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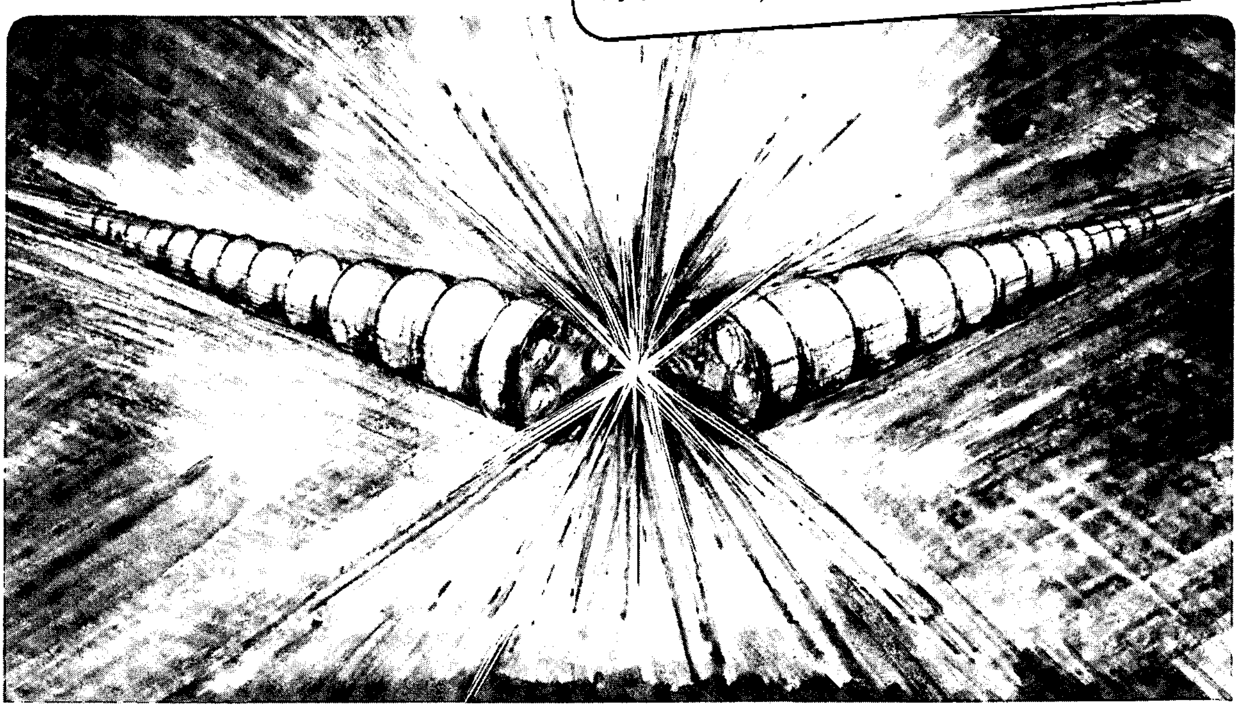

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The Neutralizer Plasma of a High Power, Positive Ion Beam*

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Abstract

A classical point average model, based on experimentally measurable parameters, is developed for the plasma present in the neutralizer of a high power positive ion beam with a functional neutralizer gas density. The slope of j_{ip}/j_b vs V_b is predicted to change sign as the beam goes from un-neutralized to optimum. Although plasma power requirements are underestimated, predicated electron temperatures are lower than observed, which suggests that anomalous beam electron heating occurs. The total neutralizer plasma ion current is shown to be comparable to the total beam current, which indicates that the neutralizer plasma particle balance should be considered in optimizing neutralizer gas efficiency.

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Contents

Introduction

A point average model is developed for the plasma present in the neutralizer of a high power positive ion beam, with a functional neutralizer gas density. Since charge exchange neutralization requires substantial gas thickness [1,2], $n_0 L \geq 3\times10^{15}$ cm^{-2}, while practical considerations limit the neutralizer length, L, average gas density must be high, $n_0 \approx 10^{13}$-10^{14} cm^{-3}. In a large beam, the plasma density produced by beam charge exchange and ionization can exceed the beam charge density by one or two orders of magnitude, and is sufficiently high, $\geq 10^{10}$ cm^{-3}, that the so-called "plasma approximation" applies to the self-consistent potential problem [3]. For this reason, provided a functional gas density is present, the plasma present in the neutralizer is treated as a typical free-fall plasma. This results in a relatively simple model in comparison with comprehensive models which also describe ion beam properties with low neutralizer gas density [4]. For clarity, only dominant process are considered. A formulation is found in which plasma density and electron temperature are calculated as a function of beam voltage, V_b, beam current density, j_b, and neutral density. The implications for gas flow, neutral thickness, and gas density are discussed.

1. Average Plasma Particle and Power Balance

A point average neutralizer plasma model is developed which is based on experimentally measurable parameters. For clarity, only dominant processes are considered. The neutral gas is assumed to be molecular deuterium, and molecular cross sections are used for beam ionization and charge exchange. However, in the energy range of interest (20-120 keV), the relevant atomic cross sections are nearly half the molecular, so little is changed if the gas is assumed to be atomic, with twice the molecular density. With a functional gas density in the neutralizer, i.e., sufficient for charge exchange neutralization, the beam density is found to be small compared to the plasma density. Since the Debye length is also small, the local structure of the space potential associated with individual beamlets is neglected and the model is averaged over the beam cross section.

