ION EFFECTS IN FUTURE CIRCULAR AND LINEAR ACCELERATORS*

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Abstract

In this paper, we discuss ion effects relevant to future storage rings and linear colliders. We first review the conventional ion effects observed in present storage rings and then discuss how these effects will differ in the next generation of rings and linacs. These future accelerators operate in a new regime because of the high current long bunch trains and the very small transverse beam emittances. Usually, storage rings are designed with ion clearing gaps to prevent ion trapping between bunch trains or beam revolutions. Regardless, ions generated within a *single* bunch train can have significant effects. The same is true in transport lines and linacs, where typical vacuum pressures are relatively high. Amongst other effects, we address the tune spreads due to the ions and the resulting filamentation which can severely limit emittance correction techniques in future linear colliders, the bunch-to-bunch coupling due to the ions which can cause a multi-bunch instability with fast growth rates, and the betatron coupling and beam halo creation which limit the vertical emittance and beam lifetimes.

I. INTRODUCTION

Ions are recognized as a potential limitation in electron storage rings where ions generated by beam-gas collisions can become trapped in the negative potential of the beam. The ion density in the beam increases until it is stabilized by neutralization of the beam potential, second ionization, or heating by beam-gas collisions. These trapped ions are observed to cause beam emittance increases, betatron tune shifts and a broadening of the tunes, collective instabilities, and lifetime reductions.

Future storage rings typically have high beam currents and small beam emittances, increasing the deleterious effects of the ions. To avoid ion trapping, most future electron storage rings are designed to include a "gap" in the bunch train. The ions, which are strongly focused by the closely spaced bunches, are over-focused in the gap. The ions become mismatched to the beam and begin executing large amplitude oscillations. Although the ions are still trapped in the negative potential of the beam, because the beam-ion force is very nonlinear, the ion phase space density filaments and becomes irrevocably diluted. Thus the ion density decreases and the ions form a diffuse halo around the beam which does not affect the dynamics.

With a sufficiently large gap, ions are not usually thought to be a limitation. But, many of the future accelerators operate in a new regime with high current, long bunch trains and very small transverse beam emittances. In this case, ions generated and trapped within a *single* bunch train, or, in some cases, within a single bunch, can have significant effects. This is true in transport lines and linacs, where typical vacuum pressures are relatively high, as well as storage rings. It also can be true when free electrons are trapped within a positron bunch.

In the next sections, we will first discuss the relevant ionization processes and then we will describe a few of the important effects. We will consider effects in five colliders that are presently being designed: the PEP-II High Energy Ring for the SLAC B-factory [1], a damping ring [2] for the NLC [3], a future linear collider, and the pre- and main linacs in the NLC for both the NLC-I design (500 GeV center-of-mass) and NLC-II (1 TeV center-of-mass); parameters of the designs are listed in Table 1.

II. IONIZATION AND TRAPPING

In a linac, there are two primary ways in which an ion can be created: collisional ionization and tunneling ionization due to the collective electric field of a bunch. In a storage ring, the tunneling ionization is rarely significant but there are two additional processes due to the synchrotron radiation: photoionization of the residual gas and photoelectrons from the vacuum chamber surface. We will discuss each of these processes in turn.

The cross section for the collisional ionization can be expressed as [4]:

$$\sigma = 4\pi\left(\frac{\hbar}{mc}\right)^2\beta^2\left(C_1 + 2C_2(\ln\beta\gamma - \tfrac{1}{2})\right) \quad , \qquad (1)$$

where C_1 and C_2 depend upon properties of the gas. For CO, a common component of the vacuum, $C_1 = 35$ and $C_2 = 3.7$ and, in the energy range of interest, $\gamma \sim 10^3 \to 10^6$ and $\sigma_{CO} \sim 1.6 \to 2.5$ Mbarnes.

In a single bunch, the collisional ionization does not tend to generate significant ion densities. But, the ions are trapped by the bunched beams and significant ion densities can be accumulated along the length of the bunch train, provided that the ions are not over-focused and dispersed between bunches. The condition for trapping is basically the same as that for linear stability in a storage ring [5]:

$$A_{trap} \geq \frac{N r_p \Delta L}{2\sigma_y(\sigma_x + \sigma_y)} \quad , \qquad (2)$$

where N is the bunch population, r_p is the classical proton radius, ΔL is the separation between bunches, $\sigma_{x,y}$ are the rms beam sizes, and A_{trap} is the minimum atomic mass that is trapped. Values of A_{trap} are listed in Table 1 for the different designs; the first four designs have significant trapping.

