CO Electric Discharge Lasers

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Introduction

SINCE the sizeable body of literature which now exists on the CO lasers could not all be reviewed adequately within the confines of a single paper, it was decided to emphasize the more recent work, which is of current interest and which in some cases has not had wide dissemination. Earlier work is included which represented important milestones in the development of CO electric discharge lasers (EDL's), or which provided a basis for later development. In many instances decisions had to be somewhat arbitrary, and the author wishes to apologize at the outset for giving short shrift to much work that was important in the development of CO EDL's. For more complete reviews of the earlier work, the reader is referred to the review papers of Sobolev and Sokovikov[1] and that of Chen.[2]

The possibility of a laser that uses the vibrational-rotational transitions of the ground electronic state of CO was initially proposed by Legar and Legay-Sommaire in 1964.[3] Pulsed laser action on these transitions was observed by Patel and Kerl[4] in the same year at about the same time that laser action in CO_2 first was reported. During the subsequent years, the CO_2 laser has been the subject of active research and development efforts resulting in rapid and significant advances in performance and device technology. By contrast, as a consequence of the relatively dissappointing results of early experiments, indadequate understanding of the laser kinetics, and technological problems, the CO laser was the object of much less attention until the later part of the decade, when a number of developments indicated the potential of CO lasers for efficient high power operation. Interest in CO initially was spurred by the work of Osgood et al.,[5,6] who achieved power levels and efficiencies from a conventional discharge CO laser comparable to that obtainable from CO_2. Subsequently, Bhaumik et al.,[7] demonstrated an efficiency of 47%, which was the highest efficiency ever obtained in any laser system. More recently, major advances have been realized by utilizing electron beam stabilized discharge techniques. Mann et al.[8] have demonstrated an efficiency of 60% and a specific energy of 760 J/ℓ-atm, which represent the highest values yet attained in any directly excited system. Center [9] has reported single pulse energies exceeding 1 kJ. Several investigators[10-12] have reported high power (> 10 kW) quasi-cw operation. The work to date has clearly established the potential of CO electric discharge lasers, although a number of important problems have yet to be addressed. In the following sections, the history and status of CO electric discharge lasers will be reviewed, and the directions of current research and development activity will be discussed.

Theory

One of the most significant features of the CO electric discharge laser is its demonstrated high efficiency, which is attributable to several factors. First, as shown by Nighan,[13,14] by properly tailoring the electron energy distribution the excitation efficiency, i.e., the fraction of input electrical energy which is transferred to vibration, can exceed 90%. Secondly, the vibrational energy level structure of CO consists of a single ladder of slightly anharmonic (approximately1%) energy levels. A laser transition can occur between any pair of adjacent vibrational levels, and the terminal level for one transition can be the initial level of the subsequent transition. A molecule in the lowest lasing level can be re-excited by vibrational exchange collisions without ever passing through the vibrational ground state. As a result, the quantum efficiency is extremely high (>90%), the departure from unity resulting from the conversion into heat during vibrational exchange collision of the small amount of energy associated with the anharmonic defect. The direct conversion of vibrational energy into heat by the VT processes proceeds at an extremely slow rate as shown by Millikan et al.[15-17]

The vibration-vibration-translation (VVT) processes represent the most important mechanism for determining the vibrational population distribution of the CO laser system. The rates of VVT near resonant exchange collisions generally are much faster than the electrical excitation rates, and thus the energy is redistributed rapidly among the vibrational levels. It has been shown by Treanor et al.[18] and others[19-22] that, as a result of the anharmonicity of the energy levels, the kinetics of diatomic molecular gases dominated by rapid VVT exchange collisions can lead to highly excited non-Boltzmann distributions of the vibrational level population. The higher vibrational levels with smaller level spacing are pumped at the expense of the lower levels, with the defect energy going into heat. Significant departures from Boltzmann populations may be expected in levels for which the anharmonic defect is comparable to or exceeds kT. This qualitative suggestion is

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supported both by the results of complete analyses and experiments. Figure 1 shows the observed spectra from a conventional discharge laser as a function of wall temperature.[7] This shift of the spectrum towards higher vibrational bands as the temperature is increased is evident.

A complete analysis of the CO EDL requires self-consistent solution for the molecular kinetics, plasma kinetics, spontaneous and stimulated emission, and fluid dynamics. A number of such analyses have been carried out to various levels of sophistication.[23-39] A review of this work is beyond the scope of this paper. Recently, however, Lacina[40] has shown that it is possible to make several reasonable approximations that allow certain general scaling laws for CO EDL's to be formulated. These generalizations depend only upon a few basic parameters, which make it possible to predict temporal output characteristics of a large class of both pulsed and flowing cw-CO systems. Thus, except for the spectral details, it is possible to design general CO/X systems to a good approximation without resorting to extensive computer calculation.

For a high pressure oscillator operating at temperatures typically in the range of 60-300 K, spontaneous radiation and VT decay can be neglected. Consistent with this approximation, the VT contribution to the kinetic heating also can be neglected. Theoretical predictions that only a small percentage of electrical power is converted to kinetic heating ($\sim 10\%$) even after steady state has been obtained have been verified experimentally.[41,42,10] Thus, for reasonably dilute CO gas mixtures, it is a good approximation to neglect the temperature rise and changes in the molecular number densities for pulse times that are comparable to time required to reach steady state. Lacina introduces the following dimensionless quantities:

$$\begin{aligned} \tau &= p_{CO}t \\ f &= 1+(3/2)p_{tot}/p_{CO} \\ \xi &= \Delta v_{CO}/\Delta v_{tot} \\ &= \frac{p_{CO}<v_{rel}(CO,CO)>\sigma^{opt}(CO,CO)}{\sum_X p_X <v_{rel}(CO,X)>\sigma^{opt}(CO,X)} \end{aligned} \tag{1}$$

$$\tilde{\gamma} = \gamma/\xi \qquad \tilde{W}_e = W_e/p_{CO}^2$$

$$\tilde{I} = I\xi/p_{CO}^2 \qquad \tilde{E} = E/p_{CO}$$

where f is related to the number of thermal degrees of freedom, ξ is the fractional percentage of total optical line broadening caused by CO, and $\tilde{\gamma}$, $\tilde{W}_e$, $\tilde{I}$, and $\tilde{E}$ are, respectively, the scaled threshold loss (cm^{-1}), power density [W/cm^3/Torr (CO)], intensity [W/cm^2/Torr^2(CO)], and energy density [J/cm^3/Torr(CO)]. The definition of parameter ξ given here applies to a situation in which pressures are high enough (greater than or approximately equal to 20 Torr) that optical lines are predominantly pressure broadened. The set of parameters (T_{mol}, $\tilde{W}_e$, $\tilde{\gamma}$, f) completely characterize the CO EDL under these approximations. However, except for the scaled excitation powers $\tilde{W}_e$, most of these parameters do not have a sensitive effect on the power response of the system as a function of time (although detailed spectral predictions may have a more critical dependence). The reasons for this are the following: 1) the most important parameter, the scaled excitation $\tilde{W}_e$ is a measure of the electrical pumping per molecule relative to the rate of VV cross relaxation, and thus specifies the ratio of the two dominant processes in the CO EDL. 2) A pulsed high pressure CO EDL typically operates in the regime where oscillation is high above threshold, and thus, results for optical power extraction usually will be insensitive to the scaled cavity loss coefficient $\tilde{\gamma}$ unless the ratio $\tilde{W}_e/\tilde{\gamma}$ becomes very small. 3) The temperature rise for pulse times comparable to the time required to reach steady state is small, and so the results do not depend critically upon f, providing it is large. This parameter mainly is important for detailed predictions of spectral distribution. It should be noted that the scaling generalizations are valid only for times (or energy loadings) comparable to the time to reach the quasisteady condition, since for longer times (or higher energy loadings) the temperature rise can be significant. 4) Results of calculations for a wide range of parameters show a relatively weak dependence on T_{mol}.

