KNOCK-ON ELECTRONS IN THE TARGET CHAMBER

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Macroscopic magnetic fields arising from currents carried by the beam ions or by secondary electrons play a major role in determining the ion beam spot size. In a gas-filled target chamber, it has been generally assumed that the bare ion beam current I_b is almost balanced by a return current I_p which is carried by low energy secondary electrons. The resulting net current I_{net} is thus positive, leading to a magnetic field $B_\theta > 0$ which either weakly deflects the ions inward (ballistic or converging mode propagation) or pinches them more strongly into a thin, pencil-shaped beam (pinch mode propagation),[1,2]

However, we have pointed out recently that fast secondary electron may alter this picture considerably.[3] Particularly dangerous are those knock-on electrons with axial velocity $v_z > \beta_b c$, the beam velocity, since they may outrun the beam and set up a defocussing channel ahead of the beam. These electrons, which are produced by nearly head-on collisions between beam ions and both free and bound background electrons, are sufficiently numerous to alter the magnetic field substantially, and in many cases will probably reverse its direction.

Although some knock-on electrons are produced in all beam-plasma systems, they normally play a very small role. However, several unusual features make it possible for the knock-on electrons to exert a large influence on heavy ion beam transport. First, the cross section for producing these electrons scales as the square of $\hat{Z}_b$, the beam atomic number, so the knock-on current produced by a Uranium beam is almost four orders of magnitude larger than that produced by a proton beam moving at the same speed. Second, the relatively high knock-on electron energy (> 45 keV for $\beta_b = 0.4$) allows these electrons to propagate as a nearly collisionless "beam", even in the presence of moderately high self-fields. In addition, if a substantial fraction of the knock-on current does get out ahead of the ion beam and can be charge neutralized by collisional ionization, the resulting field B_θ will usually be sufficient to pinch the electrons to a radius comparable with the ion beam radius. This means that the front portion of the ion beam will encounter a pre-existing $B_\theta < 0$ magnetic field which deflects the ions outward. Finally, because of the rapid rise in conductivity produced by the arrival of the ion beam, this field may persist throughout the beam pulse. The total scenario is illustrated in Figure 1, which shows knock-on electron orbits and the pinching magnetic field.

It is not yet clear whether knock-on electrons will lead to a deterioration in beam spot size for a given set of system parameters. The problem involves complicated spatial and temporal dependences plus self-fields whose sign may not be known. However, in this paper, we will use some simple analytical models developed in our previous work, and will defer until later a more detailed description of this complex phenomenon.

ESTIMATES OF KNOCK-ON CURRENT

A crude estimate of the knock-on current $I_k(> \beta_b)$ carried by electrons with axial velocities greater than the beam velocity $\beta_b c$ can be made from the total coulomb cross section for scattering by $> \frac{\pi}{2}$ in the beam frame.[3] This cross section is given by

$$\sigma_{\pi/2} = \frac{\pi r_e^2 \hat{Z}_b^2}{\beta_b^4} \quad , \tag{1}$$

where r_e and $\hat{Z}_b$ are the classical electron radius and beam atomic number, respectively. Note that electrons scattered through an angle greater than

$\pi/2$ in the beam frame are knocked forward with axial velocities which exceed the beam velocity. The total number of knock-on electrons $\hat{N}_k^{\pi/2}$ produced after the beam propagates a distance z is $\hat{N}_b\, n_e z\sigma_{\pi/2}$, where $\hat{N}_b = N_b L_b$ is the total number of beam ions, L_b is the beam pulse length and n_e is the density of background electrons. If $\beta_k \sim 1.3\beta_b$ and L_k are the characteristic velocity and length of the knock-on "beam", then $\hat{N}_k^{\pi/2} = N_k L_k \approx N_k(L_b + (\beta_k/\beta_b - 1)z)$. The total current carried by these electrons is $I_k = -\beta_k\, ec\, N_k$ and can be written

$$I_k(> \tfrac{\pi}{2}) = \frac{-\beta_k\, \tilde{I}_b n_e z\sigma_{\pi/2}}{\beta_b + (\beta_k - \beta_b)z/L_b} \quad , \tag{2}$$

where $\tilde{I}_b$ is the beam particle current. The second term in the denominator is a correction for the finite beam pulse length and becomes important when $z \gtrsim L_b$.

