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PASSAGE OF WEAKLY INHOMOGENEOUS PLASMA STREAM THROUGH A MICROWAVE POTENTIAL BARRIER

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We have investigated the interaction of a cylindrical plasma jet, moving transversely in a round waveguide, with the field of a traveling linearly-polarized H_{11} wave. We show that for a jet of rarefied weakly-inhomogeneous plasma, the motion of the flux near the axis is determined by reflection in the force field of a one-dimensional microwave potential barrier. We have observed that an increase in the density of the plasma particles to a critical value leads to a strong perturbation of the motion of the plasma jet. The perturbation becomes strongly pronounced when the density changes by 10—20%.

1. INTRODUCTION

We have investigated experimentally the interaction between a plasma stream and a strong spatially-inhomogeneous field of an electromagnetic wave. The purpose of the investigation was to check the correspondence between the behavior of a plasma in an inhomogeneous microwave field and the theory of quasipotential forces acting on charged particles[1]

$$\mathbf{F}(\mathbf{r}) = -\nabla\Phi(\mathbf{r}), \tag{1}$$

where $\Phi(\mathbf{r})$ is the potential of the force field, which is connected with the amplitude of the electric component of the field E by

$$\Phi(\mathbf{r}) = e^2E^2(\mathbf{r})/4m\omega^2 \tag{2}$$

(e and m are the charge and mass of the particle, ω is the circular frequency of the microwave field). According to [2], expressions (1) and (2) are valid also for a transparent plasma ($\omega_{Le} \ll \omega$). An experimental verification of (1) and (2) was carried out earlier for electrons[3].

In a number of papers devoted to an investigation of the interaction of the plasma with an inhomogeneous high-frequency field[4-7], the observed interaction effects were ascribed to the forces (1). However, no attention was paid there to the fact that the observed effect could be connected with the development of instabilities in a plasma situated in a strong high-frequency field[8,9].

We confine ourselves in this paper essentially to an investigation of a transparent plasma ($\omega_{Le} \ll \omega$) under conditions which make it possible to compare the laws governing the particle motion in the microwave field with the theory of a microwave potential, as a result of which we can also solve the question of the stability of the plasma at given experimental conditions.

For convenience in the investigation, we have chosen a one-dimensional experimental setup. Let the microwave field be homogeneous and unbounded in two dimensions and inhomogeneous in the third dimension (along the x axis), and let it exist in the interval $-L/2 < x < L/2$, the amplitude of the electric field E_y being distributed in the form

$$E_y = E_0 \cos\frac{\pi x}{L}. \tag{3}$$

The forces (1) acting on the charged particles in such a field will be directed only along x. Assume that an unbounded one-dimensional stream of transparent ($\omega_{Le} < \omega$) and collisionless plasma, with specified distribution of the directed ion velocities V_x ($V_x > 0$, $V_y = V_z = 0$), moves through this field. If the ion and electron temperature is small compared with the ion kinetic energy $W = MV_x^2/2$, and if the value of the potential Φ_0 at $x = 0$ lies in the interval between the minimum and the maximum ion energies, i.e.,

$$W_{\min} < \Phi_0 < W_{\max}, \tag{4}$$

then the plasma with ion energies satisfying the left side of inequality (4) should be reflected from the microwave barrier, while the other part of the plasma, with higher ion energies, should pass through it[2]. With this, by virtue of (2) and (3), the spectral ion-energy distribution function of the transparent plasma should retain the form of the initial function at $W > \Phi_0$, and should change jumpwise to zero at $W = \Phi_0$, the width of the jump being determined by the temperature of the plasma components.

