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Plasma Suppression of Beamstrahlung

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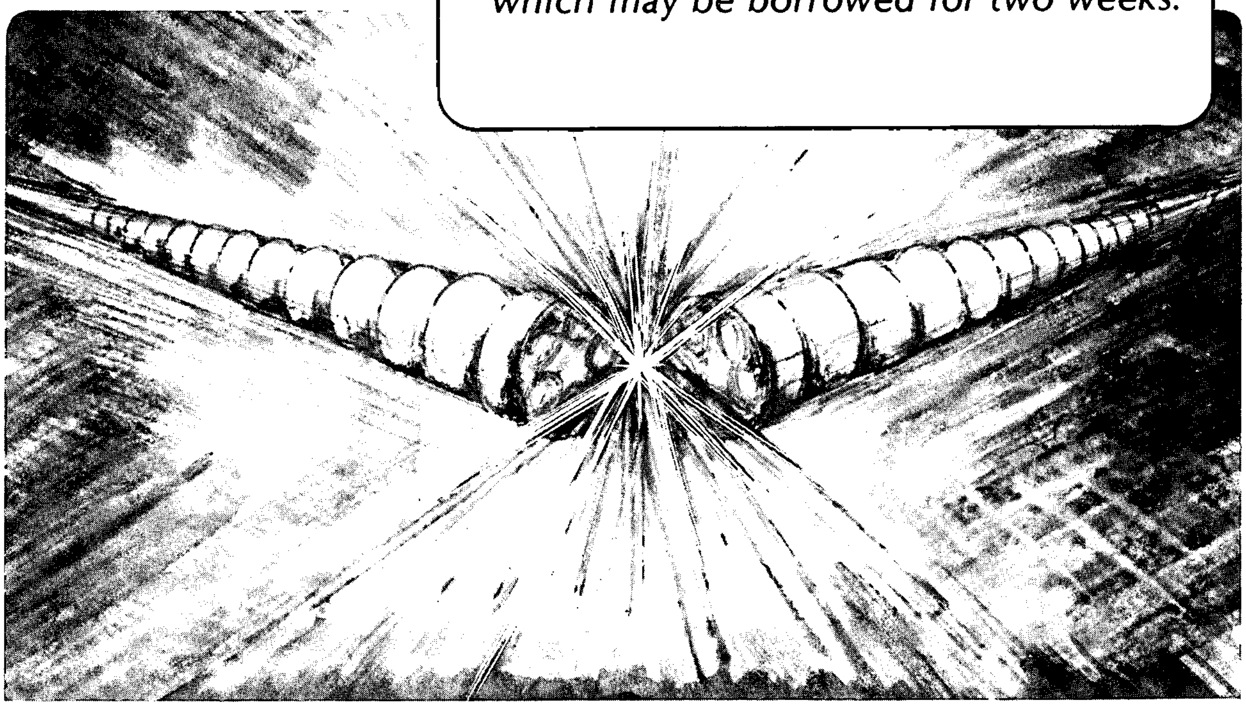

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PLASMA SUPPRESSION OF BEAMSTRAHLUNG

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ABSTRACT

We examine current neutralization in a plasma at the interaction point of an electron-positron collider, for the purpose of suppressing beamstrahlung. Conditions are derived for good current neutralization by plasma return currents and the results of numerical simulations confirming the theory are reported. Parameters are presented for a Tevatron Linear Collider employing plasma compensation. The problem of beam-plasma background reactions is noted.

INTRODUCTION

To reach high luminosity in a TeV linear elecron-positron collider we must consider beams with spot size of order 0.1 μm or smaller, and the coherent processes which occur when these fine, high current beams collide.[1] One such process is beamstrahlung, the radiation emitted by an electron or positron as it is accelerated in the megagauss field of the two colliding beams.

The physical picture consists of two oppositely charged colliding beams (positron and electron) with peak currents of order a kiloamp, millimeter lengths, sub-micron radii and energies of 500 Gev to 1 Tev (see Figure 1). The resulting megagauss field focusses the beam (luminosity enhancement) and produces synchrotron radiation (beamstrahlung).

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Beamstrahlung results in an energy loss of order 10%-30%, as well as an energy spread, in proposed designs. The effect of a large spread in energy combined with narrowly peaked reaction cross sections is to reduce the resulting reaction rate, negating the effect of increased luminosity. In addition, interactions of beamstrahlung photons with the beams will produce lower energy background events, including electron-positron pair production.[2] Thus unsupressed beamstrahlung will be detrimental to the next generation of collider physics experiments.

More significantly, however, beamstrahlung has forced designers to consider flat beams 10 nm in width or smaller, and to accept the stringent requirements on emittance and magnet alignment that such beam sizes impose.

We propose to reduce beamstrahlung and other coherent processes by providing a conducting medium, a plasma, at the interaction point, in which return currents will flow and partially cancel the B-fields of the high energy electron beam, while totally neutralizing its charge. We will find that the key problem with this scheme is the large density required (about 100 atmospheres), and attendant difficulties, such as the background beam-plasma reactions.[3]

In the next section, 1-D and 2-D Analytical Work is presented. Following that, numerical results are discussed. In the fourth section, the background problem is noted. Finally, a plasma-based Tevatron Linear Collider design is set down.

