EVOLUTION OF AN INHOMOGENEITY IN THE PUMPING DISCHARGE OF A XeCl-LASER

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Received October 20, 1997

Evolution of an inhomogeneity in the electron density and electric field strength in the pumping discharge of a XeCl*-laser is studied by a computer simulation. In this study we used a two-dimensional model developed based on the Laplace equation for the electric field potential, equation of the external electric circuitry, that, in addition allows for fundamental kinetic processes in the discharge. We show that an inhomogeneity of the electron density occurring at the initial moment in time leads to formation of a nonuniform electric field distribution. The electric field strength is lower at the inhomogeneity center the electron density is higher. The field reaches its maximum on the axis near the inhomogeneity boundary. The inhomogeneity of the electron density decreases with the progress in the discharge formation. As a result the electric field distribution becomes more uniform. The discharge becomes unstable at the stage of a step-wise ionization. The ionization rate is higher in the regions where the electron density is higher.*

INTRODUCTION

Recent advances in the excimer laser technology have faced the problem that the efficiency of such lasers is mainly limited by inhomogeneity of the pumping electric discharge. So it is evident that further progress in this field is connected first with improving the discharge homogeneity.

First attempts to simulate the discharge with the allowance for its inhomogeneity were made by use of 1D (one-dimensional) models. Those were the so-called models of parallel (series) connection of resistors.[1–3]

The 2D (two-dimensional) simulation of the initial stage of the XeCl-laser pumping discharge in a cylindrical gas volume between electrodes of the Chung profile was first performed by G. Simon and W. Boticher.[4] In Ref. 4, the discharge was simulated only in the range of low electron densities (up to $1.7\cdot10^{13}$ cm^{-3}).

In this paper we study the time and spatial evolution of the initially local inhomogeneity in a volume of a homogeneous discharge plasma in Ne–Xe–HCl gas mixture, with the account for main kinetic processes, when the electron density varying from $n_0(0, x, y) = 10^8$ cm^{-3} to $n(t, x, y) = 6\cdot10^{14}$ cm^{-3}.

INITIAL CONDITIONS

The electric circuitry consists of a dc power supply that provides output voltage $U_0 = 28$ kV, inductance coil of $L = 60$ nH, and a resistor $R_s = 2\ \Omega$. We consider a gas interval of a cylinder shape with the radius $R = 3$ cm and height (i.e., the distance between the electrodes) $d = 8$ cm. Electric field distortions at the edge of the electrode are neglected, so the electrode radius is supposed to be $r >> R$. The gas composition Ne:Xe:HCl = 1000:10:1 chosen for this study is typical for the pumping discharge of a XeCl-laser. The pressure of the working mixture is $P = 2$ atm.

The electron density was assumed to be initially uniform and amounted to $n_0 = 10^8$ cm^{-3}. The inhomogeneity of the electron density was set as a sphere with the radius $R_0 = 3.0\cdot10^{-1}$ cm at the center of the discharge gap ($x = 0$ cm and $y = 4$ cm).

Concentration of plasma particles amounted to $n_c = 10^9$ cm^{-3} at the center of the sphere and decreased to $n_0 = 10^8$ cm^{-3} at the inhomogeneity boundary.

PHYSICAL MODEL OF THE DISCHARGE

In this study we used the model based on the equation for the electric field potential variation, equations describing the external electric circuitry and the kinetics of plasmochemical reactions.

We took into account only the main processes affecting the plasma characteristics. The constants of these processes were computed when varying the electron density and electric field strength, by use of a complete OD model in which the Boltzmann equation for the electron energy-distribution function was solved by the method of weighted discrepancies,[5] with the account for more than 300 kinetic processes.

