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Chapter 1

Introduction

1-1 General Remarks

Excimer lasers are gas discharge lasers that operate at high pressure and can produce short pulses of light in the vacuum UV region with high power and high efficiency. These laser photons have high energies and, therefore, efficiently induce chemical processes. As a result, excimer lasers have found application in the semiconductor industry, photo-chemical industry, medical technologies and in laser fusion. In the semiconductor industry, the excimer laser has been used for laser CVD^[1], laser annealing, laser etching, laser lithography, because the photo-chemical processes induced by these laser photons are fast low temperature processes^[2].

There are two kinds of excimer lasers: the rare gas dimer and the rare gas-halide excimer laser. A rare gas dimer (Xe_2^*) excimer laser oscillation at 176nm was observed in 1971 by Basov et al^[3] using e-beam excited liquid Xe. Koehler et al^[4] and subsequently Gerardo et al^[5] observed a stimulated emission line of 173nm in an atmospheric Xe gas in 1972. Hoff et al^[6] (1973) observed laser emission at 145.7nm in Kr gas and at 173nm (Xe line) in Xe/Ar mixtures. Rhodes^[7] calculated a Xe excimer laser output and compared it to his experimental results. From this comparison, he demonstrated that the peak laser power depends on the pressure in a Xe laser and that the wave length shift in a Xe/Ar gas mixture depends on the Ar partial pressure. To obtain high efficiency laser light, electron beam excited rare gas dimer excimer lasers was investigated in pressures between 6 and 27atm^[7]. In these studies, it was found that there were two major quenching processes for Xe_2^* . At high Xe gas pressures above 10atm, the major quenching processes is a $\text{Xe}_2^*-\text{Xe}_2^*$ collision process, and for pressures higher than 15atm, a photo-ionization process of

Xe_2^* by stimulated emission light is the major quenching processes. The former process leads saturation of Xe_2^* number density. The latter process leads to the absorption of laser light resulting in a rapid decrease in the efficiency and intensity of laser light.

In 1975, Velazco et al^[8] demonstrated the possibility of laser emission in mixtures of rare gases and halogen gases. The first oscillation at 281.8nm from XeBr^* excimer was observed by Searles et al in 1975. Subsequently, oscillation at 308nm from XeCl^* and at 249nm from KrF^* were reported by Ewing et al^[9]. A laser line of 353.1nm from XeF^* was observed by Ault et al^[10] and at 193.3nm from ArF^* by Hoffman et al^[11].

Rare gas-halide excimer lasers have been developed further, because high number density of excimers can be easily obtained at lower gas pressures than the rare gas dimer laser and the production efficiency of excimers is higher than the rare gas dimer laser. There are three major rare gas-halide excimer lasers which are now used in various fields, i.e. ArF , KrF and XeCl excimer lasers. They provide high power and high efficiency pulse light with wave lengths of 193, 249, 308nm, respectively. In order to improve laser characteristics further, many experimental and theoretical investigations have been carried out. Greene et al^[12] provided interesting results in their work of modeling of KrF and ArF lasers. Recently, these excimer lasers have been developed further, because these photon energies are high enough to meet industrial demands. In order to apply them to industry, laser light with higher power, higher efficiency, higher repetition rate, etc. are necessary. To satisfy these requirements, a clear understanding of discharge plasmas as an excitation media for rare gas-halide excimer lasers is needed. This thesis is attempts to contribute to this need.

1-2 Principles of Operation of Excimer Lasers

1-2-1 Formation of Excimers

An excimer is excited molecule of two atoms. Previously, an excimer consisting of the two same atoms was called an excimer (excited dimer), while an excimer consisting of two different atoms was called exciplex (excited complex). Now both are called excimers.

The distinguishing feature of the molecules used in these lasers is that the excited molecule exists in a stable configuration but the ground state molecule does not. The basic molecular structure is shown in figure 1.1^[13].

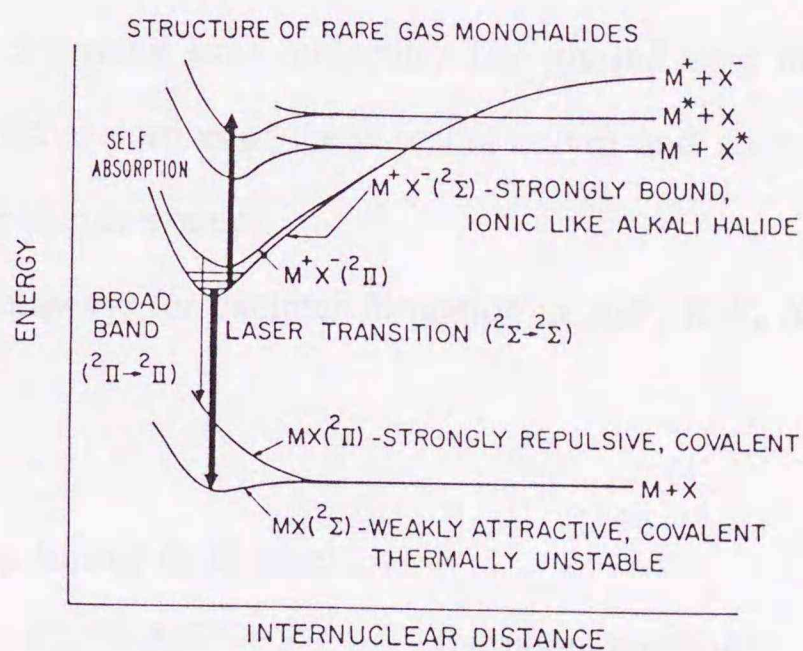


Figure 1.1. Potential energy diagram illustrating the electronic structure of the rare gas halide.

In such a system it should be possible to readily achieve a population inversion between the stable excited molecular species and the unstable ground state molecular species. Some of the implications of such a system are as follows:

- Since the transition is from a bound molecular state to a free molecular state (bound-free), laser action should be tunable over a wide range.

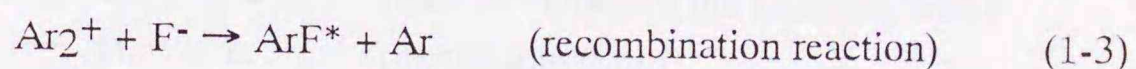
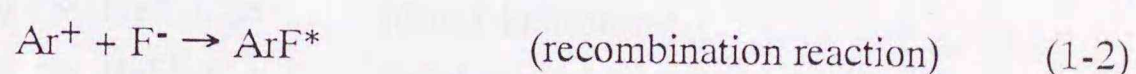
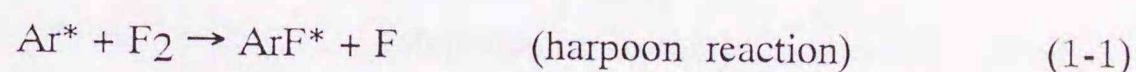
- because of the broad line width (tunability) the gain on laser transition should be low, allowing a substantial amount of energy to be stored in the upper state (high power).
- Since the transition occurs from a low excited molecular state to a state near ground, the efficiency (laser energy out over excitation energy) should be very high.

Since the ground state of excimer is repulsive, excitation can occur from the ground state atom to a low excited atomic state. The excited molecule is created by a three body conversion (or association) process.

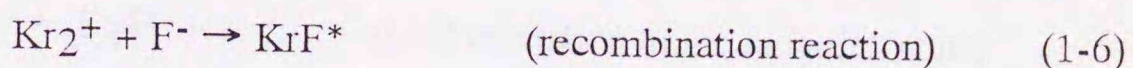
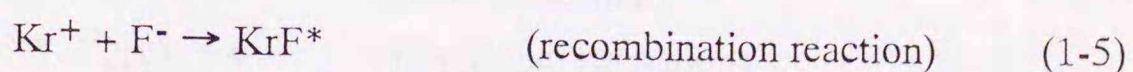
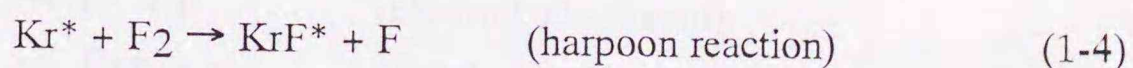
Obviously, the higher the pressure, the more rapid the conversion process and the higher the pumping rate for the upper laser level. Once the excimer is formed in sufficient numbers, stimulated emission will occur and the excited molecule will radiatively relax to a ground state molecule. The ground state molecule is unstable (created on the repulsive portion of the potential curve) and so it rapidly dissociates into the ground state atomic system.

The major pathways for excimer formation in ArF, KrF, XeCl excimer lasers are the following,

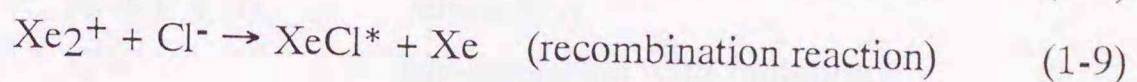
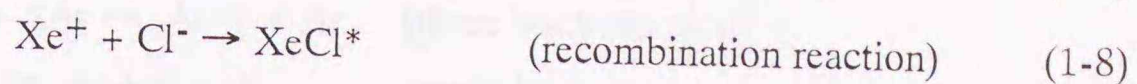
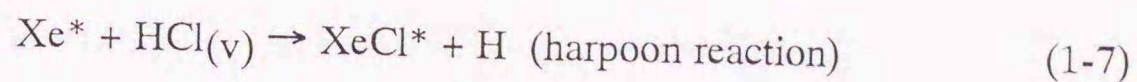
ArF* excimer formation channel



KrF* excimer formation channel



XeCl* formation channel

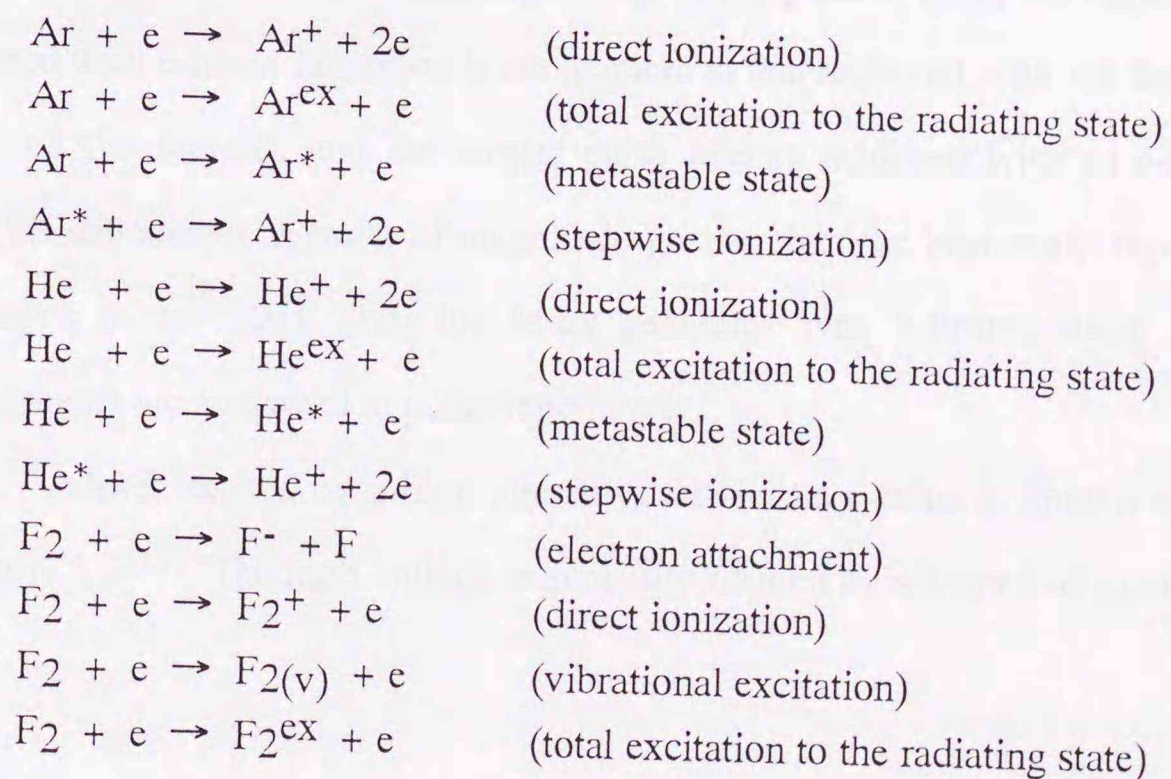


In the discharge-excited rare gas-halide excimer laser, excimer formation channels (1-2), (1-4), (1-5), (1-7) are the dominant channels. Also, at high pressure, channel (1-3), (1-6), (1-9) are increasingly important because of three body collisions.

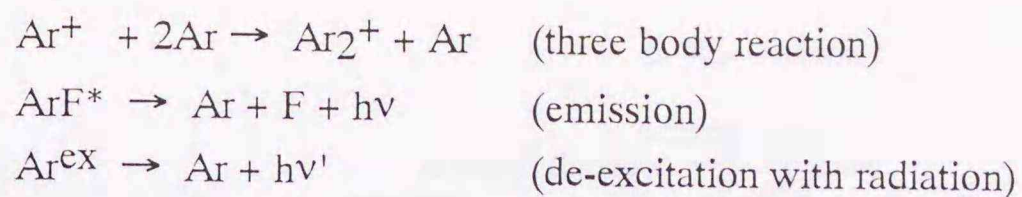
1-2-2 Plasma Kinetics

Major plasma kinetics in rare gas halide excimer laser medium discharge is presented here. Rare gas halide excimer laser gas media usually consists of a mixture of three gases; a rare gas, a halogen and a buffer gas. For example, major electron-neutral and neutral-neutral reactions of ArF excimer laser are following.

- electron-neutral reactions



- neutral reactions



1-2-3 Excitation Techniques

There are two major excitation methods, i.e. electron beam (e-beam) excitation and discharge excitation.

- E-beam excitation

The first rare gas-halide lasers were pumped by high intensity, relativistic electron beams. Such pumping schemes offer a relatively straightforward, brute force method for pumping high pressure gases with the very high power densities needed to achieve threshold. Compared with discharges, electron beams eliminate problems of discharge stability and minimize problems of circuit inductance, since they operate at higher impedances than transverse discharges. Up to the present time, the highest efficiency reported with e-beam excitation is comparable to that achieved with discharges (on the order of 1% overall), and the largest pulse energy achieved with an e-beam (about 350J) is still almost an order of magnitude greater than the best result reported from a discharge (about 50J). But, the Marx generator type e-beams used in the early experiments are awkward to pulse repetitively.

A laser excited by a high intensity, relativistic e-beam is shown schematically in figure 1.2^[13]. The high voltage is generally formed by a Marx *L-C* generator.

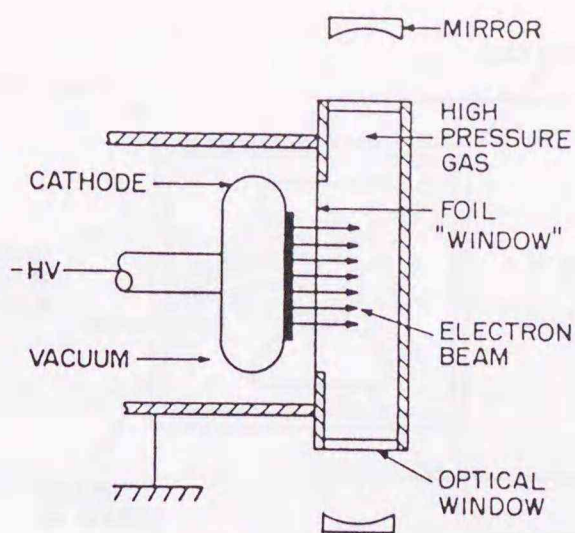


Figure 1.2. Schematic diagram of a laser excited by a high intensity e-beam.

- Discharge excitation

Compared with e-beams, discharges offer the potential for higher excitation efficiency and higher average power. The reason for the higher excitation efficiency is that it is possible, using a carefully controlled discharge, to excite the metastable levels of the rare gases directly by electron impact with very high efficiency. The higher average power is achieved by avoiding or (in electron beam stabilized discharges) reducing the problems of foil heating and beam pinching.

For many applications small pulses and somewhat lower efficiency are acceptable in the interest of simplicity. For these purpose it is possible to use unstable, fast transverse discharge, as shown schematically in figure 1.3^[13]. In rare gas-halide lasers such discharges are fundamentally unstable. Once the gas breaks down the electrons multiply rapidly and the discharge impedance collapses. The discharge current is then inductance limited, reducing the voltage across the discharge. Moreover, spatial non-uniformities in the discharge grow with time and develop into arcs, or streamers. For these reasons it is essential to minimize the inductance in the discharge circuit and keep the current pulse short.

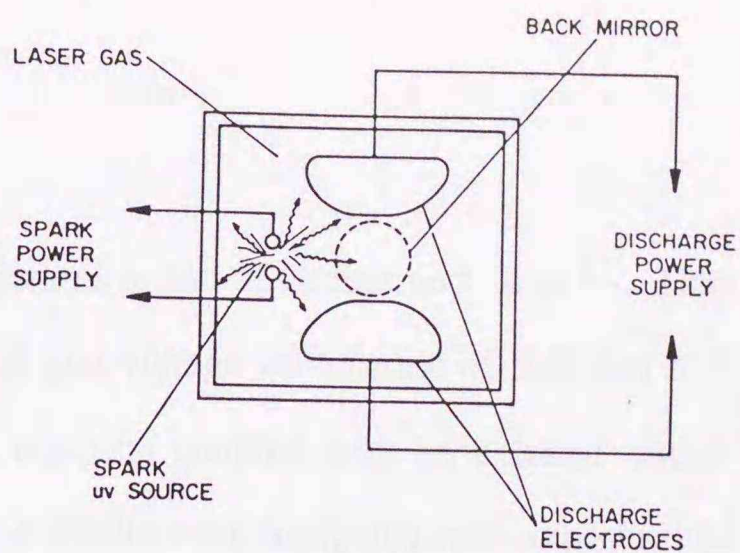


Figure 1.3. Schematic diagram (viewed along the laser axis) of a laser excited by a transverse discharge using UV radiation from a spark source to preionize the gas.

Many different configurations have been used for the power supply. These include Blumlein circuit with strip transmission lines, charged coaxial cables, pulse-forming networks, and charge transfer circuits. The power supply may be switched into the discharge with a low inductance spark gap, or the series inductance of the switch may be eliminated by impulse charging the power supply or allowing it to ring up to voltage and then allowing the laser gas to breakdown when the voltage is high enough.

1-2-4 Preionization Techniques

Because of the development of streamers, or arcs in discharge-excited excimer lasers described above, the useful electrical pulse length of lasers with no external stabilization is limited to about 30ns at low pressure ($\leq 0.5\text{atm}$), and proportionately less at higher pressures. To suppress instabilities at higher pressures, the gas can be preionized. This can be done by means of a short preionizing corona discharge pulse,

but better results have been achieved by weakly preionizing the gas with UV radiation from a series of sparks distributed along the length of the laser.

1-3 Previous Work

One of the earliest simulations is that of Greene and Brau^[12]. They predicted the laser output, discharge current and voltage waveforms of ArF and KrF excimer lasers by solving the Boltzmann equation coupled with an external circuit in a simple zero-dimensional model. Their results were compared with experimental results of Sze and Loree^[14]. In particular, the time evolution of the voltage and current waveforms^[12] agreed well with measurement of Sze and Loree^[14].

In early excimer laser models, simulations were performed to determine the main excimer formation channels and excimer precursors in laser discharges. Rate coefficients in models were adjusted so that discharge plasma characteristics obtained by modeling were consistent with experimental results. A Boltzmann equation analysis is a powerful method for analyzing the laser medium discharge in a zero-dimensional models.

Hokazono et al^[15] calculated discharge characteristics and output performance of a discharge-excited XeCl excimer laser using the Boltzmann equation in a zero-dimensional model. The difference of discharge characteristics and output power between Ne and He-based gas mixture was shown. In their analysis processes for electron-electron collisions and superelastic collisions processes were considered, but the electron dissociative attachment was neglected.

Ohwa et al^[16] simulated a discharge-excited XeCl laser using the Boltzmann equation in a zero-dimensional model, and predicted the ratio of HCl concentration to total pressure and the total pressure for high-efficiency operation for a laser pulse width of 110ns. It was found that discharge and kinetics characteristics were affected predominantly by the ratio of the Xe to HCl. They concluded that, in order to attain

high-power and high-efficiency self-sustained discharge pumped XeCl laser, it is necessary to develop an excitation circuit having a low impedance in which electric power can transfer efficiently to a low impedance discharge load.

Subsequent to Ohwa's work, multi-dimensional models were developed to study the evolution of electric field distribution, preionization electron density distribution etc.

Sorkina^[17] developed a model with one-dimensional in the direction transverse to the electric field for a discharge-excited XeCl laser. Position dependent discharge parameters were taken. Calculated laser plasma species densities, laser pulse spatio-temporal dynamics, and discharge current and voltage, were compared with experimental data. Also, the influence of electric field and preionization inhomogeneity on the spatial distributions of the various species in the laser active medium was examined.

Discharge instability has been investigated mainly for XeCl excimer lasers^[18-20]. Halogen depletion was proposed to be one of the causes of discharge instability^[18]. In this theory, a small decrease in the local halogen density resulted in a local increase of the ionization rate which might finally lead discharge filamental instability. Other causes of the discharge instability have been proposed recently, such as non-uniformity of the electric field in a ultra-long-pulse XeCl laser^[19], the field emission of electrons by strong electric field distortion near the electrodes^[20].

Turner^[19] developed a two-dimensional model for a discharge-excited gas XeCl excimer laser, and computed electric fields accurately for complex geometries. He investigated a proper profile of electrodes which may provide a stable discharge. It was shown that electrode profile affected the spatial distribution of laser output energy, but did not affect the laser energy efficiency and the discharge characteristics for lasers with pulse durations less than 200ns. Finally he concluded that for excitation voltages pulse longer than 1 μ s, different electrode designs were necessary to obtain high quality laser beams.

Kushner^[21] investigated both macroscopic and microscopic non-uniformities of the preionization density and halogen density as precursors which may lead to arcs, and microarcs in discharge-excited KrF lasers. He indicated that the macroscopic non-uniformities lead to volumetric arcing and that the microscopic non-uniformities lead to filamentation. He showed that the microarcs might terminate the optical pulse due to disruption of optical homogeneity in a plasma prior to collapse of discharge impedance and that small-scale microscopic inhomogeneities developed into microarcs sooner than into large-scale homogeneities due to higher pressure gradient afforded by their small size.

Belasri et al^[20] presented a one-dimensional model of a XeCl discharge plasma including a cathode region coupled with an external circuit. Results showed that under normal conditions of operation the cathode electric field could reach a value higher than 10^6V/cm . Finally, a possibility of discharge instabilities occurrence was discussed related to sheath evolution.

Recently, Longo et al^[22] and Colonna et al^[23] applied Fourier-transform sensitivity analysis to a simplified model of a XeCl self-sustained discharge laser. They showed that this analysis is possible to determine the sensitivity of laser output with respect to known but variable quantities, such as initial voltage on the capacitor, pressure, discharge volume, etc.

1-4 Purpose and Synopsis of the Thesis

The aim of the present work is to develop a self-consistent simulation model which enables us to investigate cause of filamental instability occurrence in an excitation discharge plasma medium.

The present thesis consists of 8 chapters. Chapter 1 is the introduction of the research treated in the present thesis, and describes the background of previous work. The purpose and synopsis of the present work are presented.

In chapter 2, the fluid model of excimer lasers is described and the swarm parameters used in the present work are shown. The present fluid model is compared with a Monte Carlo model and a Local Field Approximation (LFA) Fluid model under a condition without external circuits.

In chapter 3, the discharge plasma development in an ArF excimer laser which neglecting influence of stimulated emitted photons on the discharge development, is shown in order to reveal the details of electric field distortion and spatio-temporal distribution of species number density near the electrodes. The dependence of secondary electron emission from the cathode and preionization electron density are also examined. Possible moderation of the highly distorted electric field by field emission of electrons from the cathode is discussed.

In chapter 4, the effect of photoionization and photodetachment by stimulated emission light on the discharge development is discussed. The results on the spatio-temporal distribution of species number density, electric field, etc. are compared with those obtained from the case of no stimulated emission light.

In chapter 5, the preionization uniformity is discussed. A non-uniform preionization model in the direction of the laser light is presented. First, the dependence of the uniform preionization electron number density on the discharge characteristics are discussed. Then, the non-uniform preionization dependence of discharge characteristics are discussed. Laser light characteristics are compared with those in the uniform preionization model.

In chapter 6, the dependence of the discharge characteristics on the circuit inductance is discussed. The influence of values of the primary and secondary circuit inductance L_1 and L_2 on discharge development, especially on the electric field distortion and laser characteristics is presented.

In chapter 7, the present fluid model is applied to a XeCl excimer laser. The features in discharge development of a XeCl excimer laser are described. The

comparison of discharge development between XeCl and ArF excimer lasers are discussed.

Chapter 8 provides conclusions. The results obtained by the present work are summarized.

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Chapter 2

Modeling of Discharge Plasma Development in Excimer Lasers

2-1 Introduction

As mentioned in chapter 1, many models have been developed for excimer lasers. However, most of them are a zero-dimensional model written to predict the laser output, efficiency, etc. of specific devices for various gas mixtures, gas pressures, excitation circuits and so on.

Multi-dimensional modeling of a discharge plasma for high pressure, high charged particles density and electro-negative gas medium is difficult. But it is necessary to understand the behavior of discharge plasmas and cause of instability in excimer laser discharges.

In a high pressure and high electron number density gas discharge, the sheath length is very small and the electric field distortion becomes very high. Therefore, effect of the electric field distortion on the discharge development may not be ignored. Recently, a several types of multi-dimensional models have been reported, however, only a few works among them include a Poisson's equation^[1,2]. In this thesis a fluid model is presented in which calculations have been performed self-consistently using one-dimensional continuity equations for charged particles coupled with the Poisson's equation. A diffusion term as well as a drift term in the continuity equations are considered.

In this chapter, all the equations used and the model developed in particular for an ArF excimer laser are presented.

2-2 Basic Equations

2-2-1 Continuity Equations for Charged Particles

A typical model in one-dimension, with x , the distance from the cathode, parallel to the external field - E_{ex} , in the gap is taken.

This model consists of the following equations for discharge kinetics: continuity equations for electrons, Ar and He positive ions, F₂ negative ions radicals (ArF^{*}) and neutrals, an equation for photo-electron emission from the cathode, an electron energy conservation equation, continuity equation for the laser photons produced by stimulated emission and Poisson's equation.

The number densities of electrons n_e , positive ions $n_{+,Ar}$ and $n_{+,He}$ (in this work, F₂⁺ is neglected) and negative ions $n_{-}(F^-)$ as functions of x and time t are obtained by solving the following continuity equations

$$\frac{\partial n_e}{\partial t} = (N_{Ar}k_{ia} + N_{He}k_{ih} + n_{Ar^*}k_{si} - N_{F_2}k_a)n_e + (\sigma_{pi_{ex}}n_{ex} + \sigma_{pd}n_{-})cn_p + \frac{\partial}{\partial x}(-W_r n_e + DL \frac{\partial n_e}{\partial x}) \quad (2-1)$$

$$\frac{\partial n_{+,Ar}}{\partial t} = (N_{Ar}k_{ia} + n_{Ar^*}k_{si})n_e + \sigma_{pi_{ex}}n_{ex}cn_p + \frac{\partial}{\partial x}(W_{+,Ar}n_{+,Ar} + DL_{+,Ar}\frac{\partial n_{+,Ar}}{\partial x}) \quad (2-2)$$

$$\frac{\partial n_{+,He}}{\partial t} = N_{He}k_{ih}n_e + \frac{\partial}{\partial x}(W_{+,He}n_{+,He} + DL_{+,He}\frac{\partial n_{+,He}}{\partial x}) \quad (2-3)$$

$$\frac{\partial n_{-}}{\partial t} = N_{F_2}k_a n_e - \sigma_{pd}n_{-}cn_p + \frac{\partial}{\partial x}(-W_{-}n_{-} + DL_{-}\frac{\partial n_{-}}{\partial x}) \quad (2-4)$$

where k_j is the rate coefficients of the j th kind of reactions listed in Table 1, and N_{Ar} , N_{He} and N_{F_2} are the number densities of Ar, He and F₂, respectively. c , n_{ex} , $\sigma_{pi_{ex}}$, σ_{pd} are the speed of light, the number density of the excited Ar atom (Ar^{ex}), here metastable Ar atom (Ar^{*}) number density is not included in n_{ex} , the photoionization cross section for Ar^{ex} and the photodetachment cross section for F⁻, respectively. $W_r(DL)$, $W_{+,Ar}(DL_{+,Ar})$, $W_{+,He}(DL_{+,He})$ and $W_{-}(DL_{-})$ are the drift velocities (the

longitudinal diffusion coefficients) for electrons, Ar and He positive ions and F negative ions, respectively. Values for k_j and D_L are assumed to be a function of the mean electron energy ε , while values for W_r , W_+ , W_- , D_{L+} and D_{L-} , are taken as the local field approximation, to be a function of E/p_0 ^[3]. The laser photon number density n_p is given by equation(2-9). In the present model, the photoionization process from Ar^* is neglected, since the cross section for this process is 10^{-2} times smaller than the value from Ar^{ex} ^[4] and their densities are in the same order each other.

2-2-2 Poisson's Equation

The time dependent local field $E(x,t)$ is given as

$$E(x,t) = E_{in}(x,t) + E_{ex}(x,t). \quad (2-5)$$

Here E_{in} and E_{ex} are the space charge distorted field strength by the space charge, which is given by Poisson's equation, and the external field, respectively. They are written, using a Poisson's equation for E_{in} as

$$E_{in}(x,t) = \frac{e}{\varepsilon_0 d} \int_0^d x \rho(x,t) dx - \frac{e}{\varepsilon_0} \int_x^d \rho(x,t) dx \quad (2-6)$$

$$E_{ex}(t) = \frac{V_g}{d}. \quad (2-7)$$

Here

$$\rho(x,t) = n_+(x,t) - n_-(x,t) - n_e(x,t)$$

where e , ε_0 , d and V_g are the charge of an electron, the permittivity in vacuum, the gap length and the gap voltage respectively.

2-2-3 Energy Conservation Equation for Electrons

The mean electron energy $\varepsilon(x,t)$ in the discharge plasma is obtained using the following equation assuming the electron energy distribution being Maxwellian^[3].

$$\frac{\partial}{\partial t} \left(\frac{3}{2} n_e k T_e \right) + \frac{\partial q_e}{\partial x} = -\phi_e e E - (N_{Ar} k_{ia} H_{i,Ar} + N_{He} k_{ih} H_{i,He} + n_{Ar}^* k_{si} H_i) n_e + N_{F_2} n_e T_e - \sum_m N_m k_m n_e H_m + (\sigma_{pi_{ex}} n_e H_{pi_{ex}} + \sigma_{pd} n_- H_{pd}) c n_p. \quad (2-8)$$

Here

$$\phi_e = -W_p n_e + D_L \frac{\partial n_e}{\partial x}$$

$$q_e = \frac{5}{2} T_e \phi_e - \kappa \frac{\partial T_e}{\partial x}$$

$$\kappa = \frac{5}{2} n_e D_L$$

where k , T_e , $H_{i,Ar}$, $H_{i,He}$, H_{si} , H_m , $H_{pi_{ex}}$, H_{pd} and κ are the Boltzmann constant, the electron temperature, the ionization potential for Ar and He, the step-wise ionization energy, the excitation energy to the m th state, the energy for secondary electrons produced from Ar^{ex} by photoionization, the energy for secondary electrons produced from F^- by photodetachment and the electron thermal conductivity, respectively. m indicates the m th excitation state for Ar and He.

2-2-4 Continuity Equation for Laser Photons

The discharge excitation medium is assumed to be uniform in the direction of the optical axis. The photon density n_p may be expressed in terms of the optical gain g , the absorption α and the threshold gain g_{th} ^[5], as

$$\begin{aligned} \frac{dn_p}{dt} &= \frac{c n_p}{l_c} (g - \alpha - g_{th}) + \frac{K n_{ArF^*}}{\tau} \\ g &= l_g \sigma_{st} n_{ArF^*} \\ \alpha &= l_g (\sigma_{pi_{ex}} n_{ex} + \sigma_{pd} n_-) \\ g_{th} &= -\left(\frac{1}{2} \ln R + \ln(1-L)\right) \end{aligned} \quad (2-9)$$

Here l_g , n_{ArF^*} and σ_{st} are the active discharge excitation medium length, the ArF^* excimer density and the stimulated emission cross section, respectively. R and L are the reflectivity of a mirror, and the single path optical loss (excluding particle absorption). l_c , K and τ are the cavity length, the fraction of the spontaneous emission to be amplified to the laser light and the lifetime of the ArF^* , respectively.

2-2-5 Secondary Electron Emission from Cathode by Photons

A Secondary electron emission process from the cathode by photons generated from radiative de-excitation of gases is also considered. The photoelectron number density $n_{ep}(0,t)$ at the cathode is given by the following equation^[6]

$$n_{ep}(0,t) = \frac{1}{W_v(0,t)} \frac{\gamma_p}{\tau} \int_0^t \exp\left(-\frac{t-t'}{\tau}\right) \int_0^d n_e(x,t') R_{ex} \Omega(x) \exp(-\mu x) dx dt' \quad (2-10)$$

where $W_v(0,t)$, γ_p , τ , $\Omega(x)$ and μ are the drift velocity for the photoelectrons, the efficiency factor for a photon to release photoelectrons from the cathode, the lifetime of the radiative excited states of the gas atom, the solid angle at the cathode subtended by a disk of the charge at x and the photon absorption coefficient in the gas, respectively.

2-2-6 Boundary Conditions

Boundary conditions at the cathode ($x=0$) for equations (2-1)~(2-4) and (2-7) are taken respectively, as

$$n_e(0,t) = n_{ep}(0,t)$$

$$n_+(0,t) = \frac{\phi_+(\Delta x, t)}{W_+(0,t)}$$

$$n_-(0,t) = 0$$

$$V(0,t) = 0$$

$$T_e(0,t) = 0.5$$

Here

$$\phi_+(\Delta x, t) = W_+(\Delta x, t) n_+(\Delta x, t) + DL + \frac{\partial n_+(\Delta x, t)}{\partial x}$$

where Δx is the mesh width for numerical calculation in the gap.

At the anode ($x=d$), as

$$n_e(d,t) = n_+(d,t) = n_-(d,t) = 0$$

$$V(d,t)=V_g$$

$$T_e(d,t)=0.$$

2-3 Plasma Parameters

2-3-1 Electron Collision Cross Sections

Figure 2.1 shows the electron collision cross sections used in the present work.

The cross sections for Ar and He are taken from Sakai et al^[7,8] and Ton-That et al^[9].

The electron attachment cross section for fluorine is taken from Hazi et al^[10].

2-3-2 Rate Coefficients for Electrons

The reaction processes and the rate coefficients for electrons and their threshold energies adopted in this work are listed in Table 2.1. For F₂, only the attachment process is considered, because of its low mixture ratio. The rate coefficients for the processes described in Table 2.1. The rate coefficients, $\bar{\epsilon}$, W_r and D_L are calculated using the Boltzmann equation. The rate coefficients are replotted as a function of $\bar{\epsilon}$ as shown in figure 2.2.

Table 2.1. Reactions for electrons adopted in the present model

electron-neutral reaction	H(eV)	rate coeff.	ref.
Ar + e → Ar ⁺ + 2e	15.76	k _{ia}	[7]
Ar + e → Ar ^{ex} + e (total excitation to the radiating state)	12.9	k _{exa}	[7]
Ar + e → Ar* + e (metastable state)	11.55	k _{mea}	[7]
Ar* + e → Ar ⁺ + 2e	4.21	k _{si}	[9]
F ₂ + e → F ⁻ + F		k _a	[10]
He + e → He ⁺ + 2e	24.588	k _{ih}	[8]
He + e → He ^{ex} + e (total excitation to the radiating state)	20.96	k _{exh}	[8]
He + e → He* + e (metastable state)	19.8	k _{meh}	[8]

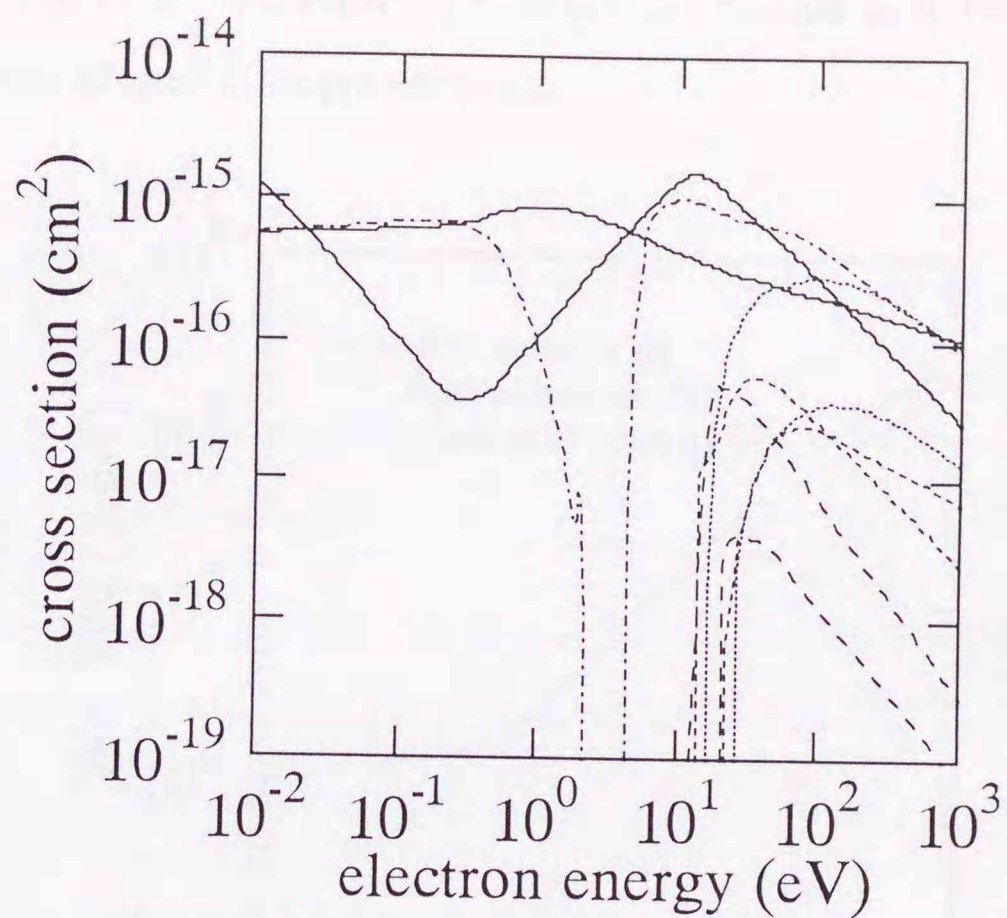


Figure 2.1. Electron collision cross sections. — $Q_m(\text{He})$; $Q_i(\text{He})$; - - - $Q_{ex}(\text{He})$; - - - $Q_{met}(\text{He})$; — $Q_m(\text{Ar})$; $Q_i(\text{Ar})$; - - - $Q_{ex}(\text{Ar})$; - - - $Q_{met}(\text{Ar})$; $Q_{si}(\text{Ar})$; $Q_a(\text{F}_2)$

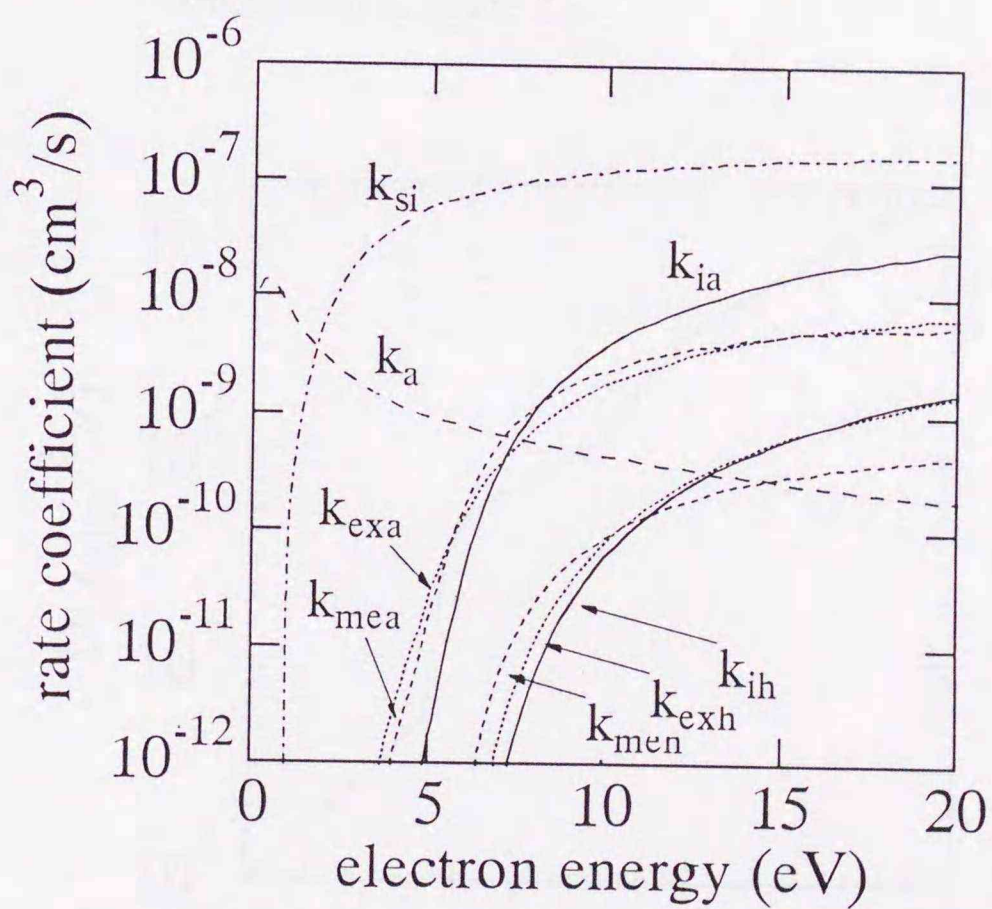


Figure 2.2. Electron-neutral reaction rate coefficients as a function of mean electron energy in $\text{Ar}/\text{F}_2/\text{He}=0.0789/0.0024/0.9187$. k values are given in table 2.1.

Figure 2.3 and Figure 2.4 shows the electron drift velocity and diffusion coefficient adopted in the present work.

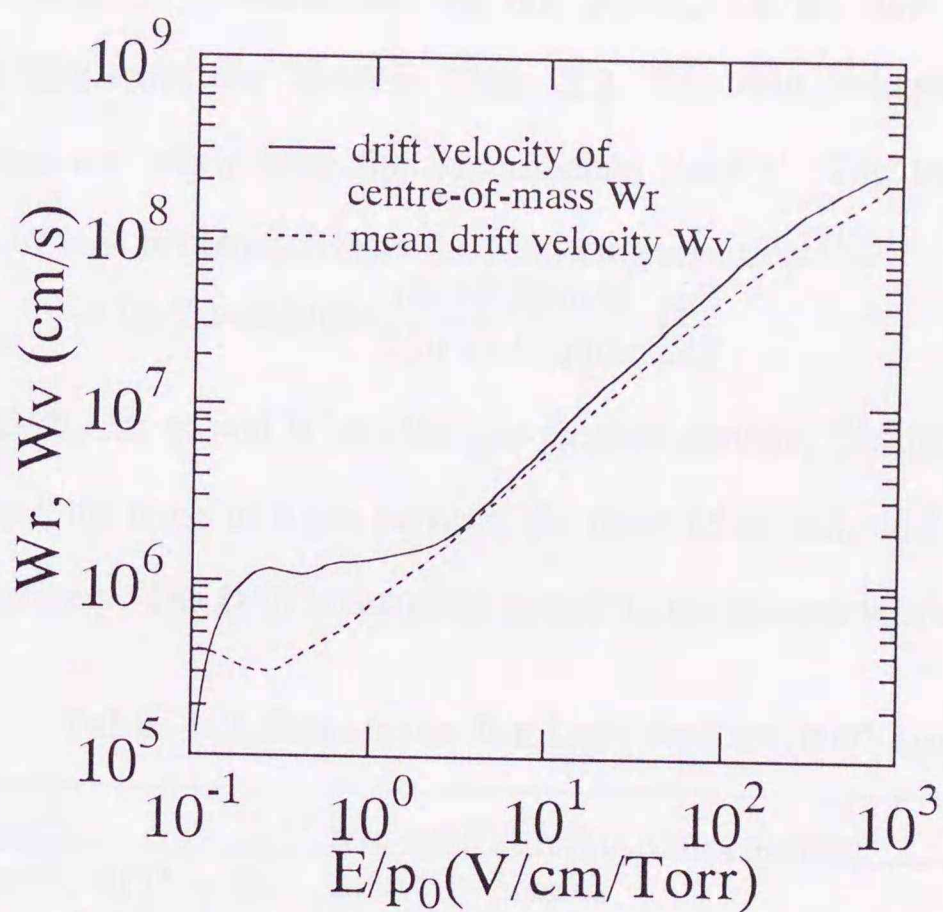


Figure 2.3. Electron drift velocity in the same conditions as described in figure 2.2.

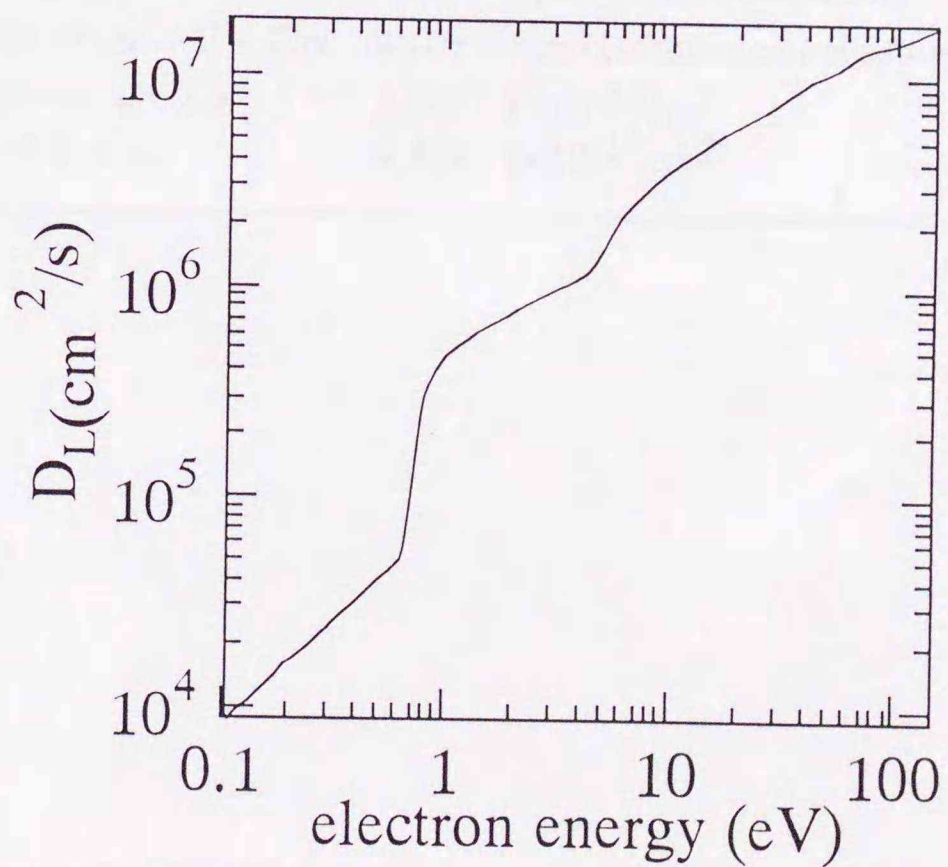


Figure 2.4. Electron longitudinal diffusion coefficient D_L in the same conditions as described in figure 2.2.

2-3-3 Rate Coefficients for Ions and Excited Species

The reaction processes and the rate coefficients for ions and excited species adopted in this work are listed in Table 2.2. The drift velocities of negative and positive ions are taken from the experimental data^[11]. The longitudinal diffusion coefficient of ions is obtained from the following equation^[11]

$$ND_L(E) = ND(0) + \frac{(M+3.72m)M}{3(M+1.908m)e} \frac{W^3}{E/N} \quad (2-11)$$

where N , $D(0)$, M , m and W are the gas number density, the diffusion coefficient at the zero-field, the mass of a gas particle, the mass of an ion, and the drift velocity of ions, respectively. The $D(0)$ is assumed to be 0 in the present work.

Table 2.2 Reactions for ions and excited species

neutral reaction	rate coeff./lifetime/cross section	ref.
$\text{Ar}^+ + 2\text{Ar} \rightarrow \text{Ar}_2^+ + \text{Ar}$	$2.5 \times 10^{-31} \text{cm}^6/\text{s}$	[12]
$\text{Ar}^* + \text{F}_2 \rightarrow \text{ArF}^* + \text{F}$	$8.0 \times 10^{-10} \text{cm}^3/\text{s}$	[13]
$\text{Ar}^+ + \text{F}^- \rightarrow \text{ArF}^*$	$1.0 \times 10^{-6} \text{cm}^3/\text{s}$	[13]
$\text{Ar}_2^+ + \text{F}^- \rightarrow \text{ArF}^* + \text{Ar}$	$1.0 \times 10^{-6} \text{cm}^3/\text{s}$	[13]
$\text{Ar}^{\text{ex}} \rightarrow \text{Ar} + h\nu'$	1.0ns (de-excitation with radiation)	[estimated]
$\text{ArF}^* \rightarrow \text{Ar} + \text{F} + h\nu$	4.2ns (spontaneous emission)	[14]
$\text{ArF}^* + h\nu \rightarrow \text{Ar} + \text{F} + 2h\nu$	$4 \times 10^{-16} \text{cm}^2$ (stimulated emission)	[13]
$\text{Ar}^{\text{ex}} + h\nu \rightarrow \text{Ar}^+ + e$	3.565 $1 \times 10^{-18} \text{cm}^2$	[4]
$\text{F}^- + h\nu \rightarrow \text{F} + e$	4.324 $1 \times 10^{-17} \text{cm}^2$	[15]

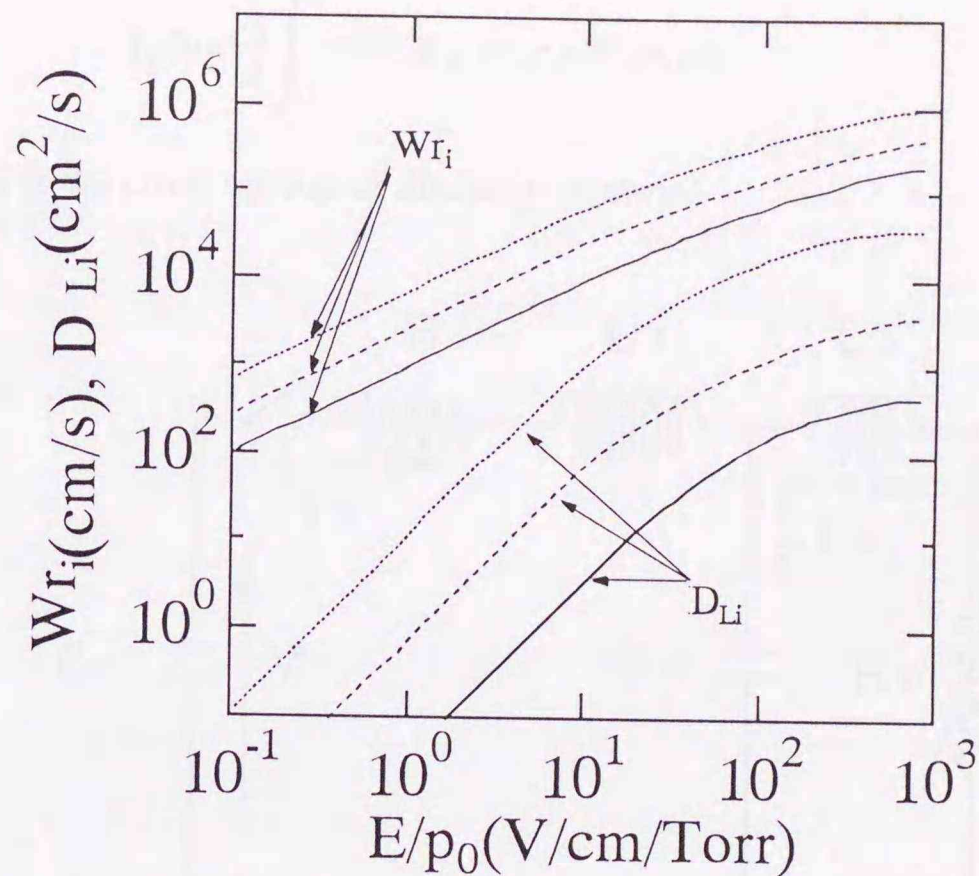


Figure 2.5. Drift velocity and longitudinal diffusion coefficient of ions.
 He⁺; — Ar⁺; F⁻

2-4 Excitation Circuit

As an excitation circuit, a charge-transfer circuit^[14] is taken here, as shown in figure 2.6. The circuit equations are written, as

$$\begin{aligned}\frac{dV_1}{dt} &= -\frac{I_1}{C_1} \\ \frac{dV_2}{dt} &= \frac{I_1 - I_g}{C_2} \\ \frac{dI_1}{dt} &= \frac{-RI_1 + V_1 - V_2}{L_1} \\ \frac{dI_g}{dt} &= \frac{-R_D I_g + V_2}{L_2}\end{aligned}$$

Here the equivalent resistance R_D is taken to be $R_D = R_{D0}$ for $R_D > R_{D0}$. R_D is given as follows,

$$R_D = \frac{V_g}{I_g} \quad (2-10)$$

where I_g is written as^[16],

$$I_g(t) = \frac{eS}{d} \int_0^d (W_+ n_+ - W_- n_-) dx \quad (2-11)$$

where S is the cross section of discharge plasma.

