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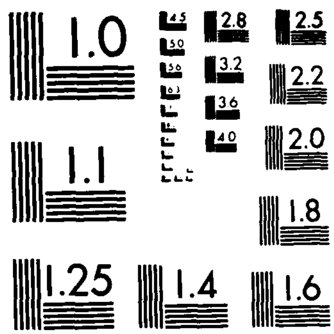
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NEUTRAL BEAM PROPAGATION EFFECTS IN THE UPPER ATMOSPHERE

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This report presents a simple theoretical model of beam induced stripping of a neutral particle beam as it propagates in the upper atmosphere. A comparison of beam induced stripping with stripping induced by the atmosphere demonstrates that for 1 MeV neutral hydrogen beams propagating at 200 km altitude beam induced stripping is negligible when compared with the stripping of the neutral beam caused by the atmosphere.

This model leads to two important conclusions:

1) beam effects will be important only when the neutral beam density is of the same order or larger than the atmospheric density.

2) at high launch altitudes, beam induced stripping will be the dominant energy loss mechanism for neutral beams.

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1. INTRODUCTION

The propagation of neutral particle beams in the upper atmosphere is of substantial scientific interest. Since the time of Alfven [1] this interest has been motivated by the consideration of natural phenomena such as the origin of solar systems and aurorae. Most recently there has been considerable interest in this problem because of the possibility of artificially created particle beams.

The most important parameter of a neutral beam is determined by its energy density. Thus it is imperative to understand the energy loss mechanisms of a neutral beam as it propagates in the upper atmosphere. The energy loss mechanisms can be divided into three main categories: 1) dispersive effects which reduce the energy of the beam by lowering its density, 2) particle energy loss mechanisms which reduce the energy per particle in the beam and 3) stripping processes which lower the neutral beam energy density by ionizing particles in the beam and thus subjecting them to the influence of the geomagnetic field.

Depending on the energy and current density of the neutral beam, there are six main physical processes which will diminish the beam energy density:

1) the geometric dispersion of the beam,
2) scattering processes due to weak collisions with atmospheric constituents,
3) nuclear interactions,
4) radiative processes,
5) ionization processes due to strong collisions with atmospheric constituents,
6) self-ionization of the beam.

The first process is an effect determined by the generation of the beam and depends on the degree of collimation of the beam. It causes no particle energy loss and only reduces the density of the beam by broadening it. The second process, scattering collisions, reduces both the energy per particle and density of the beam but is relatively unimportant for high energy beam particles since they would become ionized before undergoing significant energy loss due to scattering collisions [2]. The third and fourth processes may be neglected for neutral beam energies less than 30 MeV [2]. Obviously these processes would become much more significant and even dominate the energy loss mechanisms for high enough beam energies. The fifth and sixth processes provide the main particle energy loss mechanisms in the 1 MeV energy range and therefore are the most effective in reducing the energy density of the neutral beam. This Report examines the last process in order to determine its relative importance with respect to other energy loss mechanisms.

2. CROSS SECTION DATA REVIEW

When a neutral hydrogen beam propagates through the upper atmosphere there is some probability for collisions with the atmospheric constituents. Numerous experiments have been performed over the years to investigate the effects of atom-atom and other collisions among the atmospheric constituents [3]. These experiments have determined that there are three main interactions: 1) stripping or separation of the beam hydrogen atom into a proton and electron, 2) ionization of the atmospheric or target particle with the resultant release of a free electron and ion, and 3) electron-ion (proton) recombination. Most of the data available in the literature [3] give results for the total cross section for the production of various reaction products over a wide range of energies. These results demonstrate that for beam energies above ~ 100 KeV the cross section for recombination is so low that this process may be neglected. It can also be observed that the cross section for stripping or ionization is essentially proportional to the number of electrons in an atom and further that there is negligible difference in the stripping cross section due to a neutral atom or due to its ion and electron components [4].

The more recent experimental cross section investigations are worth noting in more detail. Current investigations are being conducted mainly by four groups. Gilbody et al [5] have performed numerous experiments and obtained total cross section results over a wide range of energies for proton beams incident on various gases. This group has measured cross sections both for ionization and excitation of gases due to proton bombardment. Van Zyl et al [6] have investigated the interaction of neutral Hydrogen with Nitrogen and Oxygen molecules but their reported results have been restricted to very low beam energies for application to auroral phenomena. Toburen et al [7] have investigated proton-atom collisions over a wide proton beam energy range and reported differential cross section results for molecular Hydrogen and Nitrogen. Rudd et al [8] have also performed a number of proton-atom experiments. In addition they have reported cross section results differential in energy and angle for the electrons emitted by stripping or ionization of neutral Hydrogen in Hydrogen-Helium collisions at intermediate energies. These differential cross section results clearly indicate the presence of two distinct groups of electrons. One group appears with very low velocities and is presumably the result of ionization of the stationary Helium target. The other group of electrons has a clearly defined velocity distribution centered around the equivalent atomic Hydrogen beam velocity and is presumed to arise from the stripping of the neutral Hydrogen atoms in the beam.

Unfortunately no detailed differential cross section results are available for neutral atomic Hydrogen-Nitrogen or Hydrogen-Oxygen collisions in the 1 MeV or greater energy range. Also, while the investigations of Rudd et al [8] have yielded useful information about the electron products very little is known experimentally about the resulting ion distributions.

