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Plasma Suppression of Beamstrahlung

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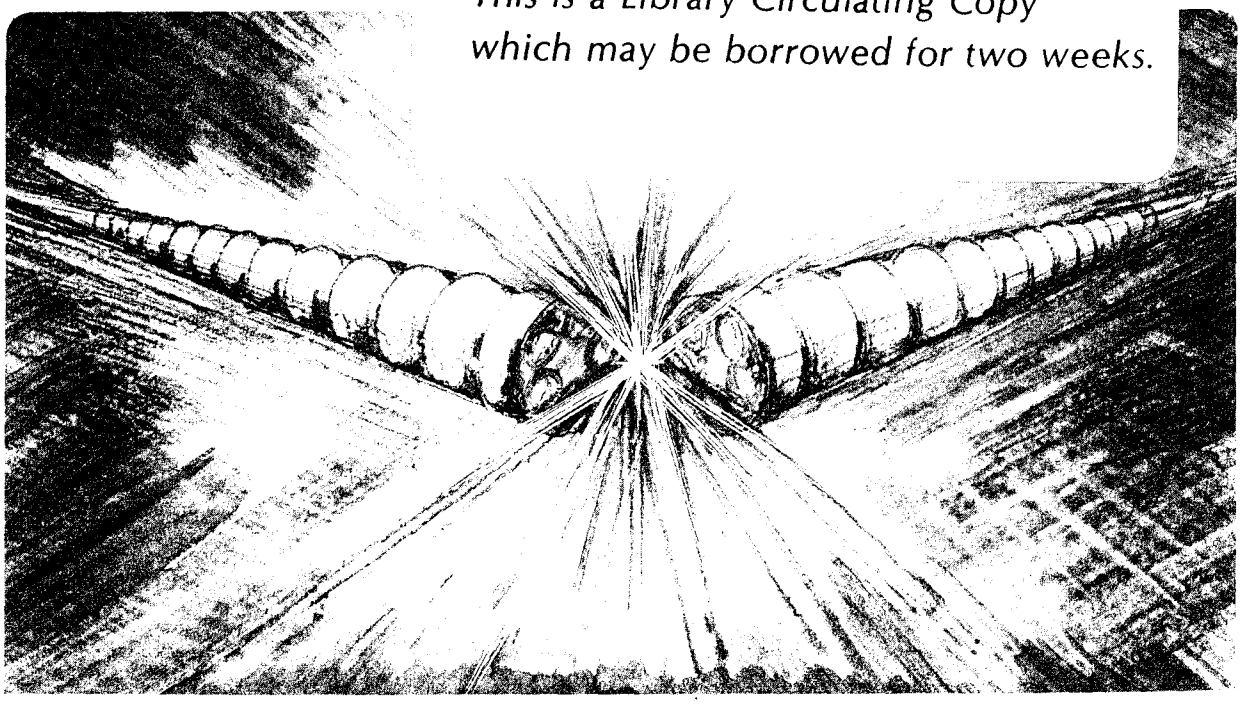

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Abstract

We investigate the use of a plasma at the interaction point of two colliding beams to suppress beamstrahlung and related phenomena. We derive conditions for good current cancellation via plasma return currents and report on numerical simulations conducted to confirm our analytic results.

I. Introduction

To reach luminosities of interest for the next generation of particle physics experiments it is necessary to consider submicron beams[1] and phenomena attendant to them: beamstrahlung and luminosity enhancement.[2] The physical picture is as follows. Two oppositely charged beams (positron and electron) with peak currents of ~ kiloamp, short lengths of ~ millimeter, small radii of ~ fractions of microns and energies of 100 Gev to 1 Tev, collide (see Figure 1).

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As the beams collide, the net radial electic field drops to zero due to charge cancellation, while the net azimuthal B field is doubled. This megagauss field curves the electron and positron trajectories, resulting in a focussing of the beam (luminosity enhancement) and synchrotron radiation (beamstrahlung). Note that particles near the axis see a very small B field and radiate little, so that in addition to a net energy loss, beamstrahlung results in an energy spread, and, consequently, an experimental uncertainty in the energy of the incoming states.

This spread for parameters of interest for future colliders is $\sim 10\%$ or more. In addition, the effect of a large spread in energy combined with narrowly peaked reaction cross sections is to greatly reduce the resulting reaction rate, negating the effect of increased luminosity. Thus unsupressed beamstrahlung could prove highly detrimental to the next generation of collider physics experiments.

We propose to reduce beamstrahlung by providing a conducting medium (a plasma) at the interaction point, to inhibit the diffusion of the B-fields as the beam current rises and in which return currents will flow and partially cancel the B-fields of the high energy electron beam, while totally neutralizing its charge. Since the energy spread increases roughly as the square of the effective current, partial shielding of, say $\sim 80\%$, will reduce the energy spread by $\sim 96\%$. We will find that there are two key problems with this scheme and that they can likely be resolved within the colliding beam parameter range of interest.

The first problem is that of the experimental background. Interactions of the high energy beams with the hadronic constituents of the plasma will produce a large number of gammas and charged pions[3], which will have to be kept from the detector via magnetic fields, or discriminated against based on their relatively lower energy. Much theoretical and experimental work remains to be done to determine whether the background can be made acceptable.[4]

One possible means of circumventing this background problem which has been suggested by Paul Channel[5] is to use a positronium plasma at the intersection point. This solution appears, however, to suffer from the difficulty of generating sufficiently large plasma densities.

The second problem with the plasma suppression scheme is that in order to reach a plasma conductivity high enough to shield the B-field sufficiently, the plasma temperature (or the energy of drift motion of secondaries with respect to the stationary ion background) must be large. We find that for a preionized plasma and for parameters of interest, the combination of Ohmic heating, direct beam heating, and large secondary electron drift velocities are sufficient to drive the collision rate down (i.e., to drive the conductivity up).

The organization of the paper is as follows. The first section is this Introduction. In the second section, we discuss 1-D and 2-D Analytical Work. In the third section we discuss Numerical Work, which consists of a PIC simulation. In the fourth section, we summarize our Conclusions.

