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NEW DISCHARGE PUMPING METHOD FOR CO<sub>2</sub> LASER

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FINAL TECHNICAL REPORT

Sponsored by

Defense Advanced Research Projects Agency (DoD)  
Defense Small Business Innovation Research Program

ARPA Order No. 5916

Issued by U.S. Army Missile Command Under  
Contract #DAAH01-86-C-1074

Contract Dates: September 26, 1986 - May 30, 1987

Prepared by

Dr. Jonah H. Jacob

617-547-1122

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REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION <b>Unclassified</b>		1b. RESTRICTIVE MARKINGS <b>None</b> <b>A181 635</b>	
2a SECURITY CLASSIFICATION AUTHORITY <b>N/A</b>		3 DISTRIBUTION/AVAILABILITY OF REPORT <b>Unlimited</b>	
2b DECLASSIFICATION/DOWNGRADING SCHEDULE <b>N/A</b>		5 MONITORING ORGANIZATION REPORT NUMBER(S)	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) <b>01/F/1987</b>		7a NAME OF MONITORING ORGANIZATION <b>U.S. Army Missile Command</b>	
6a. NAME OF PERFORMING ORGANIZATION <b>Science Research Laboratory</b>		6b. OFFICE SYMBOL (if applicable)	
6c. ADDRESS (City, State, and ZIP Code) <b>15 Ward St. Somerville, MA 02143</b>		7b. ADDRESS (City, State, and ZIP Code) <b>AMSMI-PC-BFA/DARPA Proj OFC Ms. Goldie Hill Redstone Arsenal, AL 35898-5280</b>	
8a. NAME OF FUNDING/SPONSORING ORGANIZATION <b>DARPA</b>		8b. OFFICE SYMBOL (if applicable)	
8c. ADDRESS (City, State, and ZIP Code) <b>1400 Wilson Blvd. Arlington, VA 22209</b>		9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER <b>DAAH01-86-C-1074</b>	
11 TITLE (Include Security Classification) <b>New Discharge Pumping Method for CO<sub>2</sub> Lasers (U)</b>		10 SOURCE OF FUNDING NUMBERS	
12. PERSONAL AUTHOR(S) <b>Jonah Jacob</b>		PROGRAM ELEMENT NO	PROJECT NO <b>PAN:RADB1-6</b>
13a. TYPE OF REPORT <b>Final Technical</b>		13b. TIME COVERED FROM <b>9/26/86</b> TO <b>5/30/87</b>	TASK NO
14. DATE OF REPORT (Year, Month, Day) <b>May 27, 1987</b>		15. PAGE COUNT <b>49</b>	
16 SUPPLEMENTARY NOTATION			
17 COSATI CODES		18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUB-GROUP	
19 ABSTRACT (Continue on reverse if necessary and identify by block number)			
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20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS		21 ABSTRACT SECURITY CLASSIFICATION <b>Unclassified</b>	
22a. NAME OF RESPONSIBLE INDIVIDUAL <b>Jonah Jacob</b>		22b. TELEPHONE (Include Area Code) <b>617-547-1122</b>	22c. OFFICE SYMBOL

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Unannounced	<input type="checkbox"/>
Justification	
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Distribution/	
Availability Codes	
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## NEW DISCHARGE PUMPING METHOD FOR CO<sub>2</sub> LASERS

### ABSTRACT

A new pulsed laser discharge concept is proposed to meet military and civilian requirements for efficient operation of compact, high energy CO<sub>2</sub> lasers. This discharge concept promises pulse lengths of up to 100 microseconds duration, scalability to multi-kilojoule single pulsed energy, high volumetric efficiency ( $\geq 50$  Joules/liter-atm) and high electrical efficiency ( $\geq 20\%$ ). This discharge concept relies on a new method for maintaining discharge stability for long pulse durations. This new CO<sub>2</sub> laser discharge concept promises increased efficiency, repetition rate, laser pulse length, extracted energy per unit volume and reliability. The concept utilizes a current source to insure volumetric stability. Such a source will not stabilize the discharge against streamer formation. Streamer formation can be inductively inhibited by the use of RF. Hence an RF current source could result in a more stable laser discharge.

## 1.0 INTRODUCTION

A new laser discharge concept has been identified which is compatible with military and civilian applications which require efficient operation of compact high power CO<sub>2</sub> lasers. This concept is based on a new discharge method which will insure the macroscopic and microscopic stability of the discharge at high pump power density and for long pulse lengths. This discharge concept promises pulse lengths of up to 100 microseconds duration, scalability to multi-kilojoule single pulse energy, high volumetric efficiency (up to 50 Joules/liter-atm), and high electrical efficiency. This new discharge method utilizes spatially uniform x-ray or UV preionization of the laser medium followed by a discharge pulse which initially supplies a voltage across the discharge electrodes, approximately equal to twice the sustaining voltage, to avalanche the electron density uniformly to  $10^{12}$  electrons/cm<sup>3</sup>. The current source drive prevents volumetric discharge instabilities. The oscillating discharge voltage prevents localized electron density avalanche by controlling the ionization and recombination during the peaks and valleys of waveform and by limiting, by inductance, the localization of discharge current.

In Section 2 of this report the analytical and numerical model of this new CO<sub>2</sub> laser discharge concept is presented, regions of stable discharge operation and efficient CO<sub>2</sub> laser performance will be identified. In Section 3 this model is applied to the special case of a CO<sub>2</sub> laser discharge. Section 4 discusses inductive stabilization by the use of RF. Section 5 discusses the impact of RF on the CO<sub>2</sub> laser



operation. In Section 6 this report a conceptual design for a single pulse CO<sub>2</sub> laser experiment which can be used to validate this new discharge concept is presented.

## 2.0 VOLUMETRIC DISCHARGE STABILITY MODEL

Two rate equations are important in determining the stability of the discharge. The first is the electron production and loss

$$\frac{dn_e}{dt} = \nu n_m n_e - \alpha n_e^2 - \beta n_e \quad (1)$$

and the second is the metastable production and loss

$$\frac{dn_m}{dt} = \langle \sigma v \rangle n_e n_a - n_m / \tau_m \quad (2)$$

where  $n_e$  is the electron density,  $n_m$  is the metastable density,  $\alpha$  is the recombination rate,  $\beta$  is the attachment rate,  $\langle \sigma v \rangle$  is the electron impact metastable production rate constant and  $\tau_m$  is the metastable lifetime. The ionization rate constant  $\nu$  in Eq. (1) is assumed to be the result of metastable ionization. Since the metastable levels have a much smaller ionization energy than the ground state the ionization rate of the discharge is dominated by electron impact ionization of the metastables. The stability of Eqs. (1) and (2) will be analyzed for both current and voltage sources and for a voltage source having an arbitrary impedance.

### 2.1 STABILITY OF THE DISCHARGE DRIVEN BY A VOLTAGE SOURCE

The rate Eqs. (1) and (2) are a pair of nonlinear simultaneous differential equations. If the discharge electric field (voltage source) is constant in time they can be solved by a perturbation analysis around the steady state, i.e.,

$$n_e = n_{e0} + \delta n_e \quad (3)$$



and

$$n_m = n_{m0} + \delta n_m \quad (4)$$

Substituting Eqs. (3) and (4) into (1) and (2) and seeking solutions of the form  $\delta n_m \sim \exp(-i\omega t)$  results in the following quadratic equation in  $\omega$

$$\omega^2 + i\omega \left( \alpha n_{e0} + \frac{1}{\tau_m} \right) + \frac{\beta}{\tau_m} = 0 \quad (5)$$

The two roots of (5) are

$$\omega_{\pm} = -\frac{i}{2} \left[ \left( \alpha n_{e0} + \frac{1}{\tau_m} \right) \pm \left\{ \left( \alpha n_{e0} + \frac{1}{\tau_m} \right)^2 + \frac{4\beta}{\tau_m} \right\}^{1/2} \right] \quad (6)$$

From Eq. (6) one can draw the following conclusions for a voltage source driven discharge

(a) The discharge is marginally stable when the attachment rate  $\beta$  is zero. The two roots are  $\omega_1 = 0$  (marginally stable) and  $\omega_2 = -i(\alpha n_{e0} + 1/\tau_m)$  decaying.

(b) For a finite attachment rate there are no stable roots. For a recombination dominated discharge, the decaying root is the same as for the case with zero attachment and growing root is given by

$$\omega_1 = \beta (1 + \alpha n_{e0} \tau)^{-1}$$

To verify these solutions Eqs. (1) and (2) have been numerically integrated and the results are shown in Figs. 1, 2 and 3.

Figure 1 shows plots of  $n_e$  and  $n_m$  as a function of time for the special case of zero attachment.  $n_{e0}$  was initialized to  $10^{14} \text{ cm}^{-3}$  and  $n_{m0}$  to zero. The electron density decreases rapidly initially until

