PIERCE DIODE INSTABILITIES IN GLOW DISCHARGE PLASMAS AND THEIR RELEVANCE IN CO_2 LASERS

K. H. Tsui, R. A. D. Zanon, C. A. Massone

Laboratório de Espectroscopia e Laser, Instituto de Fisica, Universidade Federal Fluminense, CP 100296, Niterói, 24020 RJ.

ABSTRACT

Pierce diode instabilities are extended to the collisional glow discharge regime, where electron thermal velocity is very much larger than the drift velocity, to account for the voltage pulsations, or spikes, in CW CO_2 laser discharges with hollow cathode. Experimental results with this cathode geometry and high nitrogen and helium partial pressures give extraordinary laser output power without auxiliary cooling.

1. INTRODUCTION

The working medium of gas lasers is a partially ionized low temperature thermal plasma of several eV maintained by either DC or pulsed discharges. The importance of this plasma medium in determining some aspects of the laser properties has been the subject of several recent studies. In pulsed nitrogen lasers, the plasma impedance matching between the spark gap and the laser discharge channel plasmas can lead to a resonant narrowing of the laser pulsewidth [1,2]. In CW carbon dioxide lasers, the transport properties of the plasma produced by an axial discharge with a cathode that has a small indented cavity (hereafter named as hollow cathode) allows the laser be operated at high nitrogen concentration mixtures [3-5]. Contrary to the low nitrogen concentration mixture cases, auxiliary cooling system for the discharge tube can not be used. This high nitrogen concentration, no external cooling regime is related to the hollow cathode plasma [6]. We believe that due to the larger electron density in the hollow cathode region, the single-pass gain factor of the laser signal is higher than the one with planar cathode. Consequently, this allows a viable operation of the laser in this regime.

2. DOUBLE PLASMA RELAXATION

Formation of double layer plasma is a familiar subject in plasma physics [7-9]. This kind of plasma presents typical low frequency, small amplitude oscillations [8,9]. Similar behavior is also present in commercial fluorescent mercury/noble gas lamps [10]. These oscillations can be caused by moving double layer structures or by Pierce diode instabilities [11,12]. In Pierce diodes, the collisionless electron beam propagating in a neutralizing ion background can excite instabilities even taken into considerations of finite ion mass [13]. The growth rate of this instability depends on the external parameters [14,15] and electron thermal velocity [16].

In CO_2 laser operation mentioned in Ref. [6], the gas pressure is in the range of torrs which is much higher than the mtorrs range of typical plasma double layer studies. The laser power output is associated with the voltage pulses having 10 μs width superimposed on the DC voltage. We believe that these voltage pulses are the Pierce diode instabilities at the high plasma pressure limit. The pulsations therefore indicate the double plasma structure near the hollow cathode which enhances the single pass gain of the laser amplification.

3. COLLISIONAL PIERCE DIODE INSTABILITIES

Pierce diode instabilities have been analyzed theoretically and experimentally in the low plasma pressure, collisionless regime, although thermal spread was treated ocassionally [16]. The existing theory is not adequate to examine the plasma discharge in CO_2 lasers. At high plasma pressure, the collisional plasma inhibits the electron beam to propagate at high velocity. Also, dissipations thermalize the plasma to an electron temperature of typically a few eV. Consequently, the electron thermal velocity is much larger than the electron drift velocity which is the opposite of the classical Pierce diode case. Collisional dissipations also introduce an internal plasma resistance which enters into the circuit equation. The plasma resistance for glow discharge is usually negative in the sense that an increase on the voltage leads to a decrease on the current. In order to understand partially the experimental manifestations of the hollow cathode discharge of CO_2 lasers, we seek to generalize the collisionless Pierce diode instabilities to the high pressure collisional regime.

Let us consider the glow discharge arrangment in Figure 1 together with its equivalent circuit where R, L, C are the external circuit parameters, R_p is the plasma resistance. The large L_x additional inductance in parallel to C is to complete the DC discharge circuit only. Taking a uniform quasi-neutral plasma equilibrium without external field, from the fluid equations, the perturbed scalar potential

$$\Phi(x)$$

is described by

$$[\, v_e^2\ \partial/\partial x^2 - (v\ \partial/\partial x - i\omega)^2 - \omega_{pe}^2\,]\ \partial/\partial x^2\ \Phi(x) = 0 \quad (1)$$

where v_e, v, ω_{pe} are the electron thermal velocity, drift velocity and plasma frequency, respectively.

