Ionization of a low-pressure gas in a very intense microwave field

M. P. Brizhinev, A. L. Vikharev, G. Yu. Golubyatnikov, B. G. Eremin, O. A. Ivanov, A. G. Litvak, S. F. Lirin, I. V. Plotnikov, E. I. Soluyanov, V. E. Semenov, O. N. Tolkacheva, and O. V. Shevchenko

Applied Physics Institute, Academy of Sciences of the USSR
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An experimental study has been made of nanosecond microwave discharges produced in various gases by the very intense field of an electromagnetic beam in which the oscillator energy of the electrons appreciably exceeded the ionization potential of the atoms and amounted to $\varepsilon_\sim = 1.2$–3.5 keV. The electron-impact ionization rate as a function of the microwave field amplitude was observed to approach a constant for $E/\omega = 5\times10^{-7}$–$2\times10^{-6}$ V sec/cm. The existence of a lower limit of the gas breakdown range with respect to pressure, a limit independent of the microwave field amplitude, was established. It was found that because of the high translational electron energies acquired in the microwave field, the gas ionization process continues after cessation of the microwave pulse and results in formation of a dense plasma with density far above the critical density. During the collapse of the discharge plasma, intense fluxes of accelerated ions, up to 20 keV, were recorded.

1. INTRODUCTION

In the last few years, in connection with the development of powerful sources of electromagnetic radiation, the freely localized microwave discharge in a wave beam has been extensively studied theoretically and experimentally.[1-3] Such a discharge is an interesting new subject in nonlinear physics, since nonlinear electrodynamic processes play a fundamental role in its formation and dynamics. The discharge in an electromagnetic beam has been studied in a fair amount of detail at a moderate field strength, in which the oscillatory energy of the electrons

$$\varepsilon_\sim = e^2E^2/2m(\omega^2+\nu^2)$$

is much lower than the average electron energy $\bar{\varepsilon}$ and the ionization potential of the atoms I_i: $\varepsilon_\sim \ll \bar{\varepsilon} < I_i$.

Progress in relativistic microwave electronics[4,5] has opened up an essentially new area in discharge physics, i.e., the study of ionization processes acted upon by a very intense microwave field[6-10] in which the energy of the oscillatory motion of the electrons $\varepsilon_\sim$ is much higher than the ionization potential of the atoms I_i: $\varepsilon_\sim \gg I_i$. Under these conditions, the development of a discharge is accompanied by a number of effects not observed during the breakdown of gas in fields of moderate intensity. Certain effects, for example, appearance of discrete ionization sites at individual primary electrons,[9] change in the kinematics of the breakdown wave in the beam,[10] and nonlinear shifting of the frequency of an electromagnetic pulse in an ionizing medium,[11] are associated with high values of electron-impact ionization frequency. Other effects, for example, ionization self-channeling of electromagnetic radiation in a wave beam in a plasma,[12] can manifest themselves as a result of the decrease in ionization frequency as the strength of the very intensity field increases.

The variety of possible effects accompanying the process of ionization in a very intense field has stimulated experimental studies of nanosecond microwave discharge (produced by radiation of high intensity and short duration) in a wave beam. An important objective of such studies is to determine how the ionization frequency depends on the magnitude of the field in the little-studied region of very intense fields. The present paper deals mainly with an experimental study of a microwave discharge in a very intense field in low-pressure gases, where the frequency ν of electron collisions with neutral particles is much smaller than the field angular frequency ω. At low pressures in the experiment, electron oscillatory energies on the order of several kiloelectron volts were achieved, and new effects associated with high translational energies of the electrons were detected. Use of low gas densities also made it possible to study the breakdown of a gas under conditions in which the electron mean free path was comparable to the characteristic electric field gradient length, so that the electron impact ionization frequency is no longer a local function of the field amplitude.

2. SKETCH OF EXPERIMENT

In the experiments, the discharge was initiated in a conventional arrangement.[10] The radiation, generated by a relativistic microwave oscillator (carcinotron,[4] wavelength $\lambda \approx 3$ cm, pulse width $\tau_p \approx 50$ nsec), was transformed by a quasioptical converter into a wave beam with a Gaussian distribution of the field along the transverse coordinate, and was directed into a vacuum chamber, where it was focused by a parabolic mirror of focal length $F = 40$ cm.