0235-6880/98/02-03 137-04 $02.00

The electric field potential $\Phi(t, x, y)$ was obtained by solving the Laplace equation

$$\nabla \mathbf{j}(t, x, y) = \nabla\sigma(t, x, y)\ \mathbf{E}(t, x, y) =$$
$$= -\nabla\sigma\ \nabla\Phi(t, x, y) = 0 \qquad (1)$$

with the boundary conditions

$$\frac{\partial}{\partial x}\Phi(t, 0, y) = 0,\quad \frac{\partial}{\partial x}\Phi(t, 3, y) = 0,$$

$$\Phi(t, x, 0) = 0,\quad \Phi(0, x, 8) = 28\text{ kV}.$$

Here $\mathbf{j}(t, x, y)$ is the electric current density, $\sigma(t, x, y)$ is the plasma conductivity, $\Phi(t, x, y)$ is the electric field potential, $\mathbf{E}(t, x, y)$ is the electric field strength. We consider the distributions of particle concentration and electric field potential that are symmetric with respect to the azimuth angle. So the problem can be reduced to a two-dimensional case, and then we deal with radial distributions in the coordinates x (radius) and y (distance from the cathode).

The equation (1) is valid for electrically neutral plasma with low local electric fields caused by charge separation. The criterion of plasma electric neutrality is the relation

$$d^2/(\Lambda\ R_0) \approx \delta n/n_e \ll 1, \qquad (2)$$

where

$$\Lambda = \bar{\varepsilon}/(e\ E).$$

Here d is the Debye radius, Λ is the length of energy relaxation, E is the electric field strength, $\bar{\varepsilon}$ is the mean energy of electrons, e is the electron charge, R_0 is the characteristic size of an inhomogeneity, δn is the density of an uncompensated charge. At a characteristic value of the field strength $E \sim 3.0{\cdot}10^3$ V/cm and $R_0 = 3.0{\cdot}10^{-1}$ cm, the criterion (2) is satisfied already at $n_e \sim 10^{10}$ cm^{-3}.

The equation (1) was solved by the method of weighted discrepancies that is based on Galerkin methods.[6] We made calculations using curvilinear quadrangular grids and the isoparametric transforms.[5] We used 60×60 grids. The accuracy of solutions obtained was checked by relative difference of the maximum and minimum values of the total current through the discharge cross section. This value did not exceed 3% in our calculations.

RESULTS AND DISCUSSION

Figure 1 presents oscillograms of the plasma current and voltage applied to it. They were obtained by 2D-modeling. Figures 2*a* and 2*b* present distributions of the electron density and electric field strength at the initial time moment. Characteristically, the maximal value of the electric field $E = 4.8$ kV/cm is at the discharge axis, at the boundary of inhomogeneity. In the center of the inhomogeneity, the electric field strength is approximately twice as low as its average value due to the higher electron density.

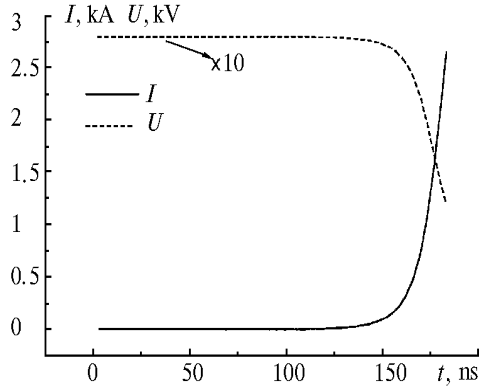

FIG. 1. Oscillograms of current I(t) and voltage U(t) calculated by the 2D model.

