New mechanism of gasdynamic propagation of a discharge

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Results are presented of an experimental investigation of an equilibrium microwave discharge produced in an oversize waveguide channel. The causes of the onset of the discharge in the pre-breakdown field are analyzed and the discharge dynamics is investigated. On the basis of experimental investigation of the motion of the ionization front counter to the incident electromagnetic wave, a new mechanism of discharge is proposed, connected with heating of the gas ahead of the thermal ionization front. This heating is due to absorption microwave energy in the plasma of the non-self-maintaining discharge produced by the ionizing ultraviolet radiation from the thermal-discharge region. It is shown that the stationary velocity of the ionization front is proportional, if the considered mechanism is realized, to the energy flux density of the incident microwave radiation, and the plasma and gas-temperature distributions are of universal character.

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One of the promising methods of additionally heating plasma in toroidal thermonuclear facilities is to irradiate it with a beam of electromagnetic waves of frequency corresponding to electron-cyclotron resonance (ECR). Estimates[1] have shown that the power needed for the heating should reach 10^7 W in a pulse of duration up to 10 sec. Transfer of this much energy from a generator to a plasma entails definite difficulties due to the onset of breakdowns in the transmission channels that screen completely the incident radiation. To estimate the feasibility limit of channeling systems, it is necessary to start with the dielectric strength of air, equal at atmospheric pressure to $E_{\rm br} = 3\times 10^4$ V/cm. Accordingly, the maximum power that can be transmitted in a Gaussian beam of diameter d [cm] in air at atmospheric pressure is $P_i^m \approx 10^6 d^2$ W. In real conditions electromagnetic energy is transmitted through waveguide channels or quasi-optic waveguide lines. The maximum power that can be transmitted from the source to the consumer is then much lower than P_i^m. These are precisely the difficulties encountered in the preparations for the investigations of additional plasma heating at the electron-cyclotron frequency in the T-10 tokamak ($f_0 = 8.5\times 10^{10}$ Hz). It was observed that the maximum power that could be passed through a round waveguide channel of 8 mm diameter dependent on the duration τ_i of the radiation pulse. At $\tau_i \leqslant 5\times 10^{-3}$ sec the radiation power could exceed $P_i > 2\times 10^5$ W. With a longer pulse, breakdown set in at $P_i \lesssim 5\times 10^3$ W. It is easy to estimate that a waveguide diameter $d = 50$ cm is necessary to transfer the power needed for heating in this case. Such channel dimensions exceed substantially the dimensions allowed by the facility construction.

To assess the feasibility of increasing the dielectric strength of waveguide systems, the dynamics of a discharge in an oversize waveguide was investigated in pre-breakdown fields ($E < E_{\rm br}$).[3] Analysis of various factors that determine the value of the field $E_{\rm thr}$ at which breakdown occurs in a waveguide[4–6] has shown that principal among them is the presence of small-scale (compared with the wavelength) metallic inhomogeneities, near which quasistatic field enhancement sufficient for local breakdown of the gas occurs. In the plasma produced near sharp tips, energy is absorbed from the electromagnetic wave and the gas is intensely heated. Further development of the discharge in a strong pre-breakdown field is possible only if the gas is heated to a temperature that ensures effective ionization. In this case the discharge propagation is due to successive heating of new batches of the surrounding cold gas. Raizer[7] considered in his monograph different discharge-propagation mechanisms connected with heating of cold gas via heat transfer from a heated region. The character of the heat-transfer processes is determined by the gas-heating intensity, i.e., depends on the ratio of the gas pressure P_0 to the energy flux density S_0 in the incident wave.

In its time, numerous experiments at both optical and microwave frequencies have demonstrated the exceptional usefulness of the analogy with heating. However, measurements of the parameters of a microwave discharge at high radiation-energy flux density (up to several dozen kilowatts per square centimeter) have pointed to the existence of a principally new discharge-motion mechanism, not connected with heat transfer and having no analogy with combustion. The principal role in this mechanism is played by ultraviolet radiation (UVR) from the heated region, which ionizes the cold gas in front of the discharge.[1)] This gas is heated to the thermalionization temperature by absorbing the microwave-field energy in the pre-plasma, i.e., in fact in the non-self-maintaining discharge. We report here a qualitative investigation of the general laws governing this "photoionization" mechanism of the gasdynamic propagation of a discharge and analyze the results of the experiments that attest to its realization.

