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VISIBLE LASER DISCHARGE STUDIES

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VISIBLE LASER DISCHARGE STUDIES QUARTERLY PROGRESS REPORT

Task II

Introduction

Plasma return current discharge technique is based on the utilization of the return current to produce a volumetrically large plasma. This discharge technique has two important uses;

- (a) It is a very convenient way of studying processes such as ionization, attachment and discharge stability over a wide range of pressures and discharge conditions.
- (b) It is also useful for pumping visible and UV lasers at low pressures. The discharge operation for this case is not limited to high pressures (≥ 1 atm) since energy is coupled into the discharge through the return current. Furthermore, because the e-beam current is exactly cancelled by the return current in steady state, current and aperture scaling are not limited by; (a) beam pinching due to the magnetic field of the discharge; and (b) skin effect or inductance.

Theory

The plasma return current discharge is a method in which an e-beam is fired through a grounded wire mesh and collected on a floating plate some distance from the wire mesh. On the way to the plate, the beam ionizes the neutral gas (laser mixture) in its path so that a tenuous plasma is formed. Since the beam collector plate is floating, it will quickly charge negatively

until it reaches a potential that is sufficient to drive a plasma return current equal in magnitude but in the opposite direction of the e-beam current. The plasma return current is driven by an electric field E given by

$$E = - \rho J_b = \rho J_p \quad (1)$$

where ρ is the plasma resistivity J_b , the beam current density and J_p , the plasma return current density. Initially, the secondary electron density is low and consequently the resistivity and, the electric field are large. Very rapidly, however, the electric field heats the plasma electrons and avalanches the plasma density. The electric field then self-adjusts to a value, which in the case of constant beam current, is just sufficient to produce a total ionization rate equal to the loss of electrons due to recombination or attachment. Because of this mechanism, the discharge is inherently stable.

The purpose of the present effort is to develop a numerical model for the plasma return current discharge for a wide range of discharge conditions likely to be encountered in making visible lasers. The resulting model will be used to calculate the temporal variation of the electric field and secondary electron density as a function of the following parameters:

- (1) e-beam current density
- (2) gas composition
- (3) gas pressure

A representative numerical formulation would proceed as follows. Since the plasma return current density, J_p , is equal and opposite to the e-beam current density, J_b , hence

$$J_b = e n_e V_D (E/N, n^*/n) \quad (2)$$

where n_e is the plasma electron density, e the electronic charge and V_D , the drift velocity. In general the drift velocity is a function of the electric field, neutral density (i.e., gas pressure) and the fractional population of the excited states. In addition for cases where electron-electron collisions play an important role; the effect of these collisions on the drift velocity must be accounted for. Equation (2) when used in conjunction with the Boltzmann code and relevant kinetics code would provide the time evolution of the electric field and secondary electron density. In general, a complete theoretical description requires the solution of the coupled Boltzmann transport equation for the electrons and the kinetic equations for the excited and ionic states of the atoms. Although such numerical techniques have been developed; considerable computation time and expenses can be saved by using a quasi-steady technique. This technique employs a procedure in which various rates of excitation and ionization of species constituting the gas mixture is determined by seeking steady state solution of the Boltzmann equation. These rates are determined for different apriori selected values of the parameters E/N and n^*/n . Thus determined values are utilized in the solution of the kinetic rate equations for excited and ionic states. The coupling of the results from the Boltzmann code and kinetic rate equations is based on utilizing Eq. (2). If an initial value of electron density is assumed, Eq. (2) can be used to determine V_D for a given J_b . Using this value of V_D and an initial value of n^*/n ; the relevant rates to be used in the kinetic rate equations are determined by a two-dimensional interpolation technique. The results of this interpolation are then used in the kinetics code which yields a new value of n_e and n^*/n for a small increment in time. Repetition of the above procedure leads to the time evolution of the electron density and discharge electric field.

Results

Using the procedure described above, the following studies for plasma return current discharge were made:

- (1) Helium, Krypton with small percentage of fluorine added (representative of attachment-dominated discharges).
- (2) Pure Argon at 1, 5 and 10 torr (representative of discharges in the rare gases). Two different high e-beam energies of .15 MeV and 1.5 MeV were considered for this case.
- (3) Argon at 10 and 100 torr with small percentages of SF₆ added (representative of attachment-dominated discharges).