At pressures of 1 torr or greater, the current predicted by Eq. (2) can be quite large in some cases. Neglecting the finite pulse length correction, and setting $\beta_k/\beta_b = 1.3$, the ratio of the knock-on current to the beam particle current for a Uranium beam can be rewritten as

$$\frac{I_k(> \frac{\pi}{2})}{\tilde{I}_b} = \frac{9.7 \times 10^{-5}\ pz\, \hat{Z}_g}{\beta_b^4} \ . \tag{3}$$

Here p is the pressure in torr and $\hat{Z}_g$ is the number of electrons per background gas atom (or molecule). For a 20 GeV Uranium beam propataing 1 m in 1 torr of He, $I_k(> \frac{\pi}{2}) \approx I_b$. However, for a 10 GeV beam propagating in 1 torr of Ne (which is typical of most recent reactor scenarios), $I_k(> \frac{\pi}{2})$ is increased by a factor of 20. Since $\tilde{I}_b$ is typically 1 kA, it is clear that the knock-on current will often approach or exceed the Alfven current $I_A = 17\ \beta_k\gamma_k$ (kA) after propagating less than 1 m. If a substantial fraction of this current can get out ahead of the beam and become charge neutralized, it will tend to be strongly pinched by its own magnetic field even if the radius of this knock-on beam is initially large.

KNOCK-ON BEAM RADIUS AND ION ORBIT DEFLECTIONS

As a result of the collisional ionization process, knock-on electrons acquire a transverse velocity $v_{\perp k}$ which is comparable in magnitude with the axial velocity v_{zk}. Thus, the knock-ons would quickly fly out to a large radius R_k in the absence of self fields. However, as soon as the knock-on beam is charge neutralized, the self magnetic field will tend to pinch the beam to a smaller radius. If $I_k(> \frac{\pi}{2})$ is less than the Alfven current, the knock-on beam radius can be estimated by assuming that beam to be in a quasi-static Bennett equilibrium.[3] If the knock-on beam emittance is constant,[4] $R_k \Delta v_{\perp k}$ is constant, where $\Delta v_{\perp k}$ is the transverse thermal velocity of the knock-on beam. In a Bennett equilibrium,[4] $(\Delta v_{\perp k}^2/\beta_k^2 c^2) = -\ \alpha\ I_k(z)/I_A$. Here $I_k(z)$ is calculated from Eq. (2), and α is the fraction of that current which gets out ahead of the ion beam. For a converging beam in a chamber of radius L, one can eliminate $\Delta v_{\perp k}$ to get

$$R_k(z) = \frac{\Delta v_{\perp k}(0)}{c\beta_k}\ \frac{R_b(0)}{2}\ (2 - \frac{z}{L}) \left\{\frac{-\ I_A}{\alpha I_k(z)}\right\}^{\frac{1}{2}} . \tag{4}$$

This expression is valid only for $|\alpha\ I_k| < I_A$. If the knock-on beam current exceeds I_A, $\nabla \vec{B}$ drifts tend to focus the beam to a radius smaller than the ion beam radius. Otherwise, the knock-on radius is usually a few times the ion beam radius.

Only that fraction of the knock-on beam current which lies inside the ion beam radius can contribute to the defocussing magnetic field. For a radially uniform knock-on beam, this effective current is

$$I_k^{eff}(z) = \alpha\, I_k(z) \left(\frac{R_b(z)}{R_k(z)}\right)^2 \quad . \tag{5}$$

It is important to note that for ballistic focussing, it is possible to have $I_{net} < 0$ through the entire ion beam pulse so long as the resulting ion orbit deflections are sufficiently small. In our previous work[3], we numerically integrated the standard paraxial envelope equation for the ion beam using $I_{net} = I_k^{eff} < 0$ to estimate the ion beam spot size. That study demonstrated that for propagation in He at 20 GeV, there could be a severe deterioration in spot size for a 1 kA ion beam at pressures above a few torr.

