BEAM ION INSTABILITY IN ILC DAMPING RING WITH MULTI-GAS SPECIES†

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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 2 pm. The beam ion instability with various beam filling patterns for the latest lattice DTC02 is studied using PIC code. The code has been benchmarked with SPEAR3 experimental data and there is a good agreement between the simulation and observations. It uses the optics from MAD and can handle arbitrary beam filling pattern and vacuum. Different from previous studies, multi-gas species and exact beam filling patterns have been modeled simultaneously in the study. This feature makes the study more realistic. Analyses have been done to compare with the simulations.

INTRODUCTION

When the beam emittance becomes small, the trapped (or partially trapped) ions can cause beam instability and emittance blow-up as first predicted by Raubenheimer and Zimmermann [1]. The beam ion instability in ILC damping rings has been evaluated for various optics designs [3-6]. The DTC lattice has been recently selected as the official baseline lattice for the TDP-II (Technical Design Phase) of International ILC damping ring [2]. The beam ion instability depends on the optics and beam filling pattern. Therefore, it is important to evaluate the beam ion instability with the new lattice design. In previous studies[3-6], single gas species CO is used. It is more accurate to use a realistic vacuum, for instance, the vacuum with multi-gas species from the existing accelerators. Multi-gas species could provide additional damping to the instability due to the increment of ion frequency spread. Single gas-species model may overestimate the beam ion instability. Therefore, it is more realistic to use multi-gas species vacuum model.

The beam ion instability is sensitive to the beam filling pattern. Multi-bunch train is very effective on reduction of the ion density near the beam, for instance [3]. The effects of the beam filling pattern depend on both beam density and the mass of ion [7], therefore, the ion species in the vacuum. Hence it is essential to accurately model both the beam filling pattern and the vacuum simultaneously.

The vacuum in the vacuum chamber of different accelerators varies. For most light sources, Hydrogen is dominant gas. Table 1 shows the average vacuum in SPEAR3 vacuum chamber. This paper studies the beam ion instability in ILC damping ring baseline lattice DTC02 with a multi-gas model shown in Table 1, which is a good approximation.

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Table 2 lists the main parameters and beam filling patterns for three different configurations, which have different beam filling patterns. KCS and DRFS have the same number of bunches and beam current. They are different only in the beam filling pattern: KCS has longer bunch train and bunch train gap. FP upgrade mode has the highest beam current and the longest bunch train.

Table 1: Vacuum in the SPEAR3 vacuum chamber

Gas Species	Mass Number	Percentage in Vacuum
H_2	2	48%
CH_4	16	5%
H_2O	18	16%
CO	28	14%
CO_2	44	17%

Table 2: Main parameters of ILC DTC damping ring

Parameter	KCS	DRFS	FP upgrade
Energy[GeV]	**5.0**	**5.0**	**5.0**
Circumference[m]	**3238.76**	**3238.76**	**3238.76**
Emittance $\varepsilon_x/\varepsilon_y$ [pm]	**637/2**	**637/2**	**637/2**
Harmonic number	**7022**	**7022**	**7022**
Number of bunches	**1312**	**1312**	**2625**
Beam current[mA]	**389**	**389**	**779**
Bunch spacing [λ_{RF}]	**4**	**4**	**2**
Beam Filling period	**19**	**14**	**29**
Fill pattern (1period)			
Train [bunch number]	**34**	**22**	**44**
Gap [in λ_{RF}]	**45**	**33**	**31**
Train [bunch number]	**34**	**22**	**45**
Gap [in λ_{RF}]	**49**	**33**	**31**
Train [bunch number]		**22**	
Gap [in λ_{RF}]		**33**	
		23	
		33	
Bunch length[mm]	**6**	**6**	**6**
Energy spread, σ_δ	**1 x 10^{-3}**	**1 x 10^{-3}**	**1 x 10^{-3}**
Mom. compaction, α	**3.36 x 10^{-4}**	**3.36 x 10^{-4}**	**3.36 x 10^{-4}**
Tunes, ν_x / ν_y / ν_s	**48.36 /27.22 /0.03**	**48.36/27.22/ 0.03**	**48.36/27.22 /0.03**
Damp times τ_x /τ_y /τ_s [ms]	**22 / 22 / 11**	**22 / 22 / 11**	**22 / 22 / 11**
E loss/turn, U_0 [MeV]	**4.87**	**4.87**	**4.87**
RF voltage, V_{RF} [MV]	**12.83**	**12.83**	**12.83**

ANALYSIS

Figure 1 shows the betatron function of the whole ring. There is a large variation of betatron function (700%), and hence the beam size, which causes a large variation of the ion frequency. This large frequency spread provides effective Landau damping to the beam ion instability.

