IONS IN THE LINACS OF FUTURE LINEAR COLLIDERS*

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Introduction

Ions have been identified as a potential limitation in high current storage rings, but they are not usually thought to be a problem in electron linear accelerators. In this paper, we consider the effects of ions in the linacs of future linear colliders. Future linear collider designs call for long trains of closely spaced bunches and/or very dense bunches. Thus, significant ion densities can be generated through the collisional ionization process and "trapping" in a long train of bunches or through the tunneling ionization with very dense bunches.

We consider two principal effects of these ions: first, they provide skew fields which cause transverse betatron coupling and increase the vertical emittance of the flat beams, and, second, the ion fields increase the rate of filamentation, making correction of the emittance dilutions more difficult; this could lead to tighter alignment tolerances. Both of these effects are verified with simulations. We will not consider other potential limitations that the ions impose.

We will consider these effects in four illustrative linear collider designs [1]: the NLC, the old NLC design, the DESY S-band design, and the Russian design, VLEPP; parameters for the linacs are listed in Table 1. In all cases, the emittances listed are 40% smaller than the emittance specified at the IP, allowing for 60% emittance dilution in the linacs, collimators, and final foci. In addition, we assumed that the β functions scale with the square root of the beam energy. The designs will not conform to this scaling exactly, but it roughly approximates the growth of the beta functions along the linacs. Finally, note that the NLC design requires two bunch compressions and thus the linac is divided into two sections: a short S-band linac from 2 GeV to 15 Gev, referred to as the NLC pre-linac, and the main X-band linac that accelerates the beam to the final energy.

Generation and Trapping

There are two ways in which an ion can be created: collisional ionization and tunneling ionization due to the collective electric field of a bunch. The cross section for the collisional ionization can be expressed as [2]:

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

where C_1 and C_2 depend upon 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 focused by the bunched beams and significant ion densities can be accumulated, provided that the ions are not over-focused and dispersed between bunches. This condition is basically the same as that for linear stability in a storage ring [3]:

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

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 three designs trap the ions. Finally, the trapping is illustrated in Fig. 2 which is a simulation in the NLC pre-linac with only 30 bunches and a 10^{-7} Torr partial pressure of CO; the bunch train was shortened to keep the simulation times reasonable, but since the ions are trapped the results are similar to those in a 90 bunch train at a pressure of 3×10^{-8} Torr.

The other method of ion generation is the tunneling ionization. The transition rate for tunneling ionization in a static electric field is [4]:

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

where $\mathcal{E}$ is the electric field and E_{ion} is the ionization energy. Because of the exponential factor, this process is very sensitive to the electric field. For example, the time to ionize CO in a 3.5 V/Å electric field is less than 10 femtoseconds (the static electric field approximation is valid in this case). But, in a field of 1.8 V/Å, the ionization time is roughly 60 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 three designs, but, in the last two designs, the surrounding gas is fully ionized. Finally, results of a simulation of the tunneling ionization in the old NLC design is plotted in Fig. 3.

Beam Dynamics

The transverse potential due to the electrostatic field of the ions can be expanded in a power series:

$$V = \gamma mc^2 e^{-z^2/2\sigma_z^2} \sum_{i,j} V_{ij}\frac{x^i y^j}{i!j!} \quad . \qquad (4)$$

With a uniform distribution of ions, only the linear focusing shifts are non-zero: $V_{20} = V_{02} = 2\pi\rho_{ion} r_0/\gamma$. But in non-uniform distribution, the higher order coefficients are also non-zero. Assuming a gaussian distribution with rms widths σ_x and σ_y, the first few coefficients are:

$$V_{02} = \frac{2\lambda_{ion} r_0}{\gamma\sigma_y(\sigma_x + \sigma_y)} \qquad V_{22} = -\frac{2\lambda_{ion} r_0}{\gamma\sigma_x\sigma_y(\sigma_x + \sigma_y)^2}$$

$$V_{04} = -\frac{2\lambda_{ion} r_0(\sigma_x + 2\sigma_y)}{\gamma\sigma_y^3(\sigma_x + \sigma_y)^2}$$

where the horizontal coefficients V_{20} and V_{40} are assumed

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Table 1. Linac Parameters

	main NLC	NLC pre-linac	DLC	old NLC	VLEPP
Particles/Bunch N $[10^{10}]$	0.7	0.7	2.2	1.9	20
Initial Energy E_0 [GeV]	15	2	3	15	3
$\overline{\beta_0}$ [m]	8	6.5	13	5	1
$\gamma\epsilon_x$ $[10^{-8}$ m-rad]	300	300	600	300	1200
$\gamma\epsilon_y$ $[10^{-8}$ m-rad]	3	3	60	3	4.5
σ_z [μm]	100	500	500	100	750
Bunches n_b	90	90	170	10	1
Bunch Separation ΔL [m]	0.42	0.42	3.0	0.42	—
A_{trap} at injection	24	4	9	112	—
$\hat{\mathcal{E}}$ at 250 GeV [eV/Å]	0.9	—	0.4	3.6	2.9

Table 2. Effects of ions with 10^{-7} Torr of CO gas

	main NLC	NLC pre-linac	DLC	old NLC	VLEPP
Bunches tracked	30	30	60	3	1
$\Delta\hat{\nu}/\nu$ [%]	10.1	13.4	12.3	6.4	4.7
$\gamma\epsilon_{y0}$ $[10^{-8}$ m-rad]	3	3	60	3	4.5
$\gamma\hat{\epsilon}_y$ $[10^{-8}$ m-rad]	4.80	4.55	150	3.90	5.71

to be small since σ_x is assumed much greater than σ_y.