Under experimental conditions it is impossible to produce an unbounded plasma stream. One usually deals with a plasma jet, in which the distribution of the particle density over the radius ρ is of the form

$$n(\rho) = n_0 \exp(-\rho^2 / a^2). \qquad (5)$$

As shown in [10], such an infinitely long jet, placed in a homogeneous external field, will be acted upon by a radial force, which when calculated in the approximation $a \ll \lambda$ (λ is the wavelength of the microwave field) is equal to

$$F_\rho(\rho) = 2\Phi \frac{\omega_{Le_0}}{\omega} \frac{\rho}{a^2} e^{-\rho^2/a^2}, \qquad \omega_{Le_0} = \omega_{Le}(\rho)\,|_{\rho=0}, \qquad (6)$$

and which arises as the result of the perturbation of the external homogeneous microwave field by the field of the plasma itself. The radial electric polarization connected with this force causes the ions to become radially accelerated.

Thus, a bounded plasma stream in a microwave field (3) that is inhomogeneous in the x direction will already be acted upon by a two-dimensional force field. If we choose in the experiment conditions under which the forces (6) can be neglected, so as to reduce the experiment to the one-dimensional case, then the passage of the ions of the plasma through the microwave barrier should correspond in the absence of instabilities to the inequality (4).

2. EXPERIMENTAL CONDITIONS

The experimental setup is illustrated in considerable detail in Fig. 1, so that we point out only the most essential features of the setup and of its parameters.

The plasma jet was produced by spark source 9 and injected into a round waveguide 6, in which the traveling linearly-polarized H_{11} wave was excited by a pulsed microwave generator operating in the 10-cm band. The injection was transverse to the waveguide in the x direction and perpendicular to the electric force lines of the waves. The amplitude of the electric field of the wave had a distribution in the x direction in the form

$$E_y(x) = B_0 J_1'\left(1.84 \frac{2|x|}{L}\right), \qquad y = z = 0, \qquad (7)$$

where B_0 is an amplitude coefficient, L the waveguide diameter, and J_1' the derivative of the Bessel function.

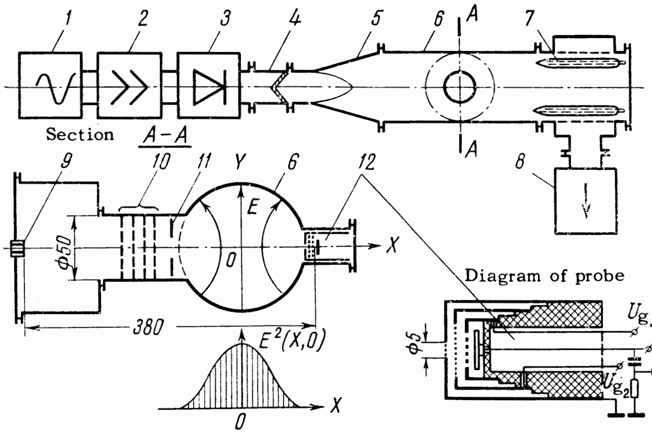

FIG. 1. Diagram of setup. 1–Microwave generator, 2–attenuator, 3–ferrite gate, 4–ceramic microwave window, 5–wave converter, 6–section of round waveguide, 7–evacuated unit with microwave load, 8–vacuum post ($P = 2 \times 10^{-6}$ Torr), 9–spark source, 10–grids for reducing the plasma density, 11–diaphragm, 12–multigrid plasma probe.