3. CHARGED PARTICLE DRIFT

The charged particles produced from the neutral hydrogen beam stripping and atmospheric ionization processes will have different behaviors. Most of the ions and electrons produced by ionization of the neutral atmospheric atoms can be assumed to gain little kinetic energy and thus will essentially remain stationary and contribute to the ambient plasma background. Since the combined electron-ion effective cross section for stripping of the neutral beam is practically equivalent to that of the neutral atom [4] their effect on beam propagation is negligible. The fast protons and electrons which arise from the stripping of the neutral hydrogen beam by the atmospheric constituents cannot be dismissed in a similiar manner. Obviously this stripping reduces the density of the neutral beam. Also, numerous recent experiments [9] have indicated that a sufficient density of neutralized ions will establish a polarization electric field and propagate transversely to a magnetic field with a transverse velocity almost equal to the initial velocity of the neutralized ions (protons).

Charged particle motion across magnetic field lines was first proposed by George Schmidt [10]. His theory has since been refined by a number of authors [11] and confirmed by various experiments [9]. Peter and Rostoker [11] have established a criterion for the initiation of charged particle drift accross magnetic field lines. The condition is that the initial neutralized ion beam energy should exceed the energy density necessary to establish the driving electric field. In other words the static dielectric constant must be greater than the neutralized plasma mass ratio. For a hydrogen (proton) beam we have

$$\varepsilon = 1 + \omega_{pi}{}^2/\Omega_i{}^2 \gg (\frac{M}{m})^{1/2} = 43 \tag{3.1}$$

where $\omega_{pi}{}^2 = \frac{4\pi e^2 n}{M}$ is the ion plasma frequency

and $\Omega_i^2 = \frac{e^2 B^2}{M^2 c^2}$ is the ion gyrofrequency

They quote experimental evidence to demonstrate that the polarization drift will occur for the static dielectric constant $\varepsilon > 200$. This condition is satisfied for ion (proton) densities $n_i > 10^4$ part/cm^3.

The theory of Peter and Rostoker [11] is applicable for large gyroradius neutralized ion beams injected from a field free region to a region of high magnetic field. Large gyroradius beam implies that the ion (proton) gyroradius is much larger than the neutralized ion beam radius. It does not appear that a large magnetic field is a necessary component of the theory. A more serious defect of the theory is the tacit assumption of the formation of the polarization charge layers which initiate the plasma drift. Experimental evidence has conclusively demonstrated that these charge layers are formed when a neutralized beam is injected into a vacuum. However, the situation is different in the upper atmosphere (a) because of the presence of the ambient plasma background, and (b) because of the large ion gyroradius-beam radius ratio prevailing in the geomagnetic field. It is conceivable that the ambient plasma may act as a short to prevent the formation of a virtual anode and thus the polarization electric field. The theory of Peter and Rostoker [11] should be carefully examined to investigate this possible effect.

4. THE EFFECT OF BEAM INDUCED STRIPPING

From the experimental cross section results [8] we know that the velocity of the electrons produced by the atmospheric stripping of the neutral beam suffer little degradation of their equivalent initial atom velocity. We assume that this is also true for the protons produced by the same stripping reactions. Once a critical ion (proton) density is reached the stripped ions and electrons will propagate across the magnetic field lines with the neutral beam at some small relative velocity difference. These ions and electrons will then enhance the stripping of the neutral beam and therefore diminish its effective propagation distance. The importance of this effect can be quantified by adopting a simple model.

In order to investigate the relative importance of the ionization of beam particles due to collisions with atmospheric constituents versus self ionization of the neutral beam we have made a number of simplifying assumptions. First we ignore beam dispersion and scattering processes which lower the beam density by broadening the beam. Second we ignore atmospheric density variation with height (this would be strictly applicable to horizontal beam propagation). Neither of these assumptions are critical and can be accounted for in this model fairly easily but both would increase the complexity of the numerical calculations. We also have made no attempt to provide a detailed mechanism which allows the stripped ions and electrons to propagate with the neutral beam. Clearly for the case of neutral beam propagation parallel to the magnetic field this is not a problem. The previous section has reviewed relevant references and experiments which provide a mechanism for neutralized ion drift transverse to a magnetic field but no detailed theoretical or experimental treatments exist for ion propagation at an arbitrary angle to the magnetic field. Our simple model assumes that this will occur and introduces a geometric factor, γ, as an adjustable parameter. This parameter, γ, can be thought of as the ratio of electrons (ions) travelling within the beam to the total number of electrons (ions) produced by the stripping process and is allowed to vary between 0 (no electrons (ions) travelling with the beam) and 1 (all electrons (ions) produced by the stripping process confined within and travelling with the neutral beam).

Under these assumptions the change in beam density with distance of propagation is given by

$$\frac{db}{dx} = -\sigma[\alpha a + \alpha_+ a_+ + \alpha_- a_- + \gamma_+ \beta_+ b_+ + \gamma_- \beta_- b_-]b \tag{4.1}$$

where x is the propagation distance

σ is the stripping cross section

$a_\pm$ are atmospheric neutral, ion and electron densities

$\alpha_\pm$ are cross section corrections to account for species variations

$b_\pm$ are beam neutral, ion and electron densities

$\beta_\pm$ are cross section corrections to account for species variations

$\gamma_\pm$ are geometric factor corrections

It is obvious that the rate of production of beam ions and electrons are equal and equal to the rate of loss of beam neutrals. Thus

$$\frac{\partial b_+}{\partial x} = \frac{\partial b_-}{\partial x} = \frac{-\partial b}{\partial x} \tag{4.2}$$

We can assume that the beam ions and electrons are confined within the beam and allow the geometric factors ($\gamma_\pm$) to account for the density variation. Then (4.2) becomes

$$\frac{db_+}{dx} = \frac{db_-}{dx} = \frac{-db}{dx} \tag{4.3}$$

which can be integrated immediately to yield

$$b_+ = b_- = N-b \tag{4.4}$$

where N is the initial density of the beam.

