Influence of Ramsauer Effect on Bounded Plasmas in Magnetic Fields

N. Sternberg[1], C. Sataline[2], V. Godyak[3]

[1] *Clark University, Worcester, MA, USA*

[2] *Clark University, Worcester, MA, USA*

[3] *RF Plasma Consulting, Brookline,MA, USA*

Abstract

A study of the fluid model for cylindrical, weakly-ionized, quasi-neutral plasmas in an axial magnetic field is presented. The model takes into account ionization, ion and electron inertia, as well as frictional forces for ions and electrons. Two cases for the electron frictional forces are considered: with the Ramsauer effect and without the Ramsauer effect, while the ion frictional force is defined by the charge exchange process. For each case, the behavior of the plasma parameters for arbitrary magnitudes of the magnetic field, gas pressure and plasma size is presented, making the model applicable for a wide range of discharge conditions and gases. A magnetic field parameter is introduced, which specifies a parameter range for the magnetic field, gas pressure and plasma size where the Boltzmann equilibrium with the ambipolar field for the electron distribution is satisfied. A parametric relation for the magnetic field, gas pressure and plasma size is obtained, which separates the region of weak magnetic field effects from the region of strong magnetic field effects. In addition, analytical transformations between the corresponding parameters with and without the Ramsauer effect are obtained.

1. Introduction

Behavior of plasmas in a magnetic field has been a central problem in plasma fusion, and is of great importance for many plasma discharges used in processing semiconductor materials. Different approaches have been used to study these two very different types of plasmas. The Guided Center Approximation is often considered for fusion plasmas and assumes no collisions, no ionizations, and a strong magnetic field with a weak non-uniformity. The Diffusion Approximation is usually considered for high pressure gas discharge plasmas when the ion inertia and ionization in the plasma momentum transfer can be neglected. Those approximations, however, are not suitable for bounded gas discharge plasmas in a weak or moderate magnetic field with gas pressures ranging from low to intermediate. A study of a more general fluid model for an infinite cylindrical plasma immersed into an axial magnetic field was given in [1]. That model takes into account ionization, ion and electron inertia, ion and electron collisions with gas atoms; it does not assume the Boltzmann equilibrium for the electrons. However, the analysis and computations in [1] were performed for the benchmark argon gas that is characterized by a well pronounced Ramsauer effect. How the plasma parameters change without the Ramsauer effect present remained an open question, which we here attempt to answer.

2. Analysis and Results

Due to the reduction in electron temperature with gas pressure in Ramsauer gases, the electron mean free path λ_e is not inverse-proportional to the gas pressure p. As a result, λ_e is not proportional to the ion mean free path $\lambda_i \propto p^{-1}$. Based on experimental data from [2] in argon gas for a wide range of gas pressure, the following relationship for the ion-atom and electron-atom collision parameters were used in [1]: $\alpha_e = 50\alpha_i^{1/2}$ if $\alpha_i \neq 0$ and $\alpha_e = 30$ if $\alpha_i = 0$, where $\alpha_i = R/\lambda_i$ and $\alpha_e = (M/m)^{1/2}R/\lambda_e$, R is the radius of the plasma cylinder, M is the ion mass, m is the electron mass. In general, without the Ramsauer effect, both, λ_e and λ_i are inverse proportional to p. In particular, for argon, $\lambda_i = (300p)^{-1}$, $v_{Te} = 5.9 \cdot 10^7$, $\nu_e = v_{Te}/\lambda_e = 10^9 p$, and therefore, $\alpha_e = 15\alpha_i$ for $\alpha_i \neq 0$, while for $\alpha_i = 0$ one can set $\alpha_e = 10$. Note that for $\alpha_i \approx 11$, the Ramsauer effect has no influence on the plasma characteristics, since $50\alpha_i^{1/2} \approx 15\alpha_i$.

Following [1], we consider a cold, cylindrical, active, neutral, axially symmetric, weakly-ionized plasma under the action of the axial magnetic field $(0,0,B)$ with ionization frequency Z. Such plasma can be described in cylindrical coordinates as follows:

$$\frac{d}{dr}(rnv_r) = rZn \tag{1}$$

$$Mnv_r\frac{dv_r}{dr} - Mn\frac{v_{i\theta}^2}{r} + en\frac{d\varphi}{dr} + MZnv_r - env_{i\theta}B + \frac{\pi}{2\lambda_i}Mnv_r\sqrt{v_r^2 + v_{i\theta}^2} = 0 \tag{2}$$

$$Mnv_r\frac{dv_{i\theta}}{dr} + Mn\frac{v_{i\theta}v_r}{r} + MZnv_{i\theta} + env_rB + \frac{\pi}{2\lambda_i}Mnv_{i\theta}\sqrt{v_r^2 + v_{i\theta}^2} = 0 \tag{3}$$

$$kT_e\frac{dn}{dr} - en\frac{d\varphi}{dr} + env_{e\theta}B = 0 \tag{4}$$

$$mnv_r\frac{dv_{e\theta}}{dr} + mn\frac{v_{e\theta}v_r}{r} + mZnv_{e\theta} - env_rB + nm\nu_e v_{e\theta} = 0 \tag{5}$$

