Investigation of Drift-Beam Instability of a Plasma-Ion Beam System in a Longitudinal Magnetic Field

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Drift-beam instability in a plasma-ion beam system located in a longitudinal magnetic field is studied theoretically and experimentally. It is found that in a system consisting of two opposite argon or helium beams with equal current strengths and energies moving through their own gas at a pressure of 2×10^{-5}–7×10^{-4} mm Hg along a magnetic field of 2–10 kOe, oscillations are excited with frequencies which are several times greater than the respective ion-cyclotron frequencies. The experimental data are in satisfactory agreement with the theoretical analysis.

INTRODUCTION

INTEREST in investigation of the collective interaction of ion beams with a plasma is due, on the one hand, to the possibility of using collisionless relaxation of the ion beam for the accumulation, heating, and diagnostics of a plasma in magnetic traps and, on the other hand, to the practical importance of the problems of plasma microwave techniques, methods of shaping and transporting ion beams in accelerating systems, etc. By now the most thoroughly investigated effects from the experimental point of view are those of excitation of ion-acoustic[1,2] and electron Langmuir[3,4] plasma oscillations by ion beams in the absence of a magnetic field. Yet the theory predicts a number of instabilities of ion beams injected into a plasma both along the magnetic field and transverse to it[5-9]. A special class is made up of instabilities due to the spatial inhomogeneity (radial boundedness) of the ion beams and plasma streams[10-12]. These also include the drift-beam instability in a system consisting of a plasma and an ion beam in a longitudinal magnetic field, which has been investigated theoretically and experimentally in the present study.

THEORY

Assume that an ion beam passes through a semi-infinite plasma that fills the region $x \geq 0$ and is situated in a longitudinal magnetic field $\mathbf{H}_0 \uparrow\uparrow \mathbf{Z}$. The plasma ion and electron concentrations are N_i and N_e and the ion beam has a velocity $\mathbf{V}_0 \uparrow\uparrow \mathbf{H}_0$ and density n_0 (the electroneutrality condition $N_e = N_i + n_0$ is satisfied at each point). We examine the stability of such a system against small perturbations of the type $\xi(\mathbf{r}, t) = \xi(x)\exp\{ik_y y + ik_z z - i\omega t\}$ with frequency ω lying in the interval $\omega_{Hi} \lesssim \omega \leq \sqrt{\omega_{Hi}|\omega_{He}|}$ (where ω_{Hi} and ω_{He} are the ion and electron cyclotron frequencies), and with a transverse wavelength $\lambda_\perp$ greatly exceeding the average Larmor radius ρ_i of the ion and the thickness δ of the inhomogeneous transition layer on the boundary of the plasma and of the beam with the vacuum. It can be shown by the method described in[12,13] that the dispersion equation of the potential long-wave perturbations of the surface-wave type, localized near the plasma boundary[1)] takes in this case, at $k_y \gg k_z$, the form

$$1+\sqrt{\varepsilon_\perp\left(\varepsilon_\perp+\frac{k_z^2}{k_y^2}\varepsilon_\parallel\right)}+\frac{k_y}{|k_y|}q=0, \tag{1.1}$$

where $\epsilon_\perp$ and $\epsilon_\parallel$ are the transverse and longitudinal dielectric constants of the magnetoactive plasma and q is the convective term connected with allowance for the spatial inhomogeneity of the system (see[12]).