1. EXPERIMENTAL INVESTIGATION OF AN EQUILIBRIUM DISCHARGE

The discharge was investigated with a setup that served as the prototype of a module used for electron-cyclotron heating of plasma in the T-10 tokamak. The waveguide diameter was $d = 8$ cm and the waveguide section was $L = 100$ cm long. The microwave generator was a gyrotron operating at a frequency $f_0 = 85.71$ GHz ($\lambda_0 = 3.5$ mm) and

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generating pulses of duration τ_i from 0.1 to 20 msec. The maximum pulse power of the generator reached 250 kW. The generator shaped a Gaussian pulse of 5 cm diameter and with a divergence angle $\theta = 4°$. Emission of the beam into the 8-cm-diameter waveguide established in the latter an H_{11} mode at a length $l \approx 50$ cm.

The following characteristics were measured:

1. The discharge propagation velocity and the dimensions of the luminous region. They were determined with a collimated photomultiplier.

2. The electron-density distribution. It was measured with two double probes constituting two parallel wires of 0.1 mm diameter stretched across the waveguide perpendicular to the field **E** and separated by 3 mm.

3. The electron density averaged over the discharge diameter. It was calculated from the absorption of the weak probing signal propagating along a two-conductor line (distance between conductors 2 mm) passing in a plane perpendicular to the waveguide axis.

The investigations have shown that the discharge was usually produced at the flange junctions or at the corner bend of the waveguide.

At the instant when the microwave radiation was turned on, a corona microwave discharge similar to the described in Ref. 6 was produced at the sharp points and the small-scale metallic inhomogeneities on the end cut of the waveguide or of the edges of the corner. At low power ($S_0 = 10$ kW) the corona discharge was localized at the sharp point during the entire time of action of the radiation pulse. At high power the discharge was detached from the wall and started to move towards the radiater at a velocity that changed from 10^3 to 10^4 cm/sec when the power was increased from 10 to 250 kW. An analysis of the oscillograms of the double probe and of the signal propagating along the two-conductor line,[2)] which are shown in the figure, leads to the following conclusions concerning the plasma-density distribution in the direction of the discharge motion.

1. The main growth of the electron density occurs in a region less than a millimeter thick. In this region, which could be naturally related to the leading front of the thermal (equilibrium) discharge, the electron density increased from $N_e = 10^{13}$ to $N_e > 10^{14}$ cm^{-3}.

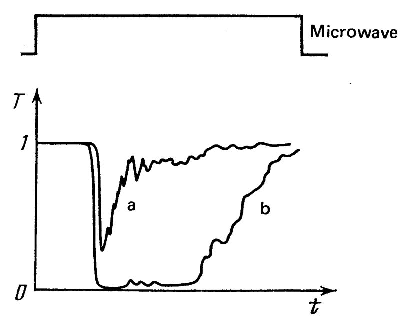

FIG. 1. Oscillograms of double-probe current (a) and of the signal from the two-conductor line (b); $T = 1$—total passage of the sounding microwave signal, $T = 0$—total absorption of the signal in the plasma.

2. After reaching the maximum density, the plasma started to decay in this region of space. The characteristic decay time was $\tau_{dec} = 0.5$ msec; the plasma-layer thickness reached 5 cm, proving that the ionization in the discharge was thermal (equilibrium). Indeed, at an electron density $N_e > 10^{14}$ cm^{-3} in the plasma the depth of the skin layer was not more than 0.1 cm and the field of the incident microwave did not penetrate into the plasma. Therefore the decay of the nonequilibrium plasma (after the screening of the field) would take place within the recombination time of the cold electrons, which equals $\tau_{dec} \sim 10^{-7}$ sec at $N_e \sim 10^{14}$ cm^{-3}, much less than the measured value.

3. An extended region about a centimeter thick, filled with relatively rarefied plasma whose density decreases slowly with increasing distance from the front and amounts to 10^{12} cm^{-3} at approximately 1 cm from the latter, is observed ahead of the equilibrium-decay front. Estimates show that such a pre-plasma absorbs a noticeable fraction (up to 20%) of the incident microwave radiation, and the gas is consequently effectively heated.

