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Neutral depletion in a collisionless plasma

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Abstract

The effect of neutral depletion on collisionless plasma is studied. It is shown that, as in the collisional case, the total number of neutrals determines the electron temperature. When neutral depletion is large the plasma density profile is flat far from the walls while the neutrals are located at a narrow layer near the wall.

The model

In weakly-ionized plasma, the neutral density that determines the rate of plasma generation and transport is specified. Useful analytical relations have been found for such plasma within various diffusion models[1]. In many important partially-ionized plasmas, the larger ionization makes the ion and neutral dynamics coupled[2]. Recently, this nonlinear more difficult problem was solved for the case that neutrals and plasma are in pressure balance[3]. In the present paper we address the effect of neutral depletion on the steady-state of collisionless plasma.

Assume one-dimensional quasi-neutral collisionless plasma. The sum of the ion and electron momentum equations results in the plasma generalized pressure being constant and decoupled from the neutral-gas pressure

$$mnv^2 + nT = n_0 T. \qquad (1)$$

Here m and v are the ion mass and velocity, T is the (assumed constant) electron temperature (the ion temperature is neglected), n is the plasma density, and n_0 is the maximal plasma density. At the sheath boundary $v = c \equiv \sqrt{T/m}$ and therefore the density is $n_0/2$. The particle flux density to the wall is $n_0 c/2$, and the deposited power per unit area P equals that flux density multiplied by ε_T, the energy deposited in each such particle[4]:

$$P = \frac{n_0 c}{2}\varepsilon_T. \qquad (2)$$

The coupling of the plasma and the neutrals is through ionization:

$$\frac{d\Gamma_i}{dx} = \beta N n, \qquad (3)$$

where $\Gamma_i = nv$ is the ion flux density, N the neutral gas density and $\beta(T)$ is the ionization rate. Using Eq. (1) we express the density as $n = n_0\left(1+\sqrt{1-\Gamma_n^2}\right)/2$, where $\Gamma_n \equiv 2\Gamma_i / n_0 c$. With this relation we integrate Eq. (3) to obtain

$$\arcsin \Gamma_n - \frac{\Gamma_n}{\sqrt{1-\Gamma_n^2}+1} = \frac{\beta}{c}\int_0^x N dx', \qquad (4)$$

and, substituting $\Gamma_n(x=a)=1$, we obtain

$$\frac{\pi}{2} - 1 = \frac{\beta}{c}\int_0^a N dx' = \frac{\beta}{c} N_T. \qquad (5)$$

Equations (4) and (5) are generalizations of the case of weakly-ionized plasma to the case of a nonuniform neutral density induced by high ionization. In particular, relation (5) shows that, as in the pressure balance case[3], the total number of neutrals replaces the Paschen parameter of the weakly-ionized plasma as the parameter that determines the electron temperature.

We turn now to describe the neutral dynamics that was unspecified until now. The neutrals are assumed to move balistically either in the positive or negative x direction with a velocity v_a . The flux densities are $\Gamma_1(x)$ and $\Gamma_2(x)$ in the positive and negative directions, respectively. The continuity equations for the neutral fluxes are

$$\frac{d\Gamma_1}{dx} = -\beta N_1 n, \quad \frac{d\Gamma_2}{dx} = \beta N_2 n, \qquad (6)$$

where the neutral densities are $N_1 = \Gamma_1 / v_a$ and $N_2 = \Gamma_2 / v_a$. From the last equation we obtain

$$\Gamma_1\Gamma_2 = \Gamma_0^2, \qquad (7)$$

where Γ_0 is a constant that will be specified later.

Equations (3) and (6) together with the relation between n and Γ_i are the governing equations. We solve these equations here for the following configuration. We assume symmetrical plasma with respect to x between walls at $x = \pm a$. The net mass flux is zero so that $\Gamma_i + \Gamma_1 - \Gamma_2 = 0$. We assume that N_T and P are specified. Then the electron temperature is specified through Eq. (5) while the particle flux is determined through Eq. (2). In order to derive the density profiles we combine the equations to

$$\frac{d\Gamma_n}{d\xi} = \frac{P_n}{4}\left[\frac{\left(\sqrt{\Gamma_n^2+D^2}-\Gamma_n\right)^2 + D^2}{\sqrt{\Gamma_n^2+D^2}-\Gamma_n}\right]\left(1+\sqrt{1-\Gamma_n^2}\right), \qquad (8)$$

where

$$\xi \equiv \frac{x}{a}, \quad P_n \equiv \frac{\beta a n_0}{v_a} = \frac{(2\pi - 1) a P}{N_T v_a \varepsilon_T}, \quad D \equiv \frac{4\Gamma_0}{n_0 c} = \frac{2\varepsilon_T \Gamma_0}{P}. \qquad (9)$$

Here P_n is the ratio of ion flux to average neutral flux and denotes normalized power. The rate of neutral depletion is denoted by $1/D$. As P_n increases D decreases.