The wake field of ion-cloud is [7]

$$W_y(s) = \hat{W}_y \, e^{-\frac{\omega_i s}{2Qc}} \sin\left(\frac{\omega_i s}{c}\right), \qquad (1)$$

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$$\hat{W}_y = N_i \left(\frac{r_p S_b}{A N_e}\right)^{1/2} \left[\frac{4}{3}\frac{1}{\sigma_y(\sigma_y+\sigma_x)}\right]^{3/2}. \quad (2)$$

where c is the speed of light, r_p is the classical radius of proton, A is the mass number of the ion, N_i is ion number, ω_i is the ion frequency, N_e is electron bunch population, S_b is bunch spacing and $\sigma_{x,y}$ is the transverse root mean square (*rms*) beam size of the electron bunches. Figure 2 shows the total vertical wake in KCS configuration due to different ions with a total vacuum pressure of 0.5nTorr. The wake can't be simple represented by a single resonance model as shown in Eq. (1) due to the large variation of the beam size along the ring. This indicates a low Q and a large damping to the beam instability. Each wake can be fitted to multiple resonance model according to Eq. (1) and then the growth rate of the beam ion instability can be estimated using the fitted parameters $\hat{W}_y$, Q, and ω_i [7].

The alternative way is to calculate the coherent tune shift directly from the wake function shown in Figure 2. This method is straight forward and can be used in general case. In certain situation, it can be difficult and also less accurate to fit the wake according to the resonance modes. When the beam is evenly filled along the ring, the exponential growth rate of the coupled bunch instability for mode $y_j^\mu \propto e^{2\pi\mu j/n_b}$ is given by the imaginary of the coherent frequency shift with mode number μ [8]

$$\Omega_\mu - \omega_\beta \approx \frac{r_e c N_e}{4\pi\nu_\beta\gamma}\sum_{m=0}^{M-1}\left[\sum_k W_y\left(kC+\frac{m}{M}C\right)e^{2\pi i\nu_\beta k}\right]e^{2\pi i(\mu+\nu_\beta)\frac{m}{M}}. \quad (3)$$

Here ν_y is the betatron tune, M is the bunch number, C is the circumference and r_e is the classical radius of electron. Figure 3 shows the estimated growth rate and tune shift due to ions for various configurations. A negative growth rate means unstable. There is a minimum growth time of 0.89 *ms* and maximum tune shift 0.002 for KCS beam. Benefitting from the shorter bunch train, the DRFS configuration has a longer growth time of 1.2 *ms* although it as the same beam-current as KCS. The FP upgrade configuration has shortest growth time of 0.7 *ms* due to its high beam current.

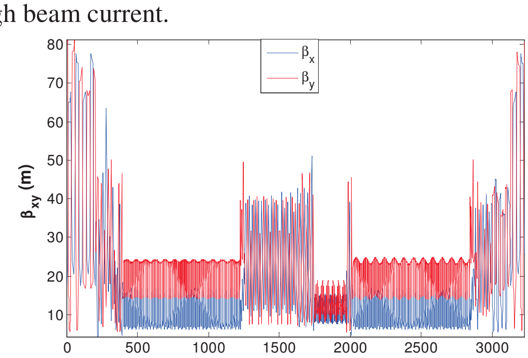

Figure 1. Betatron functions of the DTC02 lattice

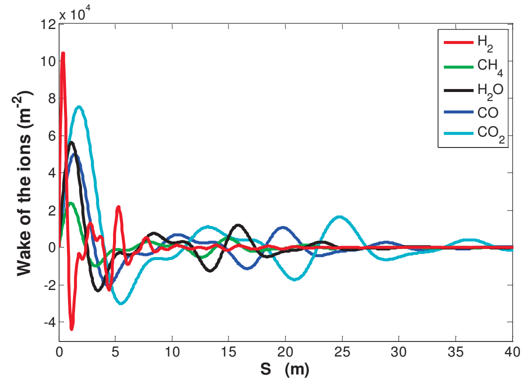

Figure 2. Wake field due to the ions along the whole ring with KCS beam. The total vacuum pressure is 0.5 *nTorr* with partial gas pressures shown in Table1.

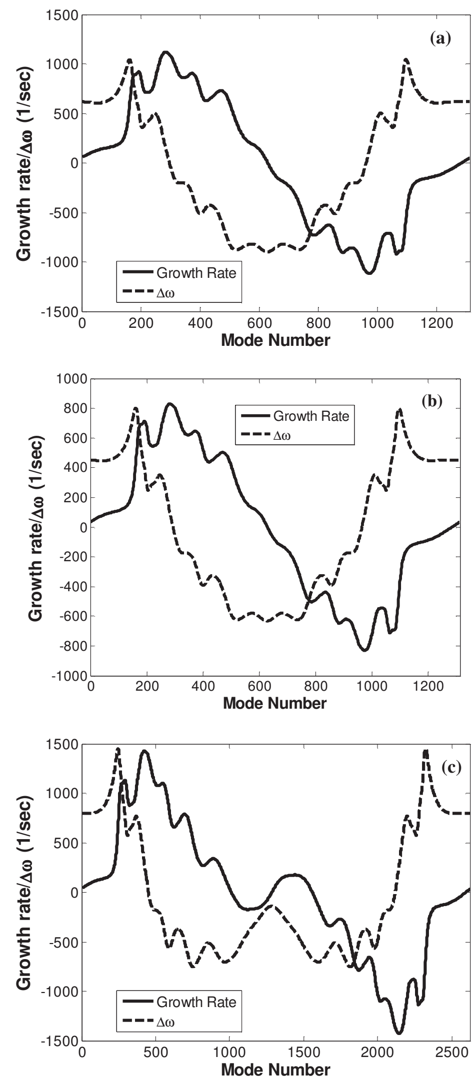

Figure 3. Calculated growth rate and frequency shift due to ions for different beams (a) KCS; (b) DRFS; (c) FP upgrade.