Considering only the full energy component of the beam, charge exchange, $(\sigma_{ib,o})_{cx}$, and beam ionization of neutral gas, $(\sigma_{ib,o})_e$ or $(\sigma_{ob,o})_e$, dominate plasma production [5]. Assuming free fall ion losses, plasma particle balance is given by,

$$\frac{n_{ip}}{\tau_i} = \left[(\sigma_{ib,o})_{cx}\, n_{ib} + (\sigma_{ib,o})_e\, n_{ib} + (\sigma_{ob,o})_e\, n_{ob}\right] v_b n_o + \langle \sigma v \rangle_e n_e n_o \,. \qquad (1)$$

A term for electron ionization, $\langle\sigma v\rangle_e$, has been included for completeness. For temperatures less than 20eV, thermal electron ionization may be neglected, although secondary electrons, generated either by beam ionization of background neutrals or ionization of beam neutrals, can also produce ions. Since secondary electrons have a relatively large angular divergence [6], secondary ionization is neglected at present, even though their ionization cross section is comparable to the beam. The ion loss time, τ_i, is just the average ion free-fall time, $\tau_i \cong L\, A_b / v_i\, A_s$, where, L denotes the length of the neutralizer, A_b the beam cross section, and A_s the total surface area of the beam, including the sides. For a rectangular beam, with cross section of dimension, WxH, $LA_b / A_s = W\,H/2(W + H)$. The average ion free-fall speed, $v_i = (2\delta\phi/m_{ip})^{1/2}$, is determined by the average potential drop across the beam, $\delta\phi$, which is a fraction of the plasma potential, typically of order T_e [3]. Implicitly, only losses orthogonal to the beam direction are considered in the particle balance. Even with sonic plasma flow in the beam direction [7], ion particle losses are essentially perpendicular, since the beam cross section is small compared with the surface area, i.e., $A_b \ll A_s$. Using $(\sigma_{ib,o})_e \approx (\sigma_{ob,o})_e$ and neglecting electron ionization, Eq. (1) may be rewritten,

$$\frac{n_{ip}}{\tau_i} = \left[(\sigma_{b,o})_e + (1-f)\, (\sigma_{ib,o})_{cx} \right] v_b n_b n_o, \qquad (2)$$

where f represents the beam neutralization fraction, which varies axially.

The dominant coupling of beam power to the plasma is assumed to be beam generated secondary electrons, either from beam ionization of background neutrals, or ionization of beam neutrals. The mechanism for energy transfer from secondaries to the plasma is unspecified, but assumed to be anomalous; a point which is discussed later. For densities typical of the neutralizer plasma ($\lesssim 10^{11}$ cm^{-3}), electron drag [8] on beam ions is a small contribution to the overall plasma power balance. Thus, to lowest order, the beam power per unit volume transferred to the plasma by secondaries is written as,

$$P_e = \left[\overline{E}_e (\sigma_{b,o})_e + \frac{m_e}{m_b} V_b (\sigma_{ob,o})_{ib}\, f \right] v_b n_b n_o , \qquad (3)$$

where, $(\sigma_{bo,o})_e \approx (\sigma_{bi,o})_e$ has been assumed, $\overline{E}_e$ (eV) denotes the average energy of ionization secondaries, and secondary electrons have been assumed to have the same speed as the beam, with energy (eV) given by, $V_b\ m_e/m_b$. Limited experimental data are available [6] for $\overline{E}_e$ (for hydrogen) and are illustrated in Fig. 1. A reasonable upper bound for $\overline{E}_e$ is given by the electron equivalent energy, in which case Eq. (3) becomes,

$$P_e \approx \frac{m_e}{m_b} \left[(\sigma_{b,o})_e + f\, (\sigma_{ob,ib}) \right] V_b n_b n_o \ . \qquad (4)$$

The only plasma power losses considered are ambipolar particle losses to the wall, a substantial underestimate of the total. For cases of interest, electron temperatures are a minimum of a few eV, and the plasma potential, ϕ_{pl}, tens of eV. Although the rates for plasma electron generation of line radiation and dissociation of molecules are comparable to the ion loss rate, much less energy is involved in the electron processes (each ion removes $\sim\phi_{pl}$), and the power associated with classical electron processes is relatively small. The ambipolar power drain is treated in a manner similar to a single cell mirror, with some additional consideration of the beam charge state history. As usual in free fall plasmas, the higher mobility of the electrons means that the neutralizer plasma operates at a positive space potential, typically $\phi_{pl} \geq 4T_e$. This means that only the energetic tail of the electron distribution can escape. For the thermal part of the electron distribution, the average electron energy lost per ion is approximately T_e [9,10,11]. Neglecting ion temperature, the minimum energy lost per ion is ϕ_{pl}. Since the beam enters the plasma as an ion beam, the charge state history of the beam must be considered in the neutralizer plasma power balance. For the un-neutralized beam, each ion brings energy, ϕ_{pl}, into the system; this energy leaves with the first charge exchange ion. Thus, the first charge exchange event results in no net energy transfer to the system. All plasma ions created by beam ionization of neutrals are are counted as a plasma power loss. Using Eq. (2), and assuming that the relative density of these two classes of ion is in proportion to their cross section, the ambipolar power drain for plasma produced by an un-neutralized beam is,

$$(P_{pl})_{f=o} = \left[\frac{(\sigma_{b,o})_e \quad \phi_{pl}}{(\sigma_{b,o})_e + (1-f)\,(\sigma_{bi,o})_{cx}} + T_e \right] \frac{n_{ip}}{\tau_i}$$

$$= \left[\eta\,(\sigma_{b,o})_e + (1-f)(\sigma_{bi,o})_{cx} \right] T_e \frac{J_b}{e} n_o \,, \qquad (5)$$

where, $\eta = 1 + \phi_{pl} / T_e$ and $J_b/e = v_b n_b$. As the beam approaches optimum [1] neutralization, a typical beam ion is likely to have undergone previous charge exchange and re-ionization. Therefore, in this downstream region, plasma ions generated by charge exchange are counted in the ambipolar power drain,

$$(P_{pl})_{optimum} = \eta\, T_e\, n_{ip} / \tau_i \qquad (6)$$

$$= \left[(1-f)(\sigma_{bi,o})_{cx} + (\sigma_{b,o})_e\right] \eta\, T_e\, J_b\, n_o .$$