Another method of ion generation is field ionization where the collective electric field of the bunch ionizes the atom or molecule. Field ionization can be divided into two regimes depending upon the strength and temporal duration of the field. In most cases of interest, the field is sufficiently strong and the bunch is sufficiently long that the ionization arises from tunneling ionization. In the notation of Ref. [6], $\gamma \equiv$

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Table 1. Storage Ring and Linac Parameters

	PEP-II HER	NLC DR	NLC-I pre-linac	NLC-I linac	NLC-II linac
Particles/Bunch N [10^{10}]	2.7	0.65	0.65	0.65	1.3
Initial Energy E_0 [GeV]	9	2	2	10	10
$\overline{\beta_0}$ [m]	15	2	13	8	8
$\gamma\epsilon_x$ [10^{-6} m-rad]	850	3	3	5	5
$\gamma\epsilon_y$ [10^{-6} m-rad]	34	0.03	0.03	0.05	0.05
σ_z [mm]	10	4	0.5	0.1	0.1
Bunches n_b	1658	90	90	90	90
Bunch Separation ΔL [m]	1.26	0.42	0.42	0.42	0.42
A_{trap}	0.1	14	2 at 2 GeV 10 at 10 GeV	10 at 10 GeV 50 at 250 GeV	20 at 10 GeV 140 at 500 GeV
$\hat{\mathcal{E}}$ [eV/Å]	0.0003	0.007	0.02 at 2 GeV 0.05 at 10 GeV	0.5 at 10 GeV 1.1 at 250 GeV	1.1 at 10 GeV 2.9 at 500 GeV

$c\sqrt{2m_eE_{ion}}/\sigma_z e\mathcal{E} \ll 1$ where $\mathcal{E}$ is the electric field of the bunch and E_{ion} is the ionization energy.

In the tunneling regime, the transition rate for ionization is approximately [7]:

$$W = 8\frac{\alpha^3 c}{\lambda_c^2}\frac{E_{ion}}{e\mathcal{E}}\exp\left[-\frac{4}{3}\frac{\alpha}{\lambda_c}\frac{E_{ion}}{e\mathcal{E}}\right][\mathrm{sec}^{-1}] \quad , \qquad (3)$$

Because of the exponential factor, this process is very sensitive to the electric field. For example, the time to ionize CO in a 2.9 V/Å electric field is roughly 7 femtoseconds (the static electric field approximation is valid in this case). But, in a field of 1.5 V/Å, the ionization time is roughly 40 picoseconds and there is negligible probability of ionization by a bunch.

Peak electric fields in the bunches are listed in Table 1. There is no tunneling ionization in the first four designs. However, in the last design, the surrounding gas, within roughly $\pm 2\sigma_{x,y}$ of the beam center, is fully ionized at the end of the linac. There will also be significant tunneling ionization in the collimation, arc, and final focus regions of both the NLC-I and NLC-II designs. In general, trapping is not important where the fields are strong enough for tunneling ionization. Furthermore, because the ions are over-focused and the gas does not fully re-populate between bunches, the ion densities in the trailing bunches will be much lower than that in the leading bunch.

In a storage ring the synchrotron radiation will also ionize the residual gas, forming a swath of ions between the beam and the vacuum chamber wall. In the PEP-II rings and the NLC damping ring, this process yields roughly an order of magnitude more ions than does the collisional ionization. Fortunately, the density of these ions is very low; they will form a halo around the beam without having a significant effect on the beam dynamics.

Finally, the synchrotron radiation will also generate many orders of magnitude more photoelectrons at the chamber wall than ions. These photoelectrons will be accelerated towards the core of a positron beam and may provide a significant coupling between bunches [8].