The microwave discharge is thus at equilibrium in air at atmospheric pressure and at an energy flux density $S_0 \approx 1$ kW/cm^2. However, the discharge structure (the distribution of the plasma density in space) and its propagation cannot be explained within the framework of known models of motion of thermal discharges. First, according to the slow-combustion model[7] of the heat-conduction mechanism of discharge propagation, a model applicable under the experimental conditions, the plasma-density growth scale should be 0.3–0.03 mm. Consequently, the experimentally observed extended pre-plasma layer (1 cm thick) contradicts this model. Second, the measured discharge propagation velocity v [cm/sec] in the laboratory frame is $\approx 4 \times 10^2 S_0$ [kW/cm^2] and corresponds (with allowance for the gas convection[8]) to absorption by the discharge of $\approx 20\%$ of the incident microwave radiation flux. This also contradicts the one-dimensional heat-conduction model of microwave-discharge propagation,[9] according to which a very strong reflection of the incident radiation from the discharge plasma should be observed at high microwave-energy flux densities. Estimates of the absorption coefficient Q of the incident energy flux within the framework of a simplified model with an abrupt plasma boundary[9,12] leads to a relation $Q \propto S_0^{-1/2}$, and to value $Q \approx 4\%$ for $S_0 = 20$ kW/cm^2.

The ionization of the air in front of an equilibrium discharge can be effected under our conditions by ultraviolet radiation from a discharge. The presence of photons that ionize the gas over a length on the order of 1 cm can be connected with different factors, in particular with high density of atomic oxygen and nitrogen in the plasma discharge. The observation of a pre-plasma in which up to 20% of the incident microwave radiation flux is absorbed is evidence, in our opinion, of the possibility that a decisive role in the preheating of the gas to the thermal ionization temperature is played by the absorption of the microwave energy in the preplasma rather than by the escape of energy by heat conduction from the region of the equilibrium discharge. In other words, only a discharge propagation connected with absorption of microwave energy in the pre-plasma is possible.

2. THEORETICAL INVESTIGATION OF A ONE-DIMENSIONAL OF THE NEW MECHANISM OF GASDYNAMIC DISCHARGE PROPAGATION

We confine ourselves for simplicity to a one-dimensional model of stationary discharge motion. The influence of the gas heating in the pre-plasma on the propagation of the ionization front will be investigated in the framework of the isobaric approximation of the gasdynamic model proposed by Raizer for the heat-conduction regime of discharge motion.[7,9] The gas-temperature distribution in space is described in this case by the equation.

$$\rho_0 u c_P \frac{dT}{d\xi} + \frac{d}{d\xi} \varkappa \frac{dT}{d\xi} + \sigma |E|^2 = 0. \qquad (1)$$

Here T is the gas temperature, ρ_0 is the density of the unpeturbed gas, u is the discharge velocity relative to the unperturbed gas, c_P is the specific heat of the gas at constant pressure, $\varkappa$ is the thermal-conductivity coefficient of the gas, ξ is the coordinate in a system connected with the discharge and increases in the direction of the discharge motion, and E is the complex amplitude of the electric field. The conductivity σ of the discharge plasma is determined by the electron density N_e

$$(\sigma = \nu N_e / 4\pi N_c = \nu e^2 N_e / m(\omega^2 + \nu^2)),$$

where ν is the effective frequency of the collisions of the electrons with the molecules, ω is the frequency of the incident microwave, N_c is the critical density of the plasma which we assume, in contrast to Ref. 9, to be in disequilibrium because of the photoionization:

$$N_e = N_s(T) + F(J, T), \qquad (2)$$

where N_s is the equilibrium electron density corresponding to the temperature T, and J is the intensity of the ionizing UVR; the function $F(J,T)$ is determined by the ionization balance of the gas. Assuming that the main source of the UVR is the equilibrium-discharge plasma, we can obtain from the usual transport equations for the intensity of the thermal radiation the following equation for the summary intensity of the ionizing UVR:

$$\lambda(T) \frac{d}{d\xi} \left[\lambda(T) \frac{dJ}{d\xi} \right] + J_s(T) - J = 0, \qquad (3)$$

where $J_s(T)$ is the equilibrium radiation intensity and $\lambda(T)$ is the mean free path of the ionizing UVR. To make the system closed it is necessary to add to Eqs. (1)–(3) the equation for the field:

$$d^2E/d\xi^2 + \omega^2 c^{-2} \varepsilon E = 0, \qquad \varepsilon = 1 - (1 + i\nu/\omega) N_e/N_c. \qquad (4)$$