The opening through which the plasma was injected into the waveguide had a relatively large diameter (2a = 50 mm), and was therefore covered with a nickel grid to prevent distortion of the microwave field. A multigrid probe (12) was located in the right-hand tube (2a = 30 mm) and made it possible to vary the plasma-ion energy spectrum by the retarding-potential method. The diameter of the inlet opening of the probe was 5 mm, i.e., the probe analyzed only the plasma particles closest to the axis. A diagram of the probe is shown in the lower part of Fig. 1. The probe consisted of three grids and a collector. The first two grids had a transparency of 0.76 and a mesh dimension 0.15 mm, the Debye length of the investigated plasma being not larger than five times this dimension. The third grid was made of tungsten wire 50 μ thick with a square mesh of 5 mm. The collector was in the form of a flat disc. All interelectrode distances were equal to 3 mm. The first grid was grounded. The retarding potential was applied directly on the second grid ($U_{g_2} = U_d = 0 - 300$ V). which picked up the plasma the ions of energy larger than zeU_d and fed them to a collector with negative potential ($U_c = -100$ V). The third grid produced lower potentials at the collector, to suppress the electron emission from the collector, and was made looser in order to reduce its own emission current. For the same reason, a high negative potential was applied to the third grid, −1.5 kV. The spark source, which was similar to that described in [6,7], was a discharge gap separated by a 6 mm layer of Plexiglas. The source capacitor, rated 0.15 μF, was charged to 2 kV. Its discharge time was 0.2 —0.3 μsec. The plasma density in the waveguide was regulated with the aid of low-transmission grids in the range $5 \times 10^8 - 5 \times 10^{10}\ \mathrm{cm}^{-3}$. Inasmuch as the electron temperature in a plasma injected by a spark source of such a type is several electron volts, the characteristic times of the electron and ion collisions with each other or with the atoms of the residual gas were negligibly small compared with the travel time of the plasma through the waveguide. The cross section of the plasma jet was varied by varying the diameter of the diaphragm (11) from 10 to 50 mm.

The distribution of the plasma-jet ions with respect to longitudinal energies, at different jet diameters, can be obtained from the delay curves shown in Fig. 2. It is seen from an analysis of these curves that a decrease in the initial jet diameter, with the source operating under unchanged conditions, leads to a decrease in the total number of ions in the part of the jet next to the axis and to a loss of ions with small longitudinal energies on the part of the jet1).

The H_{11} traveling-wave field has an inhomogeneous distribution in both the x and y directions, owing to the structure of the wave. However, near the x axis the inhomogeneity of the field distribution with respect to y is small and can be neglected when the plasma stream next to the axis is considered. This stream is separated at the input to the probe by a diaphragm having an aperture diameter of 5 mm. The field inhomogeneity with respect to z, which is always present under real conditions and is connected with reflection of the traveling wave from the microwave load, was negligibly small (VSWR < 1.1).

Finally, in order to exclude the influence of the radial forces (6) on the plasma next to the axis, a broad plasma beam was produced, since the radial force decreases in proportion to a^2.

An estimate of the initial plasma-jet diameter at which the influence of the radial force on the density of the near-axis plasma could be neglected when $\Phi_0 = W_{av}$ (average plasma-ion energy) has shown that the initial jet diameter should be not smaller than 50 mm. This estimate is inexact, since it does not satisfy the condition $a \ll \lambda$ at which expression (6) is valid, and is furthermore obtained by assuming F_ρ to be constant, which is likewise incorrect. Therefore the jet diameter at which radial effects near the x axis are negligibly small was determined experimentally.

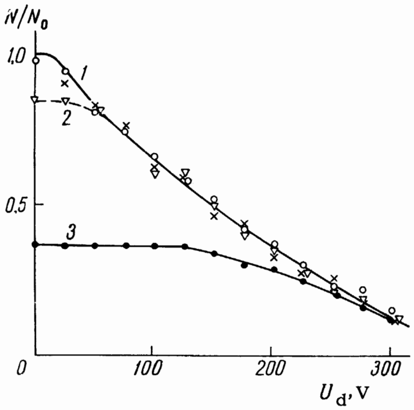

FIG. 2. Delay curves for $\Phi_0 = 0$: 1 – 2a = 50 mm (×), 2a = 30 mm (○); 2 – 2a = 20 mm; 3 – 2a = 10 mm.