Clearly (4.4) is not true, for two reasons. First, when the relative velocity difference between the ions and the beam is not ignored then $b_{\pm}$ are not equal but probably less than N-b. However, this is the limiting (worst) case and the discrepancy can be accounted for by the geometric factors, $\gamma_{\pm}$. Second, if the velocity difference between the neutral and ion beams is not ignored, then $b_{\pm}$ are not limited to N-b and could in fact exceed this value at some distance. In this model there is no difference between distance and time. These two variables are equivalent and simply related by the beam velocity. The removal of this equivalence can be accomplished by replacing equation (4.3) above by a true divergence equation which is not symmetric in distance and time. Such a refinement is presently being investigated and some of the aspects are discussed below.

Using (4.4) in (4.1) yields

$$\frac{db}{dx} = -\sigma[\alpha a + \alpha_{+}a_{+} + \alpha_{-}a_{-} + (\gamma_{+}\beta_{+} + \gamma_{-}\beta_{-})(N-b)]b \tag{4.5}$$

which can be written as

$$\frac{db}{dx} = -(A+BN)\ b + Bb^{2} \tag{4.6}$$

where

$$A = \sigma[\alpha a + \alpha_{+}a_{+} + \alpha_{-}a_{-}]$$

$$B = \sigma[\gamma_{+}\beta_{+} + \gamma_{-}\beta_{-}]$$

Note that A>0 and B>0 by definition. Rearranging (4.6) leads to

$$\frac{db}{b[-Bb + (A+BN)]} = -dx \tag{4.7}$$

where the expression in the brackets [ ] is always positive since N≥b and A,B>0. Equation (4.7) can be integrated immediately with the result

$$\frac{1}{A+BN}\ \ln\left[\frac{b}{A+B(N-b)}\right] = -x+C \tag{4.8}$$

or

$$\frac{b}{A+B(N-b)} = \exp\left[-(A+BN)(x+C)\right] \tag{4.9}$$

With the initial condition that at x=o, b=N we can eliminate C from (4.9). Simplifying yields

$$\frac{b}{A+B(N-b)} = \frac{N}{A} \exp\left[-(A+BN)x\right] \tag{4.10}$$

This equation (4.10) specifies the beam density as a function of propagation distance and known or assumed constants. In the limit of no beam-beam interaction $B \to 0$ and (4.10) reduces to

$$b = N \exp(-Ax) \tag{4.11}$$

which is the correct behavior.

From (4.10) it is easy to see that there is no combination of constants which leads to zero beam density for any finite propagation distance. It is also apparent that the neutral beam density decreases more rapidly when beam effects are included. A comparison of equations (4.10) and (4.11) leads to the conclusion that beam self ionization effects become important when $BN>A$. If we ignore minor variations in the cross sections and geometric factors this implies that beam effects will be important when the density of the beam is equal to or greater than the atmospheric density.

This can be illustrated by substituting the appropriate data into equation (4.10). At 200 km altitude the neutral atmospheric density $a \sim 10^{10}$ part/cm^3 [4] while the maximum ambient plasma densities are $a_{\pm} \sim 10^6$ part/cm^3. Since the ambient plasma densities are at least four orders of magnitude lower than the neutral density they can be safely ignored. At a beam energy of 1 MeV there is very little variation in the cross sections for the various processes. Thus we can take $\sigma = 2 \times 10^{-16}$ cm^2/part [3] and set all the cross section corrections equal to 1.

We have chosen to let the beam density be variable and given by

$N = .446 \times 10^7$ part/cm^3 (times beam current in mA).

These approximations have been made only to simplify the calculations and are by no means an integral part of the derivation. It would be a simple matter to use more precise numbers but equation (4.10) is relatively insensitive to small changes in these constants and more precise numbers would not significantly alter the results.

The solution of equation (4.10) can be obtained for any desired beam density, distance and altitude. We have chosen to present the solution in the form of Figures 1, 2, and 3. These figures are illustrative of the strengths of the various processes and are useful for discerning trends. However, in light of the various approximations inserted for the numerical constants, one should understand the limitations of the numerical results. In other words, these figures accurately portray the shapes and relationships of the curves (and underlying processes) but do not yield accurate numerical results. Figure 1 shows the distance from launch of the neutral beam where a given beam density ratio of .1 (survival probability) would be obtained as a function of the geometric factor γ for various values of the beam current (in mA). There is no beam induced stripping when $\gamma=0$. The absence of beam induced stripping would be indicated by a horizontal line. As is clear from the Figure for neutral beam currents of 10 mA or less beam induced stripping effects are negligible at 200 km altitude. A neutral beam current of 10^3mA yields a beam density which is of the same order as the neutral atmospheric density at 200 km altitude. It is obvious from the Figure that beam induced stripping is important in that case. Figures 2 and 3 are the same as Figure 1 except for different beam density ratios or survival probabilities.

It should be emphasized that all the Figures are for a fixed altitude. What is important to note is that beam induced stripping becomes important when the neutral beam density is of the same order as the atmospheric density. In other words for fixed altitude beam induced stripping increases as you increase the neutral beam density. Also, for a fixed beam density, beam induced stripping becomes the dominant process as you increase the launch altitude.

Finally, we wish to sketch how a more accurate description of the electron production, with relative electron motion can be formulated.