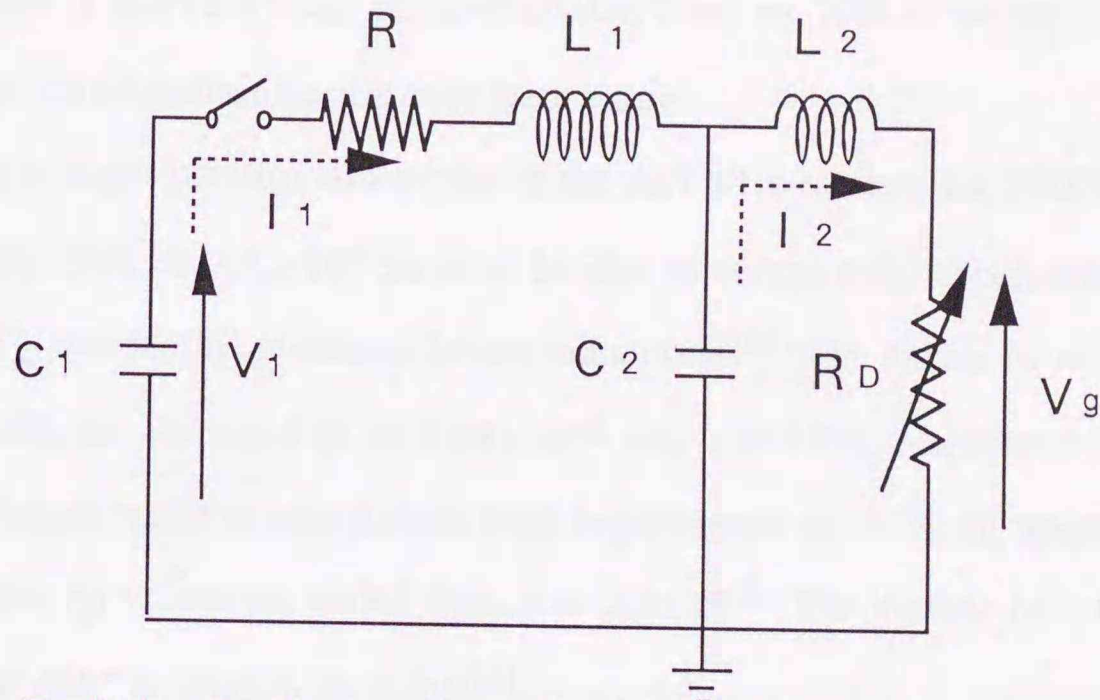


Figure 2.6. Excitation circuit of a self-sustained discharge ArF laser. R_D is the effective resistance of the discharge plasma. $C_1=10\text{nF}$, $C_2=1.5\text{nF}$, $R=1\Omega$, $L_1=600\text{nH}$, $L_2=20\text{nH}$. $V_1=20\text{kV}$ at $t=0$. The discharge volume is 90cm^3 or $1\text{cm}(d) \times 90\text{cm}(l_g) \times 1\text{cm}(\text{discharge width})$.

2-5 Numerical Method and Basic Simulation Conditions

In the present model, the kinetics of electrons and ions are calculated using a marching scheme repeating calculation every time step Δt_s . During Δt_s , $E(x, t)$ is assumed to be constant. After calculation of $n_e(x, t)$, $n_+(x, t)$ and $n_-(x, t)$, the new electric field is given using equation (2-5).

The V_g is calculated every time step Δt_s , solving the circuit equations by the Runge-Kutta method. To save the computation time, $R_D=R_{D0}(=1\text{M}\Omega)$ for $R_D>R_{D0}$. This simplification does not result in appreciable differences in the V_g waveform, for different R_{D0} , because I_g is small enough when $R_D>R_{D0}$.

For numerical calculation, Δt_S is taken to be 2ps in chapter 3 and 1ps in others. The gap is divided into 2000; the distance Δx is 5×10^{-4} cm. These values are taking into account of Courant, Neuman and $\Delta t_S < \epsilon_0 / \sigma$ conditions^[17].

The simulation is terminated when $E(x, t)$ or $\epsilon(x, t)$ at any position in the gap becomes over 1.52×10^3 kV/cm ($E/p_0 = 800$ V/cm/Torr) or 100eV, because numerical instability in the simulation occurs over these values.

The total gas pressure and a ratio of the Ar/F₂/He mixture are 1900Torr (2.53 bars) and 0.0789/0.0024/0.9187 so as to be able to compare the experimental results of I_g and V_g waveforms measured in our laboratory^[18]. The values of μ and γ_p in equation (2-8) are estimated to be 0.041 cm^{-1} and 2.0×10^{-2} , respectively, so as to obtain the proper result in comparison with experimental ones^[19]. In addition to the above values, γ_p values are varied from 0 to 2.2×10^{-2} . The lifetime of spontaneous emission for ArF* is taken to be 4.2ns^[14].

It is assumed that the circuit is switched on at $t=0$ just after the preionization. The applied voltage V_I to C_I at $t=0$ is 20kV. The number density of preionized electron-ion pairs n_{e0} is varied between 10^2 and 10^8 cm^{-3} , and the energy of preionized electrons is assumed to be 1eV.

The discharge volume is 90 cm^3 or $1 \text{ cm}(d) \times 90 \text{ cm}(l_g) \times 1 \text{ cm}(\text{discharge width})$.

2-6 Other Models

To verify the present model, a simple simulation in which an external circuit is not included has been carried out using a Monte Carlo and a Local Field Approximation (LFA) fluid methods.

The results of two models are compared to the present model. The most of the simulation conditions are the same as described in section 2-5, except for the applied reduced electric field which is $E/p_0 = 7 \text{ V/cm/Torr}$.

2-6-1 Monte Carlo Model

A Monte Carlo model used in the present work is a modified version of Yokozawa's^[20] model. The features of the present Monte Carlo model are as follows,

- In an excimer laser medium, the charged particle number densities are usually very high, so that the scaling technique is applied. The velocity distribution is divided into uniform slabs. This method can be easily applied to low pressure plasma but in high pressure plasma, the re-calculation error increases significantly due to the large collision frequencies. In the present work, the non-uniform slabs in the velocity distribution are taken to determine accurate velocity distribution.
- The discharge medium is a mixture of three gases; Ar, F₂ and He. The judgment of a kind of collisions is determined by judgment of a kind of the gases at first that is related to the ratio of gas mixture. Then the judgment of collision is done in a usual method.
- In the present gas pressure condition, the sheath region would be very small, so that the narrower slabs are taken near the electrodes.

A Monte Carlo model can give the electron energy distribution at any position even where the electron energy is not equilibrium. However, this method takes very long computation time to obtain the results because of the statistical fluctuations, especially in the high gas pressure conditions.

2-6-2 Fluid Model with Local Field Approximation (LFA)

In LFA fluid model, the electron and ion swarm parameters are determined as a function of local E/p , E and p being the local electric field and gas pressure respectively. This model indicates that in the sheath region, distribution of species

number density and electric field can not be principally expressed exactly because of non-equilibrium.

2-6-3 Comparison between Present Model and Others

Figure 2.7~2.10 show the spatial distribution of the species number densities and of the electric field in each model. The electric field near the cathode distorted highly and the peak of species number densities near the cathode can be seen. The values of electron number density in the bulk are $1.6 \times 10^{12} \text{cm}^{-3}$ in the Monte Carlo model, $1.1 \times 10^{12} \text{cm}^{-3}$ in the LFA model and $1.6 \times 10^{12} \text{cm}^{-3}$ in the present model. The results agree well with each other in qualitatively. However, in the sheath regions, differences is seen in each other.

- The location of peaks in the spatial distribution of species number density obtained in the present method agrees with the Monte Carlo method.
- The values of electric field near the cathode is higher the LFA method case.
- The cathode sheath is longer the LFA method case.

Though there are many differences between the three models in detail, the LFA method agrees with the Monte Carlo method only qualitatively. However, the results of the present model agrees better with the Monte Carlo method than the LFA method.

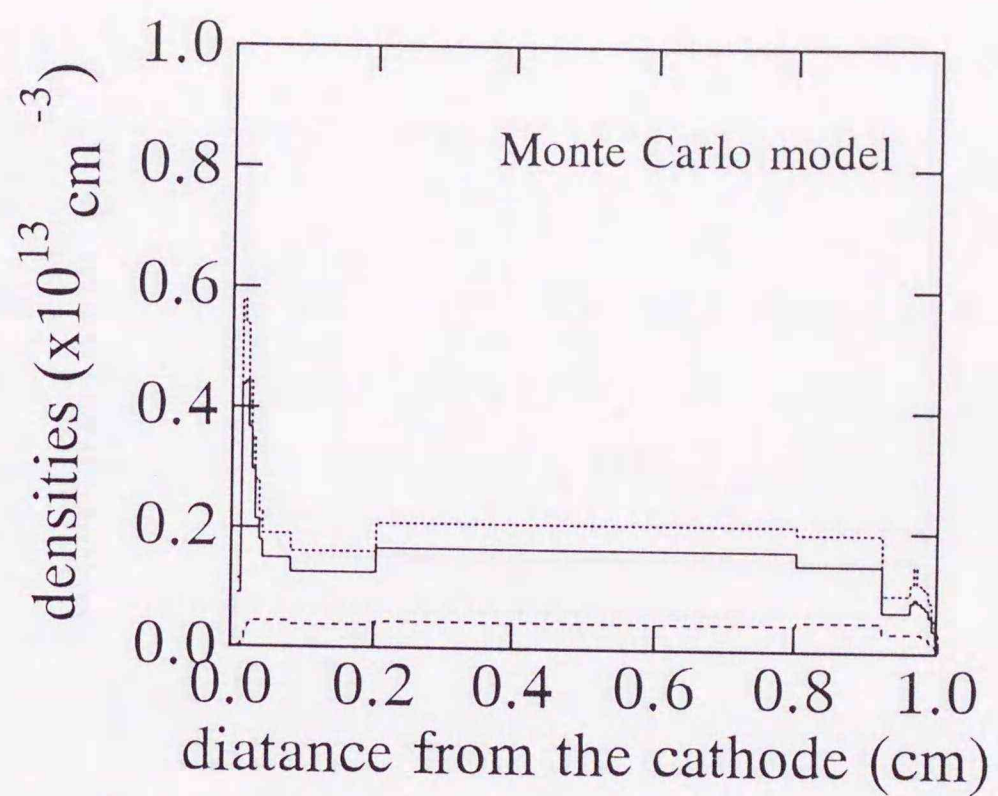


Figure 2.7 Spatial distribution of species number densities.
 n_+ ; n_- ; — n_e .

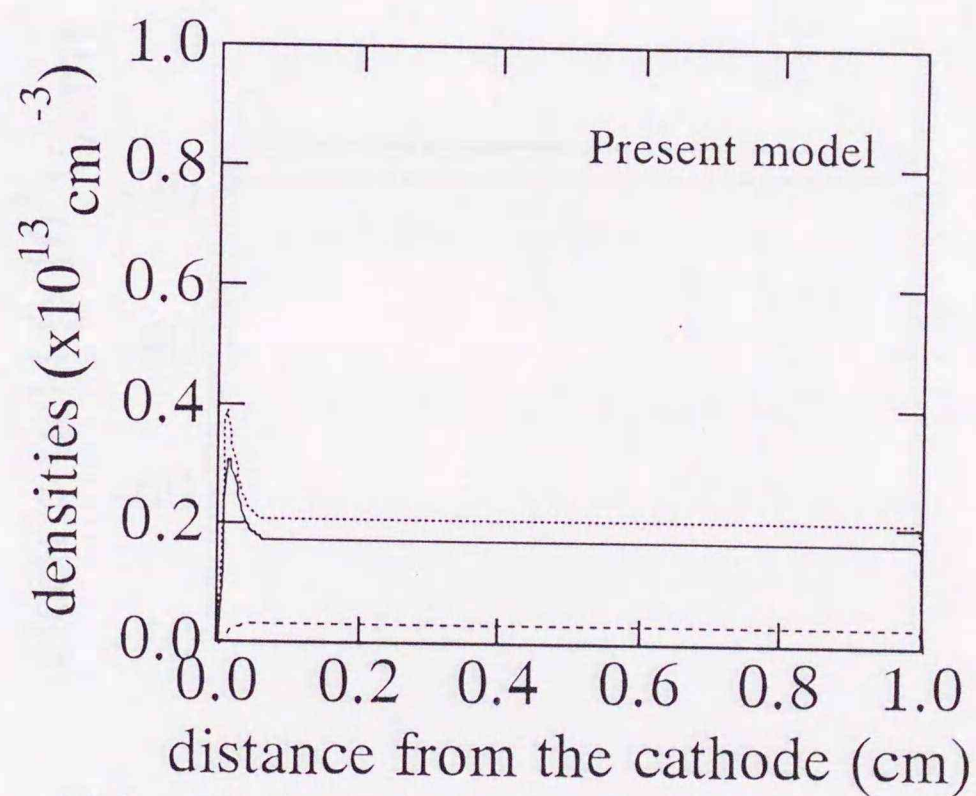


Figure 2.9 Spatial distribution of species number densities.
 n_+ ; n_- ; — n_e .

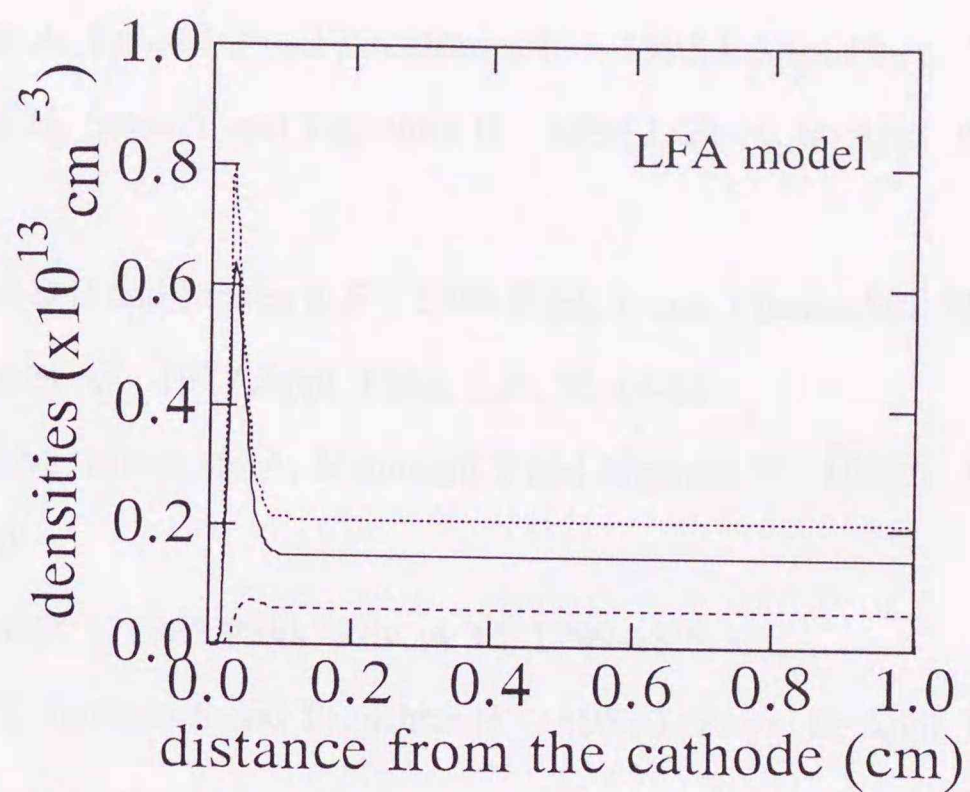


Figure 2.8 Spatial distribution of species number densities.
 n_+ ; n_- ; — n_e .

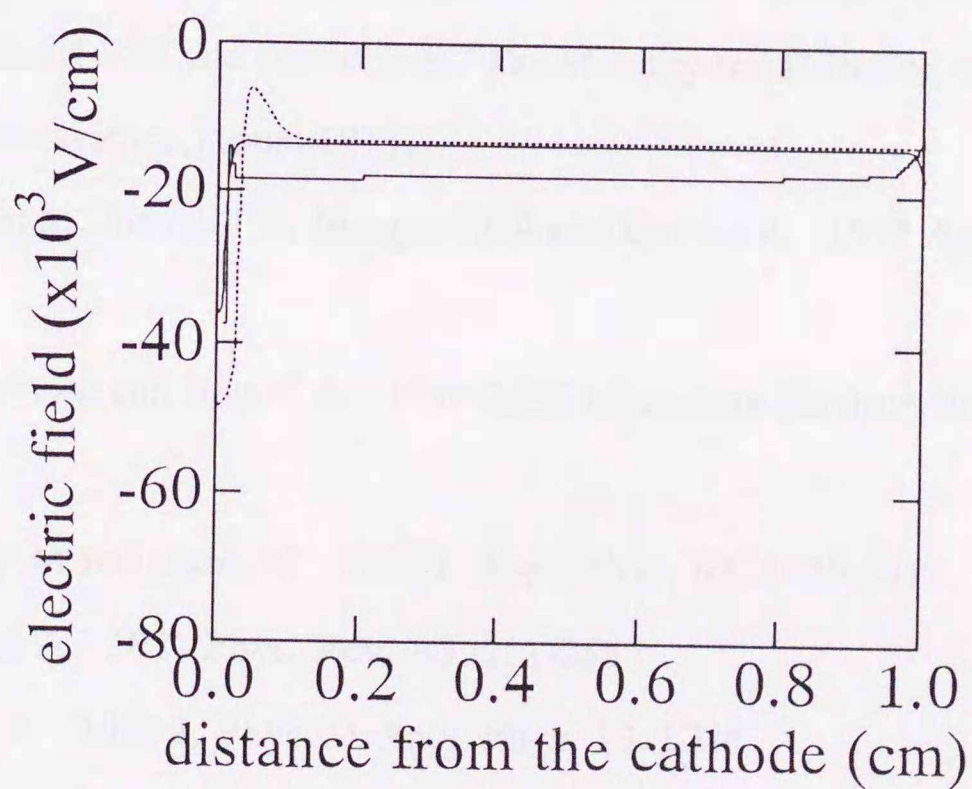


Figure 2.10. Spatial distribution of electric field.
 — Present Model LFA Model — Monte Carlo Model

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Chapter 3

Simulation of Self-sustained Discharge Development in an ArF Excimer Laser

3-1 Introduction

The objective of this chapter is to understand the behavior of self-sustained excimer laser discharges (an atmospheric pressure and a transient discharge $\sim 100\text{ns}$) under the influence of space charge, consistently.

Taking a one-dimensional model in the whole discharge gap, the effect of the field distortion, especially in the cathode and anode sheath regions in a discharge-excited ArF excimer laser, is investigated using the Poisson's equation and continuity equations for electrons, negative and positive ions, an equation for photo-electrons emission from the cathode, and an energy conservation equation for electron, coupled with the circuit equations in a charge-transfer excitation circuit. The effect of photo-electron emission from the cathode and preionization on the discharge evolution is discussed.

3-2 Simulation Conditions

The simulation conditions used in this chapter are the same as described in 2-5. In this chapter, the photoionization and photodetachment processes by laser photons are neglected to simplify the physics.

In this chapter, the results for values of n_{e0} and γ_p of 10^8cm^{-3} and 2.0×10^{-2} , respectively, are shown.

3-3 Results and Discussion

3-3-1 Discharge Current and Voltage Waveforms

Figure 3.1 shows the discharge voltage and current waveforms. They are typical ones for discharge-excited excimer lasers.

Figure 3.2 shows the time dependent discharge resistance R_D . The R_D increases up to about $3.5 \times 10^8 \Omega$ at the beginning of the discharge, since n_e decreases considerably by electron attachment. After $t=40\text{ns}$ the R_D decreases exponentially to 1.7Ω .

3-3-2 Spatio-temporal Evolution of Species Number Densities

Figures 3.3(a)~(e) show the spatio-temporal evolution of the species number densities for electrons (n_e), positive ions ($n_+ = n_{Ar^+} + n_{Ar_2^+} + n_{He^+}$), negative ions (n_-), Ar^* (n_{Ar^*}) and ArF^* (n_{ArF^*}) in the gap, respectively. The drawing of them in the bulk region where the number density is uniform is abbreviated.

(a) Electrons

As shown in figure 3.3(a), in the initial stage ($t < 8\text{ns}$), the n_e decreases rapidly to the level of $4 \times 10^3 \text{cm}^{-3}$ in the bulk (A) and $4.4 \times 10^1 \text{cm}^{-3}$ in the cathode region (B) because of strong attachment for electrons to F_2 at low E/p_0 . In this region, in addition to the electron attachment, the drift and diffusion loss of electrons are significant as well. However, any field distortion is hardly caused by this electron depletion up to this moment. For $t > 7\text{ns}$, the photo-electron emission from the cathode becomes appreciable (C), since the radiative excited atoms in the discharge increase with raising $E_{ex}(t)$.

Once photo-electron emission from the cathode begins, n_e increases up to the same level as the $n_e(x,t)$ in the bulk as seen at $t=10\text{ns}$. For the period between 10ns and 50ns n_e increases considerably up to $1.8 \times 10^{12}\text{cm}^{-3}$ (D). In this period, $\rho(x,t)$ in the cathode region becomes negative, while $\rho(x,t)$ for $t < 10\text{ns}$ is positive, which notes that $E(x,t)$ in the cathode region is smaller than $E_{ex}(t)$. After $t=50\text{ns}$, $n_e(0,t)$ becomes to be smaller than that in the bulk (E), because $n_{ep}(0,t)$ decreases extremely due to the decay of V_g . Then, positive ions becomes dominant in $\rho(x,t)$ and the distorted field grows significantly with time, since $n_{ep}(0,t)$ can't compensate for the positive space charge any more (see figure 3.6(a) and (b)).

The n_e in the bulk reaches its maximum value $\approx 1.3 \times 10^{14}\text{cm}^{-3}$ at $t=64\text{ns}$ (F), after that, it decreases gradually to $4 \times 10^{13}\text{cm}^{-3}$ at $t=75\text{ns}$ (G). The maximum point in n_e is delayed from I_g peak (H) for 2ns ($I_g=4.2\text{kA}$ at $t=62\text{ns}$).

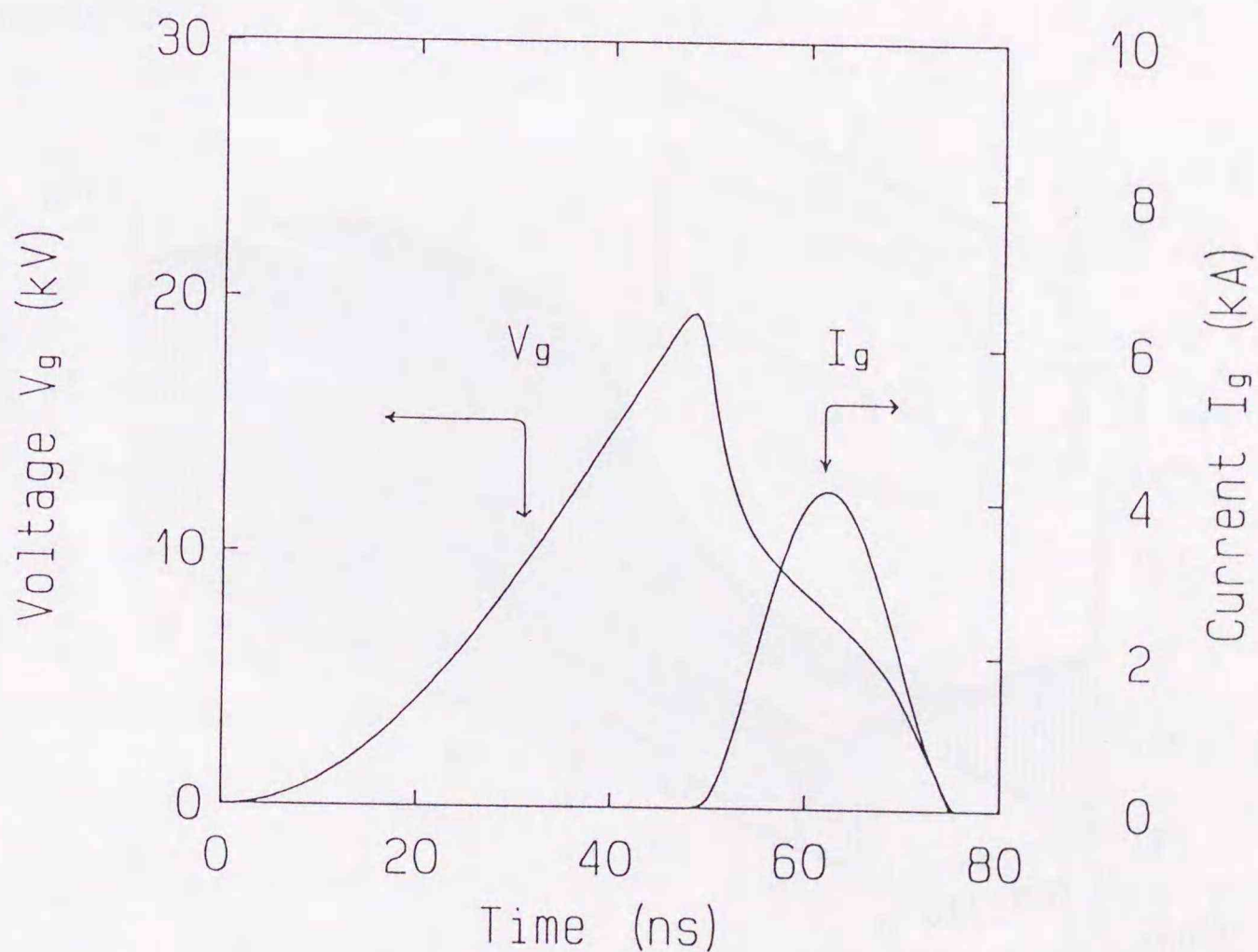


Figure 3.1. Waveforms of the discharge voltage V_g and current I_g for $\gamma_p=2.0 \times 10^{-2}$ and $n_{e0}=10^8\text{cm}^{-3}$.

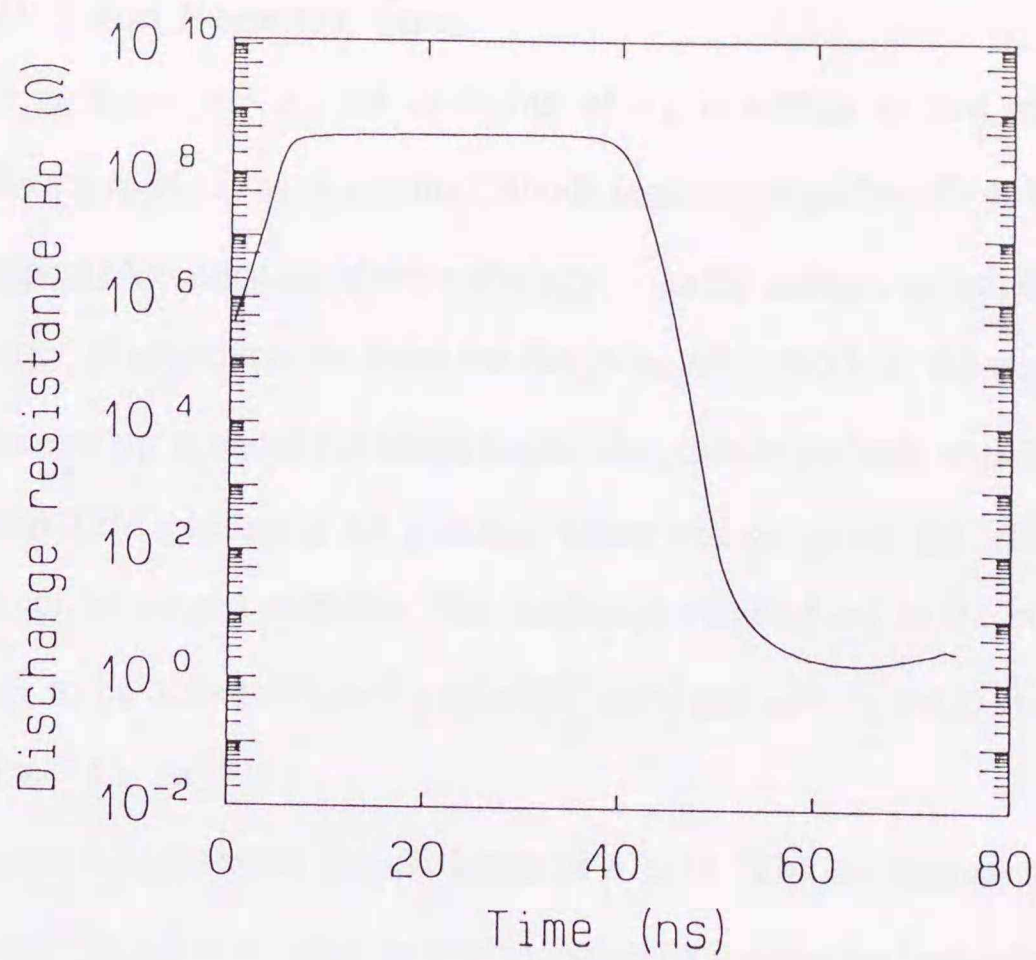


Figure 3.2. Time dependence of the discharge resistance R_D for $\gamma_p=2.0 \times 10^{-2}$ and $n_{e0}=10^8 \text{ cm}^{-3}$.

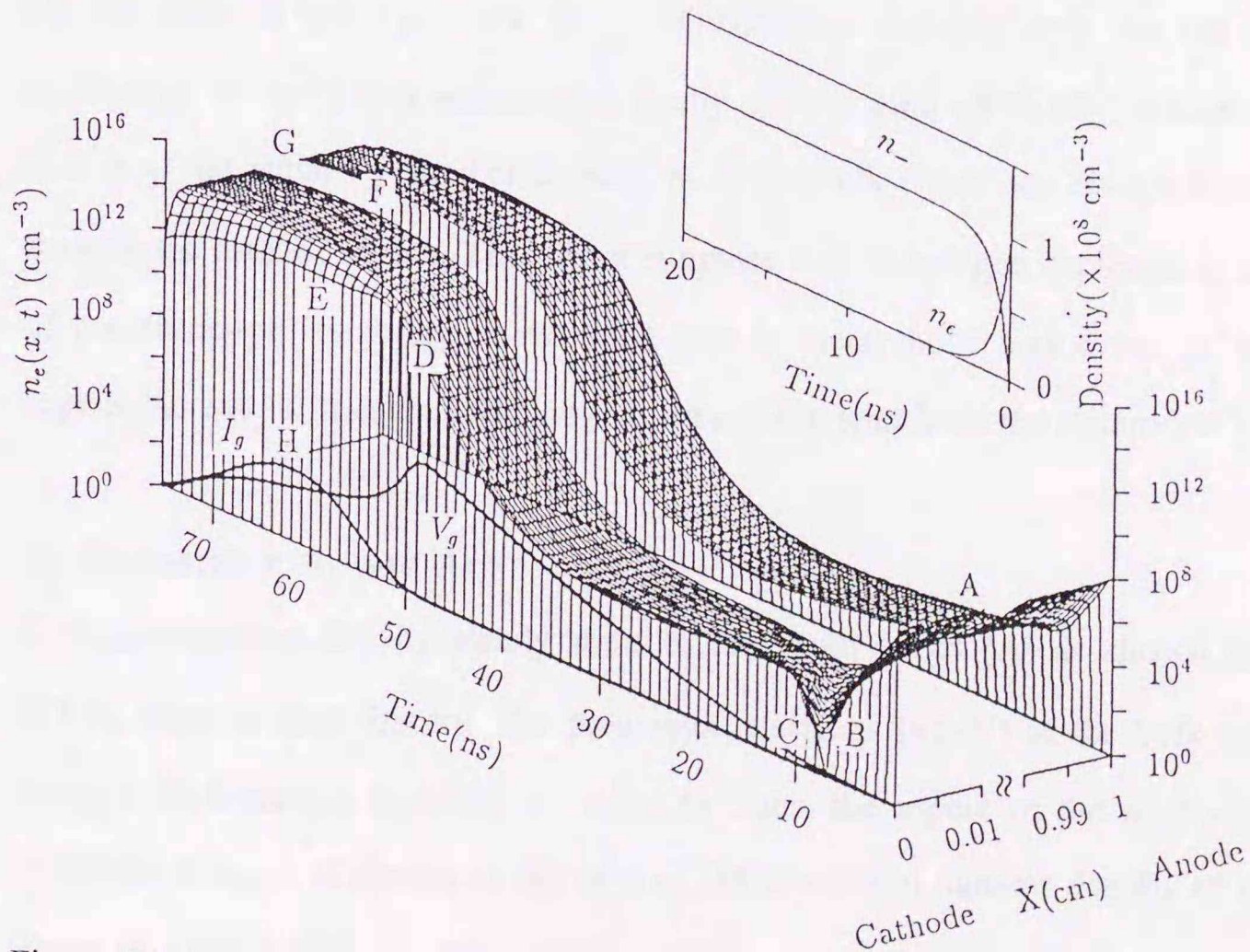


Figure 3.3 (a). Spatio-temporal evolution of the electron number densities n_e for $\gamma_p=2.0 \times 10^{-2}$ and $n_{e0}=10^8 \text{ cm}^{-3}$, along with n_e and n_- in the bulk.

(b) Positive and Negative Ions

As shown in figure 3.3(b), the evolution of n_+ is similar to that of n_e except for $t < 30$ ns. During $t = 44 \sim 55$ ns, n_+ in the cathode region is significantly lower than that in the bulk region (A), since the electron energy $\bar{\varepsilon}$ in the cathode is reduced by emission of low energy photo-electrons from the cathode. After $t = 57$ ns, the n_+ in the cathode region increases up to about 1.7 times higher than that in the bulk at $t = 75$ ns (B), since the distorted field produced by positive space charge gives the electrons enough energies to ionize the gas particles. The maximum value of n_+ in the bulk is given, at $t = 65$ ns (C), to be $1.9 \times 10^{14} \text{ cm}^{-3}$ ($1.8 \times 10^{14} \text{ cm}^{-3}$ for Ar^+ , $1.8 \times 10^{11} \text{ cm}^{-3}$ for He^+ , $1.1 \times 10^{13} \text{ cm}^{-3}$ for Ar_2^+).

Figure 3.3(c) shows the evolution of $n_-(x, t)$. The n_- increases rapidly up to about 10^8 cm^{-3} in a few ns after the preionization (A), since the preionized low energy ($\approx 1 \text{ eV}$) electrons have high attachment probability to F_2 . The n_- increases coincidentally with increasing n_e . After $t = 52$ ns, the n_- in the cathode is lower than that in the bulk (B) as seen in the n_e , since the n_- distribution depends only on the electron attachment. F^- in the bulk accumulates finally up to around 10^{14} cm^{-3} , which is about 0.06% of the initial F_2 number density. n_- in the bulk region are always higher than those in the cathode region. This result suggests that, if halogen depletion is a source of the discharge instability, it wouldn't start in the cathode region but in the bulk region. Actually a filamental discharge is reported to start from the electrodes^[8].

(c) Metastable Ar and ArF^*

The n_{Ar^*} number density clearly starts to rise from $t = 7$ ns (A) as shown in figure 3.3(d), since it takes 8 ns for the preionized electrons ($\approx 1 \text{ eV}$) in the bulk to obtain energies high enough to excite Ar. After $t = 50$ ns, the aspect of the spatio-temporal evolution of n_{Ar^*} is similar to that of n_+ . The maximum number density of n_{Ar^*} is about $4.4 \times 10^{14} \text{ cm}^{-3}$ at $t = 65$ ns (B), which is higher than the number densities of

other species. The peak of n_{Ar^*} in the cathode (C) is seen at the time at which the peak in the n_+ appears (see at B in figure 3.3(b)).

The spatio-temporal evolution of the ArF^* number density is shown in figure 3.3(e). The n_{ArF^*} increases up to $\approx 2.5 \times 10^{14} \text{ cm}^{-3}$ at $t=69 \text{ ns}$ uniformly all over the discharge gap, which may be enough to obtain lasing. ArF^* is considered to be formed by a harpooning and ion recombination channels. Here, it is seen at $t=69 \text{ ns}$ that 79.9% of the ArF^* is obtained by the former channel, 19.1% by $Ar^+ + F^-$ and 1.0% by $Ar_2^+ + F^-$ channel.

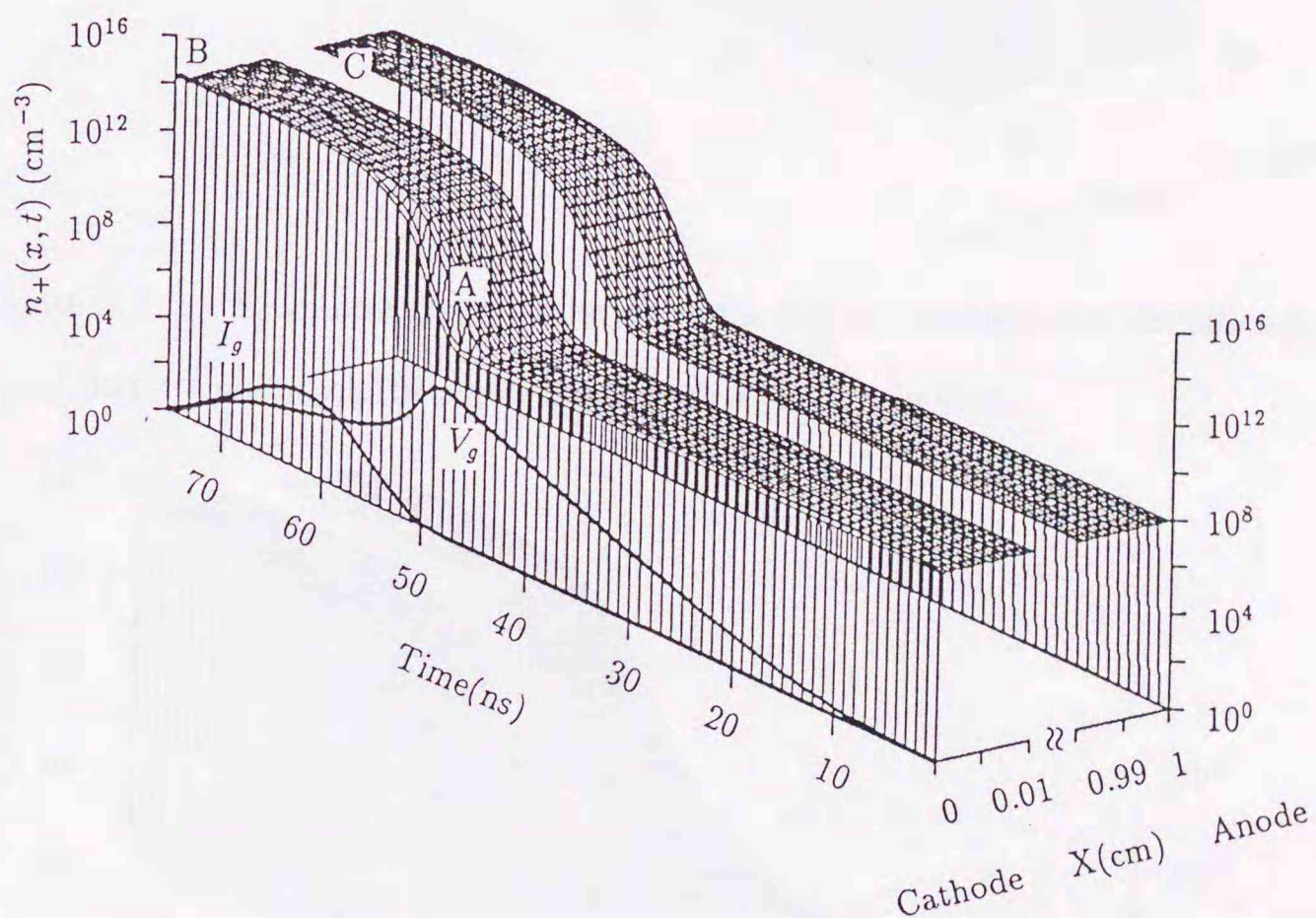


Figure 3.3 (b). Spatio-temporal evolution of the positive ion number densities n_+ for $\gamma_p=2.0 \times 10^{-2}$ and $n_{e0}=10^8 \text{ cm}^{-3}$.

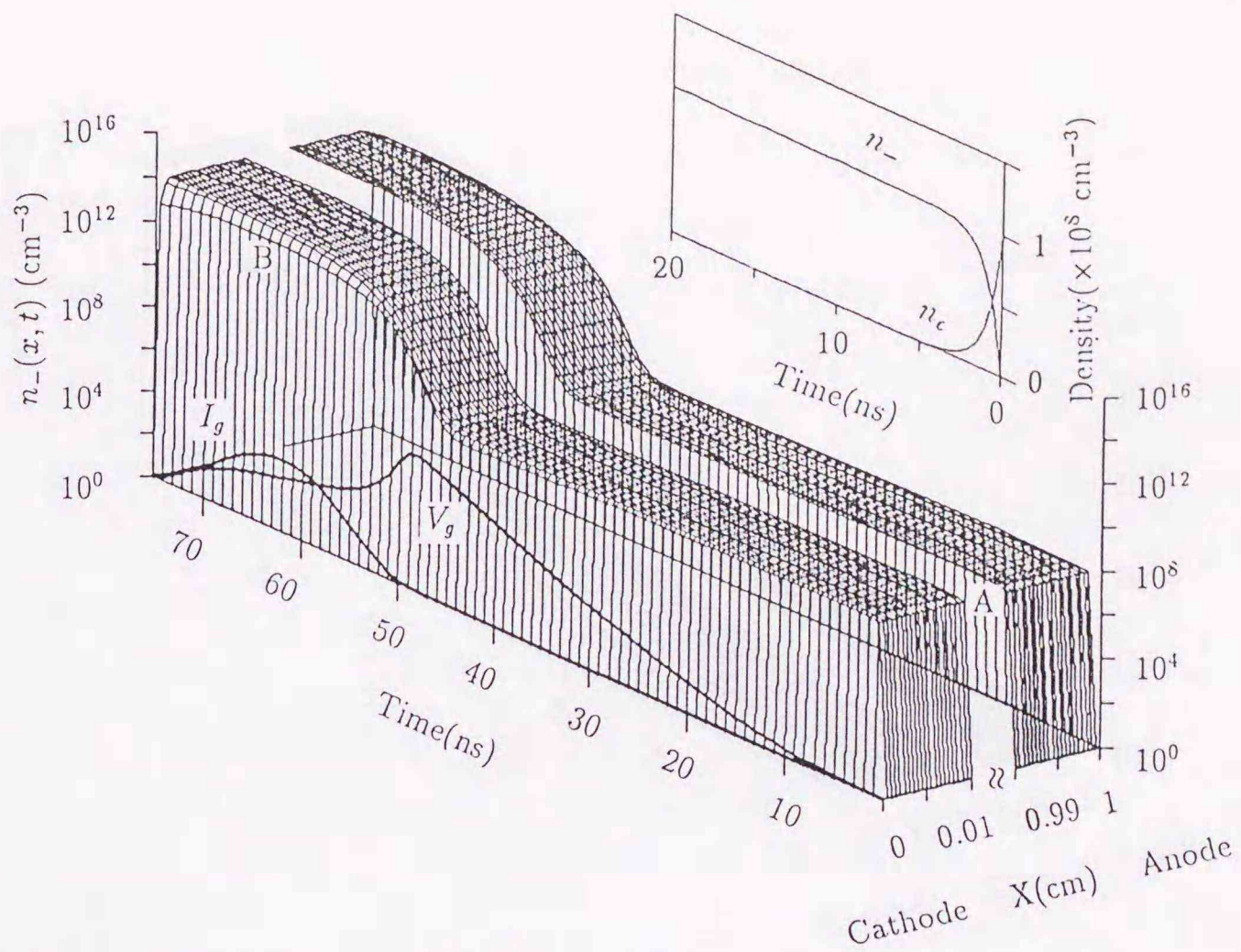


Figure 3.3 (c). Spatio-temporal evolution of the negative ion number densities n_- for $\gamma_p=2.0 \times 10^{-2}$ and $n_{e0}=10^8 \text{cm}^{-3}$, along with n_e and n_- in bulk.

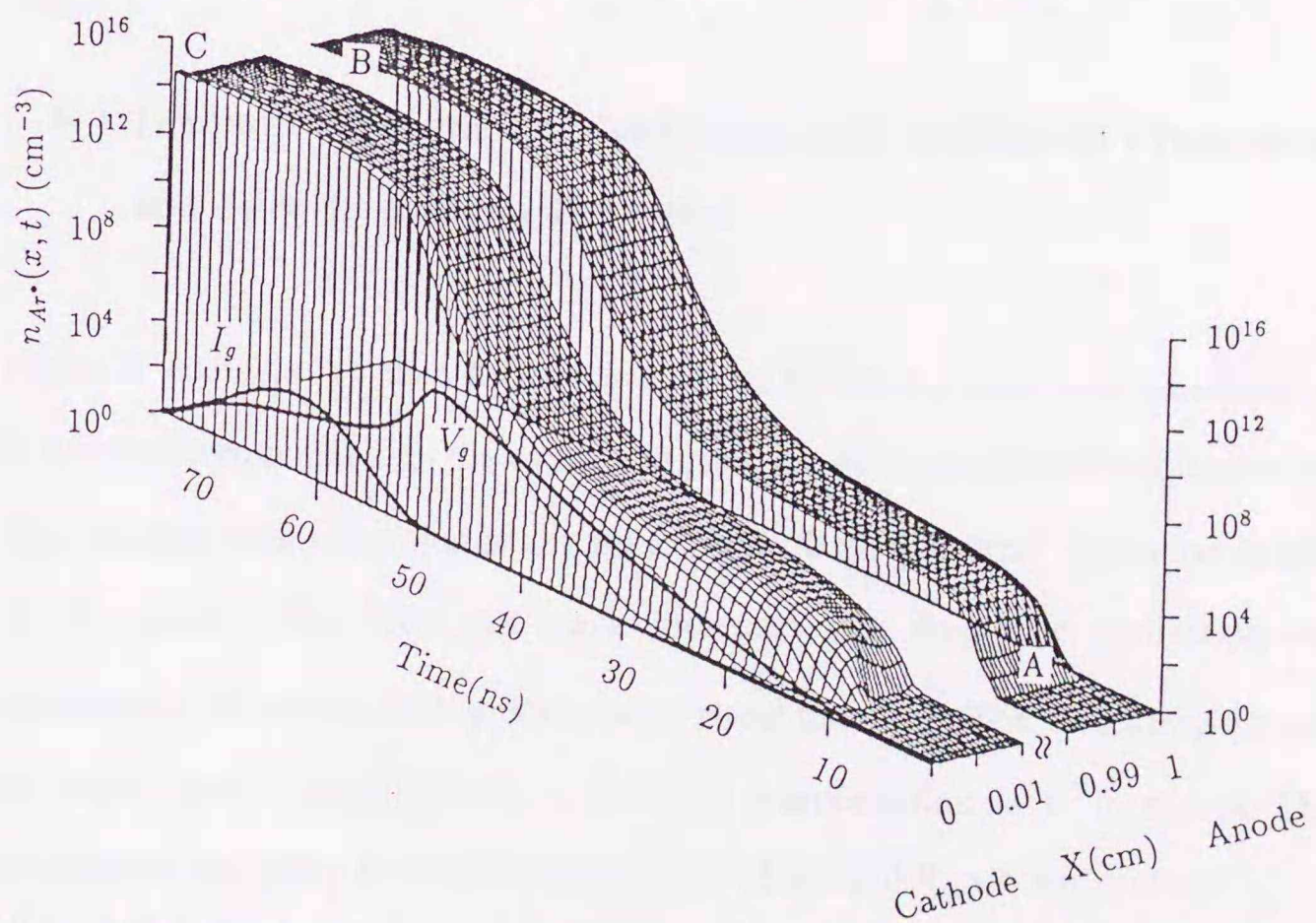


Figure 3.3 (d). Spatio-temporal evolution of the Ar^* number densities n_{Ar^*} for $\gamma_p=2.0 \times 10^{-2}$ and $n_{e0}=10^8 \text{cm}^{-3}$.

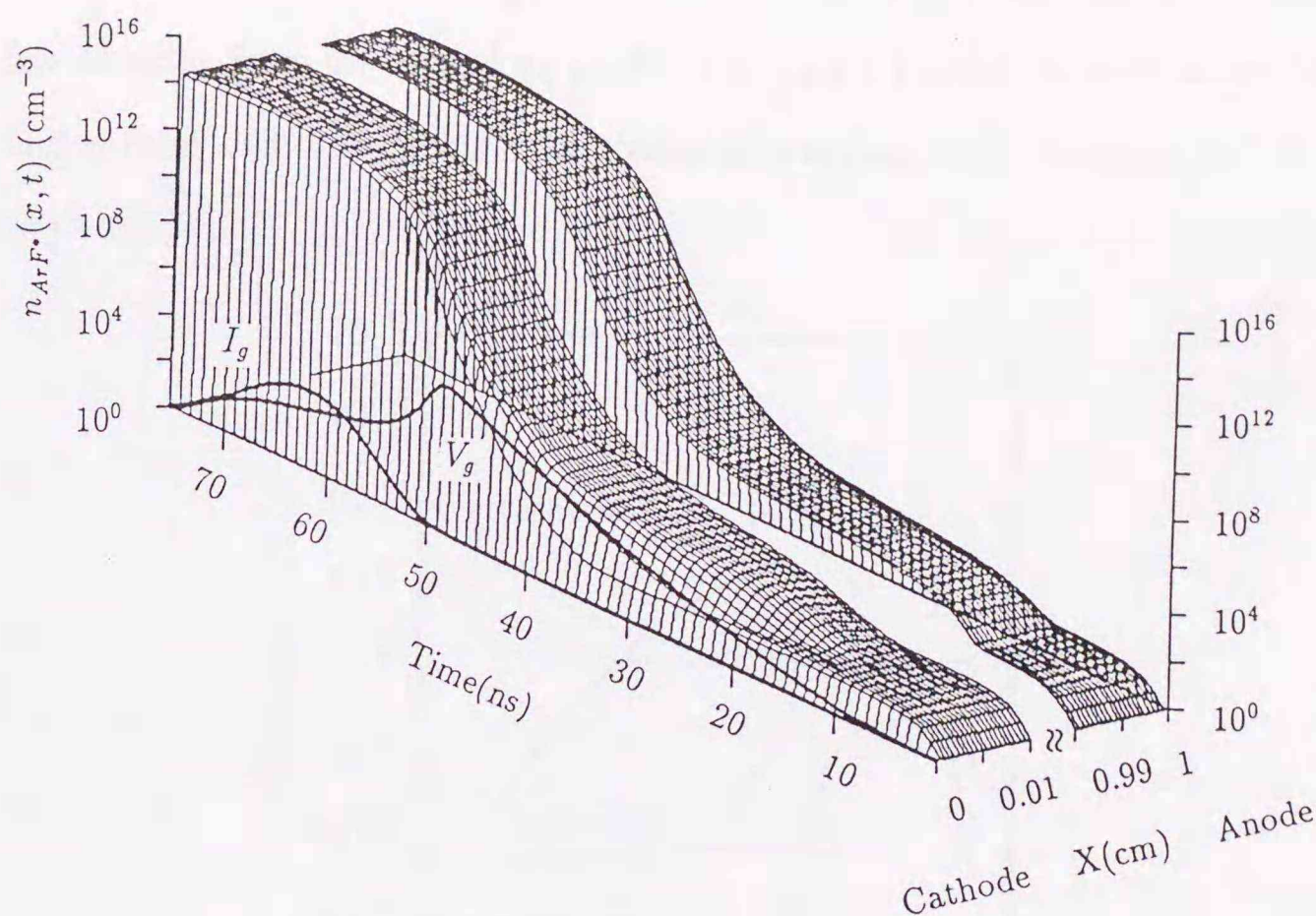


Figure 3.3 (e). Spatio-temporal evolution of the ArF* number densities n_{ArF^*} for $\gamma_p=2.0 \times 10^{-2}$ and $n_{e0}=10^8 \text{ cm}^{-3}$.

3-3-3 Temporal Evolution of Ionization and Attachment Frequencies and Species Number Densities

Figure 3.4 shows the time dependence of the direct, the step-wise ionization and the attachment frequencies. In the cathode region, the direct ionization frequency is higher than the step-wise ionization at any time. Until 50ns, the direct ionization is shown to be dominant. After 50ns, as n_{Ar^*} increases, the step-wise ionization becomes appreciable. At $t \sim 70\text{ns}$ both processes are about the same. The attachment frequency in the bulk decreases from $10^9(1/\text{s})$ to $10^8(1/\text{s})$ at around 8ns as $\bar{\epsilon}$ increases. Then, the attachment frequency becomes constant $\sim 10^8(1/\text{s})$, and $R_a > R_i$ for $t > 60\text{ns}$.

