Microwave discharge in a quasioptical resonator

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A microwave discharge in air in a quasioptical cavity is investigated experimentally at pressures $0.1 \le p \le 400$ Torr. The obtained pressure dependence of the breakdown field is compared with the calculated dependence. The electron density in the discharge plasma and the plasma decay time after termination of the microwave pulse are determined by the resonator method.

Microwave discharges in gases have been the subject of a number of experimental studies[1-3]. Interest in these discharges, apart from pure research, is due also to the large number of suggestions for their practical use particularly for the injection of plasma in various types of plasma traps, for the study of the feasibility of heating a plasma to thermonuclear temperatures[4], and to explain the nature of fireballs[5,6].

The present paper is devoted to a microwave discharge in a quasioptical resonator in the millimeter band. The use of an open resonator has made it possible to obtain a discharge insulated from the walls in a wide range of pressures.

The experimental setup is shown in Fig. 1. An open resonator made up of two round spherical mirrors of equal curvature, has the following dimensions: mirror diameter d = 15 cm, curvature radius R = 10 cm, distance between mirrors L = 19 cm. The resonator was placed in a vacuum chamber with windows for observation. The source of the microwave oscillations was a pulsed magnetron, which yielded a power up to 30 kW in a 0.8-μsec pulse. The frequency of the generated oscillations was 37 GHz. The magnetron was connected with the resonator by a waveguide channel consisting of directional couplers, a conical horn with a lens, and a grid of coupling holes in one of the mirrors of the resonator. A pressure 3–4 atm was maintained inside the waveguide channel, so that it was possible to prevent breakdowns at the junctions of the channel elements. The tuning of the resonator was monitored with the use of a directional coupler by watching the decrease of the reflected signals. The Q of the resonator excited with a rectangular grid of holes (distance between the nearest holes 4 mm, radius of hole 1.5 mm, mirror thickness 3 mm, number of holes 260) turned out to be $Q = 3.4 \times 10^4$.

The power fed to the resonator was only a fraction of the total generator power in the resonator band. The experimentally measured generator-power utilization coefficient was $\alpha = 0.6$. In addition, owing to the difference between the radii of the wave beams in the perforated mirror on the side of the waveguide channel and on the resonator side, and also owing to the fact that the curvature radius of the phase front of the incident wave turned out to be different from the curvature radius of the mirrors, a fraction $\eta = 0.9$ of the power fed to the resonator went into the TEM_{00q} excited into the resonator[7]. The rms electric field intensity at the center of the resonator was determined from the Q and from the generator power P:

$$E=[4\alpha\eta QP/\pi c\varepsilon_0 L\sqrt{2LR(1-L/2R)}]^{1/2}. \qquad (1)$$

The appearance of the discharge in the resonator was

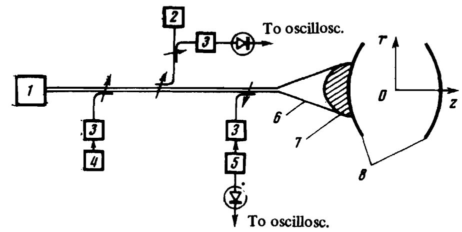

FIG. 1. Diagram of setup: 1—magnetron, 2—VI-1 power meter, 3—attenuator, 4—klystron oscillator, 5—flow-through resonator, 6—horn; 7—teflon lens, 8—open resonator.