Lacina was able to show that, for a given temperature T_{mol} and a fixed value of quantum efficiency η/η_∞ (where η_∞ is the steady-state value), a log-log plot of $p_{CO}t$ vs the scaled power $\tilde{W}_e$ is approximately linear. For example, Fig. 2 shows such a plot for the turn-on time $p_{CO}t_o$ vs $\tilde{W}_e$. The slope of these curves is approximately $-5/6$ and is independent of T_{mol} and $\tilde{\gamma}$; the variation in the magnitude of the curves is less than a factor of two within the range of temperatures chosen. Thus, for a fixed temperature T_{mol}, the time t required to attain any specified value η/η_∞ for the optical extraction efficiency satisfies

$$\tilde{e} = p_{CO}t\tilde{W}_e^{5/6} = \text{const} \tag{2}$$

which implies that, within a range of values for γ which are suitably small, a "universal" plot of efficiency vs the parameter $\tilde{e} = p_{CO}t\tilde{W}_e^{5/6}$ can be constructed (Fig. 3). [The value of the steady-state efficiency depends only slightly upon $\tilde{W}_e$, T_{mol}, and $\tilde{\gamma}$ (Figs. 4, 5)]. The significance of the parameter $\tilde{e}$ can be seen by noting that, if the exponent of $\tilde{W}_e$ in Eq. (2) were unity instead of 5/6, $\tilde{e}$ would represent the total electrical energy $\tilde{E} = W_e t/p_{CO}$ [J/ℓ/Torr(CO)] which has been deposited into CO vibrational energy up to time t. Therefore, the response of the system is approximately a function only of the specific input energy $\tilde{E}$ (which is, of course, a function of time and the excitation rate). The power efficiency can be integrated to give a universal curve for the energy efficiency ϵ/η_∞ as a function of the parameter $\tilde{e}$, and this result also is presented in Fig. 3.

Among the important conclusions to be drawn from the previous remarks are the following. Characteristic times, such as turn-on time or time required to reach steady state, satisfy a relation given by Eq. (2). For the range of temperatures and for the reasonably small values of $\tilde{\gamma}$ discussed here, turn-on occurs after a specific electrical energy $\tilde{E}_0 \sim 0.5$-1.0 J/ℓ/Torr (CO) has been deposited, and steady state is attained after an energy $\tilde{E}_{ss} \sim 1.7$-2.6 J/ℓ/Torr (CO) has been deposited. (These numbers correspond to a specific pumping rate $\tilde{W}_e = 1.0$ W/cm^3/Torr (CO)^2; for other values of $\tilde{W}_e$, Eq. (2) shows that these deposition energies increase as $\tilde{W}_e^{1/6}$.) The typical range of values for $\tilde{W}_e$ generally is sufficiently small that the $\tilde{W}_e^{1/6}$ variation is not significant, and thus experimental results may be plotted in terms of the more physically significant quantity $\tilde{E} = W_e t/p_{CO}$. The results are in good agreement with previous threshold calculations[30,34] as shown in Table 1. The results quoted here are for the case of monatomic diluents. However, approximate methods of treating the case of nitrogen diluents also have been developed.[40]

Table 1 Summary of threshold energies – j/ℓ-atm$_{CO}$

Temperature	Hall & Eckbreth[30]	Rockwood[43]	Lacina
77	400	...	400
150	700	...	...
200	...	800	800
300	900	1000	...

Table 2 Scaled saturation intensity

T_{mol}(K)	60	100	150	200	300
$\tilde{I}_s$(W/cm^2/Torr^2)	0.6	0.8	1.6	2.5	6.4

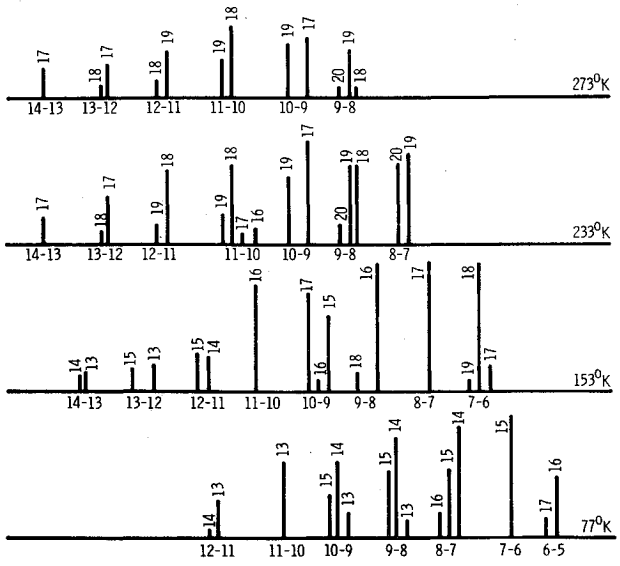

Fig. 1 CO laser spectra at various wall temperatures.[7]

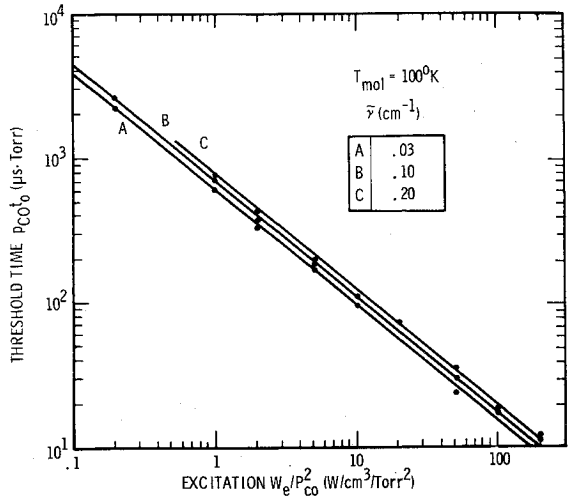

Fig. 2 Scaled threshold time $p_{CO}t_0$ as a function of scaled excitation W_e/p_{CO}^2 for several values of loss $\tilde{\gamma}$ at 100 K.[40]

