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IONIZATION OF A HIGH ENERGY NEUTRAL BEAM PROPAGATING IN THE IONOSPHERE

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Abstract

By using modeled stripping ionization cross sections and standard atmospheric density models, we calculate stripping ionization probability of high energy (MeV) neutral beams propagating in the earth's atmosphere. Numerical results as functions of altitude, beam angle and beam energy are presented. We also consider Alfvén's critical ionization velocity (CIV) process as an alternate ionization pathway. If CIV occurs as the neutral beam propagates through the geoplasma across the ambient magnetic field, it may be an important pathway to rapid ionization halting the beam. We conclude that the parametric conditions are unfavorable for CIV to occur.

I. Introduction

When a high energy (MeV) neutral beam propagates in the earth's ionosphere, the beam particles interact with the particles and fields in the ionosphere. If the beam becomes ionized as a result of the interaction, the beam may be halted since the product beam ions gyrate around the ambient magnetic field lines. The cross-sections of electron impact ionization and charge transfer are insignificant at Mev energies. We do not consider nuclear reactions because they do not occur at energies below 30 MeV. Scattering dispersion of the beam can degrade beam energy but is unrelated to ionization. The dominant ionization process for a MeV neutral beam propagating in the ionosphere is probably stripping:

$$N + A \rightarrow N^{+} + A + e^{-} \tag{1}$$

where N is a generic beam particle and M a generic atmospheric neutral particle or ion. Neutral particles are orders of magnitude more abundant than ions in the ionosphere.

II. Theoretical Model

Measurements of the cross sections σ of stripping of hydrogen H incident on various gases have been reported [1,2,3,4]. An empirical formula $\sigma(E)$ of H is given in Ref.[5]:

$$\sigma(E) = \sigma_o \frac{(Za)^{\Omega}(E-I)^{\nu}}{J^{\Omega+\nu} + E^{\Omega+\nu}} \tag{2}$$

where $\sigma_0=10^{-16}$ cm^2, $\Omega=0.75$, E is the energy (in keV) of the beam, Z, ν, J, and a are parameters of the ambient species, and I the beam ionization energy (in keV).

The density $I(z)$ of a neutral beam of energy E propagating from altitude z_o to altitude z is modeled simply as

$$I(E,z) = I(E,z_o)\exp\{-\int_{z_o}^{z}\sum_i [n_i(z)\,\sigma_i(E)]\,dz/\cos\theta\} \tag{3}$$

where θ is the angle between the beam and the vertical line ($\theta=180^0$ when the beam propagates downwards). We take the summation, i=1 to 5, over the 5 most abundant atmospheric species O, O_2, N_2, He, and H. The survivial probability $P(E,z)$ of the beam undergoing stripping is given by

$$P(E,z) = 1 - \frac{I(E,z)}{I(E,z_o)} \tag{4}$$

For atmospheric densities $n_i(z)$, we use the Stein-Walker model [6] for simplicity.

III. Results

The survival probabilities of two downward propagating neutral H beams (2 and 250 MeV) are calculated (Fig.1). The higher energy beam can survive longer until it reaches about 110 km. where it is completely ionized. The survival probability of a 2 MeV beam propagating horizontally at various altitudes through various distances (1km to 1000 km) is also shown (Fig.2).

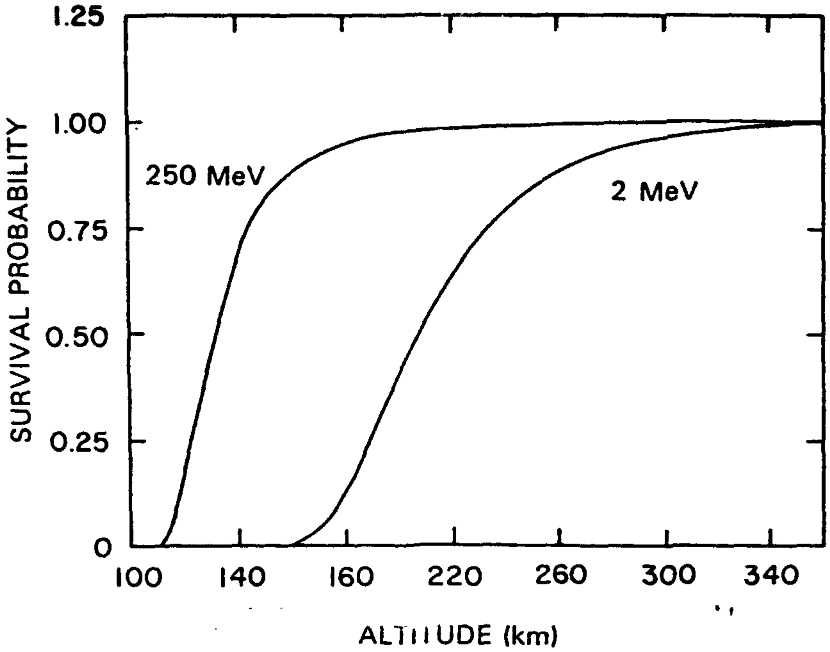

Figure 1. Survival probabilities of 2 MeV and 250 MeV neutral hydrogen beams propagating vertically downwards in the ionosphere.