The electrons emerge with somewhat less energy from the stripping process than what they had as constituents of the neutral beam in the beam frame. This leads to an average backward relative velocity, say $\underline{w}$. If the electron source function at point $\underline{x}'$ measured from the front edge of the beam and at time $\underline{t}'$ is $S(x',t')$, the electron density at $\underline{x}$ and $\underline{t}$ is is given by

$$b_-(x,t) = \int_{t-x/w}^{t} S(x'=x-w[t-t'], t')\, dt' \qquad (4.12)$$

The lower limit t_m of the integration is fixed by the condition that the most distant point from which the electrons can propagate is the beam front,

$$x' = 0, \text{ i.e. } x-w\,[t-t'_m] = 0 \qquad (4.13)$$

On the other hand, obviously

$$S(x,t) = -\frac{\partial b}{\partial t}(x,t) \qquad (4.14)$$

An equation for the time evolution of $b(x,t)$, analogous to (4.1), can now be written down (ion effects neglected here)

$$\frac{\partial b}{\partial t} = -\sigma(w)\, w[\alpha a + \alpha_+ a_+ + \alpha_- a_- \quad + \gamma_- \beta_- b_-]\, b \qquad (4.15)$$

Combined with (4.12) and (4.14) and yields

$$\frac{\partial b}{\partial t}(x,t) = -[A(w) - B(w) \int_{t-x/w}^{t} \frac{\partial b}{\partial t}(x-w[t-t'],t')\, dt'] \quad b(x,t) \qquad (4.16)$$

with

$$A = \sigma(w)w \lfloor \alpha a + \alpha_+ a_+ + \alpha_- a_- \rfloor$$

$$B = \sigma(w)w \; \gamma_- \beta_- \tag{4.17}$$

(4.16) is a complicated functional differential equation whose solution is under investigation.

5. GEOMETRIC FACTOR CALCULATION

One can note from the results of the previous section that a $1mA/cm^2$ beam propagating horizontally at 200km altitude suffers negligible beam induced stripping compared to the stripping caused by the atmosphere. It is clear that beam induced stripping becomes a more important energy loss mechanism for higher beam densities. It is also apparent that beam induced stripping will become the dominant energy loss mechanism at higher launch altitudes since the neutral atmospheric density falls off rapidly with altitude. Thus we have attempted to gain a better understanding of the geometric factor for the case of beam propagation parallel to the magnetic field by adopting a simple model in which the ions stripped from the beam continue with the neutral beam and the stripped electrons form a neutralizing cloud around the beam.

In cylindrical coordinates the equation of motion for an electron is

$$\ddot{r} = \frac{e}{m} E + \frac{eB}{m} r\dot{\phi} + r\dot{\phi}^2$$

$$\dot{\phi} = \frac{-eB}{2m} + \frac{C}{mr^2} \tag{5.1}$$

where E is the self induced electric field, B is the magnetic field (assumed constant), r and ϕ are polar coordinates, z is the direction of the beam and C is a constant of motion. Energy conservation yields the first integral and after simplification (5.1) can be written as

$$\dot{r}^2 = \frac{2}{m}\,(U-eV-\omega_H C)-\omega_H r^2 - \frac{C^2}{m^2 r^2} \tag{5.2}$$

where U is the total energy, U and C are constants, V is the scalar potential and $\omega_H = \frac{eB}{2m}$.

From the diffusion equation

$$\vec{\nabla}.j = 0 \tag{5.3}$$

and assuming isotropy in ϕ and z, we get

$$\frac{1}{r}\frac{\partial}{\partial r}(\rho \dot{r} r) = 0 \tag{5.4}$$

or

$$\rho \dot{r} r = \text{constant} = Y \tag{5.5}$$

Thus the electron density ρ is given by

$$\rho = \frac{Y}{r\dot{r}} \tag{5.6}$$

From Poisson's equation

$$\nabla^2 V = -4\pi\rho \tag{5.7}$$

We can write

$$\frac{\partial V}{\partial r} = \frac{-4\pi Y}{r} \int \frac{dr}{\dot{r}} \tag{5.8}$$

Therefore, substituting $\dot{r}$ from (5.2),

$$\frac{\partial V}{\partial r} = \frac{-4\pi Y}{r} \int \frac{dr}{\frac{2}{m}\left[(U-eV-\omega_H C)-\omega_H^2 r^2 - \frac{C^2}{m^2 r^2}\right]^{1/2}} \tag{5.9}$$

which is an equation for the scalar potential solely in terms of r (the radial distance from the center of the beam) and constants. Unfortunately this equation has no analytic solution and ultimately, it must be solved numerically. However, an insight may be obtained by using an iterative technique. We first assume there is negligible external potential V(r). We then can calculate the first-order generated potential and deviation of the orbits.

Using this approximation, eq. (5.9) becomes

$$\frac{\partial V}{\partial r} = -\frac{4\pi Y}{r}\int\frac{dr}{\left[\frac{2}{m}(U-\omega_H C)-\omega_H^2 r^2-\frac{C^2}{m^2 r^2}\right]^{1/2}} \tag{5.10}$$

which can be integrated to

$$\frac{\partial V}{\partial r} = -\frac{4\pi Y}{\omega_H r}\sin^{-1}\left[\frac{-m\omega_H^2 r+U-\omega_H C}{\left[U(U-2\omega_H C)\right]^{1/2}}\right] - E_1 \tag{5.11}$$

where E_1 is an integration constant. The boundary conditions here are set at the turning points of field-free particle trajectories:

$$r_1^2 = \frac{\left[U-\omega_H C-\sqrt{U(U-2\omega_H C)}\right]^{1/2}}{m\omega_H^2} \tag{5.12a}$$

$$r_2^2 = \frac{\left[U-\omega_H C+\sqrt{U(U-2\omega_H C)}\right]^{1/2}}{m\omega_H^2} \tag{5.12b}$$

Equation (5.11) gives the electric field due to the electrons only. We expect this to vanish at the lower limit r_1. This boundary condition yields

$$\frac{\partial V}{\partial r} = -\frac{4\pi Y}{\omega_H r}\sin^{-1}\left[\frac{-m\omega_H^2 r + U-\omega_H C}{\left[U(U-2\omega_H C)\right]^{1/2}}\right] + \frac{2\pi^2 Y}{\omega_H r_1} \tag{5.13}$$

The constant Y may be evaluated from consideration of the total electric field, due to the electrons and ions. The field due to the ions may be written as

$$E_{ions} = \begin{cases} 2\pi r\rho_i & \text{inside the beam } (r<r_o) \\ \dfrac{2\pi r_o^2\rho}{r} & \text{outside the beam } (r>r_o) \end{cases} \tag{5.14}$$

where we assume a uniform ion charge density ρi inside the beam which has radius r_o.

