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# Study of Fast Beam-Ion Instability in ILC Damping Ring

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## Abstract

By using the update damping ring parameters, the growth time of fast beam-ion instability (FBII) is analytically estimated according to the linear theory. The two different fill patterns are taken into account and the results show that the growth time is larger than the response time of current feedback system, especially when the ion frequency spreads exist along the damping ring lattice.


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# 1 Introduction

Fast beam-ion instability was first studied by T. Raubenheimer and F. Zimmermann in 1995. After that, some experiments were carried out to verify the theory of FBII. The ions generated by the head of the bunch train oscillate in the transverse direction and resonantly interact with the betatron oscillation of the subsequent bunches, resulting in the growth of the initial perturbation of the beam. This phenomenon is called fast beam-ion instability. In the damping ring of International Linear Collider (ILC), the beam emittance is smaller and the bunch train is longer compared with some existing storage rings, the number of ions ionized by a single bunch train is large (not trapping from turn to turn), therefore FBII is severe. In this note, we estimate the growth time of FBII by using the update electron damping ring parameters of ILC.

# 2 Linear Theory of Fast Beam-Ion Instability

According to the linear theory, the characteristic rise time of FBII can be described as [1, 2]

$$\frac{1}{\tau_c} = \frac{4 d_{gas} \sigma_{ion} \beta_y N_b^{3/2} n_b^2 r_e r_p^{1/2} L_{sep}^{1/2} c}{3\sqrt{3}\gamma \sigma_y^{3/2} \left(\sigma_x + \sigma_y\right)^{3/2} A^{1/2}} \tag{1}$$

where $d_{gas} = p / k_b T$ is the density of residual gas, $p$ is the gas pressure in vacuum chamber, $k_b$ and $T$ are Boltzmann Constant and gas temperature respectively. $\sigma_{ion}$ is the ionization cross section, $\beta_y$ is the average vertical beta function, $N_b$ is the particle number per bunch, $r_e$ and $r_p$ are the classical radius of electron and proton respectively, $L_{sep}$ is the bunch spacing, $\gamma$ is the relativistic factor, $\sigma_x$ and $\sigma_y$ are the horizontal and vertical beam sizes respectively, $A$ is the ion mass in unit of proton mass and $c$ is the speed of light.

The ion coherent angular frequency $\omega_i$ is given by

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

Actually, there are some sources which can cause the ion frequency $\omega_i$ spreads along the damping ring lattice structure. One of them is due to the horizontal beam density profile in a flat beam which causes the local ion frequency to depend on the horizontal position. Other sources of spread in ion frequency are due to the nonlinearity of the ion oscillations inside the beam and the presence of multiple ion species, etc.

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

$$\frac{1}{\tau_e} = \frac{1}{\tau_c} \frac{c}{2\sqrt{2} l_{train} \left(\Delta\omega_i\right)_{rms}} \tag{3}$$

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

According to Eq.(1)~(3), assuming 10%, 20% and 30% relative coherent frequency spread along the baseline and alternative damping rings, for 0.1nTorr, 1.0nTorr CO gas pressure, the growth times $\tau_c$ , $\tau_e$ versus bunch index are plotted in Fig.1-8. It can be seen that the growth time becomes less with respect to the bunch index, while considering the ion coherent frequency spread, the growth rates become much slower.

# 3 The Growth Time Estimation of FBII

According to the latest configuration of electron damping ring, the fill pattern is changeable in order to alleviate the ion effect. The baseline and alternative damping rings parameters are listed in Table 1 and Table 2 respectively [3]. In order to calculate the growth time of FBII, we use the beam sizes parameters in Frank Zimmermann's report [4]. Here, only two fill patterns are considered, one is at the left side of Table 1 and Table 2, namely the bunch charge is $2.0\times10^{10}$ and the number of bunch trains is 60 for baseline damping ring, while for 17km alternative ring, the bunch spacing is 13.85ns and there is 6 bunches per train, the bunch charge is $2.25\times10^{10}$. The other fill patterns we care about are the data from the right side of these two Tables, namely, the bunch charge is $1.0\times10^{10}$ and the number of bunch trains is 120 for baseline damping ring, while for 17km alternative ring, the bunch spacing is 4.62ns and there is 18 bunches per train, the bunch charge is $0.75\times10^{10}$. We named them mode 1 and mode 2 respectively. The two different vacuum gas pressures 0.1nTorr and 1nTorr are assumed in our calculation.