Typically [10,11], the ambipolar coefficient, η, has a value of 5-8, although it can be larger in very cold plasmas.

In principal, assuming that most of the energy in beam generated secondaries is thermalized in the plasma electron distribution, and neglecting any anomalous coupling of beam power to the plasma, lowest order plasma power balance can be solved by equating secondary electron power density, Eq. (3) to ambipolar plasma losses, Eq. (5) or (6). These equations contain three parameters which are fixed experimentally, n_o v_b, and J_b, plus undetermined parameters, f, $n_{ip} \approx n_e$, T_e, ϕ_{pl} and $\delta\phi$. A relationship between $\delta\phi$ and T_e has been calculated for a single electron beam [3], but proper extension to a large, multiple ion beamlet system is unclear. Since the ion loss time depends on this parameter, the present formulation is sensitive to the effective $\delta\phi$ within the beam region. This difficulty can be avoided by a reformulation which eliminates this parameter. Eq. (2) becomes,

$$\frac{(J_{ip})_{\perp}}{(J_b)_{av}} = \left[(\sigma_{b,o})_e + (1-f)(\sigma_{bi,o})_{cx} \right] n_o L \frac{A_b}{A_s} , \qquad (7)$$

where J_{ip} is now determined independent of the plasma power balance. The notation $\perp$ has been added to indicate explicitly that the component of ion current density to the walls is being considered. The scaling of $(J_{ip})_{\perp} / J_b$ with beam voltage is illustrated in Figure 2 for two cases, f = o, and optimum. Below 80 keV, where the charge exchange cross section is dominant, the sign of the slope differs for the two cases and suggests that measurement of $J_{ip}(V_b)$ could be used as an indicator of neutral thickness to provide an experimental point of reference for neutral gas flow calculations. The effect of mixed beam species is easily included; Eq. (7) becomes,

$$\frac{(J_{ip})}{J_b} = \sum_j \left[(\sigma_{b,o}(j))_e + (1-f_j)(\sigma_{bi,o}(j))_{cx} \right] S_j \frac{n_o L A_b}{A_s} , \qquad (8)$$

where S_j denotes the molecular species fraction. Some care is required at this point. For example, consider an un-neutralized beam with a molecular species mix of: $S_1 = 0.75$ (atomic); $S_2 = 0.15$ (di-atomic); and $S_3 = 0.10$ (tri-atomic). If the optimally neutralized beam is assumed to be fully dissociated, the total current density (ions and neutrals) would increase by a factor of $S=S_1+2S_2+3S_3$, with a species mix of full energy, S_1/S, half energy, $2S_2/S$, and third energy $3S_3/S$. For the 75:15:10 case, the dissociated beam would have a mix of 56:22:22. This case is illustrated in Figure 3. The qualitative features resemble the pure beam, although charge exchange of the molecular and fractional components softens the distinction between un-neutralized and optimal beams.

If the secondary electron power is assumed to be thermalized, from Eqs. (4) and (5), the equivalent electron temperature is independent of beam density and neutral density,

$$(T_e)_{f=o} = \left[\frac{(\sigma_{b,o})_e}{\eta(\sigma_{b,o})_e + (\sigma_{bi,o})_{cx}} \right] \frac{m_e}{m_b} V_b \quad . \tag{9}$$

Similarly, from Eqs. (4) and (6), the expected electron temperature for an optimum neutral beam is,

$$(T_e)_{\text{optimun}} = \left[\frac{(\sigma_{b,o})_e + f(\sigma_{ob,o})_{ib}}{(\sigma_{b,o})_e + (1-f)(\sigma_{ib,o})_{cx}} \right] \frac{m_b}{m_b} \frac{V_b}{\eta} \quad . \tag{10}$$

The neutralizer plasma electron temperature expected for a pure beam is illustrated in Figure 4 for both cases. Although nontrivial electron temperatures seem likely, the values are well below the range where thermal electron ionization becomes important, and the associated beam power loss is neglegible. The effect of mixed beam species should be to lower T_e, since the molecular and fractional components produce less energetic secondaries, but have a higher charge exchange cross section. Summing over species, as before, the electron temperature for an un-neutralized, mixed beam is given by,

$$(T_e)_{f=o} \quad \frac{\sum_j S_j \, (\sigma_{b,o}(j))_e / \mu_j}{\sum_j S_j \, [\eta(\sigma_{b,o}(j))_e + (\sigma_{bi,o}(j))_{cx}]} \; \frac{m_e}{m_b} \; V_b, \tag{11}$$

and, for a neutralized beam,

$$(T_e)_{optimum} \quad \frac{\sum_j S_j\,[(\sigma_{b,o}(j))_e + f_j(\sigma_{ob,o}(j))_{ib}] \quad /\mu_j}{\sum_j S_j\,[(\sigma_{b,o}(j))_e + (1-f_j)(\sigma_{bi,o}(j))_{cx}]}$$

$$x \quad \frac{m_e}{m_b} \quad \frac{V_b}{\eta} \qquad (12)$$

where the species are again assumed to be molecular for f=o and re-normalized fractional energy for f → optimum. A 75:15:10 molecular mix is illustrated in Fig. 5; electron temperatures are reduced, as expected.