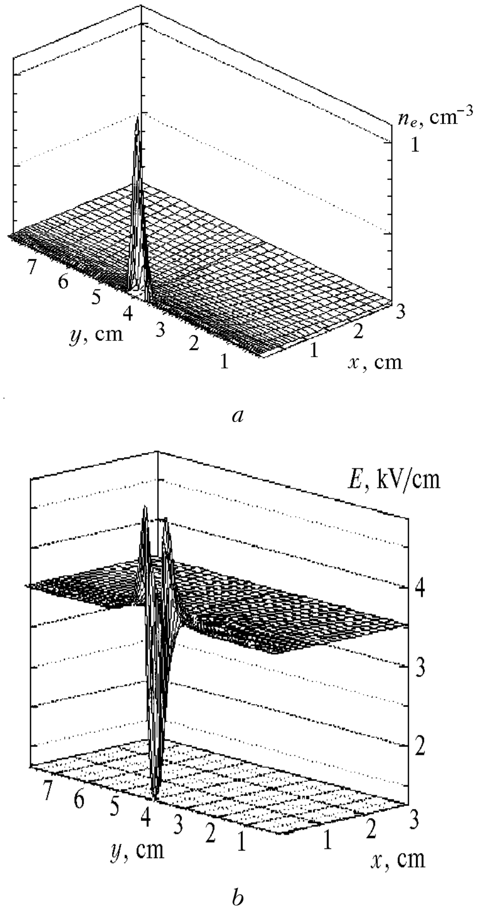

FIG. 2. Distribution of electron density $n(0, x, y)$ *(a) and electric field strength* $|\mathbf{E}(0,x,y)|$ *(b) for* $t = 0$ ns.

Figures 3*a*, *b*, and *c* present the function $n(t, x, y)$ at five points on the discharge axis. The points are in the center of the inhomogeneity ($y = 4.0$), near the inhomogeneity ($y = 4.5$), and in the rest part of the discharge volume ($y = 5.0$, 5.5, and 7.0 cm), respectively. The function value at a point distant from the discharge axis ($x = 3$ cm, $y = 8$ cm) is also shown in the figures.

At the initial stage of the discharge, the electron density grows exponentially with the time constant $\tau = 1/(\alpha v_{-})$, where α is the first Townsend coefficient and v_{-} is the electron drift velocity. The coefficient of Townsend ionization significantly depends on the field strength. So, the rate of electron density growth is lower in the center of an inhomogeneity. It reaches its maximum at the boundary of the inhomogeneity, in the region where the field is most strong (Fig. 3*a*, curve *3*). Therefore the initial inhomogeneity in the electron density and field is smoothened. Then, within the time interval t = 50–150 ns, the growth of $n(t, x, y)$ occurs at approximately the same rate for all points considered.

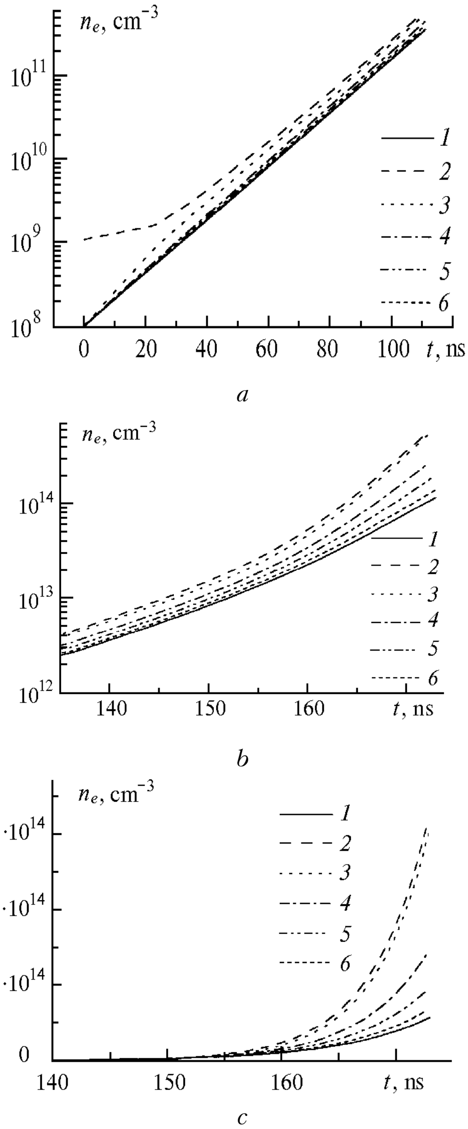

FIG. 3. Functions $n(t, x, y)$ at the points x = 3.0, y = 8.0 cm (1); x = 0, y = 4 cm (2); x = 0, y = 4.5 cm (3); x = 0, y = 5 cm (4); x = 0, y = 5.5 cm (5); x = 0, y = 7 cm (6) at the stage of direct ionization, t = 0–110 ns (a); t = 110–160 ns (b); and at the stage of stepwise ionization t > 160 ns (c).

