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ION EFFECTS IN THE ELECTRON DAMPING RING OF THE INTERNATIONAL LINEAR COLLIDER

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Abstract

Ion-induced beam instabilities and tune shifts are critical issues for the electron damping ring of the International Linear Collider (ILC). To avoid conventional ion trapping, a long gap is introduced in the electron beam by omitting a number of successive bunches out of a long train. However, the beam can still suffer from the fast ion instability, driven by ions that last only for a single passage of the electron bunches. Our study shows that the ion effects can be significantly mitigated by using multiple gaps, so that the stored beam consists of a number of relatively short bunch trains. The ion effects in the ILC damping rings are investigated using both analytical and numerical methods.

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, a long gap is introduced in the electron beam by omitting a number of successive bunches out of a train. Another way to avoid trapped ions is to introduce clearing electrodes. However, the beam can still suffer from the fast ion instability (FII) even with gaps in the train [1-4]. In FII, individual ions last only for a single passage of the electron beam and are not trapped for multiple turns. The lifetime of individual ions is therefore very short.

This paper briefly describes the fast 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

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

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, we estimate the ion effects as a function of time at each element.

The baseline design of ILC Damping Ring is one 6 km ring for the electron beam and two 6 km rings for the positron beam in order to mitigate the effects of electron cloud. A possible alternative to a 6 km electron ring is a 17 km ring or a pair of 6 km rings, to accommodate as many bunches as possible and to allow long gaps for ion clearing in the electron damping ring. This paper estimates the fast ion instability in one of the 6 km electron rings. The beam energy is 5 GeV.

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ANALYSIS FOR A LONG BUNCH TRAIN

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

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

Where r_p is the classical radius of the proton, N is the number of electrons per bunch, S_b is the bunch spacing in units of length and $\sigma_{x(y)}$ is the rms horizontal (vertical) beam size. The oscillation frequency of the trapped ions is

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

Where A is the mass number of the ion.

In general, the bunch train is followed by a long gap to clear ions. Here, we focus on the fast ion instability, which can occur in the passage of a single train. The exponential growth rate of the fast ion instability with a relative spread of ion frequency $\Delta\Omega_i^{rms}$ is given by [5]:

$$\frac{1}{\tau_e} \approx \frac{c r_e \lambda_i \beta_y}{3\sqrt{2}\gamma\sigma_y(\sigma_x + \sigma_y)} \frac{1}{(\Delta\Omega_i)_{rms}} \quad (4)$$

Here, β_y is average beta-function, γ is the relativistic gamma factor, r_e is the classical radius of the electron, and λ_i is the ion line density

$$\lambda_i = \sigma_i P N n_b / (kT) \quad (5)$$

where P is the pressure, n_b is the number of bunches, σ_i is the ionization cross-section (2 Mbarn and 0.35 Mbarn for carbon monoxide and hydrogen ions, respectively) and T is the temperature. The relative ion tune spread depends on the optics: a spread of 0.3 is typical, and is assumed in this study.

The tune shift of the electron beam from trapped ions along the train is

$$\Delta Q_y = \frac{r_e \lambda_i}{6\pi\gamma} \int_{\text{trapped region}} \frac{\beta_y}{\sigma_y(\sigma_x + \sigma_y)} ds \quad (6)$$

The transverse distribution of the trapped ion cloud is assumed Gaussian with a size $1/\sqrt{2}$ of the beam size.

Both the growth time and tune-shift are sensitive to the optics. The FII growth time is obtained by averaging along those parts of the ring where the ions are trapped during damping. The injected beam has a larger emittance than the equilibrium beam and, as a result, all ions can be trapped at injection. With the damping of the emittance, the motion of ions at the stronger focusing regions may become unstable.

A long bunch train consisting of all bunches in the ring is assumed, which means that n_b in Eq. (5) is the total number of bunches. With the damping of the beam size, the growth rate tends to increase – see Eq. (4). However, the number of trapped ions may become small, Eq. (2). Fig. 1 shows the growth time and tune shift with a partial pressure of 1 nTorr of hydrogen. There is a minimum growth time 130 µs after about five damping times, where the ions along the whole ring become unstable. The maximum tune shift is 0.009.

Fig. 2 shows the variation of the growth time due to carbon monoxide ions during the damping procedure with the same conditions as in Fig. 1. Unlike hydrogen ions, there is a minimum growth time of 3.5 µs and maximum tune shift of 0.33 near extraction time. The motion of the ions in the wiggler section becomes unstable after about five damping times (time t3 marked on Fig. 2).

Because of the light mass and smaller ionisation cross section of hydrogen, the effects of hydrogen ions are negligible even though hydrogen gas can be one of the dominant components in the vacuum. A typical spectrum in the Photon Factory [6] consisted of 48% carbon monoxide and 41% hydrogen.