The rms electric field strength at the beam focus was $E = 70$–120 kV/cm. At these field values, the oscillatory energy of the electrons substantially exceeded the ionization potential of the atoms and molecules and amounted to $\varepsilon_\sim = e^2E^2/2m\omega^2 = 1.2$–3.5 keV.

The initial gas pressure in the vacuum chamber was $p_0 = 10^{-5}$ torr. To localize the breakdown in the very intense field, use was made of pulsed injection of the gas into the focal region of the beam immediately before passing the microwave radiation with a controlled vacuum valve. The gas density distribution in space at different times relative to the start of the injection was recorded with a mobile PMI-10 transducer. The characteristic change in gas pressure with time in the region of the wave beam focus is shown in Fig. 1. The microwave breakdown at different pressures

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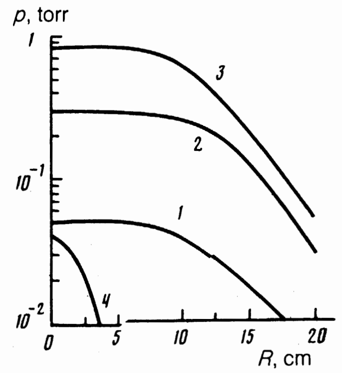

FIG. 1. Distributions of gas density at different times: 1—$t = 6$ msec, 2—8 msec, 3—10 msec, 4—6 msec (for quick-acting valve).

$p = 2\times10^{-3}$–1 torr in helium, nitrogen, and argon was studied by passing the microwave pulses at different times relative to the start of the gas injection.

The fact of microwave breakdown of the gas was determined by different methods. The change in shape of the microwave signal transmitted during the discharge was detected with a microwave located behind the focal plane of the beam. The appearance of plasma luminescence was recorded with a photomultiplier and FR-16 photodetector. The electron density in the ionization region was measured with a microwave interferometer at wavelength $\lambda = 8$ mm. The working channel of the interferometer was located in the beam cross section at a distance of 10 cm in front of the focus. These methods permitted reliable detection and study of the discharge.

3. MEASUREMENTS OF IONIZATION FREQUENCY

The gas ionization rate in a very intense field was determined, as in the experiment of Ref. 9, by measuring the time τ until the onset of breakdown, using the cutoff of the microwave signal transmitted from a calibrated detector. Another detector was used to measure the incident microwave power, and the measured distribution of the field in the focal cross section was used to calculate the rms electric field strength at the beam focus. To reduce the error associated with the measurement of the ionization frequency ν_i, conditions (incident power level, magnitude of gas pressure) were selected such that the cutoff time τ was greater than rise time of the pulse. The ionization frequency ν_i, which in view of the insignificant role of the electron losses was equal to the electron-avalanche development constant during the pulse, was calculated from the formula

$$\nu_i = \frac{\ln(N_{e\Sigma}/N_{e0})}{\tau}, \qquad (1)$$

where N_{e0} and $N_{e\Sigma}$ were the initial and final electron densities.

The experiments were carried out in two regimes. In the first case, the initial electron density N_{e0}, which was less than the value $N_{e0} \lesssim 10^6$ cm^{-3}, was produced by a spark gap located near the breakdown region, or directly by the bremsstrahlung of the relativistic electron beam of the microwave generator. At this initial electron density, the measurements of ν_i were carried out in the pressure range $p = 2\times10^{-2}$–1 torr, where the plasma emission in the ionization region was uniform. As in Ref. 9, the magnitude of the logarithm in Eq. (1) was taken in the calculations to be 20, which corresponded to a density ratio of $\sim 10^8$. The uncertainty of $N_{e\Sigma}/N_{e0}$ in this regime amounted to several orders of magnitude and essentially determined the measurement error of ν_i.

In the second series of experiments, the ionization frequency ν_i was measured at a high level of the initial electron density. The electron density at the level $N_{e0} \approx 10^{10}$–10^{11} cm^{-3} was produced by a high-frequency induction discharge. In these experiments, the logarithm was determined exactly, since the densities N_{e0} and $N_{e\Sigma}$ were located in the measurement range of the microwave interferometer. By changing the triggering time of the hf oscillator relative to the gas injection, it was possible to establish the pressure at which ν_i and the preionization level were determined. The ν_i measurements were carried out in the pressure range $p = (3$–$8)\cdot10^{-3}$ torr, where the hf oscillator produced a homogeneous plasma, and the time to onset of breakdown was significantly longer than the microwave pulse rise time.

