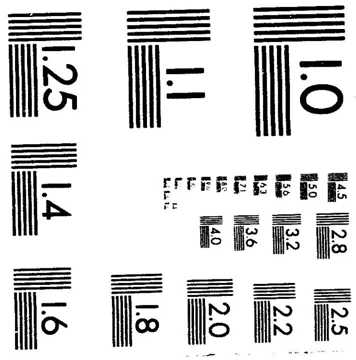
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Simulation of the Beam Halo from the Beam-Beam Interaction in LEP*

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The luminosity lifetimes of e^+e^- colliders are often dominated by the halo produced by the beam-beam interaction. We have developed a simulation technique to model this halo using the flux across boundaries in amplitude space to decrease the CPU time by a factor of one-hundred or more over "brute force" tracking. It allows simulation of density distributions and halos corresponding to realistic lifetimes[1]. Reference 1 shows the agreement with brute force tracking in a number of cases and the importance of beam-beam resonances in determining the density distribution at large amplitudes. This research is now directed towards comparisons with operating colliders and studies of the combined effects of lattice and beam-beam nonlinearities. LEP offers an ideal opportunity for both, and in this paper we are presenting the first results of LEP simulations.

We have simulated a collider corresponding to one-quarter of LEP with the parameters in Table I. We estimate that the simulation technique reduced the CPU time by a factor of 2500 for LEP.

TABLE I: PARAMETERS OF MODEL FOR ONE-QUARTER OF LEP[2]

Parameter	Value	Parameter	Value
Q_x (horiz tune)	22.56	Q_y (vert tune)	19.0475
β_x^*	2.6 m	β_y^*	0.052 m
η_x^*	0.02 m	η_y^*	0.001 m
ε_x	3.58×10^{-8} m	ε_y	2.0×10^{-9} m
σ_x	303 μm	σ_y	10.3 μm
Q_s (synch tune)	0.01625	$\sigma_\delta = \sigma_E/E_0$	1.2×10^{-3}
ξ_x (horiz beam-beam)	0.034	ξ_y (vert beam-beam)	0.021
E_0	45 GeV	I_b (single bunch)	1.8 mA
α	1.859×10^{-4}	f_{rev}	44982 Hz
U_0	32.58 MeV		
$dQ_x/d\delta$	0.5	$dQ_y/d\delta$	0.5
$d^2Q_x/d\delta^2$	−70	$d^2Q_y/d\delta^2$	−42.5
$d\beta_x^*/d\delta$	−30 m	$d\beta_y^*/d\delta$	−2 m

Contours of constant particle number are shown in Figure 1a. The contours are logarithmic, and the amplitudes are in unit of beam sizes, σ_x and σ_y. The lifetime as a function of horizontal and vertical apertures are plotted in Figure 2. One can see that the tail extends

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evenly in horizontal and vertical. This is quite different from lower energy colliders, such as PEP-II, in which the vertical tail extends significantly. This could be due to the strong damping in LEP, but we have not studied that yet. Because $\sigma_x >> \sigma_y$, it is possible that the horizontal aperture limited the lifetime.

Beam Current Dependence

The performance of most colliders is limited by the lifetime as the beam current increases. To illustrate this for LEP, simulations were performed keeping all the parameters the same except for the beam current. As the beam current increases, the tails extend to larger amplitudes. Figure 1 shows the distributions and Figure 3 shows the lifetime for different currents. The lifetime drops dramatically for certain apertures (e.g., A_x=7) as the current increases.

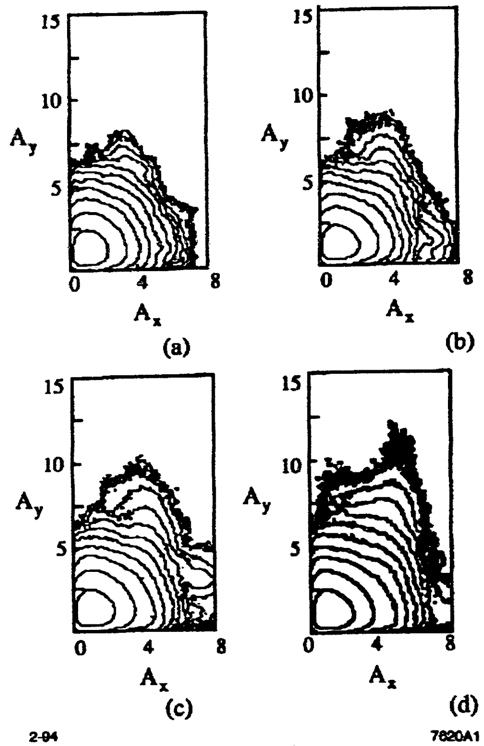

Figure 1. Logarithmic contours of particle number. (a) I_b = 1.8mA (ξ_x = 0.034, ξ_y = 0.021); (b) I_b = 2.4mA (ξ_x = 0.046, ξ_y =0 .027); (c) I_b = 3.0mA, (ξ_x = 0.057, ξ_y = 0.034); (d) I_b = 3.6mA, (ξ_x = 0.069, ξ_y = 0.041).