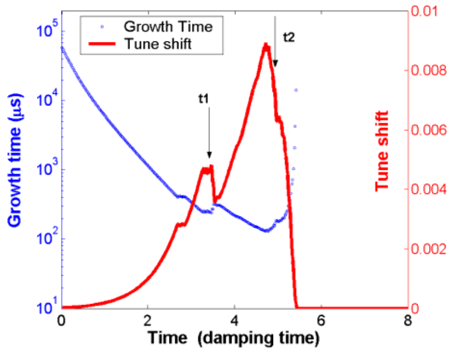


Figure 1: Growth times and tune shifts from hydrogen ions. A partial pressure of 1 nTorr is assumed. There is a total of 3629 bunches in the ring with 1.5×10^{10} particles per bunch. The linear motion of hydrogen ions in the wiggler and arc sections becomes unstable at times t1 and t2, respectively.

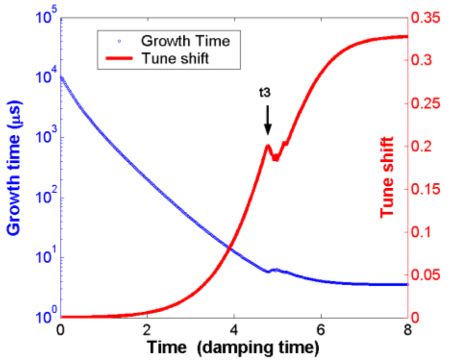


Figure 2: Growth times and tune shifts from carbon monoxide ions with the same conditions as Fig. 1. The linear motion of carbon monoxide ions in the wiggler sections becomes unstable at time t3.

SIMULATION FOR MULTI-TRAINS

In the previous section, a very long bunch train is assumed, where the ions are continuously trapped along the train. This does not occur when the space charge of the ion cloud is strong, or when the fill pattern consists of a number of short trains with gaps between them. A numerical method is necessary to study the effects of a multi-train fill pattern, feedback system, etc. A simulation program is used to track bunches and ions through the damping ring, and thereby evaluate the fast ion instabilities in ILC.

Traditional methods for clearing ions from electron (or antiproton) beams are: electrostatic electrodes; gaps in the bunch train; beam shaking. With clearing electrodes, the transverse clearing field can prevent the ions from being trapped in the beam's potential. Therefore, there is a low ion density near the beam, which depends on the gas in the vacuum chamber. The long-term trapped ions move slowly to the clearing station because of their longitudinal motion. A high beam current can be achieved with clearing electrodes; however the electrodes may increase the chamber impedance. Beam shaking requires dedicated devices to drive the beam, and may trigger coherent transverse instabilities.

Compared to clearing electrodes and beam shaking, use of a multi-train fill pattern with regular gaps is an efficient and simple remedy for the ILC electron damping ring. When a gap τ_{gap} is applied in a ring with revolution time T, the stable condition of the ion motion becomes

$$n\pi < \theta < n\pi + 2\tan^{-1}(2/\omega_{x(y)}\tau_{gap}) \tag{7}$$

Where $\theta = \omega_{x(y)}(T-\tau_{gap})$. As the gap is increased, the unstable region increases. A gap of one period of ion oscillation will have a large unstable zone (more than 60%). As the beam size damps, the ion frequency changes with time. Therefore, the stability of the ions can change from stable to unstable, and vice versa. The stable zone in frequency is given by

$$\frac{\delta\omega_{x(y)}^{stable}}{\omega_{x(y)}} = \frac{2\tan^{-1}(2/(\omega_{x(y)}\tau_{gap}))}{\omega_{x(y)}(T-\tau_{gap})} \tag{8}$$

With the help of the change in beam size, the ions are unlikely to be trapped for multiple turns even with a short gap. Simulation shows the exponential decay time of the ion cloud inside the beam during the gap is roughly one period of the ion oscillation. The ions inside the beam are defined as those ions within $\sqrt{3}\sigma_{beam}$ of the beam centroid. Note that the growth rate of fast ion instability is proportional to the ion density. The diffusion of the ions during the gaps causes a larger size of ion cloud and a lower ion density. In order to evaluate the effects the gaps, an Ion-density Reduction Factor (IRF) is defined as

$$\text{IRF} = \frac{1}{N_{train}}\frac{1}{1-\exp(-\tau_{gap}/\tau_{ions})} \tag{9}$$

Here, τ_{ions} is the diffusion time of ion-cloud. IRF is the ratio of the ion density with gaps and without gaps, estimated from Eq. (5). With a fixed gap, having a larger number of bunch trains helps. However, if the total number of bunches, the bunch separation and the ring circumference are all fixed, then increasing the number of bunch trains leads to shorter gaps between the trains. In principle, the fill pattern can be optimized in terms of achieving the smallest possible IRF. In practice, for the ILC electron damping ring, the fill patterns are decided by the requirements for the RF frequency, and the injection and extraction systems. Fig. 3 shows the build-up of ion cloud in the case of one multi-train pattern with 118 bunch trains and 49 bunches per train. The IRF is 0.017 in this case, which means that the core ion density is reduced by a factor of about 60 compared with a fill consisting of a single long bunch train.