Assuming that the plasma is sufficiently dense so that $\Omega_{pi} \gg \omega_{Hi}$ (where $\Omega_{pi} = \sqrt{4\pi e^2N_i/m_i}$ is the Langmuir ion frequency of the plasma), we confine ourselves to relatively high-frequency oscillations with $\omega \gg \omega_{Hi}$, which are at resonance with the beam, and for which $\delta\omega \equiv (\omega - k_zV_0) \ll \omega_{Hi}$. Assuming further that the beam ion velocity lies in the interval $c_s \ll V_0 \ll v_e$ (where $c_s = \sqrt{T_e/m_i}$ is the velocity of the ion sound in a nonisothermal plasma and $v_e = \sqrt{2T_e/m_e}$ is the average thermal velocity of the electrons), and neglecting small imaginary terms $\sim V_0/v_e$ that describe the resonant damping of the oscillations by the "hot" plasma electrons, we obtain, taking the inequality $k_zd_e \ll 1$ into account ($d_e = \sqrt{T_e/4\pi e^2N_e}$ is the electron Debye screening radius)

$$\varepsilon_\perp \approx 1+\frac{\omega_{pi}^2}{\omega_{Hi}^2}-\frac{\Omega_{pi}^2}{(k_zV_0)^2},$$
$$\varepsilon_\parallel \approx \frac{1}{k_z^2d_e^2},\quad q\approx\frac{\omega_{pi}^2}{\omega_{Hi}\delta\omega} \tag{1.2}$$

($\omega_{pi} = \sqrt{4\pi e^2n_0/m_i}$ is the Langmuir frequency of the beam ions). Substituting (1.2) in the dispersion equation (1.1), we see readily that under the condition

$$\Omega_{pi}\left(1+\frac{1}{k_y^2d_e^2}+\frac{\omega_{pi}^2}{\omega_{Hi}^2}\right)^{-1/2} \leqslant k_zV_0 \leqslant \Omega_{pi}\left(1+\frac{\omega_{pi}^2}{\omega_{Hi}^2}\right)^{-1/2} \tag{1.3}$$

the frequency correction $\delta\omega$ becomes complex, corresponding to unstable oscillations with $k_y > 0$.

With the aid of the formal substitution $k_y \to m/R$, where R is the radius of the beam and of the plasma and m is the number of the azimuthal mode of the oscillations ($m = \pm1, \pm2, \ldots,$) we can change over to the case of a cylindrically symmetrical system. Then the unstable waves are the axially-asymmetrical surface waves propagating azimuthally in the direction of the Larmor rotation of the ions ($m > 0$).

[1)]We have in mind a solution that decreases exponentially on both sides of the boundary: $\xi(x) \sim \exp\{-\kappa|x|\}$.

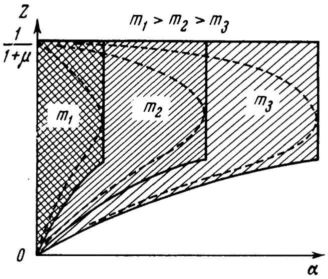

FIG. 1. Oscillation instability regions for different azimuthal modes (shaded) on the plane of the parameters $Z = (k_z V_0/\Omega_{pi})^2$ and $\alpha = (d_e/R)^2$. $\mu = (\omega_{pi}/\omega_{Hi})^2$ is a parameter. The maximum-increment lines are shown dashed.

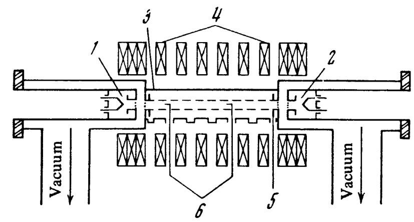

FIG. 3. Diagram of experimental setup. 1, 2—ion sources, 3—chamber, 4—magnetic-field coils, 5—diaphragms, 6—probes.

