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Ion effects are detrimental to the performance of the electron damping ring for the International Linear Collider (ILC). Irregular bunch patterns, e.g. short bunch trains with interleaved gaps, are an effective way to alleviate ion effects. In this paper, we discuss the fill patterns and their impact on the ion effects for the ILC electron damping ring.

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# STUDY OF FILL PATTERNS FOR THE ILC ELECTRON DAMPING RING

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*Abstract*

Ion effects are detrimental to the performance of the electron damping ring for the International Linear Collider (ILC). Irregular bunch patterns, e.g. short bunch trains with interleaved gaps, are an effective way to alleviate ion effects. In this paper, we discuss the fill patterns and their impact on the ion effects for the ILC electron damping ring.

## INTRODUCTION

Ions are recognized as a potential current limitation in storage rings with negatively charged particle beams. The ions may be generated by beam-gas collisions. These ions are trapped in the potential well of the beam. They couple to the motion of the beam and lead to adverse effects such as beam emittance growth, betatron tune shift and spread, collective instabilities and beam lifetime reductions [1].

There are typically two kinds of ion effects in electron storage rings. One is conventional ion trapping which occurs when the circulating beam traps ions after multiple turns. This ion trapping effect can be cured by introducing a few successive empty RF buckets (gaps), which are long compared to the inter-bunch spacing. In this case, the ions are first strongly focused by the passing electron bunches and then over focused in the gap. With a sufficiently large gap, the ions can be driven to large amplitudes, where they form a diffuse halo and do not affect the beam. Other solutions to the problem of ion accumulation such as clearing electrodes and beam shaking are also effective. However, in high current rings or linacs with long bunch trains, the ions accumulation during the passage of a single bunch train may cause a transient instability which is similar to the multi-bunch beam breakup (BBU) in the linac and called fast ion instability (FII) [2,3]. For the electron damping ring of the ILC, the bunch intensity is large and the bunch spacing is small, the fast ion instability is potentially striking [4]. Since the vertical beam emittance is much smaller (~2 pm) than the horizontal one (~0.5 nm), the FII is much more serious in the vertical plane.

In this paper, the linear theory of FII is briefly reviewed in section 2. The gap effect in the fill pattern of electron ring is discussed in section 3. Section 4 is devoted to the ion density reduction due to mini-trains in different fill patterns. Section 5 is the simulation result of FII for mini-trains. Finally a short summary is given.

## LINEAR THEORY OF FII

According to the linear theory [2, 3], the characteristic growth rate of FII strongly depends on the bunch intensity, number of bunches, transverse beam size and the residual gas pressure. It can be estimated as

$$\tau_c^{-1}(s^{-1}) = 5\,p[Torr]\frac{N_0^{3/2} n_b^2 r_e r_p^{1/2} L_{sep}^{1/2} c}{\gamma \sigma_y^{3/2} (\sigma_x + \sigma_y)^{3/2} A^{1/2} \omega_\beta} \tag{1}$$

where $p$ is the partial residual gas pressure which causes the instability, $N_0$ is the number of particles per bunch, $n_b$ is the bunch number, $r_e$ and $r_p$ are the classical radius of electron and proton respectively, $L_{\text{sep}}$ is bunch spacing, $c$ is the speed of light, $\gamma$ is the relativistic gamma factor, $\sigma_{x,y}$ are the horizontal and vertical beam size, $A$ is the atomic mass number of the residual gas molecules and $\omega_\beta \approx 1/\beta_y$ is the vertical betatron frequency.