As already stated, the experiment was based on measuring the energy spectrum of the ions of a plasma passing through the microwave barrier, and comparing it with the initial spectrum obtained in the absence of the microwave field. The multigrid probe used in the experiment made it possible to measure the delay curves $N/N_0 = f(U_d)$, where $N(U_d)$ is the total charge of the ions that overcame the delay potential, determined from the area of the ion-current pulse: $N = \int_{t=0}^{\infty} I_i(t, U_d)\,dt$; N_0 – total ion charge at $U_d = 0$. These delay curves cannot be regarded in general as integral energy spectra of the ions, since the ion energy is determined not only by the corresponding delay potential U_d, but also by the charge z, i.e., $W = zeU_d$. To construct the true energy spectrum, it is therefore necessary to know the composition of the ions by charges. We note, however, that W/Φ_z does not depend on z, since $\Phi_z = z\Phi$. This makes it possible, disregarding z, to interpret the delay curves as integral "energy" spectra of "singly-charged" ions.

3. JET OF RAREFIED PLASMA, $\omega_{Le}^2/\omega^2 \leq 0.05$, IN AN INHOMOGENEOUS MICROWAVE FIELD

Figure 3 shows oscillograms of the probe current at different delay potentials for the case $\Phi_0 = 0$ (left half of Fig. 3) and $\Phi_0 = 150$ V (right half of Fig. 3). The diameter of the entrance diaphragm was 50 mm.

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1)The observed effect can be explained as being due to the fact that the "source" of the collisionless plasma has a finite dimension commensurate with the diaphragm diameter, as a result of which the ion current directed to the probe is bounded by a diaphragm whose diameter can be much higher than the probe diameter. If it is assumed at the same time that the dimension of the "source" is inversely proportional to the ion energy, then the reason why the diaphragm cuts off more strongly ions of lower energies becomes understandable. On the other hand, the effect can be attributed to a different cause—the transverse spreading of the jet as a result of the radial electric field produced on the plasma boundary by charge separation [11]. The particle flux to the probe will then also depend on the initial diameter of the jet and on the ion mass.

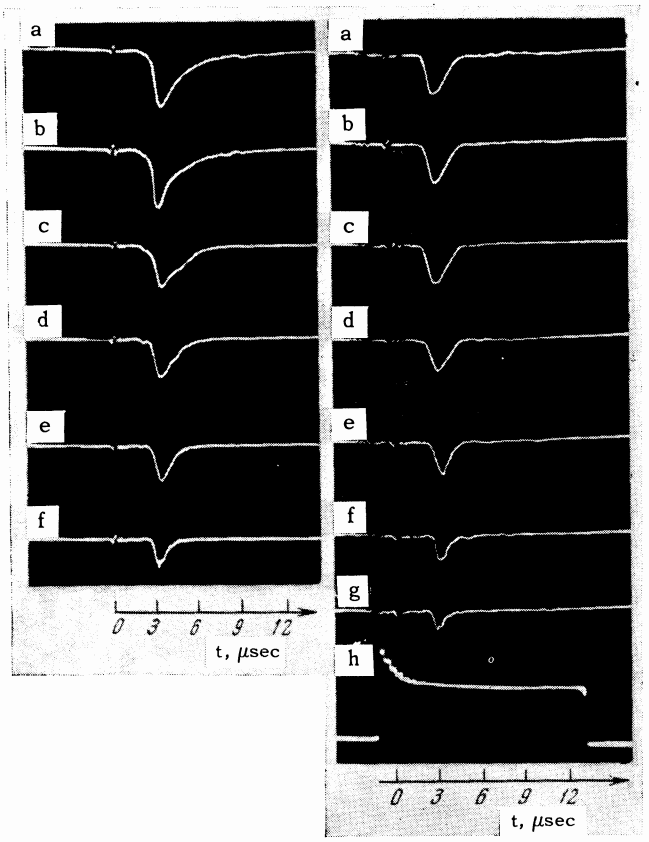

FIG. 3. Oscillograms of ion current $I_i(t, U_d)$ of a transparent plasma ($\omega_{Le}^2/\omega^2 < 0.05$) at 2a = 50 mm. Left series, $\Phi_0 = 0$: a) 0 V; b) 50 V; c) 100 V; d) 150 V; e) 200 V; f) 250 V. Right series, $\Phi_0 = 140$ V: a) 0 V; b) 50 V; c) 100 V; d) 150 V; e) 200 V; f) 250 V; g) 300 V; h) microwave pulse.