Table 1 Fill patterns of baseline damping ring

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Ring circumference [m] | 6642.4784 | | | | | | | | |
| Harmonic number | 14402 | | | | | | | | |
| Ring RF frequency [MHz] | 650 | | | | | | | | |
| Linac RF frequency [GHz] | 1.3 | | | | | | | | |
| Linac pulse length [ms] | 1.00 | | | | | | | | |
| Linac bunch spacing [linac RF wavelengths] | 480 | 450 | 400 | 384 | 360 | 320 | 300 | 288 | 240 |
| Linac bunch spacing [ring RF wavelengths] | 240 | 225 | 200 | 192 | 180 | 160 | 150 | 144 | 120 |
| Linac bunch spacing [ns] | 369.23 | 346.15 | 307.69 | 295.38 | 276.92 | 246.15 | 230.77 | 221.54 | 184.62 |
| Ring bunch spacing [linac RF wavelengths] | 5.2 | | | | | | | | |
| Ring bunch spacing [ring RF wavelengths] | 2 | | | | | | | | |
| Ring bunch spacing [ns] | 3.08 | | | | | | | | |
| Bunches per train | 45 | | | | | | | | |
| Number of bunch trains | 60 | 64 | 72 | 75 | 80 | 90 | 96 | 100 | 120 |
| Gaps per train | 75 | 67.5 | 55 | 51 | 45 | 35 | 30 | 27 | 15 |
| Gap length [ns] | 233.85 | 210.77 | 172.31 | 160.00 | 141.54 | 110.77 | 95.38 | 86.15 | 49.23 |
| Total number of bunches | 2700 | 2880 | 3240 | 3375 | 3600 | 4050 | 4320 | 4500 | 5400 |
| Bunch charge [$\times10^{10}$] | 2.00 | 1.87 | 1.67 | 1.60 | 1.50 | 1.33 | 1.25 | 1.20 | 1.00 |

Table 2 Fill patterns of alternative damping ring

| | | | |
|---|---|---|---|
| Ring circumference [m] | 17227.9195 | | |
| Harmonic number | 37353 | | |
| Ring RF frequency [MHz] | 650 | | |
| Linac RF frequency [GHz] | 1.3 | | |
| Linac pulse length [ms] | 1.03 | | |
| Linac bunch spacing [linac RF wavelengths] | 540 | 360 | 180 |
| Linac bunch spacing [ring RF wavelengths] | 270 | 180 | 90 |
| Linac bunch spacing [ns] | 415.38 | 276.92 | 138.46 |
| Ring bunch spacing [linac RF wavelengths] | 18 | 12 | 6 |
| Ring bunch spacing [ring RF wavelengths] | 9 | 6 | 3 |
| Ring bunch spacing [ns] | 13.85 | 9.23 | 4.62 |
| Bunches per train | 6 | 9 | 18 |
| Number of bunch trains | 415 | | |
| Gaps per train | 12 | | |
| Gap length [ns] | 60.00 | | |
| Total number of bunches | 2490 | 3735 | 7470 |
| Bunch charge [$\times10^{10}$] | 2.25 | 1.50 | 0.75 |

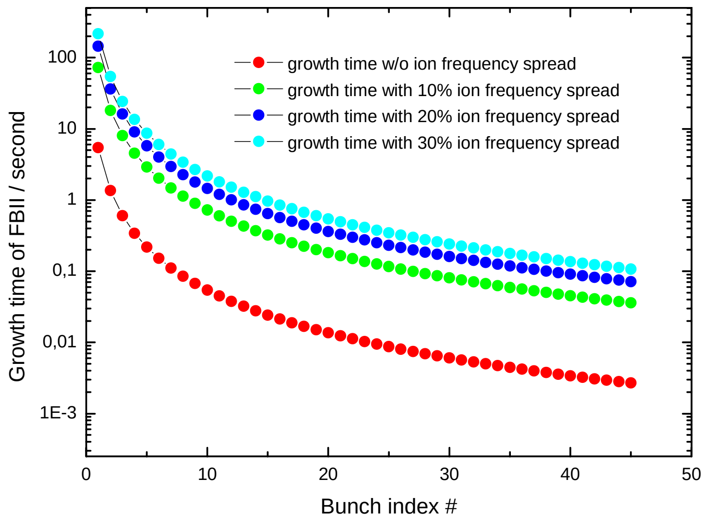


Fig.1. Growth time of FBII versus bunch index in 0.1nTorr for baseline damping ring (Mode 1)