Small and large neutral depletion

We write the relation between the parameters as

$$\int_0^1 \frac{\left(\sqrt{\Gamma_n^2 + D^2} - \Gamma_n\right)}{\left[\left(\sqrt{\Gamma_n^2 + D^2} - \Gamma_n\right)^2 + D^2\right]\left(1 + \sqrt{1 - \Gamma_n^2}\right)} d\Gamma_n = \frac{P_n}{4}. \qquad (10)$$

Once the plasma flux and density are calculated the normalized neutral fluxes $\Gamma_{jn} \equiv 2\Gamma_j / n_0 c$ for $j = 1,2$ are expressed algebraically as follows: $\Gamma_{1n} = \left(-\Gamma_n + \sqrt{\Gamma_n^2 + a^2}\right)/2$ and $\Gamma_{2n} = a^2 / 4\Gamma_{1n}$. The normalized neutral density is $\Gamma_N = \Gamma_{1n} + \Gamma_{2n}$.

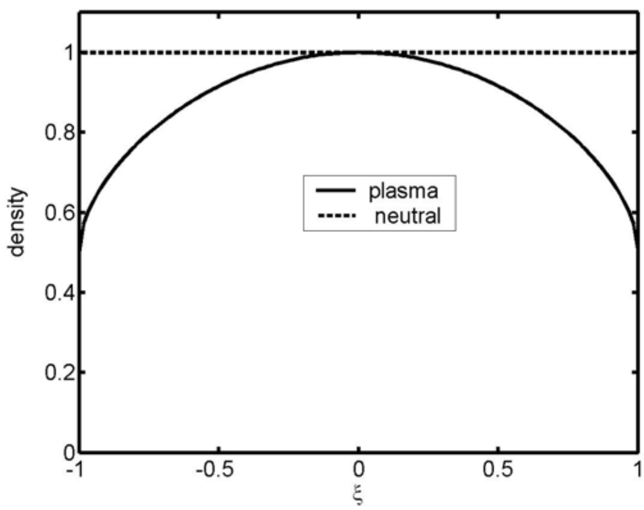

Figure 1 Normalized densities: neutrals (divided by D) and plasma - small depletion.

Neutral depletion is low if $D \gg 1$. From Eq. (10) we then recover the weakly-ionized case [Eqs. (4) and (5)]. The condition for low neutral depletion is

$$P_n \cong \frac{(\pi - 2)}{D} \ll 1 \Rightarrow P \ll N v_a \varepsilon_T. \qquad (11)$$

This sets the limit on power before neutral depletion takes place.

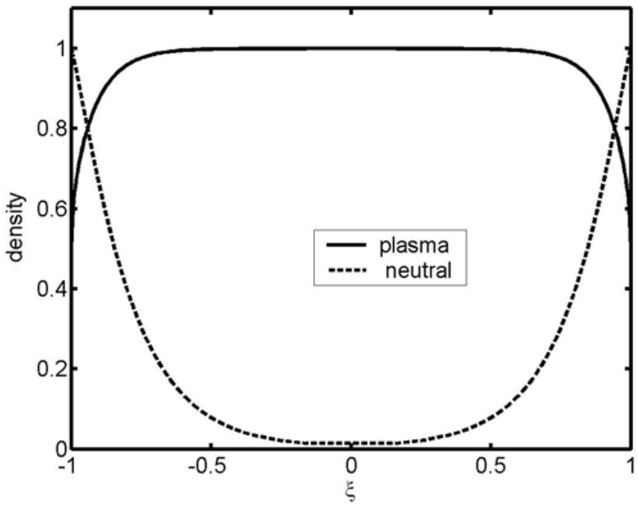

Figure 2 Normalized plasma and neutral densities in the large depletion case.

The other limit is of large neutral depletion, when $D \ll 1$. Asymptotic analysis (the details of which will be given elsewhere) yields the relation

$$D \cong \exp(-P_n). \qquad (12)$$

This important result describes D, the ratio of the neutral density at the center to the neutral density at the wall, as a function of the normalized power P_n.

The normalized densities are shown when the neutral depletion is small, $D = 100, P_n = 0.0114$, (Fig.1) and when it is large, $D = 0.01, P_n = 5.49$ (Fig. 2).

Summary

In this paper we analyzed the effect of neutral depletion on collisionless plasma. The analysis adds another aspect to our previous analysis of neutral depletion in plasma and neutrals in pressure balance[3]. Other issues, such as the effects of neutral heating and magnetic field, will be addressed in future studies.

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[1] W. Schottky, Phys. Z. 25, 635 (1924); J. R. Forrest and R. N. Franklin, Brit. J. Appl. Phys. 17, 1569 (1966), R. N. Franklin, "Plasma Phenomena in Gas Discharges" (Clarendon, Oxford, 1976); V. A. Godyak, "Soviet radio frequency discharge research" (Delphic Associates, Falls Church, 1986); A. Fruchtman, G. Makrinich, and J. Ashkenazy, Plasma Sources Sci. Technol. 14, 152 (2005).
[2] J. Gilland, R. Breun, and N. Hershkowitz, Plasma Sources Sci. Technol. 7, 416 (1998); S. Yun, K. Taylor, and G. R. Tynan, Phys. Plasmas 7, 3448 (2000).
[3] A. Fruchtman, G. Makrinich, P. Chabert, and J. M. Rax, Phys. Rev. Lett. 95, 115002 (2005).
[4] M. A. Lieberman and A. J. and Lichtenberg, "Principles of Plasma Discharges and Materials Processing" (Wiley, New York, 1994).