If beam-plasma coupling is classical, as assumed thus far, Eqs.(9) and (10) should give an overestimate of the experimental electron temperature for several reasons: (i) the energy of beam generated secondary electrons has been overestimated; (ii) secondary electron energy has been assumed to be completely thermalized by the plasma electrons; (iii) secondary ionization has been neglected; and (iv) significant plasma power losses (e.g., radiation and dissociation) have been neglected. However, preliminary plasma probe measurements indicate that electron temperatures can be a factor of two higher than predicted by even the present model [12].

2. Anomalous Beam Plasma Effects

Collective interaction of the beam with the neutralizer plasma is an obvious possiblity, since the beam velocity exceeds both the sound speed and the thermal electron velocity. The subject of beam-plasma interactions has been studied extensively [13]. Unfortunately, when applied to the case of a high power beam of finite extent with a strong gradient (in this case, the neutral gas density), competing non-linear effects can be important, and detailed theoretical models become academic. Present considerations are motivated by preliminary probe measurements which suggest that the electron temperature is anomalously high [12]. Since limited data are available, dimensional arguments are used to discuss the scaling of collective beam-electron heating, although long term interest is more concerned with the possibility that anomalous beam-ion interaction could affect beam divergence.

As mentioned previously, the electron equivalent energy of the beam is, $E_e(eV)=V_b \ \ m_e/m_b=0.55 \ V_b(kV)/\mu_b$. An instability with an effective energy transfer rate $\delta_e\omega_{pe}/2\pi$ where δ_e represents some fraction of the electron plasma frequency, ω_{pe}, would have an anomalous scale length, $L_e(cm) \approx v_b 2\pi/\delta_e\omega_{pe} = (4.9\text{x}10^3/\delta_e)(V_b/n_{ep}\mu_b)^{1/2}$. Even with a 120 kV beam and plasma density of 10^{10} cm^{-3}, δ_e of only 10^{-4} - 10^{-3} would make the anomalous scale length small compared with the neutralizer. For this reason, the previous power balance model assumed that secondary electron energy was effectively thermalized.

The maximum ion beam power density available for heating electrons may be estimated as, $(P_b)_e \sim (m_e/m_b) J_b V_b$, which is a small fraction of the total. The total beam power required to balance ambipolar losses may be estimated as,

$$P_{pl} \approx \eta \, T_e \, J_{pi} \, A_s \, . \tag{13}$$

From Eqs. (7) and (9), as $f \to o$, this gives,

$$(P_{pl}) \text{ (kW)} \lesssim \eta \left[\frac{(\sigma_{b,o})_e + (\sigma_{b,i})_{cx}}{\eta(\sigma_{b,o})_e + (\sigma_{bi,o})_{cx}} \right] (\sigma_{b,o})_e \, n_o L \, \frac{m_e}{m_b} \, I_b V_b \, . \tag{14}$$

Thru Eq. (9), this estimate implicitly assumes that all plasma electron power is provided by beam generated secondaries. The result scales like the electron equivalent beam power, $(m_e/m_b) I_b \, V_b$, multiplied by a classical coefficient, $[\sigma] \times n_o L$, which is $\sigma(1)$. This implies that classical depletion of beam power is small in a neutralizer of optimal thickness. Any anomalous beam-electron interaction would introduce an additional electron heating channel, and raise T_e. However, an anomalous beam-electron interaction would only apply to beam ions, and would still deplete beam power at the relatively small electron equivalent rate.

Collective beam-plasma interaction which involves plasma ions is another concern, because of the possibility that low frequency plasma modes might increase beam divergence. The scale length for anomalous beam-ion interaction is relatively long, since the highest frequency for such interaction is of the order, $\omega_{pi} = (m_e/m_{pi})^{1/2} \omega_{pe}$. A mechanism by which beam divergence could be affected is beam ion jitter in beam driven plasma oscillations combined with random charge exchange. The most likely candidate for a beam driven mode would be a wave with a phase velocity approximately equal to the beam velocity; to affect perpendicular divergence, that the associated electric field would need to have a substantial perpendicular component. A candidate two stream ion-ion instability with these properties has been identified [14]. Since the ion jitter energy is roughly, $(eE/\nu)^2/2m_b$, for a field $Ee^{i2\pi\nu t}$, with frequency $\nu \leq \mathcal{O}(\omega_{pi}/2\pi)$. The corresponding average fluctuating field energy density would be a few percent of the beam energy density. In this case, for anomalous beam-plasma interaction to affect beam divergence, either the associated plasma modes would have to be weakly damped, or a measurable percentage of the beam power would be dissipated. At present, beam diagnostics are inadequate to either confirm or rule out anomalous beam-plasma interaction as a mechanism for increasing beam divergence [15].

3. Discussion

The plasma present in the neutralizer of a positive ion beam has been characterized by a point average classical model. Plasma particle and power balance have been formulated in a manner which allows direct comparison of the model with experimentally measurable parameters. The slope of j_{ip} / j_b vs V_b has been suggested as a possible indicator of beam charge-exchange neutralization. A generous classical estimate of the neutralizer plasma electron temperature has been found to predict significantly lower temperatures than are observed, which strongly suggests anomalous beam interaction with the neutralizer electron plasma.