III. BEAM DYNAMICS

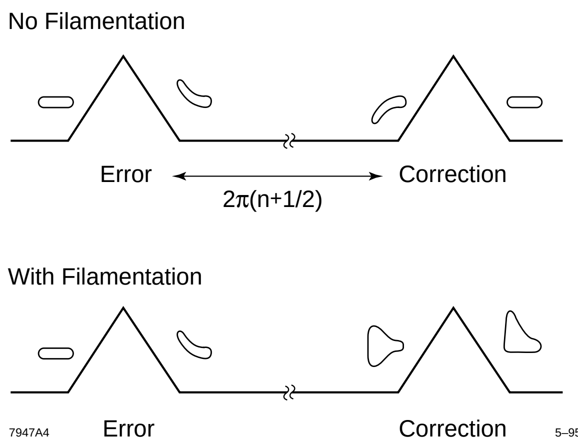

Figure 1. Schematic of emittance correction with and without filamentation (from Ref. [11]).

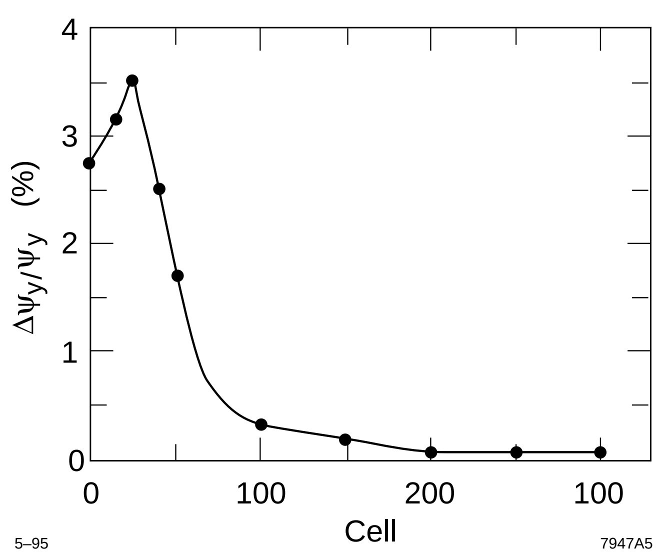

Figure 2. Fraction change in vertical focusing at the end of the bunch train in the NLC-I linac with 1×10^{-8} Torr of CO gas; the linac consists of roughly 300 FODO cells whose length is initially 8 meters and increases to roughly 40 meters by the end of the linac.

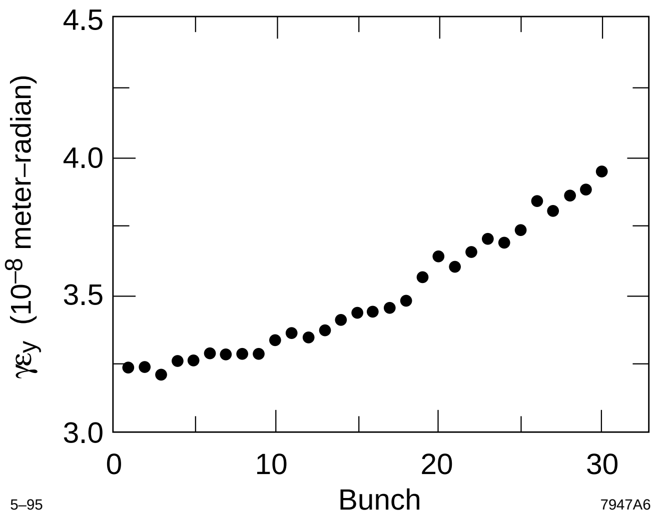

Figure 3. Simulation of emittance correction in the NLC-I pre-linac with a shortened bunch train of 30 bunches and a vacuum pressure of 3×10^{-8} Torr of CO gas; because the ions are trapped, this is equivalent to a vacuum pressure of 1×10^{-8} Torr and a train of 90 bunches.