Results of the ν_i measurements are shown in Fig. 2. To represent the dependence $\nu_i(E)$ in the region $\nu < \omega$, the plane of the parameters $(\nu_i/p; E/\omega)$ was used. The figure also shows the data from ν_i measurements in a strong field, carried out in other studies.[9,13] In our experiment, high electric field strengths made it possible to carry out the measurements of ν_i in the previously unstudied range of parameter values $E/\omega = 5\times10^{-7}$–$2\times10^{-6}$ V s/cm. As is evident from the plots, in this region of E/ω, the ionization frequency depends weakly on the electric field strength, and it can be approximated by the expression $\nu_i = A\cdot10^9 p$, where p is in torr, and $A = 1.2$ and 7 for helium and nitrogen, respectively.

Figure 2 also shows the results of calculations of the ionization frequency, carried out for a strong field in Refs. 6 and 7 in our study (see Sec. 4), and for a wide range of field values in Ref. 14.

4. CALCULATIONS OF IONIZATION RATE

Calculation of the ionization frequency requires determination of the energy electron distribution function

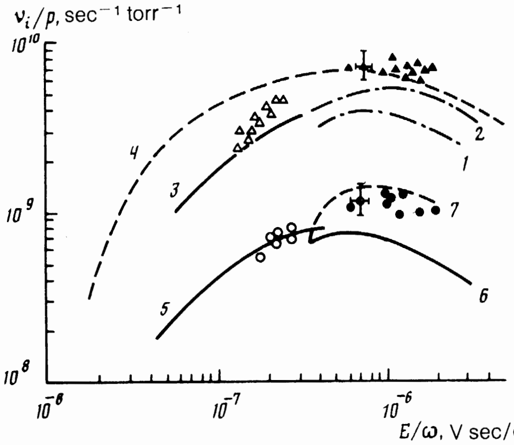

FIG. 2. Ionization frequency in nitrogen (1–4) and helium (5–7): ▲, ●—our experiment and calculation (curves 1 and 2); △, ○—data of Ref. 9; curves 3 and 5—data of Ref. 13; curve 4—calculation of Ref. 14, curve 6—calculation of Ref. 6, curve 7, calculation of Ref. 7.

(EDF). In solving the kinetic equation for the velocity EDF in an electromagnetic field, numerical methods are used[15] because of the complicated nature of the collision integral. In the limiting case of high electron energies, when the EDF is determined mainly by the "production" of new electrons as a result of the electron-impact ionization of atoms and molecules, the collision integral representation permits an appreciable simplification.[8] This permits a fairly effective analysis of the discharge kinetics in very intense electromagnetic fields.

Assuming for simplicity that the electron field is homogeneous in space and neglecting the change in electron momentum during collisions and the energy of the electrons produced by the ionization, we write the kinetic equation for the velocity EDF $f(v,t)$ in the form

$$\frac{\partial f}{\partial t}-\frac{eE}{m}\frac{\partial f}{\partial v}=\delta(v)\int_{-\infty}^{\infty}\nu_i(v')f(v',t)\,dv', \qquad (2)$$

where $\nu_i(v)=\nu_i(|v|)=\sigma_i(v)N|v|$ is the rate of ionization of neutral particles by electron impact, $\sigma_i(v)$ is the ionization cross section, N is the density of the molecules, and $\delta(v)$ is the Dirac delta function. This approximation also holds for very intense fields, when the energy obtained by the electron from the field during the characteristic ionization time reaches values at which the ionization cross section substantially exceeds the transport collision cross section. The validity of this approximation for high-frequency fields ($\omega \gg \nu_i$) is confirmed by the results of numerical modeling of the gas breakdown kinetics (see Ref. 8).

