IONIZATION OF A LOW PRESSURE GAS BY A STREAM OF ELECTRONS

Dmitry M. Karfidov*, M. Virgínia Alves, Fábio do Prado, Mário Ueda and José L. Ferreira**
Laboratório Associado de Plasma - Instituto Nacional de Pesquisas Espaciais
12221-970 - São José dos Campos - SP - Brasil
*Permanent address: Institute of General Physics, 117942, Moscow, Russia
** Present address: Dept. de Física - Universidade de Brasília - Brasília - DF - Brasil

1 - INTRODUCTION

It is well known that when an electron beam moves through a neutral gas, it produces a plasma with a density comparable to its own density. As the beam interacts with this plasma, an instability sets in, and the electric fields of the waves excited in this instability heat the plasma electrons to energies comparable to the gas ionization energy, E_i. As a result, the collisions of plasma electrons with neutral gas atoms lead to the onset of an avalanche breakdown, and the neutral gas is ionized almost completely over a time comparable to the mean free time of plasma electrons between inelastic collisions.[1] This is the basic idea behind a beam plasma discharge.

In the absence of any collective effects, the beam will ionize the neutral gas and the steady state will be established by balancing of the rate of ionization with the rate of plasma loss, i.e.,[2]

$$\frac{dn}{dt} = n_b N \langle \sigma v_b \rangle - \frac{n}{\tau} \tag{1}$$

where n_b, n and N are the beam, plasma and neutral density, σ is the ionization cross section, and τ is the confinement time. The expected steady state density from Eq. 1 is then $n_0/n_b = N\langle\sigma v_b\rangle\tau$.

When we include the collective effects, Eq. 1 has to be modified to read

$$\frac{dn}{dt} = n_b N \langle \sigma v_b \rangle + n_e N \langle \sigma v_e \rangle - \frac{n}{\tau} \tag{2}$$

where n_e and v_e are the density and thermal speed of electrons with energy above E_i.

In this paper we investigate the case of a low current beam moving through a neutral gas. We measure the plasma density generated by the beam as a function of the beam energy at different gas neutral pressures and the electron beam distribution function in a fixed position in the chamber. The shape of the beam distribution function is determined by the balance between the beam instability and the modulational instability while the electric field generated by the beam instability is not high enough to accelerate the plasma electrons to energies of order of E_i and Eq. 1 can be used to describe our experimental conditions.

2 - EXPERIMENTAL PROCEDURE

Experiments were carried out in a double plasma device with multipole surface magnetic confinement. A discharge plasma is created by accelerating primary electrons produced by tungsten, oxyde coated, hot cathod filaments in argon or helium gases. The inner diameter (plasma diameter) of the device is 0.60 m and its total length is 1.20 m. The chamber is divided into a source chamber (l_s = 0.30 m) and a target chamber (l_t = 0.90 m) by a triple grid (source, control and target grids). The whole chamber is filled with gas and a discharge plasma is created in the source chamber region. The inner side of the metallic cylinder of the source chamber is connected to the source grid so that when the source grid is negatively biased with respect to the target chamber a dc electron beam is generated, which flows towards the target chamber. This electron beam propagates into the target chamber and ionizes the gas, thus creating a plasma in that chamber. Electron plasma density and temperature measurements were performed using cylindrical Langmuir probes, calibrated for the density measurements by detecting the cutt-off frequency of a low amplitude electromagnetic wave (EMW), launched into the plasma. Plasma electric field oscillation measurements were performed with movable cylindrical probes at the floating potential connected to a spectrum analyser or to an oscilloscope. The beam electron energy distribution functions was investigated with an electrostatic multigrid energy analyser using the method of retarding potential.

Experiments were carried out in argon or helium gases at filling pressure p between 5×10^{-5} and 5×10^{-4} mbar. The electron beam were characterized by energies $E_b \leq 250$ eV, electron beam diameter of 0.60 m and total current of order of 0.20 A.

3 - DISCUSSION OF EXPERIMENTAL RESULTS

Figures 1.(a) and 1.(b) show the plasma density generated by the beam against beam plasma energy for a beam current of 0.15 A and for different values of filling pressure. We can observe that, at low pressures, there is a minimum density for E_b = 150 eV, using argon. This minimum does not appear for helium and disappears for argon at high pressures.

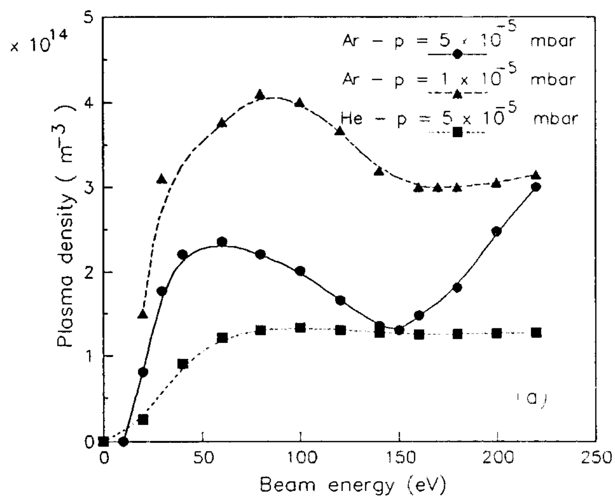

Fig.1 (a) Plasma density versus beam, energy for argon and helium at low pressures $1 \times 10^{-5} \leq p \leq 5 \times 10^{-5}$ mbar