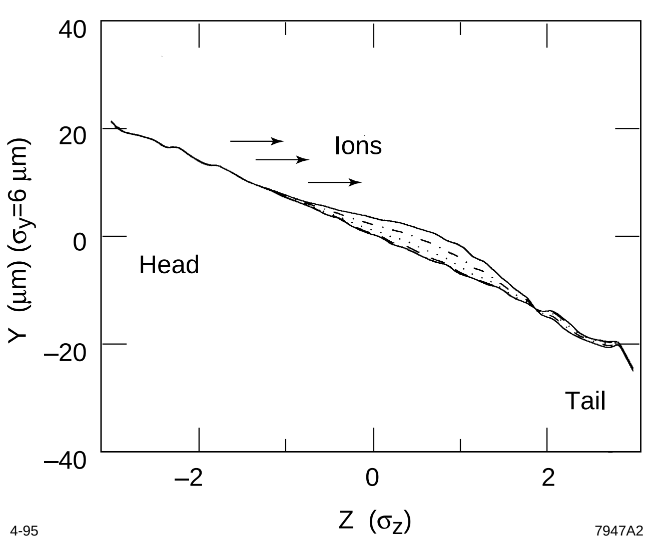

Figure 4. Simulation of electron beam injected with a linear y-z correlation after 0 m (solid), 300 m (dashes), 600 m (dots), 900 m (dash-dot), and 1200 m (solid), in the SLC arc with a vacuum pressure of 3×10^{-4} Torr.

A. Focusing Variation

In a long train of bunches where ions are trapped, the ion density increases linearly along the length of the train. Similarly, in a very dense electron bunch with tunneling ionization, the free electrons are expulsed promptly and there is a significant variation of focusing along the bunch due to the increasing ion density.

In a storage ring, the variation in focusing will cause the coherent and incoherent tunes to vary from bunch to bunch. This will provide a Landau damping mechanism for transverse coupled bunch instabilities and could be advantageous.

In a linac, non-local emittance correction has been described as a method of easing the alignment tolerances in future linear colliders [9] and is being utilized in the Stanford Linear Collider. Unfortunately, the variation in focusing will cause the mismatches and emittance dilutions to filament (phase mix). This has implications for non-local correction of the transverse emittance dilutions as is illustrated schematically in Fig. 1; the filamentation due to the ions will significantly reduce the effectiveness of the correction techniques.

An example of the increased focusing in the NLC-I linac is shown in Fig. 2. With a partial pressure 10^{-8} Torr of CO gas, the vertical focusing is increased by roughly 3% by the end of the bunch train in the beginning of the NLC-I linac. The ion focusing increases as the beam sizes decrease due to the adiabatic damping during acceleration, but, once the ions are over-focused between bunches, the focusing decreases rapidly. In addition, a simulation from the NLC-I pre-linac with emittance correction is shown in Fig. 3. Here, dispersive and wakefield emittance dilutions, introduced by $40\,\mu$m random Beam Position Monitor (BPM) misalignments, increased the emittance by roughly 100%. Non-local emittance correction was able to reduce the dilution to roughly 10% at the head of the bunch train but was much less effective at the end of the train.

Another effect, related to the variation in focusing, arises if the bunch has a correlation between transverse and longitudinal position such as that due to transverse wakefields or a correlated energy spread and dispersion. In this case, the ions generated by the head of the bunch deflect the tail of the bunch, reducing the offset, but also making it extremely difficult to remove the correlation at a later time. This effect sets a limit on the vacuum pressure in the SLC arcs [10] and will be significant in future colliders with tunneling ionization such as the arcs and final focus of the NLC. The effect is illustrated in Fig. 4 which is a simulation of an electron beam in the SLC arc.

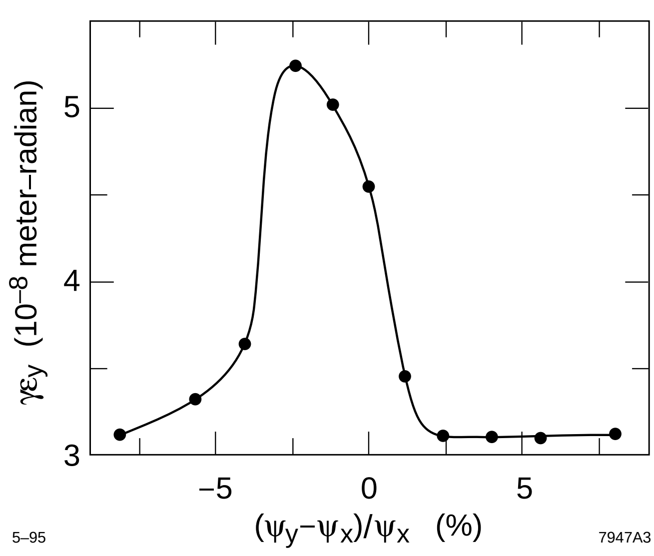

Figure 5. Emittance of the last bunch in the train versus difference between horizontal and vertical focusing in NLC-I pre-linac. This shows the effect of betatron coupling resonance; note that the resonance peak occurs for stronger horizontal focusing because of the additional vertical focusing due to the ions (from Ref. [11]).