When the frequency of the field is high ($\omega \gg \nu_i$), the ionization processes can be averaged over the field period, assuming

$$f(v,\ t)=F(v+v_0\sin\omega t,\ t), \qquad (3)$$

where $v_0=eE/m\omega$, $E=E_0\cos\omega t$, and the time dependence of the velocity distribution function of the "leading centers" $F(u,t)$ is smooth on the field frequency scale. The averaging yields the following equation for $F(u,t)$ (Ref. 8):

$$\frac{\partial F(u,t)}{\partial t}=g(u)\int_{-v_0}^{v_0}\nu_i(u'-u)F(u',t)\,du', \qquad (4)$$

where

$$g(u)=\frac{1}{2\pi}\int_{-\pi}^{\pi}\delta(u-v_0\sin\theta)\,d\theta=\frac{1}{\pi}\frac{1}{(v_0^2-u^2)^{1/2}}. \qquad (5)$$

The solution of this equation is quite simple to find if the "ionization capacity" $\langle\nu_i\rangle$ of the electron is independent of the velocity of its translational motion u ($v=u-v_0\sin\omega t$), i.e., the frequency of ionizing collisions, averaged over the field period, is the same for all electrons:

$$\langle\nu_i\rangle(u)=\frac{1}{2\pi}\int_{-\pi}^{\pi}\nu_i(u-v_0\sin\theta)\,d\theta$$

$$=\int_{-v_0}^{v_0}\nu_i(u-u')g(u')\,du'=\text{const}. \qquad (6)$$

In this case, in accordance with the results of Refs. 6–8, so-called equidistribution of electrons over the "initial phases" in a high-frequency field takes place:

$$F(u,\ t)=N_{e0}g(u)\exp(\langle\nu_i\rangle t)[1+\Phi(u,\ t)], \qquad (7)$$

where N_{e0} is the electron density at the initial instant, we have $\Phi(u,t)\to 0$ as $t\to\infty$, and

$$\int_{-v_0}^{v_0}\Phi(u,t)\,du=0.$$

If, however, as is actually the case, $\langle\nu_i\rangle(u)\neq$ const, the equidistribution of the electrons breaks down, and numerical methods are required to determine the EDF.

In cases where the ionizing capacity of the electrons undergoes little change for $-v_0\leqslant u\leqslant v_0$, one of the most important characteristics of the gas breakdown, i.e., the electron-avalanche development times constant γ, can be determined with sufficient accuracy without solving the kinetic equation, since it is evident that

$$\min\langle\nu_i\rangle\leqslant\gamma\leqslant\max\langle\nu_i\rangle. \qquad (8)$$

The condition (8) is rigorous, as can readily be ascertained by integrating Eq. (4) with respect to the velocities, and is independent of the extent to which phase equidistribution of the electrons occurs. One cannot prove the sufficiency of the criterion

$$|\langle\nu_i\rangle(u)-\langle\nu_i\rangle(u')|\ll\langle\nu_i\rangle$$

for satisfying the equidistribution condition in general. Nevertheless, when the perturbation method is applicable, it can be shown that the estimated of γ within the scope of the equidistribution hypothesis

$$\gamma=\int\int g(v')g(v)\nu_i(v-v')\,dv\,dv'$$

is correct to second order.

To estimate the time constant of the electron avalanche in gases, we evaluated the electron ionization capacity $\langle\nu_i\rangle$ numerically [see Eq. (6)] for different values of the ratio E/ω (or $v_0=eE/m\omega$) and of the electron translational velocity u (for $-v_0\leqslant u\leqslant v_0$). Data on the ionization cross section were taken from Refs. 16 and 17. Results of the calculations are illustrated in Fig. 2, which gives the values of $(\min\langle\nu_i\rangle)/p$ (curve 1) and $(\max\langle\nu_i\rangle)/p$ (curve 2), i.e., the lowest and highest values of the ionization capacity of electrons with different translational velocities u at a given oscillatory velocity v_0 as a function of the ratio E/ω. Analysis of the results obtained shows that in the range of E/ω values from 5×10^{-7} to 2×10^{-6} V sec/cm, the measured ν_i values agree with the estimate (8) with sufficient accuracy. Thus, the very simple method proposed for estimating the rate of ionization of gases in very intense microwave fields can be considered satisfactory.

Note that the correctness of the approximations employed confirms the relationship between the ionization frequency ν_i and the transport frequency of electron collisons ν_t. A calculation of their values was carried out for the velocity electron distribution function, approximated by assuming equidistribution over the initial phases of their motion in the wave field, and the data on the cross sections were taken from Refs. 16 and 17. When the parameter E/ω varies over the range 5×10^{-7}–2×10^{-6} V sec/cm, the frequency ratio is $\nu_i/\nu_t=2$–3.

