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Dynamics of Discharge Created by the Bessel Laser Beam in Homogeneous Medium

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We study in this paper the dynamics of the field and plasma in the discharge column created by axicon focusing [1 – 3] of a high-intensity laser radiation in homogeneous gas. We are focused on the effect of the natural plasma waves generation considered previously for another types of the optical and microwave discharges [4, 5].

The spatiotemporal evolution of the electric field $\tilde{\mathrm{E}} = \mathrm{Re}[\mathrm{E}(\mathrm{r}, t)\exp(-i\omega t)]$ is calculated numerically based on the vector wave equation for the slow time envelope of the field $\mathrm{E}(\mathrm{r}, t)$:

$$\frac{2i}{\omega}\frac{\partial \mathrm{E}}{\partial t} + \delta^2\nabla(\nabla\cdot\mathrm{E}) + \varepsilon\mathrm{E} - \frac{1}{k_0^2}[\nabla\times[\nabla\times\mathrm{E}]] + \hat{\Gamma}\mathrm{E} = 0\,. \tag{1}$$

This equation takes into account the spatial and time dispersion and allows us to describe the processes of resonance excitation and Landau damping of Langmuir waves in the time-varying plasma. In Eq. (1), $\hat{\Gamma}$ is the model dissipation operator: $\hat{\Gamma}\mathrm{E} = -ia\delta^2\nabla(\nabla\cdot\mathrm{E})$, $\varepsilon = 1-(N/N_c)(1-i\nu/\omega)$ is the complex permittivity of the plasma, $N_c = m(\omega^2+\nu^2)/4\pi e^2$ is the critical density, ν is the electron collision frequency, a is the coefficient of order 1, $k_0 = \omega/c$, $\delta = \sqrt{3}\,V_T/\omega$, $V_T << c$ is the thermal electron velocity.

Gas breakdown is caused by the optical-field-induced ionization processes. As an example we consider tunnel ionization of hydrogen atoms and determine the time averaged ionization rate by the known expression

$$\frac{\partial N}{\partial t} = 4\Omega\,(N_g - N)\sqrt{\frac{3E_a}{\pi|\mathrm{E}|}}\exp\left(-\frac{2E_a}{3|\mathrm{E}|}\right). \tag{2}$$

Here $E_a = m^2 e^5/\hbar^4 = 5.14\times10^9$ V/cm and $\Omega = me^4/\hbar^3 = 4.16\times10^{16}$ s^{-1} are the atomic field and frequency units, and N_g is the concentration of neutral atoms before the process of ionization. It is assumed that the following conditions are fulfilled: $\omega << \Omega$, $|E| << E_a$, and $W_\sim = |E|^2 e^2/\left(2m\omega^2\right) >> I$, where $W_\sim$ is the quiver energy of electron and I is the energy of ionization. The parameter range we are interesting here is the following: the wavelength $\lambda \sim 0.6-10$ μm, laser pulse intensity $S \sim 10^{14}-10^{16}$ W/cm^2, and the gas pressure $p \sim 0.3-50$ atm.

We consider the model of the axially symmetric discharge: $N(\mathrm{r}, t) = N(r, t)$ produced by the rotating cylindrical wave with the complex envelope of electric field $\mathrm{E}(\mathrm{r}, t) = \mathrm{E}(r, \varphi, z, t) = \mathrm{E}(r, t)\exp(i\varphi - ik_0 z\cos\theta)$ (r, φ, z are the cylindrical coordinates). Outside the plasma ($r \ge R$, $N(r \ge R) = 0$) the field is a superposition of the converging (incident) and diverging (reflected) TE and TM waves with a given angle of inclination θ to the axis of symmetry z. The incident wave is given by the axial components of electric and magnetic fields: $E_z^{(in)} = C(t) H_1^{(2)}(k_0 r\sin\theta)$, $H_z^{(in)} = -i\cos\theta E_z^{(in)}$, $C(t) = A\exp\left(-(t-t_0)^2/\tau^2\right)$, $H_1^{(2)}$ is the first order Hankel function describing the converging wave. The correlation between the amplitudes of these components (the coefficient $-i\cos\theta$) is chosen so that the transversal components of the fields in the absence of plasma are circular polarized and are the zero-order Bessel function of radius r: $E_\varphi(r) = iE_r(r) \sim J_0(k_0 r\sin\theta)$. In the presence of the plasma the transverse components are always circular-polarized at the axis ($E_\varphi(0) = iE_r(0)$).