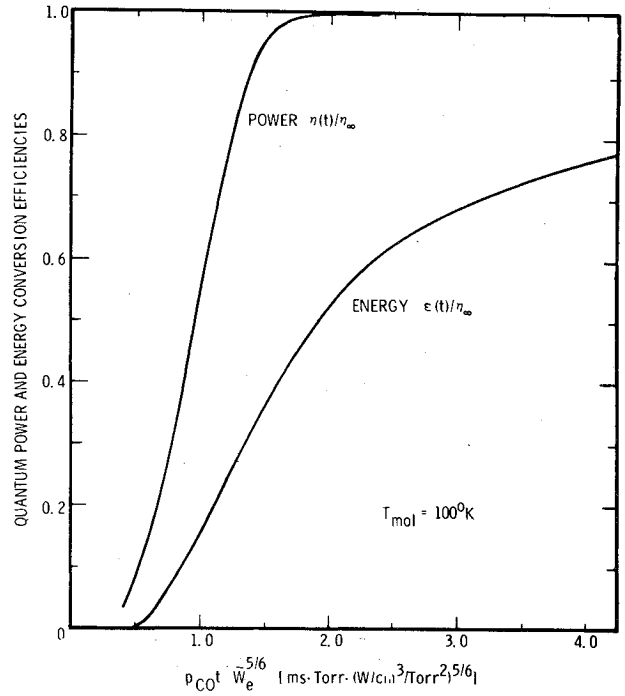

Fig. 3 Generalized power and energy conversion efficiencies.[40]

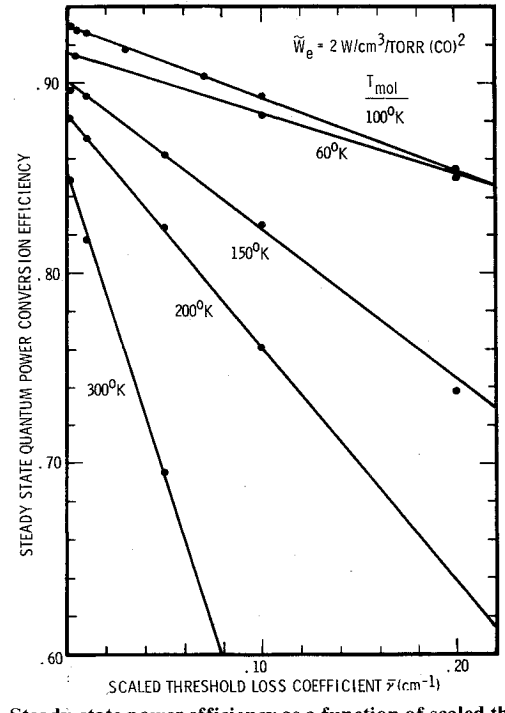

Fig. 4 Steady-state power efficiency as a function of scaled threshold loss coefficient (temperature as a parameter).[40]

By use of the same model, Lacina also was able to show that it was possible to define a scaled saturation intensity, which would show approximately how the gain saturates as a function of the total intensity of the medium. The results of this calculation are shown in Table 2.

In general, the results of the more recent analyses of CO EDL's have agreed reasonably well with experimental comparison at cryogenic temperatures. However, there have been a number of significant and disturbing discrepancies between theory and experiment. Theoretical predictions of efficiency consistently have been higher than those realized experimentally. Efficiency has been more sensitive to temperature than would be anticipated on the basis of current analysis. There also have been a number of unexplained spectral anomalies. The observed spectra generally have been one or two V bands higher than anticipated, and show more structure than predicted theoretically. In some cases, particular rotational transitions are consistently absent or appear weaker than anticipated.[44,45] Recently Lacina and McAllister have proposed that resonance self-absorption in the CO medium may be an important pressure-dependent effect, which may in part explain the observed anomalies.[46] At high pressures, the collison broadening of lines results in several significant spectral overlaps for almost every CO transition, so that laser oscillation on one vibrational-rotational line can be absorbed (or have enhanced gain) through the near-resonant transitions of other bands. Of particular importance is the fact that $P(J)$ transitions (which are the ones generally exhibiting gain) most frequently have overlaps with $R(J)$ transitions of higher vibrational bands, and thus absorptive pumping to higher V levels can result.

The results of Lacina's calculations have shown that for high pressures this mechanism can produce output spectral distributions and temporal behavior which are significantly different from those predicted on the basis of the previous theoretical models. Although definitive comparisons of the theory with experimental spectra are not yet available, it has been shown that the mechamism of near resonant absorption

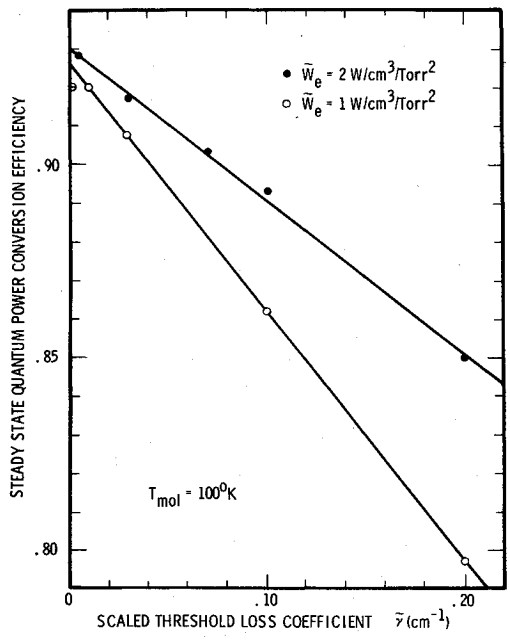

Fig. 5 Steady-state power efficiency as a function of scaled threshold loss coefficient $\tilde{\gamma}$(pump power as a parameter.[40]

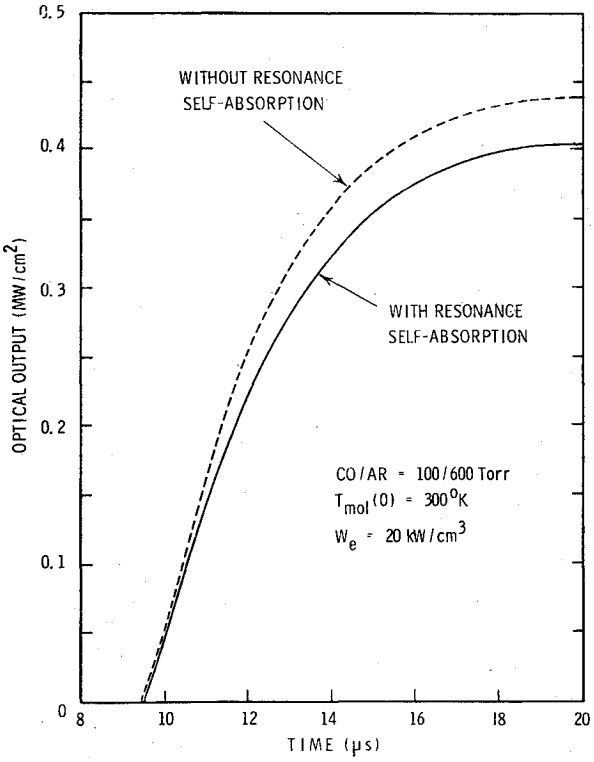

Fig. 6 Effect of resonance self-absorption on laser output.[40]

based on currently accepted optical broadening constants alters the analytical predictions at high pressures. Figure 6 shows a comparison of the predicted transient evolution of the optical output for CO/Ar=100/600 Torr at 300K, pumped at a constant rate of 20 kW/cm^3 for 20 μs). Figure 7 shows the predicted intensity distribution near the end of the pulse (18 μs) with and without resonance effects, and Fig. 8 shows a comparison of the $P(J)$ spectral designations as a function of time. Note that the intensity envelope as well as the $P(J)$ characteristics are considerably different. The significant differences orifinate completely from the resonant absorption mechanism, and not from differences in heating, as there was less than a 1% change in the temperature rise for