In the equations, k is the Boltzmann constant, φ is the potential, e is the elementary charge, n is the plasma density, v_r is the radial velocity, $v_{i\theta}$ and $v_{e\theta}$ are the azimuthal ion and electron velocities. Note that the electron inertia in the radial direction can be neglected. The symmetry of the problem with respect to the center $r = 0$ is reflected in the following boundary condition:

$$\varphi(0) = 0, \quad v_r(0) = v_{i\theta}(0) = v_{e\theta} = 0, \quad n(0) = n_0$$

It was found analytically in [1] that significant magnetic field effects occur in a Ramsauer gas if $\beta = R\lambda_e/(\rho_e\rho_i) >> 1$, where ρ_e and ρ_i are the electron and ion cyclotron radii, respectively. If $\beta >> 1$ the Boltzmann equilibrium relation for electrons is not applicable. For $\beta << 1$ the Boltzmann equilibrium holds. It was shown in [1] that for strong magnetic fields, the normalized ionization frequency is $S = ZR/v_s \approx 5.78/\beta$, where v_s is the ion sound speed, and the normalized plasma density at the boundary is $y_b = n(R)/n_0 \approx 1.25/\beta$. It was also found in [1] that the regions of weak and strong magnetic field effects are separated by a parameter value

$$G = 0.64(4+\alpha_i)^{-1/2}\beta = 1$$

In addition, according to [1], in the whole parameter range from weak to strong magnetic fields, the boundary plasma density and the ionization frequency can be represented as functions of the external discharge parameter G:

$$y_b = 0.8(4+\alpha_i)^{-1/2}(1+G+G^2)^{-1/2} \qquad S = 2.2(4+\alpha_i)^{-1/2}(1+0.59G+0.35G^2)^{-1/2}$$

Since the derivation of all those formulas did not depend on the type of gas, they hold for Ramsauer as well as for non-Ramsauer gases, and yield the corresponding relationships (index 0 refers to non-Ramsauer gases and index 1 to Ramsauer gases): $y_{b0} = y_{b1}\beta_1/\beta_0$ for strong magnetic fields and $G_0 = G_1\beta_0/\beta_1$. Furthermore,

$$y_{b0} = y_{b1}\left(\frac{1+G_1+G_1^2}{1+G_0+G_0^2}\right)^{1/2} \qquad S_0 = S_1\left(\frac{1+0.59G_1+0.35G_1^2}{1+0.59G_0+0.35G_0^2}\right)^{1/2}$$

Fig. 1 shows the normalized plasma density distribution $y = n/n_0$ obtained by solving (1–5) for both types of gases with $\alpha_i = 1$ and varying the magnetic parameter R/ρ_e. For $\beta << 1$, the magnetic field effects are negligible [1], and the plasma characteristics remain practically the same for a Ramsauer and non-Ramsauer gas. In a strongly magnetized plasma, the plasma density distribution approaches the Bessel function [1]. Fig. 1 shows that for a non-Ramsaeur gas, the plasma becomes strongly magnetized for much lower magnetic fields than for Ramsauer gases. Note that the difference in the plasma density distribution is more pronounced for intermediate magnetic fields. Collisions counteract the action of the magnetic field [1]. Thus, with increasing gas pressure, the region where the Ramsauer effect influences the plasma characteristics becomes smaller. Fig. 2 shows the plot of the normalized plasma density at the plasma boundary y_{b0} versus the parameter G_0 without the Ramsauer effect. Note that just as in the case of Ramsauer gases [1], one can set $G_0 = 1$ as the cut-off parameter between the weakly and strongly magnetized plasmas.

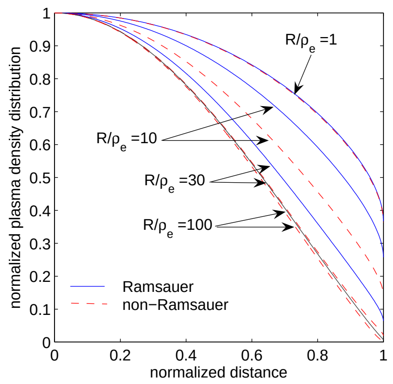

Figure 1: Normalized plasma density distribution with and without the Ramsauer effect for $\alpha_i = 1$ and varying magnetic field.

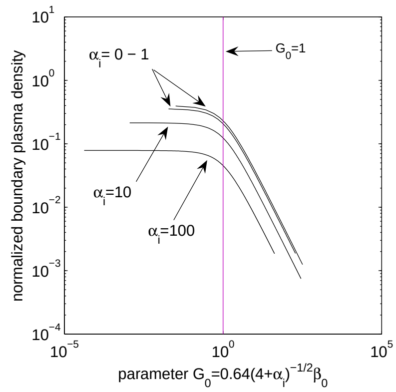

Figure 2: Dependence of the normalized boundary plasma density on the magnetic parameter without the Ramsauer effect.

3. Conclusion

In the present article, we have studied the influence of the Ramsauer effect on the plasma characteristics for a cylindrical plasma with an axial magnetic field. We have found that the theory developed in [1] for Ramsauer gases holds also for non-Ramsauer gases. We gave formulas which relate the plasma characteristics of Ramsauer and non-Ramsauer gases. We have found that the Ramsauer effect is relevant only for intermediate magnetic fields and that the theory of the cut-off by the external discharge parameter G between the regions of strong and weak magnetic fields is independent of the Ramsauer effect.

Acknowledgments

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References

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