If the defocussing magnetic field present at the front of the ion beam pulse is frozen in by the high conductivity, it is possible to make a simple analytical estimate of the attainable spot size. If the ion beam is assumed to be cold, the minimum spot size for a constant I_k^{eff} is[5]

$$R_{min} = R_o \exp\left(- \frac{(R_o/L)^2}{2K}\right) \quad . \tag{6}$$

R_o is the initial beam radius, and K is the generalized perveance[5], which for a charge neutralized heavy ion beam in the field produced by I_k^{eff} is

$$K = - \frac{6.41 \times 10^{-8}\, Z_b\, I_k^{eff}}{A\,(\gamma_b^2 - 1)^{1/2}} \quad . \tag{7}$$

Here I_k^{eff} is measured in amps, and A = 238 for Uranium. Note that $\gamma^2 - 1 \simeq \beta^2$ for the mildly relativistic ion beam. Equations (6) and (7) can be combined to give an estimate for the maximum allowable effective knock-on current in order to reach a given spot size R_{min}.

$$\left|I_{k,max}^{eff}\right| = \frac{7.8 \times 10^6 \; R_o^2 \; A\beta_b}{L^2 Z_b \ln(R_o/R_{min})} \quad . \tag{8}$$

Note that this current is determined primarily by the focussing angle $R_o/L \sim 10^{-2}$ and is only weakly dependent on R_{min}. For typical parameters, $\left|I_{k,max}^{eff}\right|$ is less than 1 kA. For purposes of making simple estimates, I_k^{eff} can be taken to be the value at the midpoint of the trajectory ($z = \frac{1}{2}L$).

As an example, consider a 10 GeV, 1 kA Uranium beam propagating a distance L = 5 m in 1 torr of Ne, and assume R_o = 10 cm and L_b = 100 cm. Eq. (2) predicts that $I_k(> \frac{\pi}{2}$, z = 2.5 m) is - 22 kA. Assume that 10% of this amount produces a charge-neutralized knock-on beam ahead of the ion beam (i.e., α = 0.1). For β_k/β_b = 1.3, I_A = 6.7 kA, and thus Eq. (4) predicts R_k = 7.2 cm at $z = \frac{1}{2}L$ (assuming $\Delta v_{\perp k}(0) = 0.55\ \beta_k c$). Since R_b = 5 cm at this point, $I_k^{eff} = (-\ 2.2)\ (5/7.2)^2 = -\ 1.1$ kA. However, the allowable $I_{k,max}^{eff}$ predicted by Eq. (8) for R_{min} = 0.2 cm and Z_b = 70 is only - 760 A. Thus, the desired spot size could not be attained if the defocussing field is frozen in. It is clear that since both α and R_k cannot be estimated accurately, changes in their assumed values could easily reverse this conclusion. If $\alpha\ I_k$ is reduced from 2.2 kA to 0.22 kA (which could be produced by lowering the pressure or reducing the assumed value of α), then I_k^{eff} would be reduced to only 11 A, and the effect of the knock-ons would be negligible.

NET CURRENT REVERSAL BY THE ION BEAM

According to the model we have been developing, the front end of the ion beam pulse experiences an effective net current I_k^{eff} (< 0) determined by the total knock-on current and beam radius. It is of critical importance to determine how quickly (if at all) this net current can be reversed by the positive ion current. We define ξ as the distance from the ion beam head back into the pulse, and ξ_{cr} as the distance from the beam head at which the net current is reversed (i.e., $I_{net}(\xi_{cr}) = 0$). For $\xi_{cr} << L_b$, only the front portion of the beam experiences the defocussing field, and the knock-on electrons will probably have only a minimal effect. For $\xi_{cr} \sim L_b$, most or all of the ion beam pulse experiences an outward deflection. For ballistic propagation, this can be tolerated so long as the effective knock-on current lies below the critical value given in Eq. (8). However, pinched mode propagation obviously requires a small value of ξ_{cr} since the pinch requires $B_\theta > 0$.