The first effect of the ions we consider is the filamentation. The coefficient V_{02} describes the additional focusing at the beam center due to the ions. This additional focusing will vary substantially from bunch-to-bunch in a long train of bunches and from head-to-tail with the tunneling ionization. Because the focusing varies, the beam will tend to filament (phase mix). This has implications for non-local correction of the transverse emittance dilutions as is illustrated schematically in Fig. 1. Non-local correction has been described as a method of easing the alignment tolerances in future linear colliders [5] and is being utilized in the Stanford Linear Collider. Unfortunately, this additional filamentation may render the technique useless for future colliders. The variation in the focusing due to the ions is listed in Table 2 for the different designs.

In addition to the filamentation, the ion fields will cause transverse betatron coupling through the V_{22} component of the field. To estimate this effect with flat beams, we can neglect the effect of the vertical motion on the horizontal. Thus, the horizontal motion can be written $x = \sqrt{2J_x\beta_x}\cos(\psi_x(s) + \phi_x)$ while the vertical motion is described as a parametric oscillator:

$$y'' + \left[k_y^2 + \tfrac{1}{2}V_{22}J_x\beta_x\cos(2\psi_x + 2\phi_x)\right]y = 0 \qquad (5)$$

where $k_y^2 = 1/\beta_y^2 + V_{02} + \frac{1}{2}V_{22}J_x\beta_x$ and we have only included the linear focusing shift and the octupole-like coupling (this is valid for $x, y \lesssim \sigma_x, \sigma_y$).

Now, parametric resonance occurs when horizontal and vertical focusing are equal. In this case, the vertical

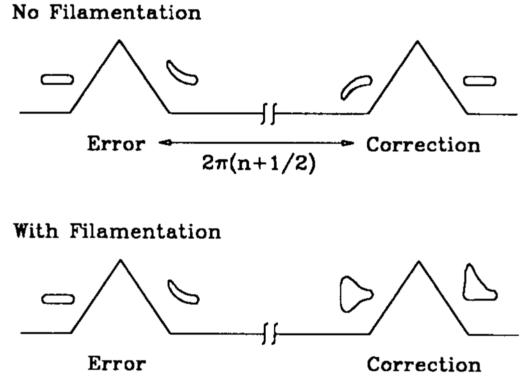

Fig. 1 Schematic of the effects of filamentation on non-local correction techniques.

motion can be written

$$y = ae^{s\kappa}\cos(sk_x + \theta_1) + be^{-s\kappa}\cos(sk_x + \theta_2) \qquad (6)$$

where a and b are constants of the motion and

$$\kappa = \frac{1}{8k_x}\sqrt{(V_{22}J_x\beta_x)^2 - 16(k_y^2 - k_x^2)^2} \quad . \qquad (7)$$

Thus, the condition for stability is

$$\left|\frac{\Delta\nu_{ion}}{\nu}\frac{J_x\beta_x}{\sigma_x^2}\right| \leq \left|4\frac{(\nu_x - \nu_y)}{\nu} - 4\frac{\Delta\nu_{ion}}{\nu} + 2\frac{\Delta\nu_{ion}}{\nu}\frac{J_x\beta_x}{\sigma_x^2}\right|$$

where $\Delta\nu_{ion}/\nu$ is the change in the vertical focusing due to the ions: $\Delta\nu_{ion}/\nu = \frac{1}{2}\beta^2 V_{02}$. This condition can be satisfied by separating the horizontal and vertical focusing. The optimal choice is to increase the horizontal focusing

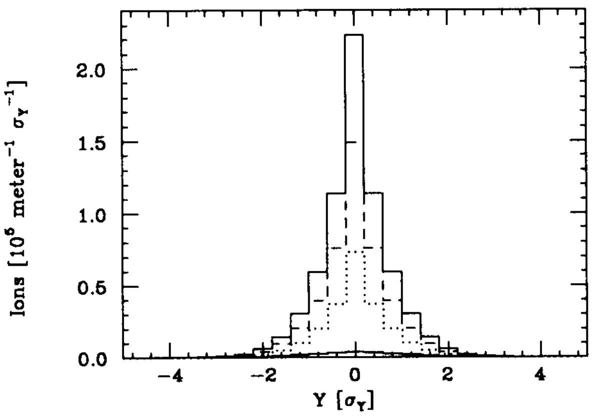

Fig. 2 Vertical projection of the ion density in the NLC pre-linac after 1 bunch (solid), 10 bunches (dotted), 20 bunches (dashed) and 30 bunches (solid) with a CO gas partial pressure of 10^{-7} Torr. Note that the ions are trapped between bunches.