The increase in the electron density up to $n_e \approx 10^{13}$cm^{-3} initiates a step-wise ionization that increases $\partial n_e(t, x, y)/\partial t$ at the points where the electron density is high.

Figure 4 presents the function $|\mathbf{E}(t, x, y)|$ on the discharge axis at t = 0, 144, and 184 ns. The maximum field distortion is observed at t = 0 ns. Within the time interval t= 0–144 ns, the field smoothens out and becomes quasi-homogeneous starting from t = 144 ns. Then, from t = 144 and until 184 ns, the field inhomogeneity increases but, nevertheless, the absolute values of the inhomogeneity are small (about 5%).

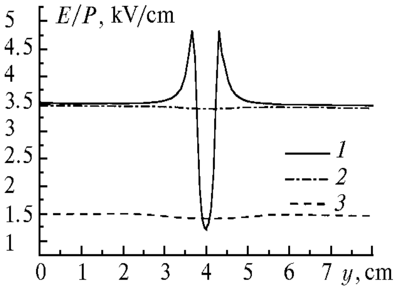

FIG. 4. Distribution of electric field strength $|\mathbf{E}(t, 0, y)|$ along the symmetry axis of the discharge at the time moments t = 0 ns (1); t = 144 ns (2); t = 184 ns (3).

DISTRIBUTION OF THE ELECTRIC FIELD

Let us consider the distribution of the electric field $\mathbf{E}(0, x, y)$ under condition that there occurs an inhomogeneity $n(0, x, y)$ in the discharge at the initial moment in time. From equation (1) we obtain the following expression:

$$\frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial n(x, y)}{\partial x}\frac{E_x}{n(x, y)} + \frac{\partial n(x, y)}{\partial y}\frac{E_x}{n(x, y)} = 0, \quad (3)$$

Here E_x and E_y are the field components in the (x, y) coordinate system. On the symmetry axis of the discharge (i.e., Y-axis), we have $E_x = 0$. Taking into account the signs of the derivatives and supposing that the direction from the anode to the cathode to be positive, we obtain, at $x = 0$, the following expression:

$$\frac{\partial n(0, y)}{\partial y}\frac{E_x}{n(0, y)} - \frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} = 0. \quad (4)$$

At the points $x = 0$, $y = y_0 \pm \delta y$, in the vicinity of the inhomogeneity center we have $E_x = 0$ and $\partial E_x/\partial x \approx 0$ and the field appears to be quasi-homogeneous. As a result and according to equation (5), we obtain the following expression that is valid in the domain $x = 0$, $y = (y \pm \delta y)$:

$$n(0, y_0 \pm \delta y)\,|\mathbf{E}(0, y_0 \pm \delta y)| \approx \text{const}$$

or $n(0, y_0)\,|\mathbf{E}(0, y_0)| = \text{const}$.

The value of $n(t, x, y)$ in the inhomogeneity center, $n(t, 0, y_0)$, is larger than out of it in the rest part of the volume. So, the field $|\mathbf{E}(0, y_0)|$ is minimal.

The maximum value E_y^m can be obtained from the equation (6) with the account for the fact that $\partial E_y/\partial y = 0$:

$$E_y^m = \frac{\partial E_x}{\partial x} \frac{n(0, y)}{\partial n(0, y)/\partial y} . \tag{5}$$

The condition $\partial E_y/\partial y = 0$ is fulfilled for $y_0 + R_0 > y > y_0 + 0.5R_0$ because $\partial E/\partial x$ increases in this interval while $\partial n(0, y)/\partial y$ decreases there. The calculated value of the maximum field, E_y^m (Fig. 4), is reached at $y = y_0 + 0.9R_0$.

The physical meaning of the E_y behavior presented in Fig. 4 is that the electron flux naturally travels, under the electric field applied, along the path with the maximum conductivity. In the domain $y = y_0 - R_0$ the current contracts to the discharge axis, thus making the E_y to be maximal there. At $y = y_0$, the charge and current density are maximal, while the field E_y being minimal. In the domain $y = y_0 + R_0$, the current flows off from the axis, and the field E_y is approaching its maximum.