The temporal evolution of the species number densities are shown along with the I_g waveform in figure 3.5. The n_e and n_+ reach their maxima at $t=64$ and 65ns , respectively, which are delayed for a few ns from the peak of I_g at 62ns . This delay

may occur due to electron energy relaxation. The peak of n_- appears at $t=70$ ns with a few ns delay from the n_e and n_+ peaks. The n_{ArF^*} reaches its peak at $t=69$ ns. This further delay comes from that it takes some time to form ArF^* through Ar^* , F_2 , Ar^+ , Ar_2^+ and F^- .

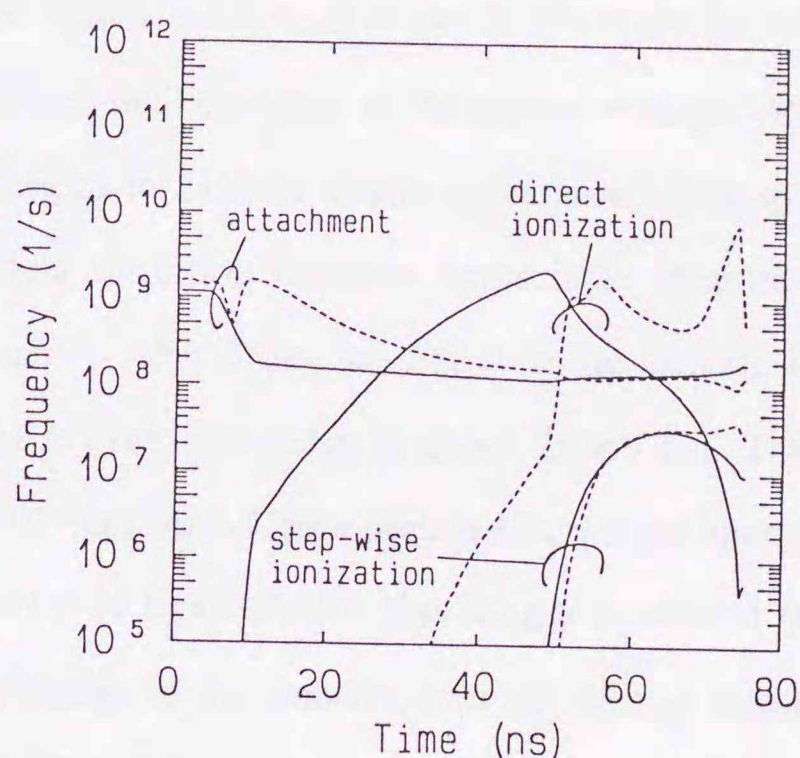


Figure 3.4. Temporal evolution of the direct and step-wise ionization frequencies and the attachment frequency for $\gamma_p=2.0 \times 10^{-2}$ and $n_{e0}=10^8 \text{ cm}^{-3}$. - - - ; near the cathode ($x=5 \times 10^{-4} \text{ cm}$), — ; in the bulk ($x=0.5 \text{ cm}$)

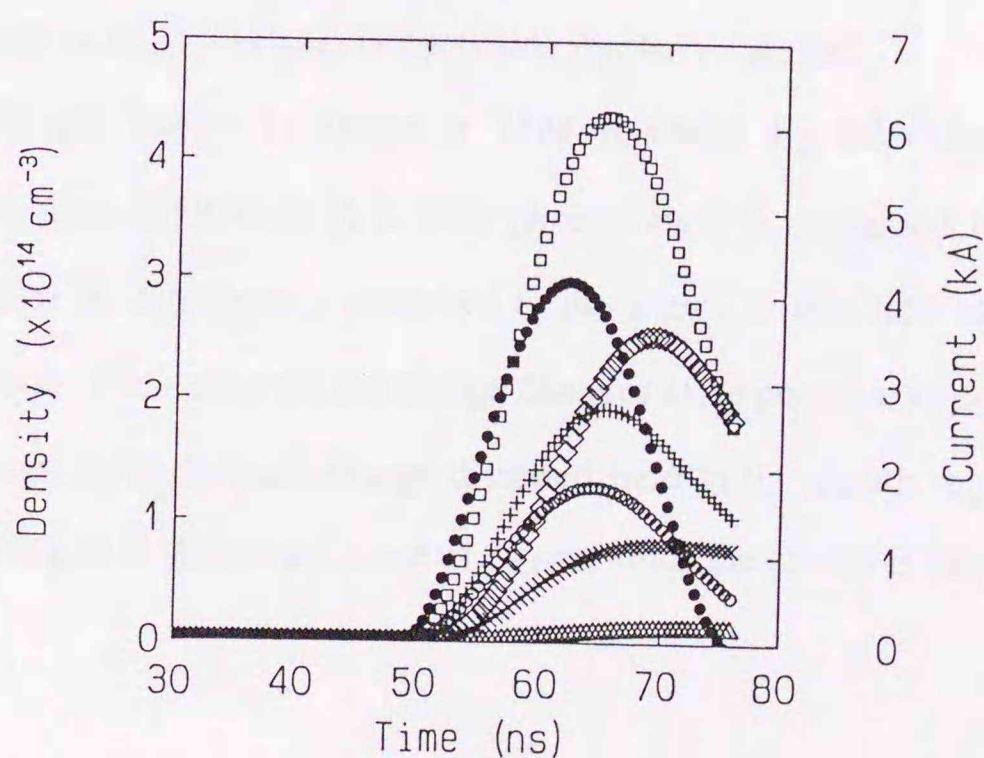


Figure 3.5. Temporal evolution of the species number densities for $\gamma_p=2.0 \times 10^{-2}$ and $n_{e0}=10^8 \text{ cm}^{-3}$. o, n_e ; +, n_+ ; x, n_- ; $\square$, n_{Ar^*} ; $\triangle$, n_{ArF^*} ; $\bullet$, $n_{Ar_2^+}$; $\cdots$, I_g

3-3-4 Spatio-temporal Evolution of Electric Field Strength

Figure 3.6(a) and (b) show the spatio-temporal evolution of $E(x,t)$, and the temporal evolution of the electric field $E(x_c,t)$ at $x=5\times 10^{-4}\text{cm}$ (in the cathode), $E(x_b,t)$ at $x=0.5\text{cm}$ (in the bulk), and $E(x_a,t)$ at $x=0.9995\text{cm}$ (in the anode). The electric field distortion is not seen until the decay of the applied voltage. After the decay, the $E(x,t)$ in the cathode begins to increase due to appearance of the space charge (A in figure 3.6(a)). This field distortion becomes appreciable after the positive space charge exceeds $\sim 10^{11}\text{cm}^{-3}$. After 55ns, the $E(x,t)$ in the cathode is found to be distorted significantly. At $t=74\text{ns}$, this value is about 250kV/cm. The width of the cathode sheath is $\sim 2.5\times 10^{-3}\text{cm}$. At $t\sim 73\text{ns}$ a peak in $E(x,t)$ at the anode appears.

It is shown in figure 3.6(b) that $E(x_c,t)$ at around $t=65\text{ns}$ has plateau (A), since the space charge at the cathode does not change considerably in this period. From $t=70\text{ns}$ to 74ns , $E(x_c,t)$ increases significantly again, since the positive space charge in the cathode increases again due to decrease of photo-electrons. After 74ns, $E(x_c,t)$ starts to decrease (B), since the positive space charge near the cathode decreases due to freezing the electron drift when $E_{ex}(t)$ becomes zero. The $E(x_b,t)$ is almost the same as $E_{ex}(t)(=V_g/d)$ in the whole discharge period.

The $E(x_a,t)$ begins to distort at 73ns at which V_g falls down to $\sim 0\text{V}$. It becomes more than -100kV/cm (C). This phenomenon is explained by the fact that electrons tend to be significantly absorbed to the anode at this time due to the local field at the anode. Eventually the net charge changes from negative to positive.

Although the high space charge distorted field in the sheath regions ($\sim 10^{-3}\text{cm}$) appears, the $E(x_b,t)$ is almost the same as $E_{ex}(t)$, since the sheath is very narrow.

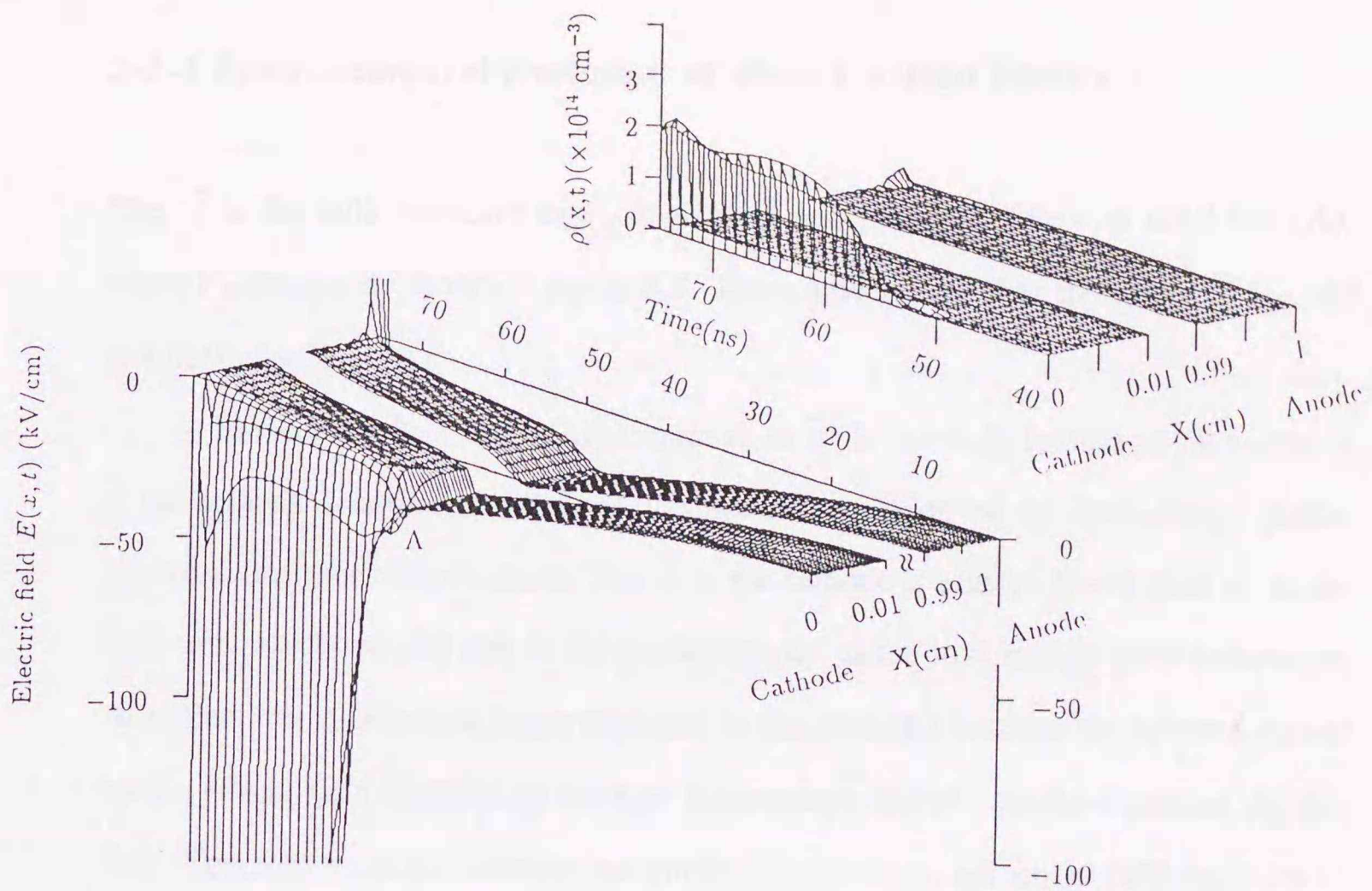


Figure 3.6 (a). Spatio-temporal evolution of $E(x,t)$ and $\rho(x,t)$ for $\gamma_p=2.0 \times 10^{-2}$ and $n_{e0}=10^8 \text{ cm}^{-3}$.

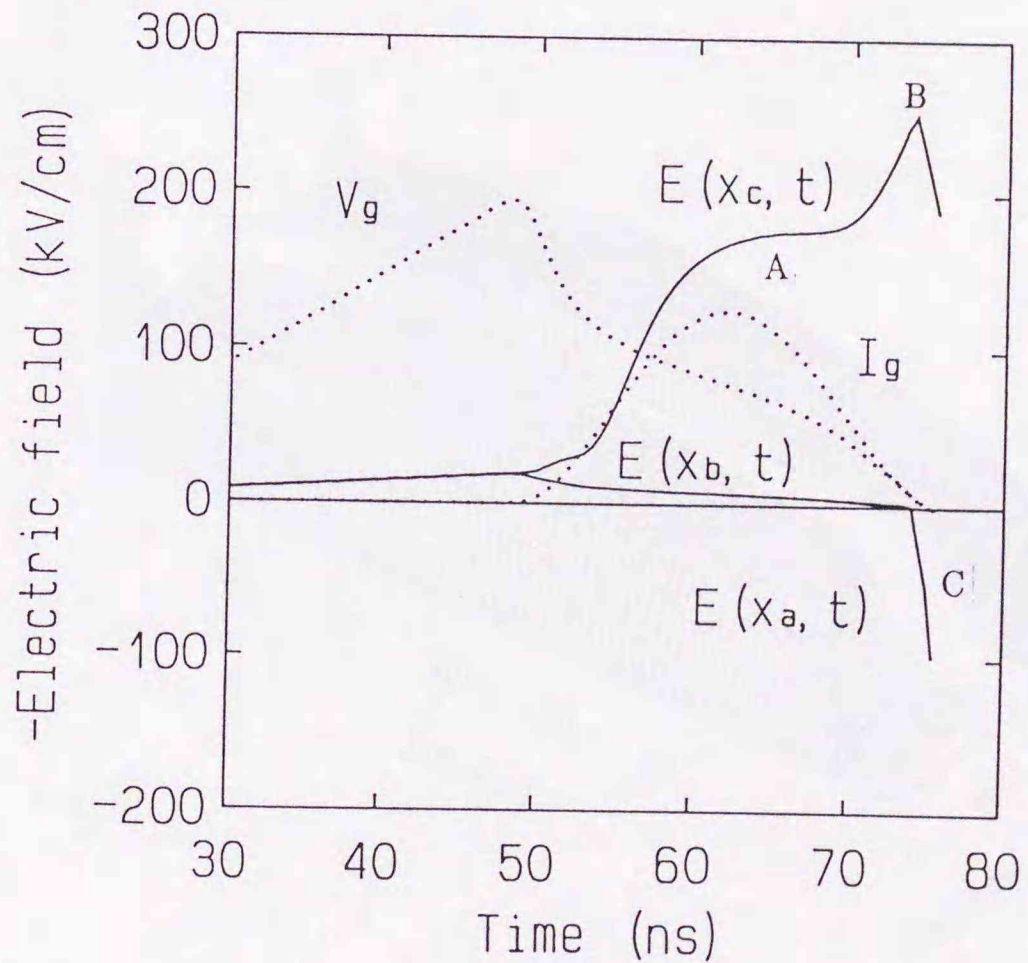


Figure 3.6 (b). Temporal evolution of the electric field $E(x_c,t)$ at $x=5 \times 10^{-4} \text{ cm}$, $E(x_b,t)$ at $x=0.5 \text{ cm}$ and $E(x_a,t)$ at $x=0.9995 \text{ cm}$ for $\gamma_p=2.0 \times 10^{-2}$ and $n_{e0}=10^8 \text{ cm}^{-3}$.

3.3-5 Spatio-temporal Evolution of Mean Electron Energy

The $\bar{\epsilon}$ in the bulk increases as V_g increases, and becomes 7.0eV at $t=48.5\text{ns}$ (A), when V_g decays as shown in figure 3.7. Then, it decreases after the decay of V_g and is 4.0eV at $t=75\text{ns}$ (B).

In the cathode $\bar{\epsilon}$ for $t < 7\text{ns}$ increases as $\bar{\epsilon}$ in the bulk increases. At $t \sim 8\text{ns}$, $\bar{\epsilon}$ at the cathode decreases to $\sim 1\text{eV}$ (C), since the emission of the low energy photo-electrons from the cathode starts. The $\bar{\epsilon}$ at the cathode is always lower than $\bar{\epsilon}$ in the bulk until $t=48.5\text{ns}$ (D) due to the predominance of the low energy photo-electrons. After that, the $\bar{\epsilon}$ becomes larger than that in the bulk (E) because the electron heated by the strong field overwhelm the low temperature (0.5eV) photo-electrons. At this time 70ns, the $\bar{\epsilon}$ at the cathode and anode sharply increases up to 8eV and 8.4eV, respectively (F and G).

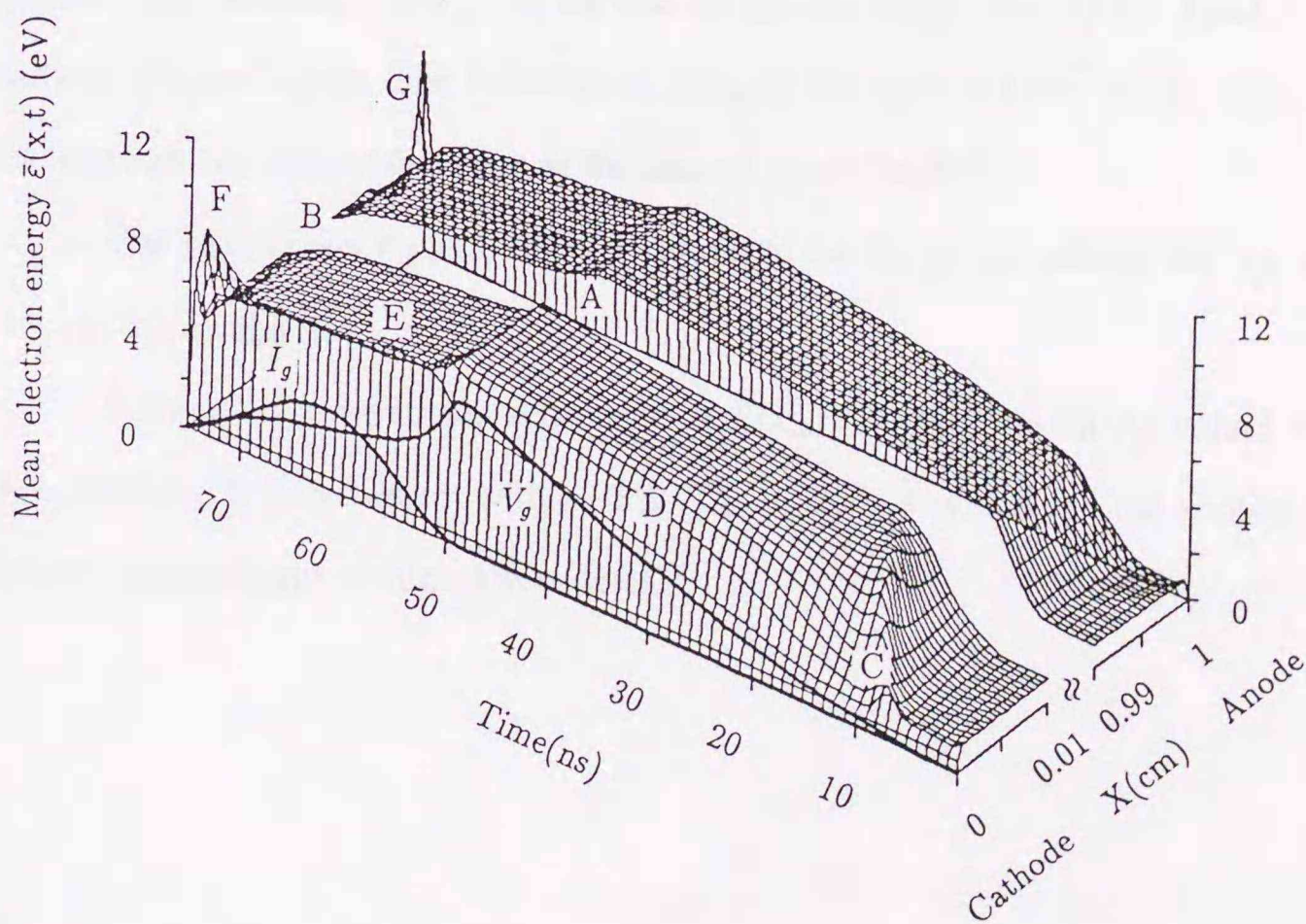


Figure 3.7. Spatio-temporal evolution of the mean electron energy $\bar{\epsilon}$ for $\gamma_p=2.0 \times 10^{-2}$ and $n_{e0}=10^8 \text{cm}^{-3}$.

3.3-6 Dependence of Secondary Electron Emission Coefficient γ_p on Discharge Development

The electric field distortion at the cathode was found to depend strongly on values of γ_p . To determine the effect of γ_p on the discharge development, simulations were carried out for γ_p values of 0.0, 1.5×10^{-2} and 2.2×10^{-2} for $n_{e0} = 10^8 \text{ cm}^{-3}$.

Figure 3.8 shows the V_g and I_g waveforms for different values of γ_p . While V_g increases ($t < 48.5 \text{ ns}$), the V_g and I_g waveforms do not depend on γ_p . For $t > 48.5 \text{ ns}$, the V_g waveform for $\gamma_p = 0.0$ differs slightly from the others, since the positive space charge near the cathode becomes significant. In the case of $\gamma_p = 0.0$, 2.2×10^{-2} , the simulation is terminated at $\sim 50 \text{ ns}$. Figure 3.9 shows the electric field $E(x_c, t)$ near the cathode, $E(x_a, t)$ near the anode and $E(x_b, t)$ in the bulk region for three γ_p values. For $\gamma_p = 1.5 \times 10^{-2}$, the V_g and I_g waveforms are almost the same as those for $\gamma_p = 2.0 \times 10^{-2}$, however, $E(x_c, t)$ for the former is about 2 times larger than that of the latter after the decay of V_g . At the end of the discharge, $E(x_c, t)$ for $\gamma_p = 1.5 \times 10^{-2}$ starts to increase again. The behavior of $E(x_a, t)$ for $\gamma_p = 1.5 \times 10^{-2}$ at the end of the discharge shows almost the same as the case of $\gamma_p = 2.0 \times 10^{-2}$.

The $E(x_c, t)$ for $\gamma_p = 2.0 \times 10^{-2}$ is found to be the lowest among the γ_p values taken in this analysis.

Although the significant difference in $E(x_c, t)$ for the present γ_p values can be seen, the $E(x_b, t)$ is consistent within $\sim 1\%$. The n_e and $\bar{\epsilon}$ which are not shown in the figures are consistent within $\sim 1\%$ as well.

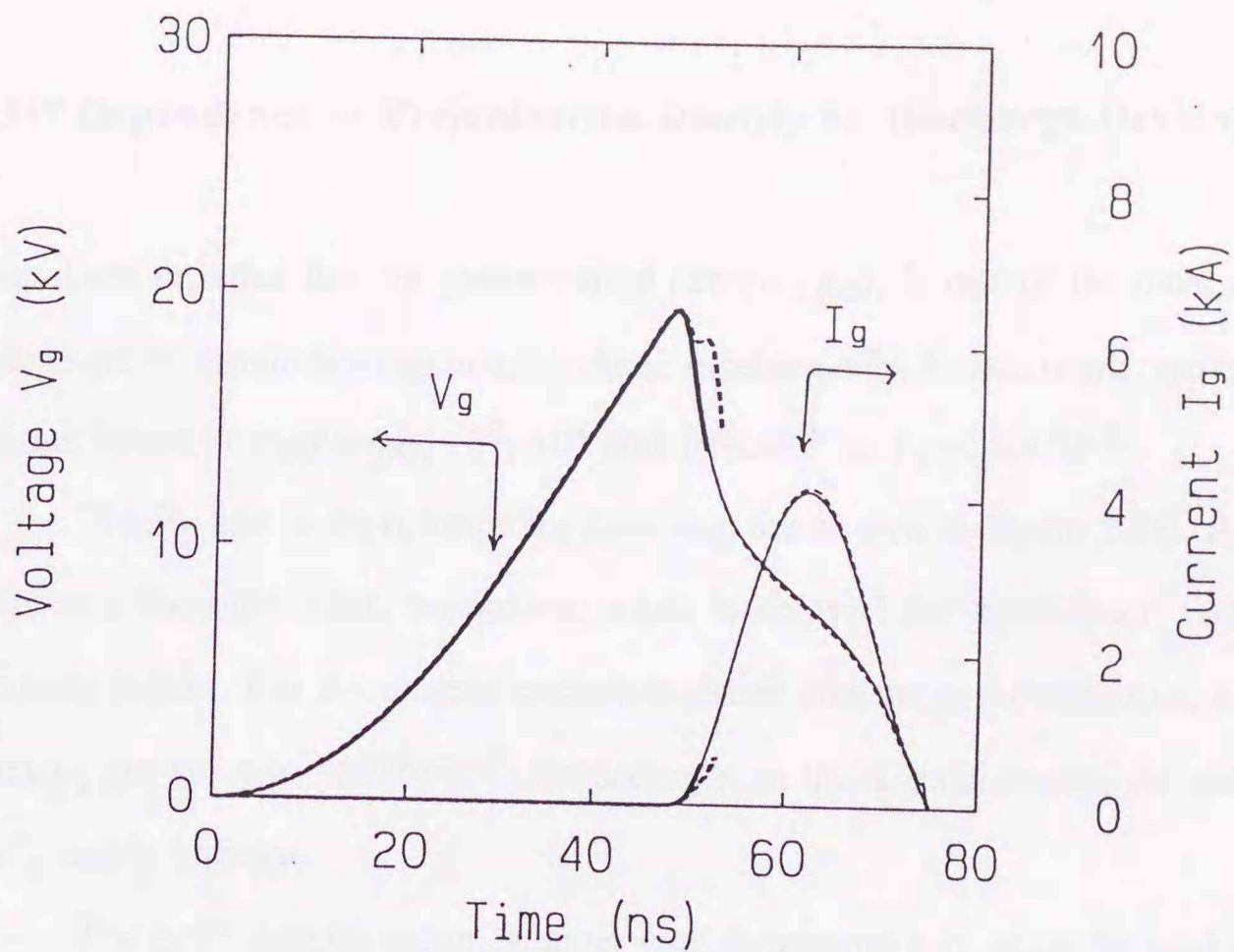


Figure 3.8. Waveforms of the discharge voltage V_g and current I_g for γ_p ---, 0.0; —, 1.5×10^{-2} ; - - -, 2.0×10^{-2} ; —, 2.2×10^{-2} .

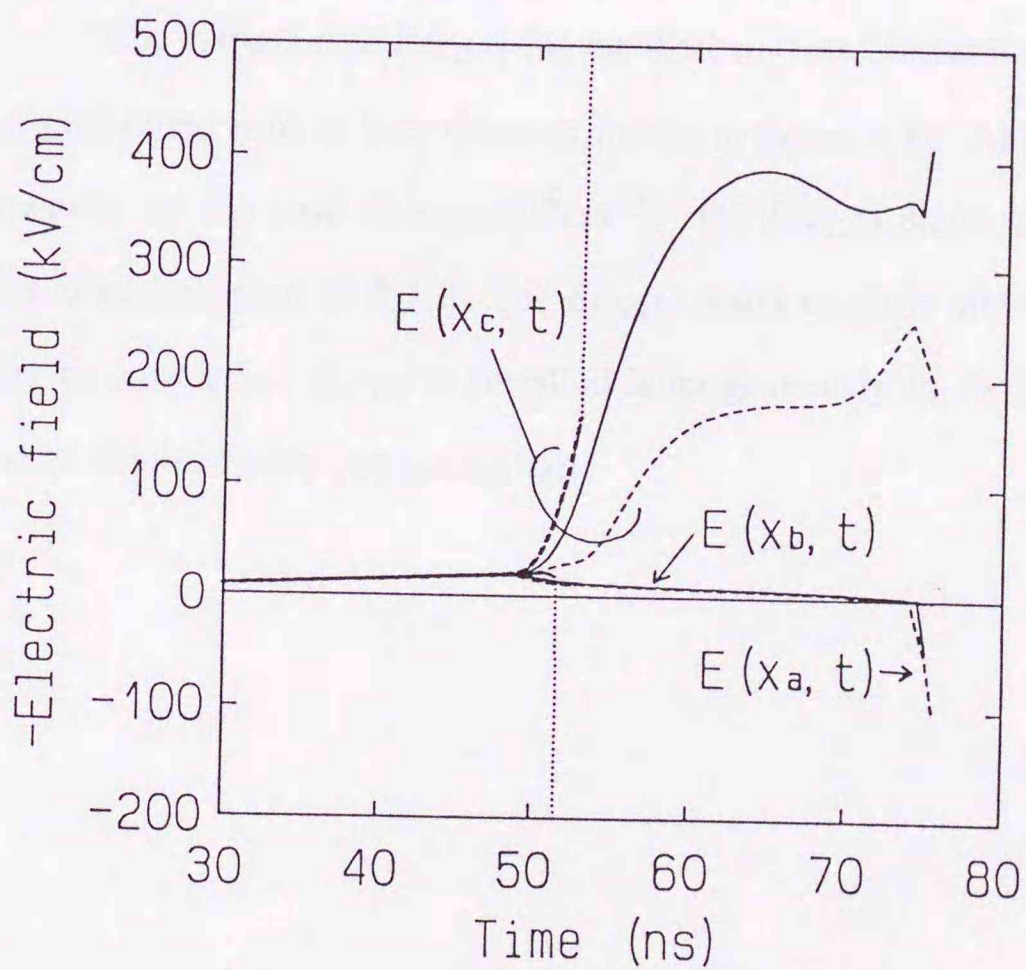


Figure 3.9. Temporal evolution of the electric field $E(x_c, t)$ at $x=5 \times 10^{-4}$ cm, $E(x_b, t)$ at $x=0.5$ cm, $E(x_a, t)$ at $x=0.9995$ cm for γ_p : ---, 0.0; —, 1.5×10^{-2} ; - - -, 2.0×10^{-2} ; —, 2.2×10^{-2} .

3-3-7 Dependence of Preionization Density on Discharge Development

It has been reported that the preionization density, n_{e0} , is one of the most important parameters to sustain homogeneous volume discharges^[8]. In this work, we investigate various values of $n_{e0}(=n_{p0})$ 10^2 , 10^4 and 10^8cm^{-3} for $\gamma_p=2.0\times 10^{-2}$.

The V_g and I_g waveforms for these n_{e0} are shown in figure 3.10. As the n_{e0} decreases, the time when breakdown starts is delayed but breakdown voltage V_{gb} becomes higher. For the present excitation circuit and the gap conditions, V_g decays when n_e grows up to $\sim 10^{11}\text{cm}^{-3}$. Accordingly, as the n_{e0} decreases, the peak values of V_g and I_g increase.

The ArF^* density becomes larger with decreasing n_{e0} , since the peak values of V_g and I_g are higher. The peak value of n_{ArF^*} for $n_{e0}=10^2\text{cm}^{-3}$ is $\sim 12.5\%$ larger than that for $n_{e0}=10^8\text{cm}^{-3}$.

The evolution of $E(x_C, t)$ for the three n_{e0} are almost the same each other except the shift of the peak to later times as shown in figure 3.11. At the end of the discharge, however, in the case of $n_{e0}=10^8\text{cm}^{-3}$, the $E(x_C, t)$ starts to decrease by the same reason as discussed in 3.1.3. The $E(x_C, t)$ starts to grow after 73ns for all the n_{e0} . It may be concluded, if n_{e0} is supplied homogeneously in the gap, that higher n_{ArF^*} can be obtained with decreasing n_{e0} .

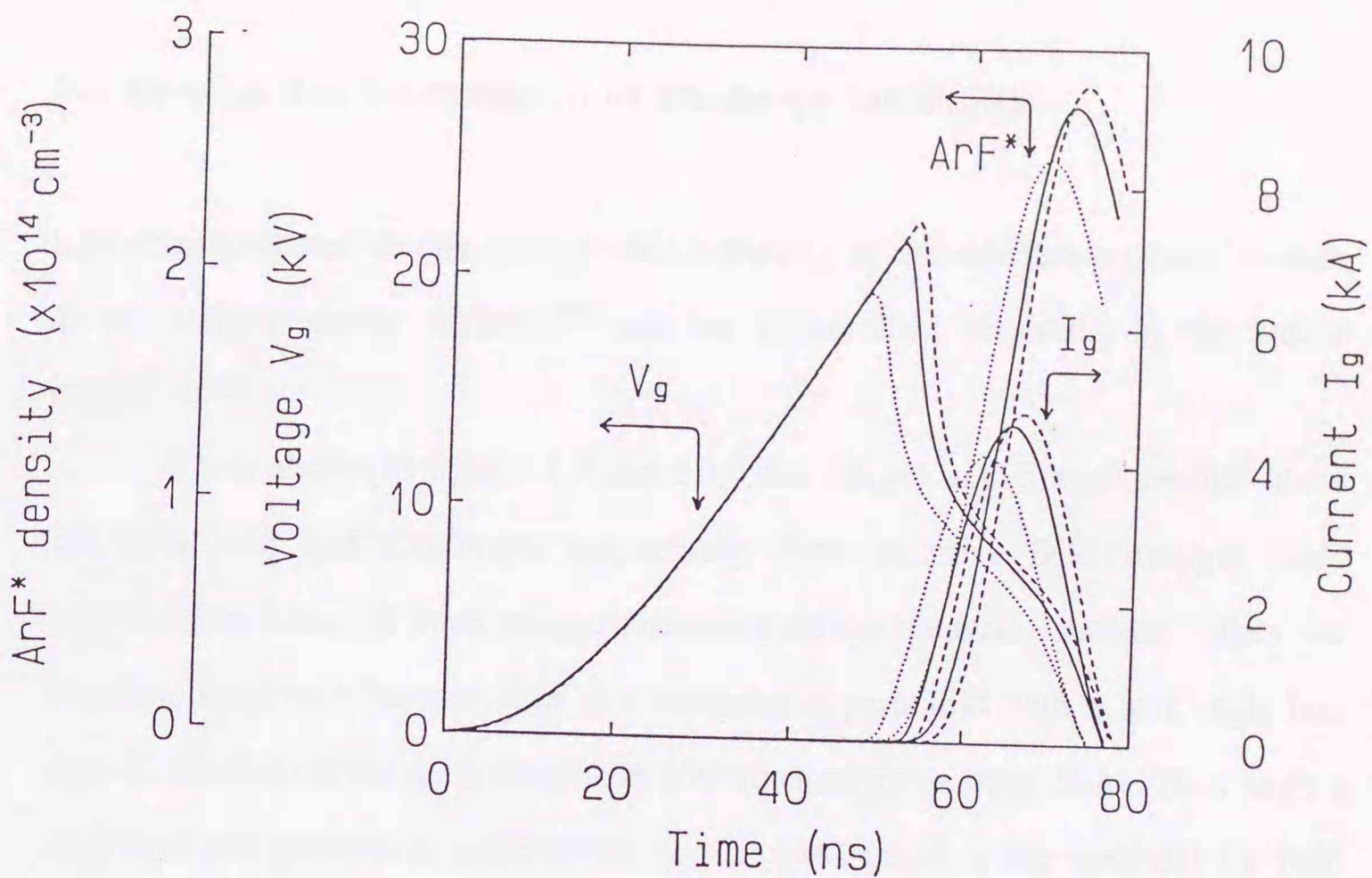


Figure 3.10. Waveforms of the discharge voltage V_g , current I_g and ArF* number density n_{ArF^*} for n_{e0} : - - - 10^2 cm^{-3} ; — 10^4 cm^{-3} ; 10^8 cm^{-3} .

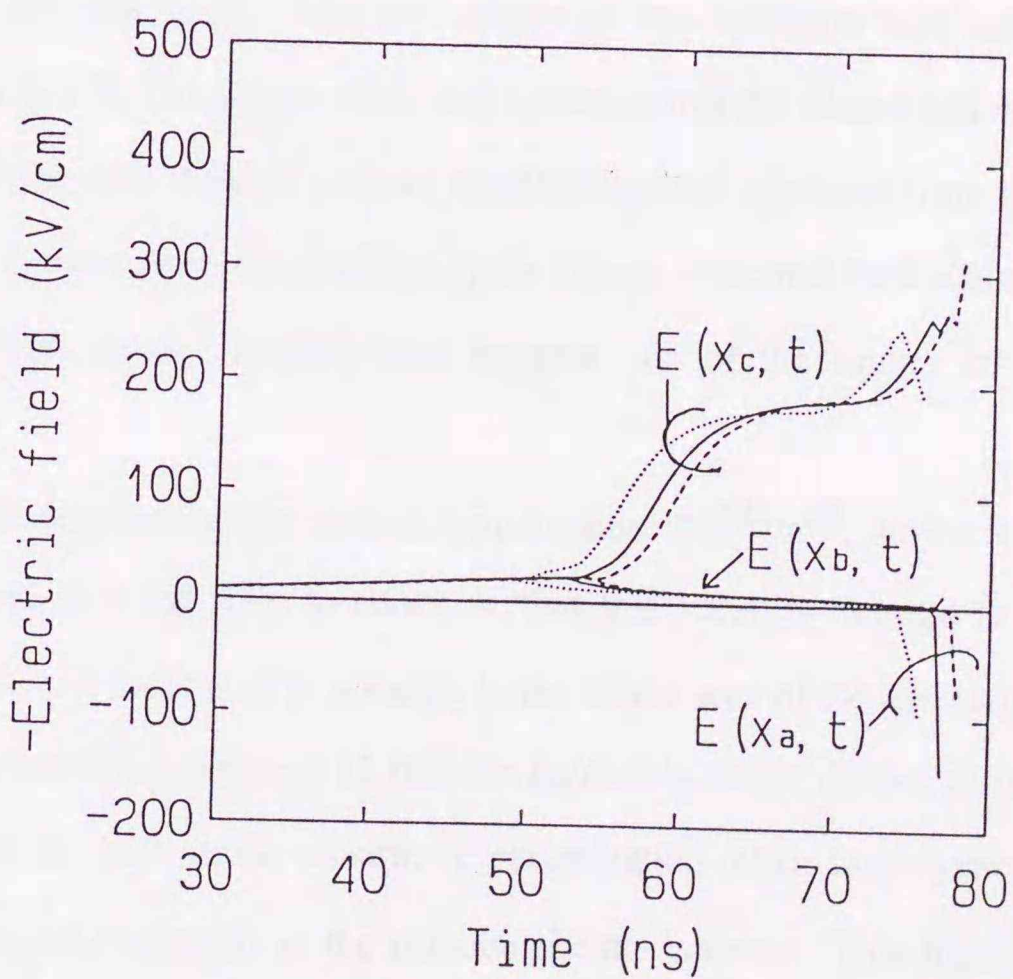


Figure 3.11. Temporal evolution of the electric field $E(x_c, t)$ at $x=5 \times 10^{-4} \text{ cm}$, $E(x_b, t)$ at $x=0.5 \text{ cm}$, $E(x_a, t)$ at $x=0.9995 \text{ cm}$ for n_{e0} : - - - 10^2 cm^{-3} ; — 10^4 cm^{-3} ; 10^8 cm^{-3} .

3-4 Examination for Initiation of Discharge Instability

It has been proposed that the filamentation instability in excimer lasers occurs because of the halogen donor depletion^[9] and the strong field distortion in the sheath region^[1,2,10].

It was shown in figures 3.9 and 3.11 that $E(x_G, t)$ and $E(x_a, t)$ reaches about 250~400kV/cm and 100kV/cm, respectively. Even at these field strength, field emission can occur, if there are protuberances on the electrode surface. When we assume a small protuberance such as a rotational hyperboloid with a half angle less than 3° , the field at the tip is more than 100 times of the average field. Then such a high field can generate a considerable current ($\sim 40\text{A/cm}^2$ at the cathode) by field emission when calculated using the Fowler-Nordheim equation^[11].

This emission has a possibility to bring about filamentation, which would develop an arc discharge. Taylor^[8] observed the initiation and development of filamentation in a XeCl excimer laser, and indicated that the filamentation was initiated from the cathode side. After it evolved another filament appeared from the anode side as well. The present result for the high space charge distorted field which appeared in the cathode and anode sheaths may suggest one of the causes of the Taylor's observation.

The F^- number density increases up to about 10^{14}cm^{-3} , which is about 0.06% of F_2 particles. It is not easy to conclude that this value is enough to lead halogen depletion or not, if it occur, it is possible in the whole area of the discharge volume.

It was shown in figure 3.11 that the n_{e0} could cause discharge instabilities, at both the cathode and anode sheath, if preionization were homogeneous. As n_{e0} decreases, the field strength in the cathode sheath increase. This higher field might brings instability, if some perturbation were to occur in the discharge.

3-5 Summary and Remarks

The simulation of an ArF excimer laser has been carried out which was neglected laser light to understand the basic behavior of charged particles and field strength in discharge development. The main results are summarized as follows.

The electric field was highly distorted by the space charge in the cathode and anode sheaths ($\sim 10^{-3}$ cm). The maximum electric field was more than 100 kV/cm when the discharge voltage decreases to 0.

Photo-electron emission from the cathode was suggested to play a role in suppressing the electric field distortion near the cathode which sustain volume discharges.

If there are protuberances on the electrodes, the distorted electric field ($\sim 10^5$ V/cm) is amplified to >100 times. This value of electric field was enough to lead field emission.

References

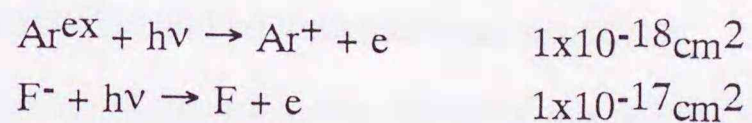
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Chapter 4

Influence of Stimulated Emission Light on Discharge Development in an ArF Excimer Laser

4-1 Introduction

In the present chapter, to understand the effect of stimulated emission light on the spatio-temporal discharge development, such as the evolution of electric field distortion, species densities, etc. The following photoionization and photodetachment processes are considered in addition to the processes described in the previous chapter,



The plasma characteristics are shown to be strongly influenced by the stimulated emission light. The generation of strong field distortion which could induce filamental instabilities at the electrodes is discussed from the view point of the influence of photoionization and photodetachment processes induced by stimulated emission light.

4-2 Simulation Conditions

The values of L_1 in the excitation circuit, the fraction of the spontaneous emission to be amplified to the laser light K , reflectivity of the mirror R , the single path optical loss L , the cavity length l_c and the active discharge excitation medium length l_g are taken to be 100nH, 1.8×10^{-5} , 8%, 8%, 105cm and 90cm^[2], respectively. The other discharge conditions, such as the discharge volume, γ_p , n_{e0} , etc. are the same as presented in 2.5.

4.3 Results and Discussion

4.3.1 Influence of Stimulated Emission Light on Waveforms of Discharge Current and Voltage, Laser Output and Evolution of Species Number Densities

Figure 4.1 shows the waveforms of discharge voltage, discharge current and laser output. The voltages after $t=40\text{ns}$, at which the laser output reaches a maximum, become appreciably smaller than the values which are obtained without considering the influence of laser light (i.e. the photoionization and photodetachment processes). In this time regime, the currents are larger than those obtained neglecting the lasing effect. This results indicates that the plasma conductivity is raised by the laser light driven photoionization and photodetachment processes.

The laser output starts to rise rapidly from $t=35\text{ns}$ when the current has a peak. This laser light waveform is a typical one^[6,9,10,11]. The peak value of $\sim 17\text{MW}$ appears at $t=39.5\text{ns}$. The FWHM (Full Width Half Maximum) of the light is 2.5ns .

In figure 4.2, the temporal evolution of the number densities of electrons n_{eL} , positive ions n_{+L} , negative ion n_{-L} , metastable state Ar n_{Ar^*L} and ArF excimers n_{ArF^*L} in the bulk region calculated considering the influence of the stimulated emission light are compared to n_{eN} , n_{+N} , n_{-N} , n_{Ar^*N} and n_{ArF^*N} when this influence is not considered. The influence of the stimulated emission light on the temporal evolution of n_{eL} , n_{+L} and n_{-L} is seen considerably after the laser power reaches a maximum. The values of n_{eL} and n_{+L} are larger than n_{eN} and n_{+N} after $t=40\text{ns}$, while the n_{-L} , n_{Ar^*L} and n_{ArF^*L} values are lowered. The n_{ArF^*L} values of decay rapidly with increasing the laser output after $t=38\text{ns}$.

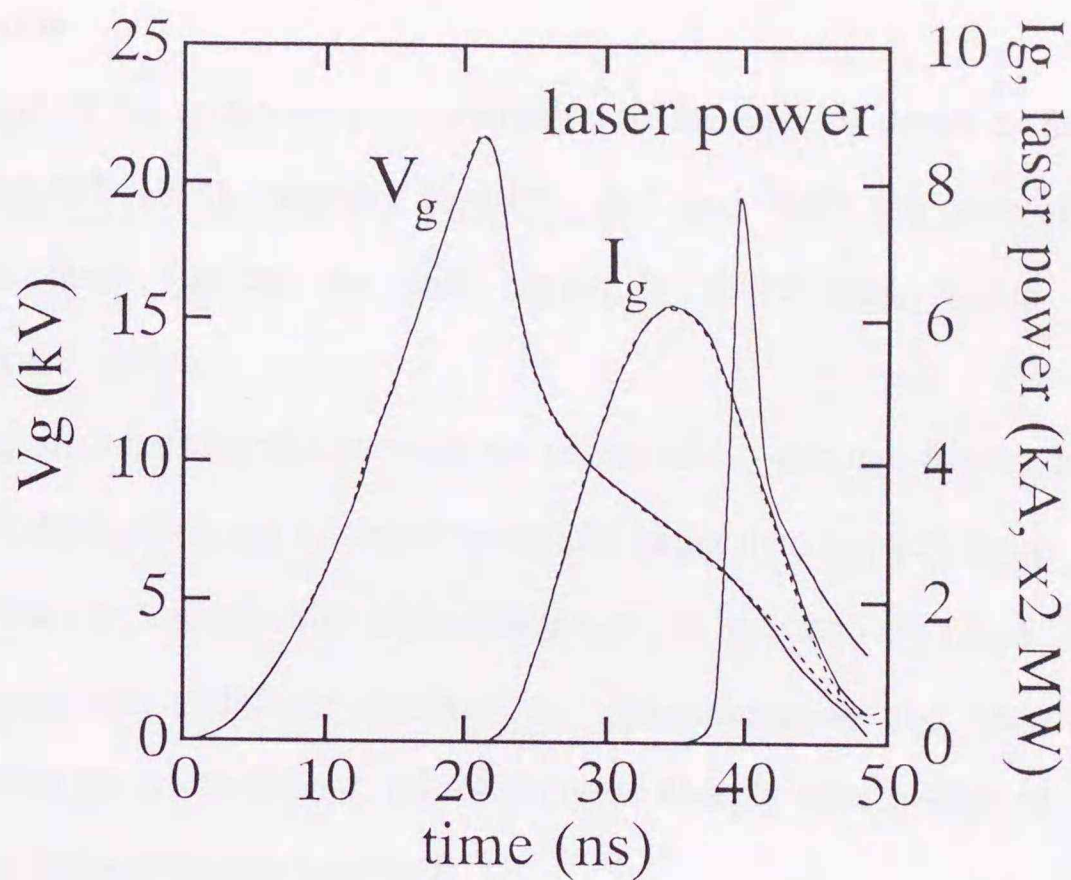


Figure 4.1. Waveforms of the discharge voltage V_g , current I_g and laser output. solid line ; with lasing effect, dotted line ; without lasing effect.

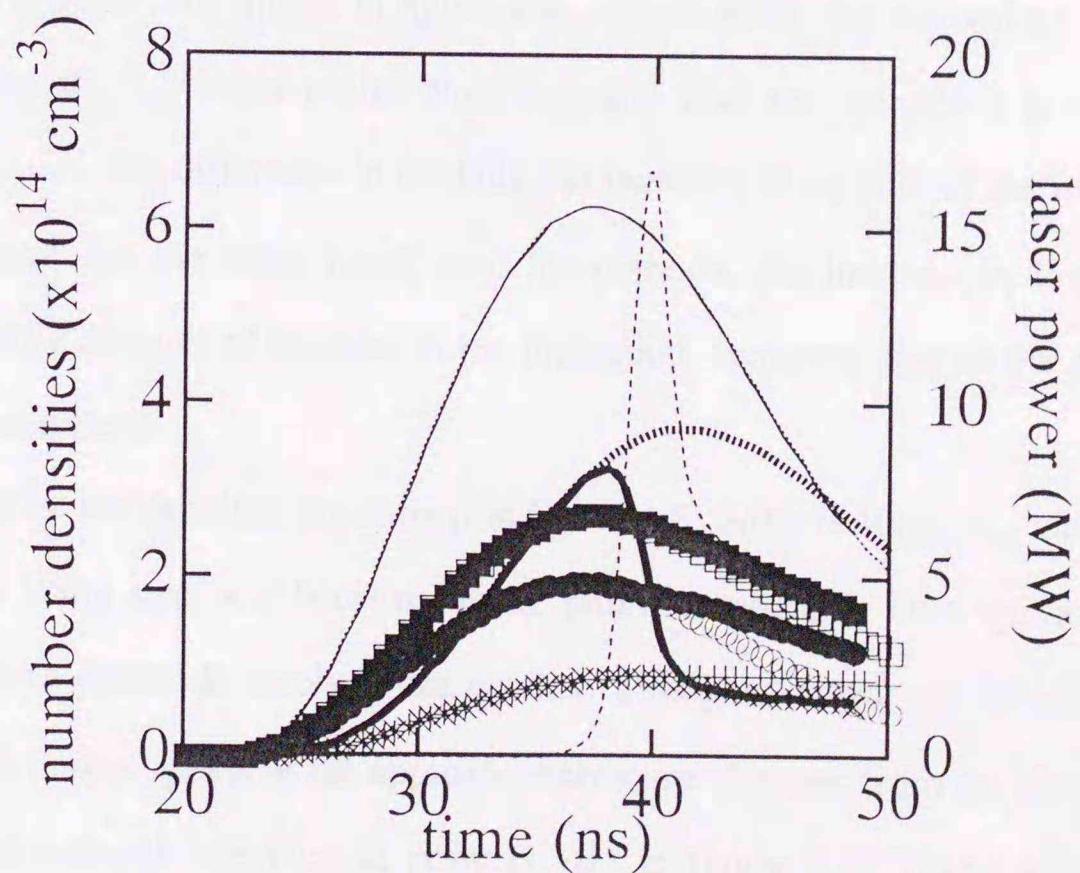


Figure 4.2. Temporal evolution of species densities in the bulk region.

○ n_{eN} ; □ n_{+N} ; + n_{-N} ; n_{Ar+N} ; n_{ArF+N} ;
● n_{eL} ; ■ n_{+L} ; × n_{-L} ; — n_{Ar+L} ; — n_{ArF+L} ;
..... laser output

4.3-2 Spatio-Temporal Evolution of Species Number Densities

(a) Electrons

A comparison of the spatio-temporal evolution of the number densities for electrons, positive ions($\text{Ar}^+ + \text{He}^+$), negative ions(F^-), Ar^* and ArF^* are shown in figures 4.3~4.7. In these figures, the bulk region is abbreviated, where the spatial distributions are uniform.

A significant difference between the values of n_{eL} and n_{eN} is seen after $t=40\text{ns}$ in figure 4.3. In the bulk n_{eL} is almost two times larger than n_{eN} (cf. figure 4.2). Near the cathode the n_{eL} value is also higher than n_{eN} as indicated by (A,A'), since the laser light generates additional electrons by photoionization and photodetachment processes. Near the anode the n_{eL} values decrease sharply after $t=48\text{ns}$ with time(B), while the n_{eN} values decrease slowly(B').

(b) Positive and Negative Ions

Positive ion densities are shown in figure 4.4. After $t=40\text{ns}$, the n_{+L} values in the bulk are approximately 1.2 times higher than n_{+N} and near the cathode it is ~ 1.5 times higher than n_{+N} . The difference in the bulk ion densities is a result of the inclusion of photoionization. On the other hand, near the cathode, the increase in ion densities occurs primarily because of increase in the ionization frequency due to the high space charge distorted field.

Negative ion densities are shown in figure 4.5. After $t=40\text{ns}$, n_{-L} values in the bulk become lower than n_{-N} because of the photodetachment. Two spikes(A,B) in n_{-L} , one at each electrode, evolve after $t=48\text{ns}$. This phenomena can be explained as follows. Both spikes appear at the approximately same distance from the electrodes, at the bulk plasma-sheath interface, at points(C,D) in figure 4.8. There, electrons are accumulated from the electrode region by drift and from the bulk region by diffusion.

Then, the negative ion densities increase in proportion to the electron densities by the electron attachment.

(c) Metastable Ar and ArF*

The n_{Ar^*L} values in the bulk are almost the same as n_{Ar^*N} as shown in figure 4.6. The n_{Ar^*L} values near the cathode become higher than the n_{Ar^*N} for $t > 45$ ns due to the high excitation frequency driven by the high field.

The ArF* densities are shown in figure 4.7. The n_{ArF^*L} values before emission of laser light are completely the same as n_{ArF^*N} . The peak value in n_{ArF^*L} appears at 38 ns to be $3.3 \times 10^{14} \text{cm}^{-3}(\text{A})$, while the peak in n_{ArF^*N} is $3.7 \times 10^{14} \text{cm}^{-3}(\text{A}')$ at 41.5 ns, because of the effect of stimulated emission. Near the cathode, the second peak in $n_{ArF^*L}(\text{B})$ appears 1.5 ns later than the first peak in the bulk(A). After the second peak appears, the cathode n_{ArF^*L} values are higher than the bulk values. At the anode after $t = 45$ ns, the n_{ArF^*L} value becomes higher than the bulk values. There, the decay rate of ArF* by stimulated emission is smaller than that in the bulk, though at the cathode the n_{ArF^*} precursor densities increase due to the highly distorted field.