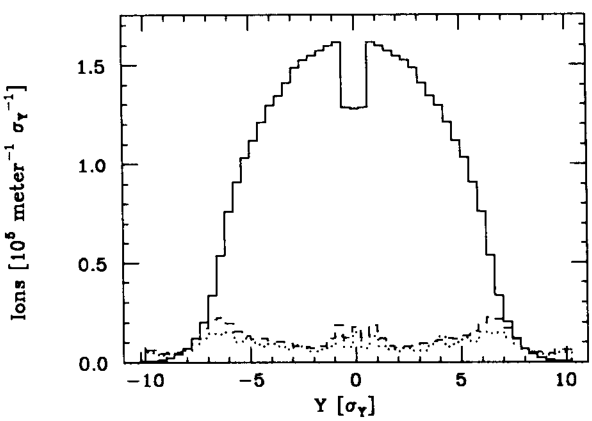

Fig. 3 Vertical projection of the ion density in the (old) NLC pre-linac after 1 bunch (solid), 2 bunches (dashes), 3 bunches (dotted) with a CO gas partial pressure of 10^{-7} Torr. Note that the ions are strongly over-focused by the beam.

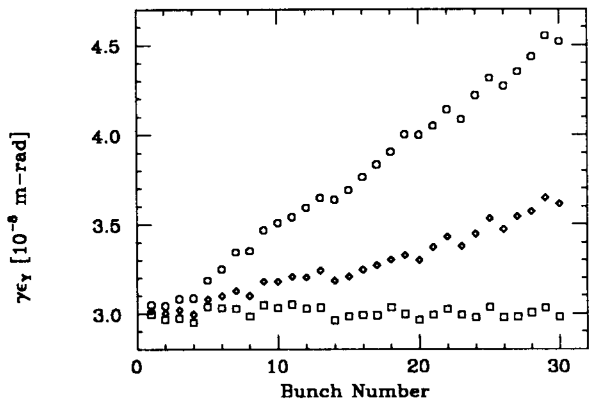

Fig. 4 Vertical emittance vs. bunch number in the NLC pre-linac at the beginning (squares), middle (diamonds), and end (circles); the linac has equal horizontal and vertical focusing of 90° per cell and a CO partial pressure of 10^{-7} Torr.

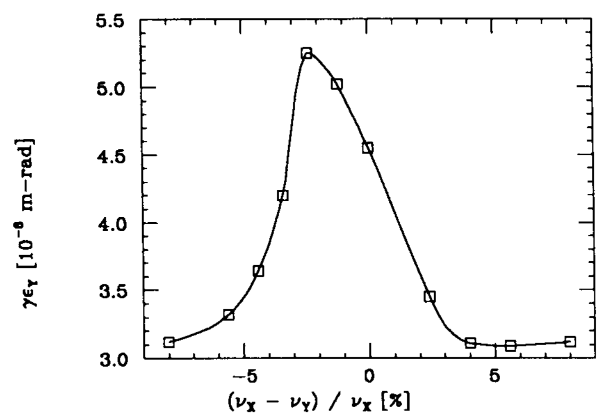

Fig. 5 Vertical emittance vs. difference between horizontal and vertical quadrupole focusing in the NLC pre-linac; the emittance is that of the 30th bunch and the partial pressure of CO is 10^{-7} Torr. Note the peak occurs when the horizontal focusing is weaker than the vertical.

over the vertical so that the resonance condition is not encountered at any amplitude. In this model, the separation required is equal to the linear focusing shift due to the ions; in simulations, the actual separation required is less because of the amplitude dependent focusing from the ions and the energy spread in the beam.

This effect is illustrated in Figs. 4 and 5 which are results of simulations in the NLC pre-linac with equal horizontal and vertical quadrupole focusing. We simulated only 30 bunches in a CO partial pressure of 10^{-7} Torr; the effects would be similar with a train of 90 bunches in 3×10^{-8} Torr of CO. Results for the other designs are listed at the bottom of Table 2.

Summary

We have discussed two effects of ions in the linacs of future 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 and transverse coupling. While the latter effect can be alleviated by separating the horizontal and vertical phase advances, the increased filamentation will reduce the effectiveness of non-local correction techniques, thereby leading to tighter alignment tolerances. To reduce the effect of the ions in the designs considered to the level of the intrinsic energy spread, one would need to achieve vacuum pressures less than 10^{-9} Torr.

References

1. These parameters were listed at the 4th Workshop on Future Linear Colliders in Garmisch, Germany, 1992.
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5. T. O. Raubenheimer, "The Generation and Acceleration of Low Emittance Flat Beams," Ph.D. Thesis, Stanford Univ., SLAC–387 (1992).