II. Analytic Work

First, we note in passing that a thorough theoretical understanding of this scenario is of interest for many applications, a few of which are listed in Table 1. We also list, for the reader's convenience, in Table 2, some of the major issues which he will find are involved in relativistic electron beam - gas physics. In the following we will confine ourselves to a discussion of beamstrahlung suppression, but much of this work carries over into other devices.

We consider a high current, relativistic electron beam impinging on a dense gas. A channel may have been pre-ionized via laser through the gas, or the e-beam may make its own channel via production of secondary e^- and subsequent breakdown. We may divide the time evolution into three regimes (see Figure 2):

Very Early Time:
(Highly Collisional Regime)

$$\nu \tau_r >> 1$$

$$\tau_r >> \tau_m = (k_p a)^2 \nu^{-1}$$

Early Time:
(Moderately Collisonal Regime)

$$\nu \tau_r >> 1$$

$$\tau_r << \tau_m = (k_p a)^2 \nu^{-1}$$

Late Time:
(Collsionless Regime)

$$\nu \tau_r << 1$$

Where our notation is :

ω_p = plasma frequency
$= 3.1\ 10^{14} \text{rad/sec}\ (n_p/3\ 10^{19} \text{cm}^{-3})^{1/2}$

$k_p = \omega_p / c$

τ_r = beam current rise time

a = beam radius

$n_b(r,\tau) = n_{b0} \exp(-\tau^2/\tau_r^2) \exp(-r^2/a^2)$)

τ = $t-z/v$

v = beam velocity ~ c

τ_m = $(k_p a)^2 / \nu$

= magnetic diffusion time

ν = $\nu(t)$ = collision rate of secondaries with ions

$= 5\ 10^{13}\ \text{sec}^{-1} (n_p/3\ 10^{19}\text{cm}^{-3})\ \Lambda/T_{eff}^{3/2}$

Λ = Coulomb logarithm

T_{eff} = effective temperature

We will find that in order for the plasma return currents to suppress the beam B-fields, the plasma must pass through the first regime in a time short compared to the current rise time. In addition, once having arrived in the moderately collisional or collisionless regime, the current neutralization skin depth, k_p^{-1} must be small compared with the beam radius, a . We also require that the plasma be effective in neutalizing space charge, however this is a much less stringent constraint. We summarize these results (to be derived below) in Table 3.

The most crucial question here is: How fast does the collision rate drop? (i.e., how fast does the B-field diffusion time rise---once $\tau_r << \tau_m$, any further rise in B is frozen out of the plasma.). It is to answer this question that we resort to numerical simulations. The answer, as we will see, is that the collision rate drops fast enough to permit substantial current cancellation, provided we preionize the channel.

1. 1-D Approach

Before analyzing the detailed 2-D MHD problem , let us make a quick estimate of the important parameters involved with a 1-D approach. Since $\omega_p \tau_r >> 1$, the current rise is adiabatic with respect to space charge oscillations;and we may therefore neglect high frequency oscillations attendant to Debye sheath formation.

The charge neutralization time is

$$t_{neut} \cong n_b/(n_b\, n_g\, \sigma^i_{bg}\, c)$$

$$= 0.5\ \text{ps}\ (3\ 10^{19}\text{cm}^{-3}/n_g)\ (2\ 10^{-18}\ \text{cm}^2/\sigma^i_{bg})$$

(since $\sigma^i_{bg} \sim 10^{-18}$ cm^2) and since this is a bit too long for the beam to provide its own completely ionized channel, we will assume the plasma is 100% ionized prior to the arrival of the beam.

The time for the Debye sheath to form, once secondaries have been stripped from the ions, is very short:

$$t_{Debye} \sim \text{larger of } 1/\omega_p,\ \nu/\omega_p^2$$
$$\sim 5\ 10^{-3}\ \text{ps}\ (3\ 10^{19}\text{cm}^{-3}/n_p)^{1/2}$$
$$\text{or}$$
$$\sim 6\ 10^{-5}\ \text{ps}\ (n_g/n_p)$$
$$\sim \text{short !}$$

In addition, the Debye sheath, once formed, is effective in screening charge:

$$k_d a = 7.4\ 10^2\ a\,(\mu\text{m}) \left(\frac{n_p\,\text{cm}^{-3}}{3\ 10^{19}\,\text{cm}^{-3}} \right)^{\frac{1}{2}} T_p(\text{ev})^{-\frac{1}{2}}$$

$$>> 1$$

i.e., the Debye length is short compared to other scales of interest.
Our notation here is:

n_b= beam density
n_g= gas density
σ^i_{bg}=ionization cross section for beam-electron & gas collisions
c= speed of light
ν= momentum collsion rate
ω_p= plasma frequency
k_d=Debye wave number

Thus we have the picture of a completely ionized channel, much denser than the beam at its peak density, which responds rapidly to the beam space charge and screens it completely. We are interested, in this situation, in determining the degree of current cancellation. We have

$$E_z \approx -\frac{1}{c}\frac{\partial A_z}{\partial t} \approx -\frac{L}{c^2}\frac{\partial}{\partial t}(I_b + I_p)$$
$$\frac{\partial I_p}{\partial t} = \frac{\omega_p^2 a^2}{4} E_z - \upsilon I_p$$

which may be rewritten as an equation for total current $I_{tot}=I_b+I_p$:

$$\frac{\partial I_{tot}}{\partial t} = \frac{1}{1+\theta}\frac{\partial I_b}{\partial t} - \frac{\nu}{1+\theta}(I_{tot} - I_b)$$

where

$$\theta = (k_p a)^2 L / 4 \approx (k_p a)^2$$

This equation determines I_p(=plasma current) given I_b(=beam current). (Here L is a dimensionless inductance of order unity which depends on the radial variation of the fields.) Note that if the collision rate drops before the beam current has risen substantially, then total current will remain more or less constant at whatever value it has attained[6] . Evidently a rapid drop-off of collision rate is desirable. (On the other hand, if the collision rate were to remain substantial throughout, then after the beam current dropped off we would expect to see a tail in the total current decaying away on a time scale $\sim (1+\theta)\,\nu^{-1} \sim (k_p a)^2\,\nu^{-1} \sim \tau_m$.)