The total electric field is just the sum of (5.13) and (5.14). Using the boundary condition that the total electric field is zero outside the charge region ($r > r_2$), we get

$$Y = \frac{\omega_H r_o^2 \rho_i}{\pi(1 + r_2/r_1)} \tag{5.15}$$

We can now write the expression for the total electric field:

$$E_{total} = \frac{4r_o^2\rho}{r}\left\{\frac{1}{1 + r_2/r_1}\sin^{-1}\left[\frac{m\omega_H^2}{[U(U-2\omega_H C)]^{1/2}}(r_2^2-r^2) + 1\right] + \frac{\pi}{2}\right\} - \frac{2\pi r_o^2\rho_i}{r_1 + r_2} \tag{5.16}$$

Unfortunately, (5.16) cannot be analytically evaluated to give the potential $V(r)$. Thus, we approximate the potential which generates (5.16) by a parabolic form

$$V_e(r) = ar^2 + br + c \quad \text{for} \quad r>r_o \tag{5.16a}$$

$$V_i(r) = -\alpha r^2 + \beta \qquad \text{for } r<r_o \tag{5.16b}$$

with boundary conditions:

$$V_i(r_o) = V_e(r_o) \tag{5.17}$$

$$V_i'(r_o) = V_e'(r_o)$$

$$V_e(r_2) = 0$$

$$V_e'(r_2) = 0$$

$$\nabla^2 V_i(r) = -4\pi\rho_i \qquad r<r_o$$

These boundary conditions allow determination of the 5 coefficients in equations (5.16). The result is

$$\begin{aligned} V(r) &= \frac{\alpha r_o}{r_2-r_o}(r-r_2^2) & r>r_o \\ &= -\alpha(r^2-r_o r_2) & r<r_o \end{aligned} \tag{5.18}$$

where

$$\alpha = \pi\rho_i$$

We now use this potential to solve for the new turning points of the motion. This yields an estimate for the geometric factor γ

$$\gamma \sim \frac{r_o^2}{(r_2-r_1)^2}$$

It is illuminating to write the equations for r_1 and r_2 in terms of characteristic length parameters,

$$R_E^2 = \frac{K}{e\alpha}$$

$$R_L^2 = \frac{K}{m\omega_H{}^2}$$

$$R_C^2 = \frac{C^2}{mK} \qquad (5.19)$$

where K = electron kinetic energy at the point of scattering (r_o) and the total energy U is given by $U = K + \alpha r(r_o-r_2)$. In terms of these parameters and equation (5.18) for the potential, the equations for the turning points r_2 and r, are:

$$1 - \frac{R_C}{R_L} + \frac{r_o(r_o-r_2)}{R_E{}^2} - \frac{r_2^2}{2R_L{}^2} - \frac{R_C^2}{2r_2^2} = 0 \qquad (5.20a)$$

$$\frac{1}{R_L^2}(r_2^2-r_1^2) + R_C^2\left(\frac{1}{r_2^2} - \frac{1}{r_1^2}\right) + \frac{2}{R_E^2}(r_1^2-r_o r) = 0 \qquad (5.20b)$$

These equations have been solved numerically, using a perturbation technique with initial values from the field-free turning points. While the perturbed value of r_2 can vary strongly at low energies, r_1 is not very sensitive to these parameters.

6. SUMMARY

Present research efforts can be divided into four main areas: 1) Investigation of "worst case" theory of beam induced stripping to obtain results as a function of altitude and beam energy. 2) Refinement of "worst case" theory of beam induced stripping effects by obtaining a numerical solution of the equations which break the distance-time symmetry of the present theory and explicity account for the velocity variation between the beam ions and the neutral beam. 3) Calculation of the geometric factor by solving the equations for the electron density self consistently. 4) Investigation of the polarization drift theory to account for the presence of the ambient plasma background in the atmosphere and for the possibility of the buildup of sufficient neutralized ion density to initiate the polarization drift.

7. CONCLUSIONS

We have demonstrated through a simple model that there is no catastrophic self-induced quenching of the neutral beam. It is likely that this feature will remain true even when the model is modified to include time dependent effects.

We have shown that for a $1mA/cm^2$ beam current and 200 km atmospheric altitude beam induced stripping is an insignificant energy loss mechanism for the neutral beam compared to the stripping induced by the atmospheric constituents.

On the other hand, we have also demonstrated that beam induced stripping is significant when the density of the neutral beam and the atmosphere at the launch altitude are comparable. This would be the case for higher beam densities (currents) at a given altitude or for a given density beam at higher altitudes. It is also clear for high launch altitudes that beam induced stripping would be the dominant energy loss mechanism for the neutral beam since the neutral atmospheric density decreases rapidly with increasing altitude. In absolute terms, at high beam current densities ($\sim 1A/cm^2$) the beam induced stripping might set severe limitations on the useful propagation range of the beam.

8. APPENDIX

This appendix disucsses the application of the theory described in this Report to the proposed BERT II experiment. It is clear from the results obtained in this study that the stripping (and thus the energy loss) of a $1 mA/cm^2$ neutral beam due to beam induced effects is negligible compared to the stripping due to the atmosphere at a launch altitude of 200 km and thus will not be an important process in the proposed BERT II experiment.