5. ELECTRON DENSITY AFTER THE MICROWAVE PULSE

To study the electron component of the discharge plasma, a fast-response microwave interferometer at wavelength $\lambda = 8$ mm was used. The interferometer arrangement was chosen so that the phases and level of the signal transmitted through the plasma were recorded simultaneously. The accuracy with which the phase shift introduced by the plasma in attenuating the probing signal from 0 to 13 dB could be measured was 2–10 degrees. The upper limit of the plasma density being measured was determined by the critical density for the probing plasma, $N_c \approx 1.7\times10^{13}$ cm^{-3}, and the lower limit was $N_{e,\min} = 3\times10^{10}$ cm^{-3}. The electron density was measured with a 300-nsec delay after cessation of the microwave pulse.

It was found from the analysis of the interferograms that in the range of nitrogen pressures $p = 10^{-1}$–1 torr, the probing signal cutoff for 1–2 μsec, after which the plasma began to decay. At lower nitrogen pressures $p = 3\times10^{-2}$–10^{-1} torr, no cutoff was observed, but there was a change in the sign of the signal phase at times $t \sim 0.5$ μsec after the microwave pulse. This indicated that for $t \sim 0.5$ μsec, the electron density N_e increased, then decayed. In helium at pressures $p > 0.1$ torr, the cutoff time of the probing signal was $t \sim 10$–30 μsec. In argon, the cutoff was observed in the entire range of pressures $p = 2\times10^{-2}$–1 torr for a long time, for example, at $p\times10^{-2}$ torr, $t \approx 50$ μsec was obtained. Figure 3 shows the curves of maximum electron density reached following the microwave pulse in the ionized region as a function of gas pressure. In the analysis of the interferograms, the plasma density was assumed to be uniform along the interferometer axis, and its dimensions, determined from integrated photographs of the discharge, remained unchanged during the entire measuring time $\sim 10^{-5}$ sec.

Thus, the measurements showed that the electron density after the microwave pulse substantially exceeded the critical density $N_{c0} \approx 10^{12}$ cm^{-3} for powerful microwave radiation. This effect appears to be a characteristic feature of the discharge in very intense fields.

In the plasma formed as a result of gas breakdown in very intense fields, after the field has been switched off for some time, there are electrons whose energy substantially exceeds the ionization potential. The bulk of these electrons lose energy chiefly as a result of ionizing collisions. Therefore, after the intense field has been switched off, an appreciable increase in plasma density is possible owing to the continuing process of ionization. Let us note for comparison that in the plasma of a microwave discharge in a weak field, the electrons lose energy mainly as a result of excitation of atoms and molecules, since at electron temperatures typical of such a discharge ($T_e \sim 1$–10 eV), the excitation frequency substantially exceeds the ionization frequency. Therefore, after the weak microwave field has been switched off, the electrons cool too fast to produce any appreciable additional ionization of the gas.

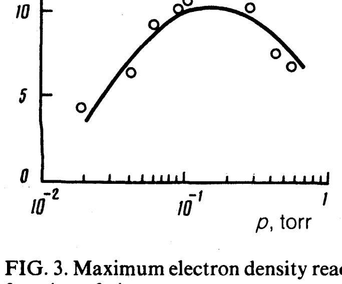

FIG. 3. Maximum electron density reached after the microwave pulse as a function of nitrogen pressure.

The main characteristics of the process of additional ionization of the gas after the microwave pulse has been switched off can be estimated by means of a spatially uniform model, since the additional ionization takes place faster than the expansion of the ionized region as a result of the quasineutral expansion (or diffusion, if the mean free path of the particles is short) of the plasma. Assuming that an ionization collision causes the electron to lose energy of the order two ionization potentials I_i, we find that after the microwave pulse has been switched off, the plasma density can grow by a factor of approximately $\varepsilon_\sim/2I_i$ in a time

$$\tau_{di} \approx \int_{I_i}^{\varepsilon_\sim} \frac{d\varepsilon}{2I_i\nu_i(\varepsilon)}. \tag{9}$$

If the dependence $\nu_i(\varepsilon)$ is approximated by the function

$$\nu_i(\varepsilon) = \nu_{im}(\varepsilon_m/\varepsilon)^{1/2},$$

where ν_{im} is the maximum value of the ionization frequency and ε_m is the electron energy corresponding to it, then the time of additional ionization is

$$\tau_{di} \approx \frac{1}{\nu_{im}}\frac{\varepsilon_m}{3I_i}\left(\frac{\varepsilon_\sim}{\varepsilon_m}\right)^{3/2}. \tag{10}$$