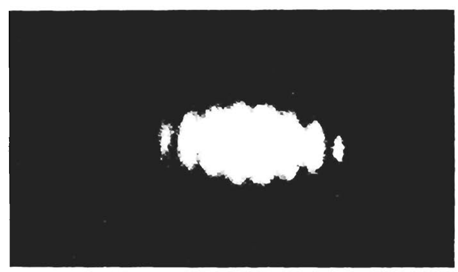

FIG. 2. Photograph of discharge at pressures less than 1 Torr.

registered visually (by the glow of the discharge) and by the change of the waveform of the reflected signal. At a total magnetron power ~30 kW, the discharge was observed at an air pressure $0.1 \le p \le 400$ Torr in the chamber. At ~400 Torr, the discharge was ignited in the central antinode of the field and had a spindle-like form elongated in the direction of the electric field. When the pressure was lowered, the discharge expanded taking the form of a disk, and at p < 100 Torr the discharge was produced at several neighboring antinodes in the central region of the resonator. At p < 1 Torr, the number of antinodes with breakdown increased to 12–13, and the characteristic form of the discharge at these pressures is shown in Fig. 2.

For different values of the pressure in the chamber, we measured the generator power P at which the discharge set in. Formula (1) was used to determine the corresponding value of the electric field intensity at the center of the resonator. The obtained dependence of E_{br} against the pressure p is shown in Fig. 3.

As is well known, there is no theory of a microwave discharge in a strongly inhomogeneous field. In different pressure ranges, however, it is possible to use certain approximations which enable us to estimate the breakdown fields. If the adhesion diffusion length $L_a = \sqrt{D/\nu_a}$ (D is the diffusion length and ν_a is the electron adhesion frequency) is small in comparison with the dimension $\tilde{a}$ of the inhomogeneity of the field, then we can use the homogeneous-field approximation. The field-inhomogeneity dimension was assumed to be the distance a over which the field decreases to one-half ($\tilde{a}_z = 0.13$ cm and $\tilde{a}_r = 0.54$ cm, where $\tilde{a}_z$ and $\tilde{a}_r$ are the dimensions of the field inhomogeneities along the axes z and r), so that the homogeneous-field approximation was used at pressures $p > 80$ Torr, so long as $L_a < \tilde{a}_z$. In a homogeneous field, the diffusion of the electrons is negligible and the breakdown condition is equality of the ionization frequency ν_i to the electron adhesion frequency ν_a.[1)] This condition is satisfied by the value of the effective breakdown field in the continuous-generation regime[3]:

$$E_e[\mathrm{V/cm}]=30p[\mathrm{Torr}], \tag{2}$$

where $E_e = E_{br}\nu_{em}/\sqrt{\omega^2 + \nu_{em}^2}$, ω is the cyclic frequency of the field, and ν_{em} is the frequency of the electron-molecule collisions. In the pulsed regime at a pulse duration 0.8 μsec, the breakdown field increases by approximately 1.2 times[3]. The corresponding theoretical curve 1 is shown in Fig. 3.

In the pressure region $20 < p < 80$ Torr, where the diffusion adhesion length is smaller than $\tilde{a}_r$ but larger than $\tilde{a}_z$ ($\tilde{a}_z < L_a < \tilde{a}_r$), we can use for the calculation of the breakdown field the results of a solution of a problem pertaining to microwave breakdown in the field of a standing wave. The dependence of the ionization frequency on the electric field intensity can be written in the form[8]

$$\nu_i=\nu_a(E/E_{br}^0)^4 \cos^4 kz, \tag{3}$$

where E_{br}^0 is the breakdown value of the homogeneous field. When solving the problem, this dependence is approximated by a piecewise-homogeneous function with period $\lambda/2$. Using the graphic relation $\nu_i/\nu_a = f(p\tilde{a})$ and the procedure described in[2] for estimating the breakdown field in the pulsed regime, we can obtain curve 2 of Fig. 3. The error in the calculation of the breakdown field when using the piecewise-homogeneous approximation for the ionization frequency does not exceed 6%.

In the pressure range $1 < p < 20$ Torr, the diffusion adhesion length L_a is larger than the dimension of the inhomogeneity of the field along the r axis ($L_a > \tilde{a}_r$). In this region, the diffusion along the z axis did not lead to a loss of the electrons, since the discharge was produced in many antinodes of the field, and the electron leaving one antinode as a result of diffusion along the z axis entered into the discharge region of another field antinode. In this range of pressures we can therefore use the approximation of a cylindrically-inhomogeneous field[2] (curve 3 of Fig. 3).