For more quantitative results, let us take a beam current profile of the form:

$$I_b(t) = I_0 \exp\left(-\frac{t^2}{\tau_r^2}\right)$$

This gives us, for $I_{tot} = I_b + I_p$ and ν constant,

$$I_{tot}(t)/I_b(t) = \frac{1}{1+\theta}\left[1 + \sqrt{\frac{\pi}{2}}\,\theta\Delta\left(1 + \mathrm{erf}\left(\frac{t}{\tau_r} - \frac{\Delta}{2}\right)\right)\exp\left(\frac{t}{\tau_r} - \frac{\Delta}{2}\right)^2\right]$$

where

$$\Delta = \frac{\upsilon\,\tau_r}{1+\theta}$$

Thus the plasma current consists of an inductive component in phase with the beam current and a resistive term which lags behind the beam current. We see that good current cancellation obtains provided

$$k_p a >> 1$$
$$\frac{\nu \tau_r}{(k_p a)^2} << 1$$

Noting that

$$\tau_m = (k_p a)^2 \nu^{-1}$$

is the magnetic diffusion time, we see that current cancellation is good provided the B-field is slow in diffusing into the plasma, and provided that, while the B-field is diffusing, the return currents are confined within a radius $a+k_p^{-1}$, where $k_p^{-1} << a$. This situation corresponds to a small lagging current and an inductive, in-phase current close in magnitude to the beam current and opposite in sign.

However, this 1-D approach has some shortcomings in that it gives us no information about the radial profile of the B field and it depends on the phenomenological constant L. This motivates us to consider a 2-D description.

2. 2-D MHD Equations

Neglecting the small space-charge oscillations which will be superimposed on the response of the plasma, and assuming 100% ionization we may set down our 2-D MHD Equations[7]:

Maxwell's Equations

$$\frac{1}{r}\frac{\partial}{\partial r} r B_\phi = \frac{4\pi}{c}(J_{pz} + J_{bz})$$

$$\frac{\partial E_z}{\partial r} = -\frac{4\pi}{c} J_{pr}$$

$$\frac{\partial B_\phi}{\partial \tau} = 4\pi J_{pr}$$

Electron Fluid Dynamics

$$\frac{\partial J_{pr}}{\partial \tau} = \frac{\omega_p^2}{4\pi} E_r - \Omega J_{pz} - \nu J_{pr}$$
$$\frac{\partial J_{pz}}{\partial \tau} = \frac{\omega_p^2}{4\pi} E_z + \Omega J_{pr} - \nu J_{pz}$$

where:

$\Omega = eB_\varphi/mc$

$\nu = \nu(t)$ = e^- collision rate

$\tau = t - z/v$

Approximations

We make a number of approximations.

1.From symmetry we have neglected

$$\frac{\partial}{\partial\phi} \approx B_r \approx B_z \approx E_\phi \approx v_\phi \approx 0$$

2.We have neglected the displacement current terms above, consistent with the large $\omega_p\tau_r$ approximation in which we neglect space charge oscillations.

3.We have made the "frozen field" approximation which is equivalent to neglecting the influence of the rear of the beam on the front (or, said another way, we neglect the interaction of the beam with its own radiation.):

$$\frac{\partial^2}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} \approx \frac{1}{v^2\tau_r^2}\frac{1}{\gamma^2} << \frac{1}{a^2} \approx \nabla_\perp^2$$

4.We neglect convection, i.e., beam dragging of the plasma:

$$\vec{v}\cdot\vec{\nabla} \approx v_{pz}\frac{\partial}{\partial z} \le \frac{n_b}{n_p}c\frac{\partial}{\partial z} \approx \frac{n_b}{n_p}\frac{\partial}{\partial t} << \frac{\partial}{\partial t}$$

5.We neglect ion motion:

$$a/v_{ion} \approx 10^2 ps \cdot a(\mu m)\cdot M_{ion}(amu)^{1/2}\cdot T_{ion}(ev)^{-1/2}$$
$$>> \tau_r$$

6.We assume the beam is unperturbed; this amounts to neglecting the length of the interaction region (a few mm) in comparison to the characteristic lengths associated with : Nordsieck expansion, resistive hose instability, sausage instability, Weibel (filamentation) instability, two-stream instability, ion-acoustic loss, etc.. This is an excellent approximation for parameters of concern here. (Note however, that due to the high energy of the beam, even a fractionally minute loss of beam energy can result in substantial plasma heating---a desirable feature.)

7.We are also neglecting the change in beam current density due to pinching from the residual B field (i.e., since the radial E field due to space charge has been neutralized by the plasma, any azimuthal B field remaining after partial current cancellation will pinch the electron beam, increasing the beam current density) This is a good approximation for plasma

compensation schemes where the residual B is low (Note, however that for plasma lens applications, one should examine beam pinching, since there the intent is to provide *poor* current cancellation---combined with good charge neutralization---to produce just such a focussing of the beam)

8.One additional approximation which greatly simplifies the analytic work is to neglect the pinch force on the secondary electrons. Since for early times I is small, ν large and for late times I is small provided we have current compensation, we may neglect

$$\Omega/\nu = 35\ I(kA)/a(\mu m)\ (10^{12} sec^{-1}/\nu) << 1$$

We will use this approximation throughout our analytic work, but not our numerical work.

