is 0.13μm in order to improve the beam's lifetime. The APS beam has long bunch spacing of 46*m*, where ions are not trapped at all. Table 1 shows ILC damping ring has the maximum driven force of the beam-ion instability. It is about two orders of magnitude higher than the B-factories. Since Super B-factory has a high vacuum pressure of 5*nTorr* of CO+ [5], it also will have strong instability, which can be faster than ILC damping ring.

Table 1: Comparison of main parameters and driven force of ion instability

RING	E (GeV)	CIR(m)	Nb	I (mA)	S_B(m)	q 10^{13}	E_X/σ_x nm·rad/μm	E_Y/σ_Y nm·rad/μm	F
KEKB	8.0	3016	1387	1200	2.1	7.62	24/500	0.4898/75	2.5
PEPII	8.0	2199	1588	1550	1.26	7.1	31/660	1.4/144	0.9
SUPERB	3.5	3016	5120	9400	0.6	59.5	24/600	0.96/120	83
ALS	1.5/1.9	196.8	320	400	0.6	0.1657	6.3/160	0.06(0.13)/23	4.5
APS	7.0	1104	24	100	45.9	0.23	3.0/276	0.025/11	7.6
PLS	2	280	180	360	0.6	0.2	12.1/350	0.12/35	0.8
ATF	1.3	138	20	64	0.77	0.01	1.2/70	0.0045/5	2.8
ILC	5	6000	3~6K	400	0.5~1	6.0	0.8/120	0.002/6	170

MITIGATIONS AND DAMPING MECHANISMS

Multi-train beam filling

Without gaps in the beam fill pattern, the ions with a relative molecular mass greater than $A_{x(y)}$ will be trapped horizontally (vertically), where

$$A_{x(y)} = \frac{N r_p S_b}{2(\sigma_x + \sigma_y)\sigma_{x(y)}} \tag{3}$$

where r_p is the classical radius of the proton, n is the number of electrons per bunch and $\sigma_{x(y)}$ is the *rms* horizontal (vertical) beam size. In most electron rings, one

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single bunch train with a long gap is often used to remove the trapped ions. The ions generated by the bunches at the head of train can cause fast ion instability. A multi-bunch train filling beam is proposed for ILC in order to reduce the number of trapped ions [6], and therefore the driven force of the instability. The number of trapped ions can by reduced by a factor which inversely proportional to the number of bunch train:

$$IRF = \frac{1}{N_{train}} \frac{1}{1-\exp(-\tau_{gap}/\tau_{ions})} \quad (4)$$

Here, τ_{gap} is the length of bunch train gaps. τ_{ions} is the diffusion time of ion-cloud, which is close to the ion oscillation period:

$$T_{x(y)} = \frac{2\pi}{c}\left(\frac{3AS_b(\sigma_x+\sigma_y)\sigma_{x(y)}}{4Nr_p}\right)^{1/2} \quad (5)$$

where A is the mass number of the ion.

There are various possible beam-filling patterns in ILC. The number of bunches varies from 3000 to 6000 with a constant total beam current. We study two special beam patterns: 2767 bunches and 5782 bunches. The main parameters for these two filling patterns are listed in Table 2.

Table 2: Beam filling patterns

Filling pattern	No1	No2
Total Number of bunches	2767	5782
Number of bunch train	125	118
Number of bunch per train	22/23	49
Bunch spacing (ns)	6	3
Length of train gap (ns)	38	43
Bunch intensity ($\times 10^{10}$)	2	1
Pressure (nTorr)	1	1

The 2767 filling pattern has slight more bunch trains with a slight shorter train gaps. The τ_{ions} is the same for the two filling patterns because of their same beam line density. Simulation shows that the two filling patterns have a similar IRF and the ion density is reduced by a factor of more than 60 by using multi-train filling pattern.

