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Propagation of a microwave discharge in heavy atomic gases

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Results are presented of an experimental investigation of the parameters of a moving microwave discharge in argon, viz., the velocity, geometry, temperature, and electron density. It is found that at pressures exceeding a certain critical value diffusion of resonance radiation plays the main role in the discharge motion. At low pressures, electron diffusion exerts an additional effect on the discharge velocity. Satisfactory agreement between the experimental results and the theory of a microwave discharge set in motion by resonance-radiation diffusion {[V. I. Myshenkov and Yu. P. Raǐzer, Zh. Eksp. Teor. Fiz. 51, 1822 (1972) [Sov. Phys. JETP 24, 969 (1972)]} can be obtained by taking into account the dependence of the excited-atom ionization constant and the fraction of the microwave energy consumed by excitation of the resonance levels on E/P. The motion of the ionization front in argon is accompanied by contraction of the discharge and the formation of shock waves. Addition of molecular hydrogen or nitrogen gas reduces the discharge velocity considerably, the quenching of the argon resonance levels by the molecular impurities playing a major role in the velocity reduction.

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Earlier investigations[1,2] of the mechanism whereby a microwave discharge propagates in air or nitrogen have demonstrated the exceptional usefulness of the idea of the analogy between the propagation of a discharge and the process of slow combustion; this analogy is based on the decisive role played by the thermal conductivity of the gas.[3] However, the very first experiments on the motion of microwave discharges in inert gases at high pressure[1,4,5] have led to the conclusion that their speed, 10^4-10^6 cm/sec, can apparently not be connected with atomic thermal conductivity.

On the other hand, the use of the energy equation demonstrates that at such velocities of the discharge front, the gas behind the front remains practically unheated, i.e., we are dealing with a non-equilibrium-ionization wave, which is not connected with the motion of the gas as a whole.

From an analysis of the published data it is seen that to describe the propagation of microwave discharges in inert gases one can invoke the following mechanism[6–8]: microwave breakdown on the discharge front, diffusion of the resonant radiation, and diffusion of the charged particles.

A theoretical analysis of microwave breakdown[6] would call, in the course of the solution of the problem, for far-reaching assumptions, principal among which are constancy of the electron temperature during the course of the development of the ionization by the direct electron impact, a Maxwellian type of distribution function of the electrons, and the use of the geometrical optics approximation. It has turned out that the result of the solution depends strongly on the form of the initial distribution of the electron density in the plasma cluster, while typical values of the discharge velocities agree in order of magnitude with those observed.

Calculations of the process of the motion of the ionization wave as a result of diffusion of the resonant radiation[7] were made under the assumption that this process determines the density of the excited atoms, which are then ionized by direct electron impact. Recombination and diffusion of the electrons proceed slowly and are insignificant in the energy-release zone. The discharge velocities are large and close to those typical of microwave breakdown.

Finally, the influence of the diffusion of the charged particles was analyzed by Bulkin, Ponomarev, and Solntsev,[6] who studied the motion of an ionization front in long tubes at pressures ~0.1 mm Hg. They have assumed that during the second stage of the discharge development the ionization wave constitutes an electron-density wave whose motion is due to diffusion. The electron losses are also determined by their diffusion to the

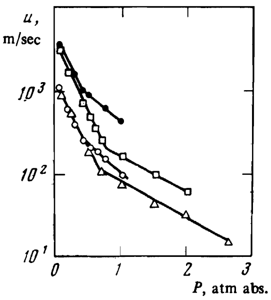

FIG. 1. Dependence of the microwave-discharge velocity on the pressure in argon for tubes of various diameters at different power-supply levels: ●— ⌀ 20 mm, W=1200 W; □— ⌀ 9.5 mm, W=1200 W; Δ— ⌀ 6.5 mm, W=1200 W; ○— ⌀ 20 mm, W=500 W.

tube wall. This has yielded a simple connection between the wave velocity, on the one hand, and the frequency of ionization by electron impact and the tube radius, on the other. The measured and calculated[8] velocities were in good agreement with one another and turned out to be of the same order as the characteristic velocities for microwave-breakdown processes and for the diffusion of resonant radiation.