The maximum oscillation-buildup increment $\gamma \equiv \operatorname{Im} \delta\omega$, equal to

$$\gamma_{max} = \frac{m}{|m|} \frac{\omega_{pi}{}^2}{2\omega_{Hi}}, \tag{1.4}$$

is reached at certain optimal values of the longitudinal wave number k_z, equal to $k_z^{(1)} \approx mc_s/RV_0$ and $k_z^{(2)} \approx \Omega_{pi}/V_0$, under the condition $\omega_{pi} \ll \omega_{Hi}$ and $d_e \ll R$. In this case the frequencies of the excited oscillations, corresponding to the maximum increment (1.4), are equal to $\omega^{(1)} \approx k_z^{(1)} V_0 \approx mc_s/R$ (transverse ion sound) and $\omega^{(2)} \approx k_z^{(2)} V_0 \approx \Omega_{pi}$ (ion Langmuir oscillations). An analysis of the dispersion equation (1.1) with allowance for (1.2) shows that the transverse wave number k_y of the unstable oscillations is bounded from above by the inequality

$$\frac{k_y{}^2 d_e{}^2}{1 + k_y{}^2 d_e{}^2} \leqslant \frac{1}{3}, \quad \text{i.e.} \quad m^2 \left(\frac{d_e}{R}\right)^2 \leqslant \frac{1}{2}. \tag{1.5}$$

Figure 1 shows the oscillation instability regions (shaded), determined by the conditions (1.3) and (1.5), on the plane of the dimensionless parameters $Z \equiv (k_z V_0/\Omega_{pi})^2$ and $\alpha \equiv (d_e/R)^2$ for different azimuthal modes m. The dashed curves are the maximum-increment lines.

A more consistent analysis of the problem within the framework of cylindrical geometry leads to a shift of the regions of the boundaries of the instability ($m^2\alpha \le 1/4$), and also to the appearance of a dependence of the maximum oscillation-buildup increment on the mode number m and on α. Figure 2 shows plots of γ_{max} against α for different m. It follows from them that when the parameter $\alpha \equiv T_e/4\pi e^2 N_e R^2$ is decreased monotonically (for example, as a result of an increase in the electron concentration or in the plasma and beam radius) there should be a successive excitation of ever-increasing azimuthal modes.

The foregoing instability of long-wave oscillations (of the surface-wave type) excited by an ion beam in a bounded plasma is the analog of the collisionless current-convective instability of an inhomogeneous plasma with a current and of the drift-beam instability of inhomogeneous electron beams in a plasma in a longitudinal magnetic field, which were previously investigated theoretically[13-15] and experimentally[16,17].

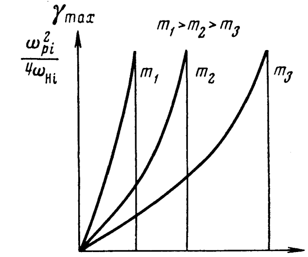

FIG. 2. Dependence of the maximum increment of the oscillations $\gamma_{max}(m, \alpha)$ on α in a system having a cylindrical geometry.

It should be noted that this instability, generally speaking, is convective. However, in the case when two opposing ion beams of equal density and velocity[2)] are symmetrically injected into the plasma along $\mathbf{H}_0$, it becomes absolute and, in spite of the smallness of the increment ($\gamma \ll \omega$), it can lead to generation of plasma oscillations of sufficiently large amplitude.

2. EXPERIMENTAL SETUP

To observe and investigate the instability of ion beams propagating along a magnetic field in a plasma produced by the beam itself, we used the setup shown schematically in Fig. 3, which operated in a stationary regime. Two identical ion sources with output openings of 7 mm diameter were placed on the ends of a metallic chamber of 14 cm diameter and 70 cm length. The source-anode openings, through which the ions were emitted, and also the openings of the ion-accelerating electrodes, were covered with tungsten grids of 0.7 mm mesh. Insulated diaphragms with 25 mm aperture diameters, to which different potentials relative to the grounded chamber could be applied, were installed near the ends of the chamber. The ion sources and the chamber were in a constant homogeneous magnetic field of maximum intensity 10 kOe. The experiments were performed with argon-ion beams of current up to 1 mA and with helium beams of current up to 3 mA. The beam energies could be varied up to 10 kV. The working gas-pressure range in the chamber was 2×10^{-5}—3×10^{-4} mm Hg in the case of argon and (1—7) $\times 10^{-4}$ mm Hg in the case of helium.