For nitrogen at pressure $p = 5\times10^{-2}$ torr and $\varepsilon_\sim = 2$ keV, we obtain $\tau_{di} \approx 0.5$ μsec. As is evident from the expressions (9) and (10), the time τ_{di} can also be estimated with satisfactory accuracy from the simple relation

$$\tau_{di} \approx \varepsilon_\sim/2I_i\nu_{im}. \tag{11}$$

Additional ionization of the gas was also observed when the level of initial preionization was high. For example, in helium at $p = 2.5\times10^{-2}$ torr and $N_{e0} = 3\times10^{-3}$ cm^{-3}, the maximum electron density following the microwave pulse was $N_{em} = 6\times10^{12}$ cm^{-3}, but the microwave pulse transmitted past the ionization region was not distorted in comparison to the incident pulse. This experiment indicated that during the microwave pulse, the electron density increased by a factor of only 2–3:

$$N_k = N_{e0}\exp(\nu_{im}\tau_p) \sim N_{e0}e,$$

but after the field was switched off, the "hot" electrons formed during the pulse performed an additional ionization during the time τ_{di}, and N_e increased appreciably:

$$N_{em} \approx N_{e0}\exp(\nu_{im}\tau_p)\frac{\varepsilon_\sim}{2I_i} \sim 5\cdot10^{12}\ \text{cm}^{-3}$$

(estimate for $\varepsilon_\sim = 2$ keV).

Thus, after a low-pressure discharge in a very intense microwave field, the stage of additional ionization, during which the average electron energy drops to values of the order of the ionization potential, is significant, and N_e increases appreciably, whereupon plasma relaxation begins.

In the range of nitrogen pressures $p = 3\times10^{-2}$–1 torr,

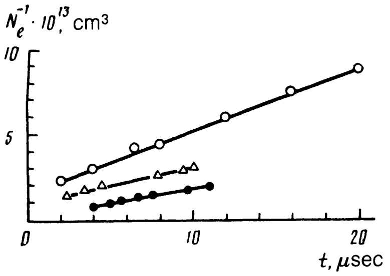

FIG. 4. Reciprocal electron density as a function of time at various nitrogen pressures: ○—$p = 5\times 10^{-2}$ torr, ●—3×10^{-1} torr, △—6×10^{-1} torr.

the initial stage of plasma relaxation was determined by the bulk recombination. Figure 4 shows the change in reciprocal electron density as a function of time. The linear dependence of N_e^{-1} on time in nitrogen characterizes the plasma decay due to dissociative recombination with coefficients $\alpha = 4\times 10^{-8}$ cm³/sec at $p = 5\times 10^{-2}$ torr and $\alpha \approx 2\times 10^{-8}$ cm³/sec at $p = 0.3$–0.6 torr. Such a recombination coefficient indicates an appreciable electron temperature at times $t\sim 10$ μsec after cessation of the microwave pulse. Indeed, by approximating the dependence of the recombination coefficient on the electron temperature by the power-law expression $\alpha = \alpha_0(300/T_e)^{0.5}$, where $\alpha_0 = 2.7\times 10^{-7}$ cm³/sec (Ref. 18), we obtain $T_e \approx 1$ and 5 eV respectively.

The prolonged relaxation of electronic energy after a microwave discharge in a very intense field, particularly at higher pressures, is apparently due to the influence of collisions between electrons and electronically excited nitrogen molecules.[15] The population of the electronic levels of nitrogen after a powerful microwave discharge can be appreciable, since a major portion of the microwave energy absorbed by the discharge, at a high value of the parameter E/N (N being the gas density), is expanded in ionization and excitation of the electronic levels of the molecules. A calculation of the EDF in a decaying plasma, carried out in Ref. 15, shows that the EDF is enriched with high-energy electrons due to collisions of the second kind with the metastable molecules $N_2(A\,^3\Sigma_u^+)$.