With approximations 1-8, our MHD Eqs reduce to an equation for B_ϕ:

$$(\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial}{\partial r}r - k_p^2)B_\phi(r,\tau) = -\frac{4\pi}{c}\frac{\partial J_{be}}{\partial r}(r,\tau)$$

$$-k_p^2\int_{-\infty}^{\tau} d\tau' \upsilon(\tau') B_\phi(r,\tau') \exp(-\Gamma(\tau,\tau'))$$

with

$$\Gamma(\tau,\tau') = \int_{\tau'}^{\tau} d\tau'' \upsilon(\tau'')$$

from which the electric fields and currents may determined via the relations:

$$J_{pr} = \frac{1}{4\pi}\frac{\partial}{\partial\tau}B_\phi$$

$$\frac{\partial E_z}{\partial r} = \frac{4\pi}{c}J_{pr}$$

$$E_r = \frac{1}{\omega_p^2}(\frac{\partial}{\partial\tau} + \nu)\frac{\partial}{\partial\tau}B_\phi$$

$$J_{pz}(r,\tau) = \frac{\omega_p^2}{4\pi}\int_{-\infty}^{\tau} d\tau' E_z(r,\tau') \exp(-\Gamma(\tau,\tau'))$$

Time Evolution of ν(t)

The response of the plasma to the beam current as dictated by these equations divides in a natural way into the highly collisional, moderately collisional and collisionless regimes as described below, based on the relative size of $\nu(t)$; it is of interest then to describe the time behavior of ν. Here ν is determined from the average secondary e-energy $\varepsilon = \varepsilon_{thermal} + \varepsilon_{translational}$, where $\varepsilon_{thermal}$ is due to preionization (if any), Ohmic heating, and energy deposition by primaries:

$$n_p \frac{\partial \varepsilon_{thermal}}{\partial \tau} = \vec{J}_p \cdot \vec{E} + n_b \frac{\partial Q}{\partial \tau}$$

Note that if good current cancellation obtains then the secondary drift velocity is $v_z \cong -c\, n_b/n_p$ so that $\varepsilon_{translational} \cong 260$ kev $(n_b/n_p)^2$ which is quite large. Thus a rising plasma current will tend to drive down ν to a significant degree. Note, for example, that for $n_b/n_p \cong 1/6$, the energy of drift motion alone, assuming good current cancellation would be, $\varepsilon_{translational} \cong 5$ kev. This corresponds to a $\nu \cong 2\ 10^9\ sec^{-1}$ (assuming $n_p = 3\ 10^{19}\ cm^{-3}$) which is much less than τ_r^{-1}, corresponding to the collisionless regime.

Late Time (Collisionless Regime)

We turn now to examine our equation for B. The time evolution of the plasma response divides naturally into several regimes (see Figure 2). We reserve for a later work an examination of the "Very Early Time" (highly collisional regime) and the "Early Time" (moderately collisional regime). For now we envision a beam incident on a preionized gas, which rapidly reaches a "collisionless" state (i.e., $\nu\, \tau_r << 1$) due to beam-secondary and ohmic heating. In this low ν limit our B_ϕ equation becomes

$$\left(\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial}{\partial r} r - k_p^2\right) B_\phi \approx -\frac{4\pi}{c}\frac{\partial J_{bz}}{\partial r}$$

so that

$$B_\phi(r,\tau) = -\frac{4\pi}{c}\int_0^\infty dr' r' I_1(k_p r_<) K_1((k_p r_>) \frac{\partial J_{bz}}{\partial r}(r',\tau)$$

where I_1, K_1 are the modified Bessel functions ($r_< = \min(r,r')$, $r_> = \max(r,r')$). An explicit solution of this for the case of immediate experimental interest is shown in Figure 3. Plasma compensation as a function of $k_p a$ is shown in Figure 4. Evidently at $k_p a \sim 2$ there is sufficient current compensation within the beam volume to produce a factor of ~ 30 reduction in radiated energy.

Asymmetric Beams

In view of proposed design parameters for the "Next Linear Collider" (NLC),[8,9] most of which include an asymmetric ("flat") beam, it is of interest to consider plasma shielding in this case as well. We find that the time evolution of the problem for asymmetric beams is not qualitatively different from the symmetric ("round") beam case considered above; there are however some slight quantitative changes in shielding as a function of ν, τ_r and $k_p a$ which tend to favor the use of flat beams.

Consider the case of a radial beam profile with $\sigma_x >> \sigma_y$ .We make the approximations:

$$\frac{\partial}{\partial x} << \frac{\partial}{\partial y}$$

$$B_z \approx 0$$

$$B_y << B_x$$

$$E_x << E_y$$

together with the other beam-plasma approximations above. We find:

$$\frac{\partial^2 B_x}{\partial y^2}(y,\tau) = \frac{4\pi}{c}\frac{\partial J_{bz}}{\partial y}(y,\tau) + k_p^2 \int_{-\infty}^{\tau} d\tau' \frac{\partial B_x}{\partial \tau}(y,\tau') \exp\left(- \int_{\tau'}^{\tau} d\tau'' \upsilon(\tau'') \right)$$

where fields and currents are determined from B_x according to:

$$\frac{\partial E_z}{\partial y} \cong \frac{4\pi}{c} J_{py}$$

$$J_{py} \cong \frac{1}{4\pi}\frac{\partial B_x}{\partial \tau}$$

$$E_y \cong \frac{1}{\omega_p^2}\left(\upsilon + \frac{\partial}{\partial \tau}\right)\frac{\partial B_x}{\partial \tau}$$

$$J_{pz}(y,\tau) = \frac{\omega_p^2}{4\pi}\int_{-\infty}^{\tau} d\tau' E_z(y,\tau') \exp\left(-\int_{\tau'}^{\tau} d\tau''\upsilon(\tau'')\right)$$

Note that in the collisionless regime the B_x equation gives:

$$B_x(y,\tau) = \frac{2\pi}{\omega_p}\int_{-\infty}^{+\infty} dy' \exp(-k_p|y-y'|)\frac{\partial J_{bz}}{\partial y'}(y',\tau)$$

which is quantitatively but not qualitatively different from plasma shielding in the collisionless regime, in the symmetric beam case. Shielding as a function of $k_p a$ is given in Figure 5 for this case. A $k_p\sigma_y$ of 0.5 gives a factor 25 reduction in radiated energy, roughly equivalent to the reduction with a $k_p a$ of 2.0 for a round beam (This corresponds to a factor of ~ 8 lower plasma density required in the flat beam case.)