The concentration of the slow ions of the plasma produced by the ion beams was estimated from the ion balance with allowance for the losses at the ends, and also from the ion current to the probe. These estimates have shown that at the indicated pressures the concentration of the slow ions greatly exceeded the concentration of the ions in the beams and could reach $N_i \sim 3 \times 10^9$ cm^{-3}. This conclusion agrees with the data of[18], where the plasma concentration was determined by a resonator method. The electron temperature was estimated from probe measurements performed at relatively weak magnetic fields, and was usually of the order of $T_e \sim 10$ eV. The oscillations were registered with movable cylindrical probes of 0.5 mm diameter and 10 mm length, oriented along the magnetic field. The frequency spectra of the oscillations were observed with the aid of an S4-8 panoramic spectrum analyzer.

2)It can readily be shown that all the results given above remain in force in this case too, if Ω_{pi} is replaced everywhere by $\tilde{\Omega}_{pi} = \sqrt{\Omega_{pi}^2 + \omega_{pi}^2/4}$.

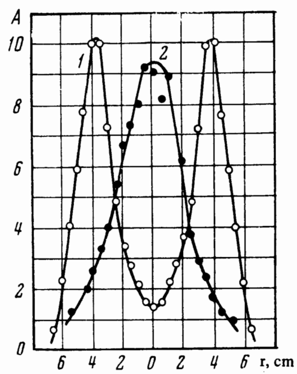

FIG. 4. Radial distribution (in relative units) of the oscillation amplitude (1) and of the ion current to the probe (2). Ar, p = 1.4 X 10^{-4} mm Hg, H = 4 kOe.

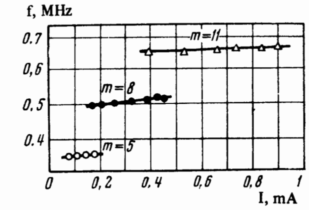

FIG. 6. Dependence of oscillation frequency on the ion-beam current. Ar, H = 4.5 kOe, p = 1.5 X 10^{-4} mm Hg.

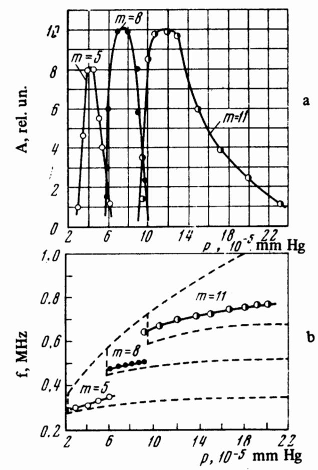

FIG. 7. Dependence of the amplitude (a) and of the frequency (b) of the oscillations for different modes on the argon pressure in the chamber (H = 5 kOe, I ≈ 0.8 mA).

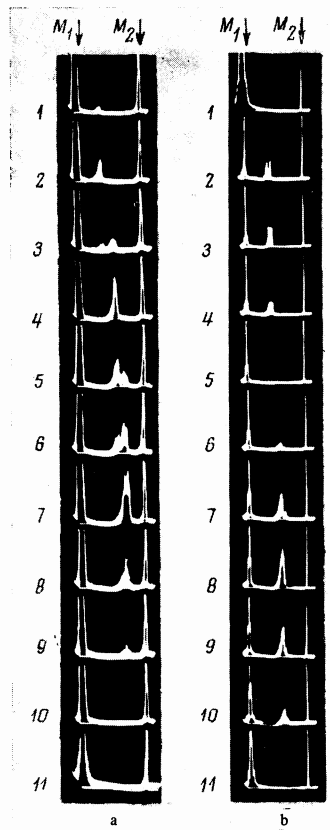

FIG. 5. Typical spectra of the oscillations vs. the beam current: a – for Ar (H = 4.5 kOe, p = 1.2 X 10^4 mm Hg, f_{M1} = 0, f_{M2} = 1.5 MHz):

Frame number:

