ONE-DIMENSIONAL MODEL OF A STABILIZED ELECTRIC-DISCHARGE XeCl*-LASER

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The one-dimensional model of plasma, describing it as a system of parallel resistors, is used to study the influence of the active medium preionization on the electric discharge that pumps a stabilized electric-discharge $XeCl^*$*-laser. The technique of initiating the discharge is based on the use of a preliminary low-current electric discharge that provides for obtaining a homogeneous discharge plasma. The model uses the time-dependent Boltzmann equation for describing the electron kinetics and allows for the electron-electron collisions as well as quite a complete kinetic scheme for active plasma particles and photons, and a system of equations describing the electric circuitry for the discharge pumping. In our investigations we have shown that the presence of regions with the initially enhanced density of electrons in the discharge may cause development of inhomogeneities in plasma and thus disturb the spatial homogeneity of the output radiation. The impact of spatial distribution of preionizing electrons,* HCl *donor, and of the low-current preliminary discharge on the high-current discharge is discussed.*

INTRODUCTION

The homogeneity of the pumping electric discharge plays an important part in achieving the high output characteristics of excimer lasers. As it follows from numerous experiments the discharge in excimer mixtures (in particular, in the active media of $XeCl^*$ lasers) tends to transform from a spatially homogeneous form, at the initial stage, to that of a group of filaments of enhanced current density observed against the uniform glow background. The instabilities that appear in the discharge may essentially decrease the laser efficiency and worsen the quality of the output radiation.

Recently, a new method has been proposed for creating a stable and spatially uniform pumping discharge for the broad aperture excimer lasers.[1]

The spatial homogeneity is accomplished by a special technique of pumping the discharge by use of a preliminary, low-current stabilizing discharge. In this paper we present some results of our study of the preionization inhomogeneity influence on the evolution of such a discharge. We also discuss here the influence of spatial distribution of the preionizing electrons and of the partial pressure of HCl donor on the evolution of the nonuniform discharge.

DESCRIPTION OF THE MODEL

For making this investigation we have chosen a model that represents the discharge plasma as a series of parallel resistors. In the model, which was first proposed in Ref. 2, the entire discharge volume is divided into N regions that are parallel to the direction of the discharge current and to the resonator optic axis. Each ith region is characterized by the cross section area A_i and by the initial concentration $n_{ei}(t = 0)$ of electrons in it. Self-consistent simulating the pumping discharge in an excimer laser requires joint solution of the system of equations for electric circuitry, system of balance equations for heavy particles and photons. The nonstationary Boltzmann equation should also be added for determining the electron kinetics in each region of the discharge. The distinguishing features of the model are the sufficient model completeness for heavy particles (22 kinds of particles and more than 150 plasmochemical reactions are taken into account) and solving of the nonstationary Boltzmann equation for each region of the discharge. The Boltzmann equation we used allows for 12 kinds of elastic and 44 kinds of inelastic collisions between electrons and other plasma particles, 4 types of electron-ion recombination processes, and 8 processes of the electron generation due to collisions between plasma particles. It also considers the electron-electron collisions.

Figure 1 presents the equivalent electric circuitry of the installation for which we made the calculations. Here $C_0 = C_1 = 200$ nF, $C_2 = 1.8$ nF, $C_3 = 0.85$ nF, $L_0 = 2.3$ mH, $L_1 = L_2 = 40$ nH, $L_3 = 0.5$ nH, and $R_c = 0.01\ \Omega$. The resultant conductivity of the discharge plasma R_d^{-1} is assumed to be a sum of conductivities, R_i^{-1}, of i discharge regions.

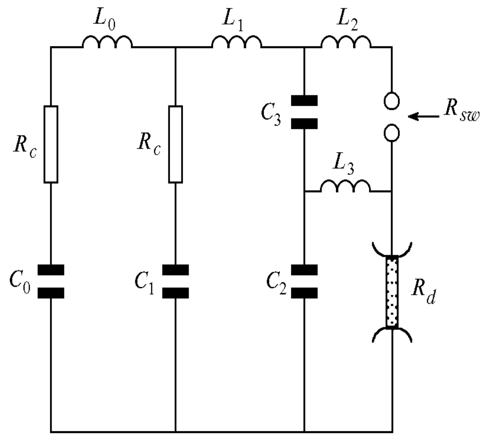

FIG. 1. Block-diagram of the equivalent circuitry.

The capacity divider C_2/C_3 included into the electric circuitry enables one to obtain the pumping discharge as a sequence of low-current and high-current discharges. The transfer between the above-mentioned discharge stages was realized by triggering the discharge switch whose resistance R_{sw} was taken into account as a preset function of time in the model.