ANALYTIC WORK

Consider a high current, relativistic electron beam impinging on a pre-ionized channel in a dense gas. The time scale for the beam to ionize enough neutrals to provide space-charge neutralization is (See Table I for notation):

$$t_{neut} \sim 1/(n_g \sigma^i_{bg} c),$$
$$=0.5 \text{ ps } (3\times10^{19}\text{cm}^{-3}/n_g)\,(2\times10^{-18}\text{ cm}^2/\sigma^i_{bg}),$$

where σ^i_{bg}=ionization cross section for collisions of beam electrons with neutrals (for nitrogen, $\sigma^i_{bg} \sim 2\times10^{-18}$ cm^2). The plasma created by the beam will always be denser than the beam, provided $t_{neut} \ll \tau_r$, the beam current rise time. For the high neutral densities envisioned for a TeV Collider, the beam completely ionizes the channel in only a fraction of a rise time.[4] For lower densities, some method of pre-ionization must be used and several methods are available: laser ionization,[5] multiple bunch ionization,[6] and discharges.[7] In the following work, we will take the channel to be preionized.

1-D Model

Before solving the full 2-D problem, we set down the scaling laws with a 1-D model. Note that the plasma responds to neutralize the rising beam charge on a time scale ω_p^{-1} or ν/ω_p^2 depending on whether the plasma is collisionless or collisional. Because this time scale is short, the beam current rise is adiabatic with respect to space charge motion. We may therefore neglect high frequency space-charge oscillations attendant to Debye sheath formation.[8]

Assuming a preionized channel we have:

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

where L is a dimensionless inductance of order unity which depends on the radial variation of the fields. These equations may be combined to obtain 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, the plasma current, given I_b, the beam current. 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 at the time of the collision rate drop.[9] Evidently a rapid drop in collision rate is desirable.[10]

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,

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

where

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

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. 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 $k_p^{-1} \ll a$. 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.

Evidently, we may divide the time evolution into three regimes (see Table II). In order for the plasma return currents to compensate for the beam current, the plasma must pass through the collisonal 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 summarize these results in Table III.

Since this 1-D approach gives us no information about the radial profile of the B field and depends on the phenomenological constant L, we are motivated to consider a 2-D description.

2-D MHD Model

As above, we neglect the small space-charge oscillations which will be superimposed on the response of the plasma, and we assume 100% ionization. Maxwell's equations are

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

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

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

and the secondary electron equations of motion, expressed as a constitutive relation for current in terms of the fields are

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

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

where $\Omega = eB_\phi/mc$, $\nu = \nu(t)$ = electron collision rate with ions, and $\tau = t - z/v$.

We made 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 make 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 by secondary electrons:

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

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.

7. We also neglect the change in beam current density due to pinching from the residual B field. This is a good approximation for the plasma compensation regime where the residual B is low.[11] The length for beam self-pinching is the betatron wavlength of a single electron, in the shielded field of the beam:

$$\lambda_\beta = 2^{1/2} \pi a \gamma^{1/2} \left(\frac{I_A}{I_{net}} \right)^{1/2}$$
$$\approx 2.6 x 10^4 a E(TeV)^{1/2} I_{net}(kA)^{-1/2}.$$

For future linear colliders this length will be longer than the extent of the plasma, corresponding to small self-pinching.

8. One additional approximation which greatly simplifies the analytic work is to neglect the "v x B" force on the secondary electrons. The time scale, T, for secondary blow-out is given by

$$T^{-1} = \frac{c}{a} \left(2 \frac{n_b}{n_p} \frac{I_{net}}{I_A} \right)^{1/2}$$
$$<< \omega_p$$

This time scale is an order of magnitude longer than the plasma period, which implies that space charge dominates, preventing blow-out.

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

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

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

with[12]

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

Time Evolution of $\nu(t)$

Evidently, the response of the plasma divides in a natural way into the highly collisional, moderately collisional and collisionless regimes based on the relative size of $\nu(t)$. It is of interest, then, to describe the time behavior of ν. The collision rate is a function of the average secondary electron energy, ε, which is determined by the energy deposited during preionization, the energy of translational motion, and energy deposited in incoherent processes with the beam

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

If current cancellation is good then the secondary drift velocity is $v_z \sim c\, n_b/n_p$ so that $\varepsilon \sim 260$ 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 $n_b/n_p \sim 1/6$, the energy of drift motion alone, assuming good current cancellation would be, $\varepsilon \sim 5$ kev. This gives a $\nu \sim 2\times10^9$ sec^{-1} for $n_p \sim 3\times10^{19}$ cm^{-3}, so that $\nu\, \tau_r/(k_p a)^2 \sim 10^{-3}$, corresponding to good current cancellation.

Late Time (Collisionless Regime)

We turn now to examine the equation for B. Consider a beam incident on a preionized gas, which rapidly reaches a "collisionless" state due to beam-secondary and ohmic heating. In this low ν limit the 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')). As an example, this shielded field profile is shown in Figure 3 for k_pa=2. Plasma compensation as a function of k_pa is shown in Figure 4. Evidently at $k_pa \sim 2$ there is sufficient current compensation within the beam volume to produce an order of magnitude reduction in radiated energy.

Flat Beams

In view of proposed design parameters,[13,14] most of which include an asymmetric ("flat") beam, it is of interest to consider plasma shielding in this case as well. 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[15]

$$\frac{\partial^2 B_x}{\partial y^2}(y,\tau) = \frac{4\pi}{c}\frac{\partial J_{bz}}{\partial y}(y,\tau)$$

$$+ k_p^2 \int_{-\infty}^{\tau} d\tau' \frac{\partial B_x}{\partial \tau}(y,\tau') \exp\left(-\int_{\tau'}^{\tau} d\tau'' \nu(\tau'')\right).$$

In the collisionless regime the B_x equation becomes

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

which is quantitatively but not qualitatively different from plasma shielding 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 5 reduction in the peak field, roughly equivalent to the reduction with a $k_p a$ of 2.0 for a round beam.