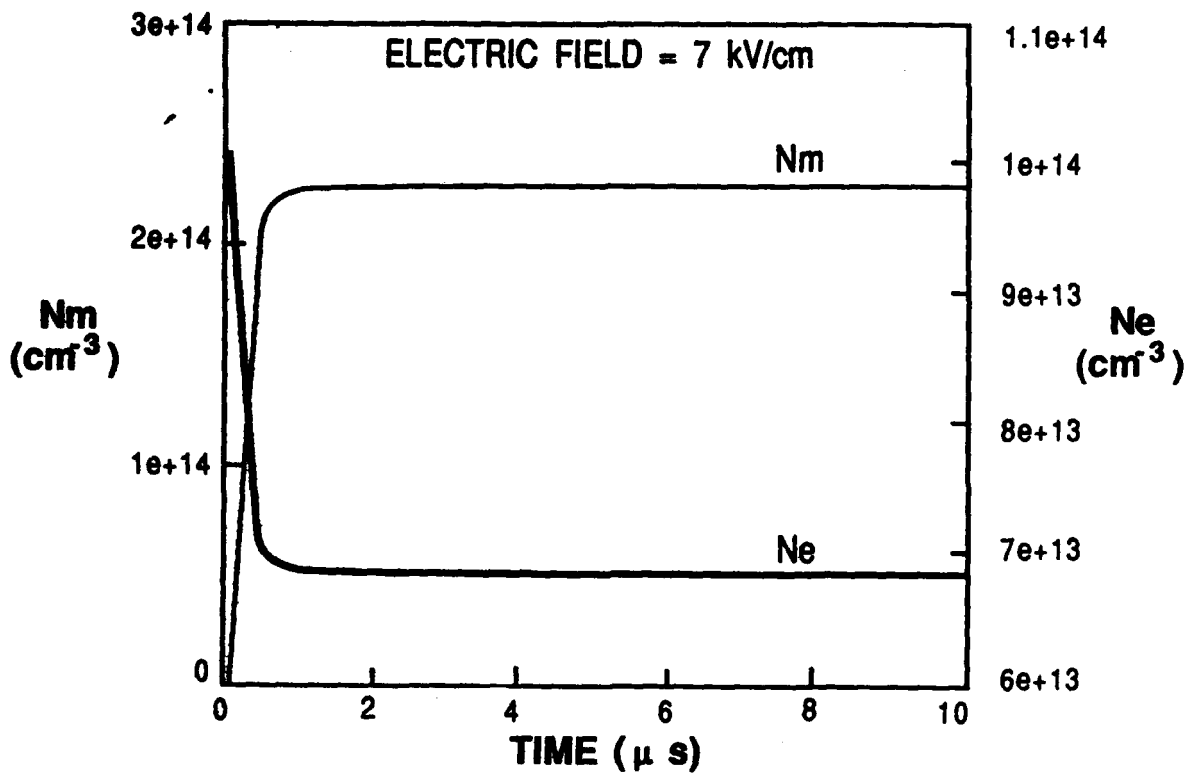


Figure 1



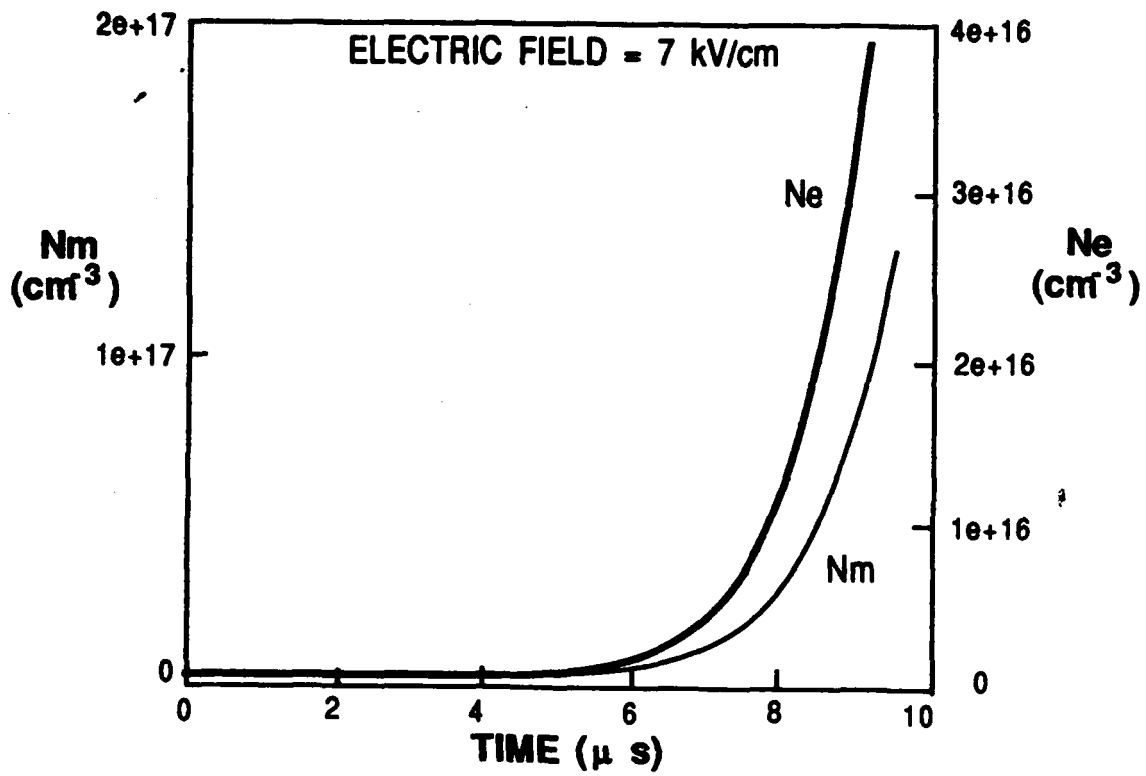


Figure 2

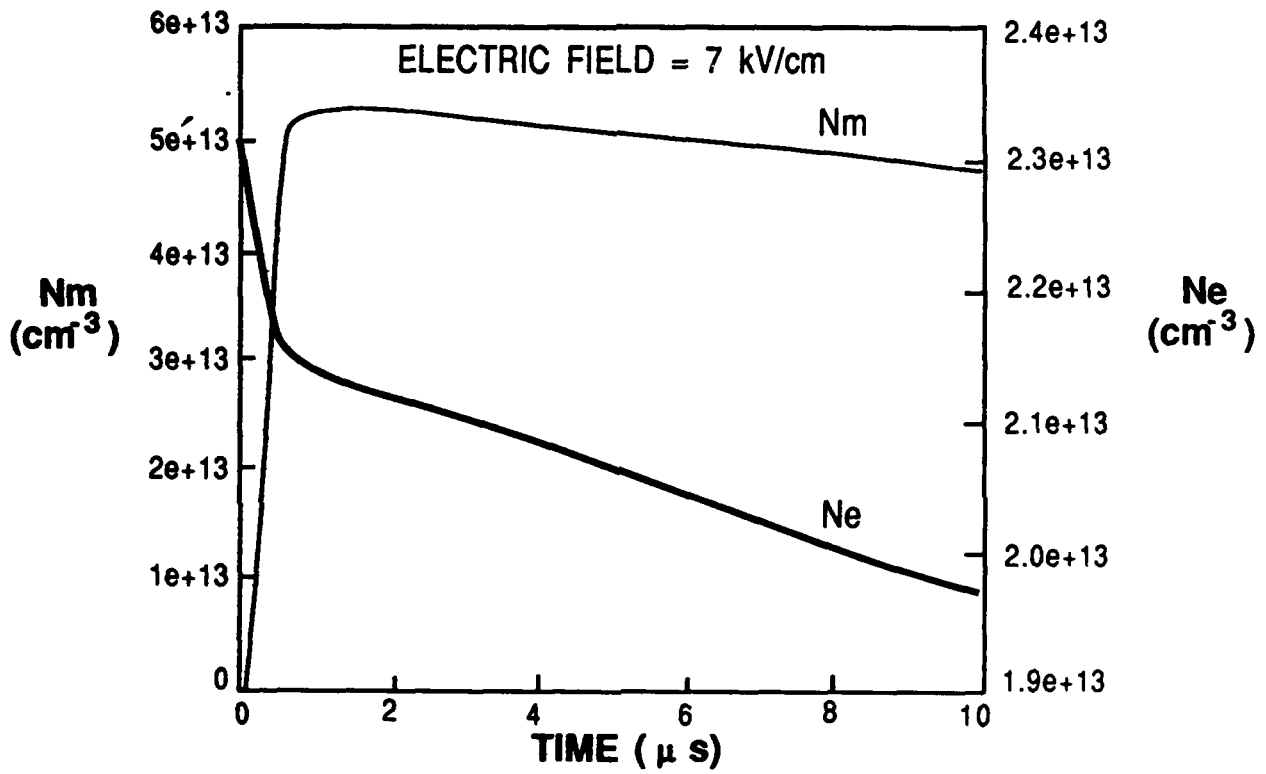


Figure 3



the metastable density reaches a steady state value of about  $2.2 \times 10^{14}$ . The electron density then stabilizes at a density of  $7 \times 10^{13} \text{ cm}^{-3}$ .

Figure 2 shows the result of introducing a small amount of attachment (i.e.,  $\beta = 10^5 \text{ sec}^{-1}$ ). Again the initial  $n_{e0}$  and  $n_m$  were  $10^{14} \text{ cm}^{-3}$  and zero notice that the discharge is unstable. However, if the initial electron density is chosen to be  $2 \times 10^{13} \text{ cm}^{-3}$  the discharge decays. By inspecting Eqs. (1) and (2) in the presence of attachment it can be shown that there exists critical electron density

$$n_{ec} = \beta (\nu \langle \sigma v \rangle \tau_m n_m - \alpha)^{-1}$$

For an initial electron density,  $n_{e1} > n_{ec}$  the discharge is unstable and for  $n_{e1} < n_{ec}$  the discharge is quenched.

## 2.2 STABILITY OF A DISCHARGE DRIVEN BY A CURRENT SOURCE

Next, Eqs. (1) and (2) will be investigated for the case of constant current source. A constant current source implies that

$$J_d = n_e v_d e = \text{const}$$

and any perturbation in the electron density must immediately result in a perturbation of the drift velocity  $v_d$ , i.e.,

$$\delta(v_d) = -v_{d0} \frac{\delta n_e}{n_{e0}} \quad (7)$$

This change in  $v_d$  can only result from change in the electric

field E

$$\delta E = (\partial v_d) \left( \frac{\partial v_{d0}}{\partial E} \right)^{-1} = - \frac{v_{d0}}{v_{d0}} \frac{\delta n_{e0}}{n_{e0}} \quad (8)$$

For CO<sub>2</sub> laser mixtures ( $\partial v_{d0}/\partial E$ ) > 0 and so Eq. (8) implies that an increase in n<sub>e</sub> leads to a decrease in the electric field which leads to subsequent decrease in production of the metastables and electrons.

The linearized rate equations for a current source drive can be written as

$$\frac{d(\delta n_m)}{dt} = n_{e0}(n_{m0}r' - n_{e0}\alpha') \delta E + \nu n_{e0} (\delta n_m) + (\nu n_{m0} - 2\alpha n_{e0}) \delta n_e \quad (9)$$

$$\frac{d(\delta n_e)}{dt} = \langle \sigma v \rangle n_a n_{e0} (\delta E) - \frac{1}{\tau_m} (\delta n_m) + \langle \sigma v \rangle n_a (\delta n_e) \quad (10)$$

Substituting Eq. (8) into (9) and (10) and assuming the form  $\delta n_{e,m} \sim \exp(-i\omega t)$  and that  $\alpha$  is small one gets

$$\nu n_{e0} (\delta n_m) + \left( i\omega + \nu n_{m0} - 2\alpha n_{e0} - \frac{v_{d0} n_{m0} r'}{v_d'} + \frac{\alpha' n_{e0} v_{d0}}{v_d} \right) \delta n_e = 0 \quad (11)$$

and

$$i\omega - \frac{1}{\tau} (\delta n_m) + \left( \langle \sigma v \rangle n_a - \frac{n_a v_{d0} \langle \sigma v \rangle'}{v_d} \right) \delta n_e = 0 \quad (12)$$

Equations (11) and (12) can be combined to give

$$\omega^2 + i\omega \left( \alpha n_{e0} + \frac{1}{\tau_m} + \frac{v_{d0} n_{m0} r'}{v_d} - \alpha \frac{v_{d0} n_{e0}}{v_d'} \right) - \frac{\nu v_{d0} n_{m0}}{v_d \tau_m} \left( \frac{r'}{\nu} + \frac{\langle \sigma v \rangle'}{\langle \sigma v \rangle} - \frac{\alpha'}{\alpha} \right) \quad (13)$$



The two roots of the equations are

$$\omega_{\pm} = -\frac{i}{2} [A \pm (A^2 + 4B)^{1/2}] \quad (14)$$

where

$$A = \alpha n_{e0} + \frac{1}{\tau_m} + \frac{v_{d0} n_{m0} v'}{v_d} - \alpha' \frac{v_{d0}}{v_d'} n_{e0} \quad (15)$$

and

$$B = -\frac{v v_{d0} n_{m0}}{v_d' \tau_m} \left( \frac{v'}{v} + \frac{\langle \sigma v \rangle}{\langle \sigma v \rangle} - \frac{\alpha'}{\alpha} \right) \quad (16)$$

At the electric fields that result in efficient laser operation both  $v'$  and  $\langle \sigma v \rangle'$  are positive and  $\alpha'$  is negative, and hence  $B$  is negative and both roots of Eq. (14) results decaying exponentials, i.e. the system becomes absolutely stable. Physically this comes about because any increase in the current will result in a decrease in the electric field and hence in the rate constants for the metastable production and ionization will decrease. In the presence of attachment Eq. (13) becomes

$$\omega^2 + i\omega A + \left( \frac{B}{\tau_m} + B \right) = 0 \quad (17)$$

So when  $B > |B\tau_m|$  the one of the roots are unstable, when  $B = |B\tau_m|$  the discharge is marginally stable and when  $B < |B\tau_m|$  the discharge is absolutely stable. Physically Eq. (17) says that the discharge is marginally stable if the electron production rate is not a function of the electric field. However, if the electron production rate decreases as the electric field increases (i.e.,  $B < |B\tau_m|$ ) the discharge is stable and if the electron production rate increases as the electric field decreases the discharge is unstable