A theoretical analysis of the different models of fast-discharge propagation has shown thus that the characteristic values of the velocities are of the same order. This circumstance, with allowance for the serious character of the assumptions made in the analysis, makes it impossible to determine the mechanism responsible for the discharge propagation by simply comparing the calculated and measured velocities. Additional experimental proof of the predominance of one mechanism or another is necessary. There is in effect only one published attempt at such an approach to the problem. Betke and Ruess[9] have investigated experimentally the motion of a discharge in inert gases in the pressure range from 0.35 to 3 mm Hg at electromagnetic-power flux densities from 0.1 to 100 W/cm^2 at a frequency 8.35 GHz. Depending on the experimental conditions, the discharge velocities ranged from 2×10^3 to 10^7 cm/sec.

On the basis of the results of the investigation of the influence of various factors on the discharge velocity, Betke and Ruess have arrived at the conclusion that the mechanism of the motion depends on the power level and on the gas pressure. At minimal pressures and at energy flux densities exceeding 10 W/cm^2, diffusion of charged particle prevails, in good agreement with the results of Bulkin, Ponomarev, and Solntsev.[8] At pressures of 1 mm Hg and at low energy flux densities, the decisive factor is diffusion of the resonant radiation. Finally, at pressures larger than 1 mm Hg and at flux densities exceeding 10 W/cm^2, microwave breakdown takes place on the discharge front. Unfortunately, a direct comparison of the measured discharge velocities with those calculated in accordance with Jen's paper[6] is impossible in this region, because many of the assumptions made by Jen are not satisfied. At the same time, the calculations of Myshenkov and Raĭzer[7] for this region result in good agreement with the plasma parameters, but turn out to be undervalued by a factor 5–10 when it comes to the discharge propagation velocity.

This brief analysis of the published data has stimulated a thorough experimental investigation, aimed at identifying the motion mechanisms, of both the process of microwave-discharge propagation in heavy inert gases at different pressures, and of the influence exerted on this process by different external factors (power level, geometry of the discharge volume, external magnetic field, etc.).

To investigate the discharge we used a previously described experimental setup,[1] which made it possible to excite a discharge in long glass and quartz tubes at pressures up to several atmospheres and at power inputs up to 2000 W. The investigated gases were Ne, Ar, and Xe but, recognizing that the discharge velocities, their dependence on the microwave power level and on the gas pressure, as well as the waveforms of the discharges are practically the same for all the investigated gases,[4,10] we shall report mainly the experimental results on argon.

The very first experiments on the discharge development and on the formation of the plasma mirror have shown that, in contrast to discharge in nitrogen or air, there is no initial section in which the motion has a higher velocity. The discharge moves uniformly along the entire tube, with the possible exception of a region on the order of the tube diameter, as is evidenced by a signal from an electrostatic probe that records the picture of the standing wave in front of the moving discharge. When the discharge moves past the electrostatic probe, the recorded signal indicates that the power is practically entirely absorbed over a distance ~10 cm behind the discharge front and there is no leakage to the region behind the discharge. The reflections from the discharge amount to approximately 25–30% of the incident power and depend little on the pressure.

The dependence of the discharge velocity on the pressure at different power-supply levels and different tube diameters is shown in Fig. 1. Attention is called to the presence of pressure region where a rather distinct change takes place in the character of the function $u(P)$ and may demonstrate that one motion mechanism is replaced by another.

Additional information, in many respects unexpected, was obtained in the investigations of the waveform of the discharge, using streak photography of the motion of the discharge along slits in the narrow and broad walls of the waveguide and photography of the discharge through the same slit by using a camera with its shutter open during the entire discharge motion. Photographs of this type are shown in Fig. 2, while the scan of the motion is shown in Fig. 3. Attention is called above all to the filamentary character of the discharge, which is most clearly pronounced at high pressures. At low pressures, besides the filaments, a plasma filling the entire tube cross section is observed. The filaments stretch both along the tube at the wide walls of the wave guide, and across the tube, and are practically station-

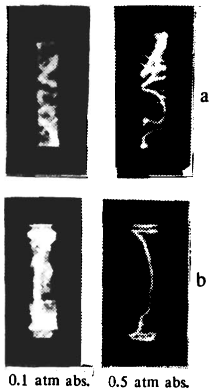

FIG. 2. Discharge in argon as viewed from the broad (a) and narrow (b) waveguide walls. $W = 1200$ W. Tube diameter 20 mm. Slit dimension 4×20 mm.

ary. Once produced in a given spot in the tube, they vanish only after the discharge front is displaced a certain distance and the power level becomes insufficient to maintain them.