Lack of detailed information about plasma wall interactions makes it difficult to predict the effect of the neutralizer plasma on gas behavior. However, Eq. (7) suggests that they may be strongly coupled. The total plasma ions to the wall is approximately,

$$I_{ip} = \oint \left(\vec{J}_{ip}\right)_{\perp} \cdot \vec{dA} \approx \left[(\sigma_{b,o})_e + (1-f)(\sigma_{bi,o})_{cx}\right] n_o L I_b, \quad (15)$$

where the integral is over a surface which encloses the plasma generation region and $\bar{f}$ is representative of the average neutralization fraction. Since $[\sigma]\, n_0 L$ is $\mathcal{O}(1)$ in a thick neutralizer, the implication of Eq.(15) is that the beam generated plasma ion current is of the same order as the total beam current. Plasma generated by secondary electron ionization may further increase the plasma current, but this suggests that any attempt to optimize beamline efficiency by increasing gas efficiency must take into consideration the disposition of the plasma particle flux. If each plasma ion were, on average, to generate a like neutral, which returns from the wall, plasma particle balance would have no affect on neutral gas thickness. On the other hand, if for any reason, e.g., cryo pumping, plasma ions did not generate an equal returning gas flux, the plasma would represent a gas pumping term. Another possibility might be plasma flowing strongly in the beam direction, which would represent a significant increase in gas depletion over cold molecular flow. Steady state gas input would have to be raised accordingly. Any associated tendency of the neutral gas to develop parallel flow would have a similar effect.

The model developed here for plasma power balance has been based on classical beam-plasma coupling with only ambipolar plasma power drain, which should lead to an overestimate of the neutralizer plasma electron temperature ($\leq$8eV). Preliminary experimental data [12] suggest that T_e can be as high as 10-20 eV, which may indicate some anomalous beam heating of plasma electrons. Scaling considerations for low frequency instabilities which could affect ions indicate that, to significantly affect beam divergence, either a few percent of the beam power would have to be dissipated, or the associated plasma modes would have to be very weakly damped.