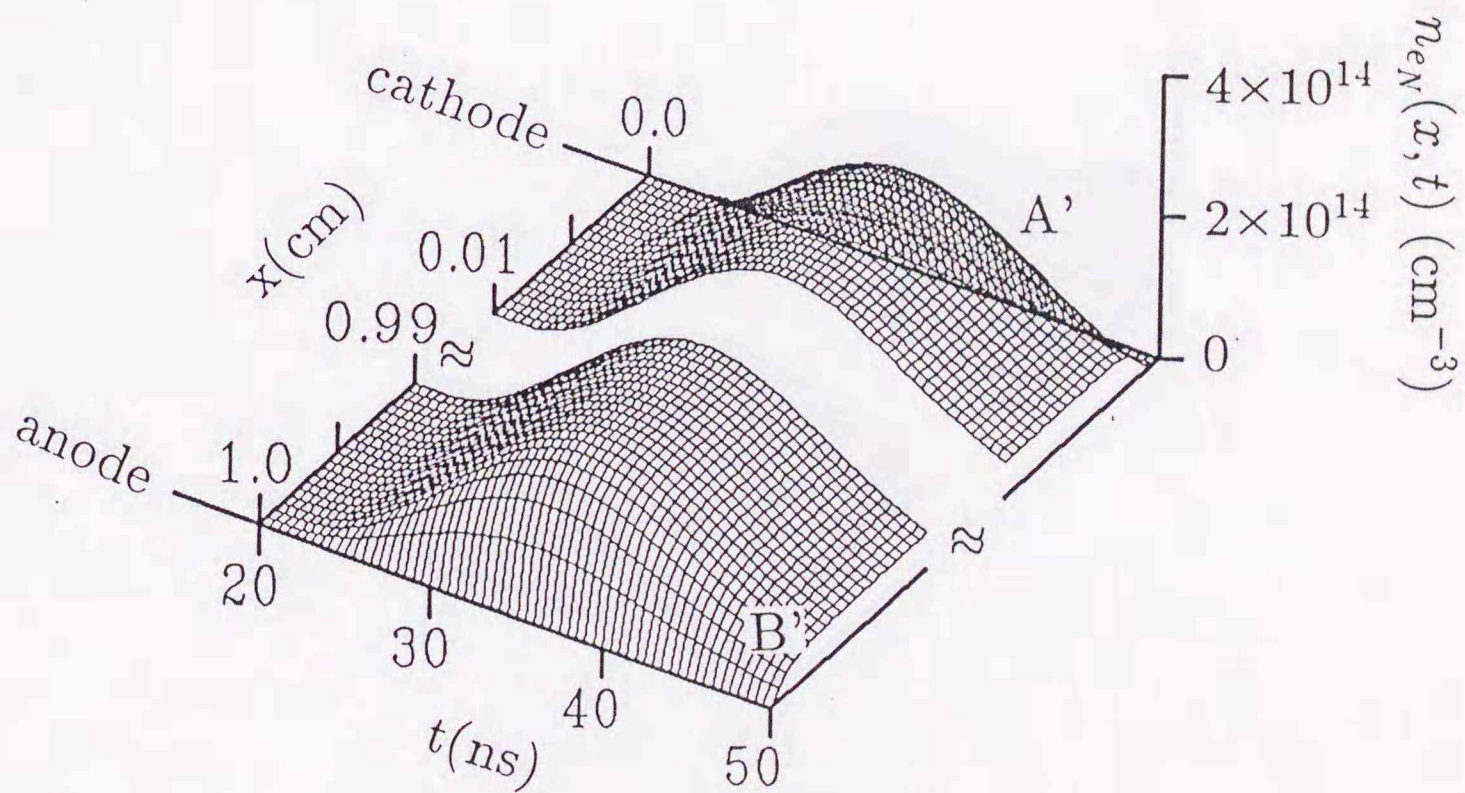
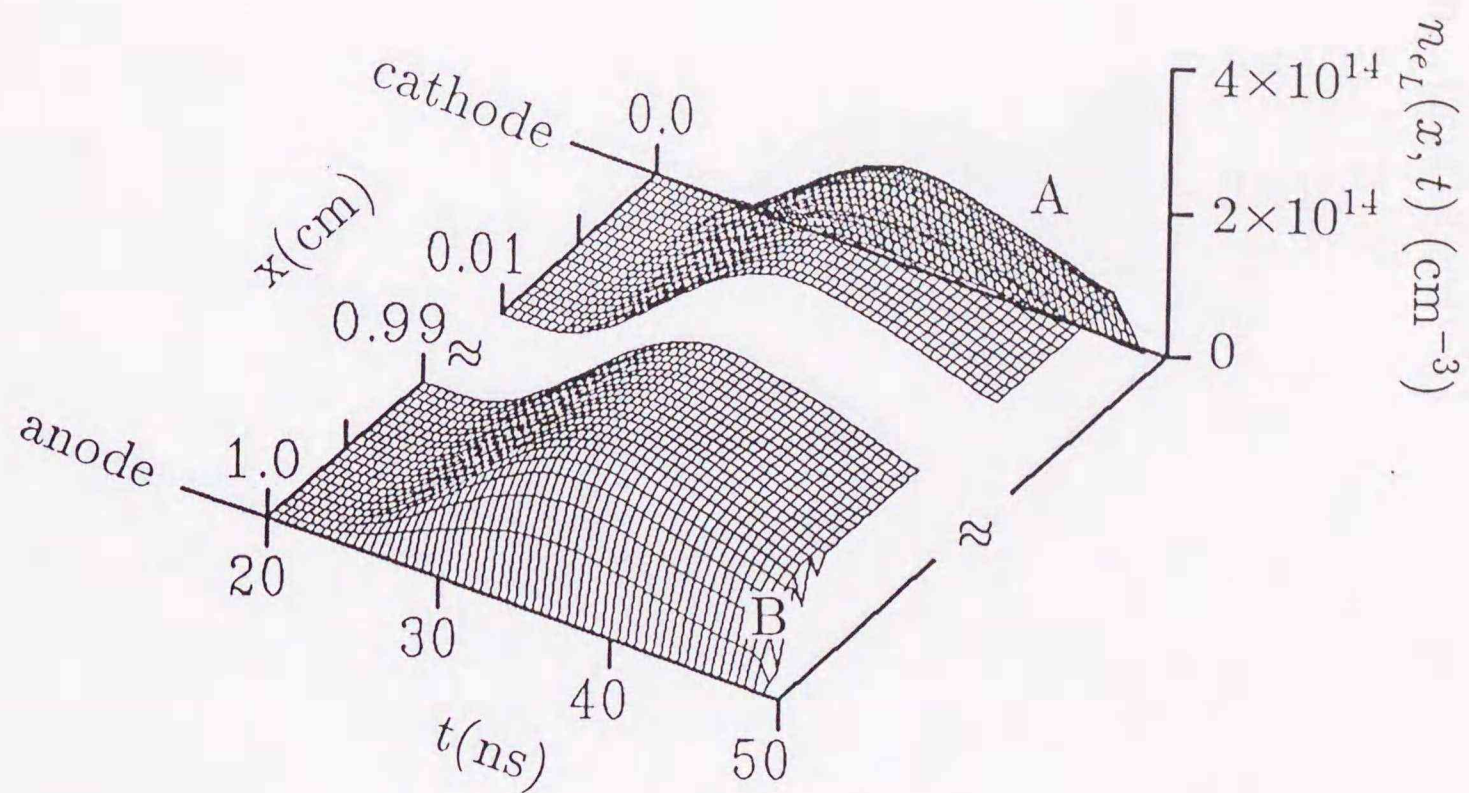


Figure 4.3. Spatio-temporal evolution of the electron number densities n_{eL} and n_{eN} .

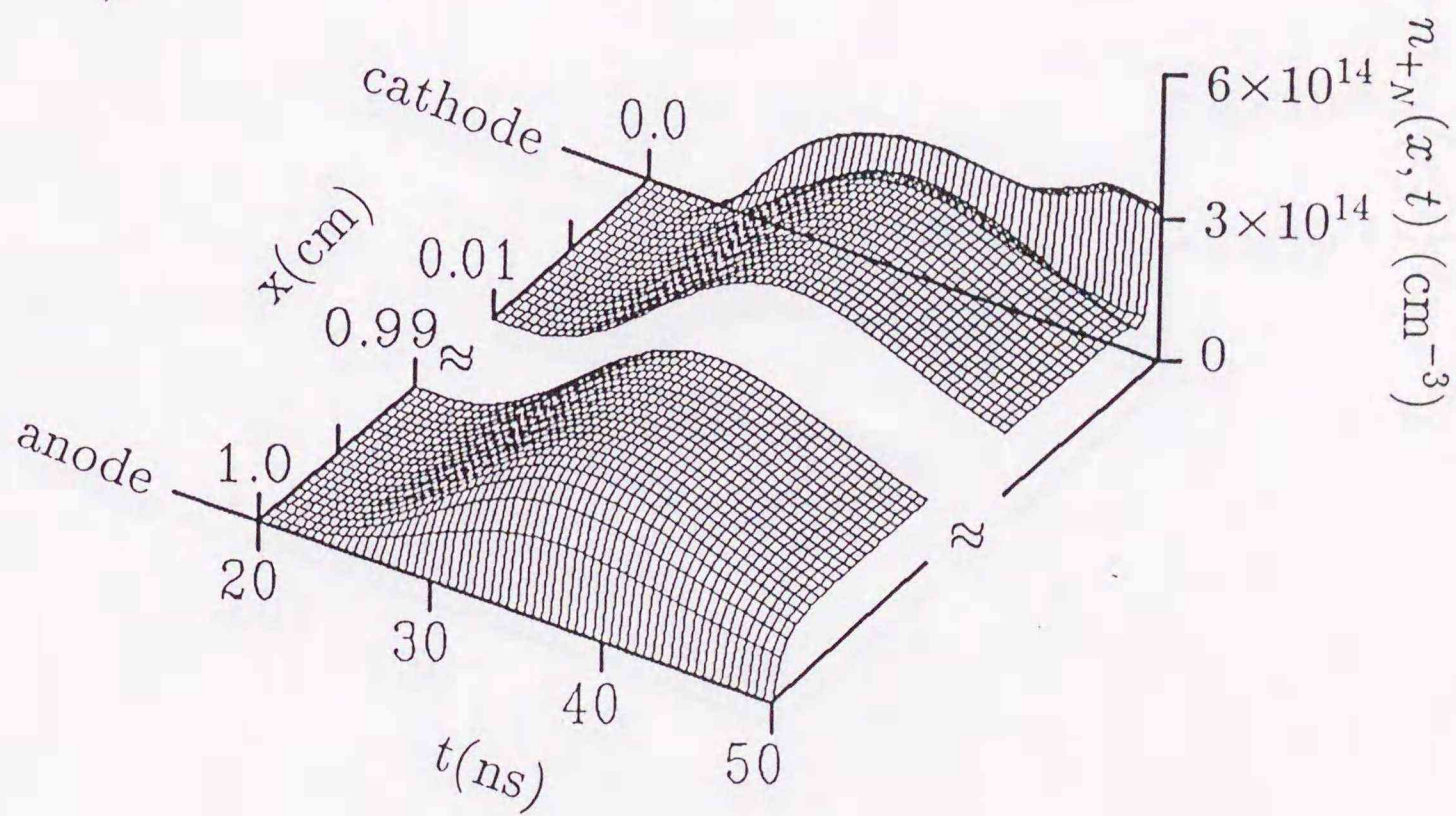
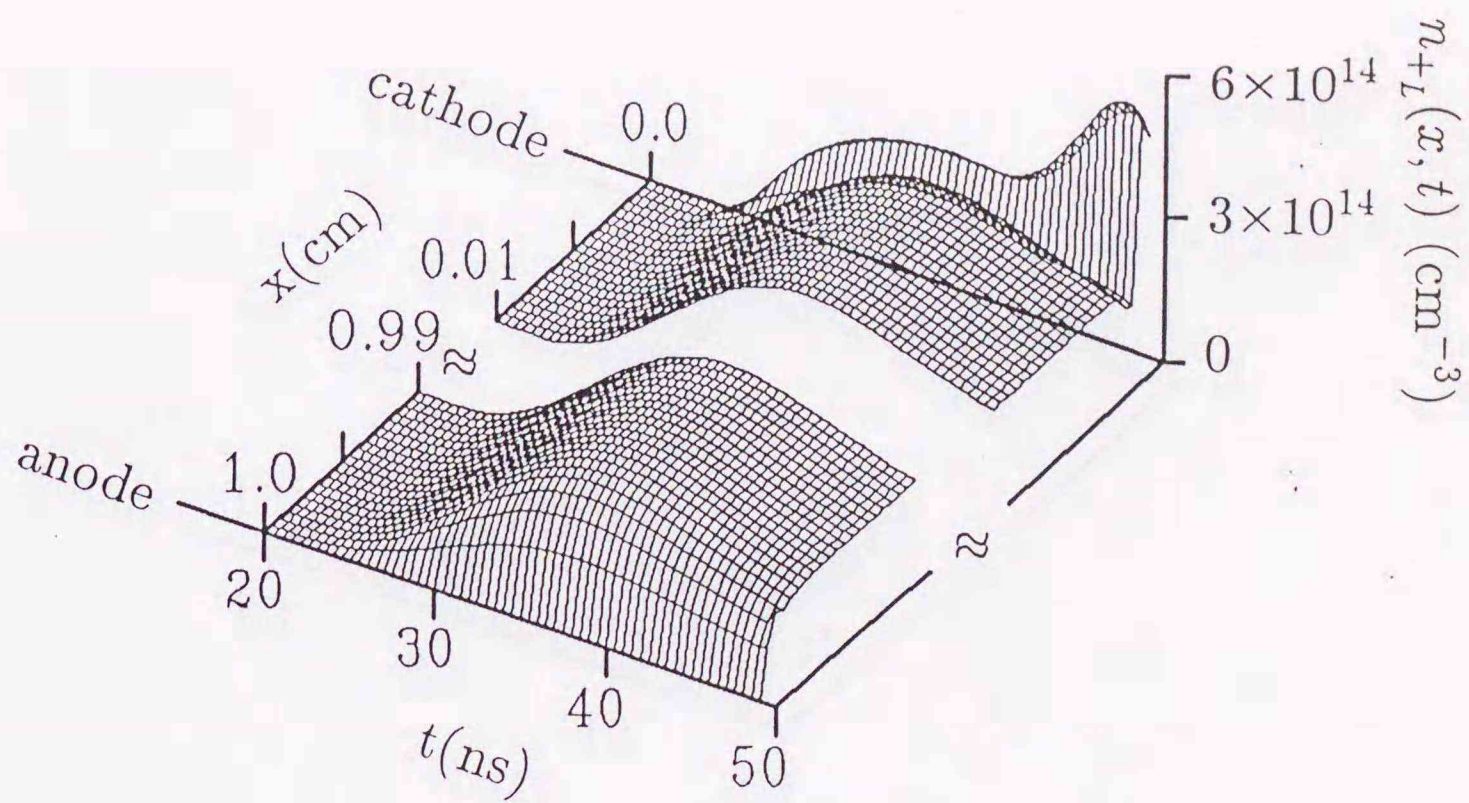


Figure 4.5. Spatio-temporal evolution of the positive ion number densities n_{+L} and n_{+N} .

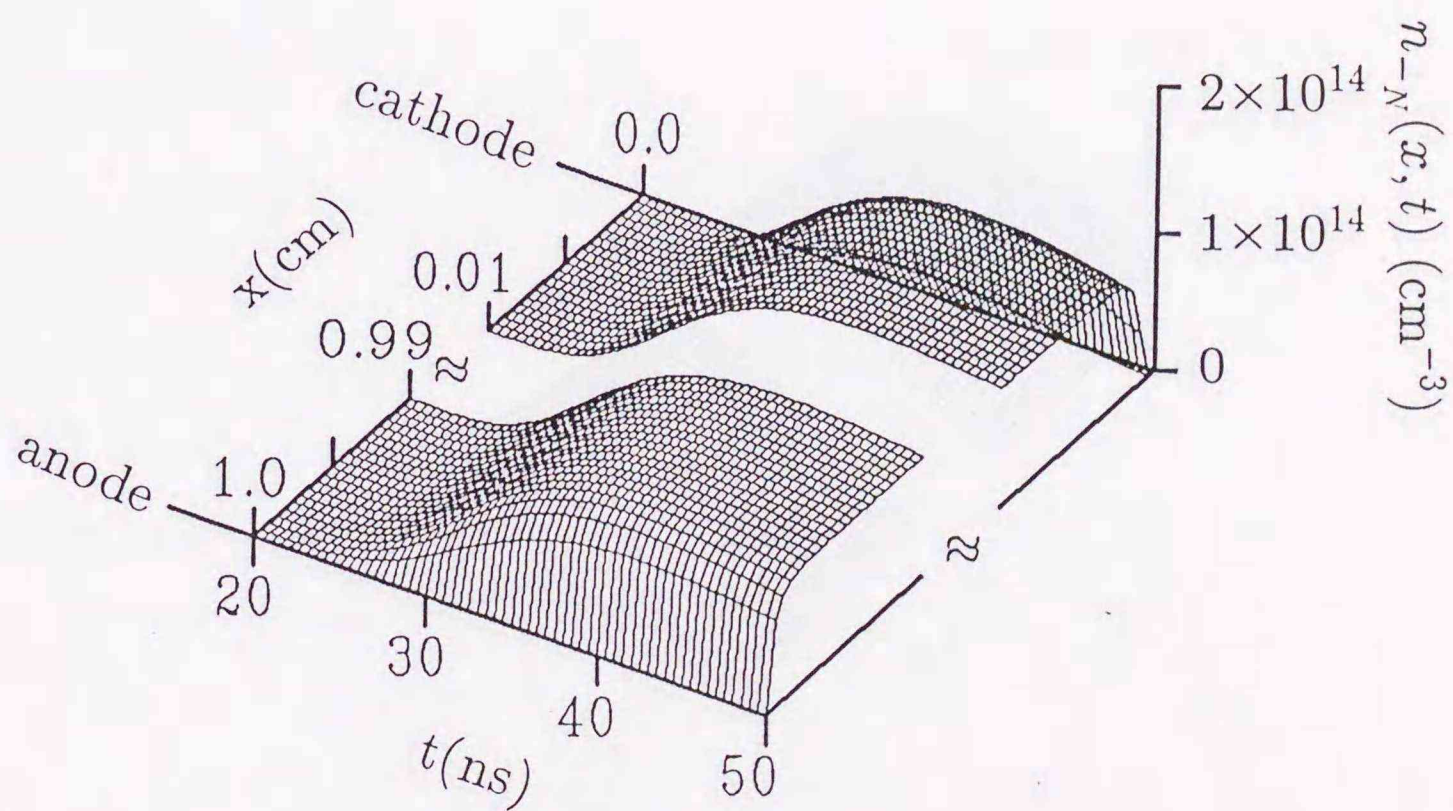
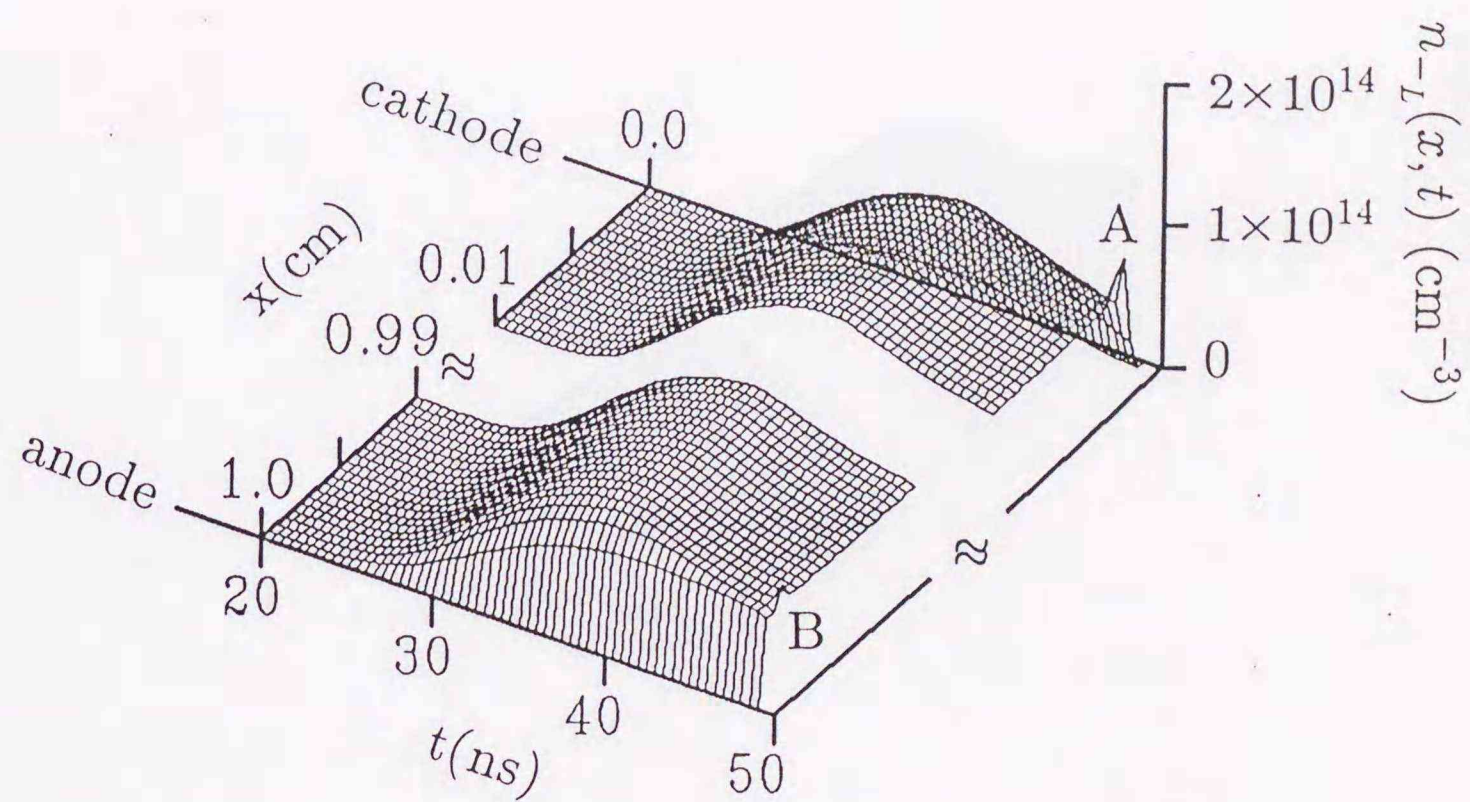


Figure 4.6. Spatio-temporal evolution of the negative ion number densities n_{-L} and n_{-N} .

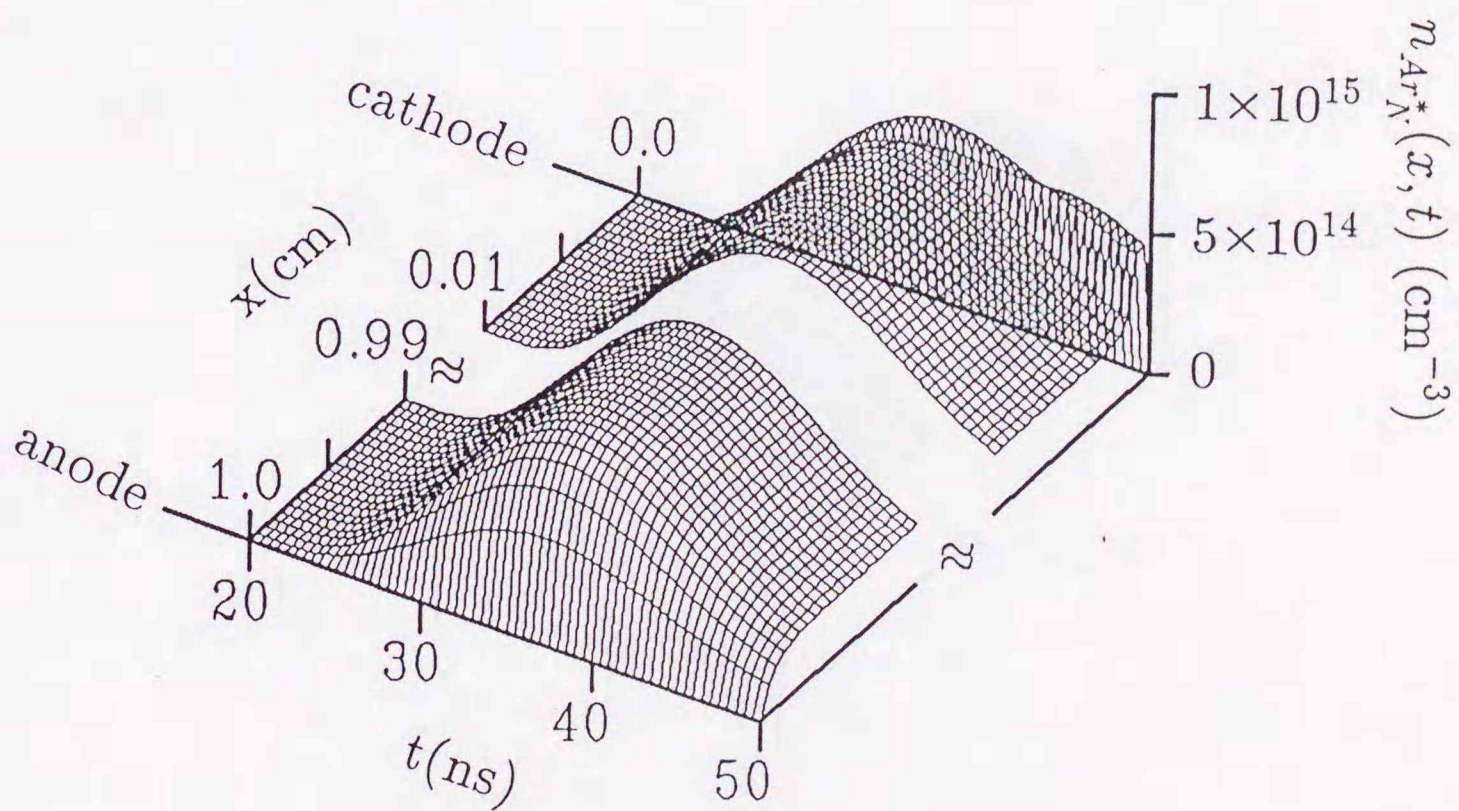
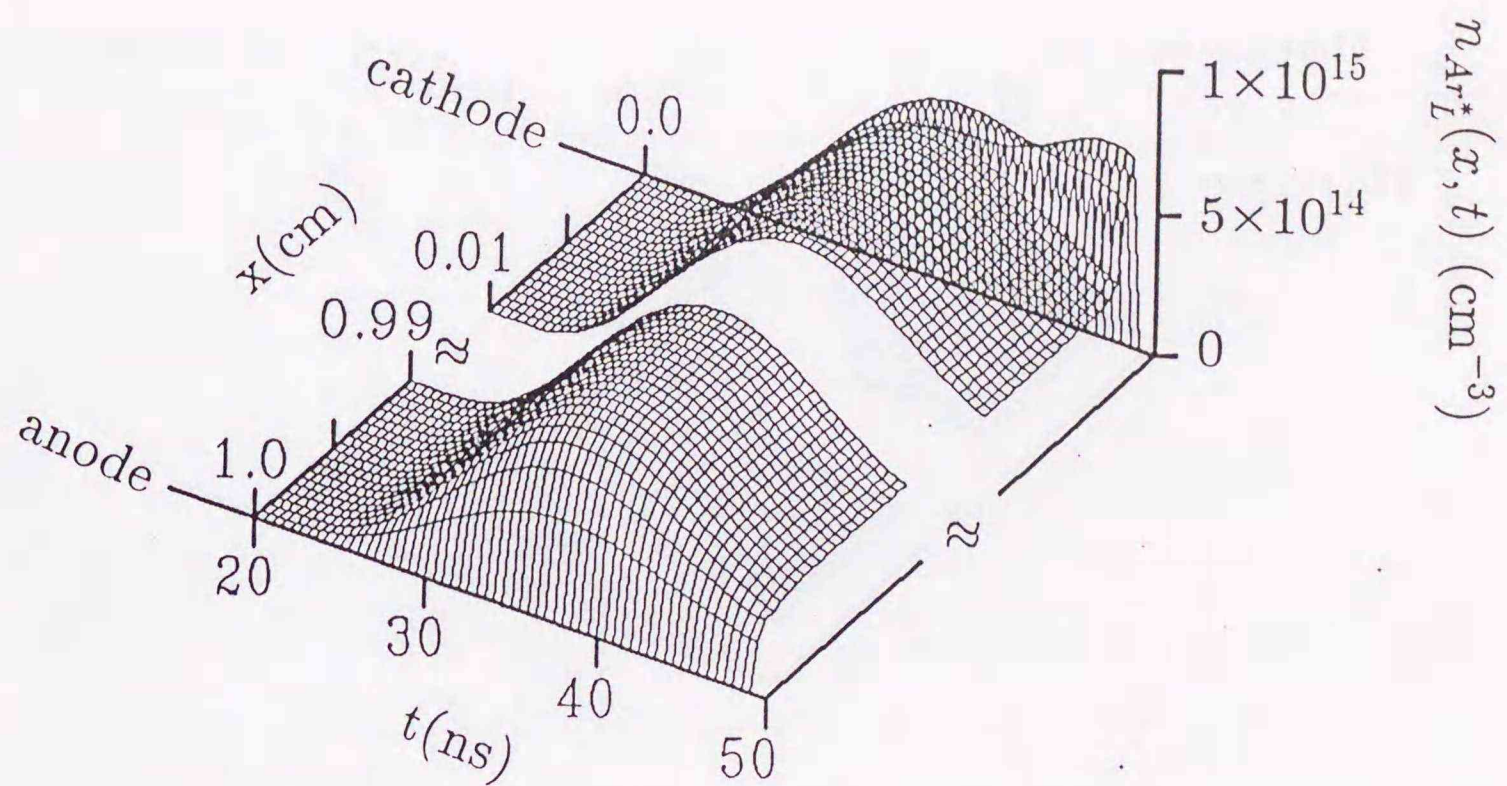


Figure 4.7. Spatio-temporal evolution of the Ar* number densities $n_{Ar^*_L}$ and $n_{Ar^*_N}$.

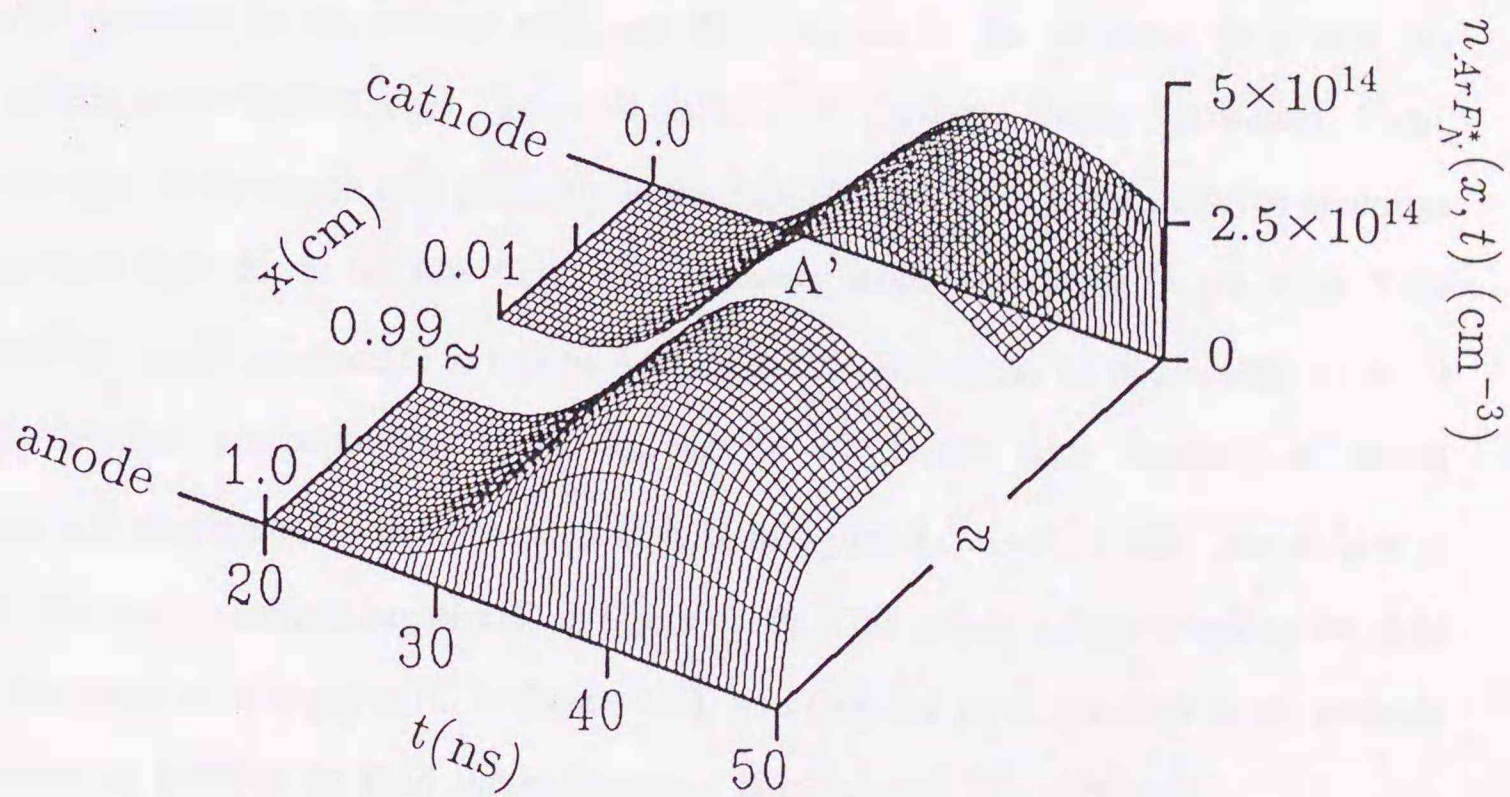
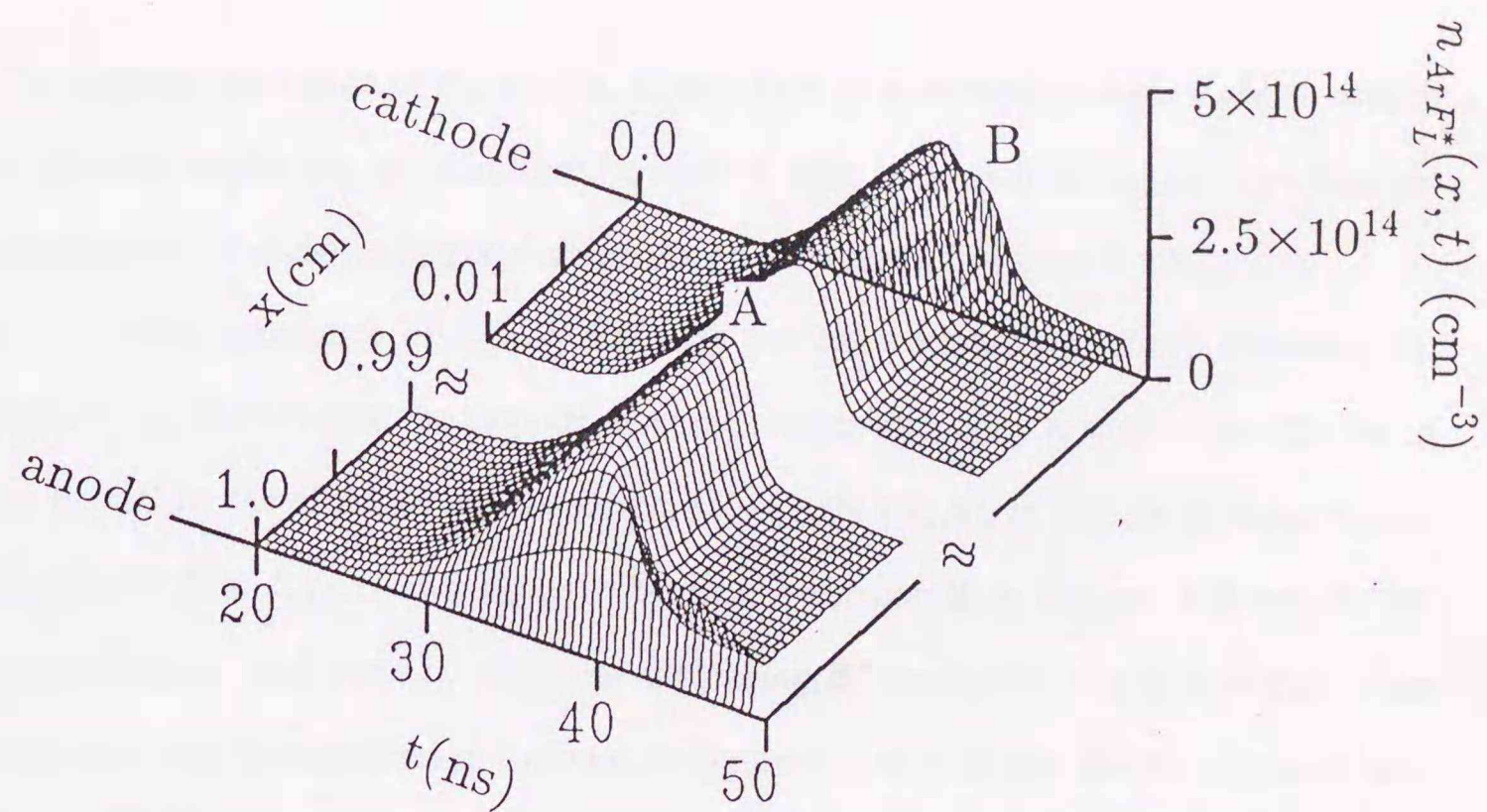


Figure 4.8. Spatio-temporal evolution of the ArF* number densities n_{ArF^*L} and n_{ArF^*N} .

4.3-3 Spatio-temporal Evolution of Electric Field and Net Charge

Number Density

The temporal evolution of the electric fields, $E_L(x,t)$ is compared with $E_N(x,t)$, which is obtained neglecting the stimulated emission light as shown in figure 4.9. The net charge number densities, $\rho_L(x,t)$ and $\rho_N(x,t)$, are shown in figure 4.10.

After appearance of a peak value in the laser output waveform ($t > 40\text{ns}$, cf. figure 4.2), $E_L(x,t)$ near the cathode becomes larger than $E_N(x,t)$ due to the increase in the $\rho_L(x,t)$ by the effect of stimulated emission light (**A, A'** in figures 4.9 and 4.10). After $t = 47.5\text{ns}$, $E_L(x,t)$ and $\rho_L(x,t)$ begin to decrease (**B** in figures 4.9 and 4.10), while $E_N(x,t)$ and $\rho_N(x,t)$ are kept increasing (**B'** in figures 4.9 and 4.10). This difference can be explained as follows. In figure 4.1, it is shown that the external field $E_{exL}(=320\text{V/cm})$ is lower than $E_{exN}(=970\text{V/cm})$ at the end of laser pulse ($t = 48.5\text{ns}$). This decrease in the external field and the increase in the distorted field near the cathode make bulk $E_L(x,t)$ lower to 9V/cm (cf. $E_N(x,t)$ being 760V/cm). Then, electrons in the sheath drift promptly in the bulk direction, but in the bulk the electrons scarcely drift due to the low field. This tendency leads n_{eL} to be larger at the bulk plasma-sheath interface (**C** in figures 4.9 and 4.10). However, an appreciable peak at the interface corresponding to the increase in n_{eL} is not seen because of strong electron attachment as demonstrated at **A, B** in figure 4.5. As a result, the $\rho_L(x,t)$ at the interface becomes negative (**C** in figure 4.10). This negative $\rho_L(x,t)$ makes the field from positive to negative (**C** in figure 4.9), and then the electrons drift in the cathode direction. Finally, the field pattern shown at **B** in figure 4.9 is obtained.

Near the anode $E_L(x,t)$ changes from negative to positive at $t = 47.5\text{ns}$ (**D** in figure 4.9) and it becomes significant. Therefore, the electrons start to drift in the bulk direction. Consequently the positive space charge increases continuously (**D** in figure 4.10). This tendency is seen only when interaction of the laser light with the plasma is considered.

These high field distortions suggest initiation of filamental instability not only from the cathode region but also from the anode as observed by Taylor^[12].

4.3-4 Spatio-temporal Evolution of Mean Electron Energy

The spatio-temporal evolution of the mean electron energy $\bar{\epsilon}_L(x,t)$ and $\bar{\epsilon}_N(x,t)$ are shown in the figure 4.11. After $t=40\text{ns}$, near the cathode the values of $\bar{\epsilon}_L(x,t)$ become higher than $\bar{\epsilon}_N(x,t)$ due to the highly distorted electric field.

In the bulk, the values of $\bar{\epsilon}_L(x,t)$ are slightly smaller than $\bar{\epsilon}_N(x,t)$ because of the generation of low energy secondary electrons by photoionization and the lower $E_L(x,t)$.

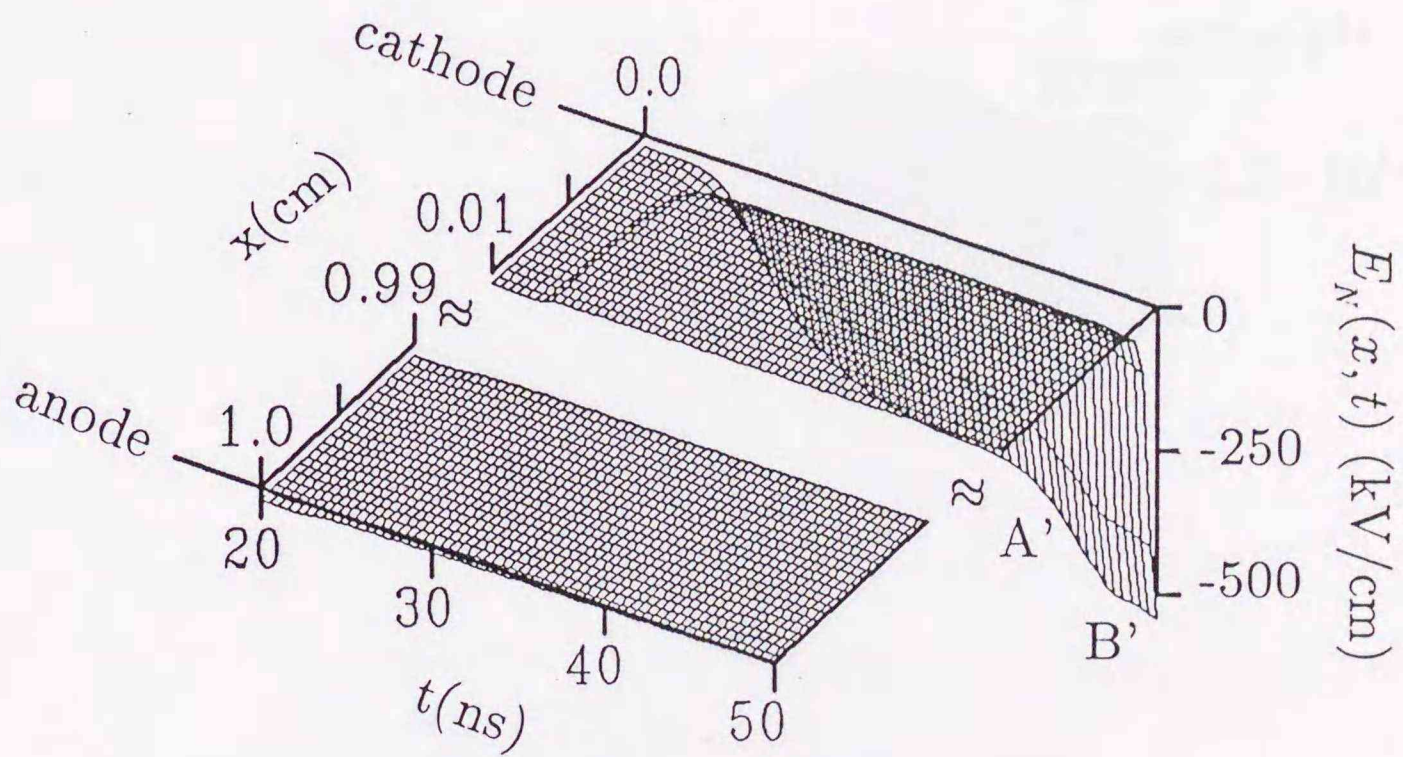
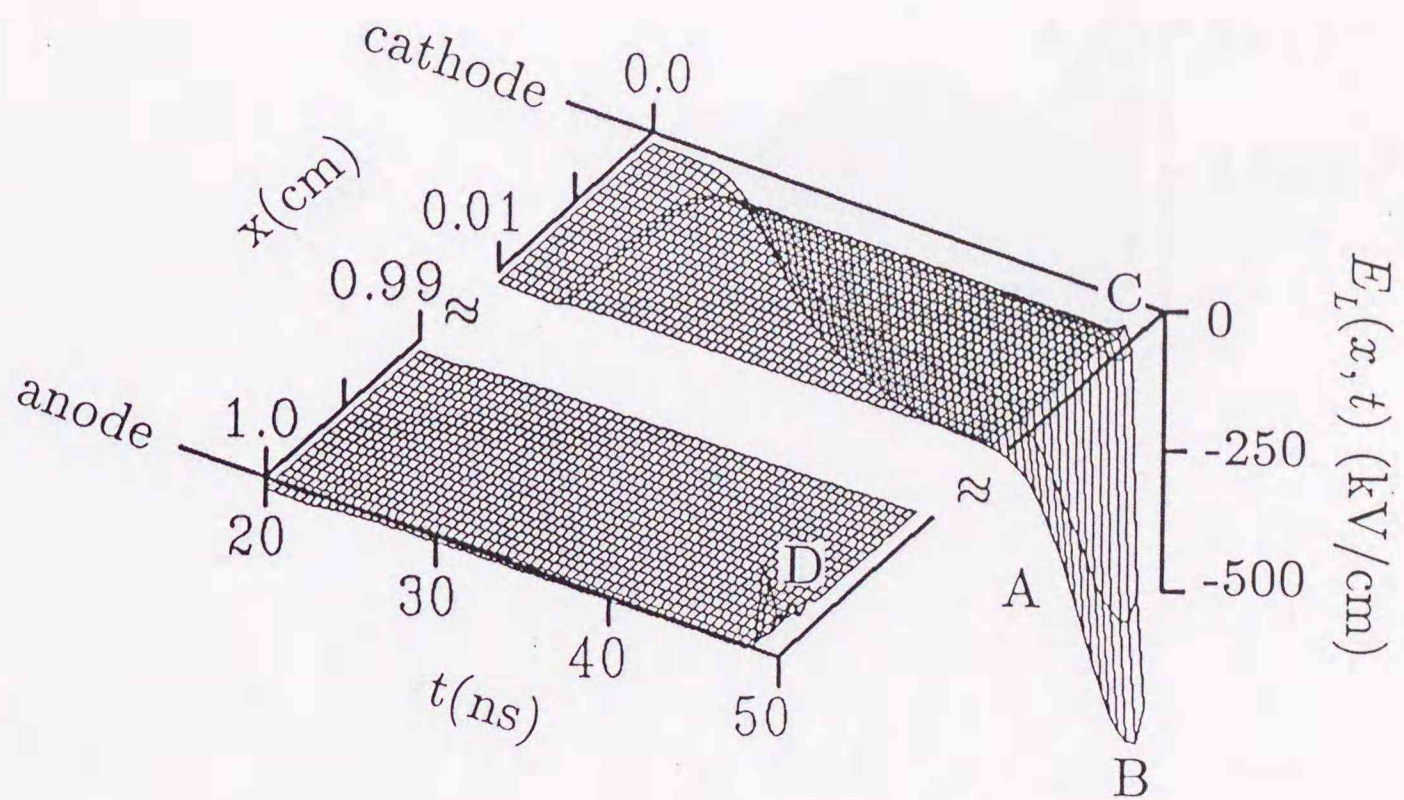


Figure 4.9. Spatio-temporal evolution of the electric field for $E_L(x, t)$ and $E_N(x, t)$.

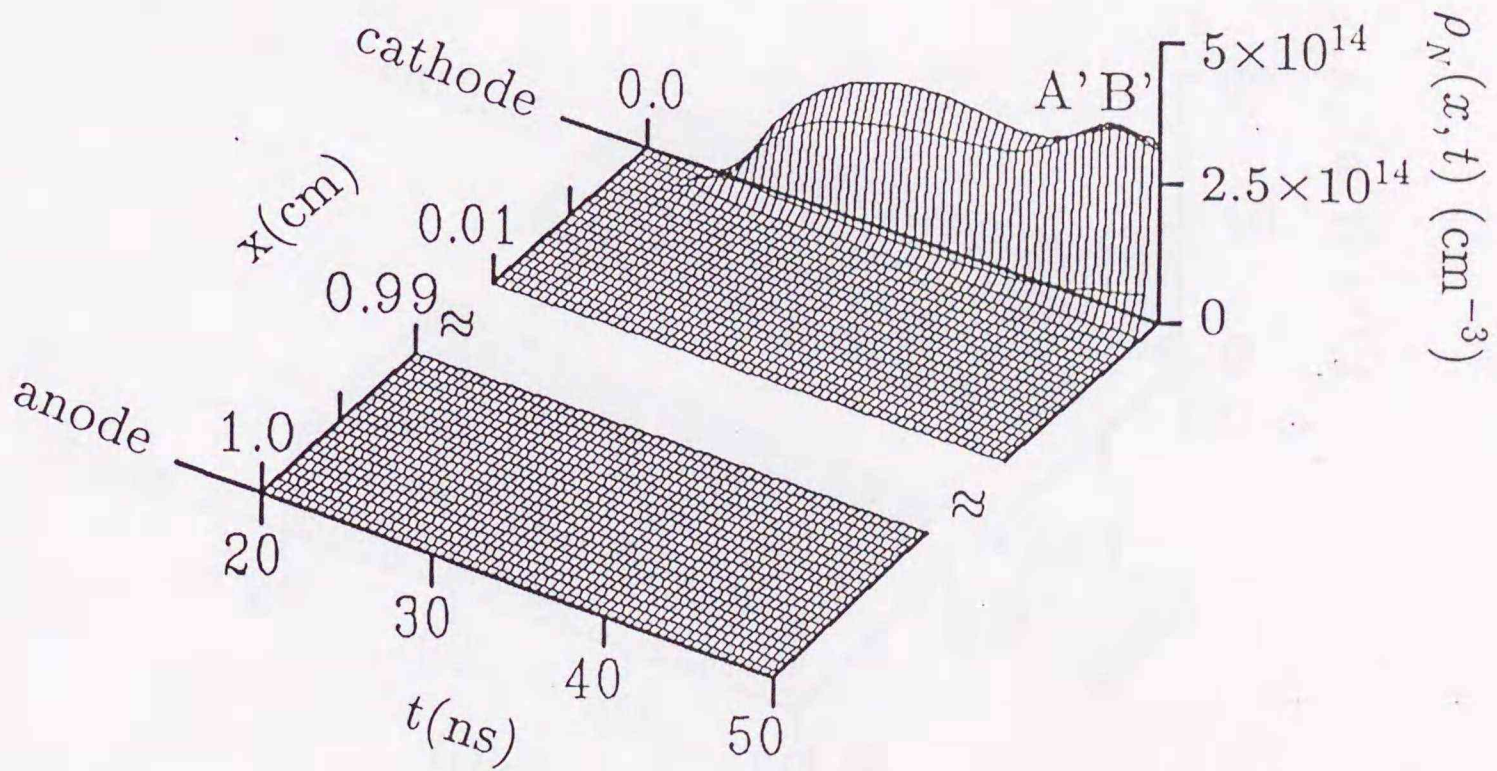
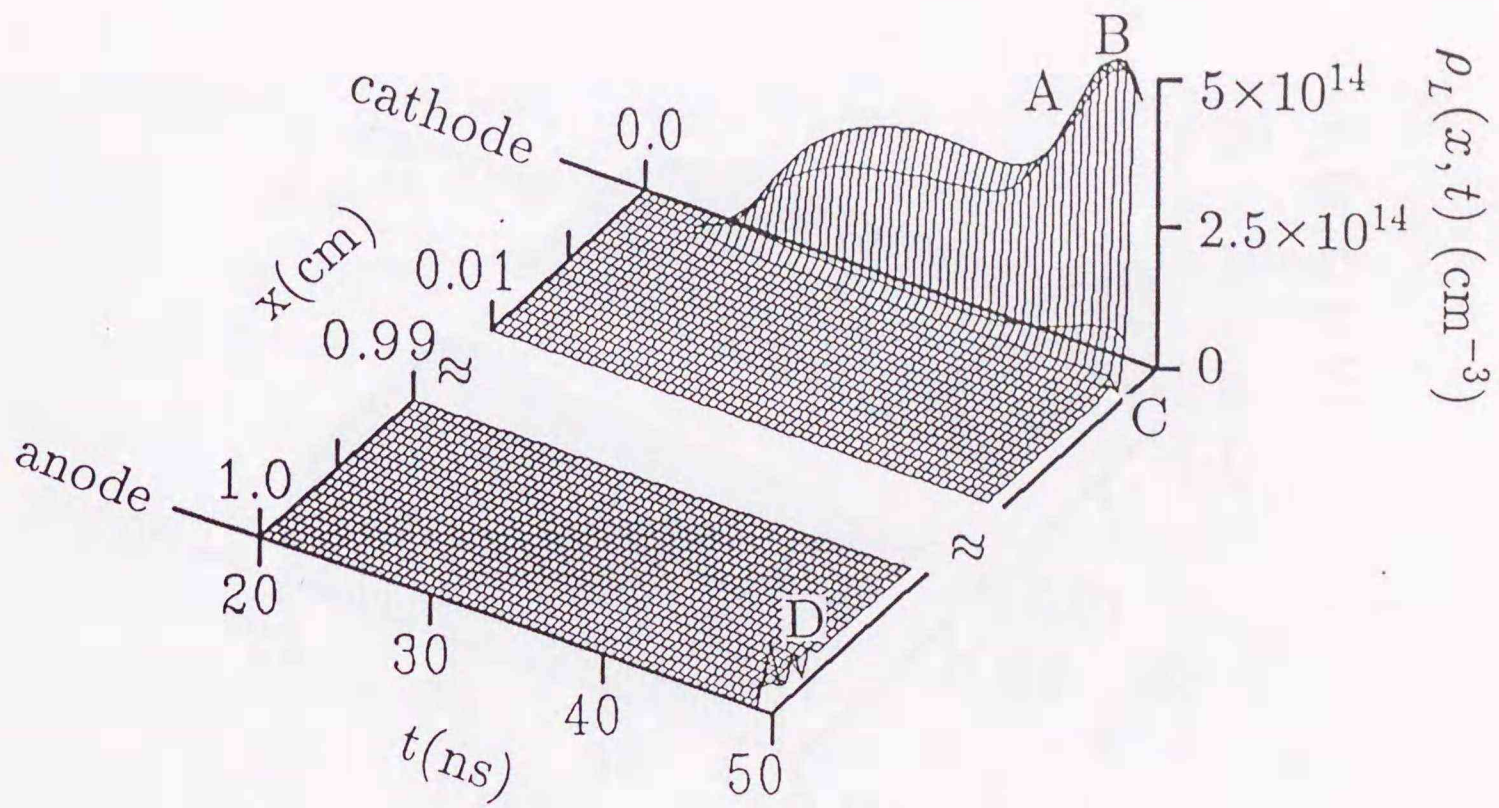


Figure 4.10. Spatio-temporal evolution of the net charge number density for $\rho_L(x, t)$ and $\rho_N(x, t)$.