### 2.3 FINITE IMPEDENCE VOLTAGE SOURCE

In practice one does not have either a voltage or a current source and so it is important to consider the effect of a finite impedance circuit on the stability of the laser discharge. A simplified circuit of the discharge and power supply is shown in Fig. 4. The power supply is assumed to be a voltage source  $V$  with an internal impedance  $\rho$ . The current  $J$  through the discharge is given by

$$J = (V - E)/\rho \quad (18)$$

where  $E$  is the electric field in the discharge. For simplicity the discharge is assumed to be a cubic centimeter. The perturbed current  $\delta J$  can be written as

$$\delta J = - \delta E/\rho = e v_{d0} \delta n_e + e n_e \delta v_{d0}$$

or

$$\delta E_0 = - e v_{d0} (\delta n_e) \left( \frac{1}{\rho} + e n_e v_{d0} \right)^{-1} \quad (19)$$

Comparing this to Eq. (8) one finds that the stability criteria developed in the previous section are valid provided  $v_d$  is replaced by

$$v_{d1} \rightarrow v_d + \frac{v_{d0}}{e \rho n_{e0}}$$



## GENERAL CIRCUIT MODEL

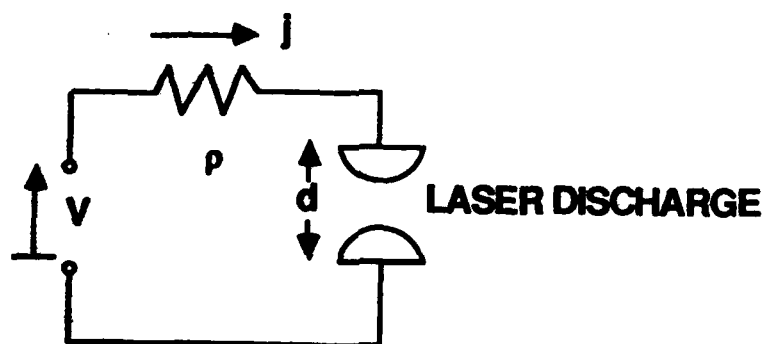


Figure 4

or 
$$v_{d1}' \rightarrow v_d' + \frac{v_{d0}}{E} \frac{\rho_{disc}}{\rho} \quad (20)$$

where 
$$\rho_{disc} = \frac{E}{J} \quad (21)$$

It is interesting to note that for a PFN supply  $\rho_{disc} = \rho$  and equation predicts that B as defined (16) decreases approximately by a factor of two. Also as  $\rho \rightarrow 0$ ,  $v_{d1} \rightarrow \infty$  and the stability criteria for a voltage source are recovered. When  $\rho \rightarrow \infty$ ,  $v_{d1} \rightarrow v_d$  and the stability criteria for a current source are recovered.

The volumetric discharge stability analysis presented in this section is summarized in Table I for the three discharge sources, voltage current and resistive sources. The voltage source is marginally stable for a discharge whose electron loss is only via recombination, any attachment, however, small results in an unstable discharge. The current and resistive sources have stable operating regions. The stable region decreases as the attachment rate increases and as the resistance of the source decreases. In the remainder of this section these regions of stable operation will be evaluated for the special case of a CO<sub>2</sub> laser discharge.

**TABLE I**  
**VOLUMETRIC DISCHARGE STABILITY**  
**CONCLUSIONS**

ELECTRON LOSS MECHANISM			
DISCHARGE POWER SOURCE	RECOMBINATION (ZERO ATTACHMENT)	ATTACHMENT DOMINATED	RECOMBINATION AND ATTACHMENT
● VOLTAGE SOURCE	— MARGINALLY STABLE	— UNSTABLE	— UNSTABLE
● CURRENT SOURCE	— STABLE OPERATING REGION*	— STABLE OPERATING REGION*	— STABLE OPERATING REGION*
● RESISTIVE SOURCE	— STABLE OPERATION REGION**	— STABLE OPERATING REGION**	— STABLE OPERATING REGION**

\*  $|B| > \beta / \tau_m$  where  $B = -v \frac{n m_0}{\tau_m}$   $\frac{V_d}{V_{d'}} \left( \frac{\langle \sigma v \rangle'}{\langle \sigma v \rangle} + \frac{v'}{v} - \frac{\alpha'}{\alpha} \right)$

\*\*  $\frac{V_{d'}}{V_d} \rightarrow \frac{V_{d'}}{V_d} + \frac{1}{E} \left( \frac{P_{disc}}{\rho} \right)$

### 3.0 MODELLING THE CO<sub>2</sub> LASER DISCHARGE

The discharge model developed so far will be applied to the specific case of a CO<sub>2</sub> laser discharge. Before this can be done, however, one has to know the relevant rate constants for the CO<sub>2</sub> mixture as a function of electric field. The mixture of choice for this effort is a 3/2/1, He/N<sub>2</sub>/CO<sub>2</sub> mixture. The rate constants for the ionization and excitation of the electronic states of N<sub>2</sub>, the fraction of discharge energy that goes into vibration excitation, the drift velocity and electron temperature as predicted by the Boltzmann code are shown in Figs. 5 and 6. From Fig. 5 which is a plot of T<sub>e</sub>, v<sub>d</sub> and efficiency of exciting the vibrational levels of N<sub>2</sub>, it is clear that efficient CO<sub>2</sub> operation occurs between 5-10 kV/cm.

Figure 6 shows the variation  $\nu$  and  $\langle\sigma v\rangle$  as a function of the electric field. Also shown in Fig. 6 is the curve for the ionization from the ground state. The curve for  $\langle\sigma v\rangle$  shown in Fig. 6 is the total excitation rate constant for all the electronic levels. This was chosen since it is difficult to identify the relevant metastable or electronic state that will be subsequently ionized. It is probable that this state will be a high lying state such as the C state of N<sub>2</sub>. The metastable ionization rate constant  $\nu$  has the same shape as the electron impact ionization of the N<sub>2</sub> (a  $\Sigma_u$ ),<sup>(1)</sup> its magnitude, however, was increased by 10<sup>2</sup>. Since this state is about 9 eV below the ionization level of N<sub>2</sub> as opposed to the C level which is only 6 eV below the ionization level. From this figure it is clear that  $\nu_m \ll \nu$  and so for any reasonable metastable density ( $n_m > 10^{12} \text{ cm}^{-3}$ ) the metastable ionization will be dominant. Figure 7 shows the