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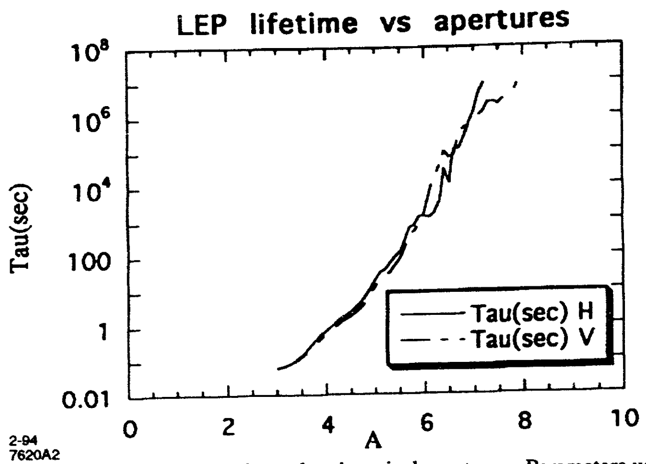

Figure 2. Lifetime as a function of horizontal and vertical apertures. Parameters used are listed in Table I, and the corresponding distribution is Figure 1a.

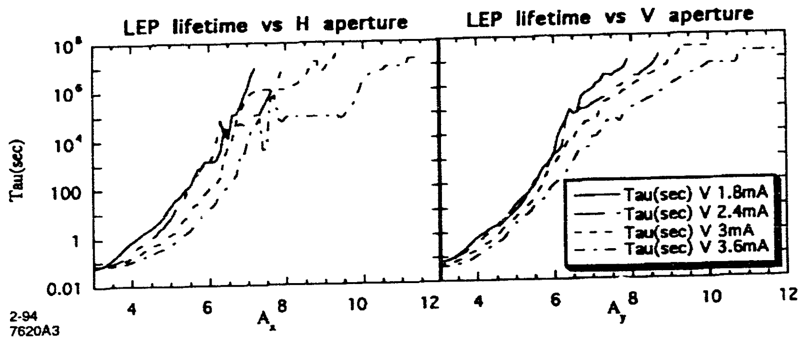

Figure 3. The lifetime as a function of horizontal and vertical apertures for different beam currents.

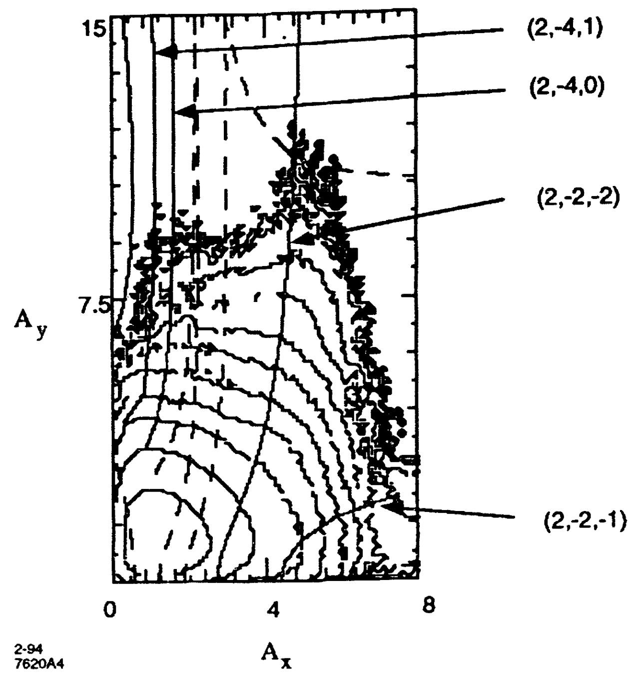

Figure 4. The location of resonances in amplitude space superimposed on the beam distribution from Figure 1d. The resonances are of a form $pQ_x + rQ_y + mQ_s = n$, and the lines are labeled as (p, r, m).