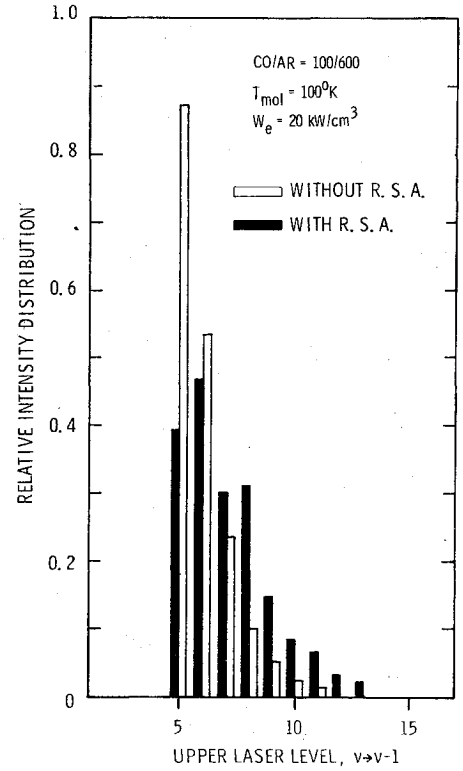

Fig. 7 Effect of resonance absorption on CO laser spectra.[40]

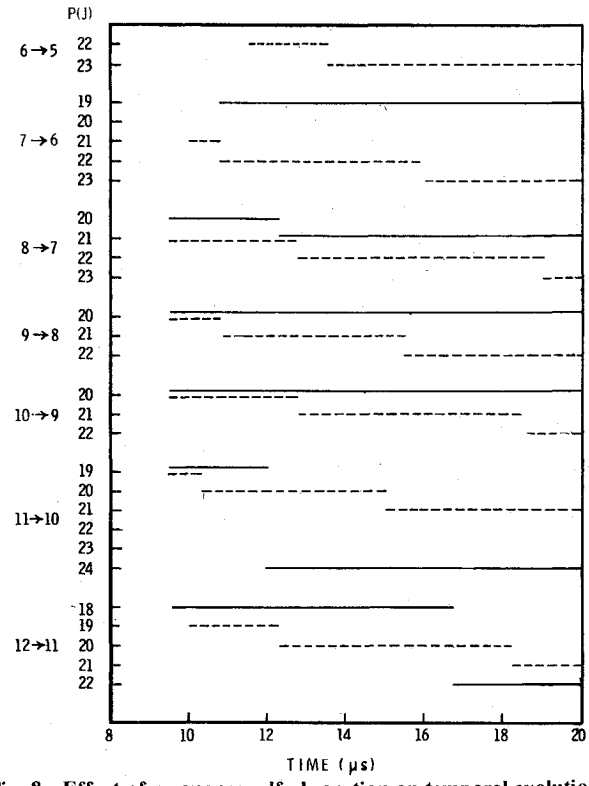

Fig. 8 Effect of resonance self-absorption on temporal evolution of spectra.[40]

the two calculations. The results indicate that resonance absorption does not have a significant effect on the predictions of total optical output efficiency, kinetic heating rates, or transient evolution. Changes are typically less than 10%, and therefore the parameter scaling generalizations previously discussed are not immediately invalidated. However the predicted spectral output distribution does change significantly with the output power redistributed to the higher

vibrational bands. It should be noted that these calculations are sensitive to the assumptions of the optical broadening cross sections and line shape, and further work may be required to improve the understanding of wing broadening in order to get accurate quantitative results.

Conventional Discharge Lasers

In 1974, Patel and Kerl first reported laser action on several *P* branch rotational transitions in the 6-5, 7-6, 8-7, 9-8, and 10-9 vibrational bands belonging to the ground electronic state of CO.[4,47] The laser consisted of a 47-mm-i.d. tube, 5 m long, with a near confocal whole couple resonator. CO pressure was about 0.8 Torr, and pulsed excitation was employed with pulses of 15 A peak current and 15 kV peak voltage and a nominal duration of 1 msec. The first cw laser action in CO was obtained by Legay-Sommaire et al.[48] by use of a mixing technique in which N_2O was pre-excited by a rf discharge and then mixed with CO in the active region. Thirty-six laser lines were observed with a total output power of 370 mW, with the strongest lines having a power of approximately 20 mW. Patel replaced the N_2O by N_2 excited by a direct discharge.[49] By employing a tube cooled with either water or methynol (-78°C), Patel was able to obtain laser emission for approximately 140 lines between 5.0 and 6.2 μ.

In Ref. 47, Patel had shown that gain in the CO laser could be considerably enhanced by operating at low temperature. Following this suggestion, Osgood and Eppers[50-54] were able to demonstrate for the first time a CO laser with an output power and efficiency comparable to that of CO_2. In these experiments they employed an LN_2-cooled tube with direct excitation of CO:N_2:He or CO:air:He mixtures, as opposed to mixing techniques used previously. In the initial experiments, an output power of 20 W at 9% efficiency was demonstrated which was increased by subsequent optimization to 95 W at 16% efficiency. Osgood et al. also operated an LN_2-cooled CO laser in a Q-switched mode by using a rotating mirror Q-switch. Peak powers of up to 13 kW and pulse energies of approximately 1 μJ were obtained with half widths of approximately 0.1 to 1 μs. The spectra in the Q-switch mode was considerably richer than that observed under cw conditions, with approximately 60 lines being observed in the transitions of 5-4 to 19-18.

The work of Osgood et al. greatly stimulated the interest in CO lasers. In addition, the theoretical work referenced earlier suggested that the limiting quantum efficiency of the CO laser should be extremely high. In an attempt to realize a laser efficiency approaching this limit, attention was focused on tailoring the electron energy distribution to improve the excitation efficiency. By employing low ionization potential additives such as Xe and Hg, the laser efficiency was significantly increased.[7] Table 3 shows the effect of the addition of Xe on a cryogenically cooled laser. The maximum efficiency of 47% was the highest value ever obtained in any laser system. The addition of Xe was also observed to produce a shift in the intensity distribution of the output spectrum toward shorter wavelengths (i.e., lower vibrational band).