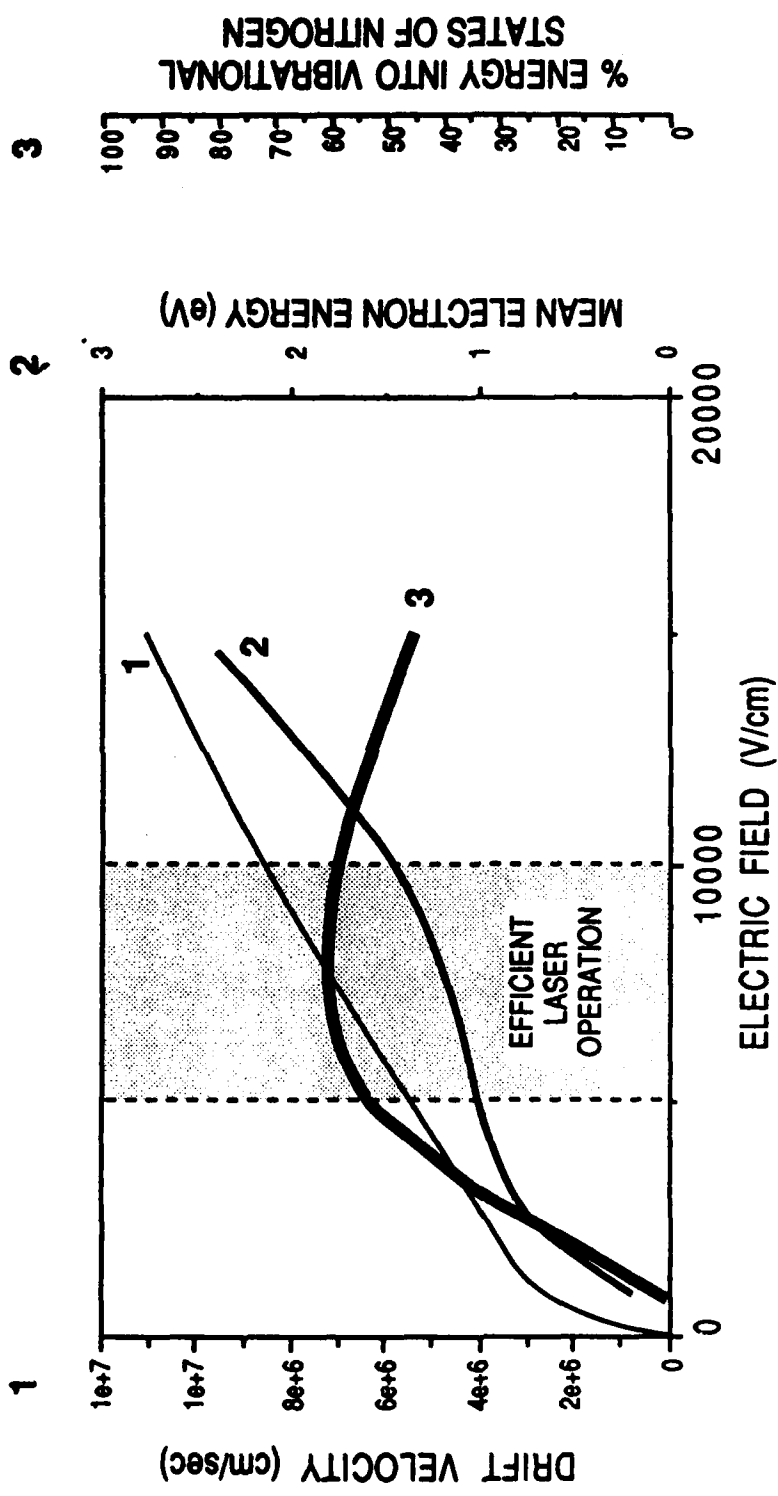


Figure 5

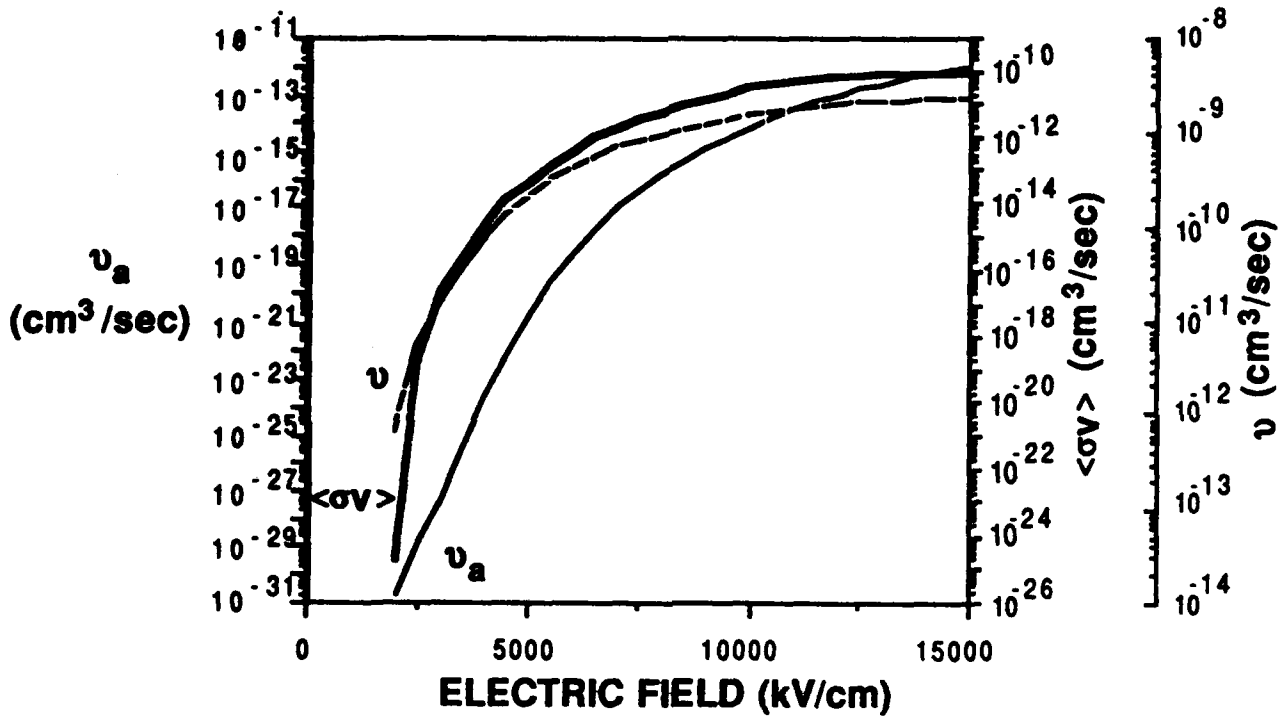


Figure 6

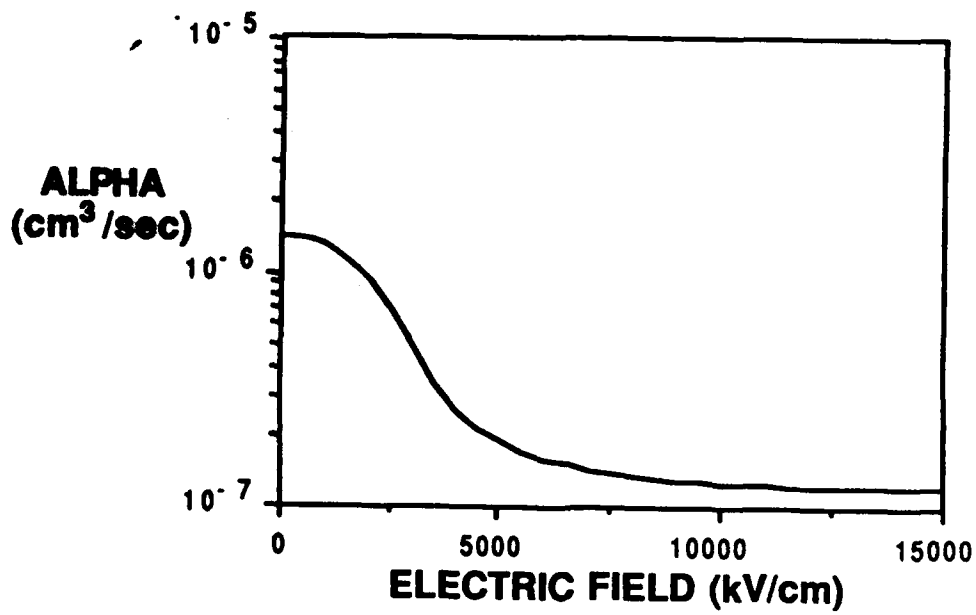


Figure 7

recombination coefficient as a function of the electric field. Measurements of the recombination coefficient for a 3/2/1 laser has been made for electric field strengths between 2.5 and 5 kV/cm.<sup>(1)</sup> The curve shown in Fig. 7 make use of these measurements.

### 3.1 REGIONS OF STABLE OPERATION FOR A CO<sub>2</sub> LASER DISCHARGE

Combining the rate constants predicted by the Boltzmann code with the stability analysis one can identify regions of stable discharge operation for the special case of a CO<sub>2</sub> laser. Figure 8 is a plot where  $C = (B/\tau_n + B)$ , as a function of electric field for an electron density of  $10^{12} \text{ cm}^{-3}$  and zero attachment. As discussed earlier the discharge is marginally stable when  $C = 0$  unstable when  $C > 0$  and absolutely stable when  $C < 0$ . The stable and unstable regions have been identified in Fig. 8. For zero attachment the discharge is marginally stable or absolutely stable as predicted by the stability analysis. For a voltage source with zero internal resistance the discharge is marginally stable. When the pulsed power impedance is equal to the discharge impedance the discharge is absolutely stable between 5-15 kV/cm and marginally stable for electric fields below 5 kV/cm. For electric fields  $> 15 \text{ kV/cm}$  the discharge will probably become unstable because  $C > 0$ . This is because  $\nu$  becomes negative. The discharge stability at these high electric fields have not been investigated because it is of little interest for the CO<sub>2</sub> lasers.

In Fig. 9 one sees the effect of adding some attachment. One immediately sees that the case of  $\rho = 0$  (voltage source) which was marginally stable before is now unstable however the case where  $\rho = \rho_{disc}$  and  $\rho = \infty$  (current source) still have stable operating regions



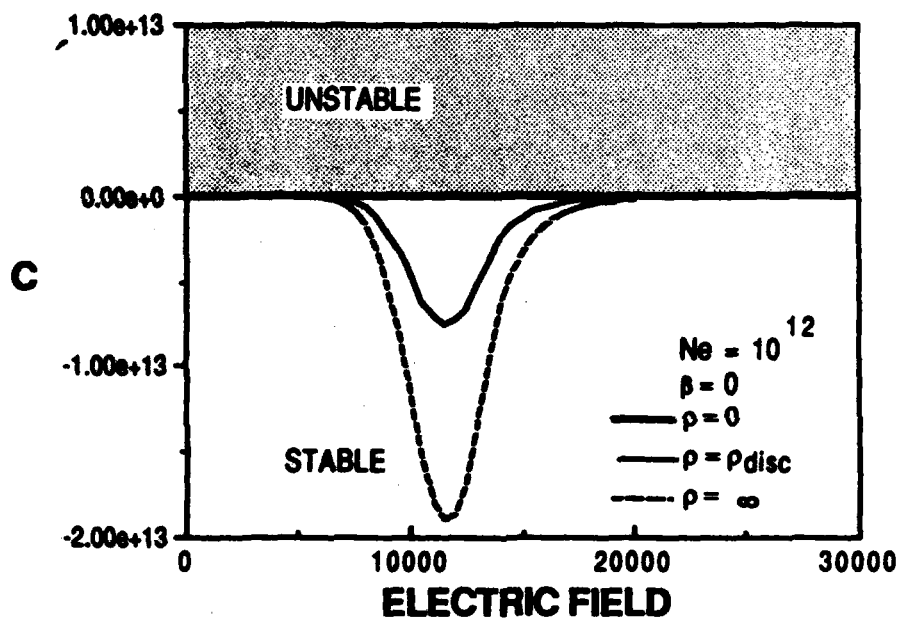


Figure 8

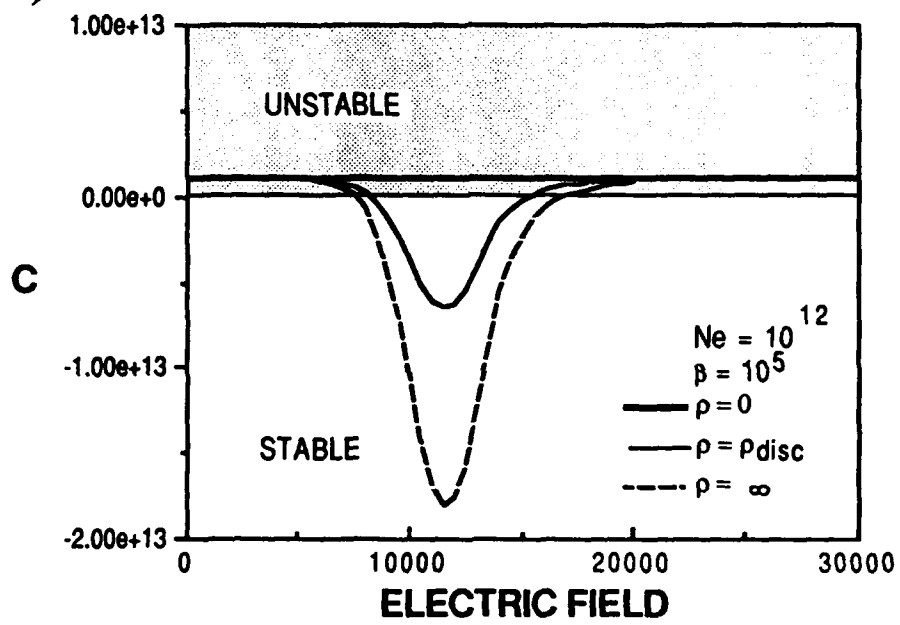


Figure 9

between 7 and 13 kV/cm. By inspecting Eq. (16) it is clear that the discharge becomes more stable as  $n_0$  increases. This is graphically shown in Fig. 10. In fact for  $n_0 < 10^{11} \text{ cm}^{-3}$  and  $\beta = 2 \times 10^5 \text{ sec}^{-1}$  the discharge is unstable for all values of electric field, this can be seen in Fig. 11. So for small values of  $n_0$  and electric fields  $> 15$  kV/cm the secondary electron density will rapidly increase until  $n_0$  is large enough and the discharge becomes stable. During this rapid growth of  $n_0$ , streamers can form, and the discharge can go unstable. To prevent this from happening the initial spatial distribution of  $n_0$  must be uniform, further by having an RF source such streamer formation can be inhibited.