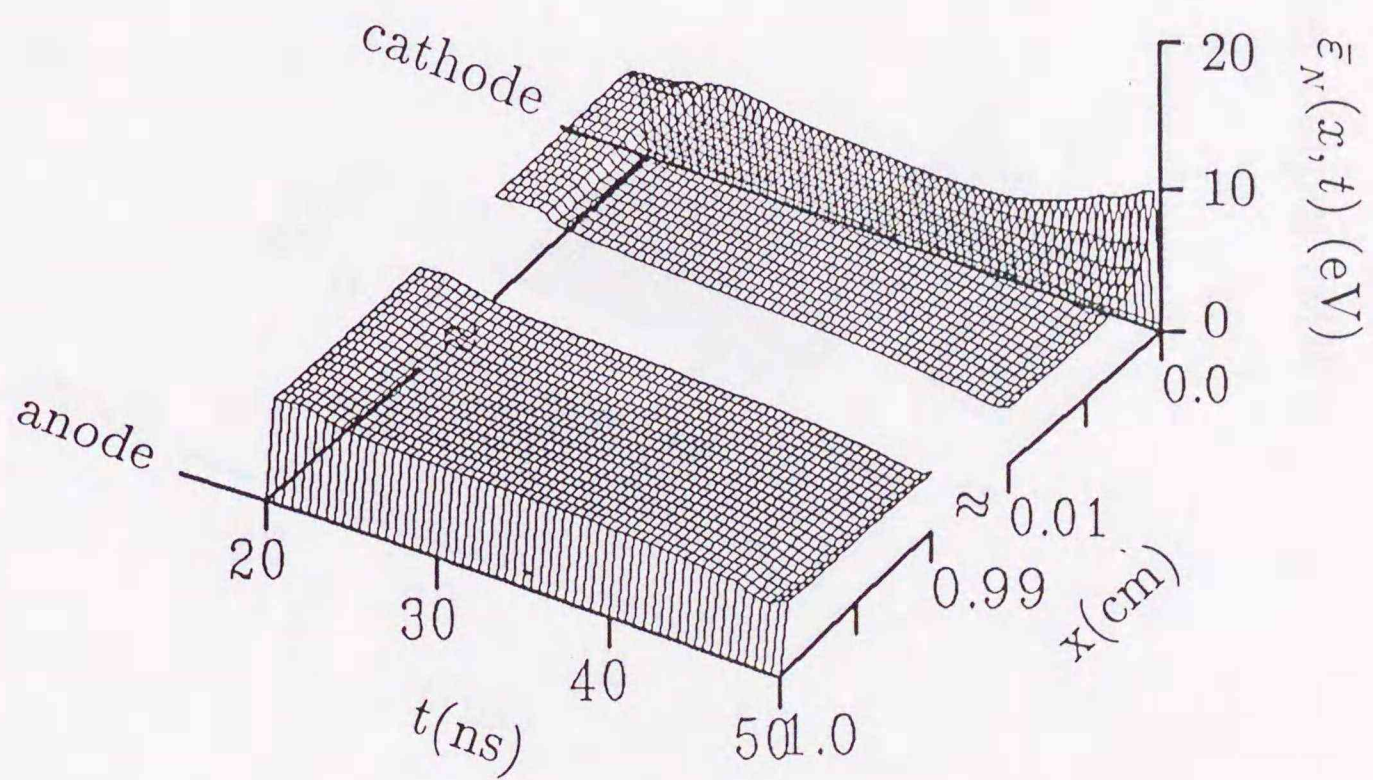
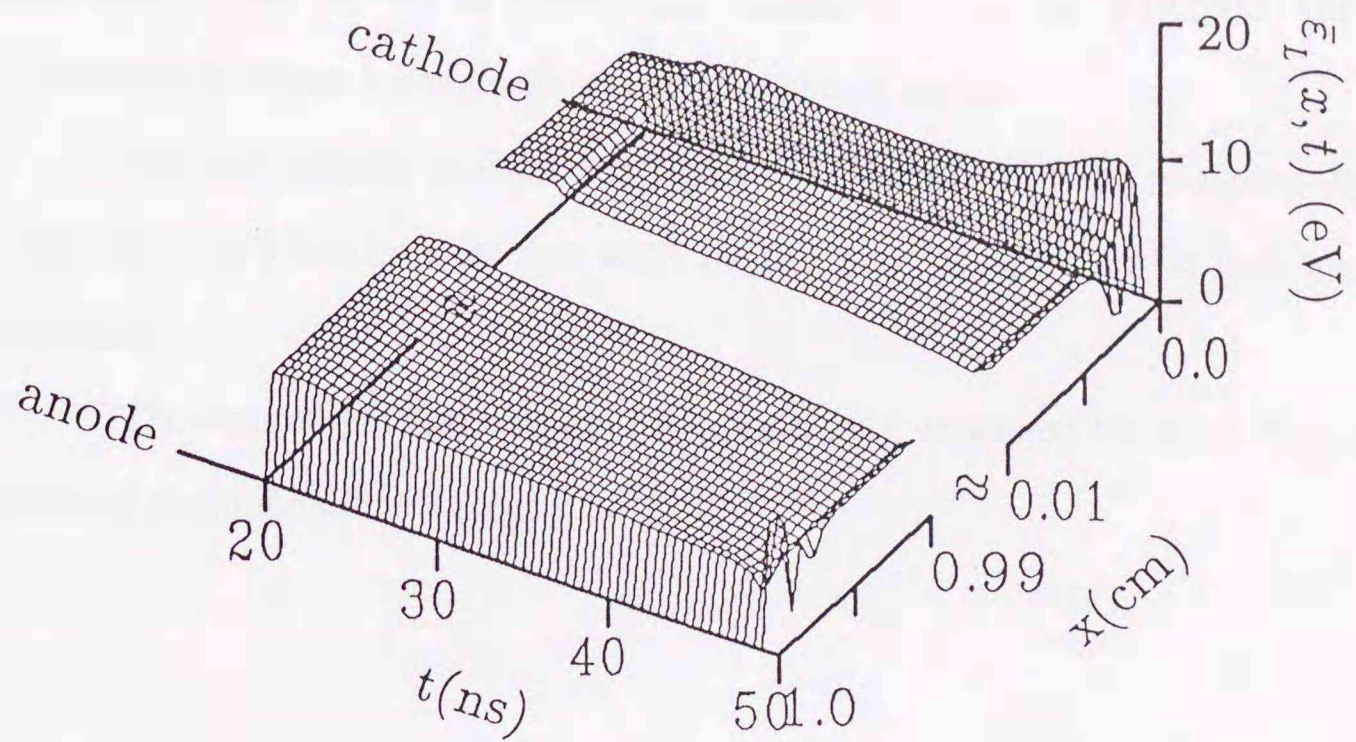


Figure 4.11. Spatio-temporal evolution of the mean electron energy for $\epsilon_L(x, t)$ and $\epsilon_N(x, t)$.

4.3-5 Output of Laser Light

The spatio-temporal evolution of laser output is shown in the figure 4.12. The laser light starts to rise at $t=35\text{ns}$ and reaches its peak at $t=39.5\text{ns}$. The light distribution is almost homogeneous except the sheath region.

Near the cathode as shown in figure 4.7, the second peak of n_{ArF*L} appears with a delay of 1.5ns from the time when the first peak of n_{ArF*L} in the bulk region is obtained.

The laser output in the whole gap consistently explained based on the spatio-temporal evolution of the n_{ArF*L} .

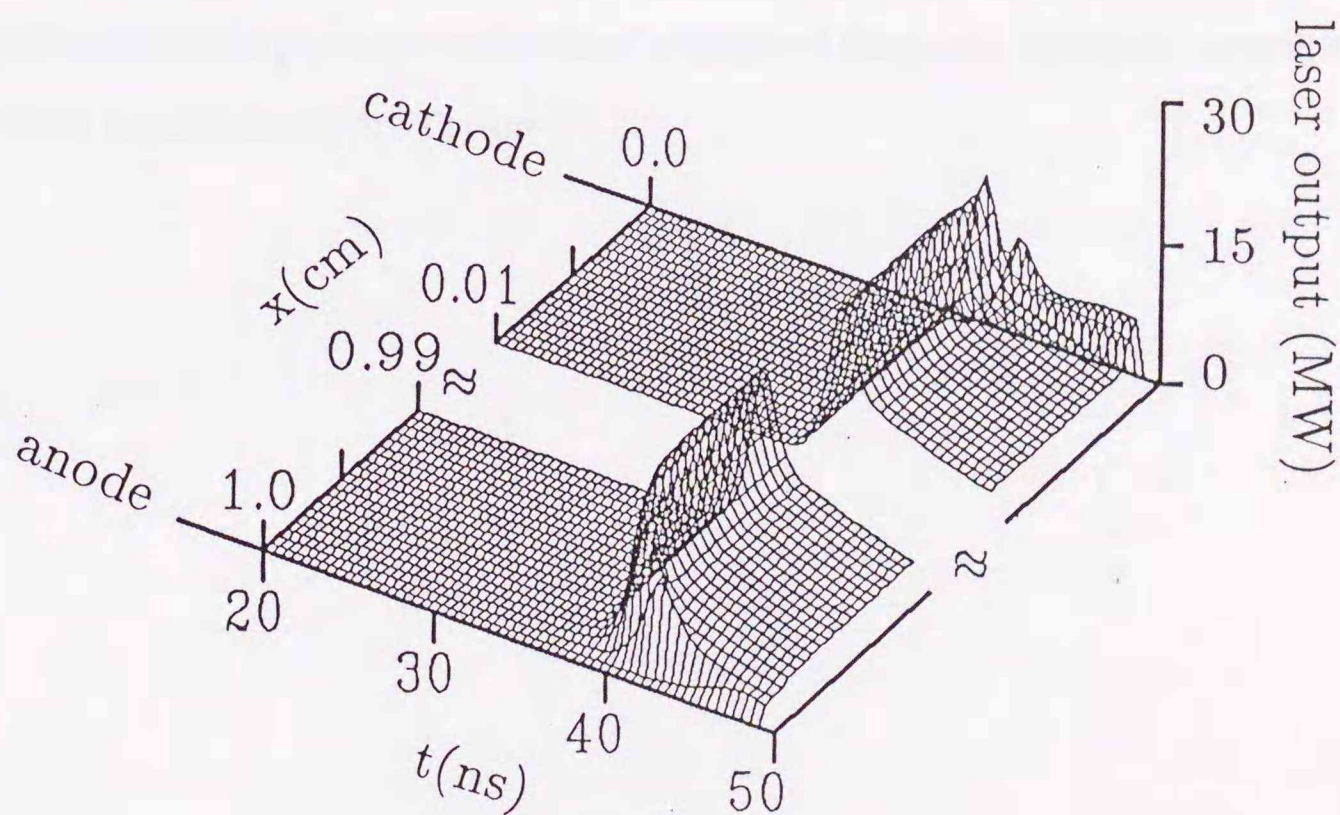


Figure 4.12. Spatio-temporal evolution of the laser output.

4.4 Summary and Remarks

The influence of laser light induced photoionization and photodetachment processes on the discharge development characteristics in a discharge-excited ArF laser was simulated.

The photon processes were shown to influence significantly the spatio-temporal discharge development, such as, n_e being two times larger, n_+ being 1.2 times larger, n_- being 0.7 times smaller, etc than values when the photon processes were neglected.

After the laser output peak appeared, the electric field near the cathode became 1.5 times higher. The electric field near the anode rapidly changed from negative to positive at the end of the discharge.

This higher field distortion may indicate that the phototization and photodetachment processes accelerates initiation of filamental discharge instabilities as shown experimentally by Taylor^[12].

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Chapter 5

Influence of Preionization Uniformity on Discharge Development in an ArF Excimer Laser

5-1 Introduction

The preionization plays an important role in sustaining uniform discharge plasmas in discharge-excited excimer lasers. Non-uniformity of the preionization is reported to be one of the causes which bring discharge instability. The preionization electron density is also one of the important parameters which determine laser power and laser output energy.

In this chapter, the influence of preionization with different values of electron-ion number densities in the direction of parallel to the optical axis on the discharge development is discussed. A comparison between the discharge development under uniform preionization and non-uniform preionization case is examined.

5-2 Simulation Parameters and Conditions

To consider the preionization non-uniformity, a model of the discharge space is shown in figure 5.1. The preionized discharge volume is divided into two region. They are a highly preionized region; n_{e01} and a weakly preionized region; n_{e02} . These regions are treated as a parallel connection of two resistances with different values. Here a n_{e01} value of 10^8cm^{-3} is taken, n_{e02} values of 1 , 2×10^7 , 4×10^7 , 6×10^7 , 8×10^7 and 10^8cm^{-3} are taken.

In the case of the uniform preionization, n_{e0} is changed from 10^6 to 10^9cm^{-3} .

The other simulation parameters and conditions are the same as those in the previous chapters.

non-uniform preionization scheme

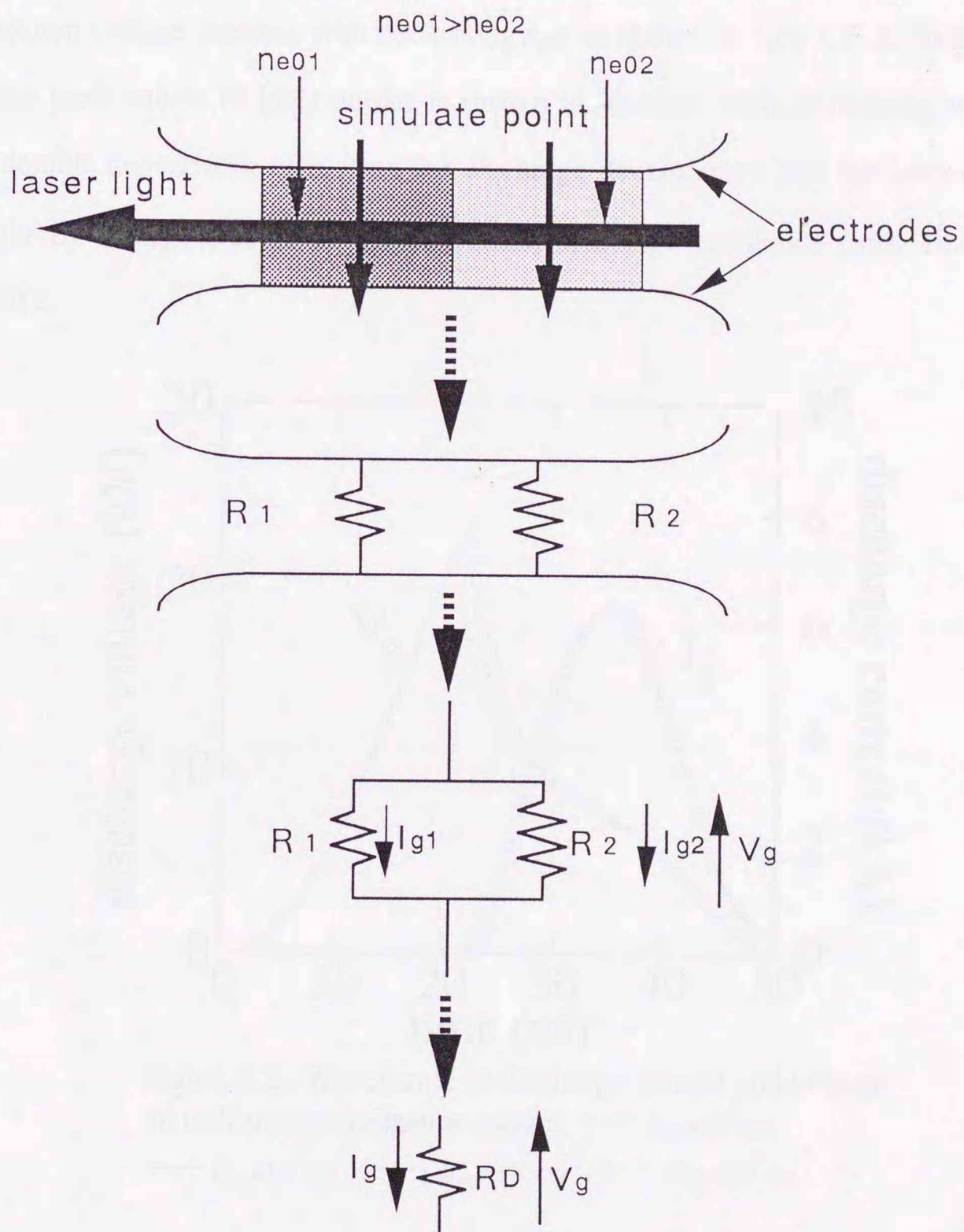


Figure 5.1. Non-uniform preionization model.

5-3 Results and Discussion

5-3-1 Dependence of Uniformly Preionized Electron-ion Pairs

In the uniform preionization model, the peak values of discharge current and the breakdown voltage increase with decreasing n_{e0} as shown in figure 5.2. In the figure 5.3, the peak values of laser output is shown to increase with decreasing n_{e0} . This considerable dependence of n_{e0} on the discharge development and the laser output is brought by a large change of the equivalent discharge resistance from $14.2\text{M}\Omega$ to $14.2\text{G}\Omega$.

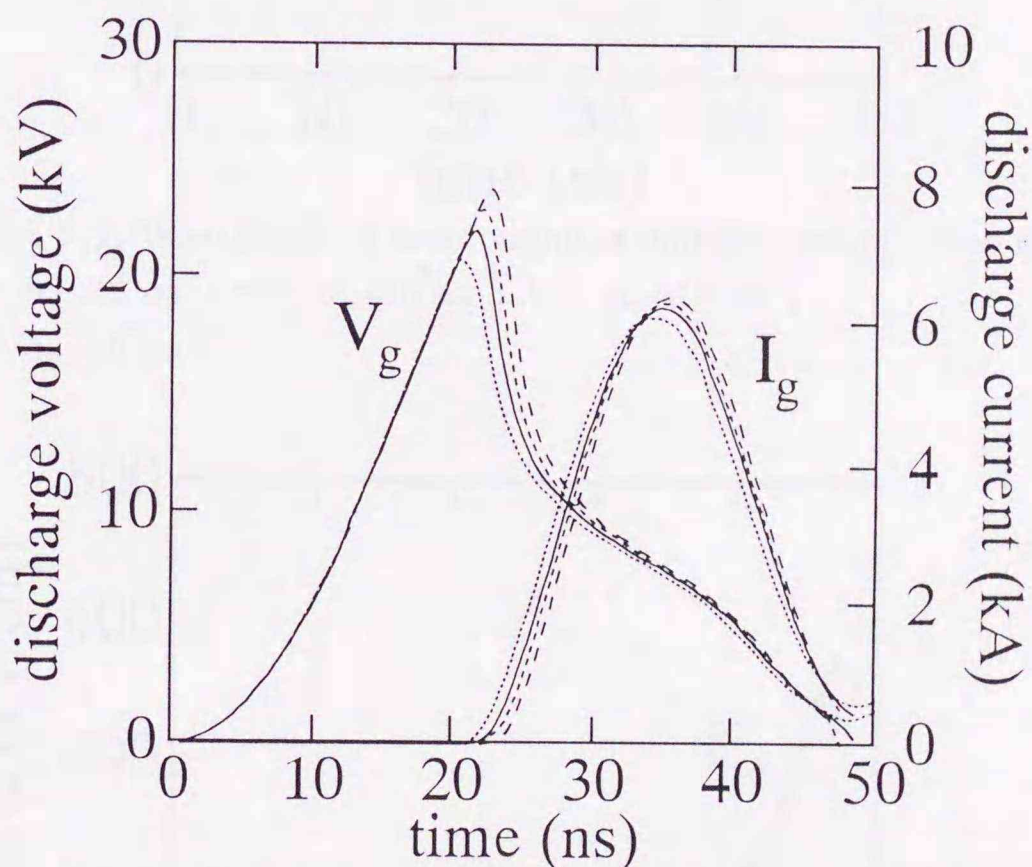


Figure 5.2. Waveforms of discharge current and voltage in uniform preionization model. $n_{e0}=10^9\text{ cm}^{-3}$;
— $n_{e0}=10^8\text{ cm}^{-3}$; - · - $n_{e0}=10^7\text{ cm}^{-3}$; - - - $n_{e0}=10^6\text{ cm}^{-3}$

On the other hand, as shown in figure 5.4, the electric fields near the cathode do not depend on n_{e0} considerably, since for small n_{e0} the additional deposited electric energy before breakdown is consumed almost to raise the electron number density. The electric fields near the anode (Ea) is distorted even for $n_{e0} < 10^8\text{ cm}^{-3}$,

because the applied voltage is very small in this discharge stage as mentioned in chapter 4.

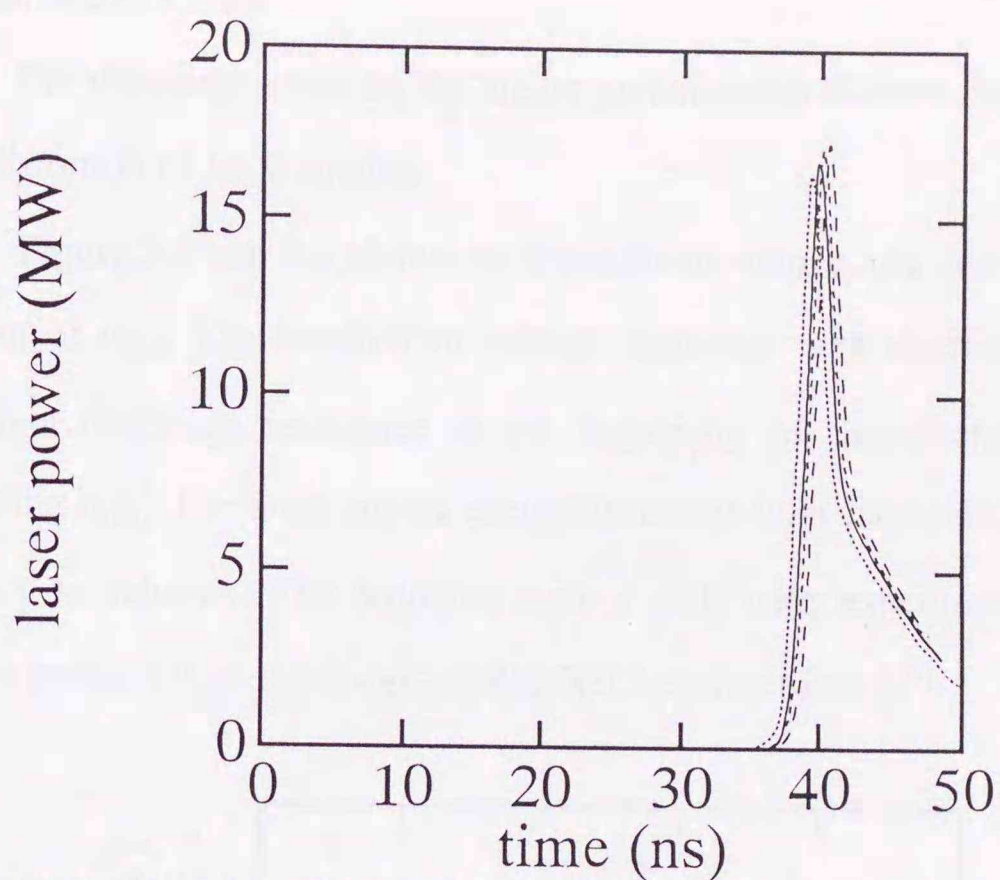


Figure 5.3. Waveforms of laser output in uniform preionization model.

..... $n_{c0}=10^9 \text{ cm}^{-3}$; — $n_{c0}=10^8 \text{ cm}^{-3}$; $n_{c0}=10^7 \text{ cm}^{-3}$;
- - - $n_{c0}=10^6 \text{ cm}^{-3}$

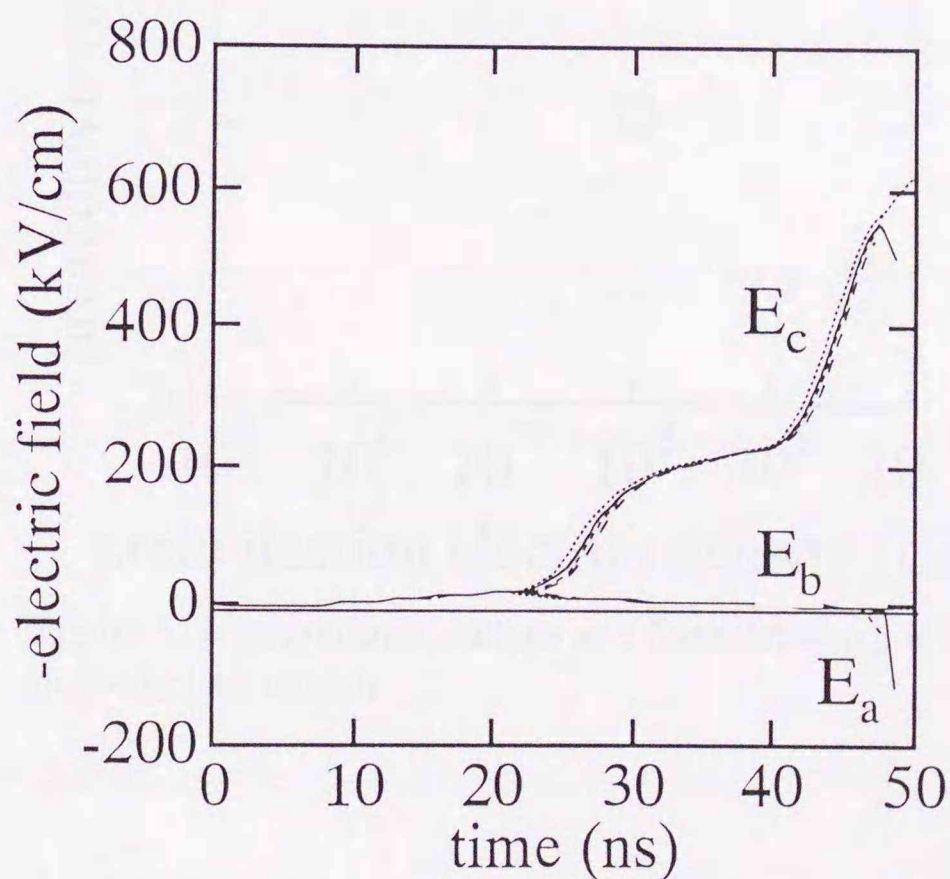


Figure 5.4. Temporal evolution of electric fields in uniform preionization model.

..... $n_{c0}=10^9 \text{ cm}^{-3}$;
— $n_{c0}=10^8 \text{ cm}^{-3}$; $n_{c0}=10^7 \text{ cm}^{-3}$; - - - $n_{c0}=10^6 \text{ cm}^{-3}$

However, in the case of $n_{e0}=10^9\text{cm}^{-3}$, E_a is not distorted because applied voltage does not become zero.

For discharge stability, the higher preionization electron density may be better, since distortion of E_a is smaller.

Figure 5.5 and 5.6 shows the breakdown voltage and laser output energy as a function of n_{e0} . The breakdown voltage increases with decreasing n_{e0} , since the equivalent discharge resistance at the beginning of the discharge increases with decreasing n_{e0} . The laser output energy increases with increasing n_{e0} , and shows a tendency to saturate. This tendency agrees well with experimental results of laser induced preionization discharge-excited XeCl excimer lasers^[5].

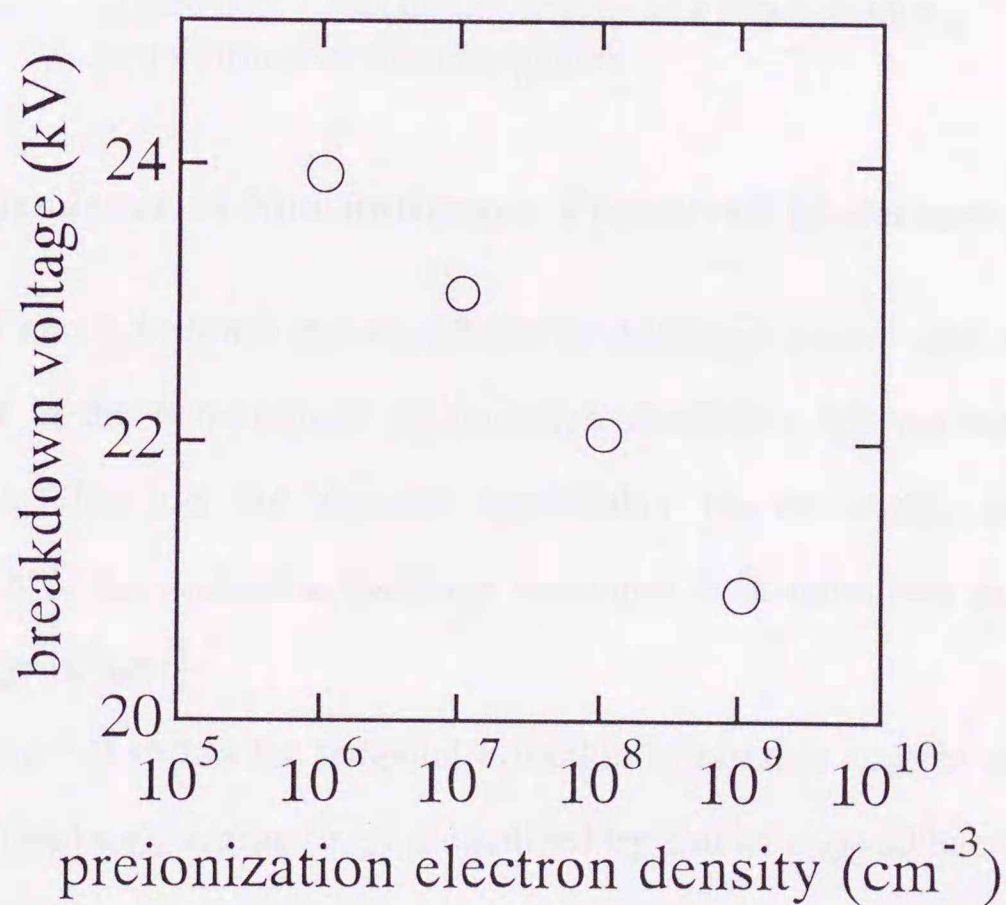


Figure 5.5. Breakdown voltage as a function of n_{e0} in uniform preionization model.

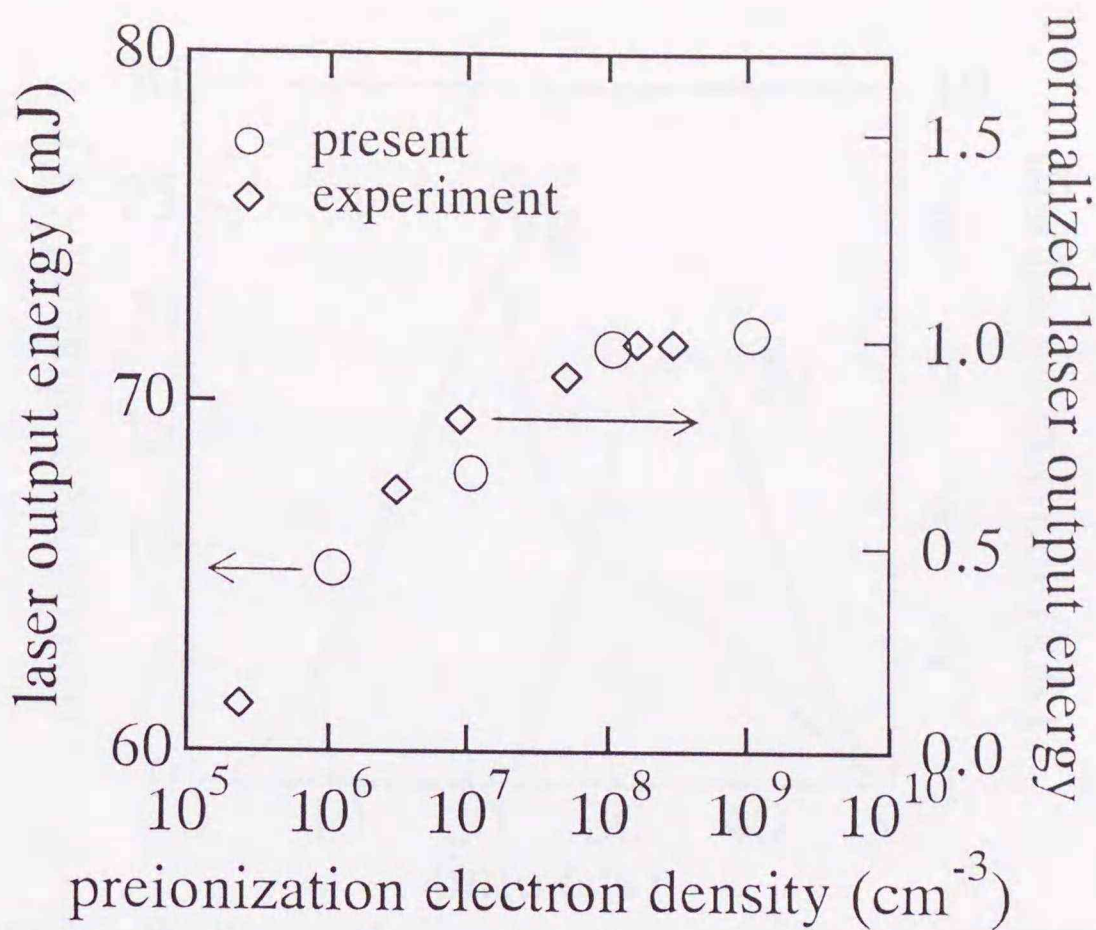


Figure 5.6. Laser output energy as a function of n_{e0} in uniform preionization model.

5-3-2 Dependence of Non-uniformly Preionized Electron-ion Pairs

Figures 5.7 and 5.8 shows the waveforms of discharge current and voltage, and of laser output in the non-uniform preionization conditions for various n_{e02} values, respectively. They do not depend appreciably on the n_{e02} , since even for $n_{e02}=10^0\text{cm}^{-3}$, the equivalent discharge resistance is at most two times larger than that for $n_{e02}=10^8\text{cm}^{-3}$.

Figure 5.9 shows the temporal evolution of electron number density in n_{e01} region (n_{e1}) and n_{e02} region (n_{e2}) normalized by that of $n_{e0}=10^8\text{cm}^{-3}$ case (n_{eu}) in the bulk region for various values of n_{e02} . The n_{e1} is always higher than that of the uniform model, because the discharge voltage is slightly higher than that of the uniform model. In the case of $n_{e02}=10^0\text{cm}^{-3}$, the peak value of n_{e1} becomes two times higher than n_{eu} , since the increase in the breakdown voltage (V_{gb}) makes n_e increase n_{e1} .

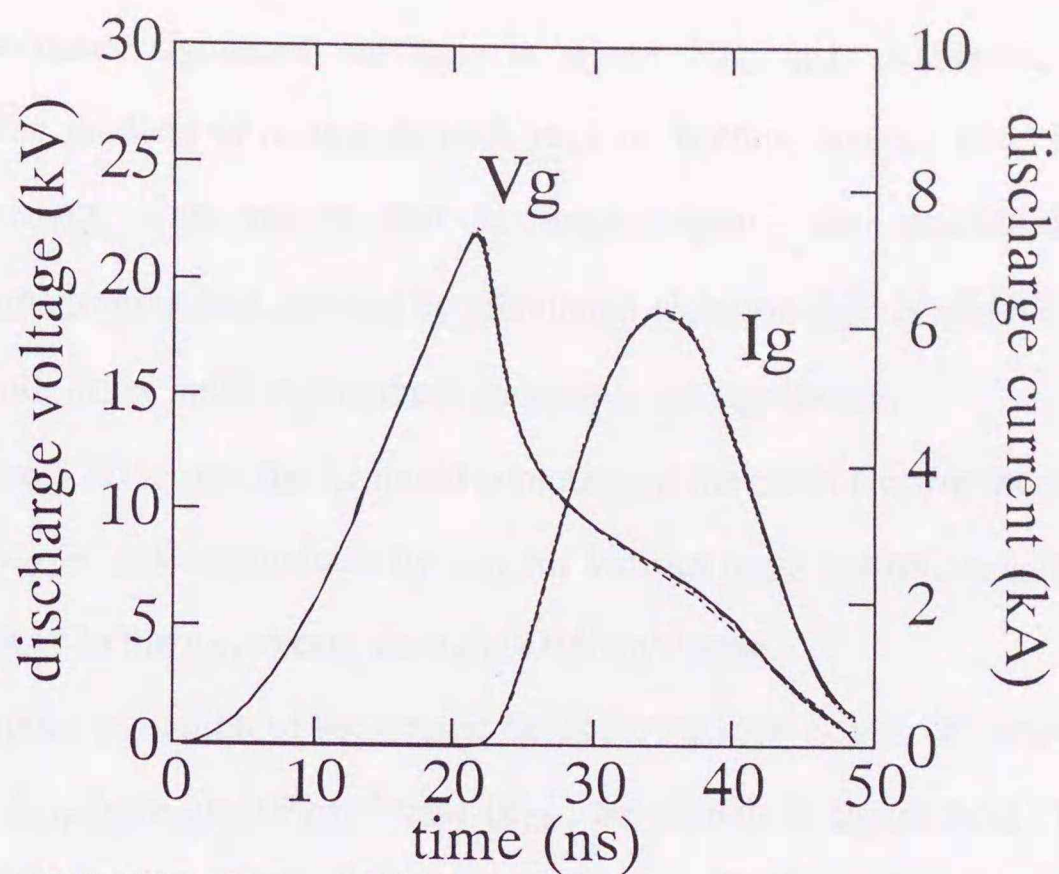


Figure 5.7. Waveforms of discharge current and voltage in non-uniform preionization model. — $n_{e02}=1 \times 10^8 \text{ cm}^{-3}$; $n_{e02}=8 \times 10^7 \text{ cm}^{-3}$; $n_{e02}=6 \times 10^7 \text{ cm}^{-3}$; - - - $n_{e02}=4 \times 10^7 \text{ cm}^{-3}$; — $n_{e02}=2 \times 10^7 \text{ cm}^{-3}$; $n_{e02}=1 \times 10^0 \text{ cm}^{-3}$

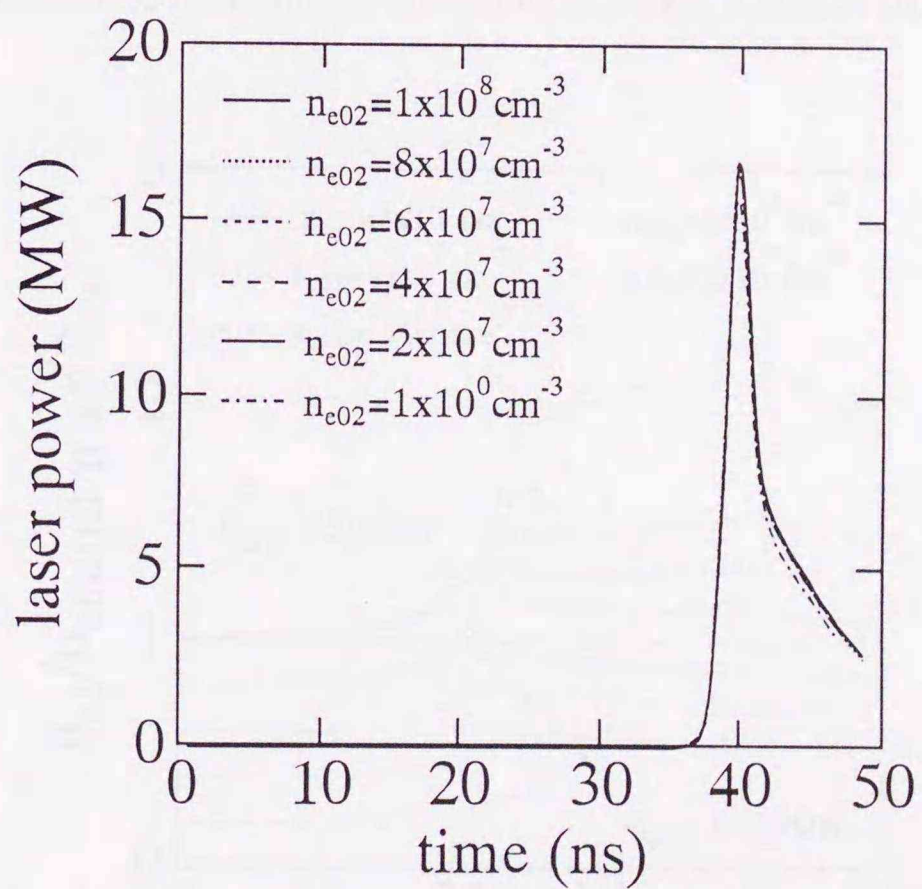


Figure 5.8. Waveforms of laser output in non-uniform model.

The peak value of n_{e2} is about 10^6cm^{-3} . After $t=40\text{ns}$ at which the stimulated emission becomes significant as seen in figure 5.8, n_{e1} decreases, while n_{e2} increases. The gradient of n_e/n_{eu} in both regions become steeper after $t=40\text{ns}$ with decreasing n_{e02} . This means that in n_{e01} region, the photoionization and photodetachment processes induced by stimulated emission light is relatively small, on the other hand, in the n_{e02} region those processes are significant.

Figure 5.10 shows the temporal evolution of the mean electron number density ($n_{em}=0.5 \times (n_{e1}+n_{e2})$) normalized by n_{eu} for various n_{e02} values. n_{em}/n_{eu} behaves in a similar way to the n_{eu} except the $n_{e02}=10^0 \text{cm}^{-3}$ case.

Temporal evolution of the electric fields for various values of n_{e02} normalized by the field E_{cu} for $n_{e0}=10^8 \text{cm}^{-3}$ case (E_{cu}) are shown in figure 5.11. The electric field near the cathode in the n_{e01} region (E_{c1}) increases with decreasing n_{e02} , on the contrary, E_c in the n_{e02} region (E_{c2}) decreases with decreasing n_{e02} . There are two maxima in E_{c1} , the first maximum can be seen at the time when E_{cu} begins to be distorted, the second maximum is around 42ns except $n_{e02}=2 \times 10^7 \text{cm}^{-3}$ case.

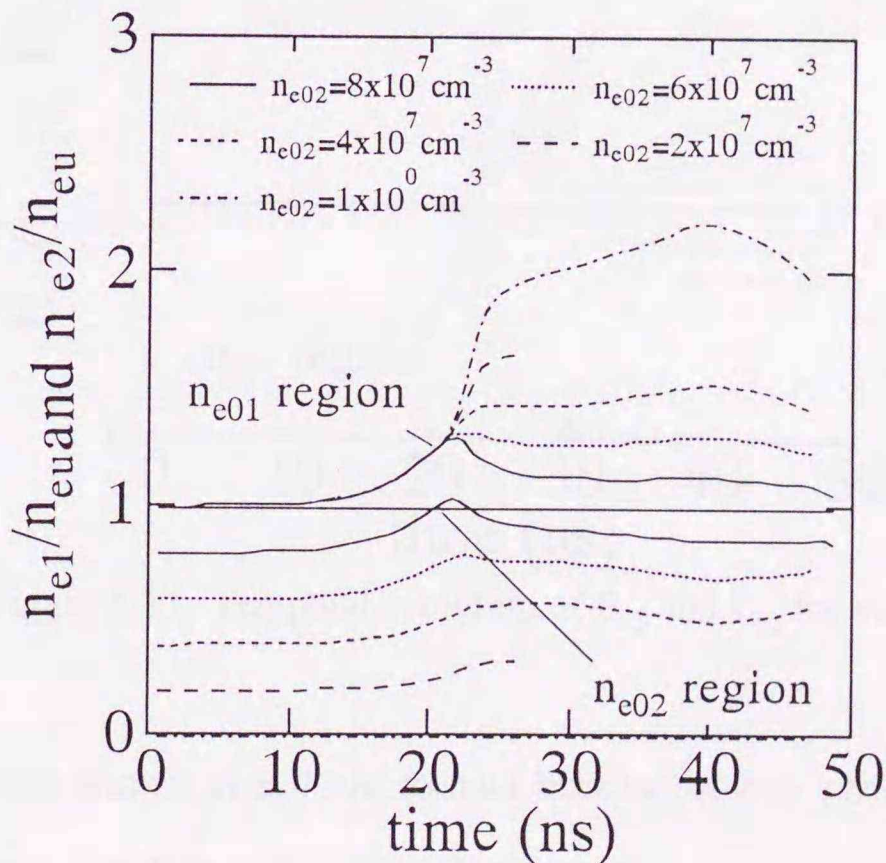


Figure 5.9. Temporal evolution of n_{e1}/n_{eu} and n_{e2}/n_{eu} for various n_{e02} .

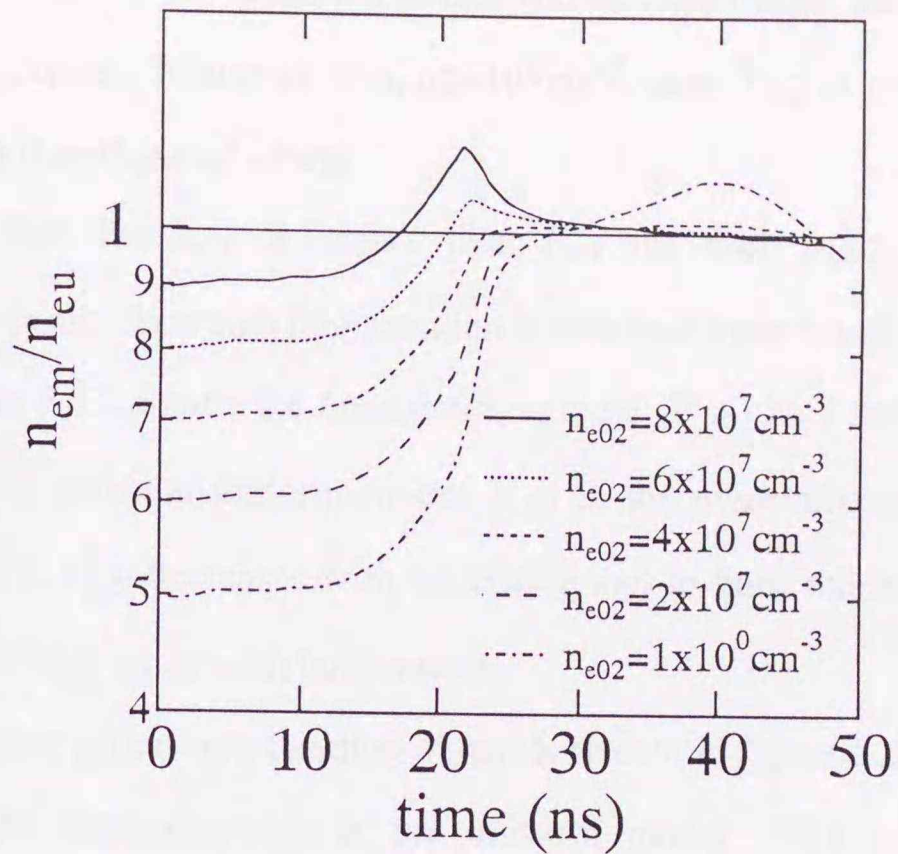


Figure 5.10. Temporal evolution of n_{em}/n_{eu} for various n_{e02} .

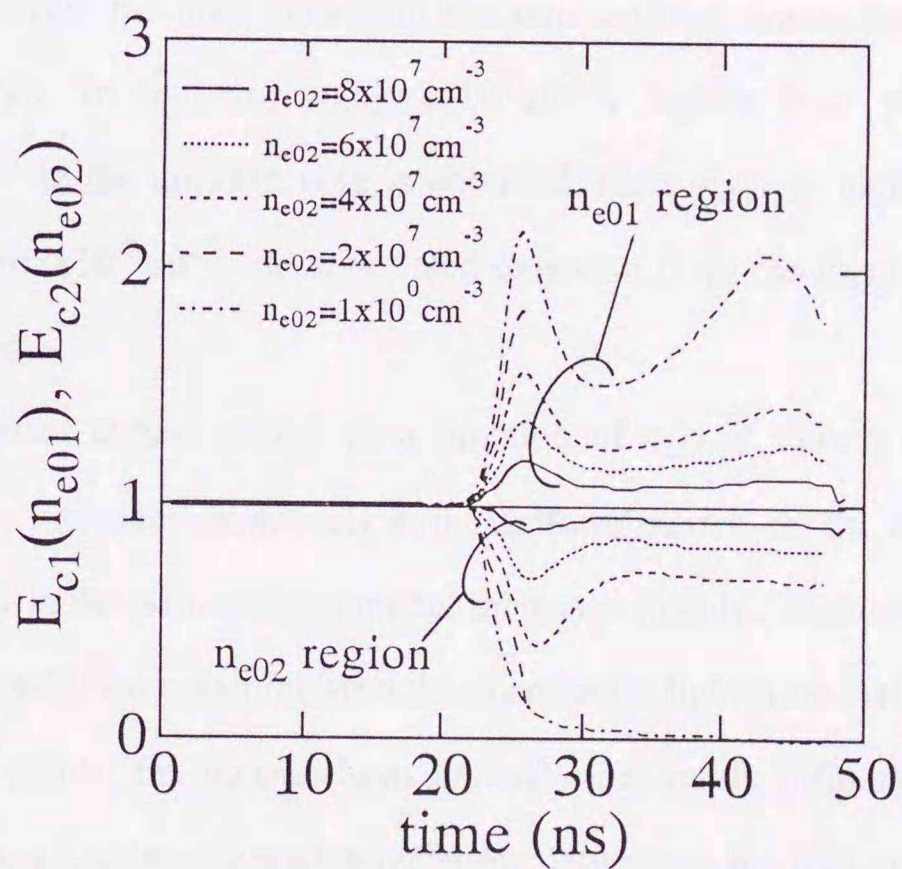


Figure 5.11. Temporal evolution of E_{c1} and E_{c2} for various n_{e02} .

The two maxima shown in E_{c1} are formed because of less photo-electron emission from the cathode than that of E_{cu} case. On the contrary, minimum in E_{c2} is caused by surplus of photo-electron emission from the cathode than that of E_{cu} case. In the case

of $n_{e02}=2 \times 10^7 \text{ cm}^{-3}$, too much photo-electron emission from the cathode makes E_{c2} negative and diverse. However, in $n_{e02}=10^0 \text{ cm}^{-3}$ case, E_{c2} is never distorted highly by lower n_{e2} than those of others.

The fact that E_{c1} is higher than E_{cu} for each n_{e02} value agrees with experimental results in which filamentation is obtained from a well preionized region.

Figure 5.12 shows the breakdown voltage (V_{gb}) as a function of n_{e0} in the uniform model and non-uniform model. n_{e0} in the non-uniform model is given as $(n_{e01}+n_{e02})/2$. V_{gb} decreases with increasing n_{e0} in both models and the values of breakdown voltage agree with both models.

The laser power as a function of n_{e0} is shown in figure 5.13. The laser power decreases with increasing n_{e0} in the uniform model. This is because that V_{gb} decreases with increasing n_{e0} .