The stripping of the neutral hydrogen beam by the atmospheric constituents and by the stripped beam ions and electrons both cause particle energy loss and a density depletion of the neutral beam. However, the polarization drift may cause the stripped ions and electrons from both processes to propagate with the beam. Thus the stripping process may not diminish the total energy deposited on the target as much as a measurement of the neutral beam would indicate. It would be very useful in the BERT II experiment to be able to distinguish between neutrals and ions striking the target and to measure their energy and velocity distributions. It would also be important to measure the surface potential of the target since a high charge buildup would alter the ion trajectories.

As the particle accelerator being developed for the proposed BERT II experiment is not 100% efficient (with a relative particle yield of 60% neutral H, 20% H+, 20% H- and 100% e-) the theory described in this Report should be investigated to account for the effect of the ions released from the accelerator. One should also carefully examine the effect of the increase in neutral atmospheric density around the accelerator caused by rocket outgassing.

Since the polarization drift effect serves to enhance the total energy delivered to the target it is important that it be thoroughly investigated.

REFERENCES

1. Alfven, H., Rev. Mod. Phys. 32, 4 (1960) 710.

2. Halverson, W. and S. Bunker, private communication.

3. Tawara, H. and A. Russek, Rev. Mod. Phys. 45, 2, (1973) 178.

4. Gillespie, G.H., Phys. Rev. A 18, 5 (1978) 1967; A 22, 2 (1980) 454; A 22, 6 (1980) 2430; "Review of Neutral Beam Atmospheric Interaction Physics", Talk presented at BERT II Payload Definition Worshop AFGL August 6-10, 1984.

5. Gilbody, H.B. and M.B. Shah, Physica Scripta 24 (1981) 712; Shah, M.B. and H.B. Gilbody, J. Phys. B 14 (1981) 2361; Williams, I.D., J. Geddes and H.B. Gilbody, J. Phys. B 17 (1984) 1547.

6. Neumann, H., T.Q. Le and B. Van Zyl, Phys. Rev. A 15, 5 (1977) 1887; Van Zyl, B., H. Neumann, T.Q. Le, and R.A. Amme, Phys. Rev. A 18, 2 (1978) 506; Van Zyl, B., "Charge-State-Equilibrated H^+/H Flux Fractions for Analysis of the Hydrogen Aurora" Geophysical Institute of U. of Alaska, November, 1978.

7. Toburen, L.H., Phys. Rev. A 3, 1 (1971) 216; Boubren, L.H. and W.E. Wilson, Phys. Rev. A 5, 1 (1972) 247; Wilson, W.E. and L.H. Toburen, Phys. Rev. A 7, 5 (1973) 1535; Manson, S.T., L.H. Toburen, D.H. Madison and N. Stolterfoht, Phys. Rev. A 12, 1 (1975) 60.

8. Crooks, J.B. and M.E. Rudd, Phys. Rev. A 3, 5 (1971) 1628; Rudd, M.E. and B.H. Madison, Phys. Rev. A 14, 1 (1976) 128; DuBois, R.D. and M.E. Rudd, Phys. Rev. A 17, 3 (1978) 843; Rudd, M.E., J.S. Risley, J. Fryar and R.G. Rolfes, Phys. Rev. A 21, 2 (1980) 506; Rudd, M.E., R.D. DuBois, L.H. Toburen, C.A. Ratcliffe and T.V. Goffe, Phys. Rev. A 28, 6 (1983) 3244; DuBois, R.D., L.H. Toburen and M.E. Rudd, Phys. Rev. A 29, 1 (1984) 70; see also Rodbrom and F.D. Anderson, J. Phys. B 12, 17 (1979) 2883.

9. Marhovic, P.D. and F.R. Scott, Phys. Fluids 14 8 (1971) 1742; Kamada R.C. Onada et al, J. Phys. Soc. Japan Letters 46 6 (1979) 1963; Robertson, S., H. Ishizuka, W. Peter and N. Rostoker, Phys. Rev. Lett 47, 7 (1981) 508; Wessel F. and S. Robertson, Phys. Fluids 24, 4 (1981) 739.

10. Schmidt, G., Phys. Fluids 3, 6 (1960) 961.

11. Lindberg, L., Astrophys. and Space Science 55 (1978) 203; Peter, W., A. Ron and N. Rostoker, Phys. Fluids 22 (8) (1979) 1471; Peter W. and N. Rostoker, Phys. Fluids 25, 4 (1982) 730.

FIGURE CAPTIONS

FIGURE 1. Plot of the distance from neutral beam launch (in km at which a given beam density ratio b/N = .1 (survival probability) would be observed as a function of the geometric factor γ for various values of the beam current (in mA/cm^2).

FIGURE 2. Same as Figure 1 except for a beam density ratio b/N = .3.

Figure 3. Same as Figure 1 except for a beam density ratio b/N = .5.