With the multi-bunch-train filling pattern, the ions can be trapped for a period longer than one bunch train, but shorter than one turn. Therefore, the beam instability is neither the traditional ion trapping instability nor the classical fast ion instability. A simulation with the realistic beam pattern would be necessary to study the bunch train effect. One bunch train was used in the simulation with multi-train filling pattern to speed the simulation [7]. However, it gave a lower ion density, and therefore a longer growth time, due to the neglect of the surviving ions from the train gaps.

Landau damping due to the tune spread

The ion bounce frequency varies along the ring due to the variation of the twiss functions. This tune spread can damp the instability by a factor of $1/\Delta\Omega_{i,rms}$, which depends on the optics of the ring. Figure 1 shows the betatron function and dispersion of one ILC damping ring design. Simulations with single and multiple beam-ion interaction points by including the realistic optics give a vertical instability time of 4 turns and 13 turns, respectively. This gives a damping factor of 3.25 due to the frequency spread, which indicates a tune spread $\Delta\Omega_{i,rms}$ of 0.3. The beam vertical oscillation and beam spectrum are shown in Figure 2 and 3, respectively. The bunch amplitude increase exponentially when the amplitude is small comparing with the beam size, and then it grows linearly with time [8].

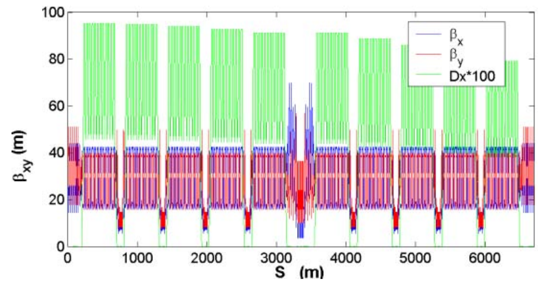

Figure 1: Optics of ILC 6km-damping ring

With multi-bunch-train filling pattern, the exponential growth time can be estimated as [6]:

$$\frac{1}{\tau_e} \approx \frac{cr_e\rho\beta_y}{3\sqrt{2}\gamma}\frac{1}{(\Delta\Omega_i)_{rms}} \quad (6)$$

Here, ρ is the simulated ion density. Note that Eq. (6) shows a simple dependence of the instability on the optics ($\Delta\Omega_{i,rms}$ and β), beam energy and ion density, which is related to the vacuum pressure and beam (current, filling pattern, and emittance). It is interesting that the form of Eq.(6) is similar to the instability of BBU due to the wake of ion cloud. Figure 4 shows the wake due to ion cloud for several beam conditions. The frequency of the wake is the same as the ion bouncing frequency and the Q-value of the wake is low. The wake generated by the preceding bunches can affect only the bunches within several bunch-trains afterward. Because of the larger ion frequency comparing to beam revolution frequency and the low Q of the wake, there are always some unstable modes. And the instability spectrum is wide-distributed even with single ion-beam interaction point as shown in Figure 2.

Effects of emittance and multi-species

The equilibrium emittance is used in the above simulation. With a larger emittance, ions are easier to be trapped and the train gaps are less effective in the clearing of ions. As a result, more ions can be accumulated and a higher ion density can be achieved. Detailed simulations with different emittance show that the instability can be faster with a larger emittance due to the higher ion density as shown in Figure 5. The instability growth time is shorter than 10 *turns* at earlier period after injection. The maximum tune shift due to the ion-cloud is 0.001.

There are a several gas species in the vacuum. Each gas ion has its own frequency. Therefore, additional tune spread is added when multi-gas is considered. Simulation shows the damping due to multi-gas species is small. The combination of its effect with those of train gap and optics makes it difficult to be identified. Another simulation concludes that the superposition rule applies for multi-species of ions [9].

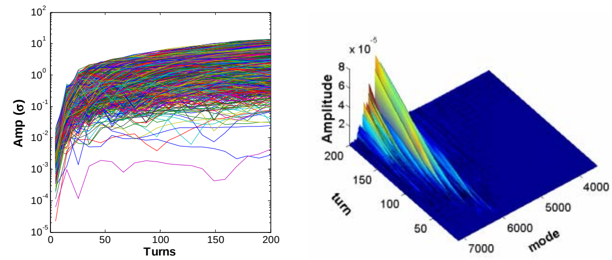

Figure 2: Simulated vertical oscillation amplitude and beam instability spectrum with one ion-beam interaction point. The total number of bunches is 5782. The pressure is 1 nTorr of CO+.