Figure 4 shows the relation between resonances and the beam distribution. The high current parameters of Figure 1d are used to show the effect better. The resonance $2Q_x - 2Q_y - Q_s = n$ (where n is an integer) is responsible for the horizontal tail, and the resonances $2Q_x - 2Q_y - 2Q_s = n$, $2Q_x - 4Q_y + Q_s = n$ and $2Q_x - 4Q_y = n$ are responsible for vertical tail at this operating point.

The Influence Of Lattice Nonlinearities

Lattice nonlinearities can change the beam distribution and lifetime significantly. Our simulation code can include amplitude-dependent tune shifts and high-order chromaticities. The lattice nonlinearities used for LEP are listed in Table II. *Group 1* includes only the contributions of sextupoles. *Group 2* contains the estimates of the actual nonlinearities due to parasitic octupoles.

The parameters used in the simulation are those in Table II in addition to those in Table I. The results are given in Figure 5. Since the beam-beam interaction is rather weak at this set of parameters (ξ_y=0.021), the lifetime is not dramatically changed by the lattice nonlinearity. However, the tail distribution is obviously changed because of the changing of resonance locations.

TABLE II: NONLINEAR PARAMETERS OF ONE-QUARTER OF LEP[2]

Parameter	*Group 1*	*Group 2*
dQ_x/dJ_x (m)	10	-2.5×10^4
dQ_y/dJ_y (m)	500	-1×10^5
dQ_x/dJ_y (m)	-8500	-5000
dQ_y/dJ_x (m)	-8500	-5000

TABLE III. PARAMETERS FOR INCREASED BEAM-BEAM TUNE SHIFT

Parameter	*Group A*	*Group B*
I_b (mA)	2.2	0.88
ε_x (m)	3.58×10^{-8}	1.2×10^{-8}
ε_y (m)	1.0×10^{-9}	4.8×10^{-10}
ξ_x	0.042	0.05
ξ_y	0.036	0.037

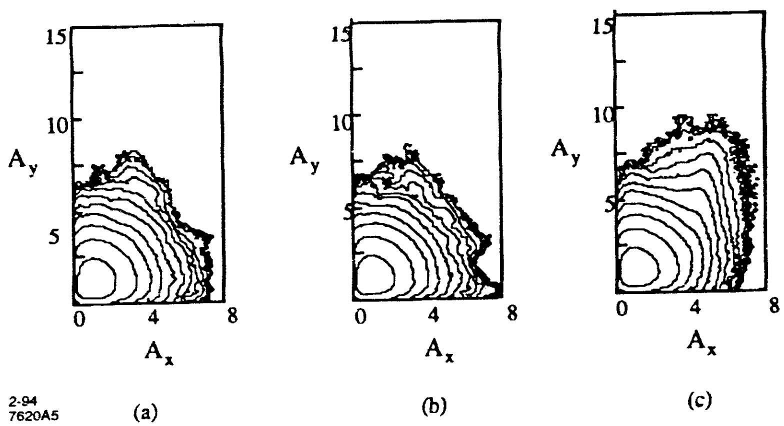

Figure 5. Distributions with: (a) no amplitude dependent tunes due to lattice nonlinearities (identical to Figure 1a); (b) lattice nonlinearities in Table II,*Group 1*; (c) lattice nonlinearities, parameters in Table II,*Group 2*.

To study increased beam-beam strengths, one can either increase the beam current or reduce the emittances. Two combinations of these parameters are investigated. They are listed in Table III. Other parameters are the same as those in Table I and Table II, *Group 2* . The distributions shown in Figure 6 are similar.

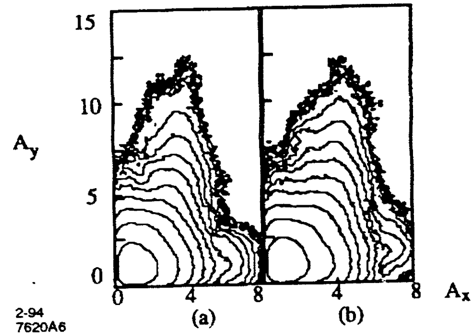

Figure 6. Tail distributions with increased ξ and lattice nonlinearities. Most parameters are the same as Table I together with Table II, *Group 2*, but the beam current and sizes are changed to obtain higher ξ's. (a) uses the parameters in Table III, *Group A*; (b) uses the parameters in Table III, *Group B*.