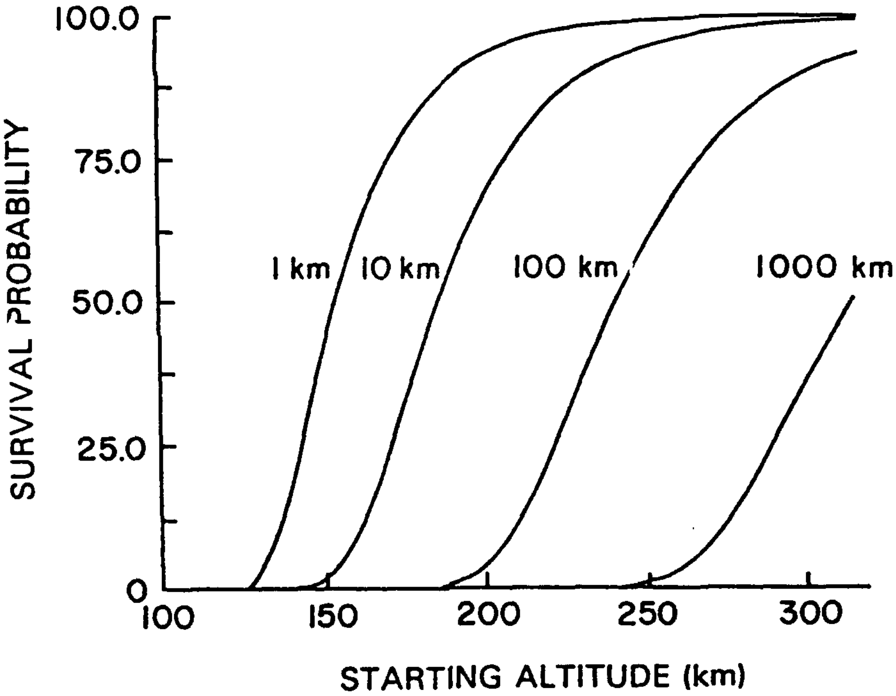

Figure 2. Survival probability of a 2 MeV neutral hydrogen beam propagating horizontally in the ionosphere.

IV. CIV Criteria

Alfvén's [7] critical ionization velocity (CIV) suggests that when a neutral gas and a magnetized plasma travel relative to each other with a velocity exceeding a critical velocity $V_c = \sqrt{(2e\phi/M)}$, rapid ionization occurs. M is the mass of a neutral particle and $e\phi$ the ionization energy. When an ion beam travels across the ambient magnetic field, beam-plasma interaction occurs. As a result, the electrons form a plateau tail distribution. Some electrons in the tail may be energetic enough to ionize. For a review of CIV, see, for example, Ref. [8].

Carini et al [9] questioned whether CIV can occur in MeV neutral beams. If CIV occurs, it could be a rapid path to ionization halting the neutral beam.

For CIV to occur, it is necessary [10] that an electron has to ionize at least once before it leaves the interaction region. This criterion requires $\tau\nu > 1$ where τ is the electron transit time and ν the ionization frequency. For a narrow low density beam, both τ and ν are small.

It is also necessary that the contact time τ_L of a neutral beam pulse with an ambient magnetic field line should be longer than the electron energization time τ_H [11].

$$\tau_L > \tau_H \tag{5}$$

For a MeV H beam pulse of length 1m, τ_L ~0.1μs. Taking $\tau_H \sim 30/\omega_{LH}$ [12] where ω_{LH} is the lower hybrid frequency, one finds that in the ionosphere τ_H ~10ms, which exceeds τ_L.

Electromagnetic modes may be excited when the beam velocity V exceeds V_s [13].

$$V_s - (1+\beta)^{1/2} V_A \tag{6}$$

where $\beta \sim nkT/B^2$ and V_A is the Alfvén velocity. These modes drain energy and may suppress CIV. Thus, for CIV to occur, the beam velocity criterion is

$$V_s > V > V_c \tag{7}$$

Since $\beta \sim 10^{-5}$ and $V_A(O) \sim 7 \times 10^2$ km/s in the ionosphere, it appears that CIV is unlikely because the beam velocity V ($\sim 10^4$ km/s) exceeds V_s ($\sim 7 \times 10^2$ km/s).

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