However, the laser power in the non-uniform model increases steeply with increasing n_{e0} . In the case $n_{e02} > 2 \times 10^7 \text{ cm}^{-3}$, higher laser power than that for $n_{e0}=10^8 \text{ cm}^{-3}$ in the uniform case is obtained, since n_{em} is higher than n_{eu} . In the case of $n_{e02} < 2 \times 10^7 \text{ cm}^{-3}$, no stimulated emission from the n_{e02} region makes laser power decrease.

The laser output energy as a function of n_{e0} is shown in figure 5.14. The output energy increases moderately in the uniform model, on the other hand, the laser output energy in the non-uniform model increases steeply. Because there are threshold in number density for obtaining stimulated emission light from ArF^* .

As a result, the non-uniform preionization rarely influence on the discharge current, voltage and laser output waveforms. However, the influence on the discharge characteristics such as, the electron number density, electric field, etc., are significant. Especially, the higher non-uniformity which has shown high field distortion at the cathode in the n_{e01} region would lead filamentary discharge instability. Also, the non-uniformity influences to the laser output characteristics significantly and results in the steep decrease of the laser output energy and peak laser power.

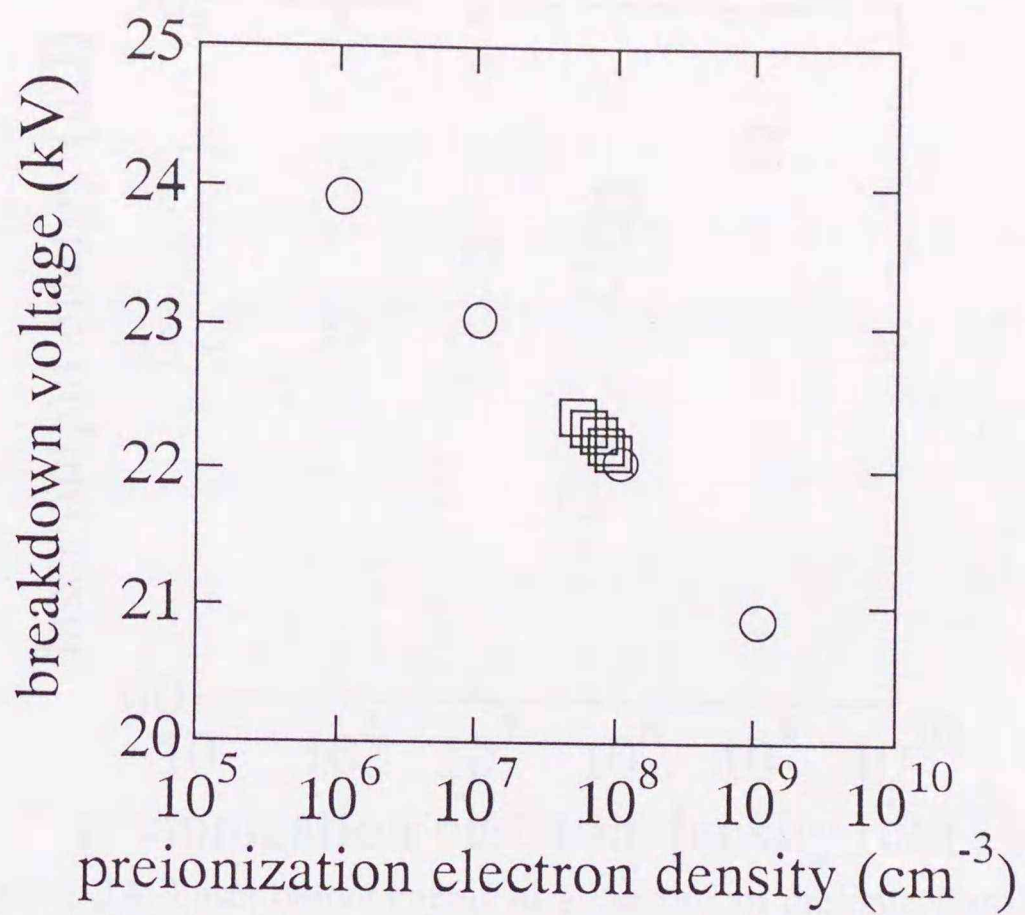


Figure 5.12. Breakdown voltage as a function of preionization densities in non-uniform preionization model.
 ○ uniform model; □ non-uniform model

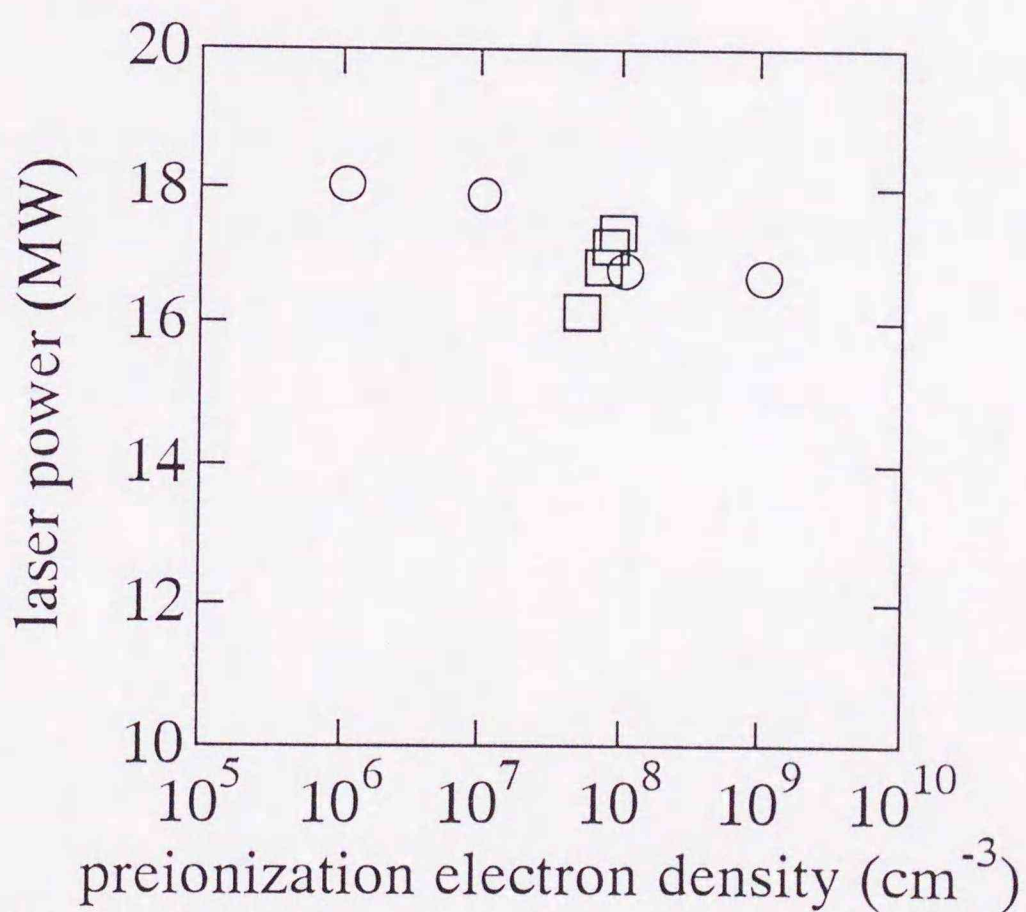


Figure 5.13. Laser power as a function of mean preionization densities in non-uniform preionization model.
 ○ uniform model; □ non-uniform model

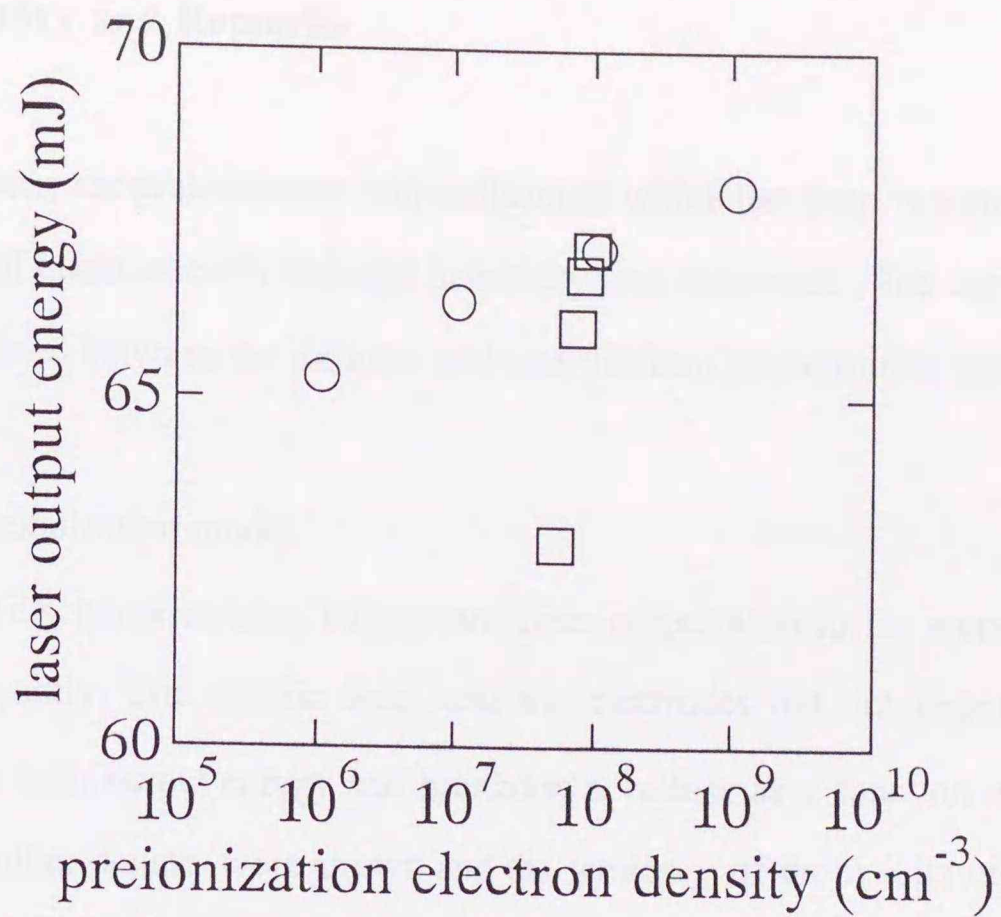


Figure 5.14. Laser output energy as a function of preionization densities in non-uniform preionization model.

○ uniform model; □ non-uniform model

5-4 Summary and Remarks

In this chapter, the preionization non-uniformity which has been reported to be one of the causes of occurrence of discharge instability was discussed. The comparison of the results obtained between the uniform and non-uniform preionization model was made.

Uniform preionization model

The discharge current, voltage and laser output waveforms were influenced by n_{e0} significantly. The electric field near the electrodes did not depend on the n_{e0} values. The laser output energy and breakdown voltage as a function of preionization electron number density were shown and the tendency of the results agreed well with experimental results.

Non-uniform preionization model

The discharge current, voltage and laser output waveforms depended slightly on the n_{e0} values. The electric field near the cathodes in the n_{e0} region was distorted two times larger than that of uniform preionization model. The breakdown voltage as a function of preionization number density agreed with that of the uniform model. It was shown that the laser power and laser output energy increased steeply with increasing n_{e0} .

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Chapter 6

Dependence of Inductance in Excitation Circuit on Discharge Development in an ArF Excimer Laser

6-1 Introduction

Values of inductance in excitation circuits, i.e., a charge-transfer circuit, are one of the important parameters^[1,2], when a laser device is constructed. It is important to find a suitable value of inductance for lasers and to understand how the discharge develops.

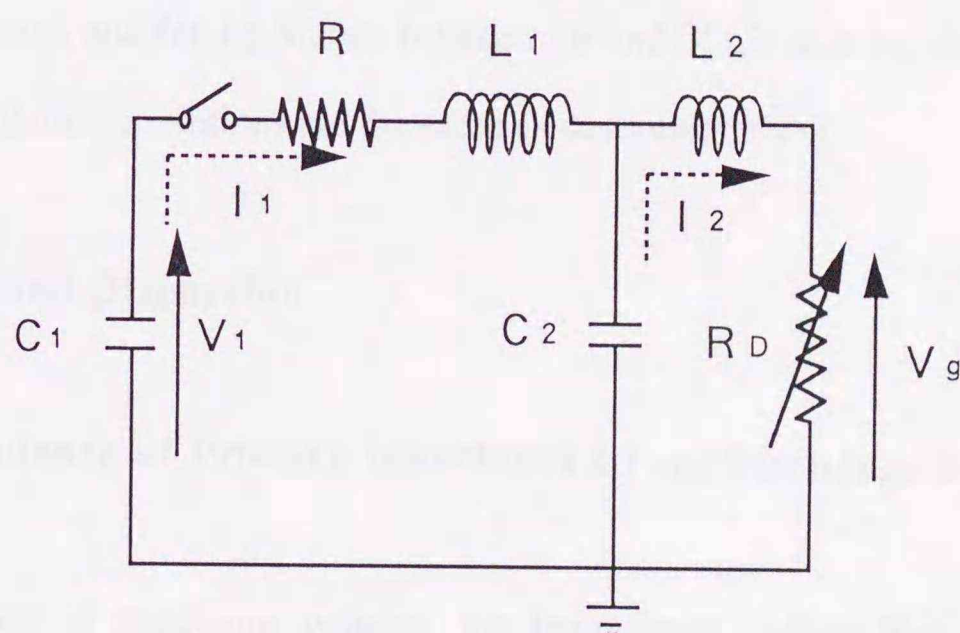


Figure 6.1. Charge-transfer excitation circuit

Primary and secondary inductance L_1 and L_2 in a charge-transfer excitation circuit is shown in figure 6.1. The L_1 determines the risetime of an excitation voltage waveform. It is known that when the risetime gets longer, the breakdown voltage and laser output energy of an ArF laser become lower. A typical value of L_1 is reported to be a several hundreds nH, this is because that a thyatron, switching device for the laser excitation circuit has already a few hundred nH inductance. It is known that the fast risetime results in production of high laser output energy. Therefore, there are

many efforts of reducing L_1 value. Recently, the L_1 in a charge-transfer circuit is reported to be reduced till 100nH . By the present simulation, we predicted the laser performance for L_1 values <100nH.

Secondary inductance L_2 in a charge-transfer circuit is also important, because L_2 determines the time of the plateau region in which uniform glow discharge can be sustained in the discharge voltage waveform. It is known that a large value of L_2 gives the longer plateau region in a discharge voltage waveform.

6-2 Simulation Conditions

In this chapter, a simulation is carried out for values of L_1 from 10nH to 800nH at a L_2 value of 20nH, and for L_2 values between 10 and 30nH at a L_1 value of 100nH. The other simulation conditions are the same as described in 2-5

6-3 Results and Discussion

6-3-1 Dependence of Primary Inductance L_1 on Discharge Development

The waveforms of discharge voltage, the breakdown voltage(V_{gb}) and voltage risetime (the time given at V_{gb}) as a function of L_1 are shown in figure 6.2 and 6.3, respectively. V_{gb} and risetime decreases and delays with increasing L_1 as shown in figure 6.2. The circles in the discharge waveforms show the time when the discharge current reaches its maximum. The voltage values at the circles are almost the same, 7.7kV ($E/p_0=4V/cm/Torr$; $N_{Ark_{ia}}+N_{Ark_{si}}+N_{Ark_{ia}}-N_{F2k_a}=0$). As shown in figure 6.3, V_{gb} decreases with increasing L_1 for small L_1 values. The risetime becomes longer exponentially with increasing L_1 .

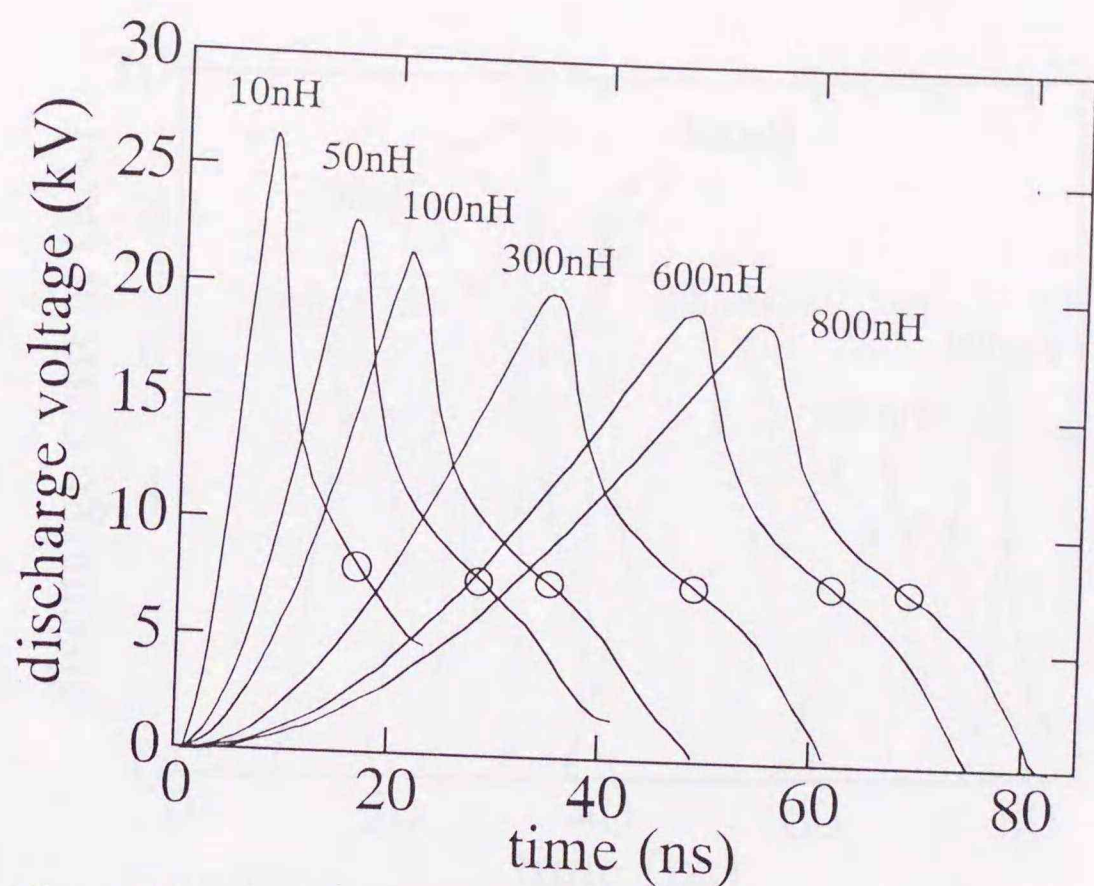


Figure 6.2. Waveforms of discharge voltage for various L_1 values.
 ○ shows the time when the discharge current becomes maximum.

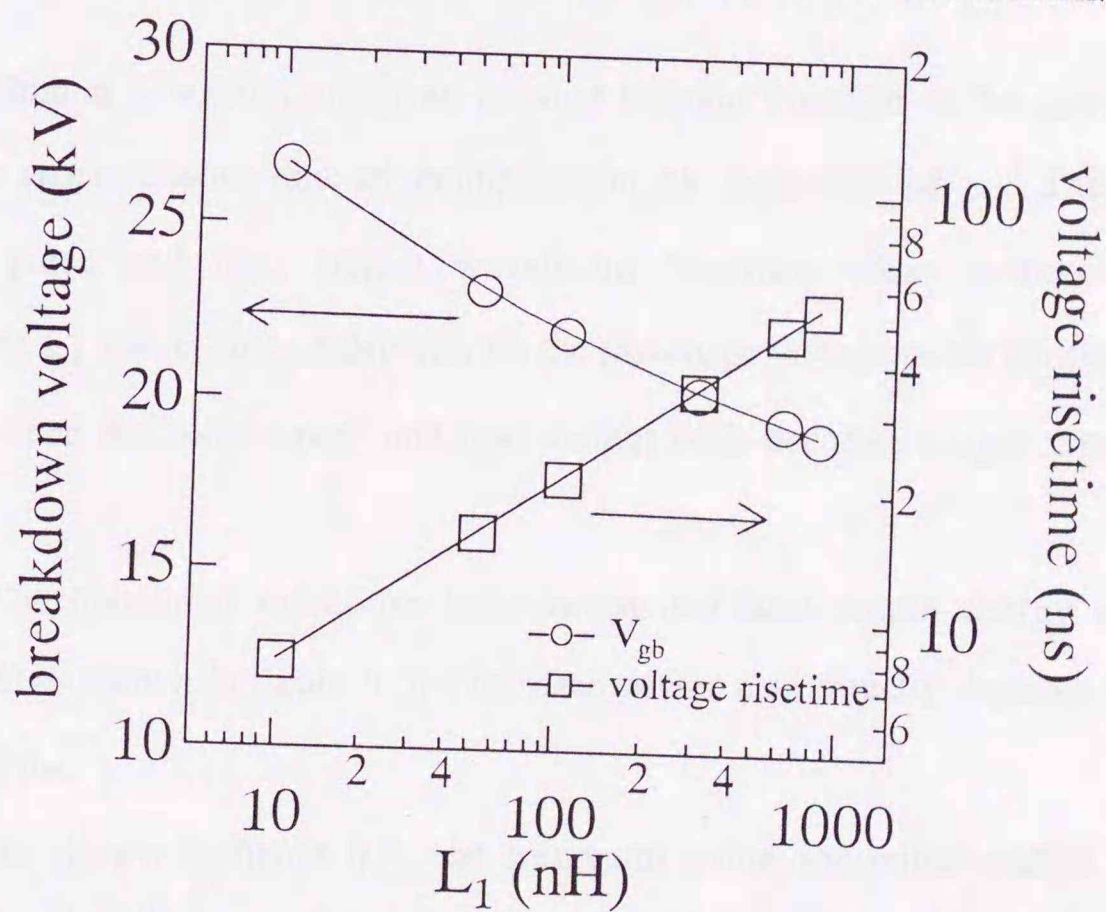


Figure 6.3. Breakdown voltage and voltage risetime as a function of L_1 .

Figure 6.4 shows the waveforms of discharge current and laser output. The maximum peak values of current and laser output is given at $L_1=50\text{nH}$, though the breakdown voltage decreases monotonously with increasing L_1 .

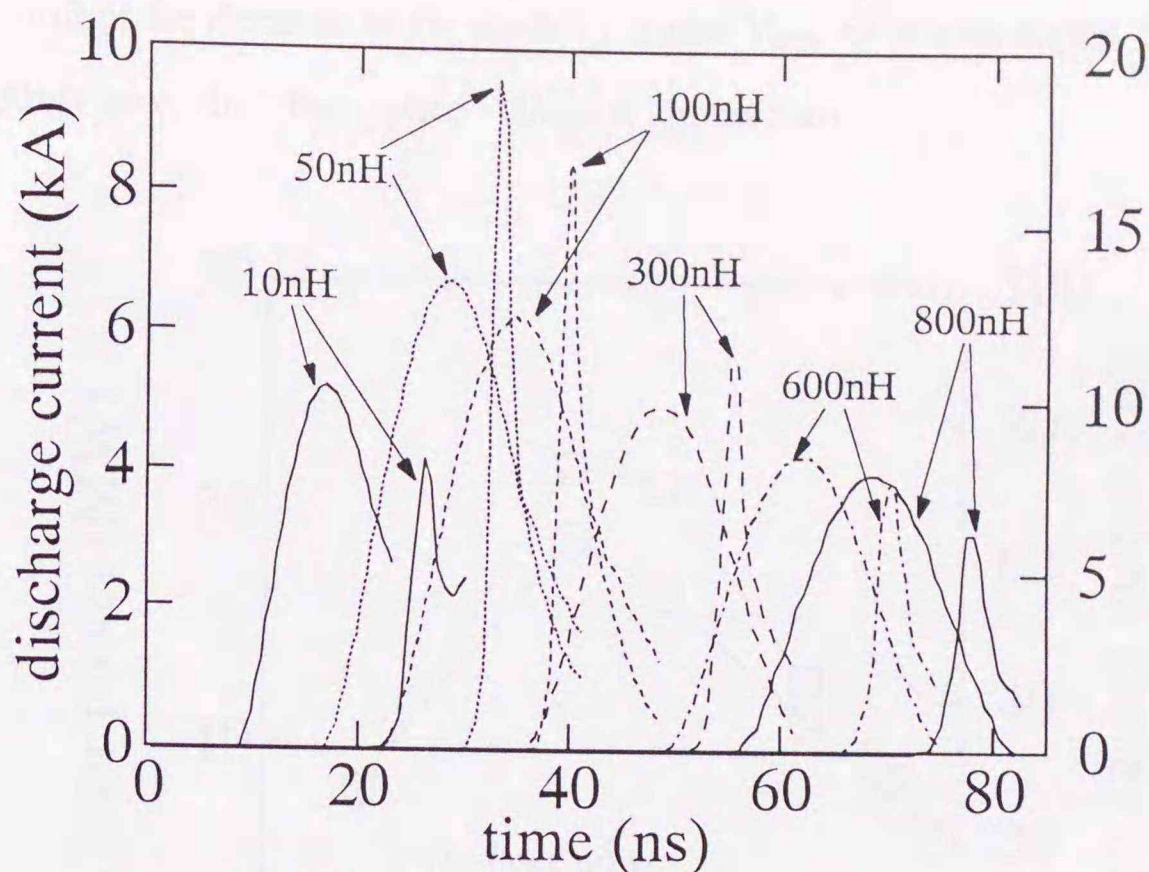


Figure 6.4. Waveforms of discharge current and laser output for various L_1 values.

The maxima at $L_1=50\text{nH}$ are given because the time constant of the circuit is shorter than the characteristic time of multiplication by ionization of n_e . The FWHM of current pulse and laser output waveforms becomes wider monotonously with increasing L_1 value, since it depends on the discharge voltage pulse widths. The delay time between the current peak and laser output peak becomes longer with increasing L_1 .

The maximum values for laser power and laser output energy are given at $L_1=50\text{nH}$ as shown in figure 6.5. The laser power also directly depends on the peak values of n_e .

As shown in figure 6.6, the minimum value for pulse widths is given at $L_1=50\text{nH}$. It increases with increasing L_1 for $L_1>50\text{nH}$. The pulse width for $L_1=10\text{nH}$ is almost the same as that for $L_1=50\text{nH}$, though the discharge current pulse at $L_1=10\text{nH}$ is narrower than that for $L_1=50\text{nH}$.

Figure 6.7 shows the temporal evolution of the electric field for various L_1 values. The peak values of E_c also take a maximum at $L_1=50\text{nH}$. Because of the

strong drift of the electrons to the anode by higher V_{gb} . E_a is also highly distorted for $L_1 > 100\text{nH}$ case, since the applied voltage is almost zero.

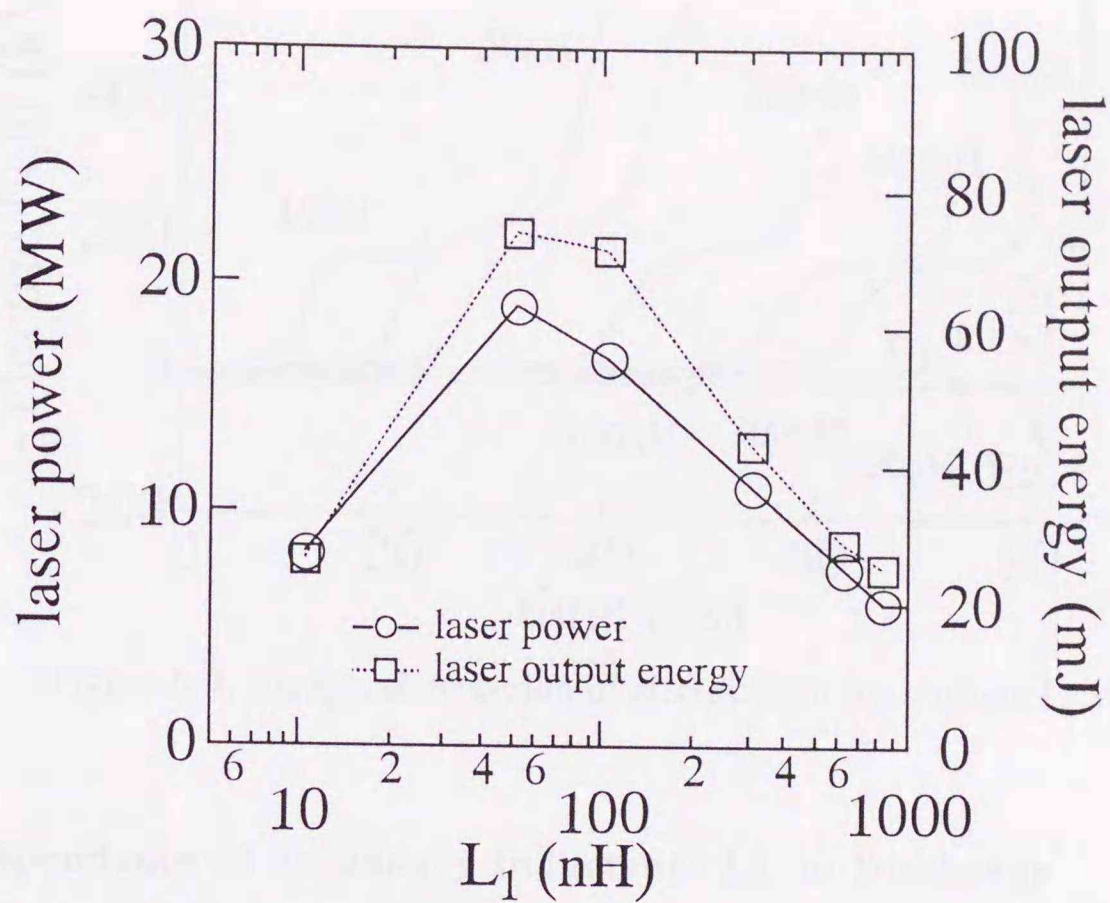


Figure 6.5. Laser power and laser output energy as a function of L_1 .

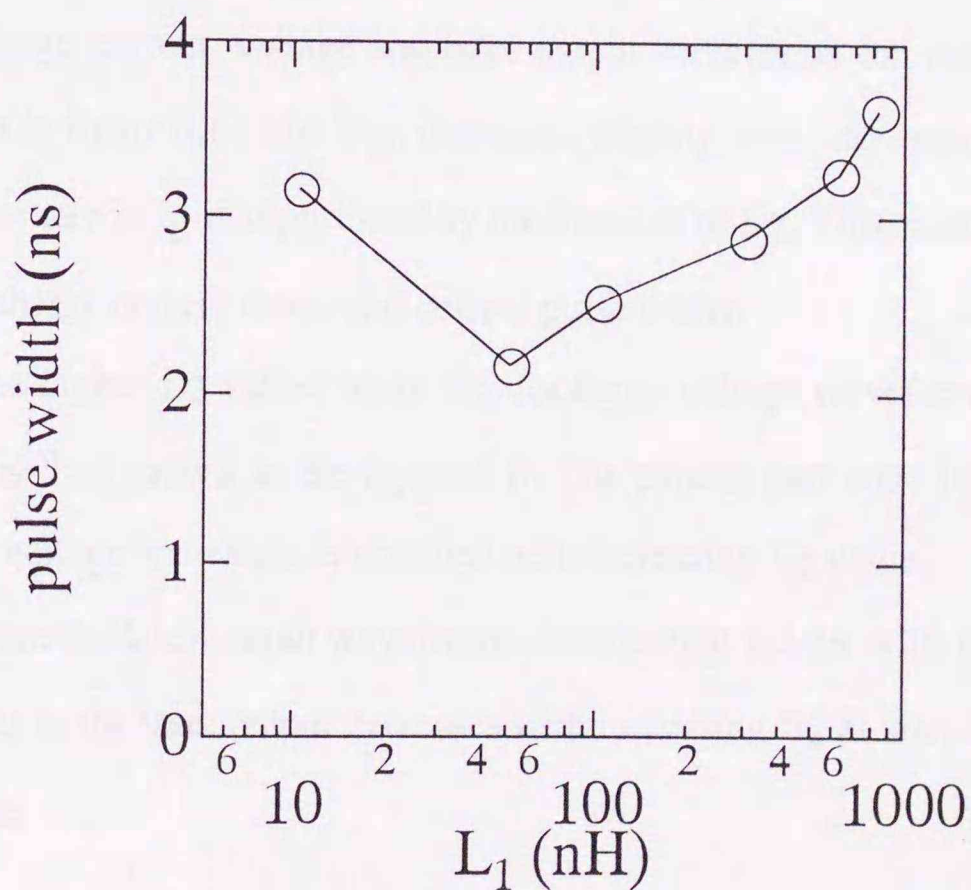


Figure 6.6. Laser pulse width (FWHM) as a function of L_1 .

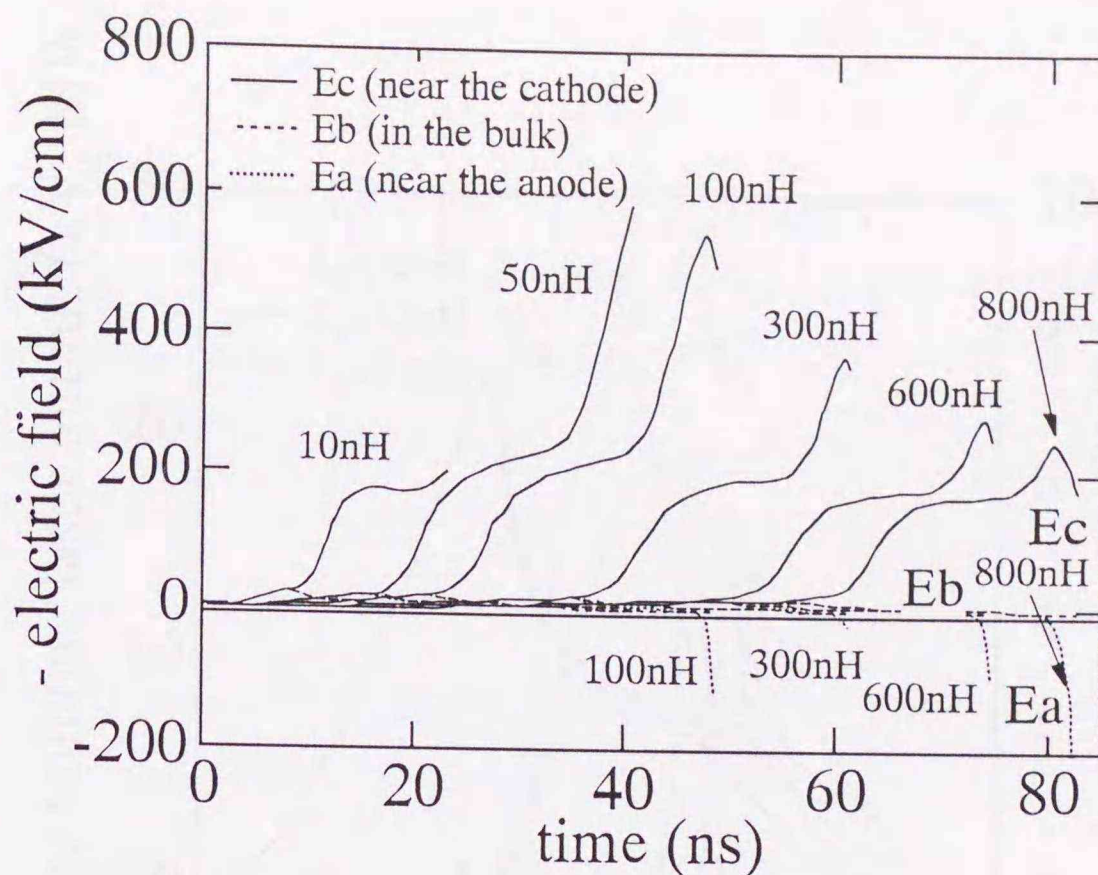


Figure 6.7. Temporal evolution of electric field for various L_1 values.

6-3-2 Dependence of Secondary Inductance L_2 on Discharge

Development

The discharge current, voltage and laser output waveforms for various values of L_2 are shown in figure 6.8. The V_{gb} decreases slightly with increasing L_2 values, since the increase rate in I_g is suppressed by the increase of L_2 . This makes the peak values of the discharge current lower and current pulse wider.

The higher L_2 values make the discharge voltage waveforms longer after the breakdown^[2] as shown in the figure 6.8. The plateau part with 10ns duration in the discharge voltage waveform is obtained with increasing L_2 value.

From the laser output waveforms, laser output delays with increasing L_2 . The peak values in the laser output decreases with increasing L_2 as well as the current peak value does.

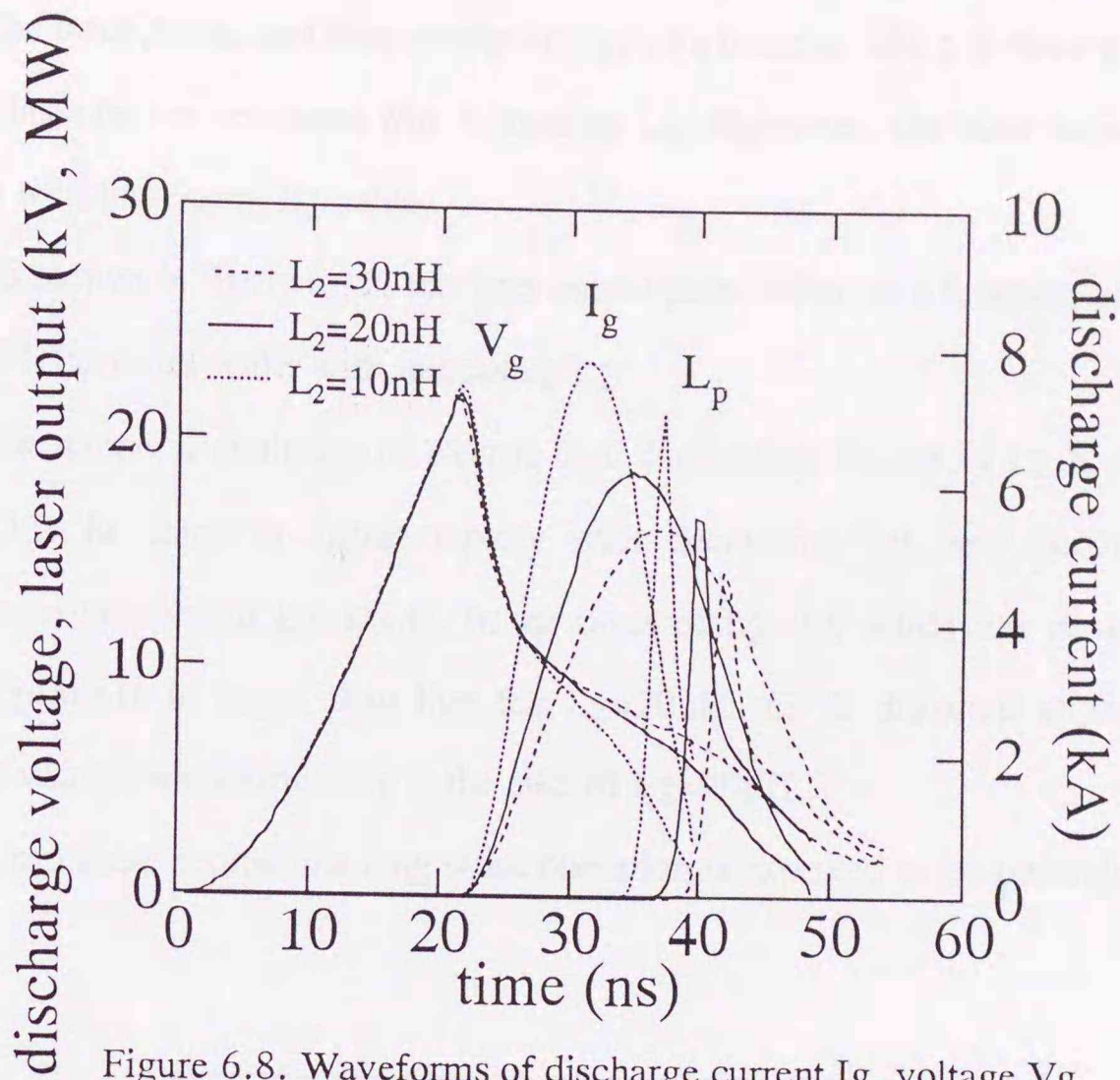


Figure 6.8. Waveforms of discharge current I_g , voltage V_g and laser output L_p .

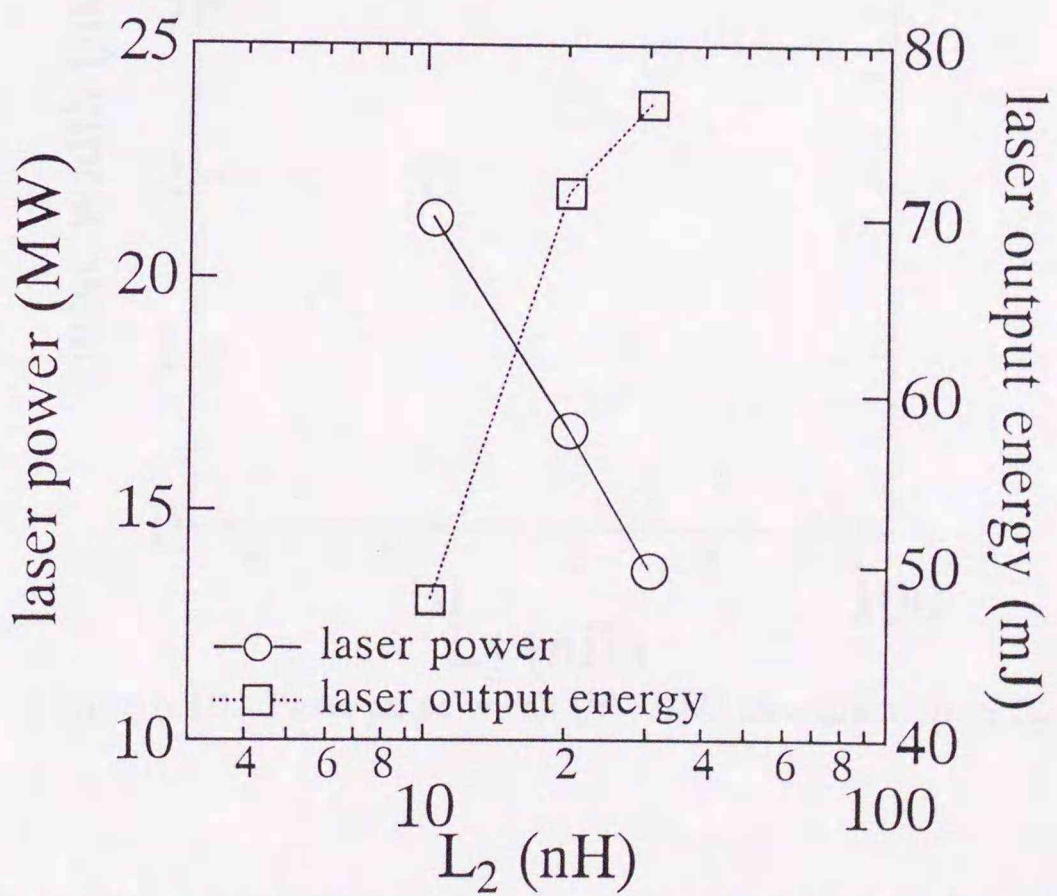


Figure 6.9. Laser power and laser output energy as a function of L_2 .

The laser power and laser output energy as a function of L_2 is shown in figure 6.9. The laser power decreases with increasing L_2 . However, the laser output energy increases with increasing L_2 value.

As shown in figure 6.10, the laser output pulse width as a function of L_2 . The pulse width becomes wider with increasing L_2 .

The temporal evolution of electric field for various values of L_2 is shown in figure 6.11. E_c starts to distort rapidly with decreasing L_2 , and becomes over 10^3 kV/cm in the case of $L_2=10 \text{ nH}$. In the cases of $L_2=20, 30 \text{ nH}$, the peak value of E_c for $L_2=30 \text{ nH}$ is larger than that for $L_2=20 \text{ nH}$. E_a is distorted at the end of discharge voltage waveform only in the case of $L_2=20 \text{ nH}$.

From these results, the long pulse operation is expected to be possible if L_2 is large.

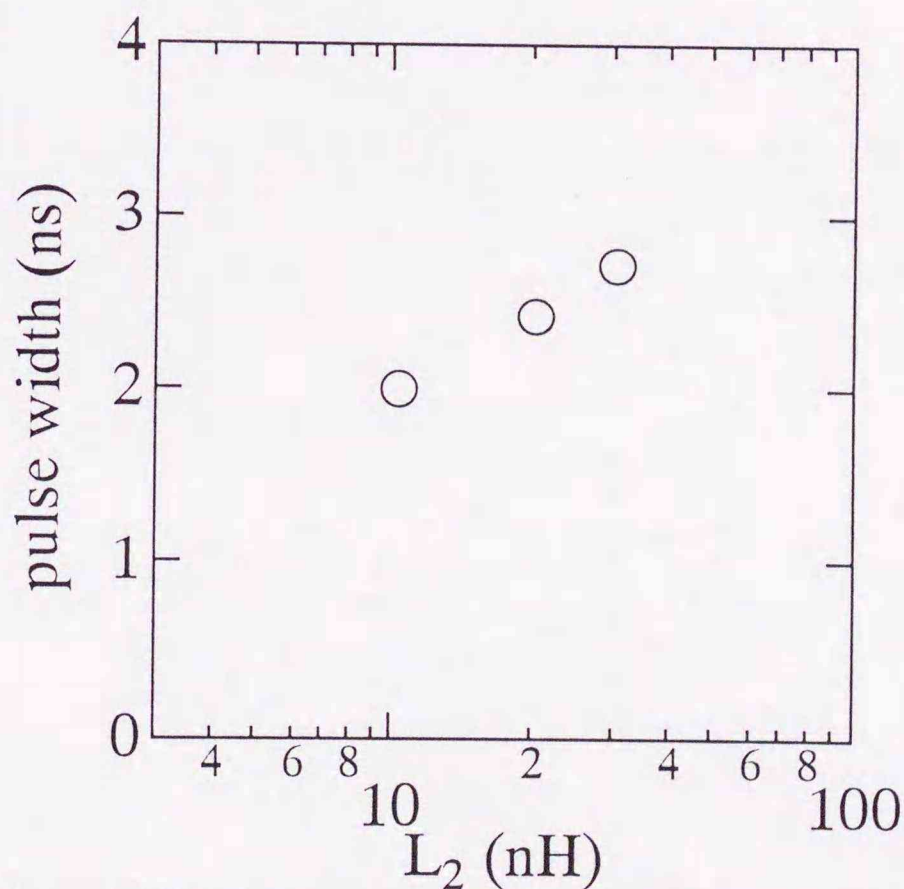


Figure 6.10. Laser pulse width (FWHM) as a function of L_2 .

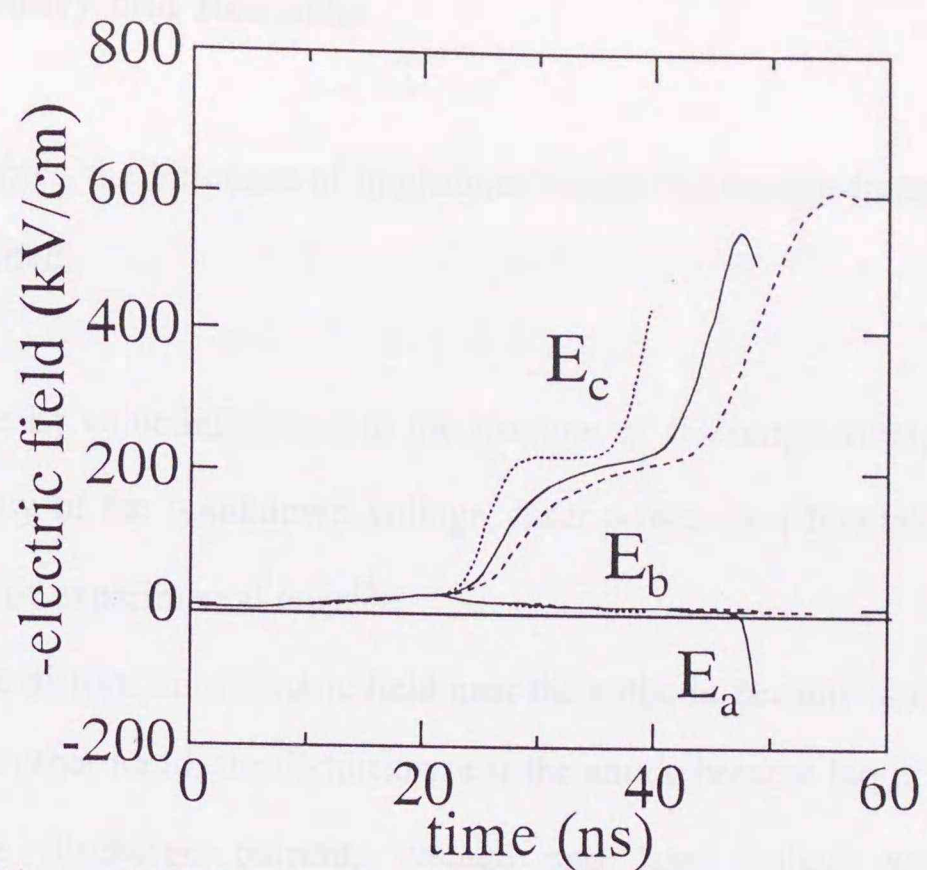


Figure 6.11. Temporal evolution of electric fields for different L_2 .
 $L_2=30\text{nH}$; — $L_2=20\text{nH}$; -.- $L_2=10\text{nH}$

6-4 Summary and Remarks

In this chapter, the influence of inductance values in a charge-transfer excitation circuit was examined.

The L_1 value influenced to the risetime of discharge voltage significantly, and the tendency of the breakdown voltage, laser power as a function of L_1 agreed with the results of experimental ones^[3].

The distortion of electric field near the cathode became smaller with increasing L_1 . On the other hand, the distortion near the anode became larger with increasing L_1 .

The discharge current, voltage and laser output waveforms after the breakdown were influenced significantly by values of L_2 . The laser pulse width became longer with increasing L_2 .

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Chapter 7

Simulation of Self-sustained Discharge Development in a XeCl Excimer Laser

7-1 Introduction

Many theoretical analyses^[1-5] and experimental works^[6-9] of XeCl excimer lasers have been done as mentioned in chapter 1. XeCl excimer lasers have many features. To obtain oscillations is easy, since discharge plasma in excitation media is comparatively stable compared to other excimer lasers. Hydrochloride (HCl) is used as a Cl⁻ seed so that erosion of a cavity wall, electrode, etc. is smaller. High efficiency is expected and high-repetition operation is possible. However, the discharge kinetics are not yet understood well. Because there are many reaction processes between hydrochloride and other gases in high pressures. In a zero-dimensional model, these kind of reactions are included and their rate coefficients are estimated^[1-5]. Many of rate coefficients are, however, still not known and there are significant differences even in the known rate coefficient values among researches^[1-5].

Recently, in experiment, higher-repetition operation, longer-pulse operation are performed, but the discharge instability appears to be a serious problem. So, simulation of a XeCl excimer laser discharge in a multi-dimensional model is demanded to know the discharge development. However, operation of XeCl excimer lasers is usually performed in the pressures higher than that of the other excimer lasers. This high pressure leads many troubles when numerical calculation is performed.

In this chapter, the present fluid model developed for ArF lasers is applied to a XeCl excimer laser, and discharge development behavior is examined. Discharge development in a XeCl excimer laser is compared with that for ArF lasers.

7-2 Simulation Conditions

The reactions included in the model is listed in Appendix. The simulation conditions are $L_1=1000\text{nH}$, $L_2=10\text{nH}$, V_1 at $t=0$ is 15kV , $\gamma_p=2\times 10^{-3}$ and $\gamma_i=0.1$. The discharge volume is 135cm^3 or $1\text{cm}(d)\times 90\text{cm}(l_g)\times 1.5\text{cm}(\text{discharge width})$. The other conditions are the same as described in 2-5

7-3 Results and Discussion

7-3-1 Waveforms of Discharge Current and Voltage

Figure 7.1 shows the waveform of discharge current and voltage. As shown in chapters 3 and 4, these waveforms are typical ones in discharge-excited excimer lasers with a charge-transfer circuit. The present L_2 is such a small value so that the plateau part in a discharge waveform is very short and applied voltages should be longer than those for ArF excimer laser. In XeCl excimer lasers, excitation time necessary for obtaining enough XeCl^* number density to oscillate is longer and the applied voltage is lower than ArF excimer laser, since, the ionization threshold of Xe atom is lower than that of Ar and the drift velocity of electrons are faster than that in ArF plasma. The electron attachment cross section for HCl is smaller than that for F_2 . Therefore, the preionized electrons are not lost so fast by electron attachment as seen in ArF discharges (see figure 7.2).