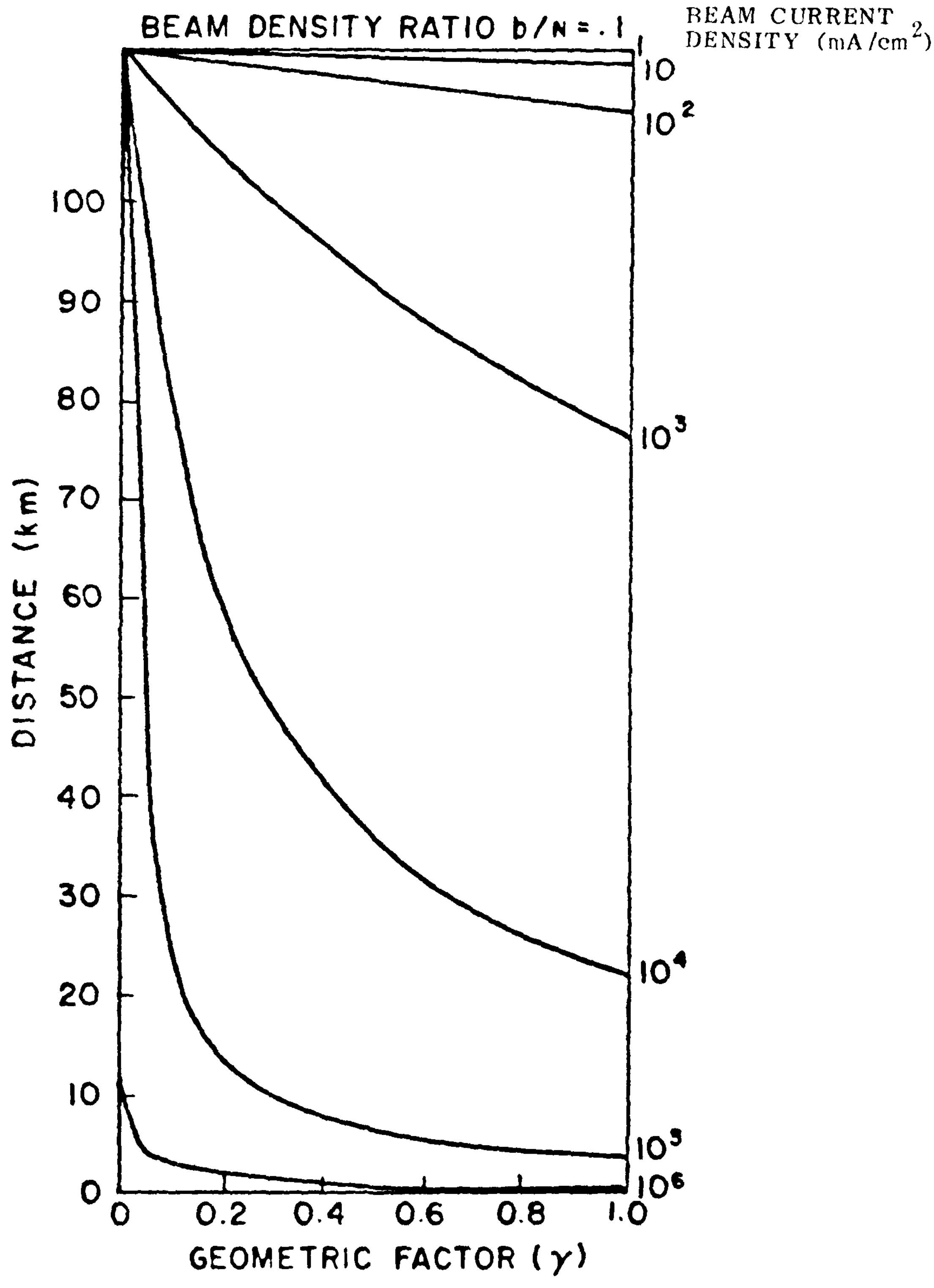

BEAM DENSITY RATIO b/n = .1
BEAM CURRENT DENSITY (mA/cm^2)
DISTANCE (km)
GEOMETRIC FACTOR (γ)
0
10
20
30
40
50
60
70
80
90
100
0.2
0.4
0.6
0.8
1.0
1
10
10^2
10^3
10^4
10^5
10^6

Figure 1.