One should pay proper attention to the fact that a one-dimensional model assumes that $\partial E_x/\partial x$ is always equal to zero and, as a result, no increase in the field should occur, at the boundary of an inhomogeneity, and the distribution of the field drastically changes.

DISCHARGE EVOLUTION AT THE STAGE OF DIRECT IONIZATION

In the gas mixture Ne–Xe–HCl considered at the concentrations $n \le 10^{13}$ cm^{-3}, electrons are born due to the ionization of Xe atoms by a direct electron impact, while their death is the result of the dissociative adhesion to $HCl_{(0)}$ molecules in the ground state. The ionization rate is

$$\frac{\partial n(t, x, y)}{\partial t} = n(t, x, y) (\alpha - \beta) v_- , \tag{6}$$

where β is the adhesion coefficient. The value αv_- strongly depends on $|\mathbf{E}(t, x, y)|$ what leads to a decrease in the gradient $\nabla n(t, x, y)$, smoothening of the field $|\mathbf{E}(t, x, y)|/P$, and to a partial smoothening of $n(t, x, y)$. As seen from Fig. 2*a*, $n(t, 0, y)$ is considerably smoothened out on the discharge axis during the first 50 ns. In the time interval from $t = 50$ to 150 ns the ionization rate $\partial n(t, 0, y)/\partial t$ becomes almost the same at different points (Figs. 2*a* and 2*b*). The equality of ionization rates at different points means that the field $E(t, x, y)$ is smoothened over the entire volume. However, the inhomogeneity in $n(t, x, y)$ still occurs even if the field is almost smoothened.

Field smoothening and a considerable decrease of the electron density gradient at the stage of direct ionization may readily be seen from data presented in Figs. 3 and 4.

Thus, the analysis of the results demonstrates that direct ionization by the electron impact leads to a significant smoothing of $n(t, x, y)$ and field strength in the discharge volume. From the viewpoint of the discharge stability, this means that the electrically neutral plasma of the gas discharge is stable with respect to random local inhomogeneities of the density $n(t, x, y)$ at the stage of the direct ionization by the electron impact.

DISCHARGE EVOLUTION AT THE STAGE OF A STEP-WISE IONIZATION

The situation is quite different when $n > 1.0 \cdot 10^{13}$ cm^{-3}. The significance of step-wise ionization increases with the growth of $n(t, x, y)$. If $n(t, x, y) > 10^{14}$ cm^{-3}, the step-wise ionization becomes dominant.

The rate of the step-wise ionization of the mixture depends on the electron density to a larger extent as compared with that on the field strength. This leads to an increase of the gradient $\nabla n(t, x, y)$ and to the corresponding redistribution of the field strength $\mathbf{E}(t, x, y)$.

As is seen from Figs. 3*b* and 3*c* the difference between the maximum and minimum values of $n(t, x, y)$ considerably increases in the time interval $t = 144$–184 ns because of the step-wise ionization.

CONCLUSIONS

1. The inhomogeneity of the electron density that may occur at the initial moment should lead to a nonuniform distribution of the electric field. In the center of an inhomogeneity, that is in the region where the electron density is higher, the strength of the electric field is lower. The field reaches its maximum on the axis, at the boundaries of the inhomogeneity.

2. At the stage of the direct ionization when $n(t) = (10^8 - 10^{13})$ cm^{-3}, the gradient $n^{-1}\nabla n(t,x,y)$ decreases and the electric field $E(t, x, y)$ is almost completely smoothened. In that case the distribution $n(t, x, y)$ is also significantly smoothened. At this stage of the discharge the electric charge is stable regarding local inhomogeneities in the electron density $\pm \delta n(t, x, y)$.

3. At the stage of a step-wise ionization ($n(t) > 10^{14}$ cm^{-3}) the discharge becomes unstable. The ionization rate increases in the regions where the electron density is higher.

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