3. Conclusions From Analytic Work

Current cancellation occurs provided the transition from $\tau_m/\tau_r<<1$ to $\tau_m/\tau_r>>1$ comes about before beam current has risen substantially, i.e., ν must drop rapidly on the time scale τ_r. Evidently numerical work will be required to examine this tranisition and to determine the rate of rise of ν. We may estimate the secondary e^- energy at this transition using

$$\tau_r/\tau_m \sim 10^3\, \tau_r(\text{ps})\,/a(\mu\text{m})^2/\varepsilon(\text{ev})^{3/2} \sim 1$$

The ε required (a few ev) favors using a pre-ionized background; however, once the plasma is ionized, the plasma return current will rise rapidly, giving a a few hundred ev translational energy, and thus reducing the collision rate, thereby raising the conductivity. The difficulty of accurately estimating the behavior of the collision rate with time motivates a numerical approach.

III.Numerical Work

This code is a PIC simulation running on the MFE Cray. In short form the equations are:

$$m_i \frac{dv^j_{ir}}{dt} = e\left(E_r - \frac{v^j_{iz}}{c} B_\phi\right)$$

$$m_i \frac{dv^j_{iz}}{dt} = e\left(E_z + \frac{v^j_{ir}}{c} B_\phi\right)$$

$$m_e \frac{dv^j_{er}}{dt} = -e\left(E_r - \frac{v^j_{ez}}{c} B_\phi\right) - \nu(\varepsilon^j) v^j_{er}$$

$$m_e \frac{dv^j_{ez}}{dt} = -e\left(E_z + \frac{v^j_{er}}{c} B_\phi\right) - \nu(\varepsilon^j) v^j_{ez}$$

$$\varepsilon^j = \frac{1}{2} m_e \left((v^j_{ez})^2 + (v^j_{er})^2\right)$$

$$\nu = n_{neutral} \langle \sigma_{e^- neutral} v_{e^-} \rangle + n_{ion} \langle \sigma_{e^- ion} v_{e^-} \rangle$$

$$\frac{1}{r} \frac{\partial}{\partial r} r(E_r - B_\phi) = 4\pi(\rho_p - \frac{1}{c} J_{pz})$$

$$\frac{1}{r} \frac{\partial}{\partial r} r B_\phi = \frac{4\pi}{c}(J_{bz} + J_{pz}) + \frac{1}{c} \frac{\partial E_z}{\partial \tau}$$

$$\frac{\partial E_z}{\partial r} = 4\pi J_{pr}$$

The code can also allow for a pre-ionized channel and recombination (not relevant for our parameter range, unless unusual gases such as SF_6 are used.) This code follows the dynamics in detail, on the space-charge oscillation time-scale. Its results confirm that space-charge oscillations can be neglected in this parameter range, and generally agree with the analytic work. Results for one run are summarized in Table 4.

IV. Conclusions

In conclusion, it has been shown that the use of a plasma compensator to suppress beamstrahlung is feasible and would make for an interesting experiment. It is relevant to note that the physics of such a device, and the problems inherent in it are very similar to that of the plasma lens[10]. The problem of beam reactions with the hadronic constituents of the background plasma remains an open question, but the plasma physics aspects would seem to merit an experimental study.

[1]Ugo Amaldi, "Introduction to the Next Generation of Linear Colliders," CERN-EP/87- 28 August 1987

[2]R.B. Palmer, "The Interdependence of Parameters for TEV Linear Colliders," SLAC-PUB-4295, April 1987

[3]D. Cline and S. Rajagopalan, 2nd Miniworkshop on a Plasma Lens for the SLC and NLCs, 9 May 1988

[4]Karl Van Bibber, private communication, May 1988

[5]Paul J. Channell, "Field Cancellation at the Intersection Point in Large Linear Colliders", LANL Report, in preparation

[6]Note that once the beam current begins to drop off, the plasma current will drop off as well. Of course,eventually, the electrons will begin to recombine (on a time scale of 30 ps or so for N_2)-and the ions will expand outward (on a time scale of 100 ps or so for a 1μm beam) but for short pulses of a few picoseconds, we may neglect recombination and ion motion.

[7]We abbreviate the derivation and analysis of the 2-D problem. A more complete treatment is given in "Theory of the Plasma Compensator," LBL Report, in preparation.

[8]W.Schnell, "Revised Parameters for CLIC," CLIC Note 56, 7 December 1987

[9]Robert Palmer, Private Communication, May 1988

[10]Pisin Chen, "A Possible Final Focusing Mechanism for Linear Colliders," Particle Accelerators, 1987, 20, 171, (1987)

Table 1: Other Applications for Beam-Plasma Physics Studies

>Plasma Lens
- increases luminosity at IP
- suppresses wakefields
- controls jitter

>Plasma Compensation
- suppresses beamstrahlung
- suppresses wakefields
- controls jitter

>Energy Booster
- transfers energy from head to tail

>Emittance Damping

>Novel X-Ray Sources (Coherent & Incoherent)

Table 2: Major Features of Beam-Gas Physics

>Cheap transport

>Mechanically Simple

>Excellent focussing

>Damping of transverse motion via anharmonic potential

>Beam centering via preionized channel

>Charge neutralization

>Current neutralization depending on regime of operation

>Synchrotron radiation

Table 3 : Conditions For Good Current Compensation

Small Current Skin-Depth
(the most stringent condition)
$k_p\, a = 1.1\, a(\mu m)\, (n_{plasma}/3\ 10^{19} cm^3)^{1/2}$
$>>1$ (in fact, ≥ 2 gives good shielding)

Long B-Field Diffusion Time
$\nu\, \tau_r / (k_p\, a)^2 = 1.3\ 10^3\, \tau_r(ps)\, /a(\mu m)^2/\varepsilon(ev)^{3/2}$
$<<1$ (this condition should obtain in a time $<< \tau_r$)