Thus the time evolution for asymmetric beams is not qualitatively different from the symmetric beam case; there are however some slight quantitative changes in shielding as a function of n, τ_r and $k_p a$ which tend to favor the use of flat beams.

Conclusions From Analytic Work

Current cancellation occurs provided the transition from $\tau_m/\tau_r \ll 1$ to $\tau_m/\tau_r \gg 1$ comes about before the beam current has risen substantially, i.e., n must drop rapidly on the time scale τ_r. Generally, once the plasma is ionized, the plasma return current will rise rapidly, giving a few hundred ev translational energy, and thus reducing the collision rate. This difficulty in accurately estimating the behavior of the collision rate with time motivates a numerical approach.

NUMERICAL WORK

To determine how rapidly the collision rate drops, we resort to numerical simulations. The code is a PIC simulation running on the MFE Cray. Collisions of secondaries and ionization by the beam are accurately followed. The beam is assumed unperturbed. In short form the equations are:

$$m_i \frac{dv^j_{ir}}{dt} = e\left(E_r - \frac{v^j_{iz}}{c} B_\phi\right),$$
$$m_i \frac{dv^j_{iz}}{dt} = e\left(E_z + \frac{v^j_{ir}}{c} B_\phi\right),$$
$$m_e \frac{dv^j_{er}}{dt} = -e\left(E_r - \frac{v^j_{ez}}{c} B_\phi\right) - \nu(\varepsilon^j) v^j_{er},$$
$$m_e \frac{dv^j_{ez}}{dt} = -e\left(E_z + \frac{v^j_{er}}{c} B_\phi\right) - \nu(\varepsilon^j) v^j_{ez},$$
$$\varepsilon^j = \frac{1}{2} m_e ((v^j_{ez})^2 + (v^j_{er})^2),$$
$$\nu = n_{neutral} \langle \sigma_{e^- neutral} \, v_{e^-} \rangle + n_{ion} \langle \sigma_{e^- ion} \, v_{e^-} \rangle,$$

$$\frac{1}{r}\frac{\partial}{\partial r} r(E_r - B_\phi) = 4\pi(\rho_p - \frac{1}{c} J_{pz}),$$
$$\frac{1}{r}\frac{\partial}{\partial r} rB_\phi = \frac{4\pi}{c}(J_{bz} + J_{pz}) + \frac{1}{c}\frac{\partial E_z}{\partial \tau},$$
$$\frac{\partial E_z}{\partial r} = 4\pi J_{pr}.$$

The code solves these equations on the ω_p^{-1} time-scale and confirms that space-charge oscillations can be neglected for slow current rise.

We summarize the results of one run. An REB with linear current rise was injected into a plasma with $n_p = 3 \times 10^{19}$ cm^{-3}, and the evolution was followed for 1.0 ps. The beam waist was a=2 μm and the peak current was 0.73 kA. We used an ionization cross-section $\sigma_{bg}^{ion} = 2 \times 10^{-17}$ cm^2, i.e., ten times larger than the actual value, to simulate preionization. Results are shown in Figure 5.

Within 1 picosecond the gas is over 50% ionized with the electrons having an average energy in excess of 400 eV. In fact at t=0.6 ps the electrons are essentially collisonless and provide plasma current to oppose the increasing beam current, so that the total current levels off. We would expect that the total current will remain around 320A while the peak beam current rises to 2.4 kA.

This simulation shows that indeed, we do get to the regime where our analytic model is applicable; i.e., that the collison rate drops early enough in the pulse.

BEAM-PLASMA BACKGROUND REACTIONS

Interactions of the high energy beams with the plasma will produce a large number of gammas, electrons and charged pions[16], which will have to be kept from the detector via magnetic fields, or otherwise discriminated against based on their relatively lower energy. Chen has made some preliminary estimates of the background.[17] However, much theoretical and experimental work remains to be done to determine whether the background can be made acceptable.[18,19]

The interesting event rate, due to beam-beam events is

$$N_I = \frac{N^2 \sigma_o(s)}{4\pi a^2}$$

where a is the beam size and $\sigma_o(s)$ is the electron-positron cross section of c.o.m. energy.

The cross section $\sigma_o(s)$ is usually expressed in terms of the ratio R to the cross section for $\mu^+ \mu^-$ pair production. The latter is

$$\sigma_{pt}(e^+ + e^- \rightarrow \mu^+\mu^-) = \frac{4\pi}{3}\frac{\alpha^2}{s^2},$$

where s is the c. o. m. energy, or twice the energy in one beam. Thus

$$\sigma_{pt} = \frac{87\,\mathrm{mb}}{E^2_{cm}(\mathrm{GeV}^2)},$$

and this is 8.7×10^{-38} cm^{-2} for 500 GeV x 500 GeV. The quantity R ranges from 0.01 to 10.0 for various processes. For our purposes we can take R=1 so that with a luminosity of 10^{33} $cm^{-2}sec^{-1}$ we have a rate of events of (about) 10^{-4} sec^{-1} or one every 3 hours. Rare events will only occur (perhaps) once a day or so.