I, mA: ~0.1 ~0.15 ~0.2 ~0.3 ~0.4 ~0.45 ~0.6 ~0.8 ~1 ~1.5

Frame 11 was obtained under conditions corresponding to frame 7; one of the ion sources was turned off; the gain of the receiving circuit was increased by 30 times. b – For He (H = 4 kOe, p = 5 X 10^{-4} mm Hg, f_{M1} = 0, f_{M2} = 8 MHz):

Frame number:

I, mA: ~0.7 ~2 ~2.5 ~2.8 ~3 ~3.2 ~3.5 ~3.8 ~4 ~4.5 ~5

3. EXPERIMENTAL DATA AND DISCUSSION

The main experimental data obtained with the installation described above reduce to the following:

1) When two opposing ion beams with equal currents and energies pass through the chamber along a magnetic field of intensity H_0 = 2—10 kOe, oscillations are registered with frequencies in the range f = 0.3—1 MHz for argon and f = 2—6 MHz for helium, which are 2—5 times larger than the corresponding cyclotron frequencies.

2) The maximum of the oscillation amplitude is localized near the beam boundary, in the region of maximum density gradient. Figure 4 shows the radial distribution of the ion current to the probe and of the oscillation amplitude.

3) In the azimuthal direction, the oscillations are almost sinusoidal waves propagating in the direction of the Larmor rotation of the ions (m > 0).

4) When the beam current is increased, a successive excitation of higher azimuthal modes is observed (m = 5, 8, 11). The oscillation frequency remains practically constant within the region of existence of the given mode, and then, at a certain critical current value I_{cr}, it increases jumpwise, corresponding to a transition to the higher azimuthal mode. Figure 5 shows typical oscillation spectra for Ar and He as functions of the beam current, and Fig. 6 shows the dependence of the oscillation frequency on this current.

5) The excitation of oscillations with different modes is analogous in character also when the gas pressure in the chamber is increased. This is illustrated by Fig. 7, which shows plots of the amplitude and of the frequency of the oscillations against the pressure.

6) With increasing magnetic field intensity, lower and lower azimuthal modes are successively excited, and the oscillation frequency first increases linearly (within the limits of a given mode), and then decreases jumpwise (on going to a lower mode). The dependence of the oscillation frequency on the magnetic field is shown in Fig. 8.

7) When one of the beams is turned off, the character of the oscillations remains unchanged, but their amplitude decreases by almost two orders of magnitude (Fig. 5, frame 11).

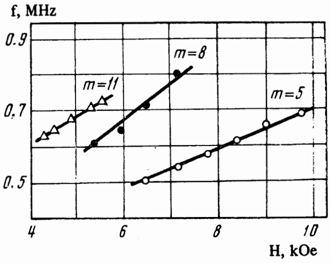

FIG. 8. Dependence of the oscillation frequency on the magnetic field for different modes. Ar, I ≈ 0.8 mA, p = 1.2 × 10^{-4} mm Hg.

8) The excitation of the oscillations does not depend on the potential applied to the diaphragms (i.e., on the potential of the plasma relative to the walls of the chamber) in a wide interval of variation of the latter (from +20 to −400 V).

Let us compare the experimental data with the results of the theoretical analysis. We note first that under the experimental conditions the plasma and beam parameters correspond to the assumptions made in Sec. 1. Thus, for example, in the case of argon beams in argon gas the ion Langmuir frequency of the plasma produced by the beams ($\Omega_{pi} \approx 4 \times 10^6 - 6.5 \times 10^6$ sec^{-1} at $N_i \approx 4 \times 10^8 - 1 \times 10^9$ cm^{-3}) exceeded by several times both the ion cyclotron frequency ($\omega_{Hi} = 10^6 - 2.5 \times 10^6$ sec^{-1} at H_0 = 4–10 kOe) and the Langmuir frequency of the beam ions ($\omega_{pi} \approx 0.7 \times 10^6 - 1.4 \times 10^6$ at $n_0 \approx 1 \times 10^7 - 4 \times 10^7$ cm^{-3}), and the velocity of the ion beams ($V_0 = 0.5 \times 10^7 - 2 \times 10^7$ cm/sec) greatly exceeded the velocity of the ion sound ($c_s \approx 5 \times 10^5$ cm/sec at $T_e \sim 10$ eV), and at the same time was much smaller than the average thermal velocity of the electrons ($v_e \approx 1.8 \times 10^8$ cm/sec).