Comparison of the probe-current oscillograms (Fig. 3) shows that after passing through the microwave barrier the plasma jet contains less slow particles, since the trailing edge of the ion-current pulse is cut off. Attention is called to the complete similarity between the form of the current pulses at $\Phi_0 = 0$ and $U_d = 150$ V (Fig. 3d—left series) and $\Phi_0 = 140$ V with $U_d = 0$ (Fig. 3a—right series). This indicates that the potential microwave barrier reflects that part of the plasma whose ions have an energy smaller than the height of the barrier, which is also confirmed by comparison of the current oscillograms for $\Phi_0 = 140$ V and $U_d = 0$, 50, 100, and 150 V (Figs. 3a, b, c, d—right series). A change in the current is observed also on going from $U_d = 100$ V to $U_d = 150$ V. This means that the plasma jet that has penetrated through the microwave barrier does not contain ions with energy lower than the magnitude of the barrier. It is important to note that no ions with energies higher than the initial ones appear after interaction with the wave in the plasma jet, as can be seen from the oscillograms of Fig.

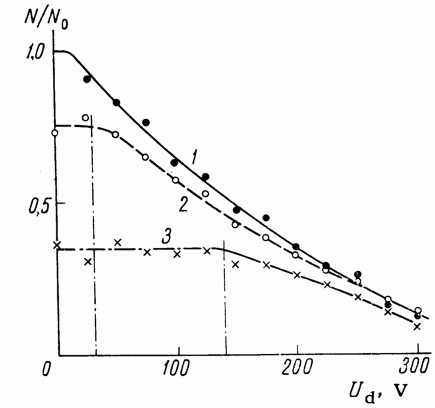

FIG. 4. Delay curves for 2a = 50 mm: 1) $\Phi_0 = 0$ V; 2) $\Phi_0 = 30$ V; 3) $\Phi_0 = 140$ V.

3. The most complete information concerning the change in the spectrum of the plasma-jet ions after penetrating through the microwave barrier can be obtained from Fig. 4. The delay curves 1, 2, and 3 correspond to $\Phi_0 = 0$, 30, and 140 V (the values of the barrier are shown in the figure by vertical lines). Each experimental point of the plots in Fig. 4 (also in Figs. 5 and 6) was obtained by integrating five identical ion-current oscillograms (typical oscillograms are shown in Fig. 3) and averaging the results of the integration. As seen from the diagrams, the results of the interaction between a plasma jet and a microwave barrier reduces to a reflection of the ions having energy $W < z\Phi_0$, and to a certain decrease in the number of ions whose energy exceeds the height of the barrier. Attention is called to the fact that the spectrum of the penetrating particles is cut off at $U_d = \Phi_0$, accurate to 10%, i.e., there is quantitative agreement between the measurement results and the theory of one-dimensional microwave potential. The higher the ion energy and the lower the barrier, the smaller the decrease in the number of ions passing through the microwave barrier relative to their initial number. (The maximum attenuation reaches 0.2 at $\Phi_0 = 30$ V and 0.35 at $\Phi_0 = 140$ V.) The observed attenuation of the plasma flux can be due to the action of the radial forces (6). This is confirmed to a certain degree by the smaller attenuation of the flux of the faster plasma (with ions of higher energy). A decrease of the initial diameter of the plasma jet greatly reduces the flux and changes qualitatively the spectrum of the ions penetrating through the microwave barrier (Figs. 5 and 6). At a jet diameter 20 mm and $\Phi_0 = 130$ V the attenuation of the flux amounts to 0.5, and at a 10-mm diameter and $\Phi_0 = 95$ V the fraction of lost particles with energy exceeding the height of the microwave