Also harmonic time perturbations of the form $\exp(-i\omega t)$ are assumed. From the charge continuity equation, we have

$$i\omega \, \partial/\partial x \, \Phi - 4\pi e\,(nv + nv) = (4\pi/A)\, i \qquad (2)$$

which is invariant in x where i is the current perturbation of

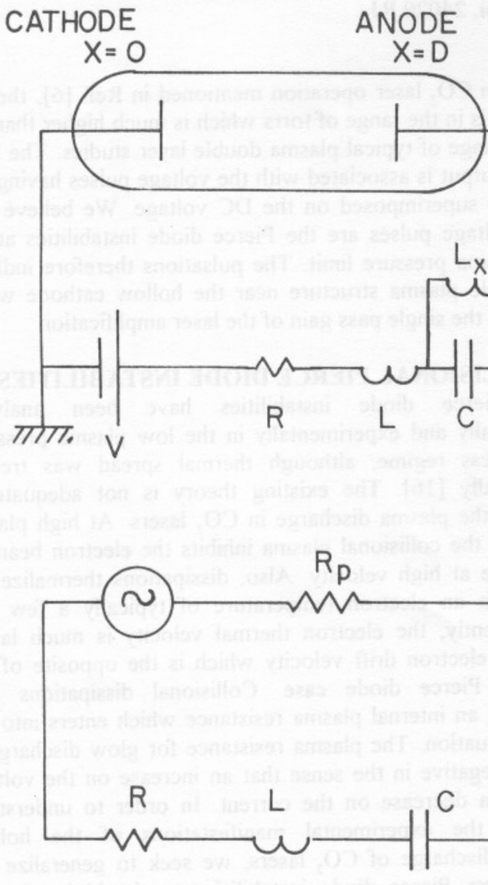

Figure 1. Glow discharge arrangment and its AC equivalent circuit

the circuit and A is the area of the electrode. To connect with the external parameters, the circuit equation gives

$$\Phi(x)\big|_{x\;D} = i\,[\,(R - R_p) - 1/(i\omega C) - i\omega L] \qquad (3)$$

where the plasma resistance R_p models the collisional dissipation of the plasma. Writing

$$\Phi(x) = A_1 e^{ik_1 x} + A_2 e^{ik_2 x} - E_o x + A_3 \qquad (4)$$

where k_1, k_2 satisfy the plasma dispersion relation

$$(v^2 - v_e^2)\,k^2 - 2\,v\,\omega\,k + (\omega^2 - \omega_{pe}^2) = 0 \qquad (5)$$

Using the boundary conditions $n(0) = v(0) = 0$, we get

$$A_1 = -i\,\Delta^{-1} k_2^2\, \omega_{pe}^2\, E_o$$

$$A_2 = -i\,\Delta^{-1} k_1^2\, \omega_{pe}^2\, E_o$$

$$\Delta = k_1 k_2 (k_2 - k_1)\,\omega^2$$

We now define the capacitance of the diode as

$$C_o = A/(4\pi D)$$

and normalize frequencies to v/D, distances to D. The circuit equation, Eq. (3), reads

$$\Theta_p^2\,(K_2^2\,(e^{iK_1} - 1) - K_1^2\,(e^{iK_2} - 1)) =$$

$$iK_1K_2(K_2-K_1)(\Theta^2 - (\Theta^2 - \Theta_p^2))(i\Theta\dot{R} - (1/\dot{C}) + \Theta^2\dot{L}) \qquad (6)$$

where $K = kD$, $\Theta = \omega/(v/D)$, $\Theta_p = \omega_{pe}/(v/D)$, $\dot{R} = (R - \dot{R} = (R-R_p)C_o\,(v/D)$, $\dot{C} = C/C_o$, $\dot{L} = LC_o\,(v/D)^2$. The plasma dispersion relation then becomes

$$(1 - \xi^2)\,K^2 - 2\Theta K + (\Theta^2 - \Theta_p^2) = 0 \qquad (7)$$

where $\xi^2 = v_e^2 / v^2$. The stability properties of the glow discharge are described by Eqs. (6,7) which, in the limit of $\xi = 0$, $R_p = 0$, reduce to the Pierce diode case.