In order to demonstrate the concept of pumping through plasma return current discharge, we have made an analytical and experimental investigation in mixtures of F₂/Kr/He. We will discuss, here, the analytical modeling and compare the results of this modeling to measured data. Unfortunately there is no published data on the electron impact cross-sections of F₂. For this reason we have neglected the effects of fluorine on the secondary electron distribution. The electron impact cross-sections of F₂ could be large enough to change the Boltzmann code predictions of excitation and ionization rates by as much as 20%. The cross-sections for Helium and Krypton were taken to be those given in Refs. 1, 2, 3 and 4. The excited state Krypton, Kr*, plays an important role in such discharges⁽⁵⁾ and therefore, we have included the Krypton metastable in our Boltzmann code calculations. The cross-sections for Krypton metastable were taken to be those from Ref. 5. We have used the various cross-sections for a

mixture of $\text{Kr}/\text{Kr}^*/\text{He}$ in our Boltzmann code in order to predict the relevant rates (that are required in our kinetics code) as a function of:

- (1) electric field (E/N)
- (2) fractional Krypton metastable population (Kr^*/Kr)

The output of the Boltzmann code is then coupled to the kinetics code that solves the kinetic rate equations for the time evolution of ionic and excited states through a two-dimensional interpolation routine. Figure 1 shows the results of our calculation. We have plotted the measured electric field at 400 ns after initiation of the e-beam versus F_2 number density at various total gas pressures. Also shown are the detailed computer kinetic model calculations of the self-consistent electric field. In general, experimental results agree well with theoretical predictions for high F_2 concentrations and low pressures. The disagreement at low F_2 concentration and high total pressure is probably due to two effects:

- (1) The effects of F_2 on the secondary electron distribution.
- (2) Our kinetic model neglects the electron impact ionization from high lying excited states of Kr.

In order to predict the time evolution of the self-consistent electron density of plasma return current discharge in pure argon, we have made kinetic calculations at various total pressures and current densities for a monoenergetic e-beam of 0.15 MeV. Discharges of this type are representative of the discharges in rare gases. Figures 2 and 3 show the electron density and electric field at total pressures of 1-10 torrs and e-beam current density of 100 A/cm^2 . It is observed from Fig. 3 that initially the electric field generated in the plasma is large which heats and avalanches the electron

Fig. 1 Calculated and Measured E-field vs F₂ Number Density at Various Total Pressures

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Fig. 2 Temporal Variation of Electron Density for E-beam Current Density (J_{eb}) of 100 A/cm^2

Fig. 3 Temporal Variation of Electric Field for $J_{eb} = 100 \text{ A/cm}^2$

density. The electric field subsequently rapidly drops. It is noted from this figure that the equilibrium condition has not been achieved for this case until about $.5 \mu\text{sec}$. Ultimately, however, we expect the electric field to asymptote at $.7 \mu\text{sec}$. These figures also show the results at an increased pressure of 5.0 torr. The qualitative behavior of the electron density and the electric field is similar to that of 1.0 torr, however, it is observed that the electron density is larger (Fig. 2) and the electric field is lower at higher pressures at all times. This trend continues when the mixture pressure was further increased to 10.0 torr. We have also calculated the time evolution of electron density and the electric field for e-beam current densities of 10 A/cm^2 and 1 A/cm^2 for different total pressures of 1.0, 5.0 and 10.00 torr. The results for these calculations are fundamentally similar in character. These predictions can be fruitfully used in future plasma return current discharge studies. Figures 4-7 show the results for these calculations. Figures 8-9 show a similar calculation for argon when a small percentage of SF_6 (0.5%) was added. We have not included SF_6 in our Boltzmann analysis due to lack of sufficient information on electron impact cross sections. The attachment rate for SF_6 were obtained from Ref. 6. From these calculations it is observed that the attaching species, SF_6 , tends to equilibrate the electron density on a shorter time scale (see Figs. 8-9 as compared to Figs. 4-5).

Fig. 4 Temporal Variation of Electron Density for $J_{eb} = 10 \text{ A/cm}^2$

Fig. 5 Temporal Variation of Electric Field for $Jeb = 10 A/cm^2$

Fig. 6 Temporal Variation of Electron Density for $J_{EB} = 1 \text{ A/cm}^2$

Fig. 7 Temporal Variation of Electric Field for $J_{EB} = 1 \text{ A/cm}^2$

Fig. 8 Temporal Evaluation of Electron Density in Argon and SF_6

Fig. 9 Temporal Evolution of Electric Field in Argon and SF_6 Mixture

REFERENCES

1. A. Gilardini, Low Energy Electron Collisions in Gases, John Wiley and Sons, N. Y., 1972.
2. D. Rapp and P. Englanders-Golden, J. Chem. Phys. 43, 1464 (1965).
3. S. T. B. Corrigan and Engel, Pro. Soc. Lond., 72, 786 (1958).
4. L. S. Frost and A. V. Phelps, Phys. Rev., 136, A 1538-1545 (1964).
5. J. H. Jacob and J. A. Mangano, Appl. Phys. Lett., Vol. 28, No. 12, 724 (1976).
6. L. G. Christophorou, D. L. McCorkle and J. G. Carter, J. Chem. Phys., Vol. 54, 1, 253 (1971).