RESULTS AND DISCUSSION

The calculations were made for the pumping discharge of a XeCl* laser in the mixture Ne/Xe/HCl at a full pressure of 3 atm and gas temperature of 293 K. The distance between the plane-parallel plates of electrodes was 8 cm. The discharge length was taken 60 cm, and the discharge width 5 cm. The primary capacity C_0 was assumed to be charged up to 39 kV voltage (see Fig. 1). The mixture composition Ne/Xe/HCl = 1000/8/0.8 was taken as standard. Under conditions of a uniform pumping discharge, the calculated output energy of radiation and the lasing efficiency are 1.4 J and 1%, respectively.

The results of simulation made for a uniform discharge have been calculated for the case when the whole discharge volume was divided into 2 regions $i = 1, 2$ with different initial electron concentrations n_{ei} ($t = 0$). Spatial distribution of the preionizing electrons was determined by cross sections A_i of the regions. Region 2 with higher initial concentration of electrons was assumed to contain the whole set of the discharge plasma inhomogeneities.

Figure 2 presents the shapes of voltage pulse U_d applied to plasma and of the discharge current density j_i, in both regions considered, for the case of $n_{e1}(t=0) = 5\cdot10^8$ cm^{-3}, $n_{e2}(t = 0) = 1.05\cdot n_{e1}(t = 0)$, and $A_1 = A_2$. Three stages may be isolated in the discharge pulse development, namely, the recharging stage (I), low-current stage (II), and high-current stage (III). The recharging stage is characterized by a monotonic increase in the plasma voltage up to the level of 23 kV. Preionization of the active medium at the moment $t = 0$ corresponds to the beginning of the low-current stage. At this stage, the discharge current density does not exceed 10 A/cm^2 at a duration about 400 ns. Then, the high-current stage begins. As seen from the time behavior of the current density presented in the figure, the calculations predict the appearance of inhomogeneities, in spite of the use of a stabilizing preliminary discharge. The difference between current density values in regions 1 and 2 increases at the high-current stage. The density of discharge current in region 2 is significantly higher and reaches its maximum value later than that of the region 1. Duration of the high-current pulse in region 1 is shorter than in region 2.

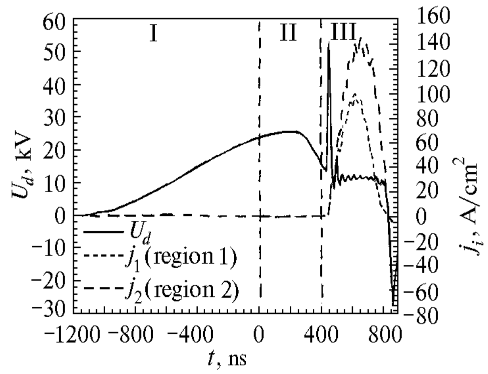

FIG. 2. Time behavior of the plasma voltage U_d and current density j_i in some regions i of the discharge: recharge stage (I), low-current stage (II), high-current stage (III).

Figure 3 presents the evolution of the isotropic part of the electron velocity-distribution function $f_{0i}(u, t)/n_{ei}(t)$. The function is normalized by the electron concentration $n_{ei}(t)$ in the regions $i = 1, 2$. The distribution functions observed during the low-current stage and in the beginning of the high-current stage in both discharge regions practically coincide. During further discharge evolution, the population of high-energy electrons in region 1 decreases as compared to that in the region 2. The evolution of distribution functions in time that is different in the discharge regions considered is accompanied by different time behavior of the corresponding transport and rate coefficients of collisions between the electrons and heavy particles. Thus, the simplified kinetics of the processes (when the corresponding coefficients are tabulated as functions of electric field strength or average electron energy) can lead to incorrect results.

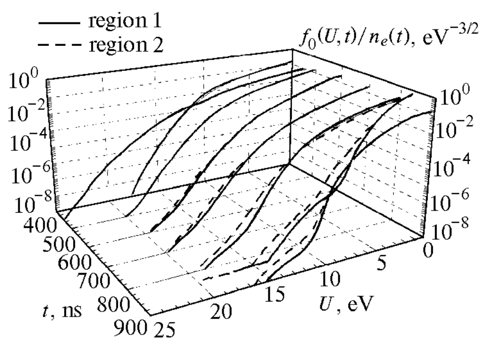

FIG. 3. Time behavior of the isotropic part of the electron velocity-disribution function.

Figure 4 presents the behavior of the electron and photon concentration in both discharge regions. The initial difference of 5% in electron concentration increases by the moment when current reaches its maximum (t = 600 ns) up to 35%, and the difference reaches an order of magnitude by the current pulse end. In region 2, the photon concentration reaches larger values and radiation pulse duration exceeds the corresponding duration for the region 1.