Short Plasma Period
$\omega_p\, \tau_r = 3.1\ 10^2\, \tau_r(ps)\ (n_{plasma}/3\ 10^{19} cm^3)^{1/2}$
$>>1$ (easy to satisfy)

Plasma Denser Than Beam
$n_b/n_p << 1$

Table 4 : Results from one PIC Simulation

Input:

a =2 μm
$I_{beam}(t)$ =.75 kA t (ps)
$I_{beam\text{-}max}$= 1.2 kA (at 1.6 ps)
n_{gas} =3 10^{19} cm^{-2} (i.e. $k_p a$=2.06)
σ_{bg}^{ion} =2 10^{-17} cm^2
(=10 x actual value to simulate preionization)

Output:

> average e^- energy after .7 ps is about 600 ev

>max total current is 400 A at 1.6 ps or 33% of I_{beam}

>max B_ϕ is about 0.5 MG at r=a which is the same as the max vacuum B_ϕ corresponding to t=1 ps at which time the e- energy rose sharply, increasing the conductivity and "freezing in" the B_ϕ field (max vacuum B_ϕ in kG is given by
0.2 I_{beam}(kA) $(1-e^{(-r/a)^2})/r$ at r=a in μm)

Figure 1: For future collider parameters, beams colliding in vacuum will experience megagauss B-fields and radiate, thereby producing a very large energy uncertainty in incoming states.

Figure 2: Time Regimes in the Plasma Compensation Problem.

Figure 3: Example of the Radial Profile of the Shielded B-Field in the Collisionless Regime.

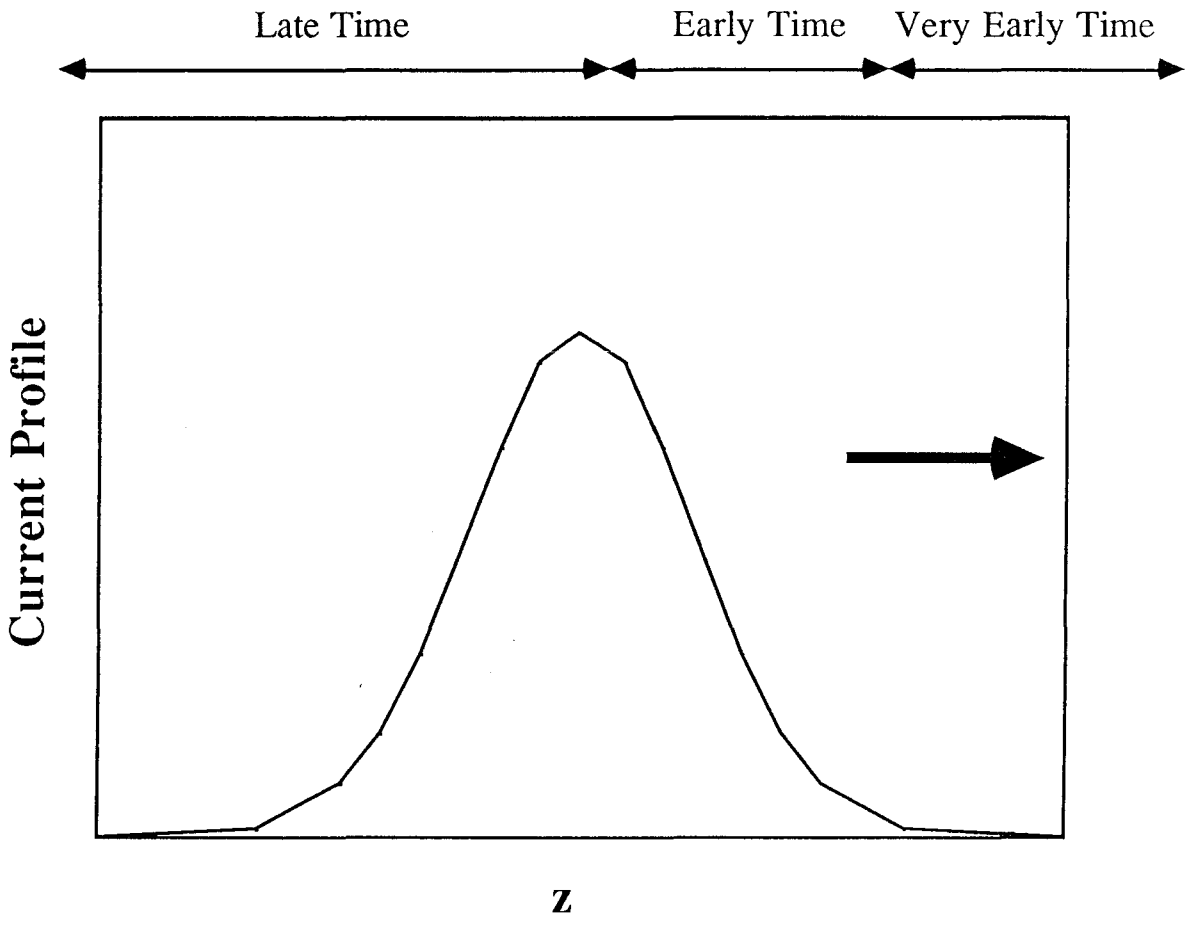
Figure 4: Shielding as a Function of $k_p a$ for a Round Beam .

Figure 5: Shielding as a Function of $k_p \sigma_y$ for a Flat Beam.

B_ϕ (megagauss)=2 I(kA)/a(μm) = large !