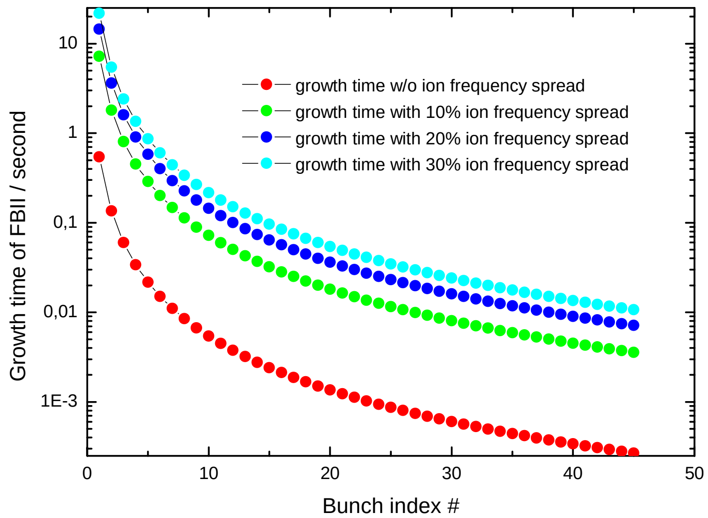


Fig.2. Growth time of FBII versus bunch index in 1nTorr for baseline damping ring (Mode 1)

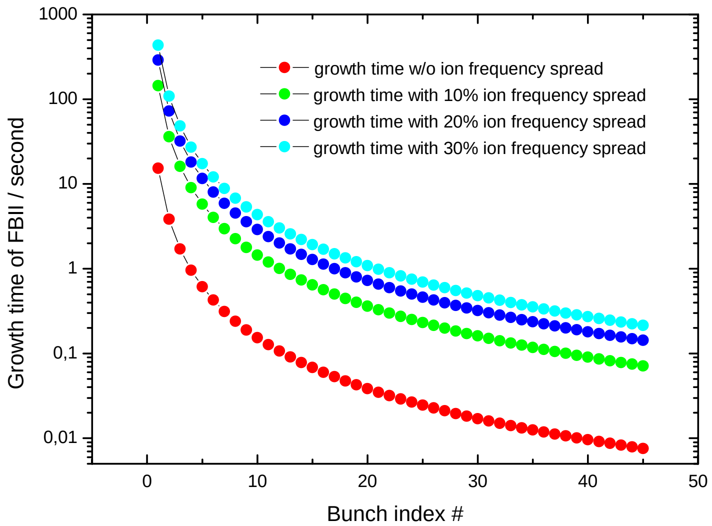


Fig.3. Growth time of FBII versus bunch index in 0.1nTorr for baseline damping ring (Mode 2)

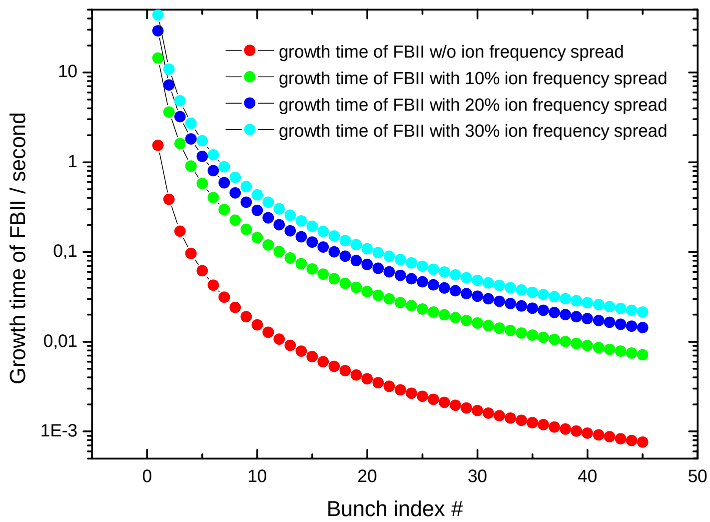


Fig.4. Growth time of FBII versus bunch index in 1nTorr for baseline damping ring (Mode 2)

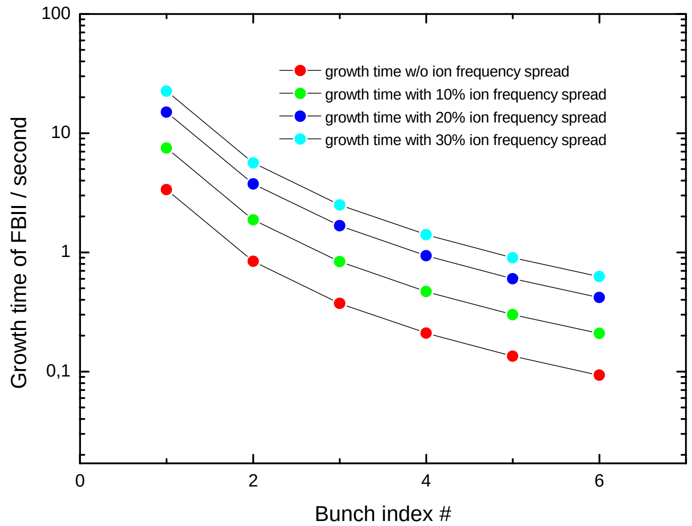


Fig.5.Growth time of FBII versus bunch index in 0.1nTorr for alternative damping ring (Mode 1)