The onset of the discharge in the resonator has led to its shift to a different resonant frequency. This has enabled us to measure the concentration of the electrons in the discharge plasma. As is well known, at an electron concentration N_e lower than the critical value N_c, the resonator frequency shift is proportional to N_e. If the cyclic frequency of the field exceeds the electron collision frequency (at a probing signal frequency $\omega = 2.64 \times 10^{11}$, this holds true in the pressure region $p < 40$ Torr), then the relation between the shift of the resonant frequency f and the concentration N_e is of the form[9]

$$\frac{\Delta f}{f} = \left(\int_{V_{pl}} N_e E^2\, dV\right) \Big/ 2N_c \int_{V_r} E^2\, dV, \tag{4}$$

where V_{pl} is the volume of the plasma, V_r is the volume

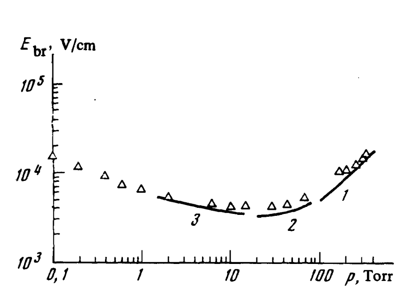

FIG. 3

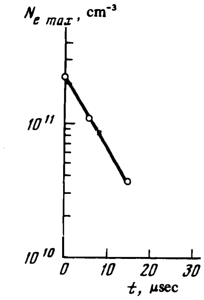

FIG. 4

FIG. 3. Dependence of the breakdown field on the pressure: f = 37 GHz, $\tau_p = 0.8$ μsec, $F_{rep} = 250$ Hz. Solid curves—calculation, △—experimental points.

FIG. 4 Plasma decay curve at 2 Torr pressure.

of the resonator, and E is the intensity of the probing field.

Simultaneously with the high-power signal, a frequency-modulated signal from a klystron generator was introduced into the resonator. The resonator tuned to the magnetron frequency was simultaneously tuned also to the frequency of the probing signal. The reflected probing signal was fed to an oscilloscope through a directional coupler and a flow-through resonator. The flow-through resonator was used to decrease the interference from the magnetron signal. A marker corresponding to the natural frequency of the resonator was seen on the klystron generation signal, and was shifted by a certain amount Δf when the discharge set in. Since the position of the discharge regions was determined by the field distribution of the high-power signal, it was necessary, in order to increase the sensitivity of the method, to choose the probing-signal frequency in such a way that its distribution near the center of the resonator was closest to the distribution of the high-power field, in which case the longitudinal indices of the oscillation modes of the high-power and of the probing signals should differ by a multiple of two. In our case these indices were 48 for the magnetron signal and 52 for the probing signal. The electron concentration N_e was determined from formula (4) under the assumption that the distribution of N_e along the z axis in each antinode of the field took the form $N_e = N_{e\,max}\cos(\pi z'/l)$, where l is the width of the plasma disk determined from the plasma luminosity and $z' = 0$ is the center of the field antinode. When the discharge was produced, the resonator was detuned relative to the magnetron frequency, the discharge stopped, and the plasma decayed. From the measurements of the resonator frequency shift we determined the electron concentration at the instant of the discharge and the change of N_e with time after the termination of the discharge. Figure 4 shows a plot of $N_e(t)$ at p = 2 Torr. The characteristic plasma-decay time was ~0.8 μsec and was determined by the adhesion and diffusion of the electrons.

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1)Generally speaking, one should compare the adhesion length L_a with the characteristic dimension of the variation of the ionization frequency ν_i, which is proportional to E^4–E^5, thereby lowering somewhat the limits of applicability of the homogeneous-field approximation with respect to pressure, and increasing the error at $L_a \sim \tilde{a}_z \gtrsim \nu_i/|\nabla\nu_i|$.

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