Background events must be reduced enough to be able to detect interesting events. The number of events per crossing is

$$N_b = N n_p l \sigma(\gamma),$$

where N is the number of high-energy electrons (or positrons), n_p is the plasma density, l is the length of the plasma, and $\sigma(\gamma)$ is the cross section for various background events. The background events may be categorized as:

1. Deep inelastic Mott scattering producing hard electrons. ($e^{\pm}$ + e-)

2. Multiple scattering, or Mohler scattering, producing soft electrons. ($e^{\pm}$ + e-)

3. Radiative Mohler scattering producing γ rays. ($e^{\pm}$ + e-)

4. Soft hadron production of π mesons. ($e^{\pm}$ + nucleus)

5. Hard hardron production of π's by jets. ($e^{\pm}$ + nucleus)

Detailed study of these events remains to be done. In particular the characterization of the angular distribution of gammas and neutral pi-mesons at large angles from the forward direction and with energies above ~ 1 GeV remains an open question and one beyond the scope of this work. Nevertheless, some general remarks can be made:

For charged background particles, it is straightforward to determine how large a magnetic field would be required to screen out the lower energy products of beam collisions with the stationary target plasma. Let the distance to the detector from the center of the interaction point be ρ. Then the magnetic field must be of order

$$B \approx \frac{mc^2}{e\rho}\sqrt{\frac{\gamma}{2}},$$

to insure that spurious pions and other charged background particles spiral out. For a TeV collider and ρ=10 cm, this gives B ~ 200 kG.

For uncharged background particles, a magnetic field is ineffective. However, the products of beam-beam collisons have zero total axial momentum and will send their products into all solid angles, while products of beam-plasma collisons will for the most part be swept forward in a narrow cone. In addition, it is possible to discriminate against neutral products of beam-plasma reactions based on their lower center of mass energy ~ 1 GeV.

PARAMETERS

We consider three colliders, the "CLIC",[20] the "TLC",[21] and the "Plasma-Based TLC" ("PB-TLC"). Results are tabulated in Table IV.[22]

Immediately we notice that for the CLIC and TLC parameters, the plasma densities required would be enormous. This is because these colliders were designed with an eye to keeping beamstrahlung under control. The large plasma density is required due to the small thickness of the flat beams involved.

It is natural to ask what a collider might look like if it were designed with no constraint on beamstrahlung, but with a constraint on the plasma densities required to compensate for any beamstrahlung. The PB-TLC is such a collider. Note that a high luminosity is obtained with a spot size of 0.1 micron. This is far larger than currently proposed spot sizes, and therefore requires lower tolerances on alignments in the focussing system. This prospect of getting high luminosities without going to nanometer beams is extremely encouraging. Furthermore, the emittance is two orders of magnitude larger than in the TLC.

CONCLUSIONS

In conclusion, analysis has been given of the use of plasma compensation to suppress beamstrahlung. The problem of background due to beam reactions with the plasma remains an open question, but the plasma physics aspects would seem to merit an experimental study.

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1 Ugo Amaldi, "Introduction to the Next Generation of Linear Colliders," CERN-EP/87- 28 August 1987. See also, R.B. Palmer, "The Interdependence of

Parameters for a TeV Linear Collider", SLAC Internal Report, SLAC-PUB-4295, April 1987.

[2]R. Blankenbecler and S. D. Drell, Phys. Rev. Lett., **61**, 20 2324, 14 Nov 1988, see also, P. Chen, "Disruption, Beamstrahlung, and Beamstralhung Pair Creation," SLAC Internal Report, SLAC-PUB-4822, Dec 1988.

[3]One possible means of circumventing the plasma compensation background problem which has been suggested by Paul Channel 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; however, work is continuing on this subject.

[4]For example, for a ~ 0.1 μm and I ~ 1 kA, n_b ~ 6.63×10^{20}, and t_{neut} ~ 20 femtosecond << τ_r.

[5] G.J. Caporaso, F. Rainer, W.E. Martin, D.S. Prono, and A.G. Cole, Phys. Rev. Lett., 57, 13, 1591,29 Sept 86.

[6]This method of creating an ionized channel makes use of multiple electron beamlets, where the first two or three beamlets would create the channel, and the remaining beamlets would then see a fully ionized plasma. This requires beamlets spaced closely together (perhaps 30 ps for a 3×10^{19} cm^{-3} plasma) to avoid significant recombination and channel expansion.

[7]This method of creating an ionized plasma, which appears to be very well suited to experimental tests of compensation, is the "back-lighted thyrotron". Martin Gundersen, 2nd Miniworkshop on a Plasma Lens for the SLC and NLCs, 9 May 1988 . Plasma densities of up to 3×10^{15} cm^{-3} have been achieved, with a temperature of 1 eV. The peak plasma density lasts about 1 msec, with a 3 μsec tail. Rep rates of 200 Hz are thought to be possible, with much higher rates achievable for lower plasma densities. The BLT box is about 5 mm long and the plasma is about 1cm in width.

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

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

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

$$k_d a = 7.4\times10^2\, a\,(\mu m)\left(\frac{n_p cm^{-3}}{3\ 10^{19} cm^{-3}}\right)^{\frac{1}{2}} T_p(ev)^{-\frac{1}{2}}$$

$$>>1$$

i.e., the Debye length is short compared to other scales of interest. Here k_d=Debye wave number

[9] 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 at 3 10^{19} cm^{-3}) 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. Note also that a high secondary drift velocity drives down recombination rates.

[10]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 ~ $(1+\theta)\ \nu^{-1}$ ~ $(k_p a)^2\ \nu^{-1}$ ~ τ_m.

[11]Note, however, that for plasma lens applications, one must examine beam pinching, since there the intent is to provide *poor* current cancellation to produce just such a focussing of the beam. See Pisin Chen, "A Possible Final Focusing Mechanism for Linear Colliders," Particle Accelerators, 1987, 20, 171, (1987.