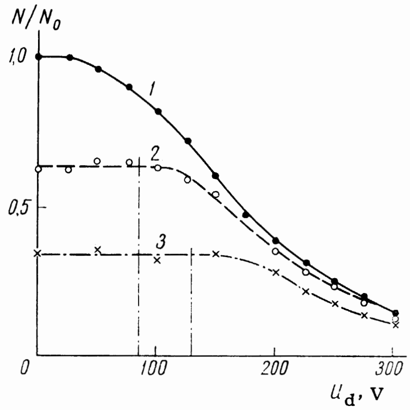

FIG. 5. Delay curves for 2a = 20 mm: 1) Φ_0 = 0 V; 2) Φ_0 = 90 V; 3) Φ_0 = 130 V.

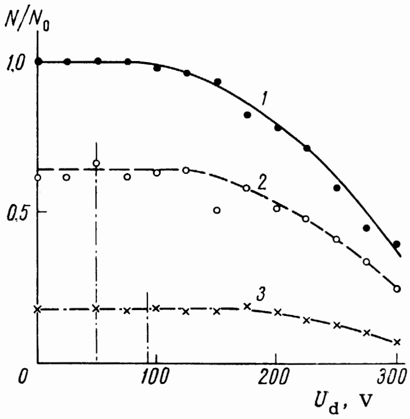

FIG. 6. Delay curves for 2a = 10 mm: 1) Φ_0 = 0 V; 2) Φ_0 = 50 V; 3) Φ_0 = 95 V.

barrier is 0.8. At the same time, the delay curves become strongly deformed. As seen from the plots in Figs. 5 and 6, the spectra of the plasma ions penetrating through the barrier do not contain ions with energy greatly exceeding the height of the barrier. Thus, at a jet diameter 10 mm and $\Phi_0 = 95$ V (curve 3 of Fig. 6) the ion spectrum is cut off at 180 V. These results correspond at small initial jet diameters to the data of [10], and point to an appreciable radial broadening of the plasma jet if the distribution of the density over its cross section is highly inhomogeneous.

The foregoing analysis of the measurement results shows that the ion spectra of a plasma penetrating through a one-dimensional microwave barrier are in quantitative correspondence with the height of the barrier, provided the plasma jet is sufficiently homogeneous over the cross section and the interaction time is shorter than 5 μsec. This leads to the conclusion that the motion of a rarefied plasma under such conditions, in an inhomogeneous microwave field, is determined by the forces of the inhomogeneous microwave field given by expression (1).

4. PLASMA JET IN A MICROWAVE FIELD AT A PARTICLE DENSITY CLOSE TO CRITICAL

The motion of a plasma cylinder in a microwave field can be due not only to the forces (1) and (6), but also to excitation of various instabilities in the plasma [8,9], especially near the critical density $\omega_{Le}^2 \approx 2\omega^2$). We investigated the penetration of a plasma through a microwave barrier (2a = 50 mm) with the particle density made to vary greatly by introducing attenuating grids. Smooth regulation of the density was obtained by varying the voltage on the source capacitance between 2 and 4 kV. As shown by the measurements, the energy spectra of the plasma ions penetrating through the microwave barrier were identical within the range of densities measured in the waveguide, $5 \times 10^8 - 1 \times 10^{10}$ cm^{-3}, thus demonstrating that the instability has little or no influence under these conditions. It was noted, however, that an abrupt change in the character of the passage of the jet through the microwave barrier was observed even at a density determined with accuracy to 30% and satisfying the condition $\omega_{Le}^2 \approx 0.4\omega^2$ (Fig. 7). A slight increase of density