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Figures

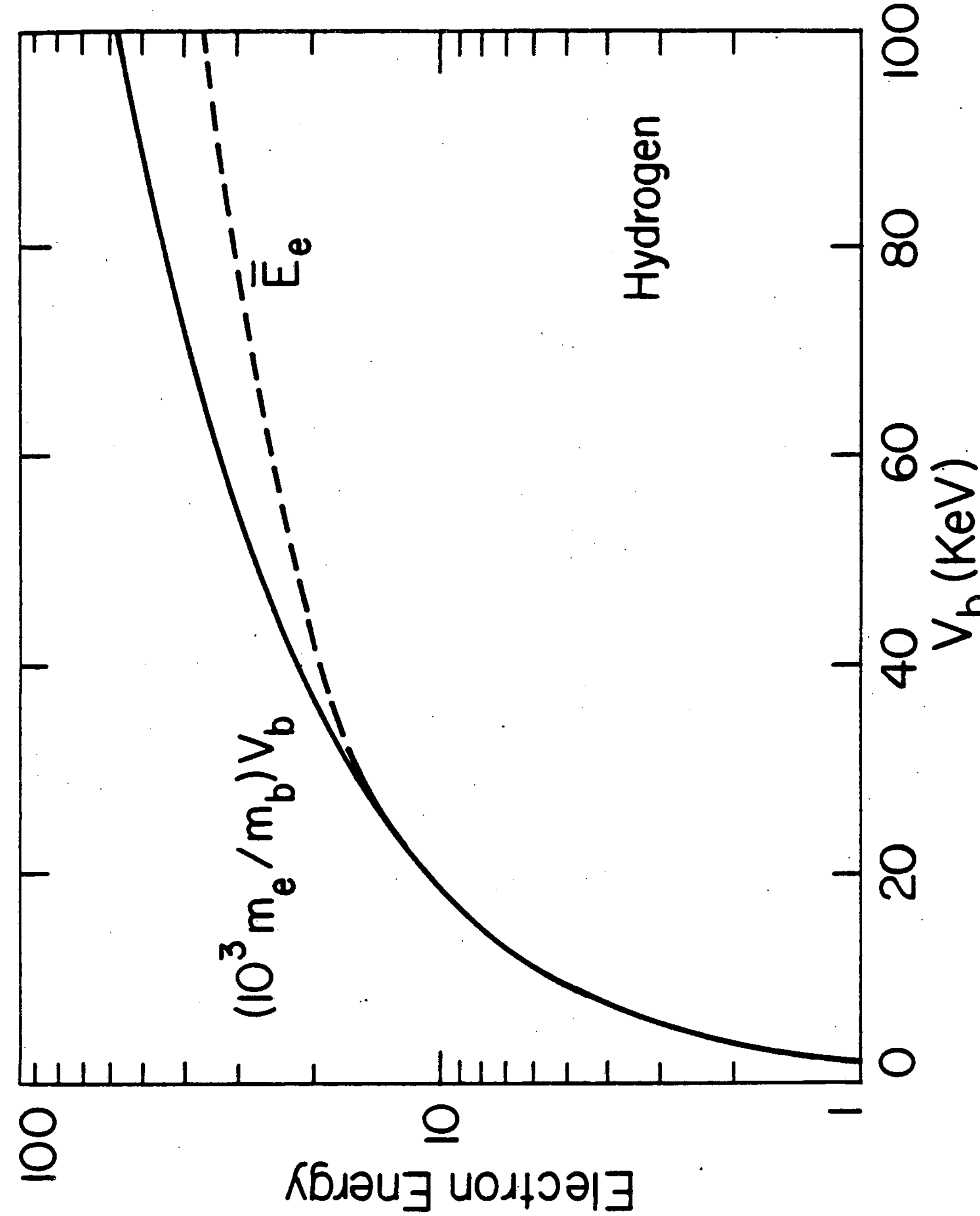

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FIG. 1

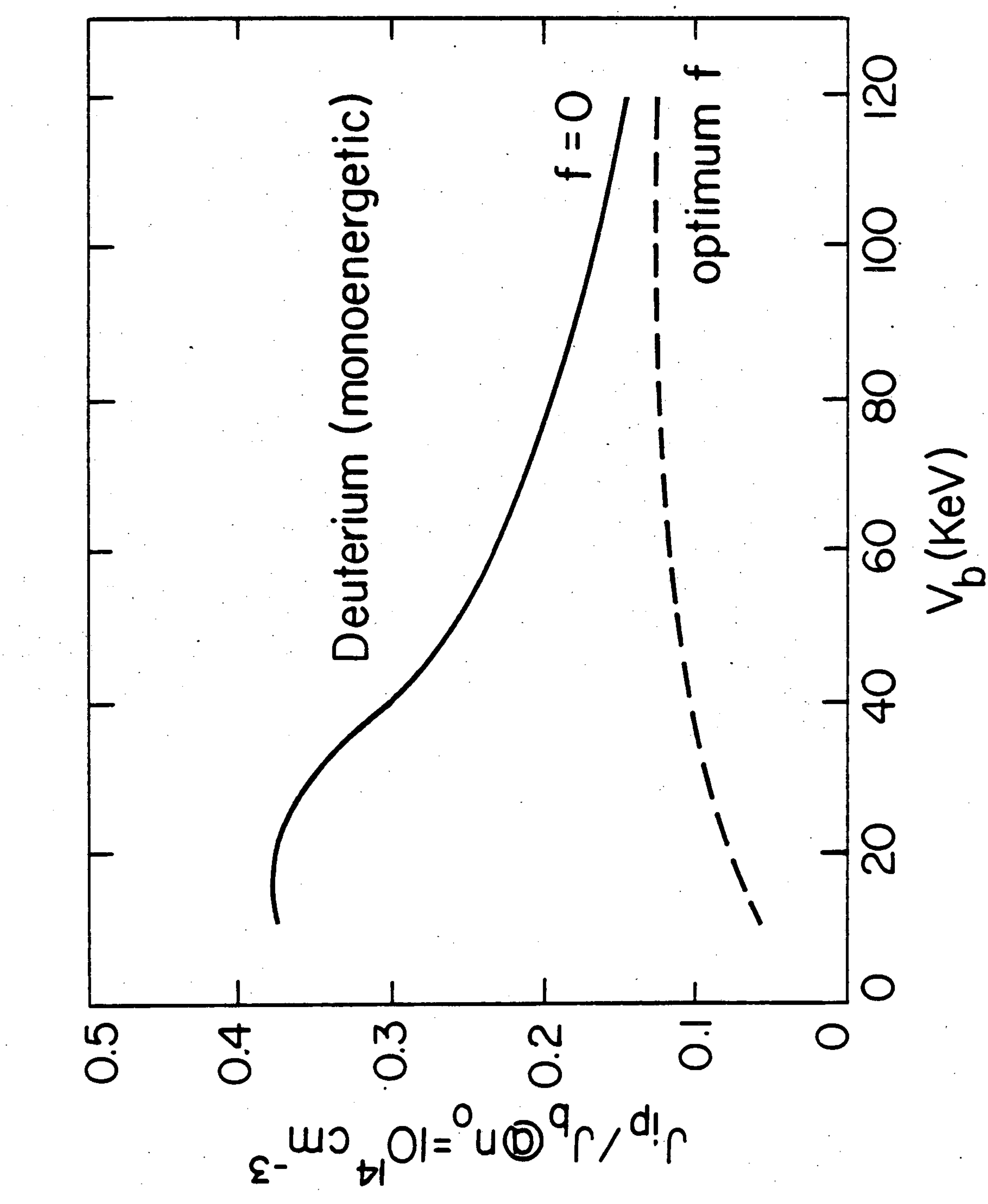

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FIG. 2

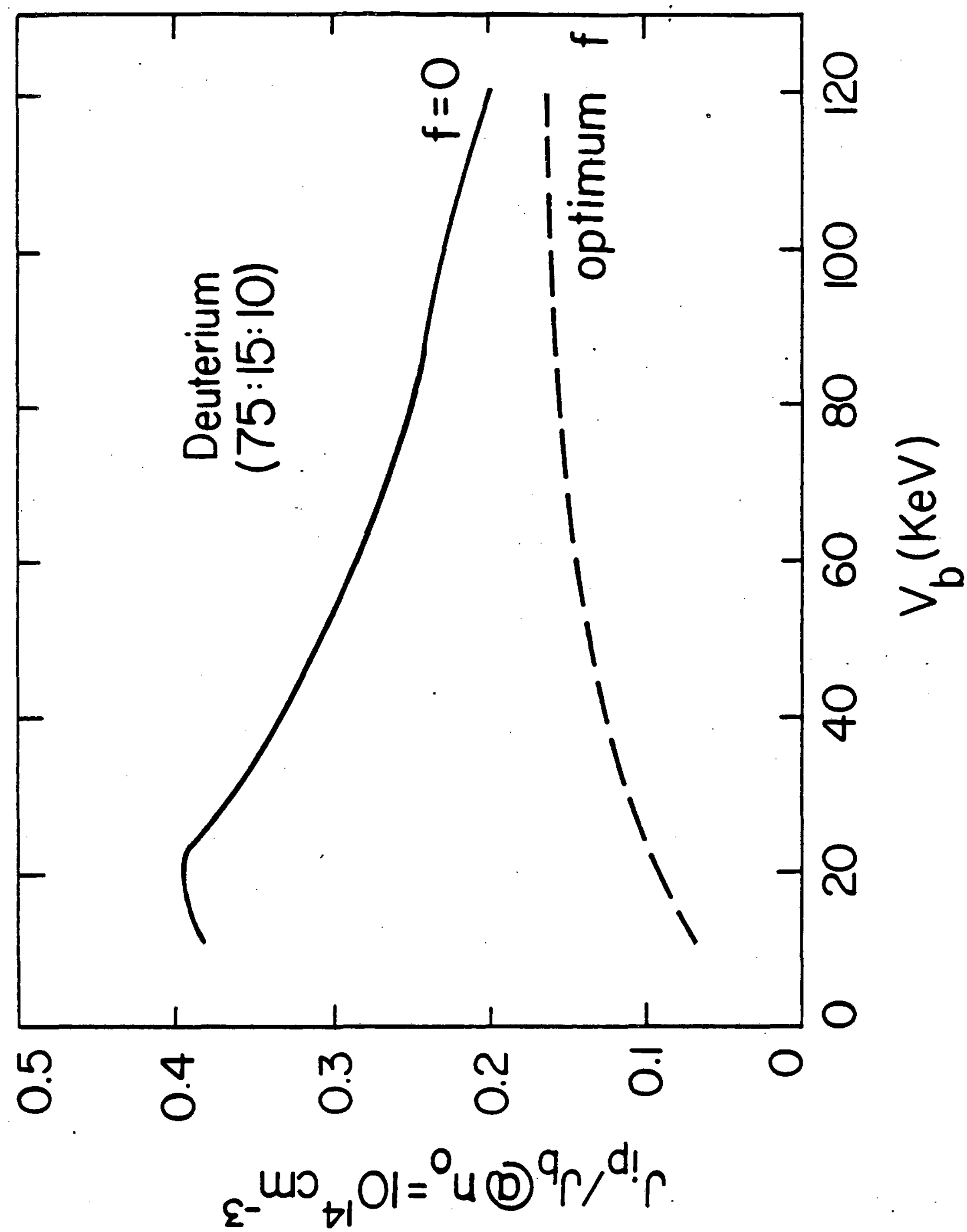