Prolonged relaxation of electron energy not only affects the decay rate of the plasma, but also gives rise to a long afterglow. The integrated emission of the nitrogen plasma (i.e., mainly the lines of the second positive system) at low pressure reaches its maximum value after cessation of the microwave pulse. This effect, previously observed in Ref. 19, is due to the high electron temperature during the microwave pulse, which substantially exceeds the energy corresponding to the maximum of the excitation cross section of the electronic levels responsible for light emission. Therefore, the main excitation of the molecules takes place after cessation of the microwave pulse, when the electron energy drops appreciably. Thus, the process of electron energy relaxation after a discharge in a very intense microwave field is nontrivial, gives rise to several effects, and apparently, requires a detailed theoretical analysis.

6. DETERMINATION OF THE BREAKDOWN THRESHOLD

For each regime of the experiment (with different initial preionizations; see Sec. 3) for specified values of the gas density gradient length Λ_N and field amplitude Λ_E, we found the lowest gas pressures at which the microwave interferometer detected appreciable ionization of the gas. At initial electron density $N_{e0} \lesssim 10^6$ cm^{-3}, the minimum gas pressure at which breakdown occurred was $p_{m1}(\mathrm{Ar}) = 2\times 10^{-2}$ torr, $p_{m1}(N_2) = 3\times 10^{-2}$ torr. At higher initial electron density (in the second regime, see Sec. 3), an increase in plasma density in the region of the wave beam was observed at gas pressures below the threshold p_{m1} and above the threshold p_{m2} in helium, argon, and nitrogen: $p_{m2}(\mathrm{He}) = 5\times 10^{-3}$ torr, $p_{m2}(\mathrm{Ar}) = 2\times 10^{-3}$ torr, $p_{m2}(N_2) = 3\times 10^{-3}$ torr.

The effect of spatial variation in the gas density and field during the breakdown in very intense microwave fields consists first, in the fact that electrons of high translational velocity leave the discharge region without being able to produce ionization; and second, that all electrons, including "slow" ones, are forced out of the region of the strong high-frequency field under action of the average ponderomotive force,[20] $\bar{f} = -m\nabla(v_0^2/4)$. The first of these effects causes depletion of the EDF by "fast" electrons, and, as a consequence, decreases the effective ionization frequency $\nu_{i,\mathrm{eff}}$, which, in the case of large ionization length $l_i > \Lambda$, can be roughly estimated from

$$\nu_{i,\mathrm{eff}} \sim \frac{\Lambda}{l_i}\langle\nu_i\rangle \approx \frac{\Lambda\langle\nu_i\rangle^2}{v_0}, \qquad (12)$$

where $\Lambda = \min\{\Lambda_N, \Lambda_E\}$. The result of the action of the second effect can be described by means of the effective frequency of electron losses from the discharge region:

$$\nu_{\mathrm{eff}} \sim v_0/\Lambda_E. \qquad (13)$$

Thus, at low gas pressures, the time constant of the electron avalanche in a strong field can be estimated by allowing for the inhomogeneity of the gas and field by means of the formula

$$\gamma \approx \max\{\Lambda\langle\nu_i\rangle^2/v_0 - v_0/\Lambda_E\}. \qquad (14)$$

The threshold pressure is determined from the condition $\gamma = 0$, or

$$\langle\nu_i\rangle = v_0/(\Lambda\Lambda_E)^{1/2}. \qquad (15)$$

For estimates of the ionization frequency, $\langle\nu_i\rangle$ can be assumed equal to the maximum value ν_{im}, and $v_0 = v_m$ is the electron velocity corresponding to this frequency. Under the experimental conditions, the spatial dimensions were $\Lambda_N \sim 15$ cm, $\Lambda_E \sim 3$ cm; therefore, for example, for nitrogen [$\nu_{im} \approx 7\times 10^9 \times p$ (sec^{-1}), $v_m \approx 8\times 10^8$ cm/sec], the minimum pressure, estimated from Eq. (15), at which microwave breakdown is possible, is $p_m \approx 4\times 10^2$ torr. This value of p_m is close to that found in the experiment, $p_{m1} \approx 3\times 10^{-2}$ torr.

At high initial electron density, the bulk of the electrons can escape from the breakdown region only together with ions, i.e., much more slowly than with the characteristic translational velocity v_0. As a result, the effective frequency of electron losses becomes $(m/M_i)^{1/2}$ times smaller than

v_0/Λ_E, and the effective ionization frequency increases in comparison with (12): $\nu_{i,\text{eff}} \approx \langle \nu_i \rangle$. This apparently accounts for the experimental reduction of the threshold pressure p_{m2} by an order of magnitude in comparison with p_{m1}.