The net current can be estimated from a circuit equation of the form

$$\frac{\partial}{\partial \xi}(\tilde{L}\, I_{net}) = \frac{c}{2\beta_b \pi R^2 \sigma} \left[- I_{net} + Z_b\, \tilde{I}_b + I_k^{eff} \right] , \tag{9}$$

with all quantities functions of ξ. The exact form of the inductance term $\tilde{L}$ depends on the details of the circuit model. We take R as constant and $\tilde{L} \sim 1$. An upper limit to ξ_{cr} can be found by retaining only the $Z_b\, \tilde{I}_b$ term on the right hand side of Eq. (9) and assuming the following forms for $\tilde{I}_b$ and σ:

$$\tilde{I}_b(\xi) = \tilde{I}_b'\, \xi ,$$

$$\sigma(\xi) = \sigma_o + \Lambda\, I_b'\, \xi^2 \quad . \tag{10}$$

This corresponds to direct ionization by a linear ramped pulse. With the initial condition $I_k^{eff}(\xi = 0) = I_k^{eff}(0)$, Eq. (9) can be integrated and solved for $I_{net} = 0$ to give

$$\xi_{cr}^2 = \frac{\sigma_o}{\Lambda I_b'}\left\{\exp\left[\frac{-\,4\pi\beta_b\tilde{L}R^2\;\Lambda\;I_k^{eff}\;(0)}{Z_b c}\right] - 1\right\} \tag{11}$$

In order to make numerical estimates, we assume that the ionization cross section $\sigma_+ = 10^{-18}\,Z_b^2\,\beta^{-2}\ \mathrm{cm}^2$ (based on Gillespie, et al[6]), and that the conductivity is given by[7] $\sigma = 1.8 \times 10^{-4}\,n_e T_e^{-1/2}$. The resulting nominal value for Λ is

$$\Lambda_o = \frac{3.2 \times 10^5\,Z_b^2}{T_e^{1/2}\,R_b^2\beta^3} \quad (\mathrm{Amp\text{-}cm\text{-}sec})^{-1} \quad . \tag{12}$$

Note that $\Lambda = \frac{1}{2}\dfrac{d^2\sigma}{d\tilde{I}_b d\xi}$.

Figure 2a plots ξ_{cr} versus $I_k^{eff}(0)$ for a typical converging beam with $\beta_b = 0.2$ (5 GeV), $Z_b = 70$, $R_b = 5$ cm, $\tilde{L} = 1$, $T_e = 4$ eV, and $\sigma_o = 10^{10}\ \mathrm{s}^{-1}$. Curves are plotted for $\Lambda = 0.3$, 1, and $3\Lambda_o$, allowing for an order of magnitude variation in conductivity. Figure 2b contains similar plots for $\beta = 0.4$ ($\sim$20 GeV). It is clear that ξ_{cr} is extremely sensitive to small variations in conductivity (or Λ) and I_k^{eff} . Unfortunately, neither quantity can be estimated with great precision. Figure 2 also indicates that in most cases, the current will be reversed close to the ion beam head ($\xi_{cr} \lesssim 10$ cm), or else the defocussing field will persist throughout the pulse ($\xi_{cr} \gtrsim L_b \sim 100$ cm). Since the minimum effective knock-on current necessary to prevent field reversal by the ion beam is typically 10^2 A for these parameters, we expect the defocussing field to persist throughout the beam pulse at sufficiently high pressures if even a modest amount of self-pinching occurs.

For pinched mode propagation, the background gas may be completely stripped and conductivity may exceed 10^{15} s^{-1}. For illustrative purposes, we consider a pinched beam with R_b = 0.2 cm, β = 0.3, I_b' = 20 A/cm, Z_b = 70, and σ_o = 10^{10} s^{-1}. Assuming that $\sigma(\xi$ = 20 cm) is 10^{15} s^{-1}, the resulting Λ is 1.25 x 10^{11} (A-cm-sec)$^{-1}$. For $\tilde{L}$ = 1, Eq. (11) predicts that the defocussing field will destroy the pinch if I_k^{eff} > 1.5 kA. However, since R_b is so small, the inductance term $\tilde{L}$ should probably be increased by at least a factor of 2, thereby proportionally reducing the allowable I_k^{eff}. One can be cautiously optimistic that at pressures below 1 torr in Ne the defocussing field can be reversed near the head of the beam, but this field reversal becomes much more uncertain at higher pressures.