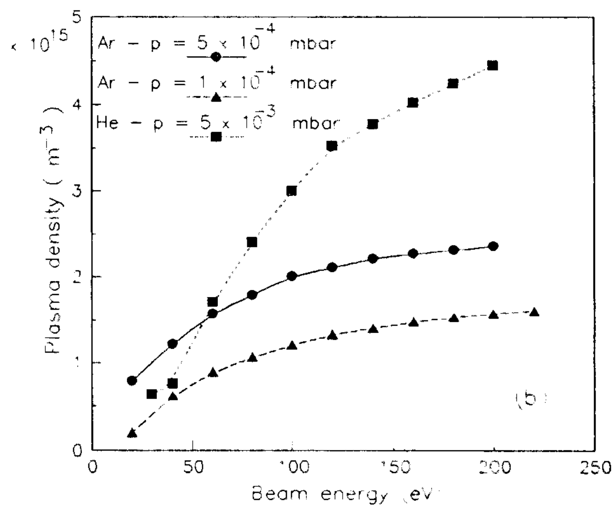

Fig.1 (b) Plasma density versus beam, energy for argon and helium at high pressures $1 \times 10^{-4} \leq p \leq 5 \times 10^{-4}$ mbar

Figure 2 shows the beam distribution function for argon at $p = 1 \times 10^{-4}$ mbar for $E_b = 75, 130$ and 200 eV, at position $x = 0.60$ m away from the injection point. We can observe that the beam distribution function is wider for $E_b = 130$ eV than for $E_b = 75$ or 200 eV. The result of that is a lower ionization frequency, ν_b, for $E_b = 130$ eV where ν_b is given by [3]

$$\nu_b = N \int_0^v \sigma(v) v_b f(v) dv \tag{3}$$

than for the other beam energies. This fact explain the minimal density observed at $E_b =$ 130 eV in Fig. 1(a).

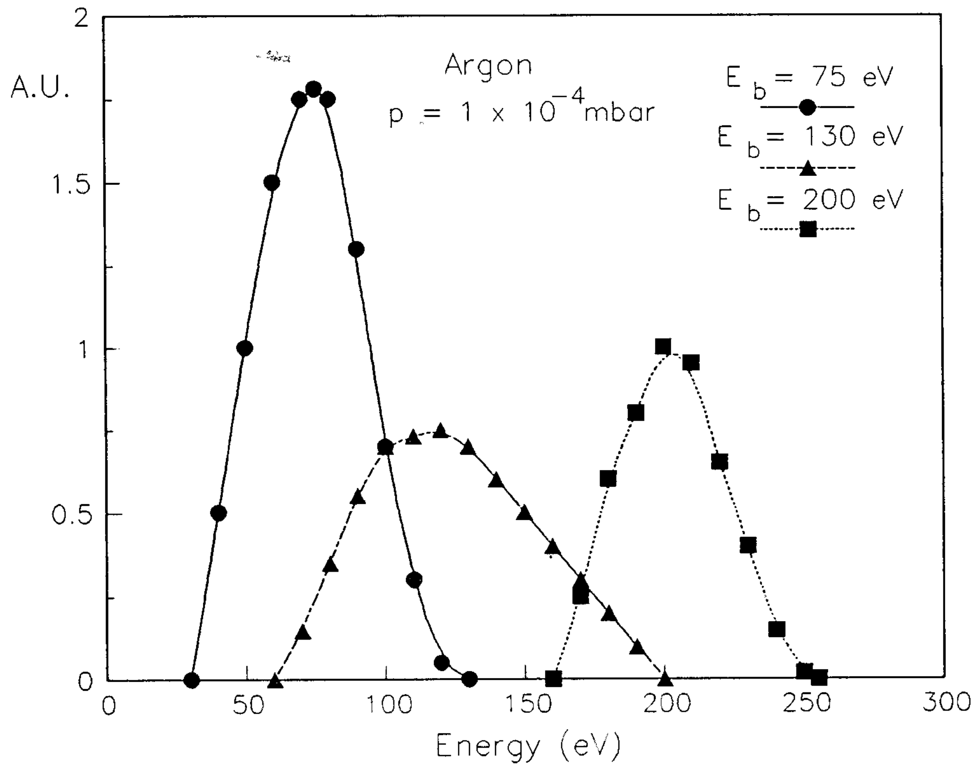

Fig.2 Electron beam distribution functions for argon at $p = 1 \times 10^{-4}$ mbar for $E_b = 75, 130$ and 200 eV, at position $x = 0.60$ m away from the grid.

The behavior of the beam distribution function can be explained by the following: in the beam quasi-linear relaxation the diffusion of the beam particles in the field oscillations excited by the beam leads to the establishment of a "plateau" on the velocity (or energy) distribution function at characteristic distances given by [4]

$$l_{QL} = \frac{v_b}{\omega_{pe}} \frac{n_0}{n_b} \frac{T_e}{E_b} \frac{\Delta E_b}{E_b} \Lambda \tag{4}$$

where Λ is the logarithm of the ratio of the final to the thermal noise which is of the order of magnitude of the Coulomb logarithm. The retardation of the beam electrons by the electrical field of the plasma waves causes the widening of the beam electron energy distribution function and a consequent reduction of the beam plasma instability growth rate. At the same position the beam with a higher energy will have a wider distribution, as we can see in Fig. 2. This type of quasilinear relaxation does not take place for $E_b = 200$ eV because at such energies modulational instablity (MI) of the waves excited by the beam occurs. MI causes a reduction of the plasma field and prevents the beam widening. The threshold condition for this instability is [4]

$$\frac{n_b}{n_0} = 10 \left(\frac{T_e}{mv_b^2}\right)^3 \tag{5}$$

This is also the explanation for the absence of a minimum density for helium, since the MI growth rate depends on the ion mass ratio. The minimum also disappears for higher pressures, since at such conditions Eq. 5 is not satisfied.

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