The plasma parameters were determined by microwave, probe, and optical methods. Microwave sounding did not make it possible to determine the plasma parameters from the change in the phase of the transmitted 8-mm signal, since the signal attenuation was close to 100%. From the calculated reflection and transmission coefficients of the wave for a plasma with length on the order of the wavelength and with different electron distributions in the layer[11] it can be concluded that at pressures ~0.1 atm the electron density in the discharge is $\sim 10^{13}$ cm^{-3}. With increasing pressure, the signal damping decreases, possibly as a result of the more clearly pronounced structure of the discharge.

Measurements using electric probes were carried out also at a pressure 0.1 atm and yielded $n_e \sim 10^{13}$ cm^{-3} and $T_e \sim 10$ eV. The value of T_e measured by the probe method, just as in the case of nitrogen plasma, must be regarded as overestimated. The results of the determination of the electron density agree well with the microwave measurements.

The plasma-discharge emission spectrum was investigated for a tube of 6.5 mm diameter through a trans-

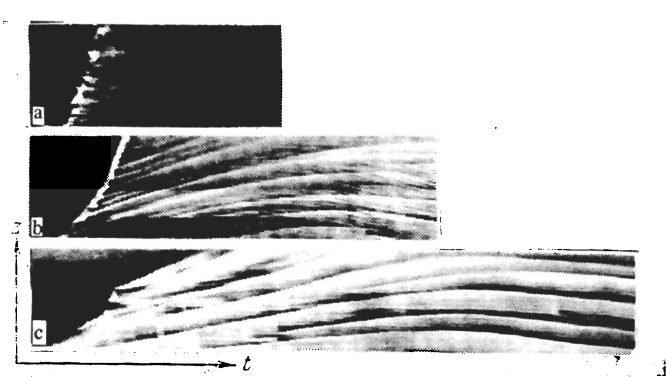

FIG. 3. Streak photograph of the discharge in argon: a) $P = 1.0$ atm abs., $W = 1200$ W; tube diameter 20 mm; b) $P = 0.5$ atm abs., $W = 1200$ W, ⌀ 6.5 mm; c) $P = 2.6$ atm abs., $W = 1200$ W, ⌀6.5 mm. Slit dimension 4×20 mm.

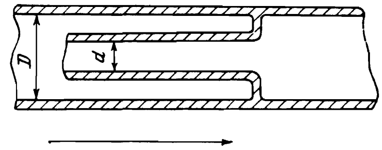

FIG. 4. Schematic diagram of the "trap." $D/d \approx 2$ for tubes with different diameters. The arrow indicates the direction of the discharge motion.

verse slit in the narrow wall of the waveguide. The spectrum contained atomic lines of argon, continuous radiation, and partially molecular bands which we identified as CN and N_2 bands. In the latter case, however, the presence of NH bands could not be excluded. It should be noted that whereas the atomic lines and the molecular bands are excited over the entire tube cross section, the continuous spectrum is present only in regions next to the tube walls facing the broad walls of the waveguide, i.e., in those regions where most filaments are concentrated. This leads to the conclusion that it is precisely these filaments which are responsible for the onset of the continuous radiation. By measuring the absolute intensity of the continuum and its frequency dependence with two monochromators tuned to two wavelengths in the near ultraviolet, we were able to determine the density and temperature of the electrons in the filaments, which were found to be $n_e = 10^{15}$ cm^{-3} and $T_e = 7500 \pm 1500$ °K, respectively, and remained practically constant for different tube diameters, power inputs, and pressures.

Thus, measurements of the plasma parameters show that the discharge, at least at low pressures, is a plasma formation with an electron density $\sim 10^{13}$ cm^{-3}, which fills relatively uniformly the entire tube cross section and is pierced through by filaments with electron density 10^{15} cm^{-3}. With increasing pressure, the plasma no longer fills the tube cross section uniformly, and the plasma with electron density $\sim 10^{15}$ cm^{-3} is concentrated mainly in the filaments. This conclusion is confirmed by direct experiment on the determination of the discharge through a constricted section of the tube (trap), a diagram of which is shown in Fig. 4. Measurements have shown that at low pressures the discharge jumps through the trap in all the tubes. Above a certain critical pressure P_{cr}, the discharge is blocked by the trap. The critical pressure coincides then, within not more than ± 10%, with the pressure corresponding to the break on the plot of the discharge velocity against the pressure for each tube.