The rate Eq. (1) and (2) has been solved simultaneously with the circuit Eq. (18) for the special case of a 3/2/1, He/CO<sub>2</sub>/N<sub>2</sub> laser discharge. This code also makes use of the rate constants and secondary electron parameters shown in Figs. 5, 6 and 7. The predictions of this code are plotted in Figs. 12 and 13. Figure 12 shows the temporal variation of  $n_0$  and E for the circuit impedance of  $10^4 \Omega$ . Such an impedance is somewhat larger than the discharge impedance of  $8 \times 10^3 \Omega$ . The initial electron density was assumed to be  $10^{12} \text{ cm}^{-3}$ . The electron density increases by about 10% to  $1.08 \times 10^{12} \text{ cm}^{-3}$  and the electric field decreases from its initial value of 9 kV/cm to slightly less than 8.5 kV/cm. The temporal variation of C is also shown in Figs. 12 and 13. For the case shown in Fig. 12 C is negative and such a discharge is stable. This discharge clearly becomes unstable when  $\rho$  is reduced to  $1 \Omega$ . For this case the initial value of C is positive indicative of an unstable discharge. The electron

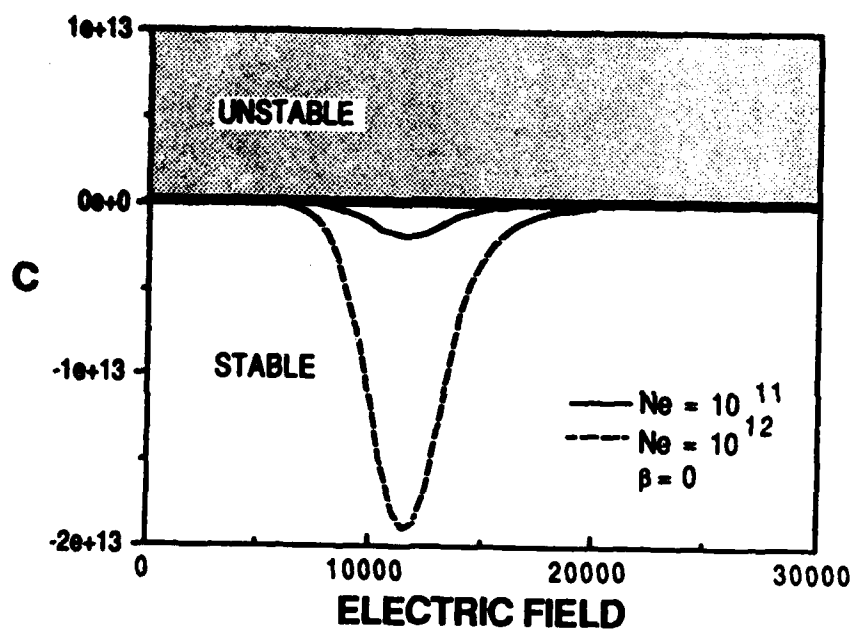


Figure 10



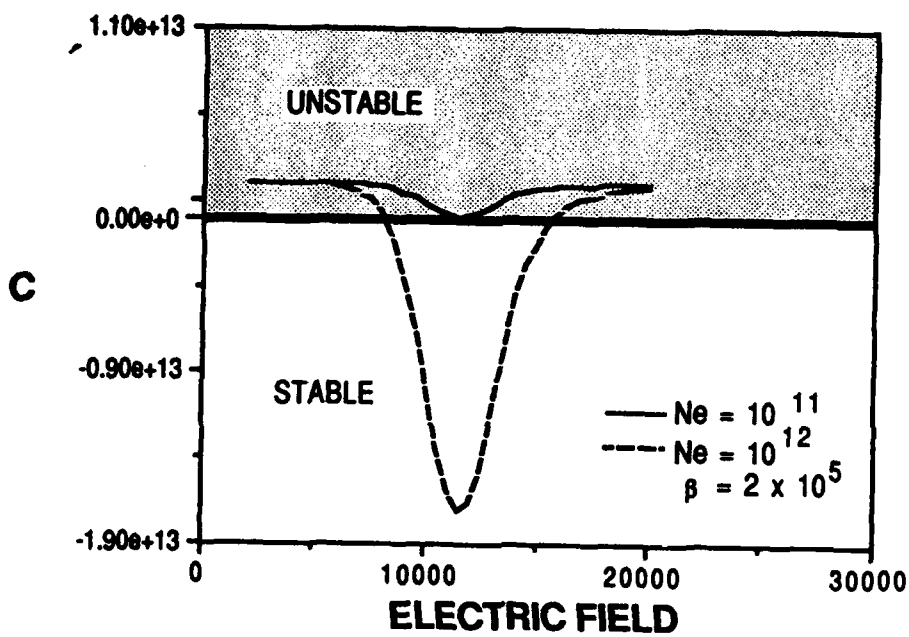


Figure 11

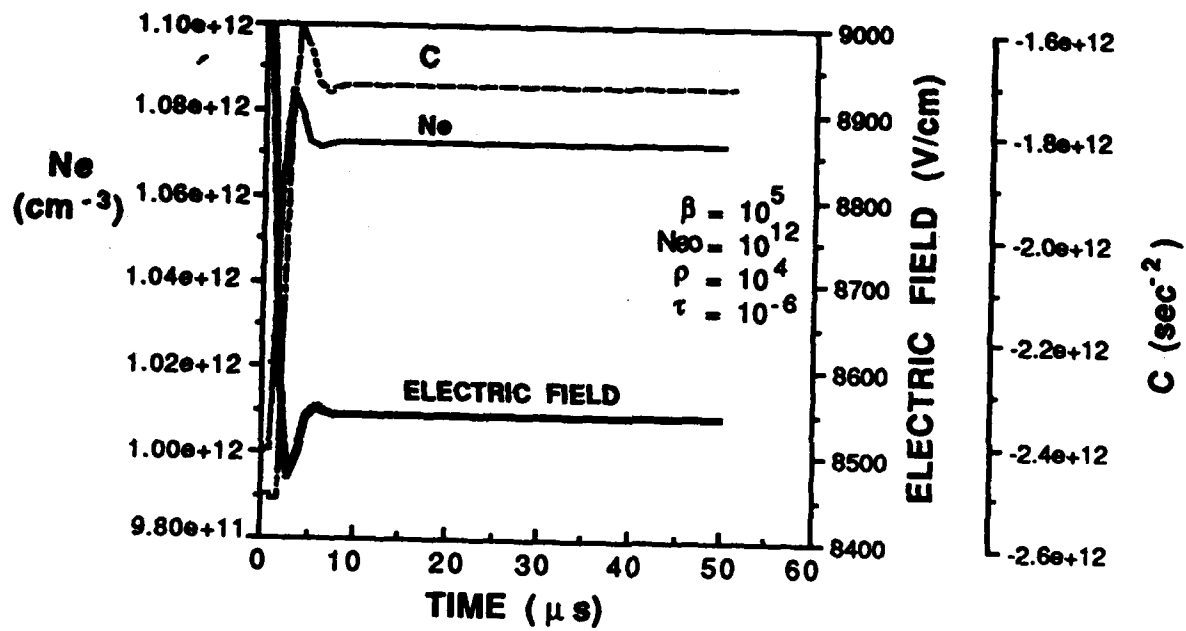


Figure 12 Curves of Ne, E, and C for a volumetrically stable discharge

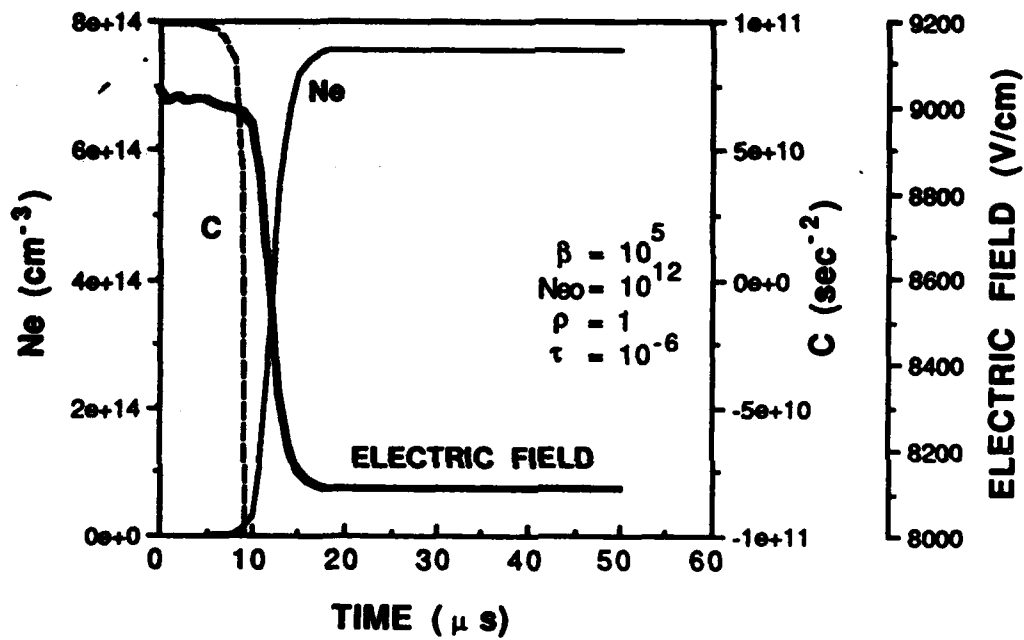


Figure 13 Curves of Ne, C, and E for unstable discharge

density suddenly increases by almost three orders of magnitude after 10  $\mu$ s. The discharge becomes stable at this large value of  $n_e \sim 8 \times 10^{14} \text{ cm}^{-3}$ . As discussed in the preceding pages  $|B|$  increases linearly with  $n_e$  and hence the discharge will once again become volumetrically stable at the large value of  $n_e$ . Also, C becomes negative at these values of  $n_e$  which is consistent with a stable discharge. However, in practice any spatial nonuniformities in  $n_e$  could result in streamer formation during this transition.



#### 4.0 INDUCTIVE DISCHARGE STABILIZATION

##### (Stabilization Against Streamer Formation)

So far the volumetric stability of the discharge has been analyzed. Although a discharge can be volumetrically stable, micro instabilities and nonuniformities can lead to constriction of the discharge and streamer formation. To stabilize the discharge against streamer formation SRL proposes to use an RF source. Since a streamer is far more inductive than the discharge, its formation and growth will be inhibited by using RF.

The effectiveness of inductive discharge stabilization can be evaluated from analysis of the equivalent circuit shown in Fig. 14. The discharge impedance, which has inductive and resistive components  $L_D$  and  $R_D$ , while operating stably, is driven by an oscillating current source. The currents through these components are  $I_L$  and  $I_R$  respectively. The voltage drop across the inductor and resistor must be equal hence

$$i\omega L I_L = R I_R \quad (22)$$

By conservation of current,

$$I_L + I_R = I \quad (23)$$

where  $I$  is the total current. Equations (22) and (23) can be solved simultaneously to give

# STABILIZATION OF DISCHARGE BY INDUCTANCE

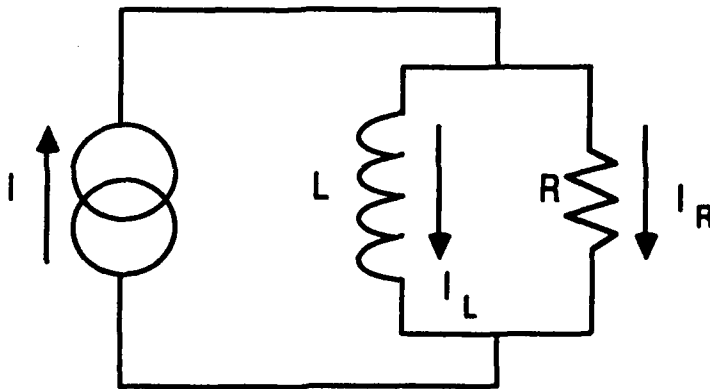


Figure 14

$$I_L = \frac{R(R - i\omega L)}{R^2 + \omega^2 L^2} I \quad (24)$$

and

$$I_R = \frac{\omega^2 L^2 + i\omega RL}{R^2 + \omega^2 L^2} I \quad (25)$$

For efficient discharge pumping the inductive current should be minimized, i.e.,  $R \ll \omega L$ , and  $I \approx I_R$ . If the reverse is true then  $I \approx I_L$  and the transfer of energy to the discharge will be very inefficient especially if additional resistive losses are present in the system.