Fig. 1

Time Regimes For Beam on Plasma in the Nb/Np << 1 Limit



- Charge neutralization occurs throughout the duration of the pulse.
- Very Early Time or "Highly Collisional Regime" (Ohm's Law Applies and diffusion time is short)
- Early Time or "Moderately Collisional" Regime (Ohm's Law applies, diffusion time is longer, and it determines the degree of current neutralization)
- Late Time or "Collsionless Regime" (Ohm's Law doesn't apply, degree of charge neutralization depends on kp a)

Fig. 2

Shielded Magnetic Field in the Collisionless Regime
(Round Beam with kpa=2.1)

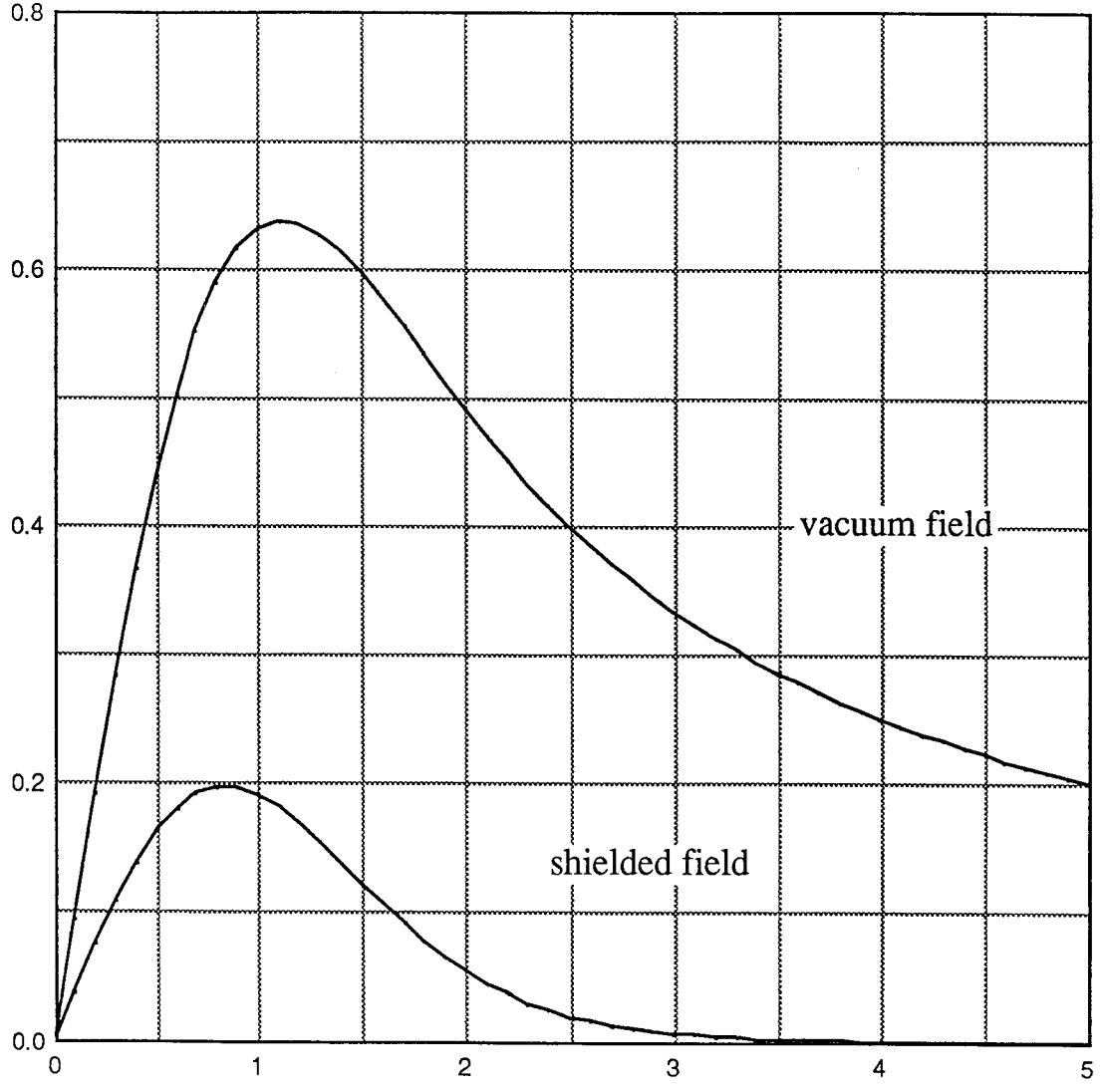


Fig. 3

Magnetic Shielding in the Collisionless Regime (Round Beam)