B. Nonlinear Resonances and Betatron Coupling

Because the trapped particle distributions are not uniform, they will generate nonlinear electric fields which can drive nonlinear resonances. Assuming a symmetric nonuniform distribution, the lowest order effect is an octupole like coupling resonance driven by the trapped particles. In a flat beam, this can cause an increase in the vertical emittance. The effect has been analyzed for linacs using a simple parametric resonator model [11] and a more complicated analysis has been performed for storage rings [12]; it should be noted that this coupling is very similar to the space charge induced coupling treated in Ref. [13] more than 25 years ago. Finally, Fig. 5 shows results from simulations of the NLC pre-linac. It is straightforward to control the emittance growth by separating the horizontal and vertical phase advances, although higher order resonances can still be important, as discussed subsequently.

In addition to the coupling, the strong nonlinear fields can lead to formation of a beam halo where high order resonances transport particles to large amplitudes. Similar effects are being studied with space charge dominated proton beams [14][15]. Beam halos will lead to a decreased lifetime in a storage ring and cause detector backgrounds in a linear collider.

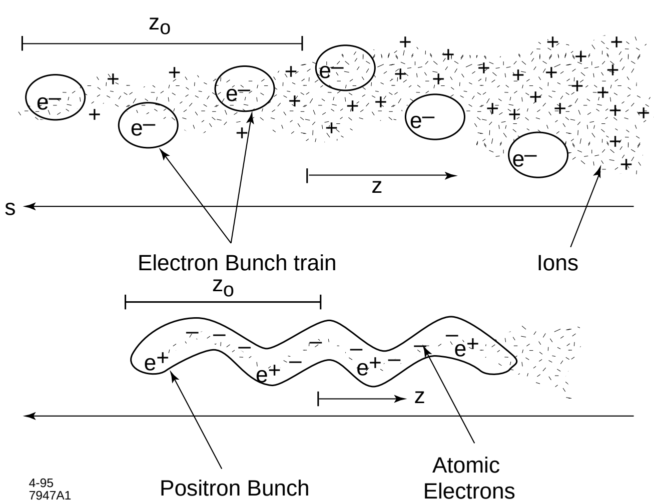

Figure 6. Schematic of fast beam-ion collective instability which can arise due to ion trapping in a long electron bunch train or trapping of free electrons in a positron bunch.

C. Collective Instabilities

Finally, the trapped ions and free electrons can drive collective instabilities. One possible effect arises due to the photoelectrons generated at the vacuum chamber in a positron storage ring. As mentioned, a large number of photoelectrons are created by the synchrotron radiation. These free electrons are accelerated towards the positron beam and can provide a coupling between the bunches. This effect is believed to be the source of a coupled bunch instability observed in the KEK Photon Factory and is described in Ref. [8]; it is presently being evaluated for the PEP-II Low Energy Ring and the NLC positron damping rings.

Another coupled bunch instability can be caused by particles trapped within the beams. The particles oscillate within the potential of the beam and can modulate the transverse beam position. The modulation then resonantly drives the trapped particles and exponential growth results. This instability can arise with trapped electrons within a positron bunch or trapped ions within an electron bunch train as is illustrated schematically in Fig. 6.