Should the discharge begin to constrict, the inductance will increase and the resistance will decrease. Under these conditions the frequency of RF modulation can be chosen to inhibit arc formation.

From Eq. (22) it is clear that the RF frequency,  $f$ , should be selected such that

$$\frac{R_D}{2\pi L_D} > f > \frac{R_s}{2\pi L_s}$$

where  $R_s$  and  $L_s$  are the resistance and inductance of the perturbed discharge region. These constraints on the modulation frequency have a simple physical explanation. The constraint,

$$\frac{R_D}{2\pi L_D} > f,$$

insures that the skin depth at the modulation frequency is larger than the transverse dimension of the discharge. This constraint leads to spatially uniform pumping of the laser medium. On the other hand, the

constraint

$$\frac{R_s}{2\pi L_s} < f$$

insures that the skin depth at the modulation frequency is smaller than the transverse dimension of the discharge constriction. Therefore, oscillating discharge power is prevented from penetrating to the center of the constricted region. Regions of ionization instability in CO<sub>2</sub> laser discharges are most likely dominated by multistep ionization processes discussed in the preceding section. In this case, the ionization rate,  $\nu_1$ , is not simply a function of the effective electric field,  $E/N$ , but is a function of the power density deposited into the discharge  $E \cdot J/N$ . Consequently the limited power flow into the constricted discharge region reduces the ionization rate in that region and enhances stability.

The intrinsic inductance of the discharge can be estimated from the geometrical considerations shown schematically in Fig. 15. Also shown in Fig. 15 is the shape of the magnetic field for the symmetric current condition with no electron density perturbations. The discharge inductance is defined as

$$L_D = \frac{\int B \cdot ds}{I}$$

For a square aspect ratio (i.e.,  $l = h$  in Fig. 15)

$$L_D = \frac{\mu_0 l^2}{4L} \quad (26)$$

# INTRINSIC INDUCTANCE OF DISCHARGE

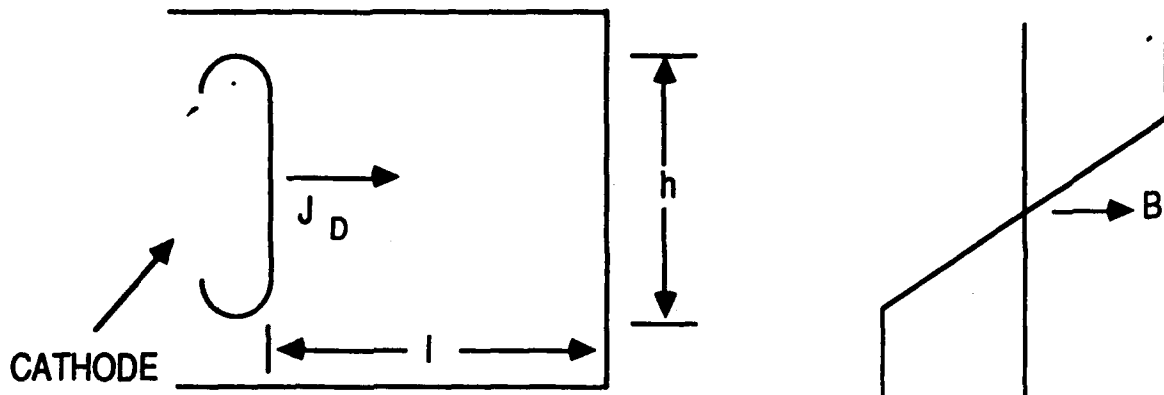


Figure 15

where  $L$  is the length of the active volume in the lasing direction and  $\mu_0$  is the permeability of free space.

The inductance of the streamer representing the electron density perturbation can be calculated in a similar manner. The geometry of the streamer is shown in Fig. 16. Assuming that the streamer collapses to a radius  $a$

$$L_s = \frac{\mu_0 \ell}{2\pi} \ln \frac{2\ell}{a} \quad (27)$$

Dividing Eq. (27) by Eq. (26) one gets

$$L_s/L_D = \frac{2}{\pi} \frac{L}{\ell} \ln \frac{2\ell}{a}$$

Typically  $\ell = 0.15$  meters,  $\ln 2\ell/a \sim 4$  and  $L_s/L_D \sim 20$ .

To calculate the required frequency of modulation the resistance of the  $\text{CO}_2$  discharge must be estimated. The conductivity of the discharge is typically  $3 \times 10^{-2}$  mhos/m. For a discharge cross section of  $1.5 \times 10^3 \text{ cm}^2$  and a discharge length,  $\ell$ , of 0.15 meters, the discharge resistance is 35 ohms. The inductance as given by Eq. (26) is 7 nH. So the RF modulation frequency should be in the range

$$5.3 \times 10^7 \frac{R_s}{R_D} \text{ Hz} < f < 8 \times 10^8 \text{ Hz} \quad (28)$$

The upper limit on modulation frequency, 800 MHz, insures that the skin depth of the discharge current is larger than the transverse dimension of the discharge so that the laser medium is pumped uniformly and efficiently. The remaining inequality relates to



# INDUCTANCE OF CONSTRICTED DISCHARGE

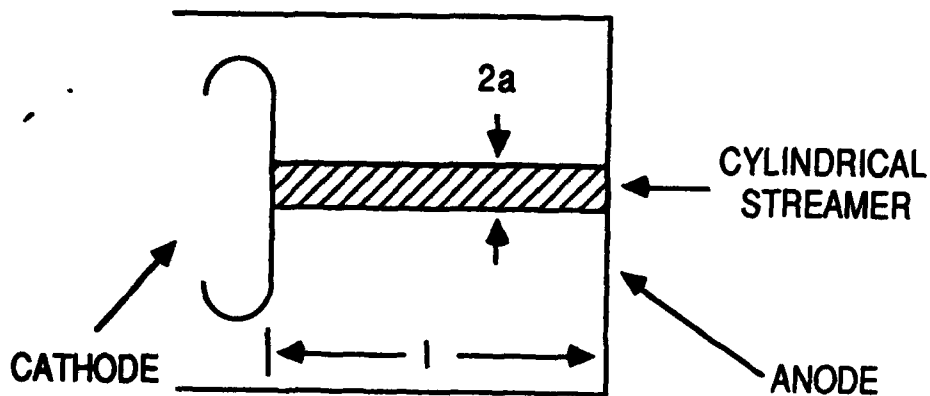


Figure 16

inductive stabilization of constrictions in the discharge current. This inequality insures that the oscillating portion of the discharge current does not contribute to the current in the constricted region. The utility of this inequality is best understood by rewriting it as

$$\frac{R_s}{R_D} < \frac{f}{53} \text{ MHz}$$

This inequality relates the streamer resistance (normalized to the stable discharge resistance) to the modulation frequency required to insure that the oscillating current does not flow through the streamer. Initially, in the stable discharge regime  $R_s$  is infinite and therefore  $R_s/R_D \gg f/53 \text{ MHz}$ . As the discharge constricts,  $R_s/R_D$  falls below  $f/53 \text{ MHz}$  and the oscillating current is cut off from the constricted region. At this point, the excess electron density in the constricted region should rapidly recombine thereby driving the discharge back to stable operation. If the modulation frequency in this example were chosen to be 50 MHz, then stabilization should begin to occur when the streamer resistance begins to drop below the discharge resistance, i.e. as the streamer begins to form.

#### 5.0 EFFECT OF RF MODULATION ON CO<sub>2</sub> LASER OPERATION

The RF modulation will have an impact on discharge and laser parameters such as electron density, temperature and small signal gain. These effects will be briefly discussed below.

The electron production and loss rate is given by

$$\frac{dn_e}{dt} = S + \nu_1 n_e - \alpha n_e^2 - \beta n_e \quad (29)$$

For a self sustained discharge,  $S=0$ . Typically,  $\text{CO}_2$  laser discharges are recombination dominated. Because of the RF modulation, the discharge electric field will vary in time. The electron temperature and recombination rate will also vary. As the electric field decreases the average electron energy decreases and recombination rate increases which will have a stabilizing effect and allow slightly constricted regions in the discharge to recover to the ambient electron density.

It is desirable to keep the electron density constant in time. From Eq. (29) it is clear that, for  $\beta \ll \alpha n_e$ , the electron density will be constant if  $f \gg \alpha n_e$ . Typically,  $n_e \sim 10^{12} \text{ cm}^{-3}$  and  $\alpha \sim 10^{-6} \text{ cm}^3/\text{sec}$  (see Fig. 7). So if  $f \gg 1 \text{ MHz}$ , which is consistent with the modulation frequency given by (28),  $n_e$  will be essentially constant.

The RF electric field will cause variations in the average electron energy. Such variations result in inefficiencies because of nonoptimal pumping of  $\text{N}_2$  vibrational levels (see Fig. 5). The electron temperature will be nearly constant if the RF frequency is

$$f \gg k_e N_a$$

where  $k_e$  is the electron impact excitation rate of ground state  $\text{N}_2$  and  $N_a$  is the  $\text{N}_2$  density. Typically  $k_e \approx 5 \times 10^{-9} \text{ cm}^3/\text{sec}$  and  $N_a \approx 5 \times 10^{18} \text{ cm}^{-3}$  and therefore  $f > 2 \times 10^{10} \text{ Hz}$ . Since the RF modulation frequency will certainly be lower than  $10^{10} \text{ Hz}$  the average electron energy will follow the modulation frequency in time.

For the small signal gain to be constant,  $f \gg k_e N_c$ , where

$k_0$  ( $\sim 10^{-12}$  cm<sup>3</sup>/sec)<sup>(1)</sup> is the vibrational transfer rate from N<sub>2</sub> to CO<sub>2</sub>, and  $N_c = 10^{19}$  cm<sup>-3</sup> is the CO<sub>2</sub> number density. So for a constant small signal gain  $f > 10^7$  Hz. From Eq. (28) the RF modulation frequency will be chosen such that the small signal gain will be constant which is important for maintaining high laser extraction efficiency.

For efficient coupling of power into the laser discharge it is important that the impedance of the discharge does not vary strongly with the RF modulation. The power reflection R from a load having an impedance  $Z_1$  is given by

$$R = \left( \frac{1 - Z_0/Z_2}{1 + Z_0/Z_2} \right)^2$$

where  $Z_0$  is impedance of the RF power supply and  $Z_1 \propto E/en_e v_D$ . From the curves shown in Fig. 5 the  $v_D \propto (E)^{1/2}$ . From Eq. (29)  $n_e \propto \nu_1/\alpha$ . From Fig. 6 one can see that  $\nu_1$  is a very strong function of the electric field while  $\alpha$  decreases with increasing electric field. So  $n_e$  could vary very strongly with the electric field, i.e.,  $n_e \sim E^7$ . Such a strong variation could result in power reflection from the discharge and the overall efficiency of the discharge could be adversely effected. It is in part for this reason that the RF frequency be chosen such that the electron density is constant, i.e.  $f \gg \alpha n_e$ .

Finally the cross section area of the discharge will be constrained by the skin effect. For a given RF frequency the cross sectional area A must be smaller than a certain value if the current through the cross section is to be uniform. This inequality is given

by

$$A \leq \frac{1}{\pi f \mu \sigma} \quad (30)$$

where  $\sigma$  the conductivity of CO<sub>2</sub> laser discharges is typically 2-3 x 10<sup>-2</sup> MHos/M.