DISCUSSION AND CONCLUSIONS

It is virtually certain that heavy ion beams will produce massive quantities of knock-on electrons for target chamber pressures above 1 torr. We have shown that the magnitude of the resulting current is more than sufficient to pinch the knock-on beam in most cases, assuming that a substantial fraction of this beam actually gets out ahead of the ion beam pulse. Although at least some of the ion beam experiences this defocussing, the overall effect on beam propagation is minimal if field reversal induced by the ion beam occurs near the beam head. Our simple model for studying this field reversal process has not been conclusive owing to uncertainties in conductivity and in the radius of the knock-on beam. For ballistic mode propagation, ion beam induced field reversal is not necessary so long as the net knock-on current lying inside R_b does not exceed the limit given crudely in Eq. (8). However, field reversal <u>must</u> occur quickly for pinched-mode propagation to be viable.

There are several factors which we have not yet discussed which could modify the model we have presented considerably. First, electric fields present inside the ion beam may prevent knock-on electrons from getting out ahead of the beam. As long as the stripped ion beam current is not exceeded by the current carried by fast electrons, the inductive field E_Z will be negative. Hence, knock-ons inside the ion beam will actually be accelerated forward to higher energies. This will tend to neutralize quickly the space charge at the head of the ion beam (especially for a ramped pulse), so any electrostatic fields near the head of the ion pulse will probably be greatly reduced.

Yu[8] has pointed out that the self pinching of knock-ons cannot occur until the knock-ons in the channel ahead of the beam become space charge neutralized. The distance for achieving neutralization must be longer than the mean free path for ionization given by

$$\lambda_i = \frac{1}{\sigma_i n_g} \quad . \tag{13}$$

Here σ_i is the ionization cross section and is typically (1-5) x 10^{-18} cm², depending on the gas specie and knock-on energy (20-100 keV). For $\lambda_i \gtrsim 20$ cm (as is typical of Ne at 1 torr), the beam will travel a considerable distance into the chamber before self-pinching begins, and I_k^{eff} will be substantially reduced. However, by raising the pressure or using a more readily ionized gas, λ_i can be reduced to a few cm or less, and self-pinching is more likely to occur. In addition, for self-pinched ion beams propagating in > 10 torr of Ne, knock-on current densities will be sufficiently large to induce breakdown or avalanching even if the beam is not initially pinched.

An additional feature which we have not discussed is the possible enhancement of conductivity by energetic secondary electrons at energies above the 1 eV bulk plasma produced by a large radius ballistically focussed beam. Such an enhancement would probably prevent the ion beam from reversing the knock-on field under any circumstances. However, if the resulting frozen net current lies well below the limit set by Eq. (8), field induced ion orbit deflections and anharmonic emittance growth[2] might actually be reduced below what has been calculated in the past. Since the estimated temperature inside a pinched beam is expected to be 100 eV, one would not expect substantial conductivity enhancement by energetic secondary electrons.

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FIGURE CAPTIONS

Fig. 1 - Knock-on electron orbits as seen in the laboratory frame. Electrons which outrun the beam produce plasma channel ahead of the beam with a magnetic field $B_\theta < 0$ which pinches the electrons and causes them to execute sinusoidal betatron orbits. This field will persist at least part of the way into the ion beam pulse (shaded area), thereby deflecting ions outward. In many cases, the ion beam will reverse the magnetic field at some point, leading to a region where electrons are magnetically expelled. The case illustrated is somewhat unusual in that field reversal, if it occurs at all, will usually occur within a few centimeters of the beam head.

Fig. 2 - Critical distance from the beam head ξ_{cr} verses effective knock-on current $I_k^{eff}(0)$, lying inside the ion beam at $\xi = 0$. Parameters assumed in Fig. 2a are for a converging beam with $\beta_b = 0.2$ (5 GeV), $Z_b = 70$, $R_b = 5$ cm, $\widetilde{L} = 1$, $T_e = 4$ eV, $I_b' = 20$ A/cm and $\sigma_0 = 10^{10}$ s^{-1}. The nominal value Λ_0 is based on the estimate in Eq. (12) and is a measure of how fast the conductivity builds up as a result of the rising beam. If $I_k^{eff}(0)$ is sufficiently small, ξ_{cr} is a few centimeters or less, and knock-on defocussing will not effect most of the ion beam pulse. Equation (11) is used to estimate ξ_{cr}. Figure 2b is a similar calculation for $\beta_b = 0.4$.