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

$$\omega_i = \left( \frac{4 N_0 r_p c^2}{3 A L_{sep} \sigma_y (\sigma_x + \sigma_y)} \right)^{1/2} \tag{2}$$

However, the ion motion becomes decoherent because the vertical ion frequency depends on the horizontal position. Furthermore, the existence of various ion species and the variation of the beam size around the ring introduce a spread in the ion oscillation frequency. Taking into account the ion coherent frequency spread, the linear theory gives the coupled bunch motion in the bunch train rising as $y \sim \exp(t/\tau_e)$, and then the exponential growth rate is given by

$$\tau_e^{-1}[s^{-1}] = \frac{1}{\tau_c} \frac{c}{2\sqrt{2} l_{train} (\Delta\omega_i)_{rms}} \tag{3}$$

where $(\Delta\omega_i)_{rms}$ is the rms spread of the ion coherent frequency as the function of the azimuthal position around the ring. $l_{train} = n_b L_{sep}$ is the bunch train length. For the baseline design of the ILC damping ring, simulation shows the spread of ion coherent frequency to be about 30% [5].

If the ions are trapped in the beam potential, they give rise to additional focusing to the beam. The ion induced coherent tune shift is given by

$$\Delta Q_{y;coh} = \frac{\beta_y r_e \lambda_{ion} C}{\gamma 4\pi \sigma_y (\sigma_x + \sigma_y)} \tag{4}$$

here $C$ is the circumference of ring, $\beta_y$ is the vertical beta function, $\lambda_{ion} = \sigma_i N_0 n_b p / kT$ is the ion line density, $\sigma_i$ is the ionization cross section (2 Mbarn and 0.35 Mbarn for carbon monoxide and hydrogen ions, respectively). $k$ is Boltzmann constant and $T$ is the temperature. Table 1 lists three typical fill patterns in the ILC damping ring, from case $A$ to case $C$ [6]. By using parameters of the baseline damping ring from the Reference Design Report of the ILC [7], the FII characteristic growth time, exponential growth time with 30% ion coherent frequency spread and ion induced coherent tune shift at bunch train end for a single long bunch train case are analytically estimated in Table 1. A CO partial pressure of 1 nTorr is assumed here. It can be seen that the growth time is extremely fast for one long train case. Even with 30% ion frequency spread, the FII growth time is still faster than one revolution period (~ 22 μs). The ion induced tune shift is large at a gas pressure of 1 nTorr for CO, so a lower vacuum gas pressure is critical. In addition gaps in the fill pattern can be introduced to reduce the ion density and tune shift.

Table 1: Typical fill patterns in ILC damping ring and analytical results from linear theory of FII.

| *Fill patterns* | *A* | *B* | *C* |
|---|---|---|---|
| Number of bunches, $n_b$ | 5782 | 4346 | 2767 |
| Particles per bunch, $N_0$ [$10^{10}$] | 0.97 | 1.29 | 2.02 |
| Bunch spacing, $L_{sep}$ | 2 | 2 | 4 |
| Number of trains, $p$ | 118 | 82 | 61 |
| Bunches per train, $f_2$ | 0 | 0 | 23 |
| Gap between trains, $g_2$ | 0 | 0 | 28 |
| Bunches per train, $f_1$ | 49 | 53 | 22 |
| Gap between trains, $g_1$ | 25 | 71 | 28 |
| Partial CO pressure [nTorr] | 1 | | |
| FII growth time at bunch train end [$10^{-9}$ s] | 3.922 | 4.527 | 4.030 |
| FII growth time with 30% ion frequency spread [$10^{-6}$ s] | 6.889 | 6.892 | 6.913 |
| Coherent tune shift $\Delta Q_{y;coh}$ | 0.325 | 0.325 | 0.324 |

## GAP EFFECT IN THE FILL

In the previous section, one long bunch train has been assumed and the ions are trapped by the bunch train. The trapping is disturbed when the fill pattern consists of a number of short bunch trains (mini-trains) with gaps in between. In the following, we will analyse the gap effect in the fill.

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 FII is proportional to the ion density [8]. The diffusion of the ions during the gaps increases the size of ion cloud and reduces the ion density.