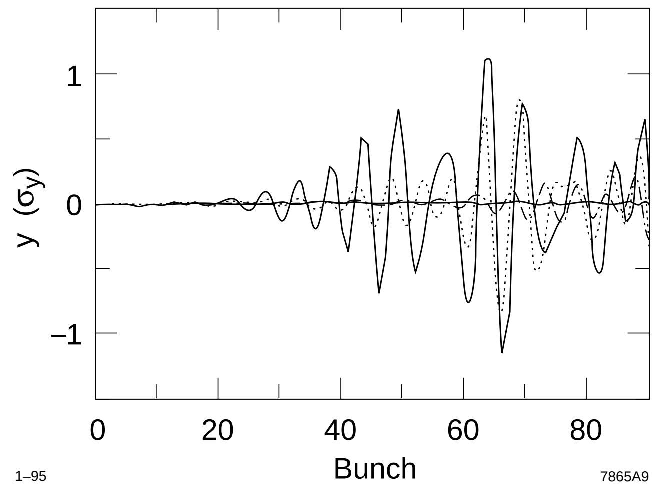

Figure 7. Position of vertical centroids along the electron bunch train after being stored for $0\,\mu$s (solid), $0.67\,\mu$s (dashes), $1.3\,\mu$s (dots), and $2\,\mu$s (solid) in the NLC Damping Ring with a vacuum of 10^{-7} Torr of CO gas; note that the modulation of the electrons goes to roughly σ_y after $2\,\mu$s (from Ref. [16]).

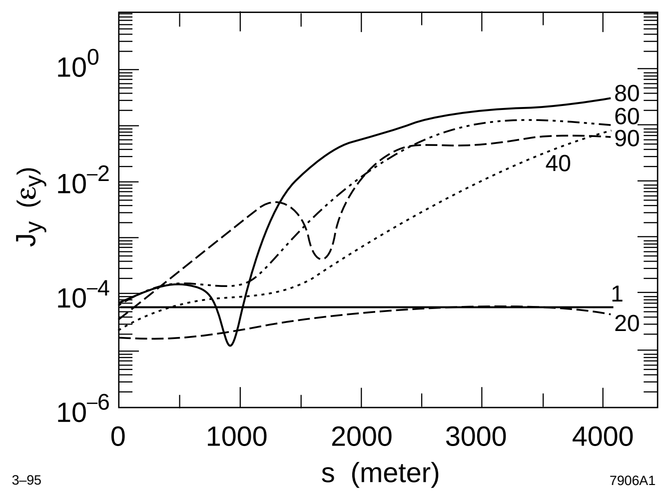

Figure 8. Growth of the action of the vertical centroid for every twentieth bunch in the NLC Damping Ring for a vacuum of 10^{-8} Torr of CO gas; note that the growth saturates at roughly σ_y because of the nonlinearity of the beam-ion force (from Ref. [18]).

The nature and analytic treatment of the instability closely resemble the beam break-up instability due to transverse wakefields. It is described in Refs. [16][17] and is summarized in Ref. [18]. The results of macro-particle simulations from the NLC damping ring are shown in Figs. 7 and 8. Because of the high bunch train charge and the very small beam emittances the instability has a very fast growth rate; with a CO partial pressure of 10^{-8} Torr, the bunches are offset by roughly σ_y after $7\,\mu$s. The instability could be a limitation in future linear colliders as well as the SLAC and KEK [19] B-factories. Because the instability growth depends quadratically on the length of the bunch train, the most straightforward solution is to add additional gaps to the train. Unfortunately, this will not reduce the instability due to free electrons created by tunneling ionization in a positron bunch.

Experiments are being planned to observe this instability at third generation light sources as well as at the Stanford Linear Collider and KEK TRISTAN Accumulator Ring. Finally, this instability is similar to the ion hose instability observed in ion focused high current induction linacs and a similar effect has been seen in the Los Alamos Proton Storage Ring (PSR) where it is believed that the proton beam traps field emission electrons; measurements from the PSR are described in Ref. [20] and the results of simulations are described in Ref. [21].

IV. SUMMARY

We have discussed three effects of trapped particles in future storage rings and linear colliders. Significant ion densities can occur in either a long train of bunches due to collisional ionization and trapping or in very dense bunches due to the tunneling ionization. These ions will cause filamentation, transverse coupling, beam halos, and will drive collective instabilities. These effects arise within the passage of a single train of bunches or, in some cases, in the passage of a single bunch. They arise in storage rings, linacs, and transport lines, and will limit the operation, as well as the acceptable vacuum, in future accelerators.

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