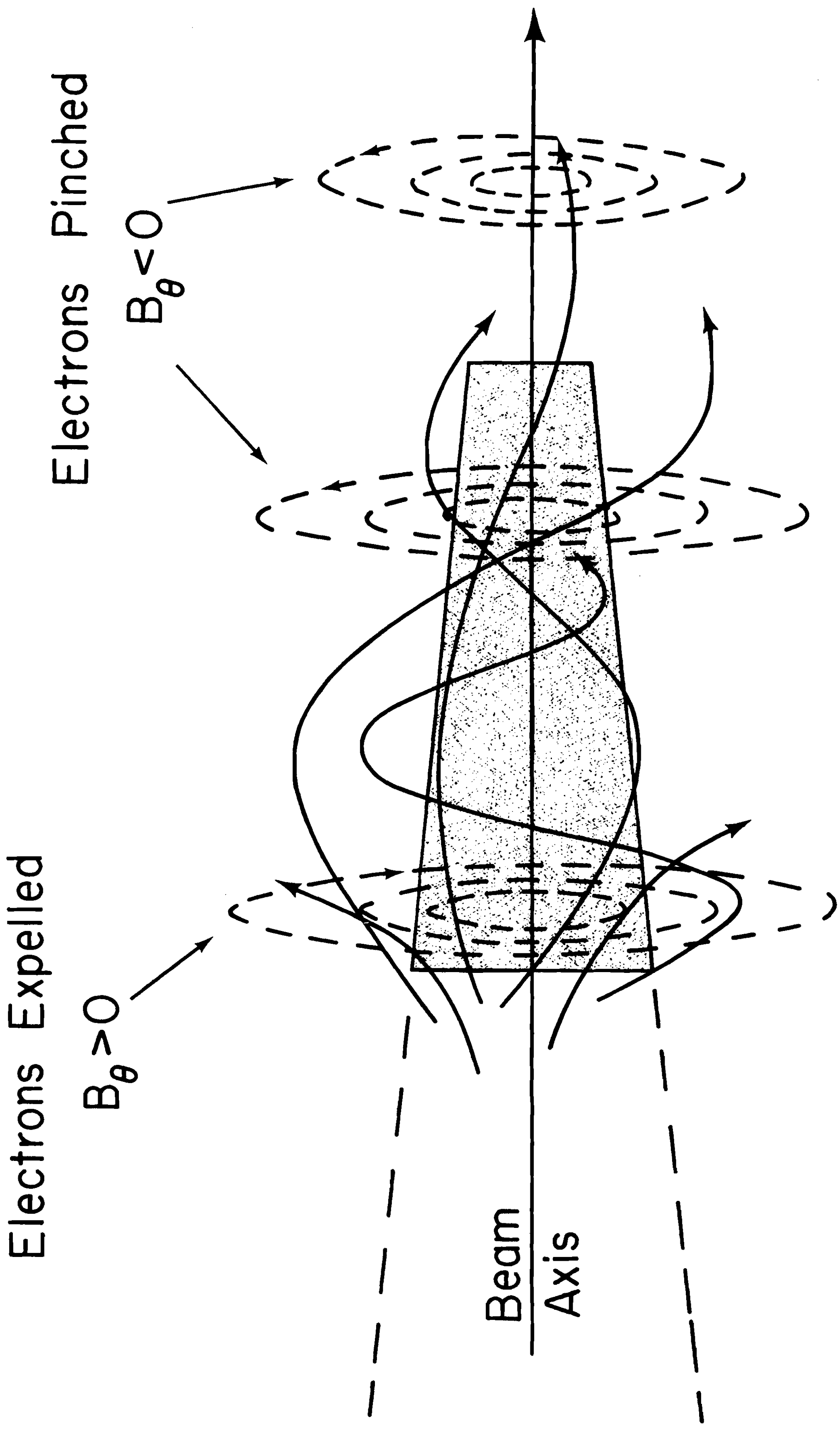
Electrons Expelled
$B_\theta > 0$
Electrons Pinched
$B_\theta < 0$
Beam Axis

Figure 1.