Substantial increases in efficiency also were obtained for a room temperature laser. The laser tube used for these experiments has a interelectrode separation of 124 cm. The electrode wells were filled with Hg. By use of the mixture shown in Table 3, an output of 25 W corresponding to an efficiency of 17% was obtained. By comparison, without the low ionization potential additives, the maximum output was 10 W corresponding to an efficiency of 5.5%. In addition to its effect in enhancing laser efficiency, the addition of Xe also was observed to reduce the dissociation of CO in agreement with the mass spectroscopy studies of Hocker.[55] Up until this point, all CO lasers had employed continuously flowing systems. In general, the flow rates were adequate to remove impurities and decomposition products but did not provide appreciable convective cooling However, the experiments with Xe suggested that it should be possible to operate a sealed off CO laser. This speculation was confirmed by the work of Freed[56] and Seguin et al.[57] In both cases, the addition of Xe was found to be crucial to reliable sealed off operation. In an interesting extension of their work, Seguin et al.[58] subsequently demonstrated that, by introducing both CO and CO_2 into the mixture, a sealed laser could be constructed which would either at 5 or 10μ. Because of the limitations of the available optics, they were not able to ascertain whether or not simultaneous emission at both 5 and 10μ could be obtained. Subsequently, Barry et al.[59] demonstrated simultaneous cw laser action at both 5-and 10-μ wavelength regions with de excitation and a slowly flowing mixture of He:air;CO.

The effect of temperature on the performance of the CO laser was methodically investigated by Bhaumik et al.[7] For these measurements, the laser tube was immersed in a temperature control bath for which the wall temperature could be maintained at any selected temperature between 77 K and ambient controlling the flow of cold N_2 gas through a bath containing a mixture of equal parts of N-methylbutane and isohexane. Spectra were taken every 10 K between 300 and 77 K. The output spectra at four different temperatures for which significant changes were observed are presented in Fig. 1. It is observed that the CO spectrum shift toward lower vibrational transitions as the molecular kinetic temperature is reduced. Laser gains typically varied from 0.1 to 0.2%/cm at room temperature up to 0.5 to 1% at 77 K wall temperature. The gain was, in general, enhanced by the addition of Xe. The sensitivity of laser efficiency to temperature is clearly demonstrated in Fig. 9. The efficiency decreases by more than a factor of 3 in varying the wall temperature from LN_2 temperature to ambient.

Table 3 CO laser operating characteristics[7]

Configuration[a] and wall temperature, K		Total	He	Pressure Torr CO	N_2	O_2	Xe	Discharge voltage, kV	Discharge current, mA	Output, W	Efficiency, %
D	77	18	16	0.5	1.5	0.01	0.3	12.4	12	70	46.9
A	77	16.00	15	0.4	0.4	0.01	0.15	12.8	10	51	39.8
A	77	16.1	15.25	0.25	0.6	0.01	...	13.6	18	60	29.2
A	77	16.25	15.25	0.25	0.6	0.01	0.15	12.8	18	70	36.7
B	77	17.3	14.9	1.6	1.8	0.01	...	12.0	27	91	28
B	150	18.32	14.9	1.5	1.9	0.02	...	12.0	10	25	20.8
C	220	16.26	12.5	0.45	3.0	0.02	0.3	9.0	22.5	42.5	21
C	300	15.97	12.5	0.45	3.0	0.02	...	14	13	10	5.5
C	300	16.26	12.5	0.45	3.0	0.02	0.3	9.2	22.5	25	12.1
E	300	16.36	12.5	0.45	3.0	0.02	0.4	14	12	12.5	7.0

[a] Configuration: Discharge length – 126 cm; cooling jacket – 115 cm; a 10-m total reflector and a plane output mirror of reflectivity *R* in each case. Cavity length for A, B, and C – 215 cm with two Brewster windows; cavity length for D and E – 165 cm with internal mirrors.

[b] Values of reflectivity: A = 95%, B = 90%, C = 85%, D = 80%, E = 85%.

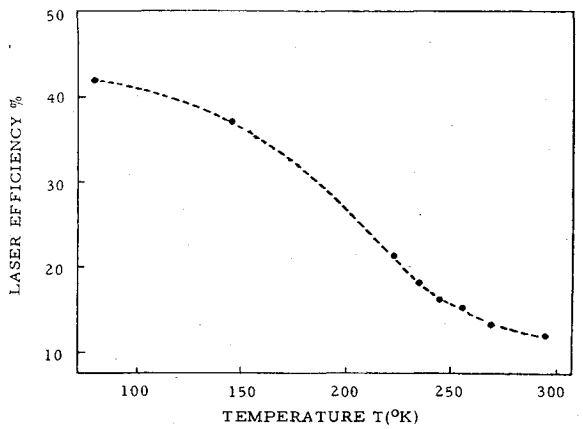

Fig. 9 Maximum laser efficiency vs wall temperature obtained by optimizing both the gas (including Xe) and the current. [7]

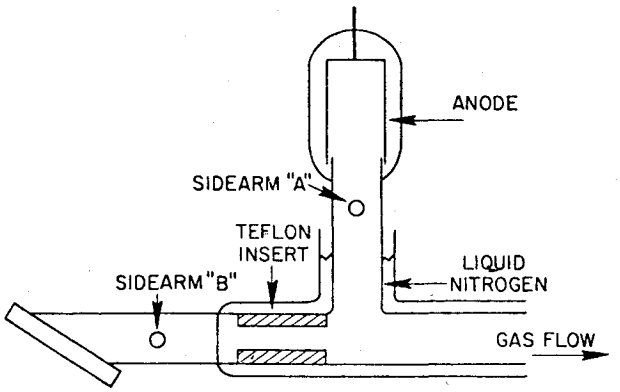

Fig. 10 Details of CO (1—0) laser construction. [62]

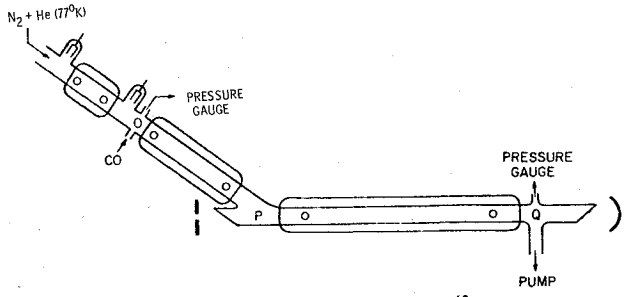

Fig. 11 Electrical mixing laser. [63]

The spectra shown in Fig. 1 are typical. However, a number of investigators have shown that, by careful control of the operating conditions, the observed spectral range can be considerably expanded. Barry and Boney[60] and Wiesbach and Chackerian,[61] succeeded in observing lines corresponding to transitions as low as $V=3$ to 2. In a very interesting experiment Djeu[62] observed single-line laser oscillation on the P9, P10, and P11 transitions in the $V=1$ to 0 band of CO. The construction of his laser is indicated in Fig. 10. The two main conditions are the LN_2 cooling of the entire laser active length and the avoidance of ground state CO beyond the discharge region. The CO self-absorption problem was solved by flowing He in through side arm B and the rest of the gases in through side arm A. The insert was used to minimize back diffusion of CO into the unexcited region. In addition, it was necessary to maintain very low CO partial pressures (≤ 0.01 Torr) in order to observe laser action on the 1-0 lines. Typical mixtures consisted of 5 Torr He, 1.5 Torr N_2, 0.1 Torr Xe, and 0.01 Torr CO. The highly dilute CO mixture presumably was employed to establish a favorable balance between CO V-