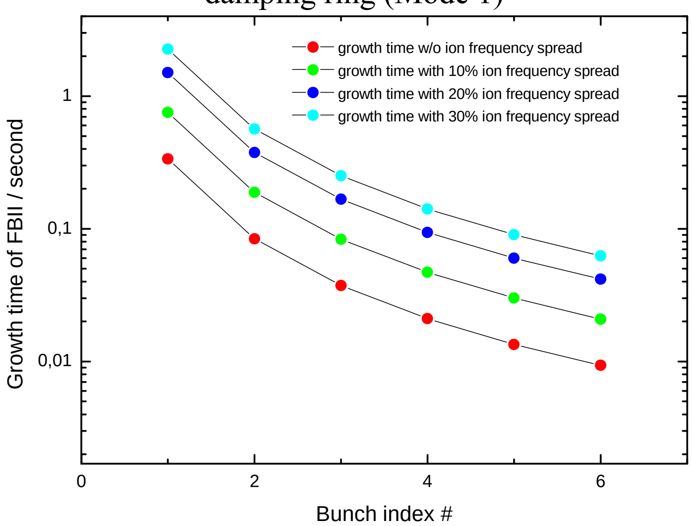


Fig.6.Growth time of FBII versus bunch index in 1nTorr for alternative damping ring (Mode 1)

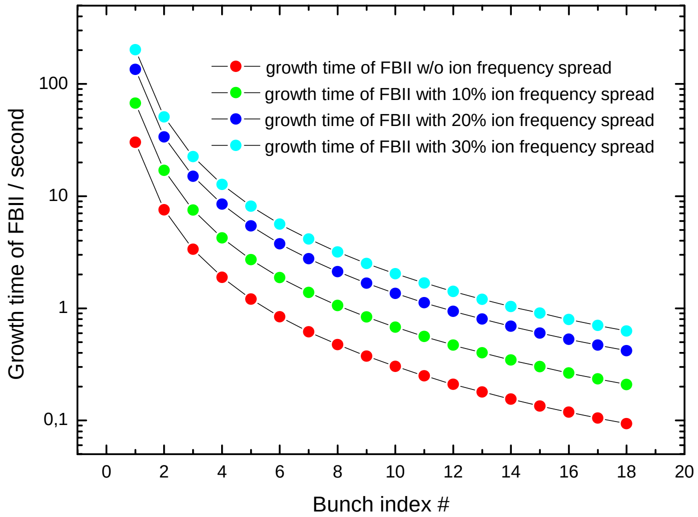


Fig.7.Growth time of FBII versus bunch index in 0.1nTorr for alternative damping ring (Mode 2)

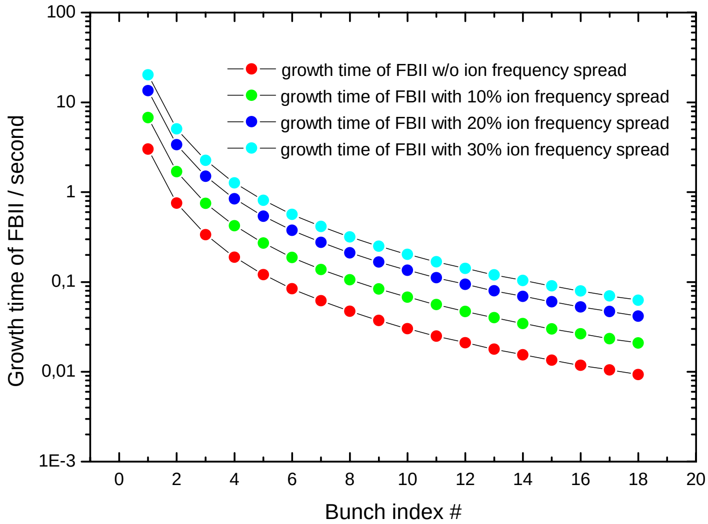


Fig.8.Growth time of FBII versus bunch index in 1nTorr for alternative damping ring (Mode 2)

# 4 Conclusion

From the analytical results one can see that the growth time at the bunch train end for baseline and alternative damping rings in both 0.1nTorr and 1nTorr is larger than the revolution period of rings (The revolution period for 6km and 17km rings are 22μs and 57μs respectively. When there is no ion frequency spread, the growth time of FBII is a few hundred microseconds, so it is within the bunch-by-bunch feedback system). Therefore it is possible to cure the fast beam-ion instability by using the fast feedback system in ILC electron damping ring.

# Acknowledgement

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## References

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[4] Frank Zimmermann, Studies of electron cloud, ion effects, and Synchrobetatron resonances for KEKB, Super-KEKB and ILC damping rings, ILC-Asia-2005-24, Nov. 2005.