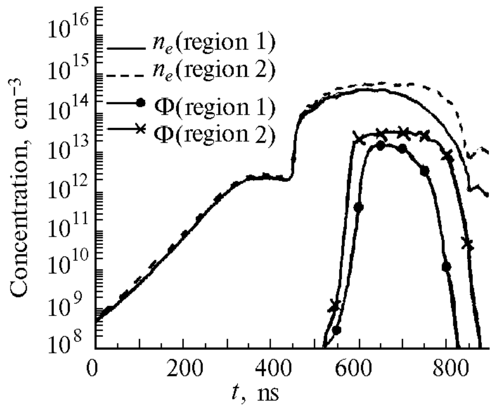

FIG. 4. Electron concentrations $n_{ei}(t)$ and photon concentrations $F_i(t)$ for the discharge regions i = 1, 2.

Analysis of HCl(v) concentrations, v = 1, 2, 3, demonstrates that concentration of undisturbed HCl (v = 0) molecule is essentially constant during the low-current stage. Concentration of the vibrationally excited HCl molecules (v = 1, 2, 3) exponentially increases in both discharge regions at this stage. After the initiation of the high-current discharge stage, the concentration of HCl (v = 0) decreases at a further increase in the concentration of the vibrationally excited HCl molecules. By the moment t = 600 ns, concentrations of HCl (v = 1, 2, 3) remain constant in time in the first discharge region while corresponding concentrations in the second discharge region decrease.

Thus, the enhanced initial electron concentration in region 2 leads to a stronger burning out of the HCl donor in this region of the discharge.

This model has been used to study the influence of inhomogeneous preionization of the active medium and HCl content on the properties of the discharge plasma and on the output laser characteristics. The analysis involved the data on maximum current density, duration of a high-current pulse, on the degree of the HCl donor burning out, maximum concentration of photons, and on the energy density of radiation.

As the calculations, made for the case of uniform preionization, have shown the above characteristics of the discharge only slightly vary when varying the initial value of electron density. At the same time the calculations, made for the case of nonuniform, though slight, preionization, predict the discharge contraction into the region of the initially enhanced number density of electrons. Thus, the increase, from 0 to 25%, of the difference between the initial electron densities in regions 1 and 2 having equal cross sections causes a considerable decrease in the maximum current density and in the duration of high-current pulse in region 1 as compared to those in the region 2. If the initial difference between the electron densities is 10%, the maximum photon concentration and the radiation energy density in region 1 are negligible as compared to those in the region 2. As a result, we have nonuniform radiation if there are inhomogeneities developed in the discharge plasma.

Similar tendencies are observed for the case when the area of the region with higher electron concentration is decreased while keeping constant relation between the initial electron concentrations.

The results of this study confirm the fact that inhomogeneous burning out of the halogen donor favors the development of inhomogeneities in the discharge. Burning out occurs more rapidly in regions where the electron density is high. The increase of the halogen donor content in the mixture makes the development of inhomogeneities in the discharge plasma more fast. Thus, to obtain the best homogeneity of the discharge, it is necessary to reduce partial pressure of HCl.

As was shown experimentally use of a special technique for the discharge initiation[1] provides for a better stability and higher homogeneity of the discharge. However, the calculations made for the case when nonuniform preionization of the active medium is used show that there appear inhomogeneities in the discharge plasma. To study the influence of the low-current stage on the discharge characteristics calculations were performed for different duration of the stage, starting from 0 to 1600 ns.

The differences between maximum values of the current density, duration of the high-current pulses, degree of the halogen donor burning out, maximum photon concentrations, and radiation energy density decrease when using a low-current discharge of 400 to 600 ns duration. However, the model constructed does not explain the stabilizing action of the preliminary low-current discharge.

CONCLUSION

This paper presents some results of numerical simulations of a stabilized electric-discharge XeCl*-

laser. The characteristics features of the developed model are:

(*i*) self-consistent solution of systems of equations for the electric circuitry, system of balance equations for heavy particles and photons, and nonstationary Boltzmann equation for the electron kinetics;

(*ii*) use of a sufficiently complete kinetic model of heavy particles and electrons.

Calculations show that the presence of a region with an enhanced initial concentration of electrons in the discharge leads to contraction of the discharge into this region.

The increase in the degree of discharge inhomogeneity, as well as in the HCl donor content in the mixture, or a decrease in the cross section of a region with higher electron density make the development of inhomogeneities in the discharge plasma faster.

The stabilizing action of a preliminary low-current discharge was not explained within the frames of this model. Studying the stabilization effect requires the use of two- or three-dimensional models.

REFERENCES

1. Yu. Bychkov, I. Kostyrya, M. Makarov, A. Suslov, and A. Yastremsky, Rev. Sci. Instrum. **65**, No. 4, 793–798 (1994).
2. M.T. Kushner, A.L. Pindroh, C.H. Fisher, T.A. Znotins, and J.J. Eving, J. Appl. Phys. **57**, No. 7, 2406–2423 (1985).