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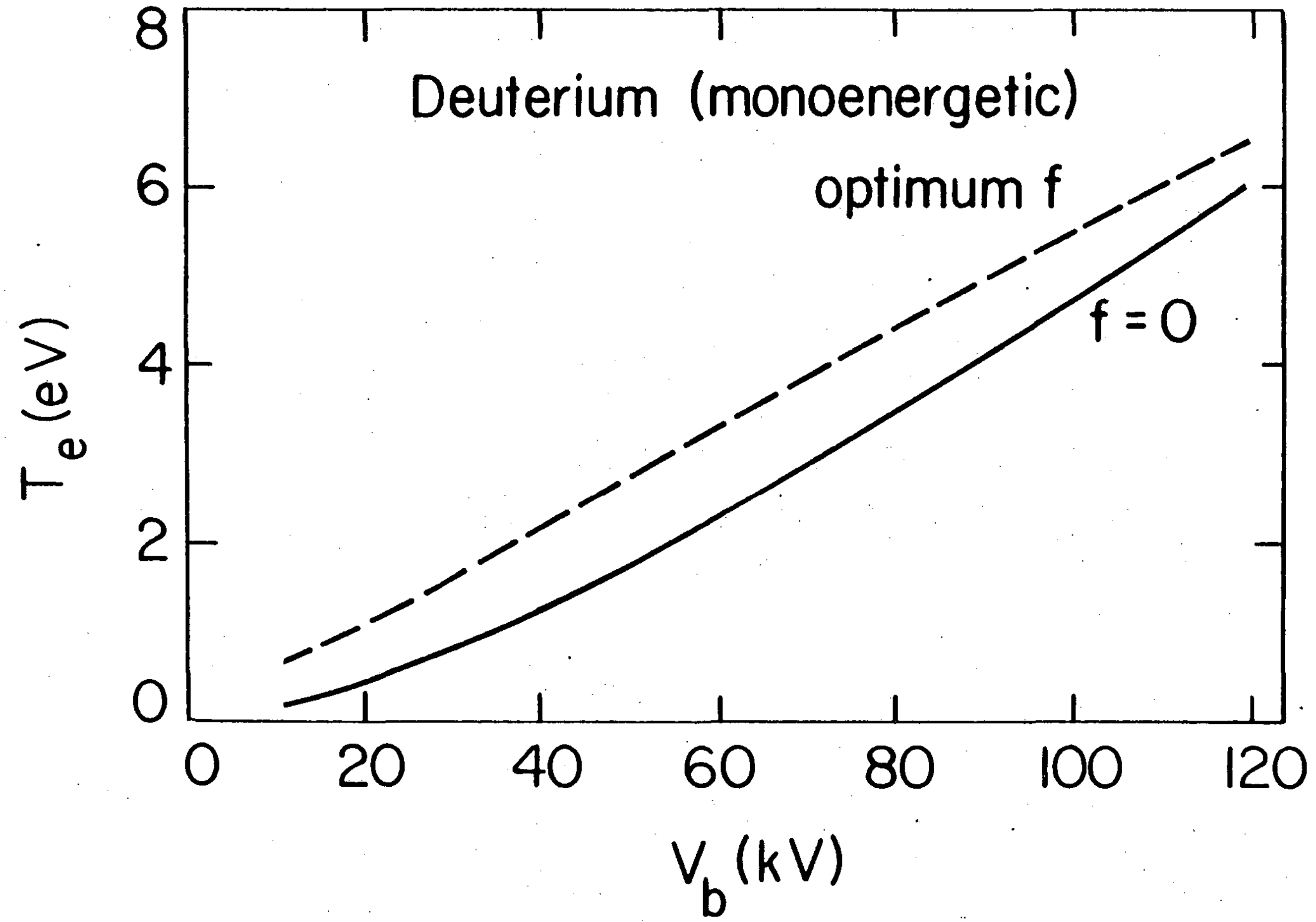
FIG. 3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6
4
2
0
Te(eV)
Deuterium (monoenergetic)
optimum f
f = 0
0
20
40
60
80
100
120
Vb(kV)
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FIG. 4