With a gap is introduced in the bunch train, one can estimate the density of the residual ions in the beam after the clearing gap as [1]

$$\rho_i \approx \frac{\rho_{i0}}{\sqrt{\left(1+L_{gap}^2\omega_x^2\right)\left(1+L_{gap}^2\omega_y^2\right)}} \tag{5}$$

where $\rho_{i0}$ is the ion density at the end of the one bunch train, $L_{gap}$ is the gap length between two adjacent bunch trains, $\omega_{x,y}$ are the ion oscillation frequencies as follows

$$\omega_{x,y}^2 = \frac{2N_0 r_p}{L_{sep} A \sigma_{x,y}\left(\sigma_x+\sigma_y\right)} \tag{6}$$

For the ILC damping ring baseline parameters, the harmonic number h = 14516, the circumference of the ring C = 6695.057 m. We made analytic estimation about the relative ion density reduction versus bunch train gap spacing. The result is shown in Fig.1. It can be seen that the relative ion density reduces with respect to the bunch train gap spacing. If the gap length is larger than 30 RF buckets, the ion density is about 10% of the initial ion density. Beyond 30 RF buckets, the ion density no longer changes significantly. Taking into account the transient beam loading effect, train gap should not be too long. For current ILC damping ring fill patterns, the length of train gap varies from 25 to 71 RF bucket.

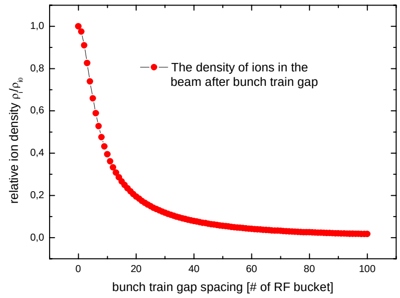


Fig.1: The density of the residual ions in the beam after the bunch train gap.

In order to evaluate the effect of the gaps, an Ion-density Reduction Factor (IRF) is defined as [8]

$$IRF = \frac{1}{N_{train}}\frac{1}{1-\exp\left(-\tau_{gap}/\tau_{ion}\right)} \tag{7}$$

where $\tau_{ion}$ is the diffusion time of the ion cloud which can be estimate from the formula

$$\tau_{ion} \approx \frac{2\pi}{c}\left(\frac{\sigma_y\left(\sigma_x+\sigma_y\right)}{4N_0 r_p}\right) \tag{8}$$

IRF is the ratio of the ion density with gaps and without gaps. In the case $\tau_{gap} \sim 0$, the ring is completely filled and the ions can accumulate indefinitely. With a fixed gap, a larger number of shorter bunch train helps to keep the ion density low. However, for a fixed ring circumference and total number of bunches, the length of gap shrinks as the number of bunch trains increases. The optimum fill pattern depends on the diffusion time, the circumference, and number of bunches. Fig.2 shows the IRF versus number of trains in OCS6 damping ring for fill pattern case *A* and *C* respectively. It can be seen here if the harmonic number and ring circumference are fixed. In order to get the specific luminosity, the IRF reduces with respect to the number of trains. Beyond 60 trains the IRF does not change a lot.

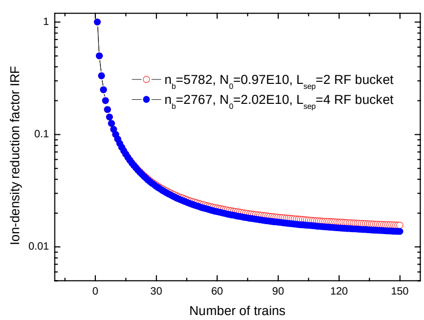


Fig.2: IRF factor versus number of trains in OCS6 damping ring for fill pattern case *A* and case *E*.

## FILL PATTERNS IN ILC DAMPING RING

The beam parameters of the ILC electron damping ring are listed in Table 2.4-1 of Ref. [7]. There are 5 different fill patterns in the ring. The notations used here are explained in Ref. [6]. For different fill patterns, the total number of particles is kept constant, namely $5.6\times10^{13}$, so that the specific luminosity $2.0\times10^{34}$ $cm^{-2}s^{-1}$ can be achieved.