The presented experimental data on the discharge motion in heavy inert gases allow us to advance certain general assumptions concerning the propagation mechanism. First, the negligibly small role of thermal conductivity of the gas in the propagation of the discharge is fully confirmed. Second, Fig. 1 and the experiments with the traps show that there exists a certain pressure region at which, it appears, a change takes place in the discharge-propagation mechanism.

Analyzing the results of the investigations of $P > P_{cr}$, we can assume that the foundation for the motion of the

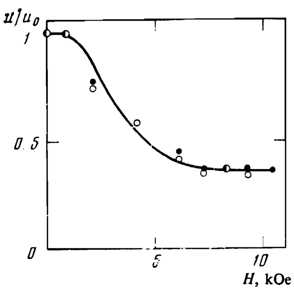

FIG. 5. Dependence of the discharge velocity in argon on the magnetic field, $P=4\times10^{-2}$ atm abs. ○—tube diameter 6.5 mm, ●—9.5 mm, ◐—6.5 and 9.5 mm.

discharge in this region appears to be the plasma preconditioning due to diffusion of the resonant radiation from regions in which the discharge already exists, followed by development of cascade ionization in the microwave field. Superimposed on the ionization-development process is a contraction of the current in the discharge,[12] which is the cause of the filamentary structure of the discharge.

At low pressures, the proposed process of discharge motion can be additionally affected by diffusion of charged particles. This process leads to an increase in the discharge velocity and to a more uniform filling of the tube cross section by the discharge plasma. At the same time, the current contraction becomes less pronounced.

Let us analyze the foregoing assumptions in greater detail. We turn first to the investigation of the role of electron diffusion. To this end, experiments were performed on the motion of the discharge in an external magnetic field oriented such that $\mathbf{H}\parallel\mathbf{E}$ and $\mathbf{H}\perp\mathbf{u}$, where $\mathbf{E}$ is the vector of the electric field in the wave and $\mathbf{u}$ is the discharge-velocity vector.

Figure 5 shows the dependence of the relative discharge velocity on the magnetic field at $P<P_{cr}$. Attention is called to the fact that the discharge velocity decreases to a definite value, which depends on the pressure, after which it remains constant and independent of H in the investigated range of magnetic fields. At $P>P_{cr}$, the discharge velocity is not sensitive to the presence of an external magnetic field of the indicated orientation. Figure 6 shows the dependence of the final discharge velocity u_f in a magnetic field on the gas pressure (lower curve). According to the hypothesis advanced above, it is precisely this discharge velocity which is determined by the diffusion of the resonant radiation. It is therefore of interest to compare the measured velocities with the results of Myshenkov and Raĭzer.[7] We note that an increase of the discharge velocity as a result of the electron diffusion at low pressures can explain the diffusion between the velocities of a discharge in xenon as calculated in[7] and measured in[9].

However, an attempt at comparing directly our present experimental results with the theory of[7] entails a considerable difficulty, due primarily to the filamentary structure of the discharge. It is impossible to get around this difficulty by assuming that the filament formation is a secondary effect of current contraction behind the discharge front and exerts no influence on its velocity. This assumption is contradicted by a number of experimental facts. First, experiments with the traps show that at high pressures the plasma is concentrated mainly in the filaments. Second, the discharge scan shown in Fig. 2 indicates that the filaments are produced directly on the front. These circumstances allow us to advance the hypothesis that the motion of the front and the contraction of the current are inseparately related, i.e., a plane discharge front is unstable. In this case the parameters of the plasma in the filaments exert a definite influence on the process of the discharge motion, but the connection between the front velocity and the plasma parameters in the filaments no longer agrees with the relations obtained by Myshenkov and Raĭzer.[7] The filaments, remaining immobile, constitute more readily an example of a stationary microwave discharge, and the parameters of the plasma in them can be estimated from the balance relations. In particular, as shown earlier,[13] if the filament radial dimensions are small the a stationary state in the filament is ensured mainly by transfer of energy to the heavy particles in elastic collisions, and by ambipolar diffusion of the electrons away from the axial zone. Indeed, simultaneous existence of six filaments of length ~15 cm and diameter 1 mm was observed at $P\sim0.5$ atm in a tube of 20 mm diameter. The discharge absorbs in this case a power ~800 W, corresponding to an energy release ~10^3 W/cm^3. By elastic collisions, the heavy particles acquire an energy