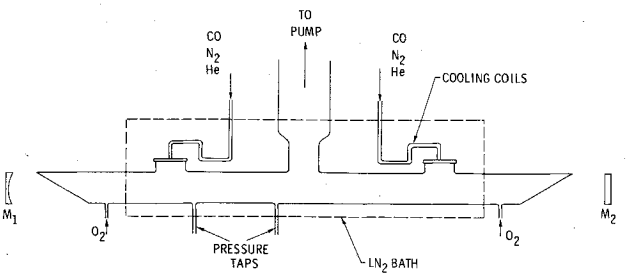

Fig. 12 Forced-convective-flow CO laser. [65]

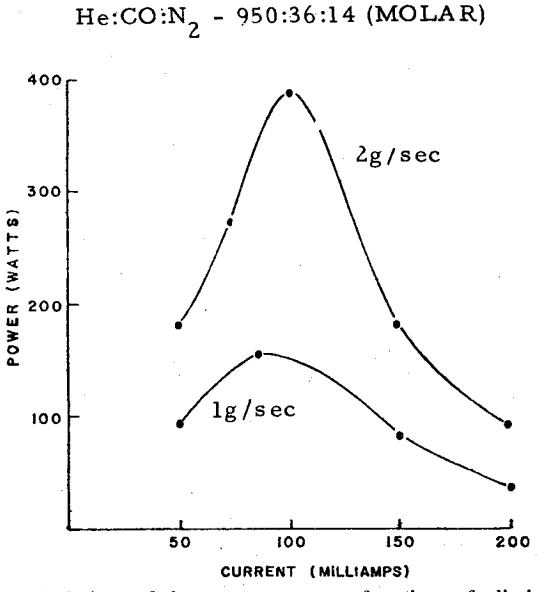

Fig. 13 Variation of laser power as a function of discharge current. [65]

V processes and the excitation of the CO $V=1$ level by electronic and N_2 -CO vibrational transfer processes. The output for the 1-0 lines was measured to be about 5 mW. Djeu also was able to expand the observed spectrum of laser transitions to $V=35$ to $V=34$.[63] The spectra observed in his mixing laser (Fig. 11) ranged from $V=2$ to 1 to $V=35$ to 34. A mixture of precooled He and N_2 was passed through a 20-cm glow discharge and subsequently mixed with CO injected at a downstream position. The cooling jackets were filled with LN_2. From the data of this experiment, Djeu was also able to infer the VT relaxation rate for the higher vibrational bands of CO. The experimental data gives a VT relaxation rate of CO($\sim V=30$) by He at 150K as 2 by 10^3/sec/Torr as compared to the Miller and Millikan[16] value of the VT relaxation rate of CO ($V=1$) of 0.1/sec/Torr. Using a Q-switched laser, Yardley[64] was able to observe transitions up to $V=37$-36.

Heat rejection in the sealed or slow flow lasers discussed so far was limited by diffusion. Kan Whitney[65] applied the technique of forced convective flow to a LN_2 cooled CO laser and achieved an order-of-magnitude enhancement of the output power density above the performance obtainable from the same laser operated in a slow flow, diffusion dominated mode. A schematic of the forced convective flow laser is shown in Fig. 12. The laser tube was 1 m long and had a 2-½-cm bore. Under slow flow conditions, the output power was 35 W. Figure 13 shows the output power for mass flows 1 and 2 g/sec. The maximum extracted power of 400 W. at 20% efficiency was obtained with the mixture shown on the figure. Under these conditions, the mean flow velocity through the tube is approximately 120 m/sec. It is evident that even high powers should be obtained at higher flow rates. The specific power implied by these results is approximately 90 kW/lb/sec. The reduction in temperature effected by the con-

Table 4 Comparison of spectral distribution for the flow and diffusion lasers[65]

	Forced convective flow		Diffusion mode	
Vibrational band	Transition	Relative normalized band intensity	Transition	Relative normalized band intensity
$v=5$-4	P(12)	0.1	...	...
$v=6$-5	P(12)-P(13)	0.8	...	...
$v=7$-6	P(11)-P(13)	1	P(14)-P(16)	0.8
$v=8$-7	P(12)	0.5	P(15)-P(17)	1
$v=9$-8	P(11)-P(12)	0.4	P(13)-P(16)	0.9
$v=10$-9	P(10)-P(12)	0.2	P(13)-P(15)	0.7
$v=11$-10	P(10)-P(11)	0.2	P(14)	0.2
$v=12$-11	P(10)	0.03	P(14)-P(15)	0.3
$v=13$-12	P(9)-P(11)	0.06	...	...
$v=14$-13	P(9)-P(10)	0.05	...	...
$v=15$-14	P(9)	0.02	...	...

Table 5 Summary of experimental results[79]

Constituents	Ratio	E/N	Pumping rate, kW/cm^3	Output, J	Efficiency	Specific energy
CO,Ar	1:10	0.5×10^{-16}	2.2-0.4	153 ± 15	63 ± 15	580 ± 90 J/ℓ-atm 100 ± 20 kJ/kg
CO,N_2	1:10	1.4×10^{-16}	3.2-1	200 ± 25	48 ± 12	760 ± 115 J/ℓ-atm 180 ± 40 kJ/kg

vective flow is evident by the change in the spectrum as indicated in Table 4. The effect of the convective cooling is to lower the first observable vibrational band and shift the P branches towards lower J values.

Although the bulk of the effort of CO lasers was directed at scaling to higher powers, the devices of Yusek and Lockhart[66] and Aswa[67] represent notable exceptions. These researchers developed compact sealed off waveguide CO lasers. Asawa's device (Fig. 14) had a discharge length of 14 cm and was cooled by dry ice and methynol to 210 K. An output of 1.1 W at 5.7% efficiency was obtained with a mixture of CO:He:Xe:N_2 in the ratio to 1:8:1:1 at a total pressure of 80 Torr.

TEA Lasers

Several investigators have reported laser action is CO using transversely excited atmospheric pressure (TEA)-type laser configurations. In general CO TEA lasers have not attracted the attention that CO_2 TEA lasers have for several reasons. Perhaps most significant is the fact that the high peak power, short pulse performance of CO_2 TEA lasers is not readily obtainable in CO, since the temporal evolution of the output is primarily determined by the molecular kinetics and is relatively insensitive to the form of the excitation pulse. The relatively high energy loadings required in order to obtain efficient operation are difficult to realize in devices of this type. In addition, there are technological and discharge stability problems associated with the cryogenic operation required for efficient performance. Thus far the primary value realized from CO TEA lasers has been as a diagnostic tool for investigating inversion and relaxation mechanisms in CO and as a laboratory source of 5 μ radiation.