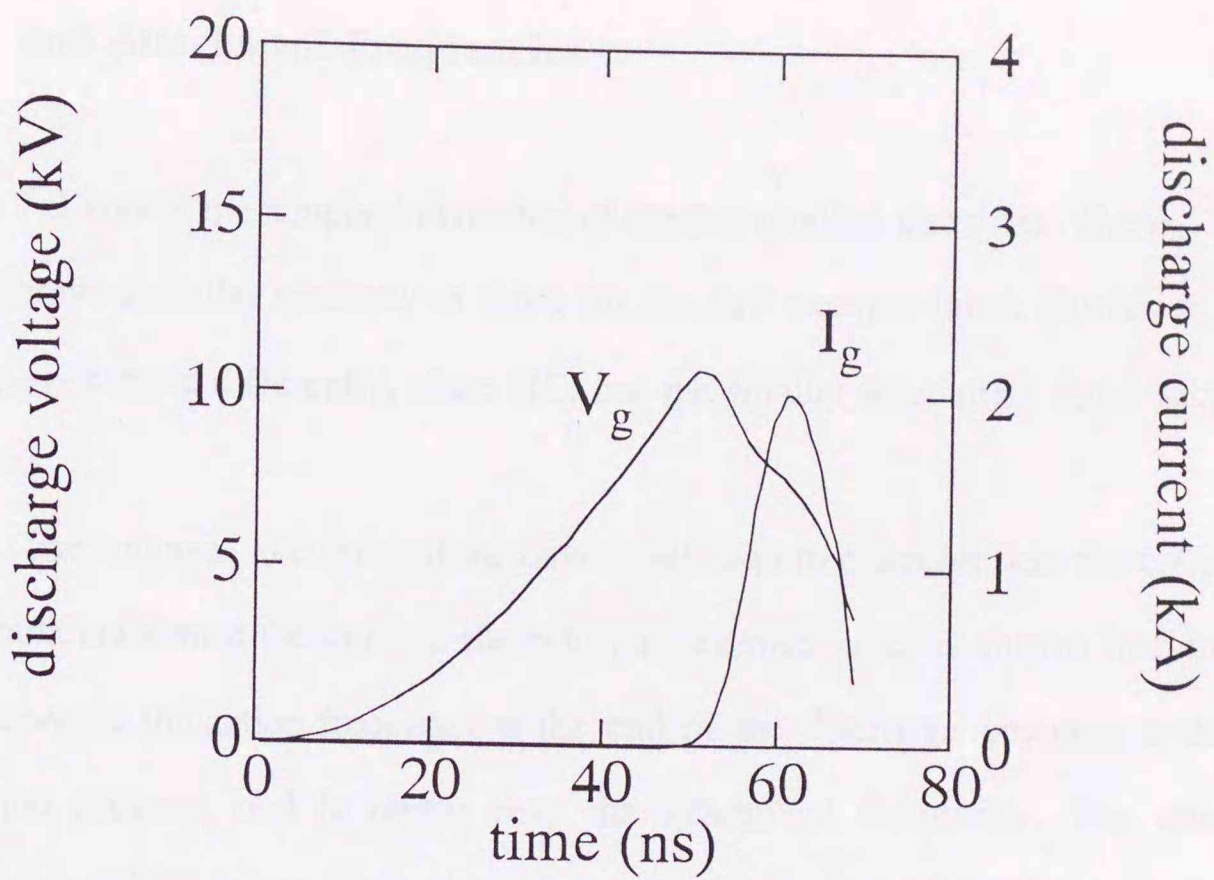


Figure 7.1. Waveform of discharge current and voltage.

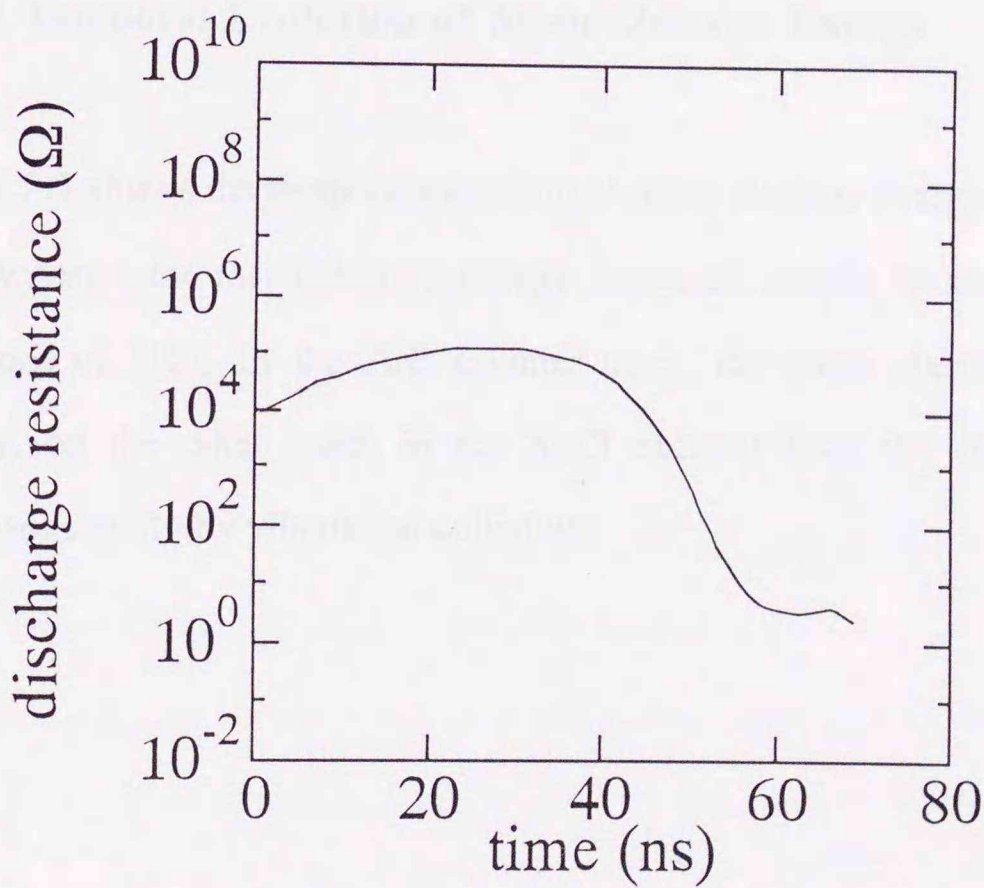


Figure 7.2. Temporal evolution of the discharge resistance.

7-3-2 Temporal Evolution of Species Number Densities and Ionization and Attachment Frequencies

Figure 7.3 shows the temporal evolution of species number densities. The n_e , n_+ and n_{Xe^*} shows a similar tendency to those for the ArF excimer laser. However, the n_- , and n_{XeCl^*} behave differently, since HCl has the smaller attachment cross section for electrons.

The temporal evolution of the direct ionization frequencies near the cathode and in the bulk are almost the same as those in ArF excimer laser as shown in figure 7.4. The step-wise ionization frequency at the end of the discharge becomes a dominant ionization process, and is higher than the attachment frequency. The attachment frequency of HCl in the beginning of the discharge is slightly different from the behavior in ArF excimer laser.

7-3-3 Temporal Evolution of Mean Electron Energy

Figure 7.5 shows the temporal evolution of mean electron energy. In the beginning of the discharge, the mean electron energy decreases rapidly because of the vibrational collisions of HCl. In the ArF excimer laser, the mean electron energy decreases slowly, on the other hand, in the XeCl excimer laser the mean electron energy decreases rapidly by vibrational collisions.

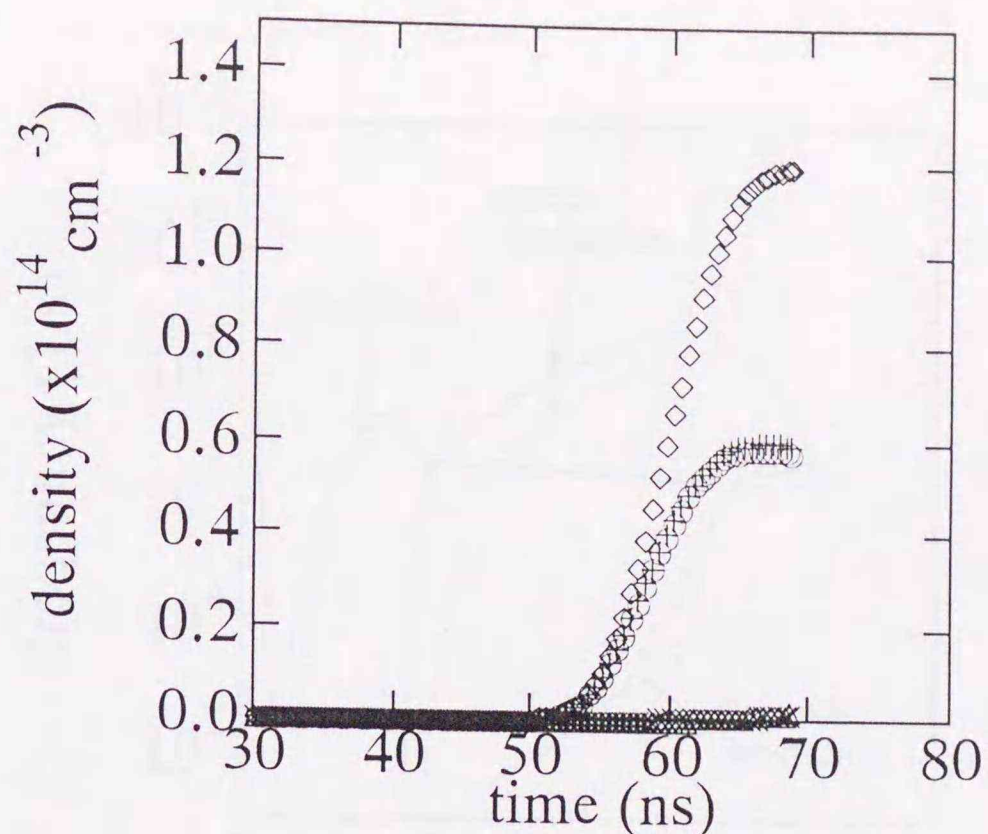


Figure 7.3. Temporal evolution of the species number densities.
 $\circ$: n_e , $+$: n_+ , $\times$: n_- , $\diamond$: n_{Xe^*} , $\triangle$: n_{XeCl^*} .

7.3-4 Temporal Evolution of Electric Field

Figure 7.6 shows the temporal evolution of electric field and number density of secondary electrons emitted from the cathode. The electric field near the cathode (E_c) is distorted higher than that of the ArF excimer laser, although the electron number density is lower than those in the ArF excimer laser. This means that the sheath length of cathode in XeCl laser is longer than that in the ArF excimer laser. At the end of the discharge, n_{ep} decreases with decreasing applied voltage, on contrary, n_{ei} increases. This increase makes the discharge at the end stable. The n_- is lower than that in the ArF excimer laser so that the secondary electron emission in the end of the discharge plays a very important role in suppressing the electric field distortion.

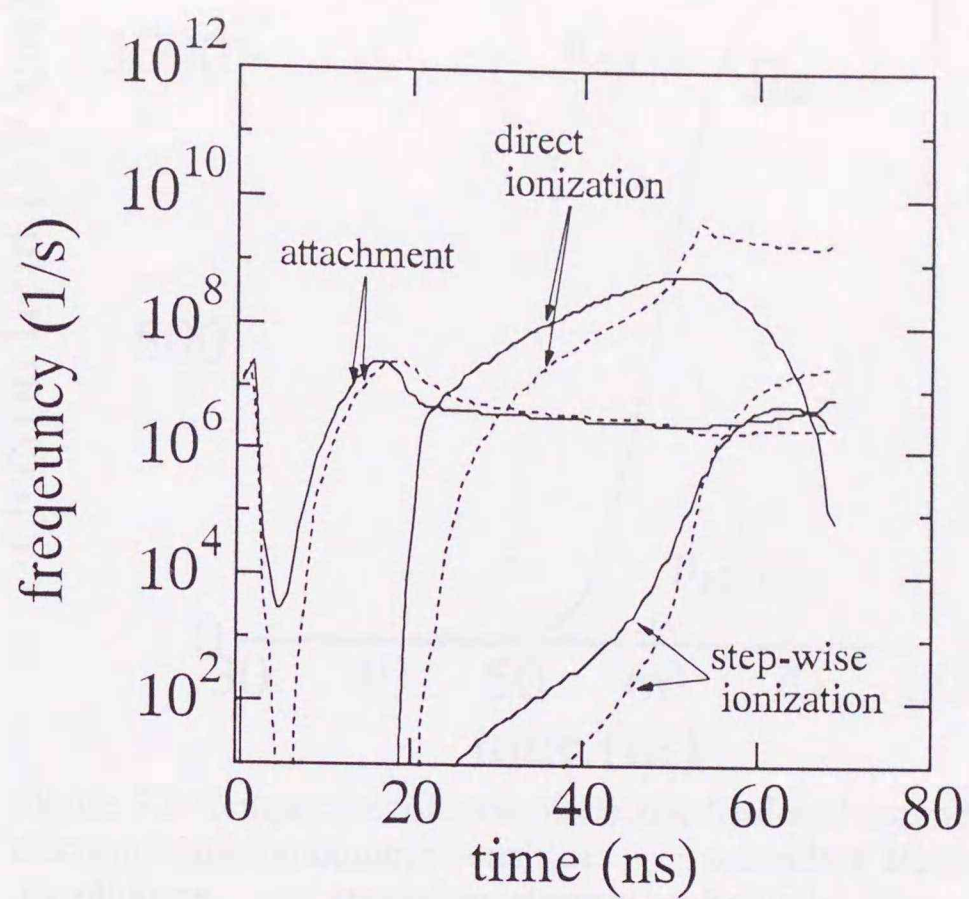


Figure 7.4. Temporal evolution of the ionization and attachment frequencies.
 near the cathode, — in the bulk.

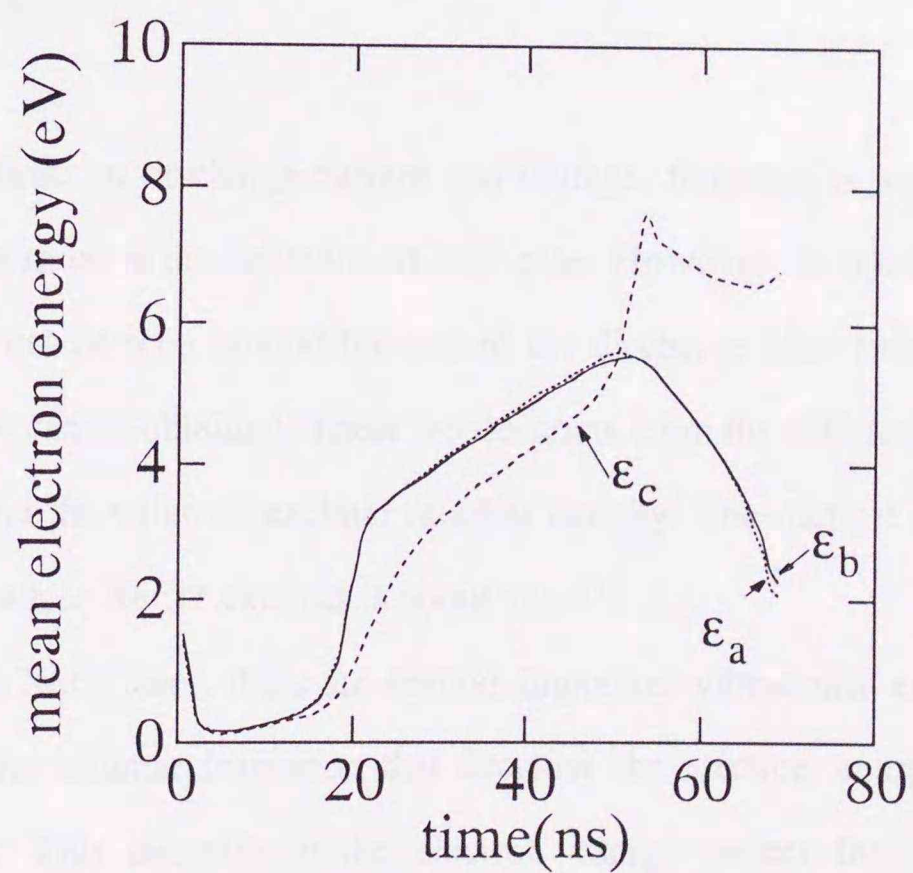


Figure 7.5 Temporal evolution of the mean electron energy.

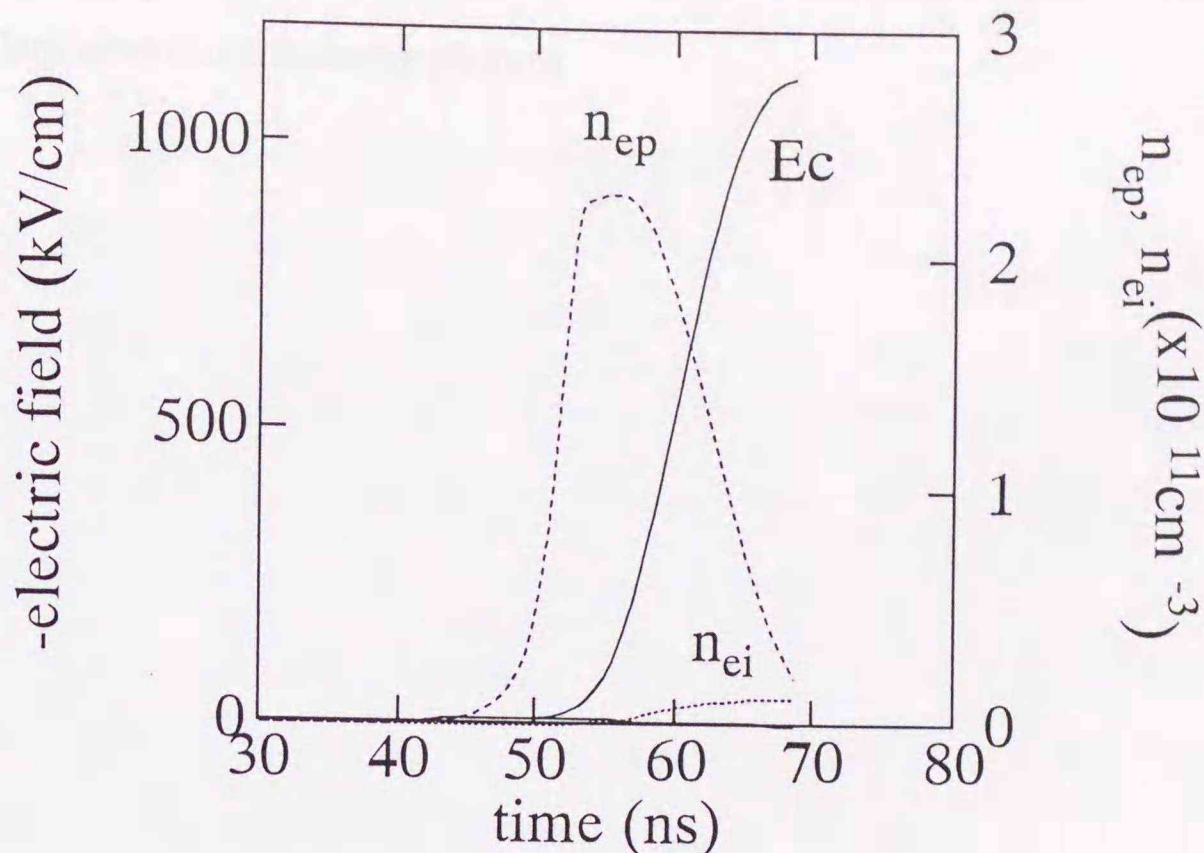


Figure 7.6 Temporal evolution of electric field and secondary electron emission number densities. ----- secondary electron emission by photons, secondary electron emission by ions.

7.4 Comparison of Discharge Development Behavior with ArF Laser

Case

The waveforms of discharge current and voltage, frequencies and the mean electron energy are similar to the behavior of ArF case. However, in the XeCl laser, the laser output can not be seen around the end of the discharge after $t=60\text{ns}$, although in an ArF laser, it can be obtained. These results come from the difference of the lifetime of excimers and the value of excimer number density. The lifetime of ArF* excimer is about 4ns, while XeCl* excimer is about 11ns^[1].

In a XeCl laser, there are several important vibrational excitations which are related to the excimer formation that decrease the electron energy rapidly after the breakdown. This decrease in the electron energy makes less secondary electron emission from the cathode by photons than that in the ArF laser. So, in the XeCl laser, the secondary electron emission by positive ions becomes more predominant than by

photons, while in an ArF laser the field near the cathode is controlled mainly by secondary electron emission by photons.

7-5 Summary and Remarks

A self-sustained discharge-excited XeCl excimer laser is investigated by the fluid model as described in chapter 2.

In a XeCl excimer laser, the secondary electron emission from the cathode by positive ions is more predominant than that by photons. The electric field distortion near the cathode becomes maximum at the end of the discharge in a similar way to that in the ArF excimer laser. The laser oscillation would begin from the end of the discharge when the electric field near the cathode becomes maximum, so that there might be a possibility of filamental instability before the laser oscillation.

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Chapter 8

Conclusions

In the present thesis, a self-sustained discharge-excited ArF and XeCl excimer laser were simulated self-consistently in one dimensional model. The behavior of the electric field distortion, species number density, etc. in cathode and anode sheath regions as well as those in the bulk was investigated for the first time in excimer lasers analyses.

The results obtained by the present simulation for each chapter are summarized as follows.

Chapter 1

First, general outline of excimer lasers was given. Next, the background of researches of discharge-excited excimer lasers has been presented. The theoretical investigation of excimer laser kinetics and discharge stability in a zero- and a multi-dimensional model were explained.

Chapter 2

A model of excimer lasers which can be calculated self-consistently in high pressure and high species densities was constructed. The present model consisted of fluid equations, energy conservation equation, the Poisson's equation, a secondary electron equation by photons, laser photon equation and a circuit equation.

The results obtained by the present model are compared with results of a Monte Carlo model and a LFA model. A LFA model which was easy to obtain its

results was not necessarily in good agreement with those of a Monte Carlo model. The results of the present model agreed well with those of a Monte Carlo model.

Chapter 3

In this chapter, the present fluid model was applied to a self-sustained discharge-excited ArF excimer laser discharge. The basic discharge development of ArF excimer laser was presented, such as, spatio-temporal distributions of species number densities, spatio-temporal distribution of electric field, and so on. The results obtained by the present simulations were summarized as follows.

- The electric field in the cathode and anode sheaths ($\sim 10^{-3}$ cm) was highly distorted by space charge. Their maximum values were more than 100kV/cm when the discharge voltage falls down to 0.
- A role of photo-electron emission from the cathode was suggested to suppress the electric field distortion near the cathode and sustain the volume discharge.
- A possibility of the occurrence of field emission of electrons from the cathode was discussed.

Chapter 4

The present model was applied to a self-sustained discharge-excited ArF laser including the effect of photoionization and photodetachment processes by stimulated laser photons. The differences of discharge development between the case including the effect of stimulated emission light and the case neglecting the stimulated emission light were shown in the spatio-temporal distribution of species number densities and of electric field. The spatio-temporal distribution of laser output was shown. The results obtained by the present model are summarized as follows.

- These processes were shown to influence significantly the spatio-temporal discharge development. After the laser output peak appeared, the electric field near the cathode was found to be highly distorted by the laser induced photoionization and photodetachment processes.
- The electric field near the anode rapidly changed from negative to positive. These field distortions were found to be a possible mechanism for initiation of the filamental discharge instability through the field emission of electrons from tips on the electrode surface experimentally shown by Taylor.

Chapter 5

In this chapter, the preionization uniformity was discussed. In the uniform preionization model, the discharge current, voltage and laser output waveforms were influenced significantly by preionization density. However, the electric field near the electrodes were almost independent of the preionization density. The tendency of the laser output energy and breakdown voltage as a function of preionization electron density agreed with experimental results.

- In the non-uniform preionization model, the discharge current, voltage and laser output waveforms slightly depended on the weakly preionized region.
- The mean electron number densities were slightly higher than those in the uniform model in the early stage of discharge, but became lower at the end of the discharge.
- The electric field near the cathodes in the highly preionized region were distorted significantly in the non-uniform preionization case. This would easily lead to filamentary discharge instability.

- The breakdown voltage as a function of the preionization number density agreed with that in the uniform model. However, the steep decrease in the peak laser power and the laser output energy as a function of the preionization electron number density were shown.
- As a result, the preionization uniformity was one of the very important parameters to indicate the stability of the discharge and the laser output.

Chapter 6

In this chapter, the influence of values of inductance in a charge-transfer excitation circuit was examined.

- The L_1 influenced to the risetime of discharge voltage significantly. The tendency of the breakdown voltage, laser power as a function of L_1 agreed with results of experimental ones.
- The distortion electric field near the cathode decreased, but the distortion near the anode increased with increasing L_1 .
- L_2 dependence of the discharge development is seen significantly in the discharge voltage waveforms after the breakdown.
- For large L_2 , the plateau region of the discharge voltage waveform was extended with L_2 , and accordingly the laser output had a longer tail, but the peak laser power decreased. For smaller L_2 , the discharge voltage waveforms became shorter and the peak laser power became higher with L_2 .
- The L_2 value could vary easier technically than L_1 could, therefore the laser output waveform was controllable by changing L_2 . However, there was still a possibility of filamentary discharge instability for smaller L_2 .

Chapter 7

The simulation of a self-sustained discharge-excited XeCl excimer laser was carried out.

- In the XeCl excimer laser, the secondary electron emission by ions was found to be more important than that by photons.
- The electric field distortion near the cathode became maximum at the end of the discharge as the same way as that in the ArF excimer laser.
- The laser oscillation would begin from the end of the discharge when the electric field near the cathode became maximum.

From these results, it was found that the electric field near the electrodes was distorted highly. The filamental instability may occur under these high field. However, in a one-dimensional model, only a possibility of occurrence of filamentation can be discussed. So, simulations in a multi-dimensional model should be carried out to make clear the mechanism of initiation and development of filamentations.

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4. ORAL PRESENTATION

[1]"Monte Carlo Simulation of discharges in ArF excimer laser medium"
H.Akashi K.Satoh H.Date Y.Sakai and H.Tagashira
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[2]"Swarm Parameters in Gases (CLXXXIII)
- Simulaition of discharges in excimer laser medium -"
H.Akashi H.Date Y.Sakai and H.Tagashira
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[4]"Monte Carlo simulation of discharges in excimer laser medium (I)"
H.Akashi H.Date Y.Sakai and H.Tagashira
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[5]"Monte Carlo simulation of discharges in excimer laser medium (II)"
H.Akashi H.Date Y.Sakai and H.Tagashira
Extended Abstracts of the 51th Autumn Meeting; The Japan Society of Applied
physics, 28a-L-9 (1990)

[6]"Swarm Parameters in Gases (CCIV)
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H.Akashi H.Date Y.Sakai and H.Tagashira
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[7]"Monte Carlo simulaition of excimer laser (I)"
H.Akashi H.Date Y.Sakai and H.Tagashira
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H.Akashi H.Date Y.Sakai and H.Tagashira
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H.Akashi H.Date Y.Sakai and H.Tagashira
Extended Abstracts of the 52th Autumn Meeting; The Japan Society of Applied
physics, 11p-L-16 (1991)

[10]"Swarm Parameters in Gases (CCXIII)
- Behavior of cumulative ionization in ArF excimer laser medium discharge -"
H.Akashi H.Date Y.Sakai and H.Tagashira
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- [11]"Monte Carlo Simulaiton of excimer laser (II)
 - Simulaiton of discharges in ArF(Ar/F₂/He) excimer laser medium -"
 H.Akashi H.Date Y.Sakai and H.Tagashira
 Hokkaido Branches Joint Convention, Jpn. Soc. of Appl. Phys. C10 (1992)
- [12]"Monte Carlo Simulation of discharges in excimer laser medium (V)
 - Simulaiton of discharges in ArF(Ar/F₂/He) excimer laser medium -"
 H.Akashi H.Date Y.Sakai and H.Tagashira
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 29p-D-12 (1992)
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 - Consideration of photoionization -"
 H.Akashi H.Date Y.Sakai and H.Tagashira
 Extended Abstracts of the 53th Autumn Meeting; The Japan Society of Applied
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- [14]"Swarm Parameters in Gases(CCXXII)
 - Computer Simulation of ArF Excimer Laser Medium Discharge using Cont. eq. -"
 H.Akashi H.Date Y.Sakai and H.Tagashira
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- [15]"Monte Carlo Simulaiton of excimer laser (III)
 - Comparison of continuity equation analysis -"
 H.Akashi H.Date Y.Sakai and H.Tagashira
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- [16]"Monte Carlo Simulation of discharges in excimer laser medium (VII)
 - Continuity equation using electron energy conservation -"
 H.Akashi H.Date Y.Sakai and H.Tagashira
 Extended Abstracts of the 40th Spring Meeting; The Japan Society of Applied physics,
 30p-Z-13 (1993)
- [17]"Swarm Parameters in Gases(CCXXVI)
 - Preionization electron density dependence in ArF excimer laser -"
 H.Akashi H.Date Y.Sakai and H.Tagashira
 Hokkaido Branches Joint Convention, IEE and Related Institutes Japan 50 (1993)
- [18]"Monte Carlo Simulaiton of excimer laser (IV)
 - Rise time dependence in excitation discharge (continuity equation analysis) -"
 H.Akashi H.Date Y.Sakai and H.Tagashira
 Hokkaido Branches Joint Convention, Jpn. Soc. of Appl. Phys. A36 (1993)
- [19]"Monte Carlo Simulation of discharges in excimer laser medium (VIII)
 - Temporary evolution of field distortion using continuity equation analysis -"
 H.Akashi H.Date Y.Sakai and H.Tagashira
 Extended Abstracts of the 54th Autumn Meeting; The Japan Society of Applied
 physics, 28p-B-15 (1993)
- [20]"Monte Carlo Simulation of discharges in excimer laser medium (IX)
 - Influence of inhomogenous preionizaiton discharge (continuity equation analysis) -"
 H.Akashi H.Date Y.Sakai and H.Tagashira
 Extended Abstracts of the 41th Spring Meeting; The Japan Society of Applied physics,
 30p-H-16 (1994)

- [21]"Monte Carlo Simulation of discharges in excimer laser medium (X)
 - Rise time dependence in excitation discharge (continuity equation analysis) -"
 H.Akashi H.Date Y.Sakai and H.Tagashira
 Extended Abstracts of the 55th Autumn Meeting; The Japan Society of Applied physics, 21p-C-2 (1994)
- [22]"Swarm Parameters in Gases (CCXXXIII)
 - Influence of laser induced photoionization and photodetachment on the discharge of excimer laser -"
 H.Akashi H.Date Y.Sakai and H.Tagashira
 Hokkaido Branches Joint Convention, IEE and Related Institutes Japan 51 (1994)
- [23]"Monte Carlo Simulaition of excimer laser (V)
 - Influence of inhomogenous preionizaiton (continuity equation analysis) -"
 H.Akashi H.Date P.Ventzek Y.Sakai and H.Tagashira
 Hokkaido Branches Joint Convention, Jpn. Soc. of Appl. Phys. B23 (1994)
- [24]"Non-equilibrium Plasma Diagnostics by Optogalvanic Spectroscopy (I)
 - Laser Light Effect in Ne gas by Boltzmann equation analysis -"
 S.Uchida H.Akashi H.Sugawara S.Sawada Y.Sakai and H.Tagashira
 Hokkaido Branches Joint Convention, IEE and Related Institutes Japan 53 (1994)
- [25]"Simulation of Dielectric Barrier Discharge (I)
 - A Excimer Lamp Model -"
 A.Oda H.Akashi P.Ventzek Y.Sakai and H.Tagashira
 Hokkaido Branches Joint Convention, IEE and Related Institutes Japan 66 (1994)
- [26]"Non-equilibrium Plasma Diagnostics by Optogalvanic Spectroscopy (II)
 - Comparison between Boltzmann equation analysis and experimental result -"
 S.Uchida H.Akashi H.Sugawara S.Sawada Y.Sakai and H.Tagashira
 Hokkaido Branches Joint Convention, Jpn. Soc. of Appl. Phys. B25 (1994)
- [27]"Simulation of Dielectric Barrier Discharge (II)
 - Influence of Dielectric Barrier affected by Excimer Lamp Discharge -"
 A.Oda H.Akashi P.Ventzek Y.Sakai and H.Tagashira
 Hokkaido Branches Joint Convention, Jpn. Soc. of Appl. Phys. B26 (1994)

Appendices

1. Reactions and Rate Coefficients Included in a XeCl Excimer Laser
2. Simulation Program List for ArF Excimer Laser

Appendices

1. Reactions and Rate Coefficients Included in a XeCl Excimer Laser
2. Simulation Program List for ArF Excimer Laser

Appendix -1-

Reactions and Rate Coefficients Included in a XeCl Excimer Laser

Table A.1 Reactions for electrons adopted in the XeCl model

electron-neutral reaction	H(eV)	rate coeff.	ref.
$\text{Xe} + e \rightarrow \text{Xe}^+ + 2e$	12.12	k_{ix}	[1]
$\text{Xe} + e \rightarrow \text{Xe}^{\text{ex}} + e$ (total excitation to the radiating state)	9.57	k_{exx}	[1]
$\text{Xe} + e \rightarrow \text{Xe}^* + e$ (metastable state)	8.32	k_{mex}	[1]
$\text{Xe} + e \rightarrow \text{Xe}^{\text{res}} + e$ (resonance state)	8.437	k_{rex}	[1]
$\text{Xe}^* + e \rightarrow \text{Xe}^+ + 2e$	3.238	k_{six}	[1]
$\text{HCl} + e \rightarrow \text{HCl}^+ + e$	11.5	k_{iHCl}	[1]
$\text{HCl} + e \rightarrow \text{HCl}^{\text{ex}} + e$	5.0	k_{exHCl}	[1]
$\text{HCl} + e \rightarrow \text{HCl}_{v3} + e$	1.06	k_{v3HCl}	[2]
$\text{HCl} + e \rightarrow \text{HCl}_{v2} + e$	0.62	k_{v2HCl}	[1]
$\text{HCl} + e \rightarrow \text{HCl}_{v1} + e$	0.35	k_{v1HCl}	[1]
$\text{HCl} + e \rightarrow \text{HCl}^{\text{rt}} + e$	0.002	k_{rtHCl}	[1]
$\text{HCl} + e \rightarrow \text{HCl}^{\text{rm}} + e$	0.002	k_{rmHCl}	[1]
$\text{HCl}_{vn} + e \rightarrow \text{HCl}_{v(n+1)} + e$		$k_{vn-v(n+1)HCl}$	[2]
$\text{HCl} + e \rightarrow \text{Cl}^- + \text{H}$		k_{aclHCl}	[1]
$\text{HCl} + e \rightarrow \text{H}^- + \text{Cl}$		k_{ahHCl}	[1]
$\text{HCl}_{v3} + e \rightarrow \text{Cl}^- + \text{H}$		k_{av3HCl}	[3]
$\text{HCl}_{v2} + e \rightarrow \text{Cl}^- + \text{H}$		k_{av2HCl}	[3]
$\text{HCl}_{v1} + e \rightarrow \text{Cl}^- + \text{H}$		k_{av1HCl}	[3]
$\text{He} + e \rightarrow \text{He}^+ + 2e$	24.588	k_{ih}	[1]
$\text{He} + e \rightarrow \text{He}^{\text{ex}} + e$ (total excitation to the radiating state)	20.96	k_{exh}	[1]
$\text{He} + e \rightarrow \text{He}^* + e$ (metastable state)	19.8	k_{meh}	[1]

Table A.2 Reactions for ions and excited species adopted in the XeCl model

neutral reaction	rate coeff./lifetime/cross section		ref.
$\text{Xe}^+ + 2\text{Xe} \rightarrow \text{Xe}_2^+ + \text{Xe}$	$3.6 \times 10^{-31} \text{cm}^6/\text{s}$		[4]
$\text{Xe}^+ + \text{Xe} + \text{He} \rightarrow \text{Xe}_2^+ + \text{Xe}$	$1.1 \times 10^{-31} \text{cm}^6/\text{s}$		[4]
$\text{Xe}^* + \text{HCl}_{\text{vN}} \rightarrow \text{XeCl}^* + \text{H}$	$2.0 \times 10^{-10} \text{cm}^3/\text{s}$		[4]
$\text{Xe}^+ + \text{Cl}^- \rightarrow \text{XeCl}^*$	$1.5 \times 10^{-25} \text{cm}^3/\text{s}$		[4]
$\text{Xe}_2^+ + \text{Cl}^- \rightarrow \text{XeCl}^* + \text{Xe}$	$2.0 \times 10^{-6} \text{cm}^3/\text{s}$		[4]
$\text{Xe}^{\text{ex}} \rightarrow \text{Xe} + h\nu'$	1.0ns (de-excitation with radiation)[estimated]		
$\text{XeCl}^* \rightarrow \text{Xe} + \text{Cl} + h\nu$	10.0ns (spontaneous emission)		[2]
$\text{XeCl}^* + h\nu \rightarrow \text{Xe} + \text{Cl} + 2h\nu$	$4.5 \times 10^{-16} \text{cm}^2$ (stimulated emission)		[2]
$\text{Xe}^{\text{ex}} + h\nu \rightarrow \text{Xe}^+ + e$	1.476	$6 \times 10^{-20} \text{cm}^2$	[4]
$\text{Cl}^- + h\nu \rightarrow \text{Cl} + e$	3.426	$2.1 \times 10^{-17} \text{cm}^2$	[4]

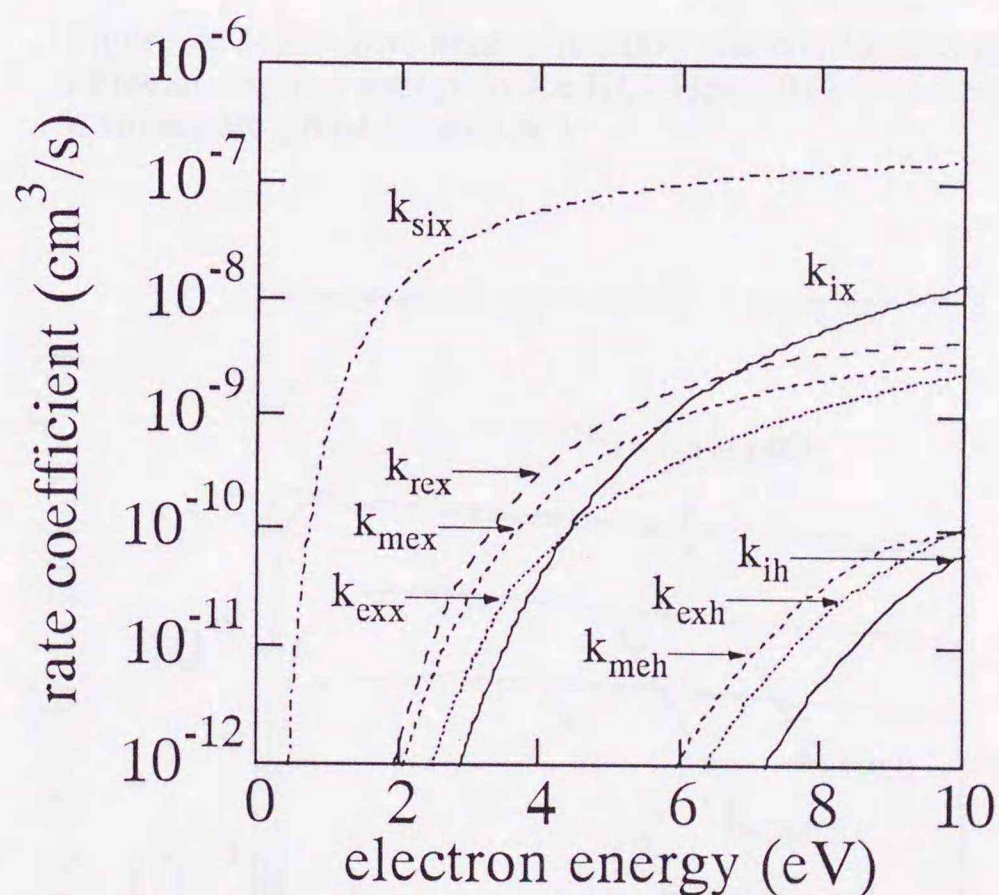


Figure A.1. Electron-neutral reaction rate coefficients as a function of mean electron energy in Xe/HCl/He=0.0124/0.0014/0.9862. k values are given in table A.1.

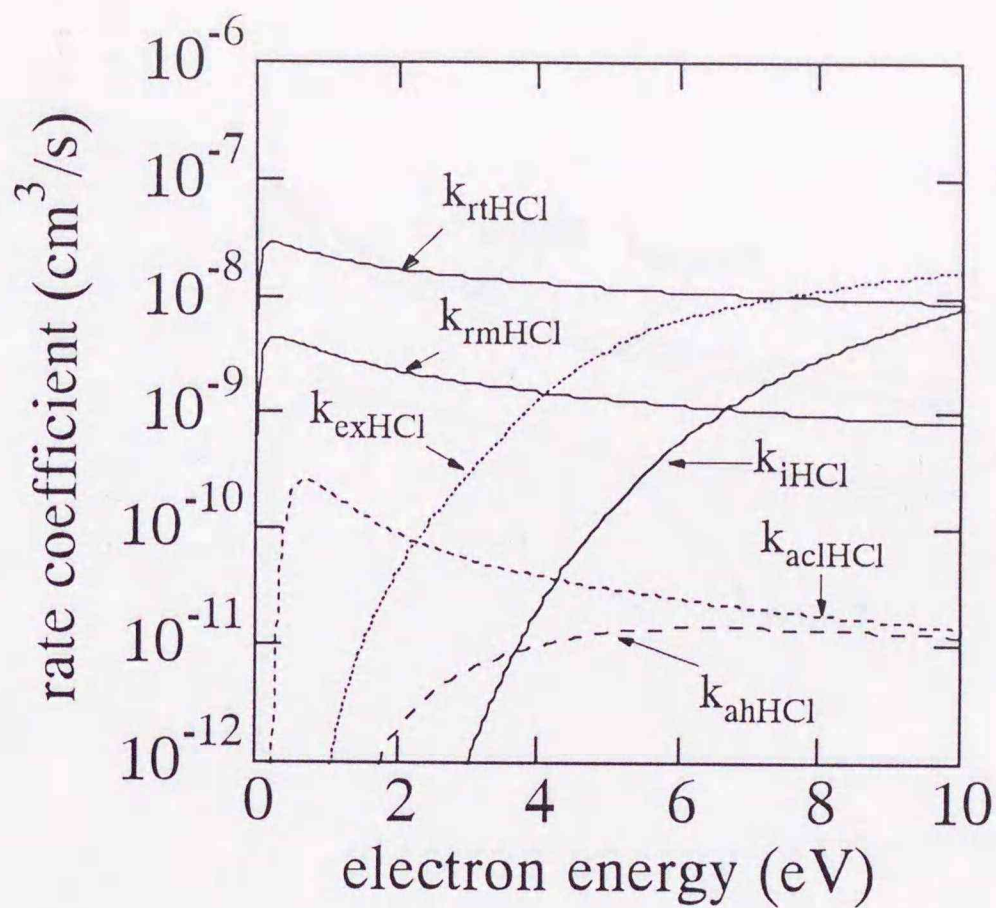


Figure A.2. Electron-neutral reaction rate coefficients as a function of mean electron energy in Xe/HCl/He=0.0124/0.0014/0.9862. k values are given in table A.1.

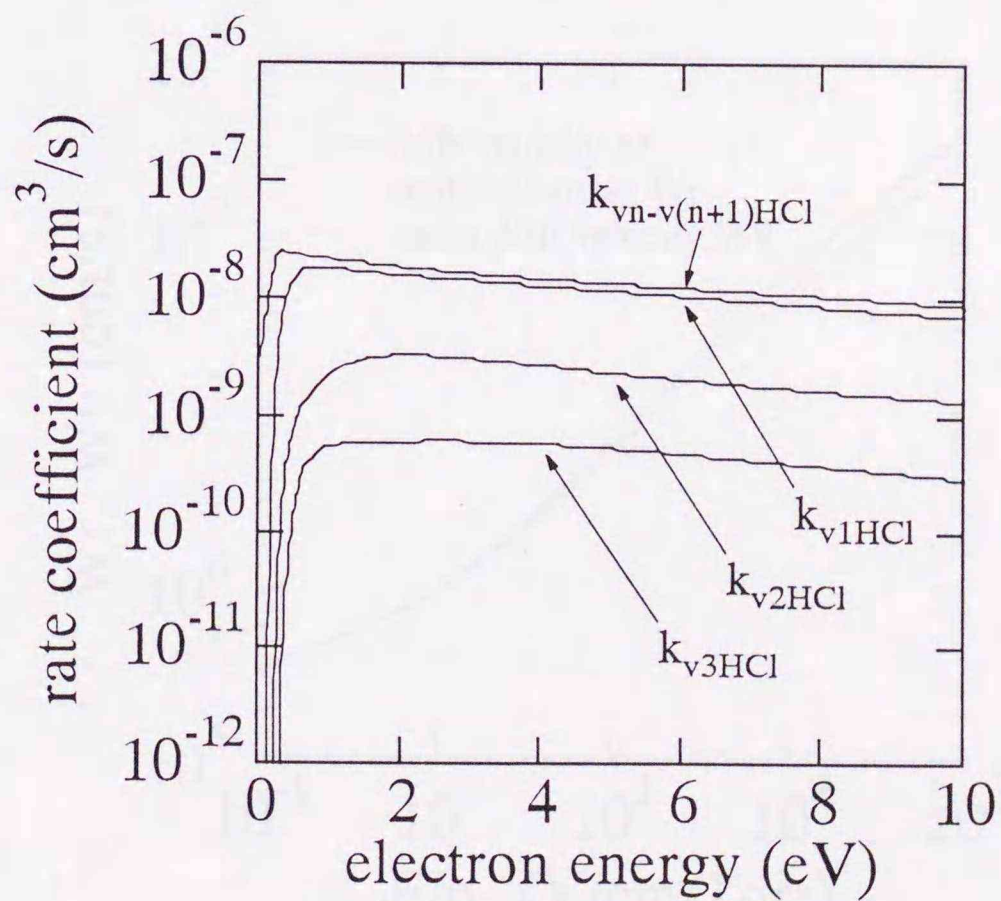


Figure A.3. Electron-neutral reaction rate coefficients as a function of mean electron energy in Xe/HCl/He=0.0124/0.0014/0.9862. k values are given in table A.1.

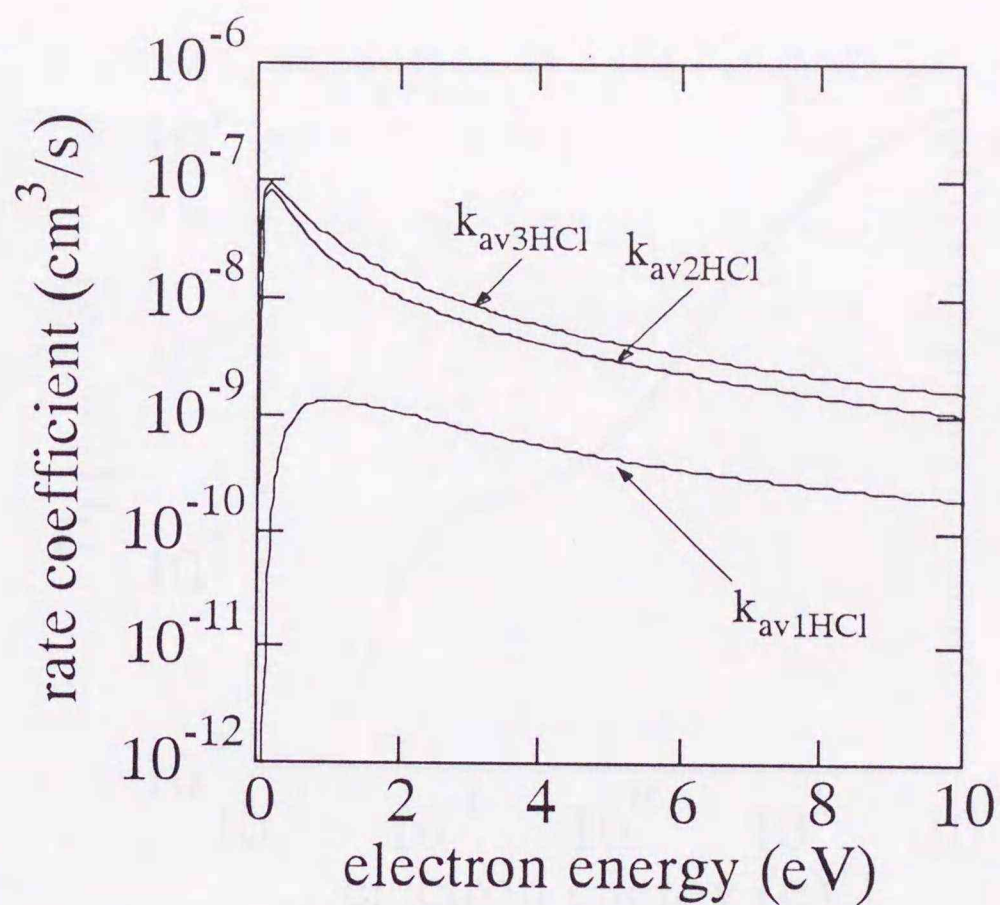


Figure A.4. Electron-neutral reaction rate coefficients as a function of mean electron energy in Xe/HCl/He=0.0124/0.0014/0.9862. k values are given in table A.1.

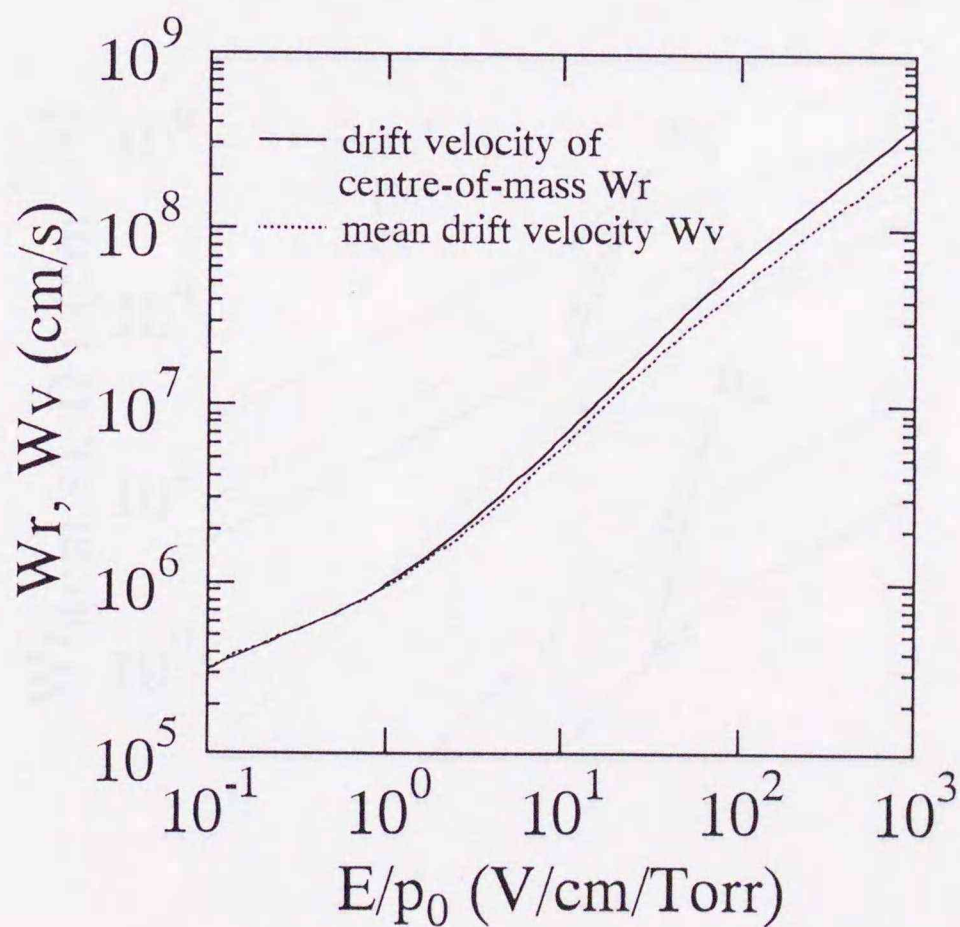


Figure A.5. Electron drift velocity in the same conditions as described in figure A.1.

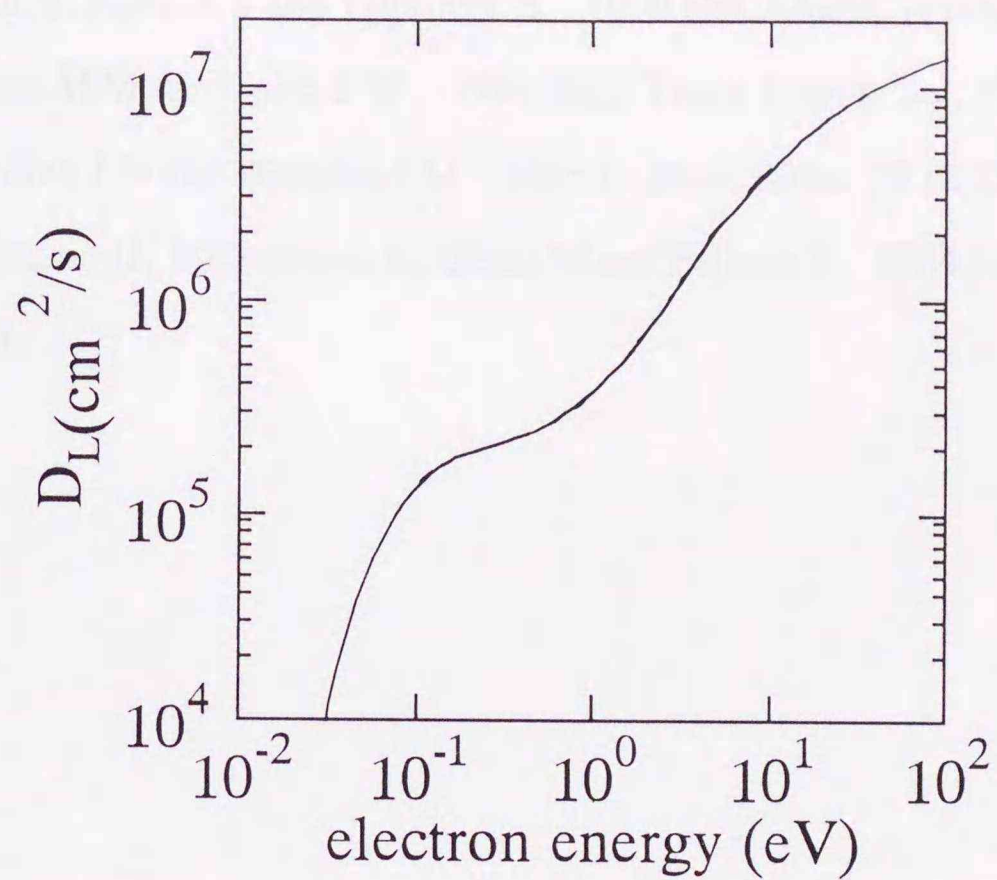


Figure A.6. Electron longitudinal diffusion coefficient D_L in the same conditions as described in figure A.1.