[12]For completeness we note that the electric fields and currents may determined via the relations:

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

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

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

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

[13] W.Schnell, "Revised Parameters for CLIC," CLIC Note 56, 7 December 1987.
[14]Robert Palmer, Private Communication, May 1988.
[15]For completeness, we note that the fields and currents are determined from B_x according to:

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

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

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

[16] D. Cline and S. Rajagopalan, 2nd Miniworkshop on a Plasma Lens for the SLC and NLCs, 9 May 1988.
[17]P. Chen, Part. Acc. **20**, 171, (1987).
[18] Karl Van Bibber, private communication, May 1988.
[19]S. Rajagopalan, private communication, May 1989.
[20]Parameters for New CLIC are taken from W. Schnell, CERN Internal Note CLIC Note 56, "Revised Parameters for CLIC," (1987).
[21] Robert Palmer, private communication, May 1988.
[22]Single-bunch luminosity is quoted.

Table I: Notation

ω_p	=plasma frequency
	$=3.1\ 10^{14}$ rad/sec $(n_p/3\ 10^{19}\ cm^{-3})^{1/2}$
k_p	$= \omega_p/c$
τ_r	= beam current rise time
a	= beam radius
$n_b(r,\tau)$	$= n_{bo}\exp(-\tau^2/\tau_r^2)\exp(-r^2/a^2)$
	$\sim \exp(-x^2/2\sigma_x^2)\exp(-y^2/2\sigma_y^2)\exp(-z^2/2\sigma_z^2)$
τ	$= t-z/v$
v	=beam velocity ~ c
τ_m	$= (k_p a)^2 / v$
	= magnetic diffusion time
$\nu = \nu(t)$	= collision rate of secondaries with ions
I	=peak current
$\mathcal{L}$	= luminosity
R	= aspect ratio = σ_x / σ_y
γ	$=E/mc^2=2.0\times10^6$ E(TeV)
δ	=fractional average energy loss due to beamstrahlung
n_p	=secondary electron density
n_g	=gasdensity

Table II. Time Regimes in the Plasma Compensation Problem

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)
$\nu \tau_r << 1$

Table III: Conditions For Good Current Compensation

Small Current Skin-Depth	$k_p a >> 1$
Long Magnetic Diffusion Time	$\nu \tau_r / (k_p a)^2 << 1$
Short Plasma Period	$\omega_p \tau_r >> 1$
Overdense Plasma	$n_b/n_p << 1$

Table IV: Example Collider Parameters

Collider	CLIC	TLC	PB-TLC
E(GeV)xE(GeV)	1000x1000	500x500	500x500
$\mathcal{L}$(cm^{-2}sec^{-1})	1.1x10^{33}	7.7x10^{32}	5x10^{32}
f (kHz)	1.69	0.186	0.1
N/10^{10}	0.50	0.79	5.2
R	5	180	1
σ_y(μm)	0.012	8.65x10^{-4}	0.1
σ_z(mm)	0.2	0.038	1
I(kA)	0.5	4	1
γ	2x10^6	10^6	1x10^6
δ	0.28	0.21	2
n_p(cm^{-3})	[4x10^{23}]	[8x10^{25}]	1x10^{22}
ε_n(m-rad)	10^{-6}	1.94x10^{-8}	1x10^{-6}
β^*(mm)	0.28	0.038	10

Figure 1: For future collider parameters, beams colliding in vacuum will experience megagauss B_ϕ-fields and radiate coherently, losing energy, and producing lower energy electron-positron pairs.

Figure 2: Example of the radial profile of the shielded B-field in the collisionless regime. The radial coordinate is normalized by a, where the radial beam profile is $\exp(-r^2/a^2)$. For larger k_pa, the location of the peak moves from 1.11 to 0.71.

Figure 3: Reduction in peak B_ϕ field (i.e., maximum as a function of r) as a function of k_pa for a round beam. The peak field value is normalized to the peak field of a gaussian beam in vacuum, which is 0.638 x 2 I/a c, where I is the peak current.

Figure 4: Reduction in peak B field as a function of $k_p\sigma_y$ for a flat beam.

Figure 5: Results from the PIC simulation. The average electron density and energy within a 2 μm radius about the beam axis are displayed. Also shown is the beam current and the total (beam plus plasma) current.