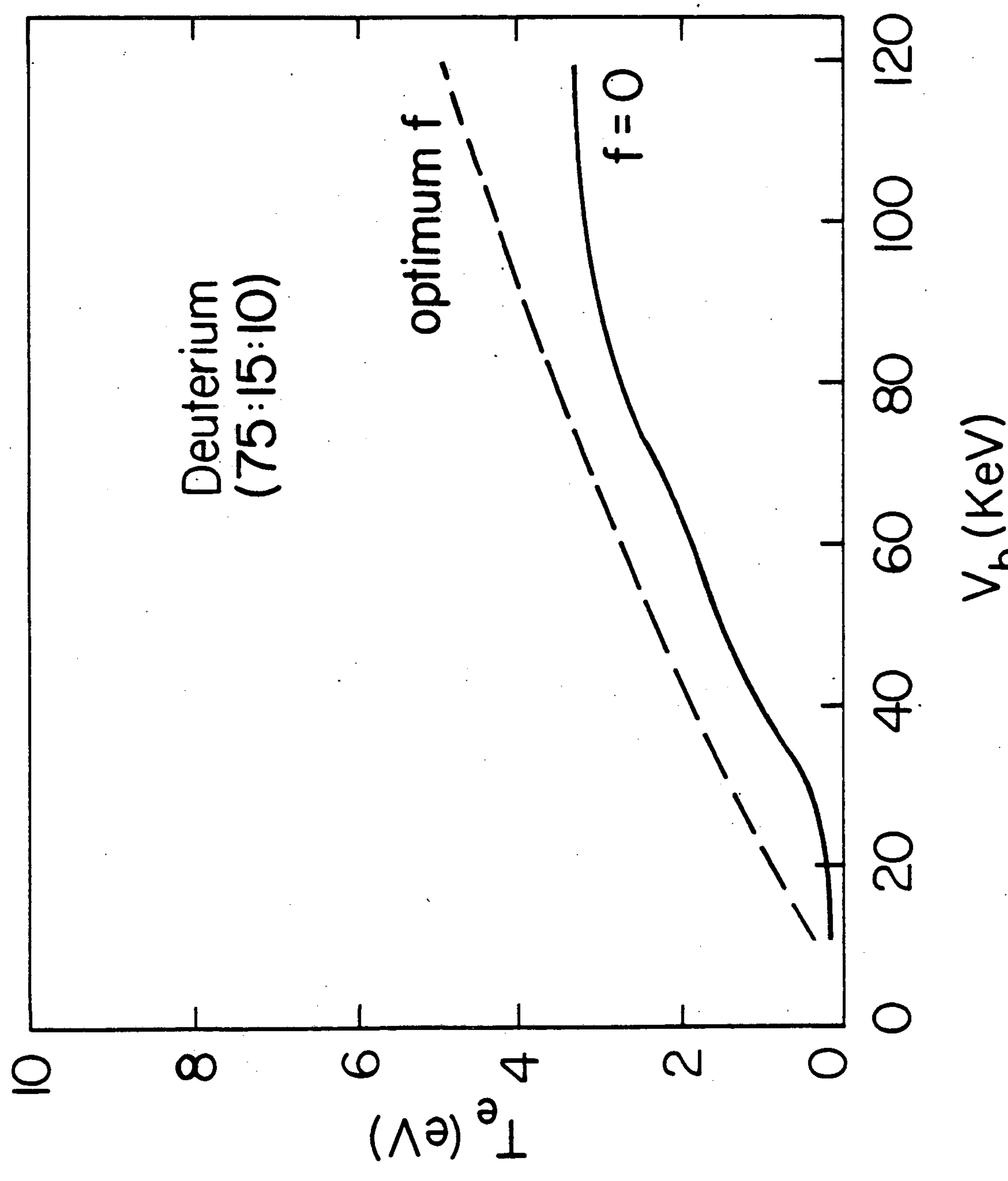

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FIG. 5

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