The first observation of laser action in a CO TEA laser was reported by Beaulieu.[68] Subsequently, as part of a survey of candidate TEA lasers, Wood et al.[69] reported seeing approximately 40 P branch transitions in the vibrational bands from 7-6 to 14-13 in a room temperature TEA laser at 200 Torr with approximately a 30% CO concentration. Jeffers and Wiswall[70] employed a room temperature CO TEA laser to investigate relaxation processes and inversion mechanisms in the CO laser. By examining the temporal evolution, and particularly the time delay between the excitation pulse and the time the first laser transition reached threshold, they were able to conclude that VV relaxation was responsible for the population inversion, and that anharmonic pumping effects were important. Of particular interest was the observation of laser action on several R branch transitions of the 7-6 band, as this was a clear demonstration that the anharmonic pumping process could lead to total inversion. Jeffers and Wiswall[71] were able to get good agreement between observed thresholds and predictions based on a model that assumed that the population distributions were determined primarily by vibrational exchange processes. The conclusion regarding mechanism received further support from the work of Osgood et al.[72] who also observed the delays between excitation and threshold for a number of vibrational transitions. The time delay was found to be inversely proportional to pressure with the proportionality constant in agreement with the earlier experiments of Patel in a longitudinal discharge laser. The times were comparable to the characteristic times associated with VV exchange.

The first investigation of a cryogenic TEA laser was reported by Cohn.[73] A schematic cross section of this device is indicated in Fig. 15. Precooled gas was passed through the tube at relatively slow rates (approximately 2 ℓ/min). An LN_2 bath completely surrounded this discharge volume. Evacuated cells terminated by a pair of CaF_2 windows were employed to prevent condensation on the antireflection-coated windows and to eliminate turbulence generated at points of contact between the cold fill gases and uncooled surfaces. The discharge geometry consisted of a 6-mm-diam cylindrical anode separated by approximately 2.5 cm from a 1½-m-long linear array of 270 resistors. The discharge typically consisted of ½-μsec pulses at approximately 30 kV, with each pin carrying a peak current of about 2 A. The optical cavity was formed by a 10-m total reflector and a 97-98% reflectivity flat. At a temperature of 77 K, laser action on approximately 60 transitions over the spectral range from 4.96 to 5.61 μ was observed.

The qualitative behavior of the laser differed markedly between room temperature and cryogenic operation (Fig. 16). The upper trace shows the output of a CO pressure of 34 Torr at room temperature. The laser output consisted of a single, nearly 3-μsec-wide pulse (full width at half maximum), delayed by approximately 3 μ sec from the exciting current

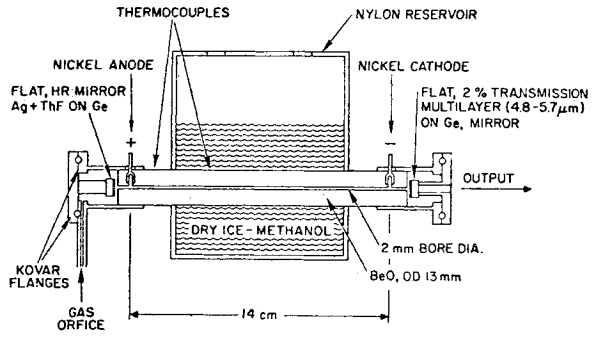

Fig. 14 Sealed CO waveguide laser.[67]

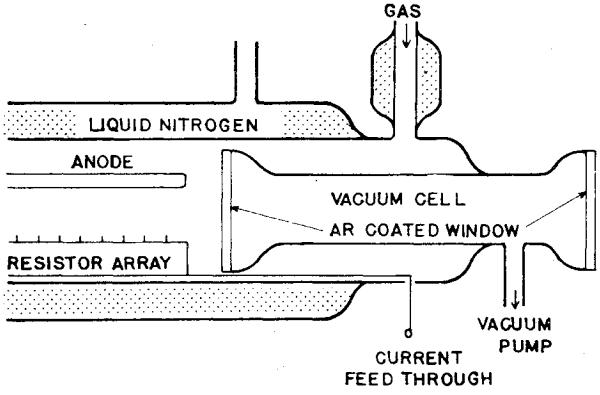

Fig. 15 Cryogenic TEA laser.[73]

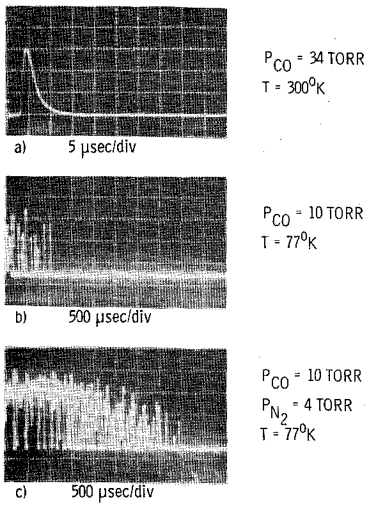

Fig. 16 Emission intensity vs time showing the effects of cryogenic operation and the addition of N_2.[73]

pulse. At LN_2 temperatures, however, the output was composed of a series of pulses of varying widths with amplitudes comparable to that obtained at 300 K, thereby greatly increasing the extracted energy as indicated in the middle figure. The pulse trains were found to last up to 2 msec in pure CO. With the addition of N_2 as indicated in the lower figure, pulse trains as long as 4 msec were observed. The total output energy was on the order of 0.1 mJ. As shown in Fig. 17, the period of the spiking was comparable to VV relaxation times, and displayed an inverse relationship to pressure. The number of pulses and the duration of pulse train were found to increase with pressure up to approximately 20 Torr, above which the long 2-msec trains collapsed into relatively short trains of approximately 60-μsec duration. The time-resolved spectra (Fig. 18) suggests that the spiking behavior is due to a

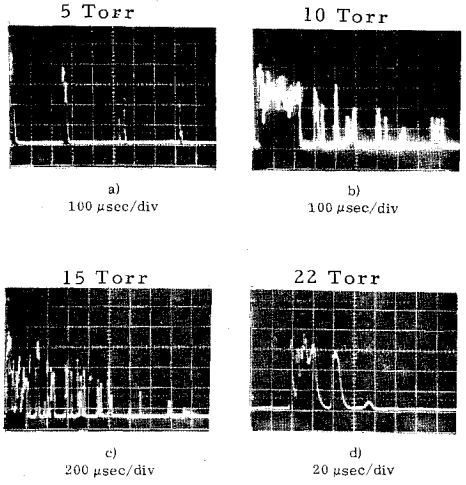

Fig. 17 Emission intensity vs time for various CO pressures at 77K.[73]

time sequencing of vibrational bands, complicated by the fact that the population cascades can cause some bands to re-emit many times. Subsequently Champagne[74] was able to increase the output power available from a CO TEA laser significantly by employing an LN_2 cooled, helical, ballasted pin discharge geometry and dilute CO:He mixtures. For pure CO mixtures, the maximum output was approximately 0.5 mJ at a total pressure of approximately 15 Torr. The output energy was increased to 35 mJ by adding sufficient He diluent to bring the total pressure up to approximately 350 Torr. Laser action in a dilute mixture was observed all the way up to atmospheric pressure. The spectral range of the laser action was from 4.8 to 5.6 μ, with the peak of the distribution occurring somewhat lower for CO:He mixtures as opposed to the pure CO. The effect of He was explained by the increased energy input and reduced heating. The maximum efficiency was approximately 0.3%.