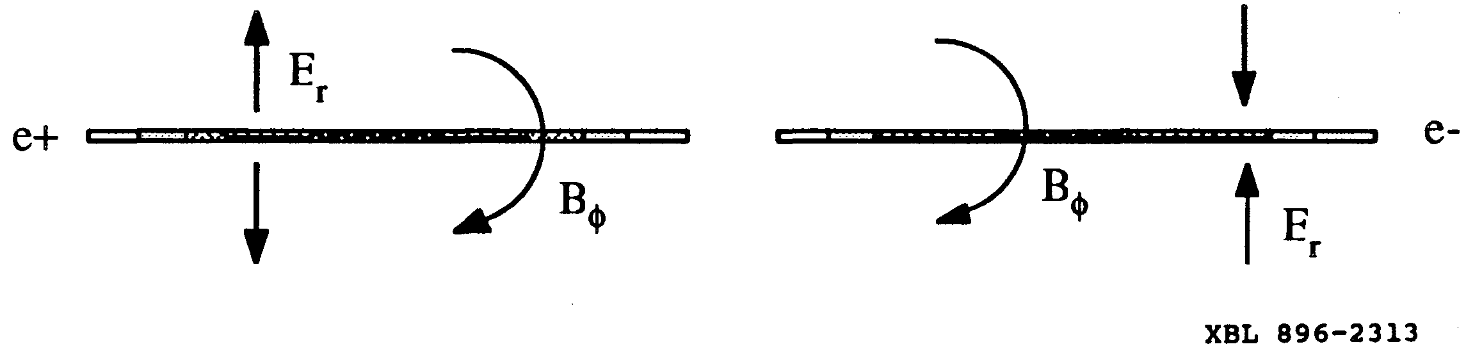
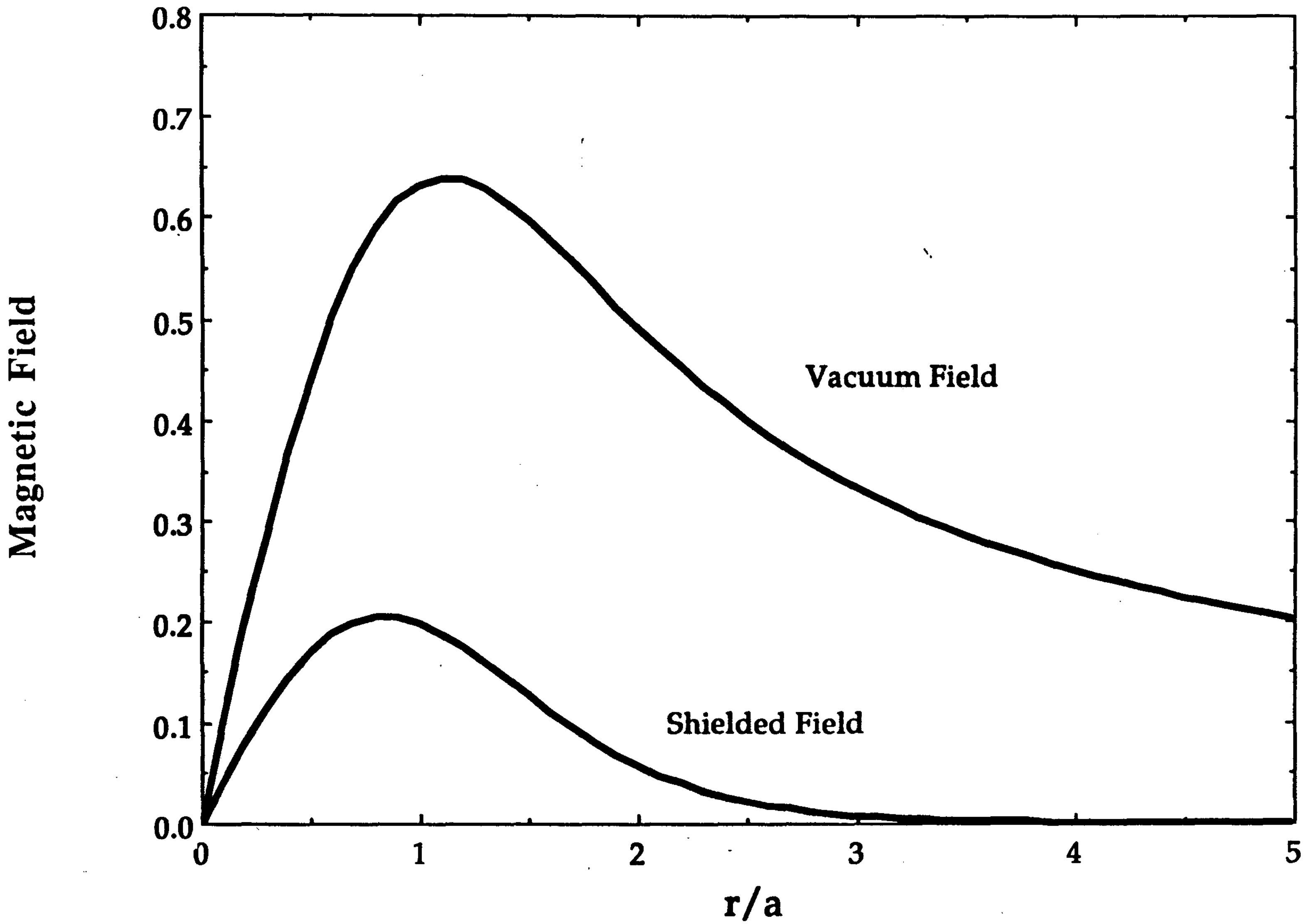


Fig. 1.



XBL 896-2314

Fig. 2.