From the preceding discussions a scaling map for CO<sub>2</sub> can be drawn such a scaling map is shown in Fig. 17. This figure is a plot of RF frequency vs cross sectional area of the discharge. As discussed earlier the RF frequency should be larger than 30 MHz for the small signal gain and electron density to be constant. On the high end the frequency is constrained by the skin effect. Also shown in Fig. 17 is the expected 10.6  $\mu$  laser energy that can be extracted per pulse. From this figure it is clear that this pumping technique can provide enough laser energy for most tactical applications.

# CO<sub>2</sub> SCALING MAP

## FREQUENCY VERSUS CROSS SECTIONAL AREA

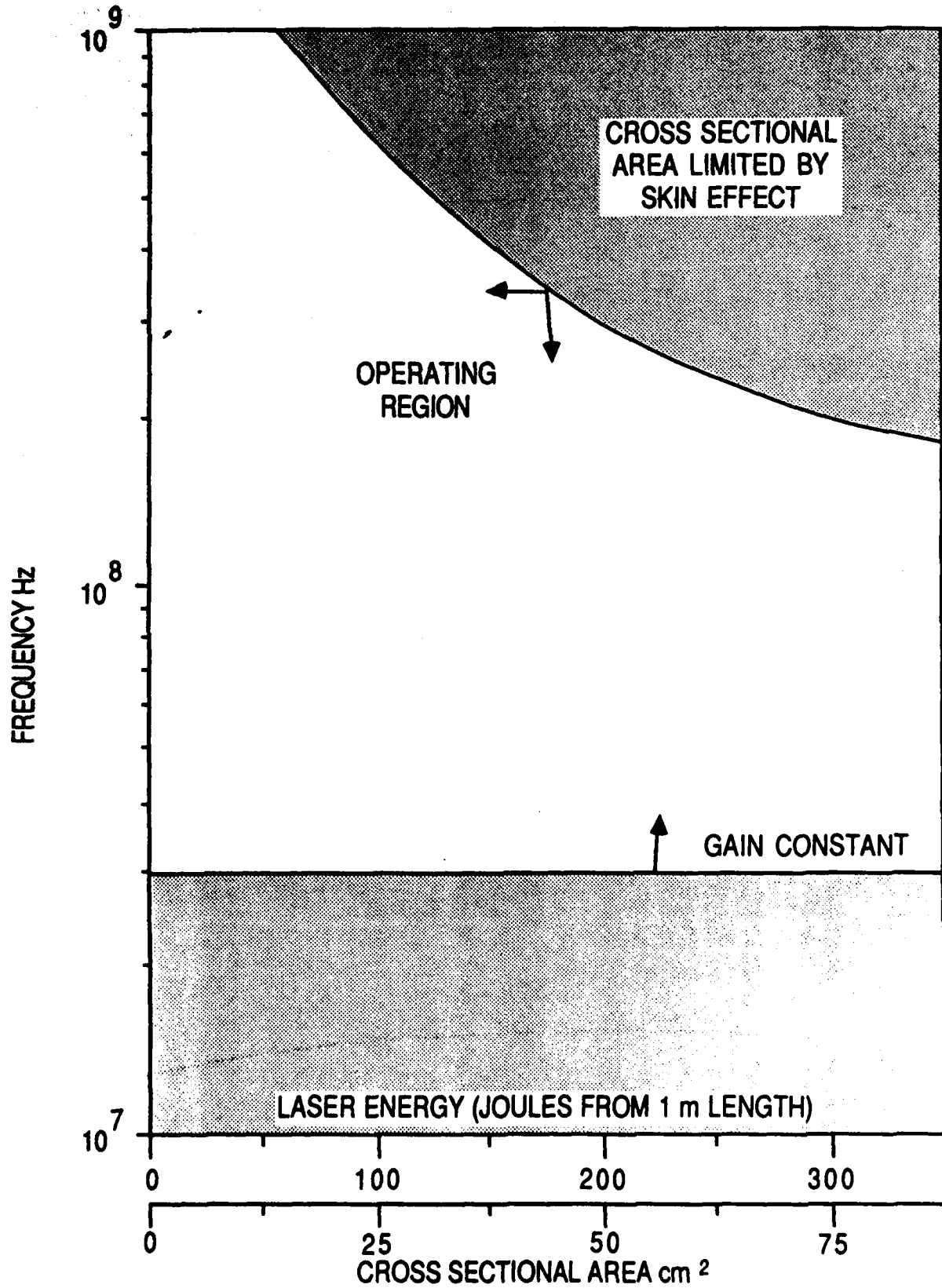


Figure 17



## 6.0 CONCEPTUAL DESIGN OF SINGLE PULSE EXPERIMENT

The conceptual design of the experiment is sufficiently flexible to allow for variation of the discharge and laser parameters over a broad range to enable determination of the optimum discharge/laser conditions. Specifically the constant current RF power supply can have the following features:

- Variable frequency (10-100 MHz)
- Variable shunt impedance to allow for discharge current variation
- Discharge initiation with a 10 nsec overvoltage pulse having variable delay to the onset of the discharge sustainer pulse. In addition a UV preionizing source will provide an initial uniform density of electrons such a source is discussed later in this section. These features will permit rapid determination of the optimum laser performance within the constraints of ensuring discharge stability.

Figure 18 shows a schematic of the laser discharge and UV preionizer. The discharge cell will be fabricated out of a quartz tube having a diameter of 1 cm (cross sectional area of  $0.8 \text{ cm}^2$ ) and a length of 50 cm. The RF power will be coupled in via a set of external electrodes that will be spaced about 1 cm apart. The RF source will be capable of delivering 6 kV and 20 A and the discharge current will be  $0.5 - 1 \text{ A/cm}^2$  and the electric field 5-6 kV/cm. The laser discharge characteristics are given in Table II. From this table one can see that the RF power supply must be capable of delivering 120 kW in a  $50 \mu\text{s}$  pulse.

Also given in Table II are the expected  $\text{CO}_2$  laser characteristics

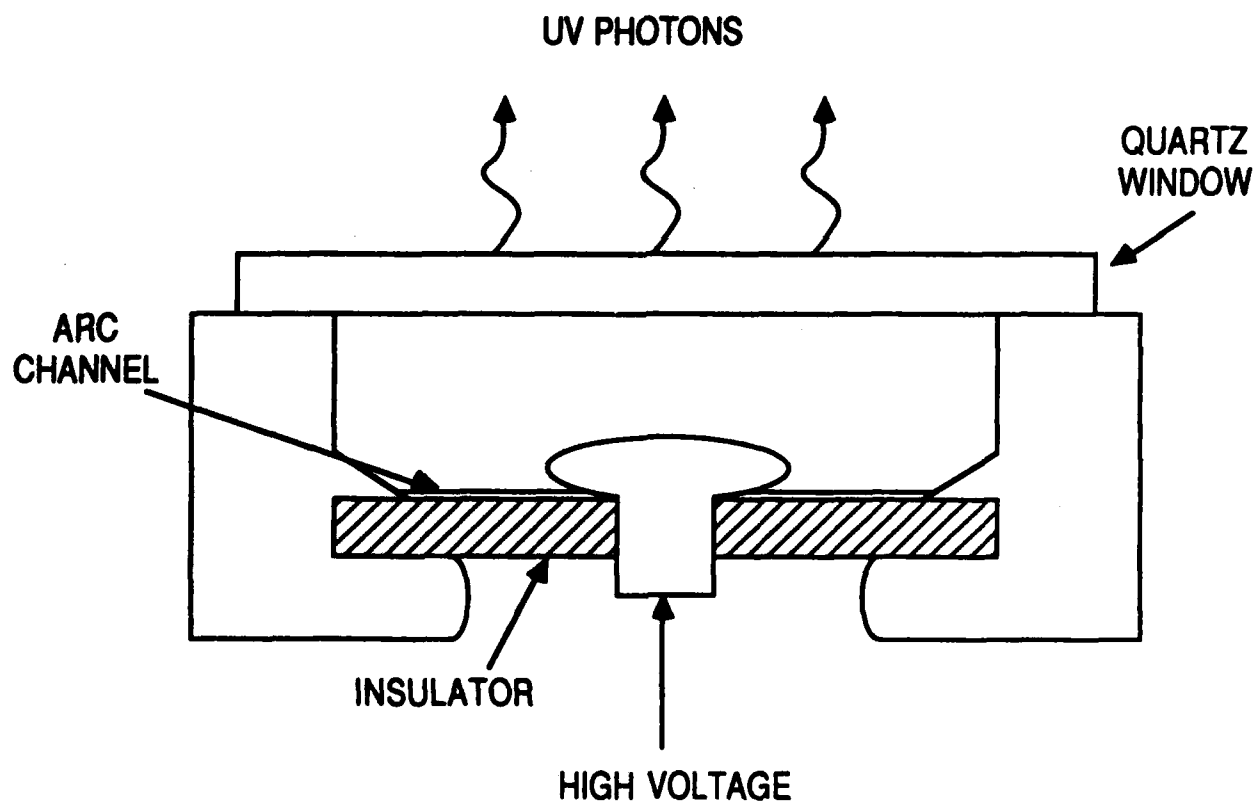
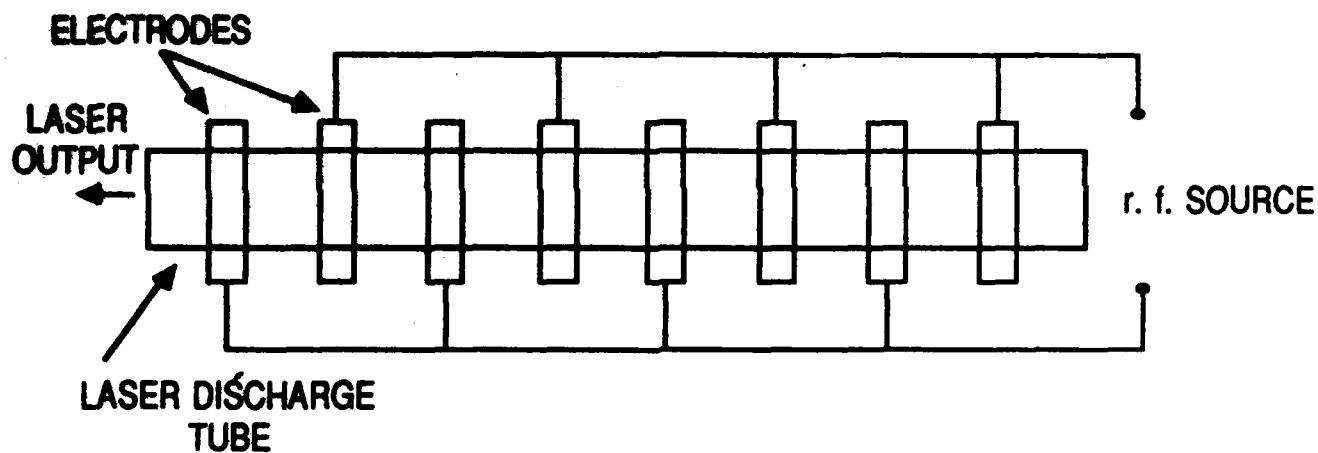


Figure 18 Schematic of laser/discharge tube and surface-spark discharge UV generator

**TABLE II**  
**LASER/DISCHARGE CHARACTERISTICS**

• **DISCHARGE CHARACTERISTICS**

GAS MIXTURE	3/2/1 He/N <sub>2</sub> /CO <sub>2</sub> AT 1 ATM
TOTAL DISCHARGE CURRENT	20 A/cm <sup>2</sup>
CURRENT DENSITY	1 A/cm <sup>2</sup>
ELECTRIC FIELD	5-6 kV/cm
PULSE LENGTH	50 μs
INPUT POWER	120 kW
ELECTRON DENSITY	1-2 x 10 <sup>12</sup> cm <sup>-3</sup>
MEAN ELECTRON ENERGY	1 eV

• **LASER CHARACTERISTICS**

GAIN AT 10.6 μm	1-2 x 10 <sup>-3</sup> cm <sup>-1</sup>
SATURATION FLUX	25 kW/cm <sup>2</sup>
LASER POWER EXTRACTION	20 kW
LASER ENERGY EXTRACTED	1 JOULE

• **DISCHARGE/LASER CELL**

CROSS SECTIONAL AREA	0.8 cm <sup>2</sup>
LENGTH	50 cm
OUTPUT COUPLING	10-20%

for 3/2/1, He/N<sub>2</sub>/CO<sub>2</sub> gas mixture at a total pressure of 1 atm. The saturation flux for this mixture is 25 kW/cm<sup>2</sup>.<sup>(2)</sup> For the pump power of 120 kW the expected gain is 1-2% per cm.<sup>(2)</sup> Using a hole coupled copper mirror with a 10-20% output coupling the energy extracted will be about a joule.