As noted in Sec. 1, one of the excited modes, with maximum increment at $\omega_{pi} < \omega_{Hi}$ and $d_e \ll R$, corresponds to transverse ion sound with frequency

$$\omega \approx mc_s/R \ (m = 1, 2, 3, \ldots). \tag{3.1}$$

It follows therefore that the oscillation frequency is practically independent of the beam current and gas pressure, and should change jumpwise on going from one mode to another, in accord with the experiments (Figs. 5–7).

Probe measurements have shown that the radius of the ion beams and of the plasma R decreases with increasing magnetic field intensity (owing, apparently, to the decrease of the Larmor radius of the ions and of the coefficient of transverse diffusion of the plasma). Thus, the oscillation frequency, according to (3.1), should increase within the limits of each mode with increasing H_0, in agreement with the experimental results (see Fig. 8). The sequence and the conditions of excitation of different azimuthal modes in the experiments can be understood with the aid of Figs. 1 and 2 (Sec. 1). Indeed, with increasing beam current or gas pressure, the concentration of the "ion-beam" plasma increases (and consequently also the electron concentration N_e), as a result of which the parameter $\alpha \equiv (d_e/R)^2 \sim 1/N_e$ decreases. As follows from Figs. 1 and 2, at definite critical values of the current $I_{cr}^{(m)}$ and of the pressure $p_{cr}^{(m)}$ all the higher modes of the oscillations should be excited in succession, as is indeed observed in experiment (see Figs. 5 and 7). We note that the relations

$$m^2/I_{cr}^{(m)} = \text{const}, \quad m^2/p_{cr}^{(m)} = \text{const}, \tag{3.2}$$

which follow from the condition (1.5) with allowance for the experimentally observed proportionality of N_e to I and p, are also well satisfied in the entire range of variation of the system parameters. Figure 7b shows, in addition to the experimental points, the boundaries (dashed) of the instability regions for different modes, calculated in accordance with conditions (1.3) and (1.5) with allowance for the growth of the plasma concentration with increasing pressure. We see that the agreement between theory and experiment is perfectly satisfactory both with respect to the value of $p_{cr}^{(m)}$ for different m, and with respect to the frequency range.

With increasing magnetic field, as noted above, a decrease of R takes place, as well as a certain increase of N_e. However, the parameter $\alpha \sim 1/R^2N_e$ increases on the whole with increasing H_0 and, according to Figs. 1 and 2, the excitation of the oscillations should occur in reversed order, from the higher modes to the lower ones, in accord with experiment (Fig. 8).

The fact that the experimentally observed oscillations are localized near the beam boundary and propagate in azimuth towards the Larmor rotation of the ions also agrees with the theory. The sharp decrease of the oscillation amplitude when one of the beams is turned off is due to the transition from absolute instability to convective instability with a small increment $\gamma \ll \omega$.

Finally, the fact that the oscillation excitation conditions do not depend on the potential of the end diaphragms indicates that the oscillations are not connected with the electric field in the plasma (in particular, with the presence of secondary electrons).

The foregoing comparison of the experimental data with the conclusions of the theoretical analysis gives grounds for concluding that we have observed drift-beam instability of radially-bounded ion beams in a plasma situated in a longitudinal magnetic field.