The rate of propagation of the discharge is determined in analogy with Ref. 9 from the condition of the existence of a solution of system of equations (1)–(4), satisfying the boundary conditions corresponding to an abrupt-profile stationary discharge wave. In our case it is necessary to add to the system of boundary conditions of Ref. 9 also the condition for the intensity of th UVR at infinity: $dJ/d\xi\,|_{|\xi| \to \infty} = 0$. Absorption of the electromagnetic wave energy in the pre-plasma of a non-self-maintaining discharge causes heating of the gas. In this sense the ionizing UVR competes with the heat conduction and plays, under conditions that will be spelled out below, a decisive role in the pre-heating of the gas.[3)] In the latter case there is realized the mechanism of gasdynamic discharge propagation due to gas heating connected with the photoionization conduction. A remarkable feature of this propagation mechanism is the universality of the profile of the stationary discharge wave for different values of the microwave-energy flux density S_0, and consequently the constancy of the ratio u/S_0. Indeed, if we neglect the thermal conductivity in the system (1)–(4), S_0 is eliminated from it and from the boundary conditions by making the change of variables

$$E = \mathscr{E} S_0^{1/2}, \qquad u = S_0 U.$$

A qualitative investigation of the conditions for the realization of the discharge-propagation mechanism proposed here can be conveniently investigated using a very simple gas dynamic system with a specified power distribution of the heat source $q = \sigma |E|^2$ in the form

$$q = \begin{cases} 0, & \xi < -L, \\ q_T, \quad T > T_i, & -L < \xi < 0, \\ q_J \exp\{-\xi/\lambda\}, \quad T < T_i, & \xi > 0 \end{cases} \qquad (5)$$

and with temperature-independent specific heat and heat-conduction coefficient (T_i plays the role of the thermal-ionization temperature, λ is the mean free path of the ionizing radiation, and L is the thickness of the microwave-energy absorption layer in the equilibrium-discharge plasma). Substituting (5) in (1) and integrating the latter with account taken of the boundary conditions.

$$T|_{\xi \to \infty} = T_0, \qquad dT/d\xi\,|_{\xi \to -\infty} = 0,$$

we easily find that at sufficiently strong absorption of the microwave energy in the pre-plasma, when

$$q_J \lambda \gg \varkappa (T_i - T_0)/\lambda,$$
$$q_J \lambda \gg [q_T \varkappa (T_i - T_0)]^{1/2} \left[1 - \exp\left\{ - \left[\frac{q_T L^2}{\varkappa (T_i - T_0)} \right]^{1/2} \right\} \right] \qquad (6)$$

the thermal conductivity no longer plays a substantial role in heating the gas to the ionization temperature, and hence in the motion of the discharge relative to the gas.

It is obvious that satisfaction of the first inequality in (6) with increasing power of the incident microwave radiation is certain, but the possibility of satisfying the second calls for a special investigation. Study of the one-dimensional model of the heat-conduction regime of microwave-discharge propagation[7,9] shows that in this case $q_T L \ll \varkappa (T_i - T_0)$ and the second inequality of (6) is equivalent to

$$q_J \lambda \gg q_T L. \qquad (7)$$

Since the temperature of the equilibrium discharge in such a model increases with increasing microwave radiation power, the intensity of the UVR increases, so that the fraction of the microwave energy absorbed in the pre-plasma should increase. The fraction of energy absorbed in an equilibrium discharge decreases in this case because of the abrupt increase of the reflection coefficient of the incident microwave radiation from the discharge plasma.[7,9] Thus, investigations of the heat-conduction model demonstrate that it is inevitable that heating the gas be replaced by photoionization. We note that the possible stabilization of an equilibrium discharge by breakup into small parts, observed in experiment, does not remedy the situation. Indeed, the influence of roughness on the electrodynamic properties of the layer can take place only at a rough-layer thickness not less than one-quarter of the radiation wavelength. In this case the possible anomalously strong absorption of the incident radiation will be concentrated in the thickness of the rough layer, so that we increasing radiation power we arrive at the case $q_T L \gg \varkappa(T_i - T_0)/L$, when the second inequality of (6) leads to the condition that the effect of the heat conduction be weak, in the form

$$q_J\lambda \gg [q_T\varkappa(T_i - T_0)]^{1/2}, \tag{8}$$

satisfaction of which at high energy flux densities S_0 is likewise not subject to doubt.