The Influence Of Chromaticity

It has been observed at LEP that the second order vertical chromaticity,

$$Q_y'' = \frac{d^2Q_y}{d\delta^2},$$

has strong influence on beam lifetime. This was not well understood and interference between chromaticity and the beam-beam interaction is suspected. We have investigated this and find dramatic influence of Q_y'' when combined with the beam-beam interaction. The second order chromaticity used in the simulation of one-quarter LEP is $Q_y'' = -1.5\times10^4$ implying $Q_y'' = -6\times10^4$ for LEP itself. Figure 7 shows the distributions as the magnitude of Q_y'' increases. It is easy to see that a large resonance island is generated at 20 - 25 σ_y by the large Q_y''. The impact on lifetime can be seen from Figure 8. We have checked that the chromaticity by itself, i.e. without the beam-beam interaction, does not cause such a dramatic tail.

Summary

This new technique allows us to investigate the tail formation and calculate lifetime in a new regime. Many phenomena are being seen for the first time, and we hope that this technique will prove helpful in understanding the beam-beam lifetime. Application to LEP has shown the following:

1) The beam tail can extend in horizontal direction, and the lifetime could be determined by the horizontal aperture. This is different from past simulations that have indicated that particle losses were always in vertical.

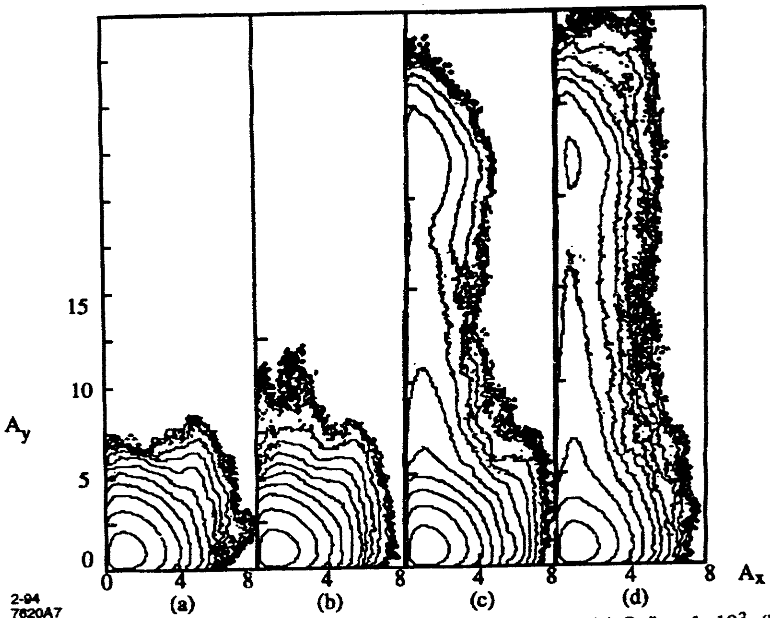

Figure 7. Distributions with high second order vertical chromaticity. (a) $Q_y" = -1\times10^3$; (b) $Q_y" = -4\times10^3$; (c) $Q_y" = -8\times10^3$; (d) $Q_y" = -1.5\times10^4$. These chromaticities are for the one-quarter LEP model. Other parameters are the those in Table I and Table II, *Group 2*.

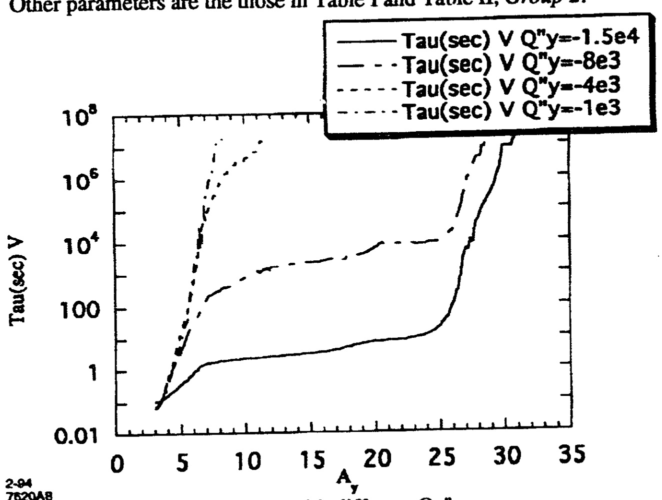

Figure 8. Lifetime versus vertical aperture with different $Q_y"$.

2) Large second order chromaticity, as well as other lattice nonlinearities, can result in dramatic changes in tail distribution and lifetime.

We look forward to further collaboration with the LEP accelerator physicists in making quantitative comparisons between the simulation and experiments.

Acknowledgment

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