Thus, in a very intense microwave field, we have established the existence of the lower limit of the gas breakdown range with respect to pressure, a limit independent of the field amplitude. The magnitude of the threshold pressure in the experiment was determined by the characteristic dimensions of the field inhomogeneity. In addition, we have detected the development of an electron avalanche at a fairly high level of gas preionization under conditions where the electron means free path appreciably exceeded the size of the field localization region.

7. SPECTRUM OF ACCELERATED IONS

During the breakdown of a gas in a very intense microwave field in a wave beam with electron energy of the order of several keV, the inhomogeneous plasma bunch acquires a high potential. Therefore, the expansion of an inhomogeneous plasma into a vacuum may involve acceleration of ions,[21,22] as, for example, in experiments with laser discharges. Thus, the appearance of ions of appreciable energy characterizes a microwave discharge in a very intense field, and the specific mechanism of ion acceleration needs to be studied.

In the experiment, the energy spectrum of the ions was studied with a five-channel analyzer located outside the vacuum chamber. The instrument's collimator axis was in the focal plane of the wave beam and coincided with the direction of the electric vector. Ions of atomic nitrogen N^+ and molecular nitrogen N_2^+ were detected for the discharge in nitrogen. The mass of the particles was determined from their transit time between the ionized region and the analyzer, and the number of recorded particles n was estimated by integrating the current with allowance for the gain in each analyzer channel. Figure 5(a) shows the energy spectra of the N^+ and N_2^+ ions.

Analysis of the results obtained showed that the energy spectrum of the ions broadens toward high energies as the gas pressure decreases. At the same time, there is a change in the ratio of atomic and molecular nitrogen ions. Such behavior of the change in the ion spectrum is in qualitative agreement with effect of additional ionization after cessation of the microwave pulse. Thus, the number of fast ions is approximately proportional to the lifetime of "hot" electrons in the plasma, i.e., to the total of the microwave pulse plus electron cooling time τ_{di}. As the pressure decreases (τ_{di} increases), the number and energy of fast ions increase. This effect is also enhanced by the increase in ion mean free path as the gas pressure decreases. In addition, the energy spectrum of the ions was affected by the fact that the scale of the gas inhomogeneity was greater than the dimensions of the ionized region, and as the plasma expanded, the ions had to get past a gas "coat."

To obtain the condition for expansion of an inhomogeneous plasma into a vacuum, an experiment with a small gas cloud was carried out. A quick-acting vacuum valve was used in the study of the ion spectrum only. In work with this valve, the scale of the gas density inhomogeneity and field amplitude became approximately equal, $\Lambda_N \sim \Lambda_E$, and the distribution of gas density in space is shown in Fig. 1 (curve 4). For this series, the energy spectrum of the ions is shown in Fig. 5, b. Thus it was established that for an electron oscillatory energy of the order of 3 keV in a microwave field, there exists a flux of ions with energy up to 20 keV. The maximum energy of the fast ions [see Fig. 5 (a and b)] increases as the scale of the gas density gradient and hence, the plasma density gradient, increases. Apparently, therefore, the acceleration effect is due to collective processes developing at the front of the expanding dense plasma.

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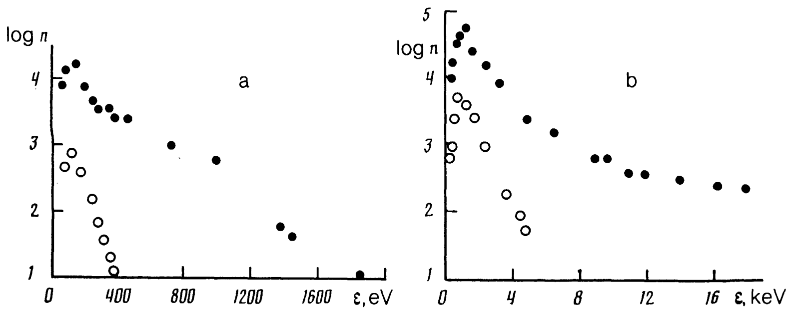

FIG. 5. Energy spectra of the ions N^+ (●) and N_2^+ (O) for different dimensions of the inhomogeneities of nitrogen density: a—$\Lambda_N < \Lambda_E$, b—$\Lambda_N \sim \Lambda_E$; pressure $p = 7 \times 10^{-2}$ torr.

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