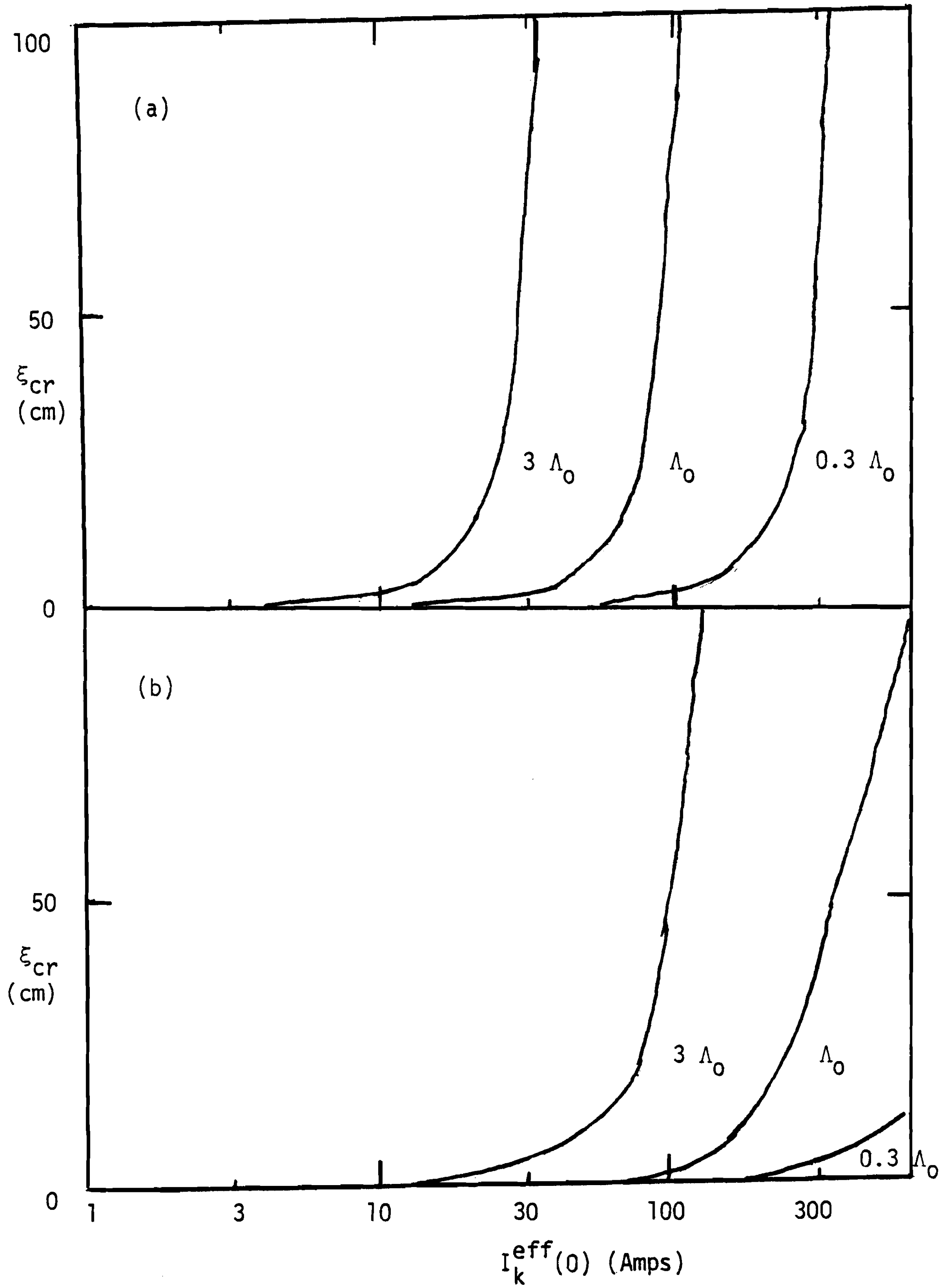
(a)
(b)
100
50
0
ξ_{cr} (cm)
3 Λ_o
Λ_o
0.3 Λ_o
1
3
10
30
100
300
$I_k^{eff}(0)$ (Amps)

Figure 2