$$w_{el}=\frac{2m}{M}\nu_e n_e\cdot\frac{3}{2}k\Delta T,$$

amounting to ~5×10^2 W/cm^3 at the measured values $n_e\approx10^{15}$ cm^{-3} and $T_e\approx10^4$ °K. The frequency $\nu_i\approx\beta n_a$ of electron production in the ionization acts (β is the ionization constant[14]), and the frequency $\nu_0=6D_{amb}/r^2$ of electron departure from the axial region of the filament (D is the coefficient of ambipolar diffusion and r is the filament radius) are also of the same order of magnitude at $n_e\approx10^{15}$ cm^{-3}, namely $\nu_i\sim\nu_0\sim10^5$ sec^{-1}.

It should also be noted that a filamentary structure of the discharge in pure argon was observed by us also in investigations of stationary discharges. The plasma parameters in the filaments turn out to be of the same order as those discussed in the present paper.

To confirm the decisive influence of the parameters of the plasma in the filaments on the discharge velocity, let us analyze the dependence of the velocity on the pressure. According to[7], the velocity should depend only

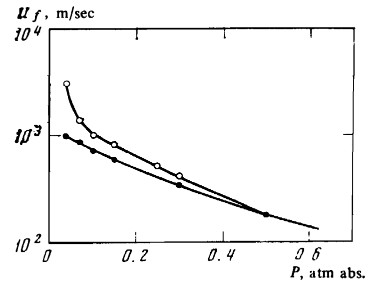

FIG. 6. Discharge velocity in a tube of diameter 6.5 mm, ○—$H=0$; ●—$H=9.3$ kOe.

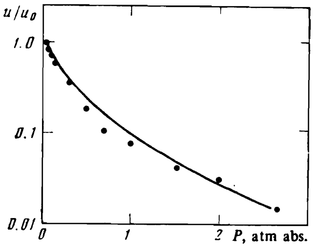

FIG. 7. Discharge velocity in a tube of 6.5 mm diameter. Solid line—calculation, points—experiment.

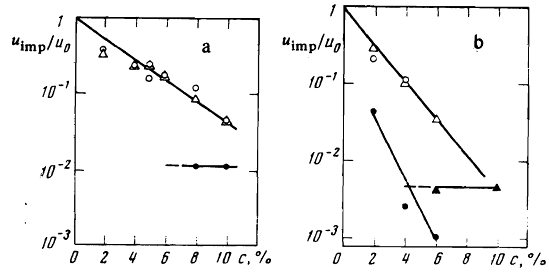

FIG. 9. Dependence of the discharge velocity in a mixture of argon with various impurities on the impurity concentration c at different pressures: a) 0.1 atm abs., b) 1.0 atm abs., circles—hydrogen, triangles—nitrogen. The light and dark symbols correspond to the fast and slow discharge-propagation mechanisms. Tube diameter 20 mm, $W=1200$ W.

little on the pressure, in view of the assumption that the atom ionization constant α as well as the fraction of the microwave energy consumed in excitation of the resonant levels are independent of the electric field. The experimental data contradict this conclusion. Estimates show that if we take into account the dependence of α and and χ on E/P[15] in the expression for the velocity of the discharge front[7]

$$u=\frac{\alpha T\chi}{2\gamma_c I^*}S$$

here T is the average time of departure of the excitation to the walls; χ is the fraction of the energy consumed in excitation of the resonant level; γ_c is a quantity characterizing the change of the absorption coefficient on the front; I^* is the potential of excitation of the resonant level; S is the density of the absorbed power flux), then the dependence of the relative velocity u^*

$$u^*=u/u_0=\alpha\chi/\alpha_0\chi_0$$

on the pressure agrees well with the experimental data of Fig. 7. It should be noted here that the plasma parameters needed to calculate α and χ were taken to be the corresponding parameters of the plasma in the filaments, while E/P was assumed equal to the ratio E/P in an empty waveguide.

Naturally, under these conditions the question of the nature of the contraction becomes exceedingly interesting. Unfortunately, we do not have enough experimental material to answer this question unambiguously, and confine ourselves therefore to two experimental facts and to some arguments that can possibly help answer this question in the future.