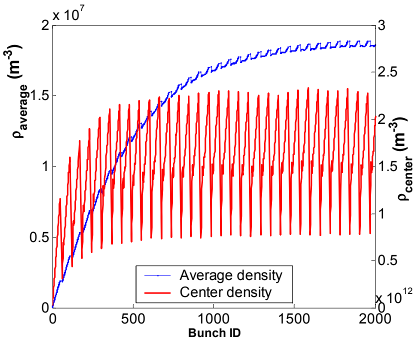
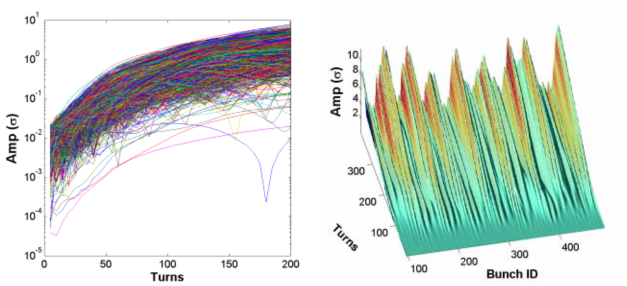


Figure 3: Build-up of CO^+ ion cloud at extraction. The total number of bunches is 5782 (118 trains with 49 bunches per train), the beam has a bunch spacing of two RF bucket spacings, and a train gap of 25 RF bucket spacing. There are 0.97×10^{10} particles per bunch, and the partial vacuum pressure is 1 nTorr.



(a) (b)

Figure 4: Growth of vertical oscillation amplitude in the beam driven by ion cloud.

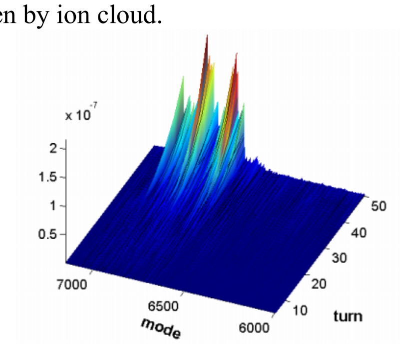


Figure 5: Instability mode due to ions. The condition is the same as Figure 3.

The ion density can be reduced by using regular gaps in the fill, but the increase of the ion density along the bunch train still results in an increase of the betatron tune shifts of subsequent bunches along each train. For the case shown in Fig. 4, the tune variation along the train is 0.003. This tune variation results in BNS damping of the coherent oscillations of electron bunches [7].

The tune spread due to nonlinear tune shifts provides further Landau damping [2]. With a multi-train fill pattern, the size of the ion cloud is much larger than the vertical beam size. Therefore, there is a larger tune spread. When the oscillation amplitude of the beam reaches the beam size, the nonlinearity effectively saturates the instability.

The growth time from simulation is 280 μs (12.5 turns); this is a factor of 80 longer than predicted analytically with a single long bunch train (Fig. 2) because of the above damping mechanisms. Fig. 4 shows the growth of the vertical oscillation amplitude. The instability is fast in the linear regime (where the amplitude is smaller than the beam size), but slows when the oscillation amplitude becomes comparable to the beam size. The amplitude of oscillation of the bunches varies significantly along the train. The instability mode is shown in Figure 5.

Another fill pattern we consider here has a smaller number of bunches (2767) with a higher bunch charge of 2.0×10^{10} particles. The entire beam consists of 61 trains with 23 bunches per train and 62 trains with 22 bunches per train. The bunch spacing is four RF buckets, and the train gap is 28 RF buckets. The growth time is 340 μs (15.24 turns), which is slightly longer than the case with 5782 bunches.

SUMMARY

The fast ion instability in the ILC electron damping ring has been studied using both analytical and numerical methods. Analytical estimates can give quick results if the gaps between bunch trains are long enough to decouple the motion between the trains. Numerical methods are needed to handle the variation of the optical functions around the ring, the effects of finite gaps between trains, and nonlinearities. Using multiple short bunch trains mitigates the fast ion instability significantly, by reducing the core ion density, and by inducing tune variation along the train. Bunch-by-bunch feedbacks will be used to suppress the fast ion instability in ILC. The requirements on the vacuum and feedback systems are achievable. A calculation with more realistic model of vacuum and feedback is underway.

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