To insure a uniform discharge SRL has designed a UV preionization source. Such a preionization is the most convenient because of factors including:

- (1) ease of coupling the UV into the discharge
- (2) typically UV sources are generated by relatively low voltages (5-10 kV) and hence they can be made compact and light weight

The disadvantage of using UV sources is the uniformity of the preionization is not as good as that generated by x-ray preionization. However, this is not expected to be a significant issue in the present discharge configuration because of the small cross sectional areas.

There are a number of alternative methods for obtaining the UV radiation ultimate choice will depend on the particular application. For long lived space applications, UV generated by rare gas flash lamps may be the most appropriate.<sup>(3)</sup> These sources are highly efficient for converting electrical power into optical radiation and at 10,000-15,000 °K they are efficient radiators in the near UV spectral region.<sup>(4)</sup>

Another attractive alternative is a vacuum surface spark discharge. The advantage of these UV sources are their simplicity and their efficient radiation in the UV.<sup>(4)</sup> Figure 18 shows a

schematic of such a source. The radiation is created by a spark along an insulating material such as  $\text{Al}_2\text{O}_3$  or  $\text{ZnO}_2$  and the photons are coupled out of the vacuum chamber through a quartz window. Typically the pulse lengths of the radiation is 5-10  $\mu\text{s}$ .

A block diagram of the constant current power supply is shown in Fig. 19. The constant current supply is provided by a push-pull cathode follower circuit using two 4PR1000 tetrodes. From the characteristics of these tetrodes shown in Fig. 20, it can be seen that the current is constant for plate voltage between 3-14 kV. The RF power will be coupled to the discharge via a transformer and the output will provide constant current pulses of up to 20 amperes for voltages up to 6 kV.

The power supply design is conservative and the tubes were chosen to be rugged enough to absorb all the RF power should fault modes develop as the limits of discharge stability are explored. Further, the circuit is capable of generating an initial overvoltage prepulse to initiate the discharge.

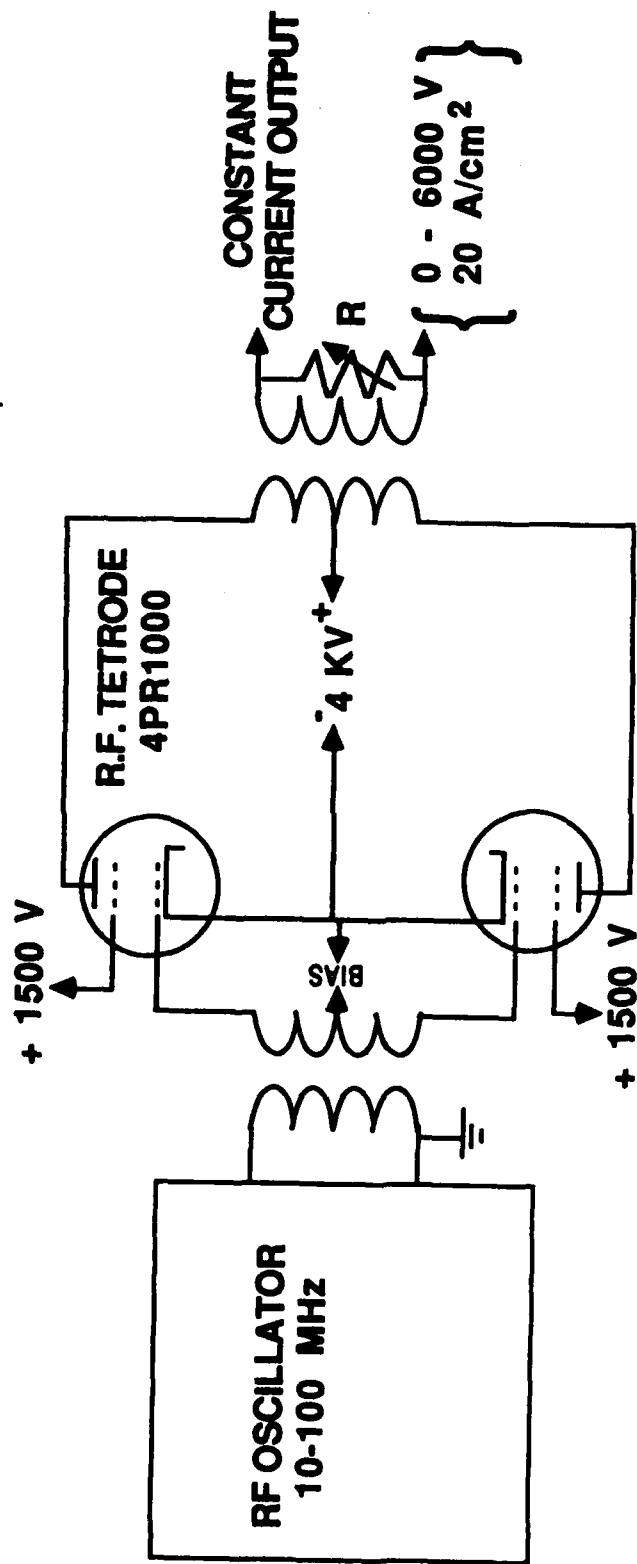
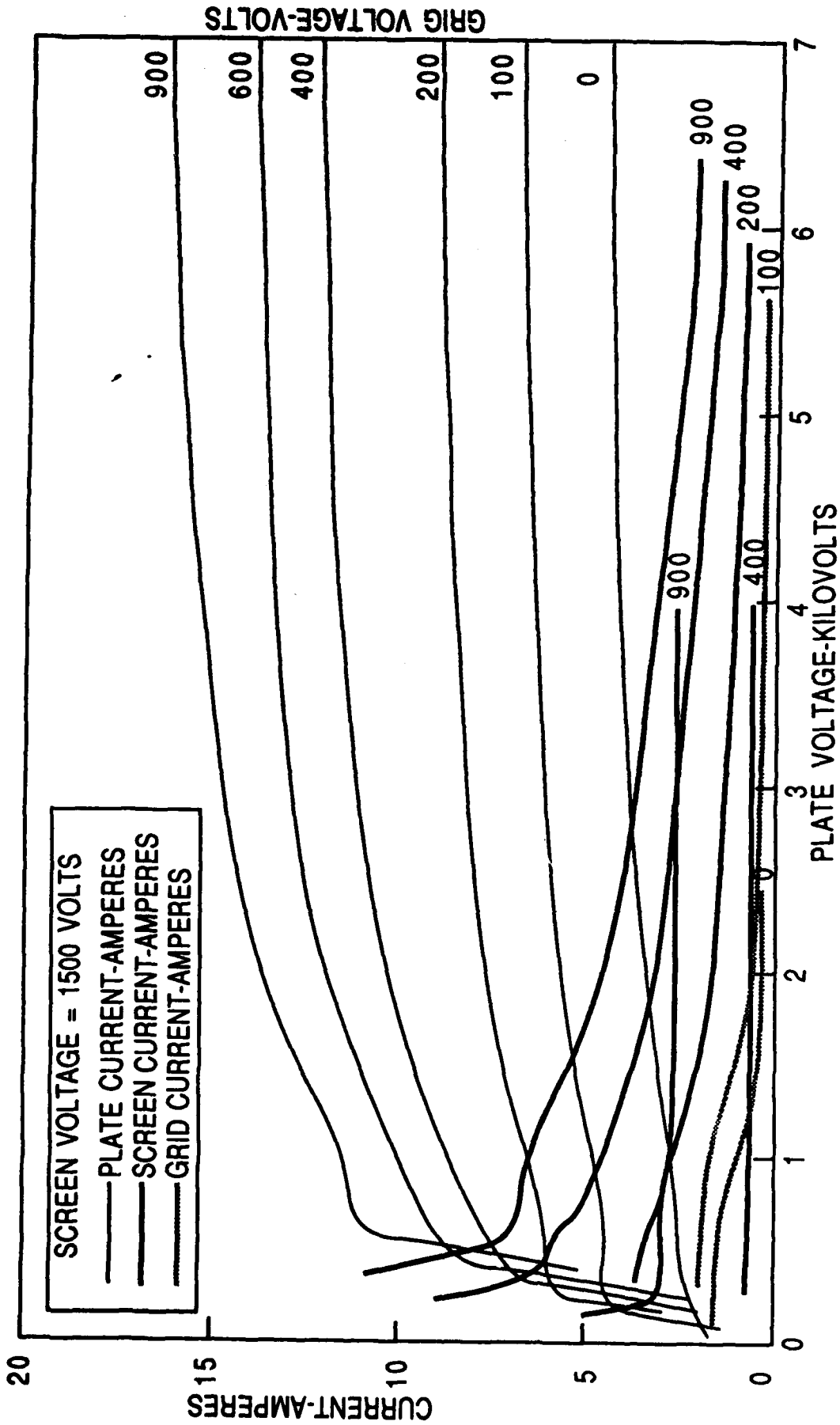


Figure 19 Constant current 10-100 MHz power supply





GRID VOLTAGE-VOLTS

Figure 20 Typical tetrode plate characteristics

## 7.0 SUMMARY

The stability of CO<sub>2</sub> laser discharges have been analyzed analytically and numerically. The discharge model includes the electrical circuit. It is clear from the analysis that a current source is more stable than a voltage source. Further by the use of RF discharge streamer formation can be inhibited. Scaling maps have been presented that identify regions of stable discharge operation.

In the last section of this report a conceptual design of an experiment to verify the stability model is presented. The experimental design is flexible enough to permit both discharge and laser experiments.

## REFERENCES

1. G.E. Caledonia, et al., "Analysis of Metastable State Production and Energy Transfer," Report #AFWAL-TR-86-2078 (1986).
2. D.H. Douglas-Hamilton and R.S. Lowder, AERL Kinetics Handbook, (1974).
3. B. Smith and F. Schula, "Flashlamps for Pulsed Solid State Lasers," Engineering Note #156, ILC Technology, Inc., Sunnyvale, CA (August 16, 1982).
4. K.D. Ware, T.M. Johnson and C.R. Jones, "Surface-Spark Discharges Compared with Exploding Wires/Films as High Temperature UV Source," Fourth IEEE Pulsed Power Conference, p. 507 (1983).