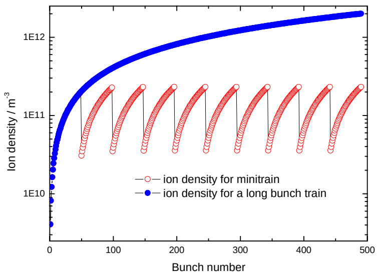


Fig. 3: Ion density versus bunch number for 10 bunch trains in fill pattern case *A*.

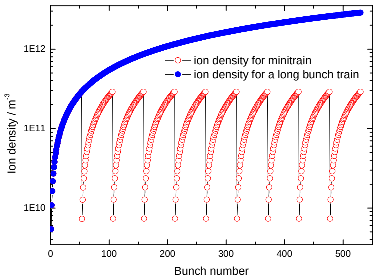


Fig. 4: Ion density versus bunch number for 10 bunch trains in fill pattern case *B*.

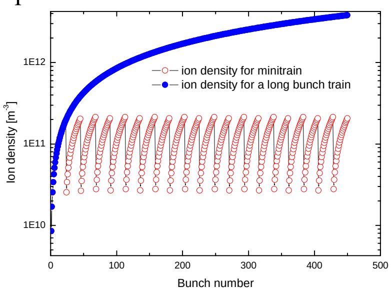


Fig. 5: Ion density versus bunch number for 10 bunch trains in fill pattern case *C*.

The ion densities for different fill patterns case *A*, *B* and *C* are shown in Figs.3–5 respectively for ten bunch trains. The CO partial pressure is 1.0 nTorr. The ion density for a single long bunch train increases linearly with the number of bunches. However, with gaps between bunch trains, the ion density is reduced significantly. The ion density for mini-trains can quickly reach the peak value after a few short bunch trains. For fill patterns *A*, *B* and *C* the ion density diminishes by about two orders of magnitudes compared to a single long bunch train. The FII growth time for mini-train grows by two orders of magnitude comparing to a single long train. The tune shift is also significantly reduced. In doing so, the FII can be potentially damped by the fast bunch-by-bunch feedback system [9].

## SIMULATION OF FII FOR MINITRAINS

A weak-strong code is employed to simulate the FII in the ILC electron damping ring [10]. The effect of mini-trains effect is taken into account. Fig.6 shows the growth of the vertical oscillation amplitude versus the number of turns for a single long bunch train and for mini-trains of fill pattern *A*. The 5782$^{nd}$ bunch is recorded here. It can be seen when the gap is introduced in the bunch trains, the growth of vertical oscillation becomes slowly. This is because in the case the ion density is less than that of a single long bunch train case in Fig.3.

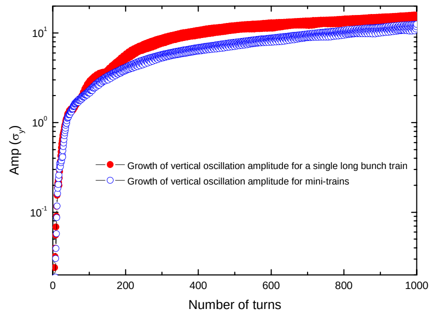


Fig.6: Growth of vertical oscillation amplitude for a single bunch train and mini-trains, respectively with fill pattern *A* for a CO partial pressure of 1 nTorr.

## CONCLUSION

Gaps between bunch trains significantly reduce the ion density in the ILC damping ring; a gap exceeding 30 RF buckets reduces the density by a factor 10. Depending on fill pattern the ion density diminishes by about two orders of magnitude compared to one long bunch train. Simulation shows the growth of vertical oscillation amplitude to be attenuated with gaps in the fill.

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