First, we call attention to the fact that the contraction and the appearance of the filaments are accompanied by formation of weak shock waves. These shock waves were recorded with a pressure pickup mounted in the discharge-tube end that does not contain the initiating electrodes. Thus, the pickup could register only a shock wave propagating in the direction of motion of the discharge. Figure 8 shows the dependence of the pressure-pickup signal amplitude on the discharge velocity in a tube of 20 mm diameter at atmospheric pressure. The velocity was varied by increasing the microwave power supply. The sharp maximum can be explained by the fact that at the maximum the velocity of the discharge, and consequently also the rate of formation of filaments, coincides with the velocity of the shock wave, for which we have $M\approx 2$ according to Fig. 8.

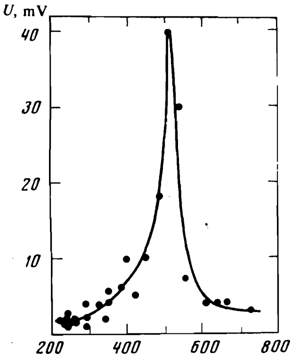

FIG. 8. Dependence of the pressure-pickup signal amplitude on the microwave discharve velocity. $P=1.0$ atm abs. Tube diameter 20 mm.

The second circumstance is connected with the sharp dependence of the discharge velocity on the admixture of the molecular gases nitrogen and hydrogen. According to Fig. 9, a small admixture of either gas influences equally the velocity, and a 10% admixture decreases the velocity by more than one order of magnitude at 0.1 atm and by more than three orders at $P=1$ atm. In our opinion this is precisely the reason why a small admixture of molecular gas in the argon is necessary to stabilize the discharge on the chamber axis in stationary waveguide microwave plasmatrons at high power. In this case the discharge, which is "smeared out" in the form of individual filaments over the discharge chambers, is converged to the chamber axis.

Figure 9 indicates also another interesting feature of the motion of the ionization front in mixtures. At sufficiently large amounts of the admixture, there exist two values of the velocity, determined by the different propagation mechanisms. Further increase of the admixture leads to a complete suppression of the "fast" propagation mechanism, and the values of the velocity agree well with the data on the propagation of discharges in the molecular gases at the corresponding pressures.

The influence of small admixtures of molecular gases on the velocity may be due to the decrease of the electron temperature as a result of inelastic collisions, and also to quenching of the resonant level by the molecules. The latter effect can be taken into account by introducing the quenching frequency with an effective cross section taken from the papers of Bochkova *et al.*[16,17] The relative change of the velocity with increasing impurity concentration then takes the form

$$u=\frac{\alpha T}{2\gamma_e I^*(1+T\sigma_M V_M N_M)},$$

where, in addition to the already employed notation, σ_M is the cross section for the quenching of the resonant level in collisions with the molecules,[16,17] V_M is the relative velocity of the colliding particles, and N_M is the molecule concentration.

When the nitrogen content is increased from 2 to 10%, the velocity, according to this expression, decreases by an approximate factor of seven, in good agreement with the experimental data.

Obviously, when the rates of excitation of the resonant level by electron impact and of its quenching in collisions with the molecules are equal, i.e., under the condition

$$B^* N_e N_a = N^* \sigma_M V_M N_M,$$

where β^* is the resonant-level excitation constant, the diffusion of the resonant radiation cannot ensure motion of the discharge. A change in mechanism should take place, accompanied by an abrupt decrease of the velocity.

It is possible that the foregoing facts indicate not only that the mechanism of discharge propagation changes, but also that the contraction mechanism changes. Most likely the contraction, as well as the motion of the front in the argon, is connected with the resonant-radiation yield. At low pressures, this effect is opposed by electron diffusion.

It is possible, however, that this does not account for the entire observed picture. The experimental section is a system in which the dielectric constant of the individual elements (air gap, tube walls, plasma filaments) undergo various jumplike changes. Under these conditions, the stationary dimension and the number of filaments can be connected also with a singularity of the interaction of the incident wave with the plasma inhomogeneities in the waveguide.

Thus, our investigations of the propagation of microwave discharges in heavy atomic gases, while confirming the basic role of the diffusion of the resonant radiation, particularly at high pressures, points to a more complicated picture of the phenomenon, the description of which calls for an examination of the question of the stability of the front and of the contraction of the current in the discharge.

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