4. GLOW DISCHARGE PLASMAS

For $\xi \ll 1$, Eqs. (6,7) amount to a small correction to the well established results of low density, collisionless, cold electron beam plasmas. The solutions are qualitatively the same. In glow discharge, high density, collisional plasmas, the thermal velocity is much larger than the drift velocity. Taking $\xi \gg 1$, the roots of Eq. (7) are

$$K = \xi^{-2}\,(-\Theta \pm \xi\,(\Theta^2 - \Theta_p^2)^{-1/2}) \ll 1 \qquad (8)$$

which gives complex K for $\Theta < \Theta_p$ and real K for $\Theta > \Theta_p$.

The eingenvalues would have to satisfy Eq. (6) which, in the limit of $K \ll 1$, reduces to

$$(K_2 - K_1)(\Theta^2 - \Theta_p^2)(-1 - (1/C) + i\Theta R + L^2) = 0 \quad (9)$$

The first two factors of Eq. (9) correspond to stable oscillations in time and space, the third factor corresponds to circuit parameter related oscillations. Considering purely resistive external loading like in CW CO_2 laser arrangments, the circuit dispersion relation gives an imaginary Θ, that is

$$\Theta = -i\,(R)^{-1} \quad (10)$$

Thus, according to our analysis, the pulsations in glow discharges is caused by $R_p > R$ and can be stablized by using a large enough external resistance. However, in order to obtain an adequate workable CO_2 discharge, the external loading resistance is only variable over a small range which is not enough to reverse the condition $R_p > R$.

5. EXPERIMENTAL STUDIES

As mentioned in the introduction, the glow discharge in a typical CW CO_2 laser set up, as shown in Figure 2 which shows the hollow cathode geometry, takes an active role in determining the laser operation parameters. By using a hollow cathode, there can be a high nitrogen mixture, no cooling regime. As reported in Ref. (6), the voltage taken at the anode with respect to the ground always presents spikes of about 10 μs width superimposed on the DC level. According to Eq. (10), we believe that the voltage spikes correspond to instabilities with $R_p > R$. Since the discharge is sustained by an external power source, it is restored immediately after the instability, thus producing voltage spikes. Scanning along the discharge tube with a photodiode, a corresponding spike is detected, having no phase shift with respect to the anode voltage spike. This indicates that the perturbation is either a standing wave or a structure with very long wavelength along the discharge tube, which is compatible with Eq. (8) having $K \cong 0$, since ξ^2 is very large. In planar cathode discharges, no spikes have been detected over a wide range of pressures. This can be understood by assuming the plasma resistance be smaller than the loading resistance.

A typical voltage spike is shown in Figure (3). The voltage drop at the anode and the DC level are denoted by ΔV and V, respectively.

To experimentally investigate the glow discharge diode instability, we have studied the variations of the voltage spike for different gas mixtures. The results in Figure 4 show even inversions of anode polarization when instabilities occur. The parameter $\Delta V/V$ of the spike is related to the growth rate Θ_i and its dependence on gas composition reflects the dependence on the plasma resistance in Eq. (10).

In Figure 5 results of laser power output with high partial pressure of both nitrogen and helium are presented. The output power of 10 watts and above is extraordinary because, under the same experimental conditions and with the same equipments, the output power for the $1(CO_2)$: $1(N_2)$: 8(He) standard gas mixtures with water cooling is about 2.5 - 3.0 watts.

With a discharge tube of the same length but consisting of two sections of hollow cathode discharge, as shown in Figure (6), typical output power can go as high as 30 watts with 16 % efficiency.

6. CONCLUSIONS

We have shown that hollow cathode glow discharge can modify substantially CO_2 laser operation parameters. The pulsations or spikes on the anode voltage associated with this kind of discharge are due to the circuit related diode instabilities when R_p is larger that R. The absence of the voltage spikes for planar cathode discharge suggests that, in such plasmas, R_p is less than R. The high output power and the advantage of doing away with the cooling system open up new applications of CW CO_2 laser with high partial pressures both for nitrogen and helium gases

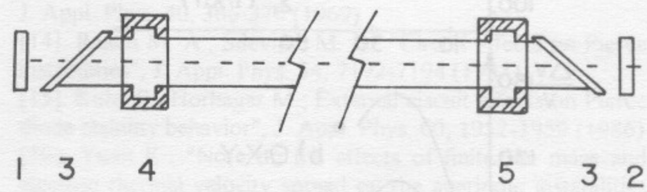

Figure 2. Typical CW CO_2 laser set up showing hollow electrodes to allow radiation passage to the mirrors with tube diameter 14 mm, length 75 cm, Ge plane output mirror with 85 % reflectivity (1), Cu totally reflecting mirror with 5 m radius of curvature (2), NaCl windows (3), cathode (4), anode (5).