Eqs. (1), (2) were solved numerically in the space interval $0 \le r \le R$ with the initial conditions: $N(r, 0) = 0$, $E_\varphi(r,0) = iE_r(r,0) = -2C(0)\cot\theta J_0(k_0 r\sin\theta)$, $E_z(r,0) = 2C(0)J_1(k_0 r\sin\theta)$, the boundary conditions at $r = 0$: $E_z = 0$, $\partial E_r/\partial r = \partial E_\varphi/\partial r = 0$, and radiation conditions for the reflected wave at $r = R$.

It has been found that the scenario of the breakdown process depends greatly on the convergence angle of the wave. If this angle is less than some critical value $\theta_c \approx 25^0$, the maximum plasma density $N_{\max} \sim \theta^2$ that is less than the critical one. However, at the angle exceeding the critical one, the plasma density at the axis increases in the sharpening regime and passes the critical point, after that the fast ionization wave containing the plasma resonance point at the leading front propagates in the radial direction. This process is accompanied by the sharp growth of the incident wave absorption and the resonance excitation of high intensity Langmuir waves in the plasma. The next increase of the plasma density in the discharge volume results in the adiabatic frequency up-conversion of the excited Langmuir oscillations. The resonance effects considered change sharply the value and spatial distribution of ionization rate and give rise to appearance of the upshifted frequencies in the spectrum of radiation reflected by plasma column [5].

The field and plasma evolution in the breakdown process is illustrated in Figs. 1 ($\theta = 6^0$) and 2 ($\theta = 30^0$), presenting the spatial distributions of both the plasma density $N(r,t)$ and the electric field amplitude $|\mathrm{E}(r,t)|$ at different time instants for the parameter values: $\Omega/\omega = 22$, $k_0\delta = \sqrt{3}V_T/c = 0.02$, $\nu/\omega = 0.01$, $a = 0.1$, $N_g = 1.5N_c$, $t_0\omega = 100$, $\tau\omega = 50$, $A/E_a = 0.0056$ for $\theta = 6^0$ and $A/E_a = 0.0204$ for $\theta = 30^0$, $k_0R = 10$ for $\theta = 6^0$ and $k_0R = 5$ for $\theta = 30^0$. These parameter values correspond to the wavelength $\lambda \approx 0.8$ μm, maximum pulse intensity $S \approx 3\times10^{14}$ W/cm^2, pulse duration (on the $1/2$ intensity level) $\tau\sqrt{2\ln 2} \approx 25$ fs, and the gas pressure $p \approx 40$ atm.

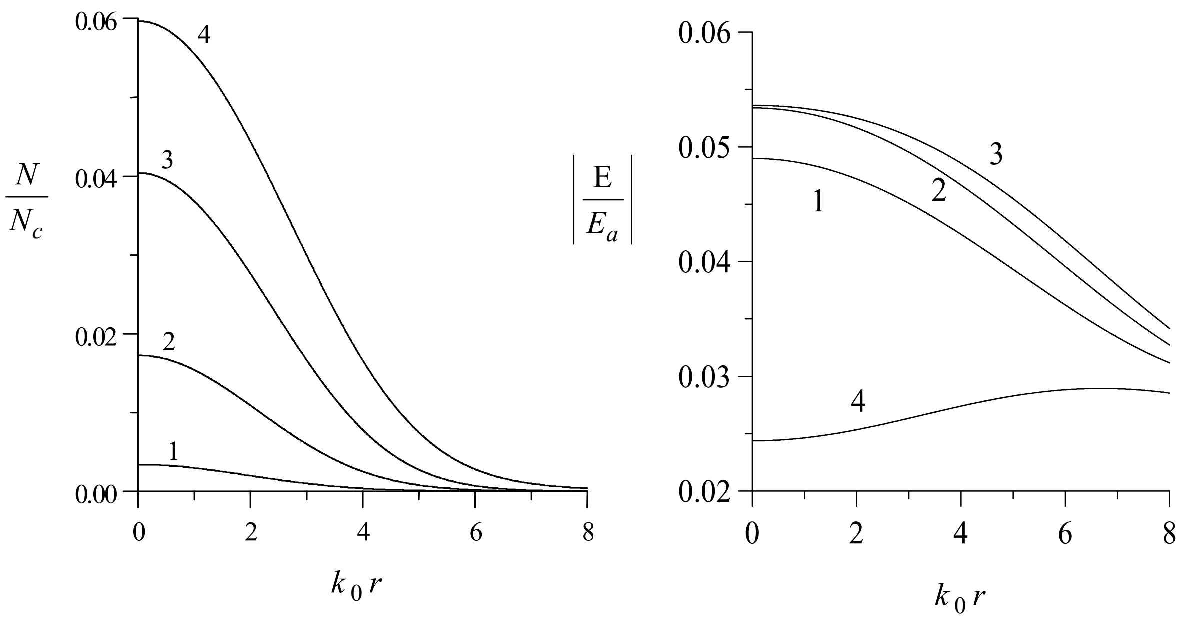

FIG. 1. Spatiotemporal evolution of the plasma density $N(r,t)$ and electric field amplitude $|\mathrm{E}(r,t)|$ at small convergence angle of the wave: $\theta = 6^0 << \theta_c$. Curves 1 – 4 correspond to the time instants $\omega t =$ 120, 130, 140, and 200, respectively.