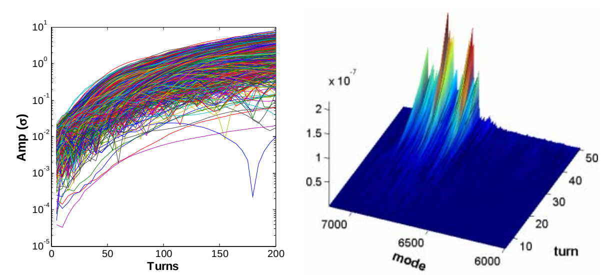

Figure 3: Simulated vertical oscillation amplitude and beam instability spectrum with realistic optics. The total number of bunches is 5782 and the pressure is 1 nTorr of CO+.

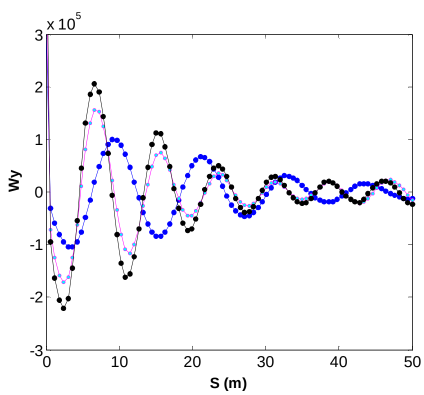

Figure 4: Vertical wake of the ion cloud for different bunch intensity.

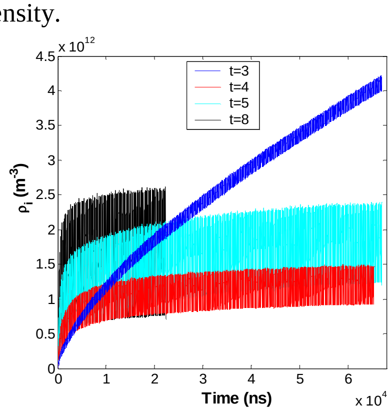

Figure 5: build-up of ion cloud with different emittance at different time after beam injection.

Feedback

The fast ion instability is transient. A slow damping, such as the radiation damping or feedback, can damp the bunch oscillation from the head to the tail in the train, and then the oscillation of all bunches is finally damped [10]. In ILC case, it is not the classical FII, the ion cloud can't be clear-up during the train gap. The surviving ions from the gaps can drive the bunches at the head of the train unstable. A bunch-by-bunch feedback is proposed to suppress the beam-ion instability. Simulation shows that a feedback with a damping time shorter than the instability growth time is required. Figure 6 shows the damping of the beam-ion instability by a bunch-by-bunch feedback system. The feedback is turned on when the beam oscillation amplitude is about 0.2σ.

As discussed above, the fast instability (exponential growth) occurs only at small amplitude. A slow feedback with a damping time longer than the exponential growth time can damp the linear instability and limit the beam oscillation amplitude within one beam size. Therefore, the beam is likely stable (not lost) even with a slow feedback. However, the remained oscillation can cause the loss of the luminosity.

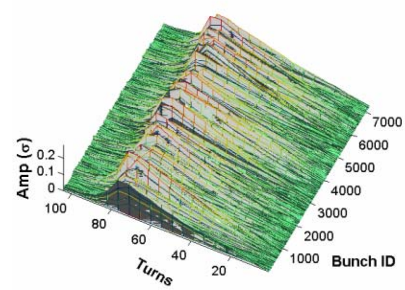

Figure 6: Damping of beam instability using bunch-by-bunch feedback. The total number of bunch is 5782.

SUMMARY

The instability can be mitigated by a factor of 60 by using multi-train beam filling pattern. However, the growth time can still be faster than 10 turns (the feedback capability).

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