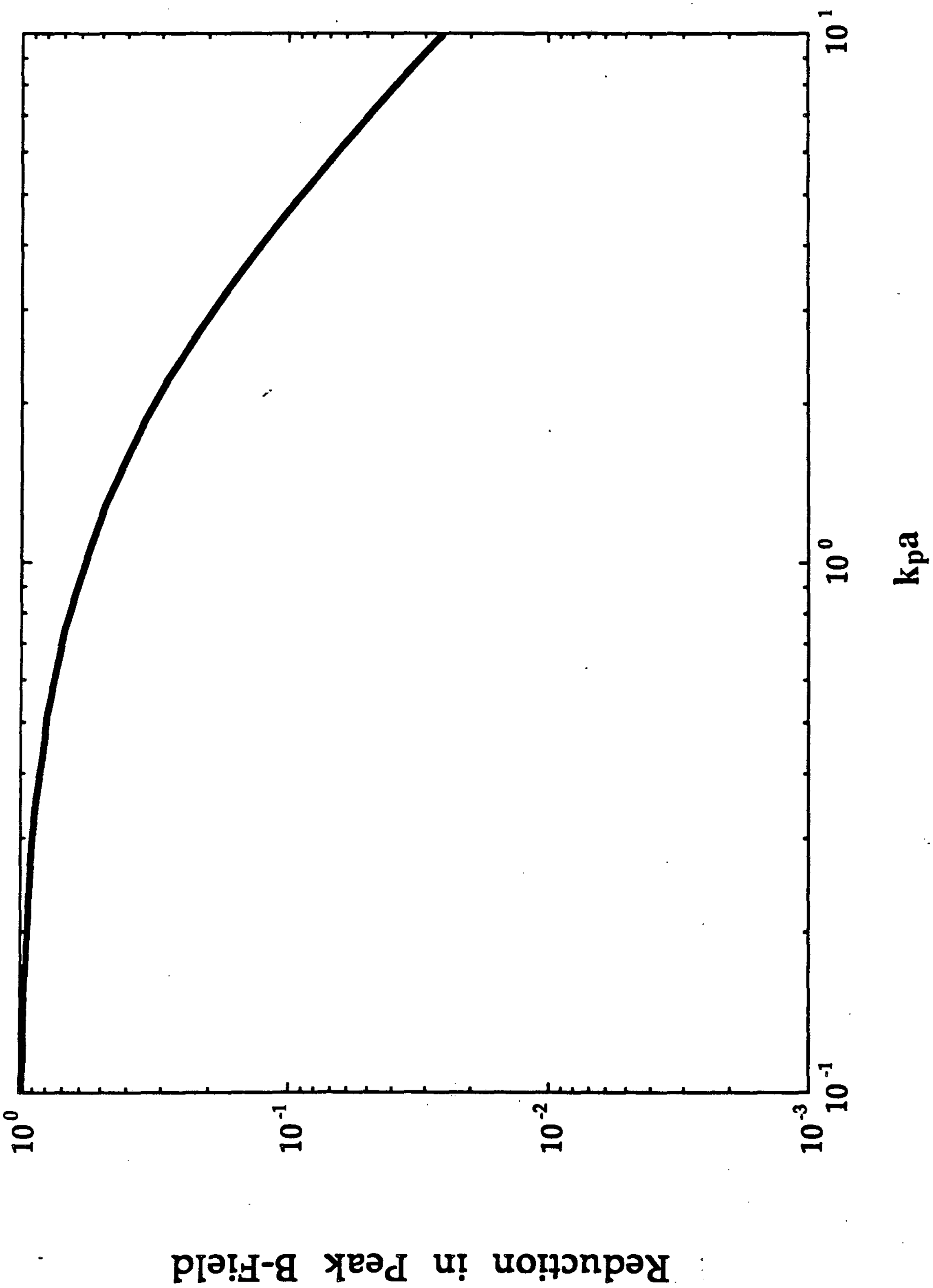
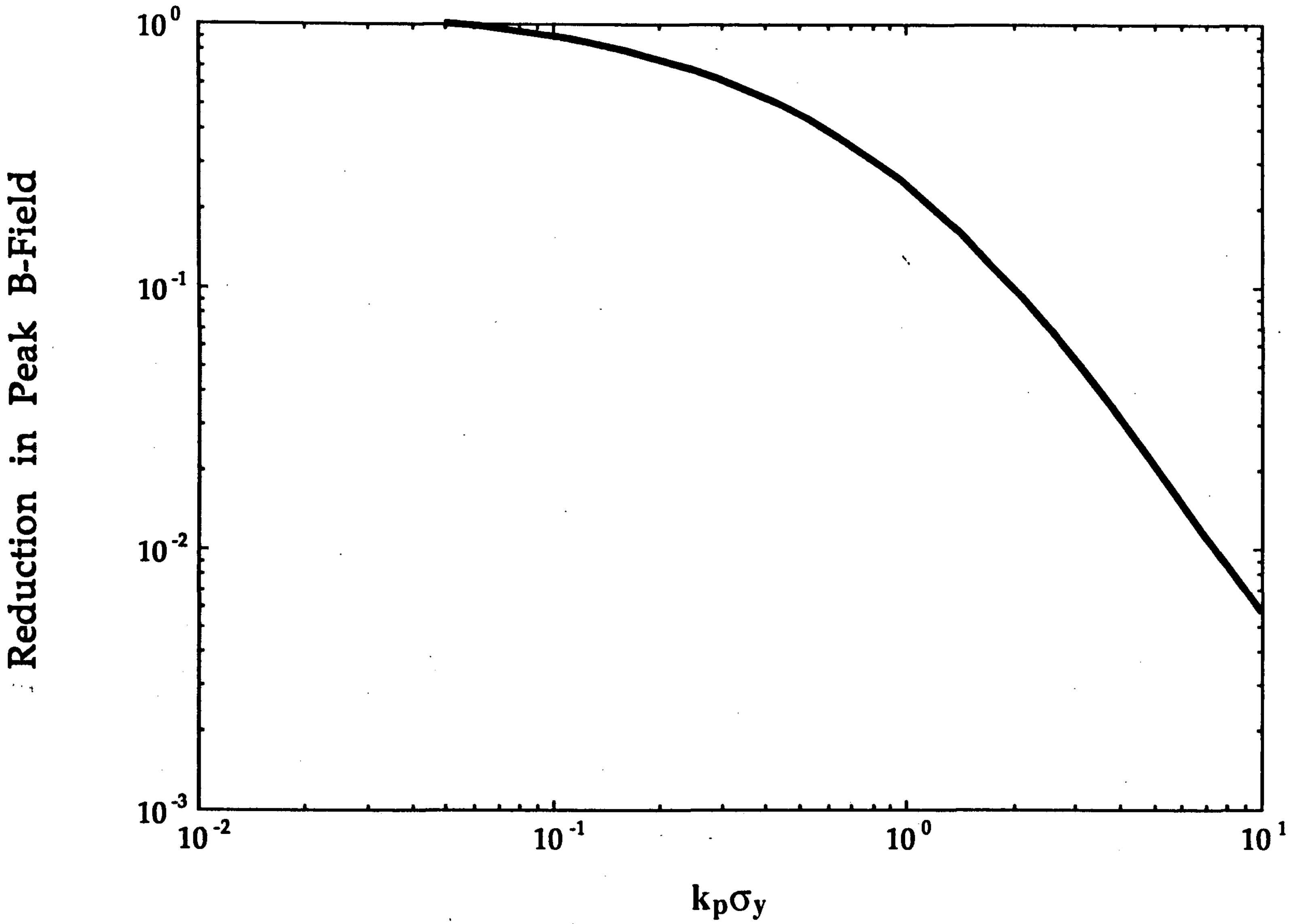