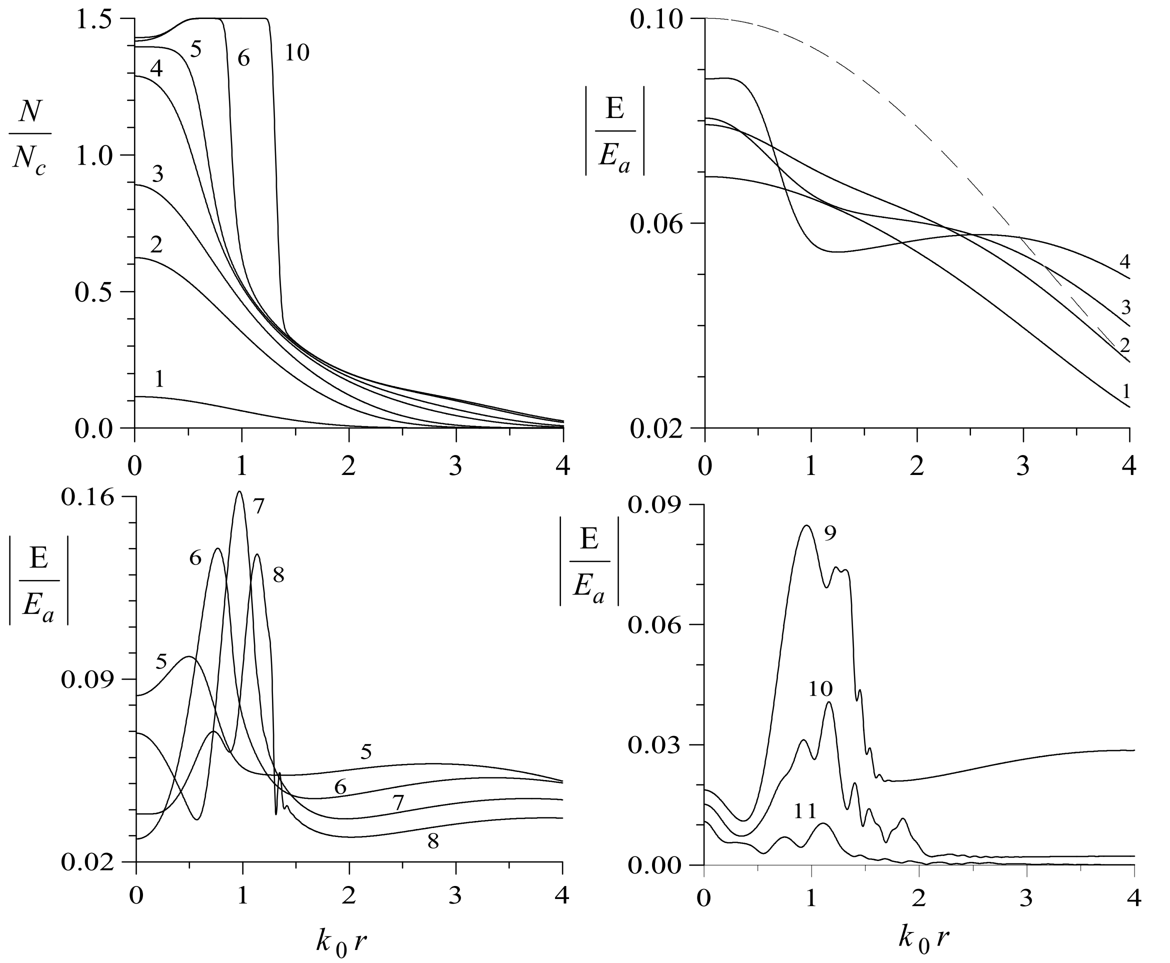

FIG. 2. Spatiotemporal evolution of the plasma density $N(r,t)$ and electric field amplitude $|\mathrm{E}(r,t)|$ under conditions of resonance excitation of Langmuir waves: $\theta = 30^0 > \theta_c$. Curves 1 – 11 correspond to the time instants $\omega t =$ 80, 90, 95, 105, 110, 120, 130, 140, 150, 200, and 300, respectively. The dotted line corresponds to the maximum intensity in the absence of plasma

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