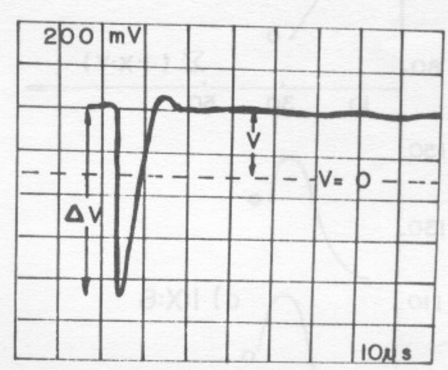

Figure 3. A typical voltage spike of about 10 μs width

ACKNOWLEDGMENTS

This work was financed by the Financiadora de Estudos e Projetos (FINEP), the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), the Third World Academy of Sciences (TWAS) and the Pró-Reitoria de Pesquisa e Pós-Graduação da Universidade Federal Fluminense (PROPP-UFF).

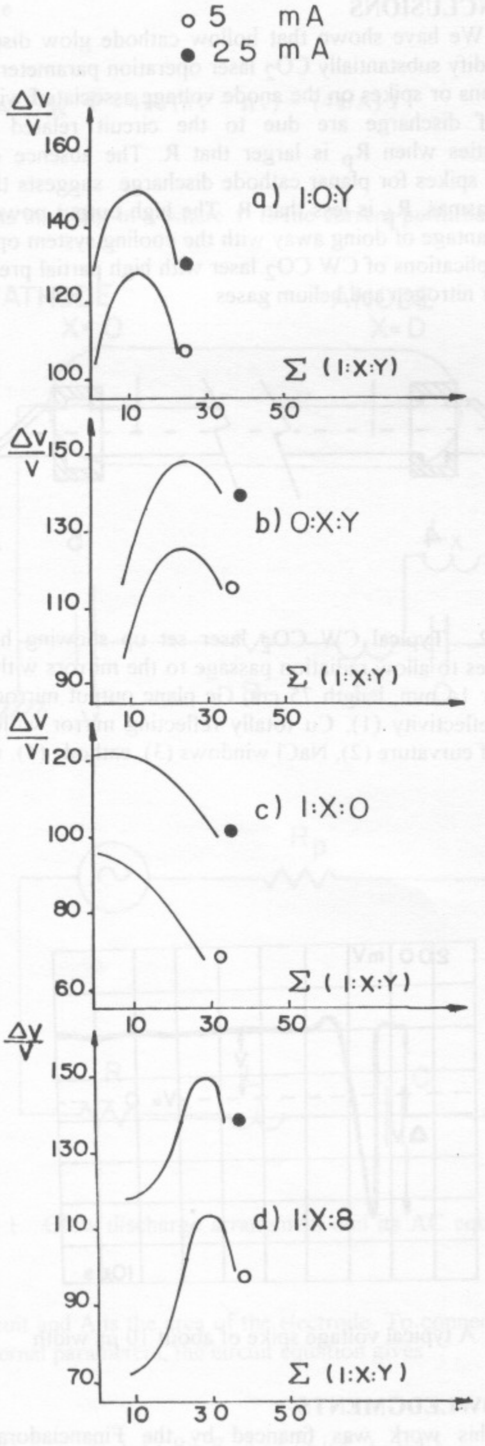

Figure 4. Variation of the voltage spike with respect to the DC level $\Delta V/V$ as a function of gas composition (a) 1 (CO_2) : 0 (N_2) : Y (He) ; (b) 0 (CO_2) : X (N_2) : 8 (He) ; (c) 1 (CO_2) : X (N_2) : 0 (He); (d) 1 (CO_2) : X (N_2) : 8 (He)

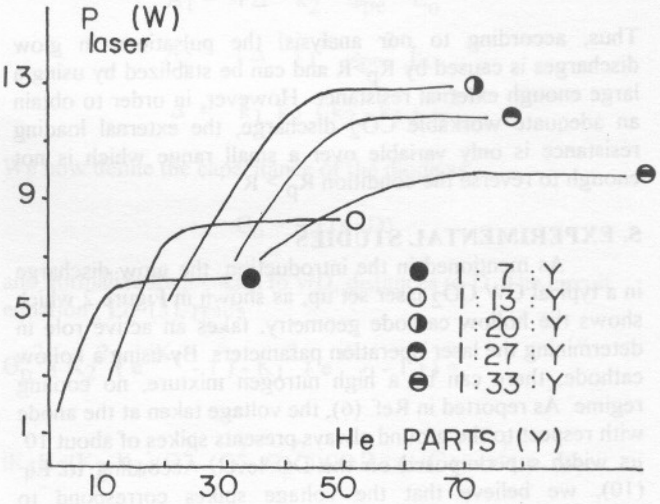

Figure 5. Maximum laser output as a function of gas composition with the set up of Figure 2, showing the best mixture of 1 (CO_2) : 20 (N_2) : 40 (He) with a 7.5 % power efficiency.