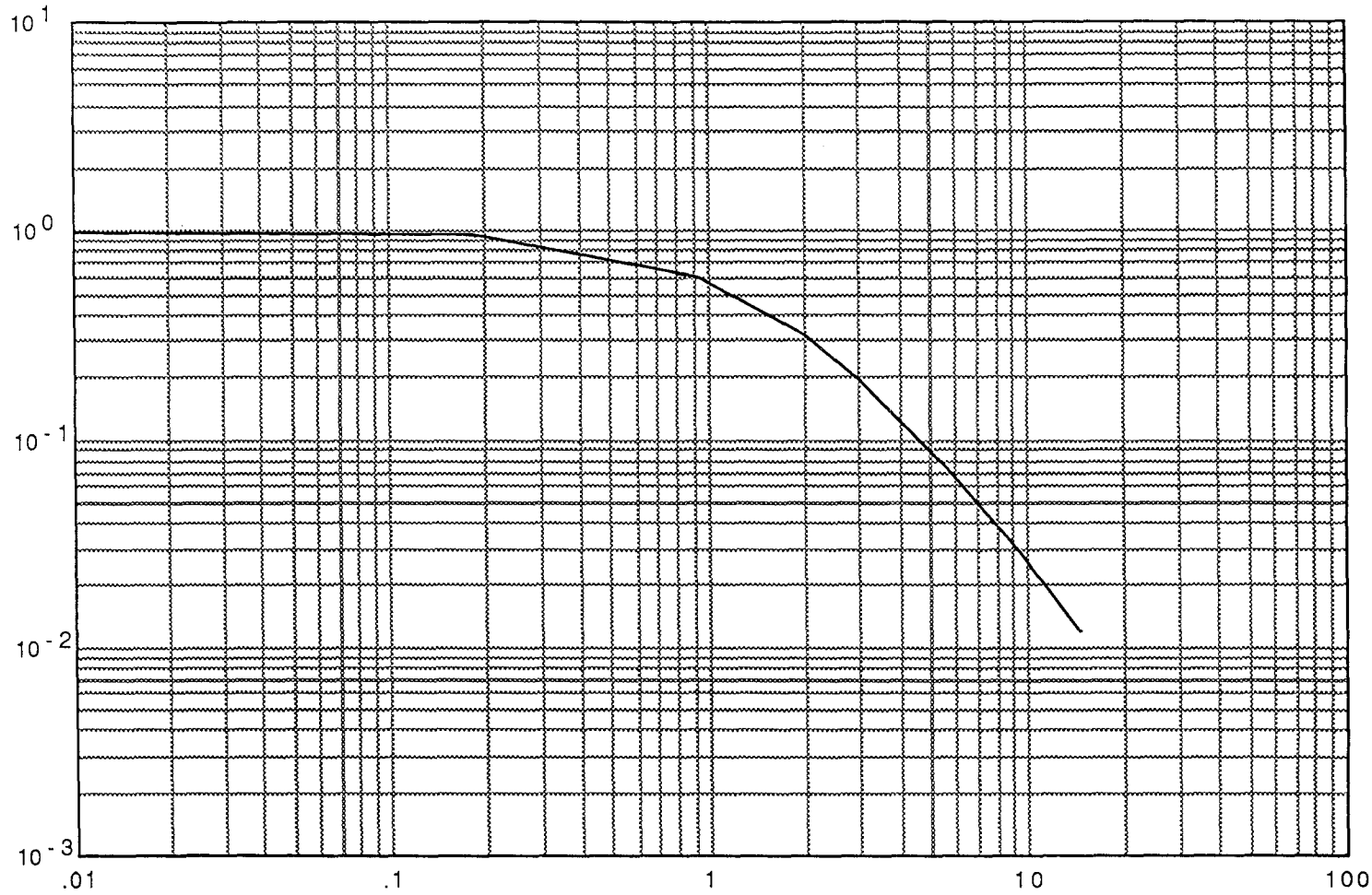


Fig. 4

Magnetic Shielding in the Collisionless Regime
(Flat Beam)

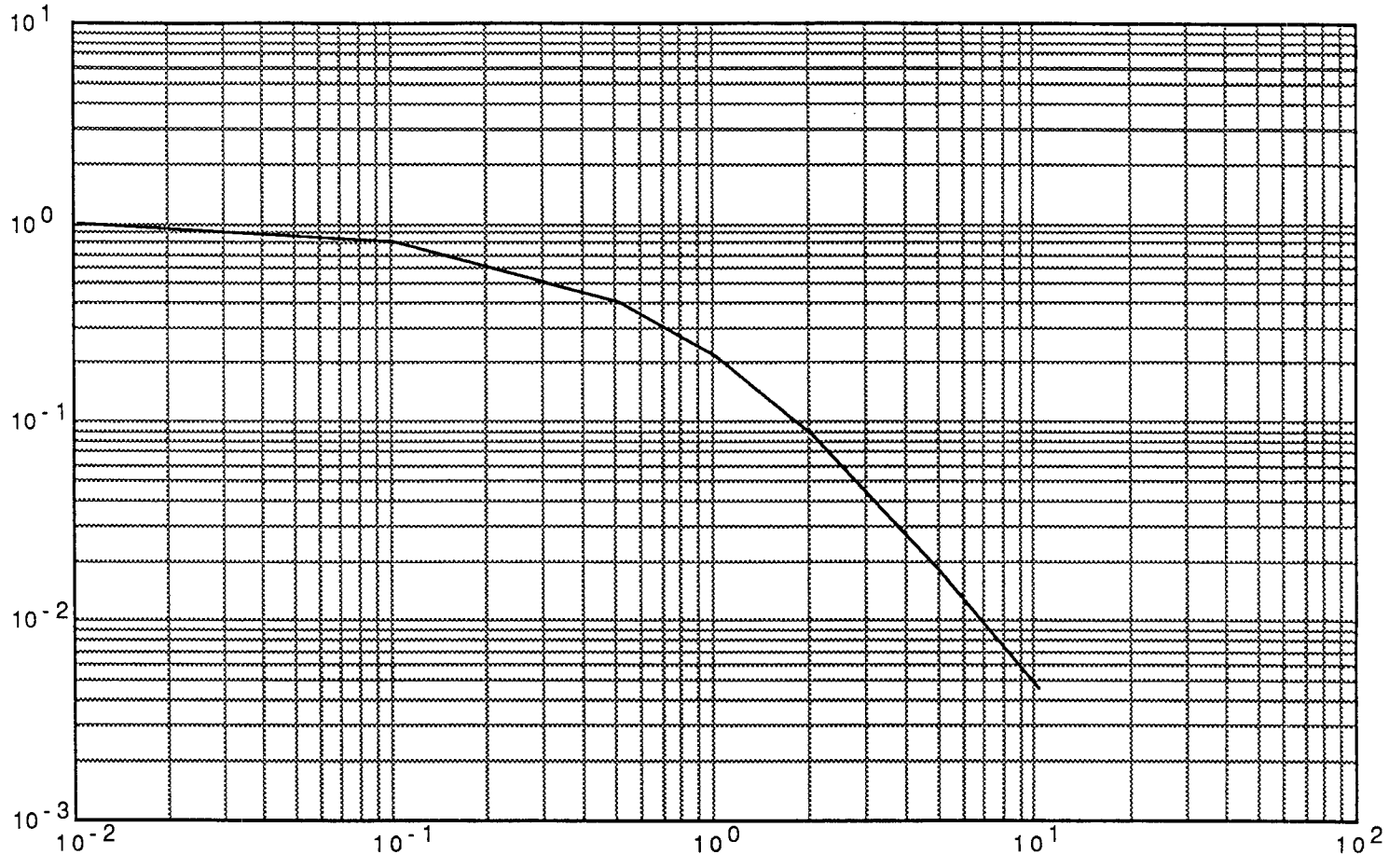


Fig. 5