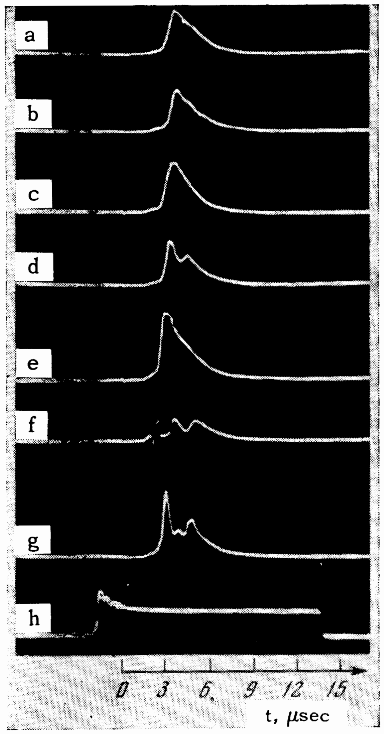

FIG. 7. Oscillograms of ion current $I_i(t)$ of a dense plasma ($\omega_{Le}^2 \approx 0.4\omega^2$) at 2a = 50 mm and at different gun voltages (U_{gun}) and Φ_0: a) U_{gun} = 2.8 kV, Φ_0 = 0 V; b) U_{gun} = 2.8 kV, Φ_0 = 60 V; c) U_{gun} = 3.0 kV, Φ_0 = 0 V; d) U_{gun} = 3.0 kV, Φ_0 = 60 V; e) U_{gun} = 4.0 kV, Φ_0 = 0 V; f) U_{gun} = 4.0 kV, Φ_0 = 60 V; g) U_{gun} = 4.0 kV, Φ_0 = 4 V; h) microwave pulse.

(within 10%) in cases c and d of Fig. 7, compared with cases a and b, leads to a plasma disturbance which becomes more intense with further increase in density (by 20%), as seen from Figs. 7e and f. When the height of the microwave barrier is reduced to 4 V (case g), i.e., to a value comparable with the electron plasma temperature, the perturbation of the plasma having a density higher than critical is still sufficiently large.

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[1] A. V. Gaponov and M. A. Miller, JETP **34**, 242 (1958), Soviet Phys. JETP **7**, 168 (1958).

[2] M. A. Miller, JETP **36**, 1909 (1959), Soviet Phys. JETP **9**, 1358 (1959).

[3] D. M. Bravo-Zhivotovskiĭ, B. G. Eremin, E. V. Zagryadskiĭ, M. A. Miller, and S. B. Mochenev, Izv. VUZov, Radiofizika **2**, 94 (1959).

[4] G. A. Swartz and T. T. Reboul, Phys. of Fluids **5**, 803 (1962).

[5] I. P. Gekker, T. G. Konstantinova, G. S. Luk'yanchikov, and K. F. Sergeĭchev, ZhTF **35**, 577 (1965), Soviet Phys. Tech. Phys. **10**, 450 (1965).

[6] V. I. Veksler, I. R. Gekker, E. Ya. Gol'ts, et. al., Atomnaya énergiya **18**, 14 (1965).

[7] I. R. Gekker, E. Ya. Gol'ts, B. P. Kononov, K. A. Sarksyan, V. A. Silin, and L. E. Tsopp, Proceedings of 7th International Conference on Phenomena in Ionized Gases, August, 1965, Belgrade. FIAN Preprint A-155, 1965.

[8] Yu. M. Aliev, V. P. Silin, and H. Watson, JETP **50**, 943 (1966), Soviet Phys. JETP **23**, 626 (1966).

[9] L. M. Gorbunov and V. P. Silin, JETP **49**, 1973 (1965), Soviet Phys. JETP **22**, 1347 (1966).

[10] G. S. Luk'yanchikov, M. D. Raĭzer, and A. G. Frank, ZhTF (in press).

[11] A. V. Gurevich, L. V. Pariĭskaya, and L. P. Pitaevskiĭ, JETP **49**, 647 (1965), Soviet Phys. JETP **22**, 449 (1966).

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