SIMULATIONS

Simulation has a number of advantages in the study of the beam-ion instability: the nonlinearity of the ion-cloud

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is automatically included; the effects of optics and bunch-train gap with arbitrary beam filling pattern can be easily handled; a realistic vacuum model with multi-gas species is straightforward in simulation. A Particle in Cell (PIC) code based on wake-strong model is used here [7]. The code bas been benchmarked with SPEAR3 experiment [9] and there is a good agreement.

The SPEAR3 vacuum shown in Table 1 with a total pressure of 0.5 *nTorr* is used in the simulation. A uniform vacuum pressure along the ring is assumed. It is essential to study the beam ion instability using realistic vacuum model with multi-gas species to accurately model the effects of optics, beam filling pattern and possible extra landau damping due to multi-gas species effect. The exact beam filling patterns shown in Table 2, which are not uniform, are used in the simulations. Figure 4-6 show the simulated vertical beam instability due to ions for the three configurations: KCS, DRFS and FP upgrade, respectively. The fastest exponential growth times are 0.61 *ms*, 0.91*ms* and 0.40 *ms*, respectively. Figure 7 shows the unstable modes with KCS beam. There is a broad band spectrum and there is a good agreement with the analysis shown in Figure 3.

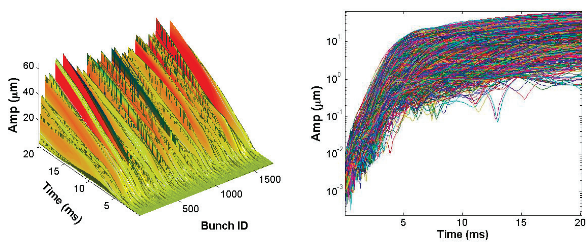

Figure 4. Simulated vertical beam ion instability in KCS configuration. The vertical oscillation amplitude in the left plot is in linear scale, while it is in logarithmic scale in the right plot. The different lines in the plots are for different bunches. The vertical instability growth time is 0.61 *ms*.

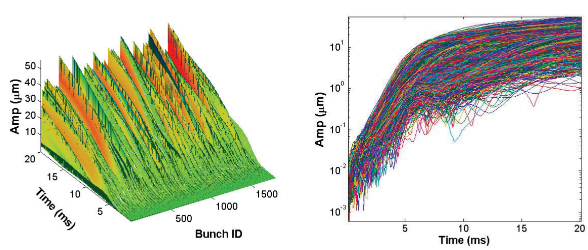

Figure 5. Simulated vertical beam ion instability in DRFS configuration. The vertical instability growth time is 0.91 *ms*.

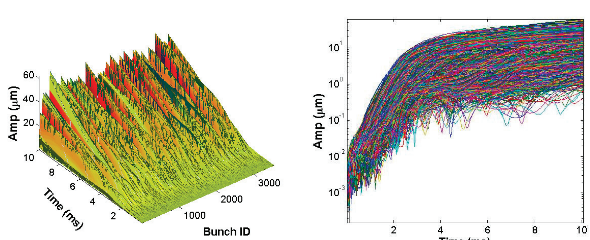

Figure 6. Simulated vertical beam ion instability in FP upgrade configuration. The vertical instability growth time is 0.40 *ms*.

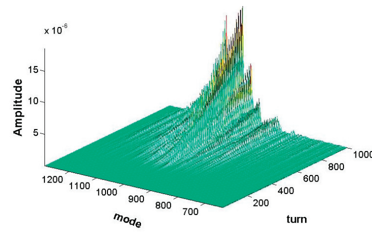

Figure 7. Unstable modes of the beam ion instability driven by ions in KCS configuration.

SUMMARY AND CONCLUSION

The beam ion instabilities in the new ILC damping ring have been studied using realistic vacuum with multi-gas species, exact beam filling pattern and exact optics. We first time calculate the ion instability using a simple analysis formula, which is close to the expensive simulation. There is also an excellent agreement in the distributions of unstable modes.

With a conservative total vacuum pressure of 0.5 *nTorr*, the growth times are 0.61 *ms*, 0.91*ms* and 0.40 *ms* for KCS, DRFS and FP upgrade, respectively. The growth time is much shorter the radiation damping time of 11.0 *ms*. The instability can be mitigated by a large chromaticity in the expense of lifetime and injection efficiency. A bunch-by-bunch feedback can be used to suppress the instability. However, how good a feedback at μm level is not yet fully confirmed experimentally, for instance, the noise. More R&D is necessary.

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