The transition to the photoionization mechanism of preheating the gas and propagation of the discharge at high microwave radiation energy flux density is due to the decrease of the effectiveness of the heat-conduction mechanism of the heating with increasing S_0. In fact, according to Ref. 7, the fraction of the incident power going to preheating of the gas (it is this fraction which determines the heating efficiency) can be small because of the strong reflection of the incident electromagnetic wave or because of the stabilization of the thickness of the absorption layer in the plasma of the discharge. In both cases the efficiency of the heat-conduction gas-heating mechanism decreases with increasing S_0 like $S_0^{-1/2}$. It is here that one should expect in fact the realization of the photoionization mechanism, whose effectiveness at any rate remains constant with increasing S_0. Estimates show that under the experimental conditions of Ref. 3 (atmospheric air, microwave radiation wavelength 3.5 mm) the photoionization mechanism becomes more effective than heat conduction starting with a value of S_0 such that the fraction $q_J\lambda/S_0$ of the microwave energy absorbed in the pre-plasma becomes larger than $(10\,S_0\,[\mathrm{kW/cm^2}])^{-1/2}$. For the 20% absorption noted in these experiment the threshold of the heat-conduction regime of discharge propagation is of the order of $S_{\mathrm{thr}} \approx 3\ \mathrm{kW/cm^2}$.

We note in conclusion that the regime brought about by photoionization via reflection leads to a regime different from that resulting from saturation of the absorption coefficient of the equilibrium-discharge plasma. In the former case the total energy absorbed in the plasma increases, and hence also the convective velocity of the gas, i.e., the discharge-propagation velocity measured in the laboratory frame increases. In the latter, the change of the total energy absorbed in the plasma is negligible, therefore photoionization heating only increases the discharge velocity relative to the gas. Special investigations are needed to observe such an effect.

Analysis of the results leads to the following basic conclusions:

1. The initiation of a discharge in guiding systems is due to local breakdown of the gas at metallic inhomogeneities of the waveguide walls. To increase the transmission ability of channeling system it therefore necessary to eliminate carefully the roughness of the inner walls of the waveguide channels.

2. Screening of the waveguide sets in after its section is covered by the plasma. The maximum duration τ_m of the radiation pulse transmitted along the channel can be estimated from the discharge propagation velocity. Under our condition, for a pulse of power $P = 250$ kW transmitted over a waveguide of diameter $d = 8$ cm the value of τ_m is 4×10^{-3} sec. Since the discharge velocity increases, in accord with the performed theoretical investigations, in proportion to the microwave-radiation energy flux density, the values of τ_m of powers P can be estimated from the formula

$$\tau_m[\mathrm{sec}] \sim 10^{-3}\, d^3\,[\mathrm{cm}]/P\ [\mathrm{kW}].$$

3. Propagation of the discharge counter of the microwave radiation at high energy flux density of the latter is due to ionization of the gas by UVR from the discharge followed by heating the gas in the field of the incident electromagnetic wave. The discharge propagation velocity under these conditions can be much higher than in the heat-conduction gas-heating mechanism.

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[1)]The main difference between the discharge-propagation mechanism considered here and the one previously investigated and connected with diffusion of resonant UVR 10 is the need for heating the gas to move the ionization front. Whereas under the conditions of Bethke's experiments[11] it sufficed to ionize the gas to make it a source of UVR, under our conditions the gas must be strongly heated.

[2)]The two-conductor line used in these experiments was the double probe itself.

[3)]We note that the decisive role of UVR in the preheating of the gas in this case has nothing in common with the radiant heat conduction mechanism considered in Ref. 7, since the energy directly carried by the UVR of the heated region of the equilibrium discharge does not play a significant role in the energy balance.

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