Free plasma pinch in a high-pressure gas

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A theory is proposed for a stationary plasma pinch with high electron temperature and in dynamic equilibrium with a surrounding dense gas.

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An investigation of a high-frequency gas discharge in a resonator at a pressure of several atmospheres, P. L. Kapitza observed the following interesting phenomenon[1]: at a sufficiently large radiation power (≈ 10 kW) applied to the discharge, a stable plasma pinch with high electron temperature ($T_e \approx 10^6$—10^7 K) is produced at the center of the resonator and hovers in the gas.

In this article we propose a theory for a stationary plasma pinch in dynamic equilibrium with the surrouding gas. The electrons of the plasma pinch are assumed to be of high energy, so that recombination of the electrons with the ions can be neglected. The outflow of the electrons (ions) from the plasma is due to ambipolar diffusion, and their appearance is due to impact-ionization processes. We have the following balance equation for the number of electrons (ions)

$$-\nabla(D_a \nabla N_e) = Z_i N_e. \tag{1}$$

Here the coefficient of ambipolar diffusion D_a and the frequency Z_i of the ionization are functions of the concentration of the neutral particles. As usual, we assume $D_a \sim N^{-1}, Z_i \sim N$.

The neutral particles enter the volume of the plasma via diffusion from the surrouding gas, and the concentration of the neutral particles is connected with the concentration of the electrons by the relation

$$NT + N_e T_e \equiv R = \text{const}, \tag{2}$$

which follows from the condition that the pressure be spatially homogeneous. (The partial pressure of the ions is neglected, since $T_i \approx T \ll T_e$).

The temperatures of the different components of the plasma are determined by the energy-balance equations. Under the conditions of P. L. Kapitza's experiment, the dissipation of the high-frequency field energy is due to the anomalous skin resistance of the plasma pinch and leads to heating of the electrons. In view of the large thermal conductivity of the electrons, their temperature in the pinch is uniform. To simplify the analysis, the temperatures of the ions and the neutral particles will also be assumed to be spatially homogeneous in the region of the pinch. Under these conditions, for the two-dimensional case, Eqs. (1) and (2) admit of the following solution

$$N_e = N_{eo} \frac{a + \cos[(1-a^2)^{1/2}(z-z_0)/\delta]}{1 + a\cos[(1-a^2)^{1/2}(z-z_0)/\delta]}, \quad (3)$$

where $N_{e0} = N_e(z = z_0)$ is the electron density on the pinch axis, $\alpha = N_{e0}T_e/R$, and $\delta = (T/R)(D_a N^2/Z_i)^{1/2}$.

Formulas (2) and (3) describe the distribution of the densities of the plasma components. We note that we neglect formally in these relations the partial pressure of the electrons ($\alpha = 0$), then we obtain a distribution similar to the plasma distribution in the Schottky theory[2] for a positive column of a low-pressure gas discharge, corresponding to the two-dimensional case. Under our conditions, a different limiting case is realized, in which the neutral-gas pressure in the pinch is much lower than the electron pressure ($1 - \alpha \ll 1$). Formula (3) then gives the electron distribution in the form of a "plateau": a quasi-homogeneous layer of width $2\pi\delta/(1-\alpha^2)^{1/2}$, dropping off abruptly at the boundary of the pinch, where the plasma is in contact with the surrounding dense neutral gas. The thickness of the fall-off region is $\approx \delta$. A similar picture is seen also in the three-dimensional case: the pinch is a quasi-homogeneous plasma cylinder with a boundary-layer thickness close to δ.

We note that formula (3) is valid so long as the plasma density is high enough to be able to regard the plasma as quasi-neutral or, in other words, the Debye radius of the plasma must be smaller than the distance characterizing the plasma inhomogeneity.

Thus, just as in the positive column of a gas discharge, an ambipolar electric field produces in a plasma pinch a potential well for the electrons. Under the considered conditions it is assumed that the electron mean free path is of the order of or larger than the pinch thickness, so that the pinch does not contain electrons with energy exceeding the potential barrier, i.e., we have a truncated electron distribution function. The electron flux (equal to the ion flux) from the pinch into the surrounding gas is the result of the fact that the electrons acquire an excess energy when they interact with the rf field or with other electrons, and overcome the potential barrier. Since these interactions are practically continuous, we have behind the potential barrier cooled electrons whose temperature becomes rapidly equalized with the temperature of the dense gas. Here, outside the limits of the pinch, the plasma recombines intensively. We note that our analysis is valid if the surrounding gas is a weakly ionized low-temperature plasma. The results will be valid with an accuracy of the same order as that of the degree of ionization of the gas.

Knowing the spatial distribution of the plasma, we can determine the energy losses. The principal energy losses of the electrons are due to the production of hot electrons and to the diffusion drift of the electrons from the pinch plasma. These losses are of the same order. In addition, at sufficiently high plasma density in the pinch (when the electron temperature is not very high), the losses to the electromagnetic radiation of the plasma may turn out to be substantial. With the aid of the energy-balance equation we can find the electron temperature as a function of the power fed to the pinch, of the gas pressure, and of the dimensions of the pinch. The obtained temperature turns out to be close in order of magnitude to that measured in P. L. Kapitza's experiment.

For a more accurate numerical comparison of the results it is necessary to have reliable information on the elementary processes that occur in the pinch plasma. For example, the coefficient of ambipolar diffusion depends on the effective cross section of the ion collision with the neutral particle, and this cross section, as is well known (see, e.g., [3]) is strongly connected with processes of charge exchange or formation of complex ions if certain impurities are present in the gas.

When the plasma pinch is acted upon by a constant magnetic field, the coefficient of ambipolar diffusion decreases, and this can lead to a narrowing of the plasma pinch. We note that P. L. Kapitza observed a similar dependence of the pinch thickness on the magnetic field.

Finally, we note the following. It is known[3] that impact ionization leads to production of a cold electron with energy of several electron volts. This electron is either heated by collision with a hot electron, or recombines with an ion. In our analysis it is assumed that all the produced electrons are heated. In the opposite case, when the probability of recombination of the cold electron with the ion is large, the problem becomes somewhat more complicated by the need for taking into account the balance of the number of particles of the cold electrons. However, the structure of the plasma pinch turns out in this case to be qualitatively the same as in the considered case.

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