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[1]M. V. Babykin, E. K. Zavoĭskiĭ, L. I. Rudakov, and V. A. Skoryupin, Zh. Eksp. Teor. Fiz. **43**, 1976 (1962) [Sov. Phys. JETP **16**, 1391 (1963)].

[2]M. D. Gabovich and G. S. Kirichenko, Zh. Eksp. Teor. Fiz. **42**, 1478 (1962) [Sov. Phys. JETP **15**, 1026 (1962)].

[3]W. Hermann and Th. J. Fessenden, Phys. Rev. Lett. **18**, 535 (1967).

[4]M. D. Gabovich and I. A. Soloshenko, Zh. Tekh. Fiz. **41**, 1627 (1971) [Sov. Phys. Tech. Phys. **16**, 1281 (1972)].

[5]B. B. Kadomtsev, Fizika plazmy i problema upravlyaemykh termoyadernykh reaktsiĭ (Plasma Physics and the Problem of Controlled Thermonuclear Reactions), Vol. 4, AN SSSR, 1958, p. 364.

[6]A. I. Akhiezer, A. B. Kitsenko, and K. N. Stepanov, Zh. Eksp. Teor. Fiz. **40**, 1866 (1961) [Sov. Phys. JETP **13**, 1311 (1961).

[7]A. A. Rukhadze, Zh. Tekh. Fiz. **32**, 669 (1962) [Sov. Phys. Tech. Phys. **7**, 488 (1962)].

[8]D. G. Lominadze and K. N. Stepanov, Zh. Tekh. Fiz. **34**, 1823 (1964) [Sov. Phys. Tech. Phys. **9**, 1408 (1965)]; Nucl. Fusion **4**, 281 (1966).

[9]A. B. Mikhaĭlovskiĭ and É. A. Pashitskiĭ, Zh. Tekh. Fiz. **35**, 1960 (1965) [Sov. Phys. Tech. Phys. **10**, 1507 (1966)].

[10]I. S. Baĭkov and A. A. Rukhadze, Zh. Tekh. Fiz. **35**, 1913 (1965) [Sov. Phys. Tech. Phys. **10**, 1477 (1966)].

[11]V. I. Petviashvili, Zh. Tekh. Fiz. **37**, 206 (1967) [Sov. Phys. Tech. Phys. **12**, 144 (1967)].

[12]É. A. Pashitskiĭ, Zh. Tekh. Fiz. **38**, 1020 (1968) [Sov. Phys. Tech. Phys. **13**, 853 (1969)].

[13]A. B. Mikhaĭlovskiĭ and É. A. Pashitskiĭ, Zh. Eksp. Teor. Fiz. **48,** 1787 (1965) [Sov. Phys. JETP **21,** 1197 (1965)].
[14]A. B. Mikhaĭlovskiĭ, Zh. Eksp. Teor. Fiz. **48,** 380 (1965) [Sov. Phys. JETP **21,** 250 (1965)]; Zh. Tekh. Fiz. **35,** 1933 (1965) [Sov. Phys. Tech. Phys. **10,** 1490 (1966)]; Zh. Tekh. Fiz. **35,** 1945 (1965) [Sov. Phys. Tech. Phys. **10,** 1498 (1966)].
[15]L. S. Bogdankevich, E. A. Lovetskiĭ, and A. A. Rukhadze, Nucl. Fusion **6,** 9 (1966); Nucl. Fusion **6,** 176 (1966).
[16]M. V. Nezlin and A. M. Solntsev, Zh. Eksp. Teor. Fiz. **53,** 437 (1967) [Sov. Phys. JETP **26,** 290 (1968)].
[17]M. V. Nezlin, M. I. Taktakishvili, and A. S. Trubnikov, Zh. Eksp. Teor. Fiz. **55,** 397 (1968) [Sov. Phys. JETP **28,** 208 (1969)].
[18]G. J. Bracenhoff and J. M. Houtcooper, 9th Intern. Conf., Phenomena Ioniz. Gases, Bucharest, 1969, p. 514.

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