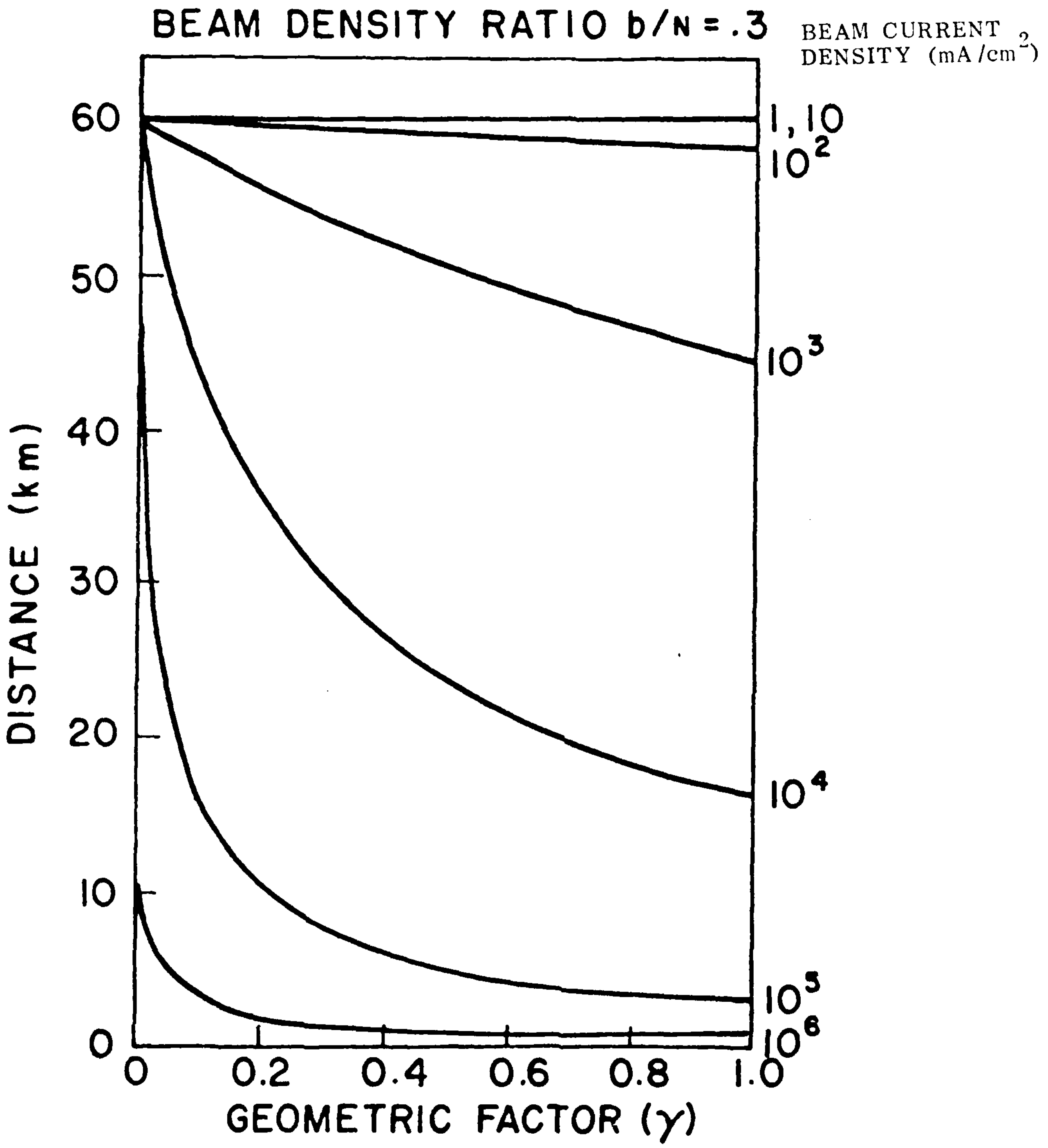
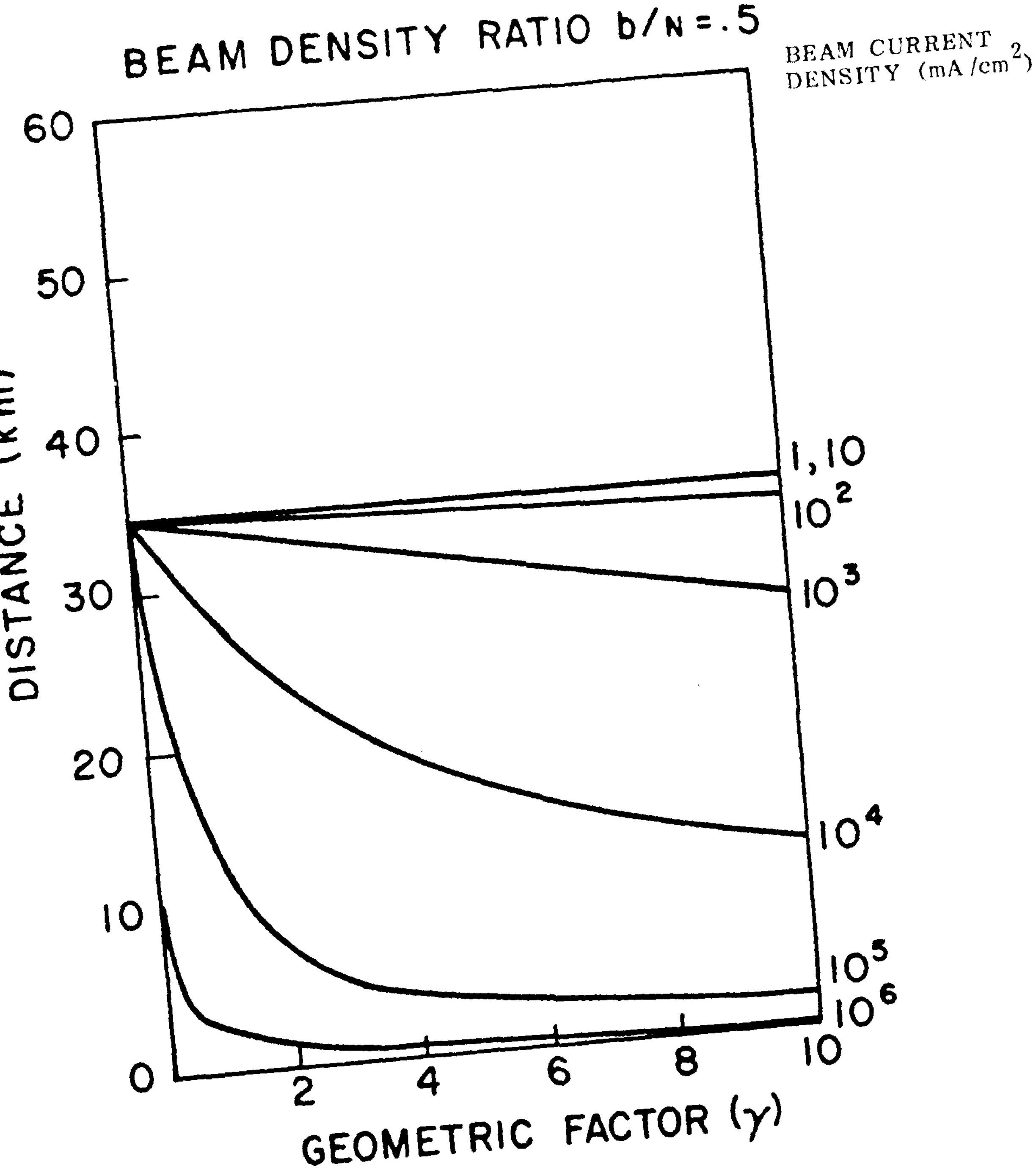

BEAM DENSITY RATIO b/N = .3
BEAM CURRENT DENSITY (mA/cm^2)
DISTANCE (km)
GEOMETRIC FACTOR (γ)
0
10
20
30
40
50
60
0
0.2
0.4
0.6
0.8
1.0
1, 10
10^2
10^3
10^4
10^5
10^6

Figure 2.



BEAM DENSITY RATIO b/N = .5
BEAM CURRENT DENSITY (mA/cm^2)
60
50
40
30
20
10
0
DISTANCE (km)
1, 10
10^2
10^3
10^4
10^5
10^6
2
4
6
8
10
GEOMETRIC FACTOR (γ)

Figure 3.

END

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