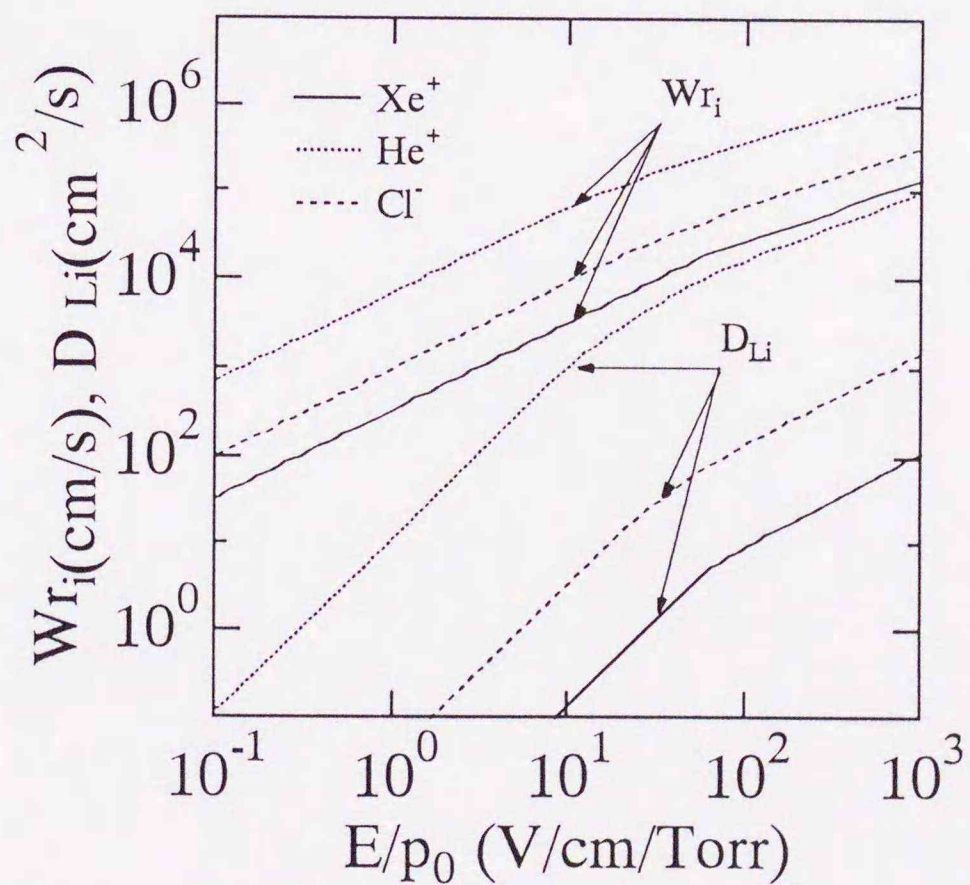


Figure A.7. Drift velocity and longitudinal diffusion coefficient of ions.

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- [3] Bardsley J N and Wadehra J M 1983 J.Chem. Phys. 78 12 7227-7234
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APPENDIX -2- SIMULATION PROGRAM LIST FOR ARF EXCIMER LASER

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*****
*
* ARGON FLUORIDE EXCIMER LASER'S
* SIMULATION WITH CONTINUITY EQUATION
*
*
*****
IMPLICIT DOUBLE PRECISION(A-H,N-Z)
PARAMETER (IMESH=2000,D=1.0)
PARAMETER
> (GF2=0.0024 ,GAR=0.0789 ,GE=0.9187 ,
> THIE=24.588 ,THEHE=20.96 ,THEHE=19.8 ,
> THIEAR=15.76 ,THEXAR=12.9 ,THEAR=11.55 ,THOAR=4.21 ,
> THOEAR=3.565 ,THDF=4.324 ,THOMAR=2.215,
> PR=1900.0 ,R=1.0 ,VC=2.998D+10 ,
> TM=1.0D-09 ,TARF=4.0D-09 ,
> RION=1.0D-06 ,HARP=8.0D-10 ,RION2=1.0D-06 ,RION1=2.5D-31 ,
> ENO=0.5 ,RDMAX=1.0D+06,
> MN =4 ,EXR1 =0.1 ,EXL1 =100.0D-09,EXL2 =20.0D-09,
> EXC1=10.0D-09,EXC2 =1.5D-09)
DIMENSION
> ANE (-1:IMESH+2),ANED (-1:IMESH+2),NPH (-1:IMESH+2),
> NN (-1:IMESH+2),NMH (-1:IMESH+2),NMA (-1:IMESH+2),
> NEXA(-1:IMESH+2),NEXH (-1:IMESH+2),NPA (-1:IMESH+2),
> NPA2(-1:IMESH+2),ARF2 (-1:IMESH+2),ARF (-1:IMESH+2),
> ARF1(-1:IMESH+2),NCIAR(-1:IMESH+2),CIAR (-1:IMESH+2),
> ROU (-1:IMESH+2),VZ (-1:IMESH+2),FAI (-1:IMESH+2),
> ELF (-1:IMESH+2),ELF1 (-1:IMESH+2),ELF2 (-1:IMESH+2),
> EN (-1:IMESH+2),ENN (-1:IMESH+2),ENI (-1:IMESH+2),
> NPAD(-1:IMESH+2),NPHD (-1:IMESH+2),NND (-1:IMESH+2),
> ARFO(-1:IMESH+2),PHOTO(-1:IMESH+2),PHOTO1(-1:IMESH+2),
> DNEXA(-1:IMESH+2),DNND(-1:IMESH+2),DNMA(-1:IMESH+2)

```

```

DIMENSION
> CI (-1:IMESH+2),DI (-1:IMESH+2),TI (-1:IMESH+2),
> CII (-1:IMESH+2),CIE (-1:IMESH+2),CIA (-1:IMESH+2),
> CIH (-1:IMESH+2),CIN (-1:IMESH+2),ROU1(-1:IMESH+2),
> A(4,4),B(4),Y(4),V(4),F(4),DD(4),
> AA1(-1:IMESH+2),BB1(-1:IMESH+2)
REAL ITIM0,ITIM1,ITIM2
REAL*8 LG,LS,LC
CC DRIFT VELOCITY :800.00,2.4232D+8 ==> DLT*WR=<DLTD
CC DIFFUSION COEFFICIENT:118.01,1.6482D+7 ==> DLT*2*DL/PR=<DLTD**2
C----- L1=100NH -----
DLT=1.0D-12
C----- L1=600NH -----
C DLT=2.0D-12
SMT=100.0D-09
OUTP=0.5D-09/DLT
COUNT=SMT/DLT/OUTP
EPS=8.8541878D-14/DLT
CL=1.6021776D-19
EPS1=CL/EPS/DLT
EBP0=1.0D-08
DLTZ=D/IMESH
DLTZ1=1.0/DLTZ
DLTZ12=DLTZ1*DLTZ1
PR1=1.0/PR
DI=1.0/D
EXLID=1.0/EXL1
EXL2D=1.0/EXL2
EXCID=1.0/EXC1
EXC2D=1.0/EXC2
NIM=1.0D+13
PQI=6.0D-15
AMYU=PQI*NIM
GAMMA=2.00D-02

```



```

SA=1.5*60.0
DH=1.0
FF=1.8D-5
LG=90.0/DH
LC=15.0+LG
QST=2.7D-16
QPI=1.0E-18
QPII=5.0E-20
QPIII=0.0
QPD=1.0E-17
RS=0.08
LS=0.08
CO=EPS*DLTT*SA/D
PE=1.0
EXT=1.0
ICAT=1
IBL=IMESH/2
IANO=IMESH-1
CALL CRSINI
EBP=700.0
EV=140.0
BOUND1=DLTZ-DLTT*WR(EBP)
BOUND2=DLTZ**2-DLTT*2.0*DL(EV)/PR
BOUND3=DLTZ-DLTT*WRH(EBP)
BOUND4=DLTZ**2-DLTT*2.0*DLH(EBP)/PR
BOUND1=(DLTT*WR(EBP)/DLTZ)**2
BOUND2=DLTT*2.0*DL(EV)/PR/DLTZ**2
BOUND3=(DLTT*WRH(EBP)/DLTZ)**2
BOUND4=DLTT*2.0*DLH(EBP)/PR/DLTZ**2
WRITE(6,5000)BOUND1,BOUND2,BOUND3,BOUND4
WRITE(7,*)'EX-CIRCUIT      (1=>YES,0=>NO)',EXT
WRITE(7,*)'PHOTO EMISSION (1=>YES,0=>NO)',PE
WRITE(7,*)'GAMMA-P=',GAMMA

WRITE(7,*)'PHOTO IONIZATION CROSS SECTION*PRESSURE',PQI
WRITE(7,*)'ABSORPTION COEFFICIENT',AMYU
WRITE(7,*)'LIFE TIME OF EXCITED STATE',TM
WRITE(7,*)'IMPURITY DENSITY',NIM
WRITE(7,*)'PROCESS OF ARF PARAMETER RECOM HARP',
WRITE(7,*)RION,HARP,GF2
***** EXTERNAL CIRCUIT PARAMETER *****
X0 = 0.0
Y(1) = 0.0
Y(2) = 0.0
Y(3) = 20.0D+03
Y(4) = 0.0
X = X0
WRITE(8,*)'INITIAL PARAMETER OF EX CIRCUIT(V0,C,L,R,S)'
WRITE(8,5000) Y(3),EXC1,EXC2
WRITE(8,5000) EXL1,EXL2,EXR1,SA
WRITE(8,5000) LG,LC,LS,RS
WRITE(8,*) ICAT,IBL,IANO
WRITE(8,*)'60-?NSEC'
AELF=50.0
AELFI=50.0
EBP=50.0
IF (EXT.EQ.1.0) THEN
  AELF=EBP0
  EBP=AELF
ENDIF
WVPE=WV(EBP)
WVPEI=WV(EBP)
IPP=0
IPP1=IMESH*IPP/100/2
PP1=IMESH*IPP/100/2
IPP2=(IMESH-IPP1)
DO 100 I=1, IMESH-1
  NPA(I)= 1.0D+08

```



```

ANE(1)= 1.0D+08
IF (1.LT.IPP1) THEN
NPA(1)=1.0E4*[*10000.0/PP1
ANE(1)=1.0E4*[*10000.0/PP1
ENDIF
IF (1.GE.IPP2) THEN
NPA(1)=1.0E8-1.0E4*(1-IPP2)*10000.0/PP1
ANE(1)=1.0E8-1.0E4*(1-IPP2)*10000.0/PP1
ENDIF
ANED(1)=0.0
NPH(1)=0.0
NPA2(1)=0.0
NN(1)=0.0
NMH(1)=0.0
NMA(1)=0.0
NEXH(1)=0.0
NEXA(1)=0.0
ELF(1)=AELF
ELF1(1)=-AELF*PR
ELF2(1)=AELF
ENK(1)=1.0
ENNK(1)=EN(1)*ANE(1)
100 CONTINUE
ANE(0)=0.0
ANE(-1)=0.0
ANE(1MESH)=0.0
ENNK(1MESH)=0.0
ELF(0)=AELF
ELF(1MESH+1)=AELF
DO 550 K=1, COUNT
IF (STIME.GE.48.0E-9) THEN
DLTT=5.0E-14
OUTP=0.2E-9/DLTT
ENDIF
DO 520 I=1, OUTP
*
***** PHOTO EMISSION *****
*
110 CONTINUE
RP=0.0
RPA1=0.0
DO 120 I=1, IMESH-1
EBP=ABS(ELF(1))
EV=EN(1)
DEXA=MAX(0.0,(NEXA(1)-(1*DLTZ)/VC*PR*REXAR(EV)*ANE(1)))
DEXH=MAX(0.0,(NEXH(1)-(1*DLTZ)/VC*PR*REXHE(EV)*ANE(1)))
RP=RP+0.5*GAMMA/TM*(1.0-(1*DLTZ)/SQRT((1*DLTZ)**2+R**2))*
> EXP(-AMYU*(1*DLTZ)*DEXA*DLTZ+
> 0.5*GAMMA/TM*(1.0-(1*DLTZ)/SQRT((1*DLTZ)**2+R**2))*
> EXP(-AMYU*(1*DLTZ)*DEXH*DLTZ
JANO=IMESH-1
EBP=ABS(ELF(JANO))
EV=EN(JANO)
DEXA1=MAX(0.0,(NEXA(JANO)-(1*DLTZ)/VC*PR*REXAR(EV)*ANE(JANO)))
DEXH1=MAX(0.0,(NEXH(JANO)-(1*DLTZ)/VC*PR*REXHE(EV)*ANE(JANO)))
RPA1=RPA1+0.5*GAMMA/TM*(1.0-(1*DLTZ)/SQRT((1*DLTZ)**2+R**2))*
> EXP(-AMYU*(1*DLTZ)*DEXA1*DLTZ+
> 0.5*GAMMA/TM*(1.0-(1*DLTZ)/SQRT((1*DLTZ)**2+R**2))*
> EXP(-AMYU*(1*DLTZ)*DEXH1*DLTZ
120 CONTINUE
IF (STIME.GT.20E-9) THEN
ANFLG=1.0
ELSE
ANFLG=0.0
ENDIF
IF (WYPE.GT.0.0) THEN
NEO=MAX(0.0,RP/WYPE)
IF (STIME.GT.100.0E-9) THEN

```



```

ANFLG=1.0
NED=MAX(0.0,RPA1/WVPE1)*ANFLG
NPADD=NPADD*ANFLG
NPHDD=NPHDD*ANFLG
NPA(IMESH)=NPADD
NPH(IMESH)=NPHDD
ANE(IMESH)=NED
ELSE
ANFLG=0.0
NED=MAX(0.0,RP1/WVPE1)*ANFLG
NPADD=NPADD*ANFLG
NPHDD=NPHDD*ANFLG
NPA(IMESH)=NPADD
NPH(IMESH)=NPHDD
ANE(IMESH)=NED
ENDIF
NEOP=MAX(0.0,PPP/WVPE*0.0)
ELSE
NEO=0.0
ENDIF
ANE(0)=NEO+NEOP
ANE(IMESH)=NED
EN(0)=ENO
EN(IMESH)=ENO
ENN(0)=ENO*ANE(0)
EBP=ABS(ELF(0))
WRN1=SIGN(WRN(EBP),ELF(0))
WRA1=SIGN(WRA(EBP),ELF(0))
WRH1=SIGN(WRH(EBP),ELF(0))
RPA=NPA(0)*WRA1
RPH=NPH(0)*WRH1
RPN=NN(0)*WRN1
C11(0)=CL*(RP+RPN+RPA+RPH)
C1E(0)=CL*(RP)

CIA(0)=CL*(RPA)
CIH(0)=CL*(RPH)
CIN(0)=CL*(RPN)

*
***** MAIN(ELECTRON) *****
*
DO 130 J=1,2
ANED(J-2)=0.0
NPA2(J-2)=0.0
NMH(J-2)=0.0
NMA(J-2)=0.0
NEXH(J-2)=0.0
NEXA(J-2)=0.0
ANE(IMESH-1+J)=0.0
ANED(IMESH-1+J)=0.0
NPH(IMESH-1+J)=0.0
NPA(IMESH-1+J)=0.0
NPA2(IMESH-1+J)=0.0
NN(IMESH-1+J)=0.0
NMH(IMESH-1+J)=0.0
NMA(IMESH-1+J)=0.0
NEXH(IMESH-1+J)=0.0
NEXA(IMESH-1+J)=0.0
130 CONTINUE
ANE(-1)=0.0
DO 140 IJ=1, IMESH
C11(IJ)=0.0
140 CONTINUE
DO 150 I=1, IMESH-1
EV=EN(I)
DL1=DL(EV)
EV=EN(I)
DL2=DL(EV)
EV=EN(I)

```



```

DL3=DL(EV)
DIFF=(DL1*PR1*ANE(I+1)-2.0*DL2*PR1*ANE(I)
> +DL3*PR1*ANE(I-1))*DLTZ12
EBP=ABS(ELF(I))
DLH1=DLH(EBP)
EBP=ABS(ELF(I))
DLH2=DLH(EBP)
EBP=ABS(ELF(I))
DLH3=DLH(EBP)
DIFFH=(DLH1*PR1*NPH(I+1)-2.0*DLH2*PR1*NPH(I)
> +DLH3*PR1*NPH(I-1))*DLTZ12
EBP=ABS(ELF(I))
DLA1=DLA(EBP)
EBP=ABS(ELF(I))
DLA2=DLA(EBP)
EBP=ABS(ELF(I))
DLA3=DLA(EBP)
DIFFA=(DLA1*PR1*NPA(I+1)-2.0*DLA2*PR1*NPA(I)
> +DLA3*PR1*NPA(I-1))*DLTZ12
EBP=ABS(ELF(I))
DLN1=DLN(EBP)
EBP=ABS(ELF(I))
DLN2=DLN(EBP)
EBP=ABS(ELF(I))
DLN3=DLN(EBP)
DIFFN=(DLN1*PR1*NN(I+1)-2.0*DLN2*PR1*NN(I)
> +DLN3*PR1*NN(I-1))*DLTZ12
IF (ELF(I).GE.0.0) THEN
ANE(IMESH)=0.0
NPA(IMESH)=0.0
NPH(IMESH)=0.0
ANED(IMESH)=0.0
NPAD(IMESH)=0.0
NPHD(IMESH)=0.0

```

```

EV=EN(I)
EBP=ABS(ELF(I-1))
WRA1=WRA(EBP)
WRH1=WRH(EBP)
EBP=ABS(ELF(I))
WRA2=WRA(EBP)
WRH2=WRH(EBP)
EBP=MAX(0.0,ELF(I-1))*ELF(I)/ELF(I-1)
EBP=(0.5+SIGN(5.0D-1,ELF(I-1)))*ELF(I)
WRN2=WRN(EBP)
WR2 =WR(EBP)
EBP=MAX(0.0,ABS(ELF(I+1)))
WR1 =WR(EBP)
WRN1=WRN(EBP)

ANED(I)=(RIHE(EV)*PR*ANE(I)
> +RIAR(EV)*PR*ANE(I)
> -RAF2(EV)*PR*ANE(I)
> +DIFF
> -(ANE(I)*WR1-ANE(I-1)*WR2)*DLTZ1)*DLTT+ANE(I)
NPAD(I)=(RIAR(EV)*PR*ANE(I)
> +DIFFA
> -(NPA(I)*WRA1-NPA(I+1)*WRA2)*DLTZ1)*DLTT+NPA(I)
NPHD(I)=(RIHE(EV)*PR*ANE(I)
> +DIFFH
> -(NPH(I)*WRH1-NPH(I+1)*WRH2)*DLTZ1)*DLTT+NPH(I)
NND(I)=(RAF2(EV)*PR*ANE(I)
> +DIFFN
> -(NN(I)*WRN1-NN(I-1)*WRN2)*DLTZ1)*DLTT+NN(I)
DCE=-(CL*(DL2*PR1*(ANE(I)-ANE(I-1))*DLTZ1))
> +(CL*(ANE(I-1)*WR2))
DCN=-(CL*(DLN2*PR1*(NN(I)-NN(I-1))*DLTZ1))
> +(CL*(NN(I-1)*WRN2))
DCA= (CL*(DLA2*PR1*(NPA(I)-NPA(I-1))*DLTZ1))

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C


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> + (CL*(NPA(1)*WRA1))
DCH= (CL*(DLH2*PR1*(NPH(1)-NPH(1-1))*DLTZ1))
> + (CL*(NPH(1)*WRH1))
C11(1)=DCE+DCN+DCA+DCH
CIE(1)=DCE
CIA(1)=DCA
CIH(1)=DCH
CIN(1)=DCN
IF (1.EQ.IMESH+1) THEN
DCE=- (CL*(DL1*PR1*(ANE(1+1)-ANE(1))*DLTZ1))
> + (CL*(ANE(1)*WR1))
DCN=- (CL*(DLN2*PR1*(NN(1+1)-NN(1))*DLTZ1))
> + (CL*(NN(1)*WRN1))
DCA= (CL*(DLA1*PR1*(NPA(1+1)-NPA(1))*DLTZ1))
DCH= (CL*(DLH1*PR1*(NPH(1+1)-NPH(1))*DLTZ1))
C11(IMESH)=DCE+DCN+DCA+DCH
CIE(IMESH)=DCE
CIA(IMESH)=DCA
CIH(IMESH)=DCH
CIN(IMESH)=DCN
ENDIF
ELSE
NPA(IMESH)=NPADD
NPH(IMESH)=NPHDD
ANE(IMESH)=NED
NPAD(IMESH)=NPADD
NPHD(IMESH)=NPHDD
ANED(IMESH)=NED
EV=EN(1)
EBP=ABS(MIN(0.0,ELF(1-1)))
WR1 =WR(EBP)
WRN1=WRN(EBP)
EBP=MIN(0.0,ELF(1+1))*ABS(ELF(1))/ELF(1+1)
EBP=(0.5+SIGN(5.0D-1,-ELF(1+1)))*ABS(ELF(1))

WR2 =WR(EBP)
WRN2=WRN(EBP)
EBP=ABS(ELF(1))
WRH2=WRH(EBP)
WRA2=WRA(EBP)
EBP=ABS(ELF(1+1))
WRA1=WRA(EBP)
WRH1=WRH(EBP)

ANED(1)=(RIHE(EV)*PR*ANE(1)
> +RIAR(EV)*PR*ANE(1)
> -RAF2(EV)*PR*ANE(1)
> +DIFF
> - (ANE(1)*WR1-ANE(1+1)*WR2)*DLTZ1)*DLTT+ANE(1)
NPAD(1)=(RIAR(EV)*PR*ANE(1)
> +DIFFA
> - (NPA(1)*WRA1-NPA(1-1)*WRA2)*DLTZ1)*DLTT+NPA(1)
NPHD(1)=(RIHE(EV)*PR*ANE(1)
> +DIFFH
> - (NPH(1)*WRH1-NPH(1-1)*WRH2)*DLTZ1)*DLTT+NPH(1)
NND(1) = (RAF2(EV)*PR*ANE(1)
> +DIFFN
> - (NN(1)*WRN1-NN(1+1)*WRN2)*DLTZ1)*DLTT+NN(1)
DCE=- (CL*(DL2*PR1*(ANE(1)-ANE(1-1))*DLTZ1))
> - (CL*(ANE(1)*WR1))
DCN=- (CL*(DLN2*PR1*(NN(1)-NN(1-1))*DLTZ1))
> - (CL*(NN(1)*WRN1))
DCA= (CL*(DLA2*PR1*(NPA(1)-NPA(1-1))*DLTZ1))
> - (CL*(NPA(1-1)*WRA2))
DCH= (CL*(DLH2*PR1*(NPH(1)-NPH(1-1))*DLTZ1))
> - (CL*(NPH(1-1)*WRH2))
C11(1)=DCE+DCN+DCA+DCH
CIE(1)=DCE
CIA(1)=DCA

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C


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C1H(1)=DCH
C1N(1)=DCN
IF (1.EQ.IMESH-1) THEN
DCE=- (CL*(DL1*PR1*(ANE(1+1)-ANE(1))*DLTZ1))
> - (CL*(ANE(1+1)*WR2))
DCN=- (CL*(DLN1*PR1*(NN(1+1)-NN(1))*DLTZ1))
DCA= (CL*(DLA1*PR1*(NPA(1+1)-NPA(1))*DLTZ1))
> - (CL*(NPA(1)*WRA1))
DCH= (CL*(DLH1*PR1*(NPH(1+1)-NPH(1))*DLTZ1))
> - (CL*(NPH(1)*WRH1))
C11(IMESH)=DCE+DCN+DCA+DCH
C1E(IMESH)=DCE
C1A(IMESH)=DCA
C1H(IMESH)=DCH
C1N(IMESH)=DCN
ENDIF
ENDIF
EV=EN(1)
EBP=ABS(ELF(1))
EV=EN(1)
RAR=RCIAR(EV)
NMH(1)=PR*RMEHE(EV) *ANE(1)*DLTT+NMH(1)
NMA(1)=PR*RMEAR(EV) *ANE(1)*DLTT+NMA(1)
NEXH(1)=(PR*REXHE(EV) *ANE(1)-NEXH(1)/TM)*DLTT+NEXH(1)
NEXA(1)=(PR*REXAR(EV) *ANE(1)-NEXA(1)/TM)*DLTT+NEXA(1)
CIAR(1)=RAR*NMA(1)*ANE(1)*DLTT
NPAD(1)=NPAD(1)+CIAR(1)
ANED(1)=ANED(1)+CIAR(1)
NMA(1)=NMA(1)-CIAR(1)
NCIAR(1)=NCIAR(1)+CIAR(1)
NPA2D=RION1*NPA(1)*(GAR*3.536D+16*PR)*
> (GAR*3.536D+16*PR)*DLTT
NPA2(1)=NPA2(1)+NPA2D
NPAD(1)=NPAD(1)-NPA2D

ECM=RION*NPA(1)*NN(1)*DLTT
ECM1=HARP*NMA(1)*(GF2*3.536D+16*PR)*DLTT
ECM2=RION2*NPA2(1)*NN(1)*DLTT
SARF0=ARF0(1)/TARF
SARF01=ARF0(1)/TARF*DLTT
SARF=ARF(1)/TARF*DLTT
SARF1=ARF1(1)/TARF*DLTT
SARF2=ARF2(1)/TARF*DLTT
PP=(FF*SARF0+VC*PHOTO(1)/LC*(LG*ARF0(1)*QST
> -LG*NEXA(1)*QPI-LG*NND(1)*QPD-LG*NMA(1)*QPI*IM
> +0.5*LOG(RS)+LOG(1.0-LS))*DLTT
PHOTO(1)=PP+PHOTO(1)
AA1(1)=PP-(VC*PHOTO(1)/LC*(0.5*LOG(RS)+LOG(1.0-LS))*DLTT
BB1(1)=(VC*PHOTO(1)/LC*(0.5*LOG(RS)+LOG(1.0-LS))*DLTT
PHOTO1(1)=PP*CL*6.425*90.0/DLTT
DNEXA(1)=-VC*PHOTO(1)/LC*LG*NEXA(1)*QPI*DLTT
NEXA(1)=NEXA(1)+DNEXA(1)
DNND(1)=-VC*PHOTO(1)/LC*LG*NND(1)*QPD*DLTT
NND(1)=NND(1)+DNND(1)
DNMA(1)=-VC*PHOTO(1)/LC*LG*NMA(1)*QPI*DLTT
NMA(1)=NMA(1)+DNMA(1)
ANED(1)=ANED(1)+ABS(DNEXA(1))+ABS(DNND(1))+ABS(DNMA(1))
ARF0(1)=ARF0(1)-SARF01+ECM+ECM1-PP
ARF(1)=ARF(1)-SARF+ECM+ECM1
ARF1(1)=ARF1(1)-SARF1+ECM1
ARF2(1)=ARF2(1)-SARF2+ECM2
NMA(1)=NMA(1)-ECM1
NPAD(1)=NPAD(1)-ECM+ABS(DNEXA(1))+ABS(DNMA(1))
NPA2(1)=NPA2(1)-ECM2
NND(1)=NND(1)-ECM-ECM2
150 CONTINUE
EBP=ABS(ELF(0))
IF (EBP.GT.0.0) THEN
WRA0=WRA(EBP)

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C      WRHO=WRH(EBP)
      WRNO=WRN(EBP)
      NPAD(0)=ABS(CIA(1)/CL/WRA0)
      NPHD(0)=ABS(CIH(1)/CL/WRH0)
      ENDIF
      EBP=ABS(ELF(IMESH))
      IF (EBP.GT.0.0) THEN
        WRA0=WRA(EBP)
        WRHO=WRH(EBP)
      C      NPAD(IMESH)=ABS(CIA(IMESH-1)/CL/WRA0)
      C      NPHD(IMESH)=ABS(CIH(IMESH-1)/CL/WRH0)
      C      NPADD=ABS(CIA(IMESH-1)/CL/WRA0)
      C      NPHDD=ABS(CIH(IMESH-1)/CL/WRH0)
      C      NND(0) =ABS((CIN(2))/CL/WRNO)
      C      PPP1=ABS(CIA(IMESH-1)/CL+CIH(IMESH-1)/CL)
      ENDIF
      NND(0) =0.0
      NPA2(0) =0.0
      NMH(0) =0.0
      NMA(0) =0.0
      NEXH(0)=0.0
      NEXA(0)=0.0
      IF (PE.EQ.0.0) ANE(0)=0.0
      ANED(0) =ANE(0)
      C      NPAD(IMESH)=NPADD
      C      NPHD(IMESH)=NPHDD
      C      ANED(IMESH)=NED
      C      WRITE(6,*)NED,NPADD,NPHDD
      C      CI(0) =0.0
      C      NPHD(IMESH) =0.0
      C      NPAD(IMESH) =0.0
      C      NND(IMESH) =0.0
      C      NPA2(IMESH) =0.0
      C      NMH(IMESH) =0.0

      NMA(IMESH) =0.0
      NEXH(IMESH)=0.0
      NEXA(IMESH)=0.0
      C      ANE(IMESH) =0.0
      C      ANED(IMESH) =0.0
      C      CI(IMESH) =0.0
      *****ENERGY CONSERVATION*****
      ICC=ICC+1
      IF (PE.EQ.1.0) THEN
        EN(0)=ENO
        EN(-1)=0.0
      ELSE
        EN(0)=0.0
        EN(-1)=0.0
      ENDIF
      EN(IMESH)=0.0
      EN(IMESH)=ENO
      DO 160 I=0, IMESH-1
        EBP=ABS(ELF(I))
        WV1=SIGN(WV(EBP),ELF(I))
        WVA=SIGN(WRA(EBP),ELF(I))
        WVH=SIGN(WRH(EBP),ELF(I))
        WVN=SIGN(WRN(EBP),ELF(I))
        VZ(I)=WV1
        CI(I)=CL*(ANED(I)*WV1+NPAD(I)*WVA+NPHD(I)*WVH+NND(I)*WVN)
        EV=EN(I)
      IF (ELF(I).GT.0.0) THEN
        EBP=ABS(ELF(I+1))
        WR1=WR(EBP)
      ELSE
        EBP=ABS(ELF(I-1))
        WR1=-WR(EBP)
      ENDIF
      EV=EN(I+1)

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DL1=DL(EV)
EV=EN(1)
DL2=DL(EV)
FAI(1)=-ANE(1)*WR1+(DL1*PR1*ANE(1+1)-DL2*PR1*ANE(1))*DLTZ1
IF (PE.EQ.0.0) FAI(0)=0.0
FAI(IMESH)=0.0
160 CONTINUE
DO 170 I=1, IMESH-1
IF (ELF(1).GT.0.0) THEN
EBP=ELF(1+1)
AA=(FAI(1)*EN(1)-FAI(1-1)*EN(1-1))*DLTZ1
ELSE
AA=(FAI(1)*EN(1)-FAI(1+1)*EN(1+1))*DLTZ1
EBP=ELF(1-1)
ENDIF
EV=EN(1+1)
DL1=DL(EV)
EV=EN(1)
DL2=DL(EV)
EV=EN(1-1)
DL3=DL(EV)
EV=EN(1)
BB=(DL1*PR1*ANE(1+1)*EN(1+1)-2.0*DL2*PR1*ANE(1)*EN(1)
> +DL3*PR1*ANE(1-1)*EN(1-1))*DLTZ12
EV=EN(1)
SS=
> PR*RIAR(EV) *ANE(1)*THIAR +PR*RIIE(EV) *ANE(1)*THIIE+
> PR*REXAR(EV)*ANE(1)*THEXAR+PR*REXIE(EV)*ANE(1)*THEXIE+
> PR*RMIEAR(EV)*ANE(1)*THMIEAR+PR*RMIEIE(EV)*ANE(1)*THMIEIE+
> PR*RAF2(EV) *ANE(1)*EN(1) +CIAR(1)/DLTT*THCIAR+
> DNEXA(1)/DLTT*THCEAR+DNND(1)/DLTT*THDF+DNMA(1)/DLTT*THOMAR
ENN(1)=
> (5.0/3.0*(AA+BB)-FAI(1)*EBP*PR-SS)*DLTT+EN(1)*ANE(1)

IF (ANED(1).LE.0.0) THEN
ENI(1)=0.0
ELSE
ENI(1)=ABS(ENN(1)/ANED(1))
ENDIF
170 CONTINUE
IF (PE.EQ.1.0) THEN
ENI(0)=ENO
ENI(-1)=0.0
EN(IMESH)=ENO
ELSE
ENI(0)=0.0
ENI(-1)=0.0
EN(IMESH)=ENO
ENDIF
ENI(IMESH)=ENO
DO 180 I=0, IMESH
EN(1)=ENI(1)
180 CONTINUE
RD1=0.0
CI2=0.0
CI21=0.0
CI22=0.0
CI23=0.0
CI24=0.0
CI3=0.0
VD=0.0
DO 190 I=0, IMESH
IF (1.EQ.0.OR.1.EQ.IMESH) THEN
DLTZ2=0.5*DLTZ
ELSE
DLTZ2=DLTZ
ENDIF
VD=VD+(-ELF(1)*DLTZ2)

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A(2, 3) = 0.0
A(2, 4) = 0.0
F(2) = (-EXRD * Y(2) + Y(4)) * EXL2D
A(3, 1) = 0.0
A(3, 2) = 0.0
A(3, 3) = 1.0
A(3, 4) = 0.0
F(3) = -Y(1) * EXC1D
A(4, 1) = 0.0
A(4, 2) = 0.0
A(4, 3) = 0.0
A(4, 4) = 1.0
F(4) = -(Y(2) - Y(1)) * EXC2D

DO 210 L = 1, MN
B(L) = F(L)
Y0(L) = Y(L)
210 CONTINUE
C IF (RD2.GT.1.0D+07.AND.RD2.LE.1.0D+08) H=5.0D-17
C IF (RD2.GT.1.0D+06.AND.RD2.LE.1.0D+07) H=5.0D-16
C IF (RD2.GT.1.0D+05.AND.RD2.LE.1.0D+06) H=5.0D-15
C IF (RD2.GT.1.0D+04.AND.RD2.LE.1.0D+05) H=5.0D-14
C IF (RD2.GT.1.0D+03.AND.RD2.LE.1.0D+04) H=5.0D-13
C IF (RD2.LE.1.0D+04) H=5.0D-13
C IF (RD2.LE.1.0D+03) H=5.0D-12
H=5.0D-15
MA=DLTT/H+1
DO 450 I = 1, MA
DO 280 LL = 1, MN - 1
L1 = LL + 1
C = A(LL, LL)
IF ((ABS(C)-1.0D-70).LT.0.0) THEN
L1 = LL
220 CONTINUE

A1=A(11,LL)
IF (A1.LT.1.0D-70) GOTO 230
L1 = L1 + 1
IF (L1.GT.MN) THEN
P = 0.0
GOTO 310
ENDIF
GOTO 220
230 CONTINUE
DO 240 K = LL, MN
C = A(LL, K)
A(LL, K) = A(11, K)
A(11, K) = C
240 CONTINUE
C = B(LL)
B(LL) = B(11)
B(11) = C
C = A(LL, LL)
ENDIF

DO 250 J = L1, MN
A(LL, J) = A(LL, J) / C
250 CONTINUE
B(LL) = B(LL) / C
DO 270 I1 = L1, MN
C = A(11, LL)
DO 260 J = L1, MN
A(11, J) = A(11, J) - C * A(LL, J)
260 CONTINUE
B(11) = B(11) - C * B(LL)
270 CONTINUE
280 CONTINUE
IF ((ABS(A(MN, MN))-1.0D-70).LT.0.0) GOTO 310
B(MN) = B(MN) / A(MN, MN)

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DO 300 K = 1 , MN - 1
LL = MN - K
L1 = LL + 1
DO 290 J = L1 , MN
B(LL) = B(LL) - A(LL, J) * B(J)
290 CONTINUE
300 CONTINUE
P = 1.0
310 IF (P.EQ.0.0) WRITE(7,*) 'NO SOLUTION'

X = X + H * 0.5
DO 320 L = 1 , MN
DD(L) = H * B(L)
Y(L) = Y0(L) + DD(L) * 0.5
320 CONTINUE

A(1, 1) = 1.0
A(1, 2) = 0.0
A(1, 3) = 0.0
A(1, 4) = 0.0
F(1) = (-EXR1 * Y(1) + Y(3) - Y(4)) * EXL1D
A(2, 1) = 0.0
A(2, 2) = 1.0
A(2, 3) = 0.0
A(2, 4) = 0.0
F(2) = (-EXRD * Y(2) + Y(4)) * EXL2D
A(3, 1) = 0.0
A(3, 2) = 0.0
A(3, 3) = 1.0
A(3, 4) = 0.0
F(3) = -Y(1) * EXC1D
A(4, 1) = 0.0
A(4, 2) = 0.0
A(4, 3) = 0.0

A(4, 4) = 1.0
F(4) = -(Y(2) - Y(1)) * EXC2D

DO 330 L = 1 , MN
B(L) = F(L)
330 CONTINUE

DO 400 LL = 1 , MN - 1
L1 = LL + 1
C = A(LL, LL)
IF ((ABS(C)-1.0D-70).LT.0.0) THEN
  LL = LL
340 CONTINUE
A1=A(LL, LL)
IF (A1.LT.1.0D-70) GOTO 350
  LL = LL + 1
  IF (LL.GT.MN) THEN
    P = 0.0
    GOTO 430
  ENDIF
  GOTO 340
350 CONTINUE
DO 360 K = LL , MN
C = A(LL, K)
A(LL, K) = A(LL, K)
A(LL, K) = C
360 CONTINUE
C = B(LL)
B(LL) = B(LL)
B(LL) = C
C = A(LL, LL)
ENDIF

DO 370 J = L1 , MN

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A(LL, J) = A(LL, J) / C
370 CONTINUE
B(LL) = B(LL) / C
DO 390 II = L1, MN
C = A(LL, LL)
DO 380 J = L1, MN
A(LL, J) = A(LL, J) - C * A(LL, J)
380 CONTINUE
B(LL) = B(LL) - C * B(LL)
390 CONTINUE
400 CONTINUE
IF ((ABS(A(MN, MN))-1.0D-70).LT.0.0) GOTO 430
B(MN) = B(MN) / A(MN, MN)
DO 420 K = 1, MN - 1
LL = MN - K
L1 = LL + 1
DO 410 J = L1, MN
B(LL) = B(LL) - A(LL, J) * B(J)
410 CONTINUE
420 CONTINUE
P = 1.0
430 IF (P.EQ.0.0) WRITE(7,*)'NO SOLUTION'
SCOUNT=1
X = X0 + SCOUNT * H
DO 440 L = 1, MN
Y(L) = Y0(L) + H * B(L)
Y0(L) = Y(L)
440 CONTINUE
450 CONTINUE
DELF3=(Y(4)-EXL2*F(2))
DELF3D=(Y(4)-EXL2*F(2))*D1*PR1
AELF=DELF3D
CDI=EPS*(AELF-AELF1)*PR*SA
ENDIF
*
***** POISSON'S EQUATION *****
*
EBP=ABS(ELF(0))
WVPE=WV(EBP)
EBP=ABS(ELF(1MESH))
WVPE1=WV(EBP)
DO 460 M=0, IMESH
ROU(M) =(NPHD(M)+NPAD(M)+NPA2(M)-NND(M)-ANED(M))
ROU1(M)=(NPHD(M)+NPAD(M)+NPA2(M)-NND(M)-ANED(M))
460 CONTINUE
ROU(IMESH+1)=0.0
ELFIN=0.0
ELFIN=EPS1*ROU(0)*((0.5*DLTZ)**2)*D1
DO 470 I=1, IMESH
DX=1*DLTZ+0.5*DLTZ
ELFIN=ELFIN-EPS1*(ROU(I))*DLTZ*DX*D1
470 CONTINUE
DO 490 I=0, IMESH
EIN=0.0
DO 480 J=1, IMESH
IF (J.EQ.0) THEN
DLTZ2=0.5*DLTZ
ELSE
DLTZ2=DLTZ
ENDIF
EIN=EIN+EPS1*(ROU(J))*DLTZ2
480 CONTINUE
ELF(1)=(ELFIN+EIN)*PR1+AELF
ELF1(1)=- (ELFIN+EIN)-AELF*PR
EBP=ABS(ELF(1))
490 CONTINUE
DO 500 I=0, IMESH

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```

DI(1)=-EPS*(ELF1(1)-ELF2(1))
500 CONTINUE
DO 510 I=0, IMESH
ANE(1)=ANED(1)
NPA(1)=NPAD(1)
NPH(1)=NPHD(1)
NN(1)=NND(1)
ELF2(1)=ELF1(1)
TI(1)=DI(1)+CI(1)
510 CONTINUE
ANED(0)=0.0
520 CONTINUE
*
***** SAMPLING *****
*
STIME=STIME+OUTP*DLTT
STIME=OUTP*DLTT*K1
WRITE(7,*) STIME
WRITE(8,*) STIME
DO 260 I=0, IMESH
DO 530 I=0, 20
PI=NPH(1)+NPA(1)+NPA2(1)
DT=I*DLTZ
EV=EN(1)
C RIA=PR*RIAR(EV)
C REXA=PR*REXAR(EV)
C RMEA=PR*RMEAR(EV)
C RAF=PR*RAF2(EV)
C RCIA=RCIAR(EV)*NMA(1)
WRITE(7,*) DT
WRITE(7,5100)PI,NN(1),NMA(1),NMH(1),ANE(1)
WRITE(7,5100)NPA(1),NPA2(1),ARF(1),ARF1(1),ARF2(1)
WRITE(7,5100)NCIAR(1),EN(1),VZ(1),ELF1(1),ROU1(1)
WRITE(7,5100)ARF0(1),PHOTO(1),PHOTO1(1)
C WRITE(7,5010)RIA,REXA,RMEA,RAF,RCIA
C WRITE(7,5010)ARF0(1),TI(1),DI(1),CI(1),CIN(1)
C WRITE(7,5010)PHOTO(1),CIE(1),CIA(1),CIH(1),CIN(1)
540 CONTINUE
EV=EN(ICAT)
RIAC=PR*RIAR(EV)
REXAC=PR*REXAR(EV)
RMEAC=PR*RMEAR(EV)
RAFC=PR*RAF2(EV)
RCIAC=RCIAR(EV)*NMA(ICAT)
EV=EN(1BL)
RIAB=PR*RIAR(EV)
REXAB=PR*REXAR(EV)
DI(1)=-EPS*(ELF1(1)-ELF2(1))
500 CONTINUE
DO 510 I=0, IMESH
ANE(1)=ANED(1)
NPA(1)=NPAD(1)
NPH(1)=NPHD(1)
NN(1)=NND(1)
ELF2(1)=ELF1(1)
TI(1)=DI(1)+CI(1)
510 CONTINUE
ANED(0)=0.0
520 CONTINUE
*
***** SAMPLING *****
*
STIME=STIME+OUTP*DLTT
STIME=OUTP*DLTT*K1
WRITE(7,*) STIME
WRITE(8,*) STIME
DO 260 I=0, IMESH
DO 530 I=0, 20
PI=NPH(1)+NPA(1)+NPA2(1)
DT=I*DLTZ
EV=EN(1)
C RIA=PR*RIAR(EV)
C REXA=PR*REXAR(EV)
C RMEA=PR*RMEAR(EV)
C RAF=PR*RAF2(EV)
C RCIA=RCIAR(EV)*NMA(1)
WRITE(7,*) DT
WRITE(7,5100)PI,NN(1),NMA(1),NMH(1),ANE(1)
WRITE(7,5100)NPA(1),NPA2(1),ARF(1),ARF1(1),ARF2(1)
WRITE(7,5100)NCIAR(1),EN(1),VZ(1),ELF1(1),ROU1(1)
WRITE(7,5100)ARF0(1),PHOTO(1),PHOTO1(1)

```



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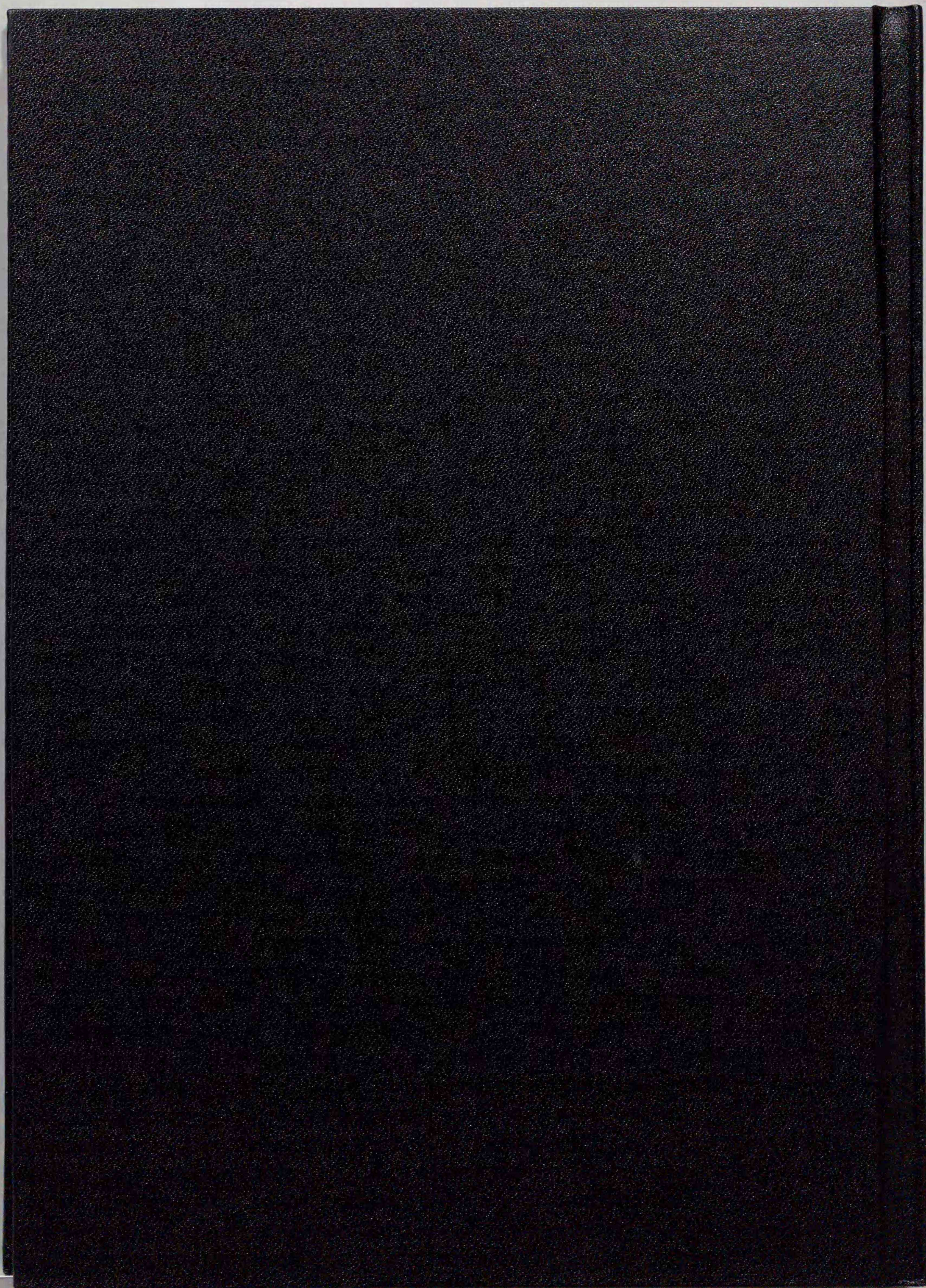
5100 FORMAT(5(D12.5,1X))
5200 FORMAT(3(D12.5,1X))
      STOP
      END

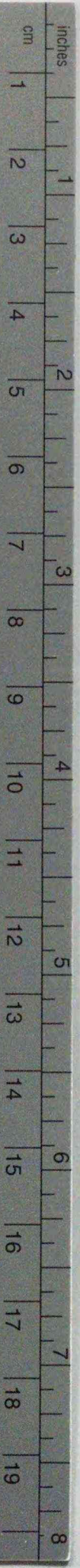
```

```

RMEAB=PR*RMEAR(EV)
RAFB=PR*RAF2(EV)
RCIAB=RCIAR(EV)*NMA( IBL)
EV=EN( IANO)
RIAA=PR*RIAR(EV)
REXAA=PR*REXAR(EV)
RMEAA=PR*RMEAR(EV)
RAFA=PR*RAF2(EV)
RCIAA=RCIAR(EV)*NMA( IANO)
FLA0=-FAI(1)
WRITE(8,5100)Y1,Y2,Y3,Y4,F(2)*EXL2
WRITE(8,5100)C12,C121,C122,C123,C124
WRITE(8,5100)C13,DEL3,AELF,RD1,FLA0
WRITE(8,5100)ANE( IBL),NPH( IBL)+NPA( IBL),NN( IBL),NPA( IBL),RD3
WRITE(8,5100)NMA( IBL),NPA2( IBL),NCIAR( IBL),NPH( IBL),RD4
WRITE(8,5100)ARF( IBL),ARF1( IBL),ARF2( IBL),ARF0( IBL),PHOTO( IBL)
WRITE(8,5100)-ELF1(0)*D,NN(0),NPH(0)+NPA(0),ANE(0),PHOTO1( IBL)
WRITE(8,5100)-ELF1( ICAT)*D,-ELF1( IBL)*D,-ELF1( IANO)*D
WRITE(8,5100)EN( ICAT),EN( IBL),EN( IANO)
WRITE(8,5100)ANE( ICAT),ANE( IBL),ANE( IANO)
WRITE(8,5100)NN( ICAT),NN( IBL),NN( IANO)
WRITE(8,5100)RIAC,REXAC,RMEAC,RAFC,RCIAC
WRITE(8,5100)RIAB,REXAB,RMEAB,RAFB,RCIAB
WRITE(8,5100)RIAA,REXAA,RMEAA,RAFA,RCIAA
      CALL ETIME( ITIM0)
      ITIM1=INT( ITIM0/60.0)
      ITIM2=ITIM0-ITIM1*60.0
      WRITE(7,*)' MIN:SEC=',ITIM1,':',ITIM2
550 CONTINUE
      CALL ETIME( ITIM0)
      ITIM1=INT( ITIM0/60.0)
      ITIM2=ITIM0-ITIM1*60.0
      WRITE(7,*)' MIN:SEC=',ITIM1,':',ITIM2
5000 FORMAT(4(D12.5,1X))

```

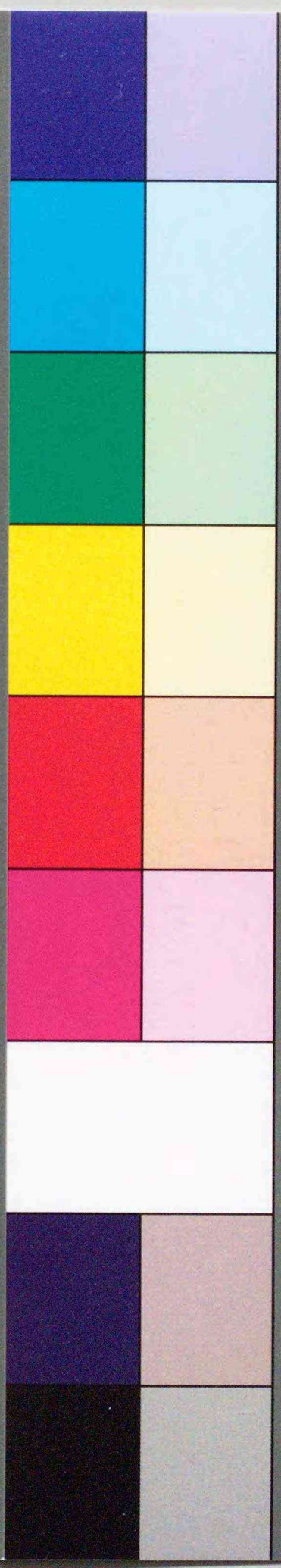





Kodak Color Control Patches

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Blue Cyan Green Yellow Red Magenta White 3/Color Black



Kodak Gray Scale



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A 1 2 3 4 5 6 M 8 9 10 11 12 13 14 15 B 17 18 19