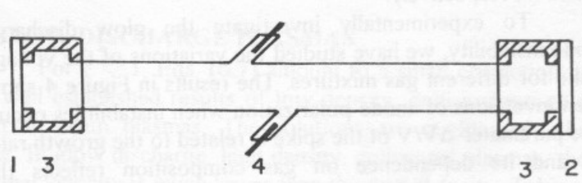

Figure 6. A two section discharge tube with diameter 14 mm, length 75 cm, same Ge and Cu mirrors (1) and (2), with NaCl windows removed, hollow cathodes (3) , anodes (4).

REFERENCES

[1]. Tsui K. H., Silva A. V. F., Couceiro I. B., Tavares Jr. A. D., Massone C. A.; "Resonant narrowing of the nitrogen laser pulse by plasma impedance matching", IEEE J. Quant. Electr. 27, 448-453 (1991)

[2]. Silva A. V. F., Tsui K. H., Pimentel N. P., Massone C. A.; "Plasma electronics in pulsed nitrogen lasers", IEEE J. Quant. Electr. 28, 1937-1940 (1992)

[3]. Da Costa A. F., Tsui K. H., Huang Y. K., Massone C. A.; "Partial pressure scaling law of CO_2 laser efficiency", Applied Physics B51, 227-232 (1990)

[4]. Zanon R. A. D., Tsui K. H., Huang Y. K., Cavalcanti G. H., Massone C. A.; Experimental analysis of a high nitrogen partial pressure carbon dioxide laser", Optics Communications 76, 350-352 (1990)

[5]. Huang Y. K., Tsui K. H., Massone C. A.; "Output power constancy of a high nitrogen partial pressure carbon dioxide laser with variable total pressure", Chinese J. of Lasers 18, 646-648 (1991)

[6]. Tsui K. H., Zanon R. A. D., Couceiro I. B., Massone C. A.; "Plasma interaction with stimulated emission in a CO_2 laser", Optics Communications 83, 60-64 (1991)

[7]. Leung P., Wong A. Y., Quon B. H.; "Formation of double layers", Phys. of Fluids 23, 992-1004 (1980)

[8]. Quon B. H., Won A. Y.;"Formation of double potential layers in plasmas", Phys. Rev. Letts. 37, 1393-1396 (1976)

[9]. Iizuka S., Michelsen P., Rasmussen J. J., Schrittwieser; "Dynamic of a potential barrier formed on the tail of a moving double layer in a collisionless plasma", Phys. Rev. Lett. 48, 145-148 (1982)

[10]. Van Den Heuvel F. C., Urehen Q. H. F.; "Striations of the convective type and feedback in low-pressure mercury/noble gas discharges", Phys. of Fluids 28, 3034-3039 (1985)

[11]. Pierce J. R.; "Limiting stable current in electron beams in the presence of ions", J. Appl. Physics 15, 721-726 (1944)

[12]. Frey J., Birdsall C. K.; "Electron-strem diode instabilities with elastic collisions", J. Appl. Phys. 36, 2962-2964 (1965)

[13]. Faulkner J. E., Ware A. A.; "The effect of finite ion mass on the stability of a space-charge-neutralized electron beam", J. Appl. Phys. 40, 366-370 (1969)

[14]. Raadu M. A., Silevitch M. B.; "Circuit effects on Pierce instabilities", J. Appl. Phys. 54, 7192-7194 (1983)

[15]. Kuhn S., Horhager M.; Ëxternal ciscuit effects on Pierce diode stability behavior", J. Appl. Phys. 60, 1952-1959 (1986)

[16]. Yuan K.; "Note on the effects of finite ion mass and electron thermal velocity spread on the aperiodic instabilities of a space-charge-neutralized electron beam in a planardiode", J. Appl. Phys. 48, 133-135 (1977)