Fig. 3.

XBL 896-2315



XBL 896-2316

Fig. 4.

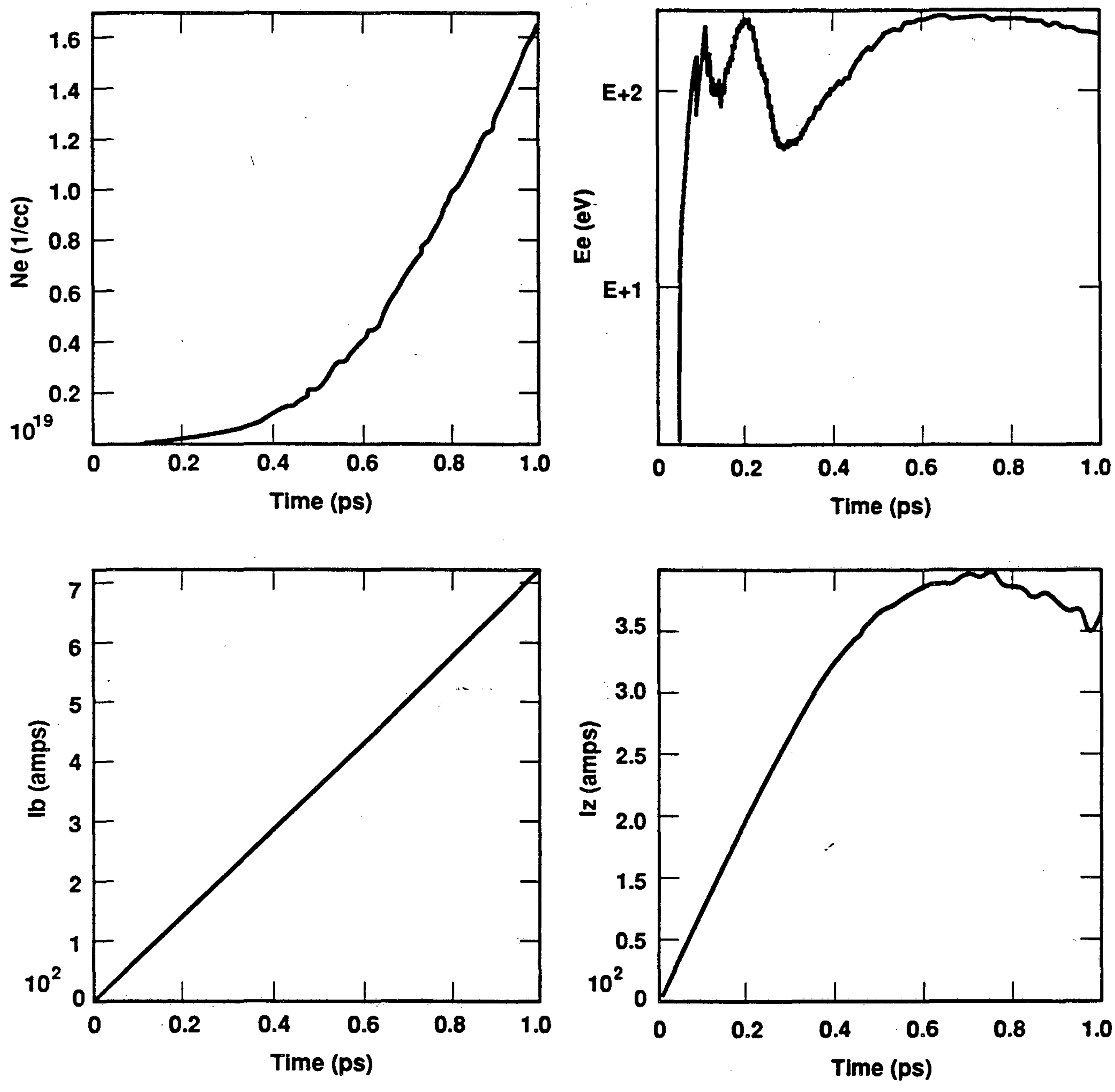

Ne (1/cc)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
10^19
0
0.2
0.4
0.6
0.8
1.0
Time (ps)
Ee (eV)
E+2
E+1
0
0.2
0.4
0.6
0.8
1.0
Time (ps)
Ib (amps)
7
6
5
4
3
2
1
10^2
0
0
0.2
0.4
0.6
0.8
1.0
Time (ps)
Iz (amps)
3.5
3.0
2.5
2.0
1.5
0.5
10^2
0
0
0.2
0.4
0.6
0.8
1.0
Time (ps)

Fig. 5.

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