The use of pin-type discharges generally results in a very inhomogeneous medium, which can degrade device performance. In order to avoid this problem, Cohn[75] constructed a laser in which a uniform photoinitiated discharge could be supported between continuous electrodes. The use of a homogeneous gain medium resulted in a marked increase in energy output and efficiency over the conventional multipin configuration. The experimental configuration is shown schematically in Fig. 19. It consists of a solid cathode with a modified Rogoswki contour and a mesh anode. The discharge volume was $2.5 \times 5 \times 50$ cm. The preionization photons were generated by an extended array of discrete discharges formed between the mesh anode and a series of pins. Discharge energy was approximately 11 J, and the current pulse duration was approximately 250 nsec. The optimum results were obtained for a 15:1 He:CO mixture at approximately ⅔ Amagat density. The system was operated sealed off, since it was found that the lasing output did not vary after multiple discharges. Repetition rates as high as 1 pps for 60 sec were achieved under these conditions.

The marked influence of temperature on the output energy and efficiency of the devices is clearly demonstrated in Fig. 20. The peak intensity increased by approximately a factor of 2½ times for a decrease in temperature from ambient to 200° K. The increase in energy for further cooling resulted from increase in the pulse duration. At the higher temperatures, the delay between discharge initiation and laser emission was on the order of 1-2 μsec. However, below 200 K, the delays became submicrosecond with the exact determination limited by electrical noise. The maximum output for the CO:He mix was approximately 100 mJ. The addition of 30 Torr of N_2 increased the output energy by approximately a factor of 2. The efficiency was approximately 2%, representing a seven-fold

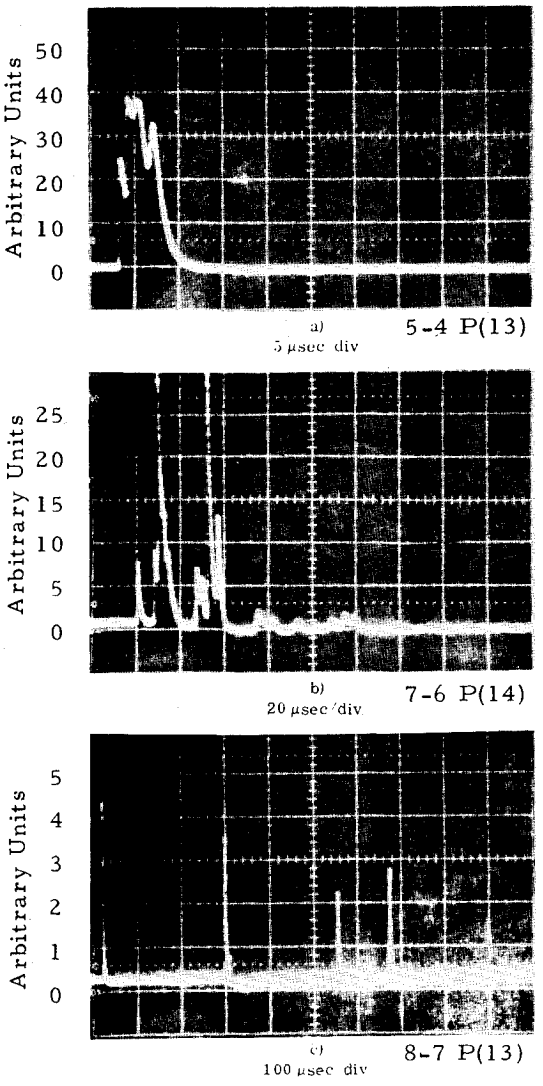

Fig. 18 Time resolved spectra for the cryogenic CO TEA laser taken with CO at 10 Torr and 77 K. [73]

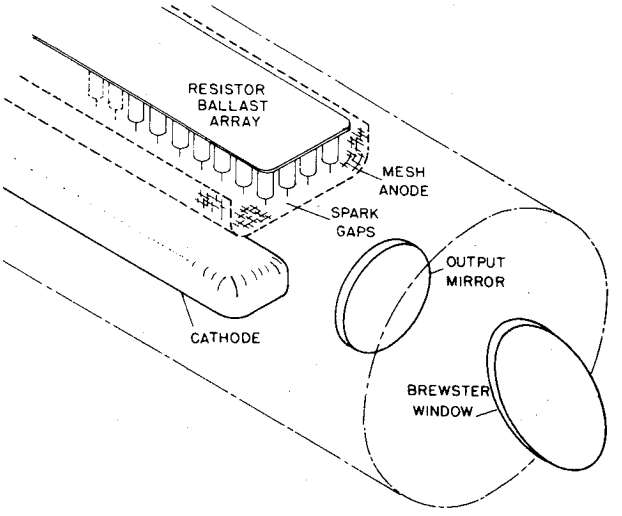

Fig. 19 Photoinitiated CO TEA laser. [75]

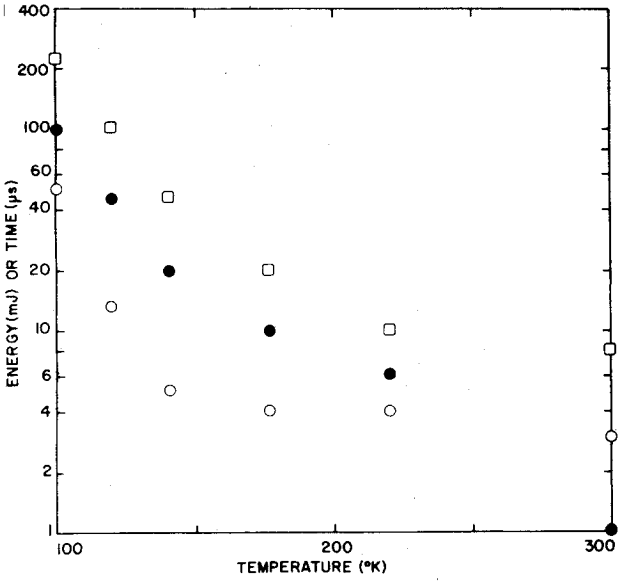

Fig. 20 Extracted energy (solid circles), total pulse length (squares), and pulse full width at half maximum (open circles) as a function of temperature. [75]

improvement over previous results. In the experimental configuration, the optical volume is approximately ⅓ of the discharge volume, and therefore Cohn suggests that the output energy and efficiency both could be increased by approximately a factor of 3 by optimizing the optical configuration.

Pulsed Electron-Beam Stabilized Lasers

In addition to the inherent high quantum efficiency association with CO, pulsed and fast flow lasers (as discussed in the next section) can exploit an important additional characteristic associated with the CO system. As pointed out earlier, the time associated with the decay of vibrational stored energy into heat is relatively long. By designing a laser such that the excitation and optical extraction periods are short as compared to this characteristic time, enhancements can be realized in the laser efficiency, specific energy, and optical quality, since all are adversely influenced by the temperature rise that occurs during the lasing period. This effect is shown clearly in Fig. 21, which shows the theoretical heating rates for a typical case with and without optical extraction. It is seen that the energy that is not extracted as optical power appears in this time scale primarily as stored vibrational energy. This property also results in a minimization of the problem of mode-medium interaction, i.e., the production of density perturbations in the medium as a result of nonuniform optical extraction.

As shown in an earlier section, in order to exploit the inherent capability of CO for high efficiency and high specific energy, it is necessary to deposit relatively large (approximately 1 kJ/ℓ-atm) amounts of energy in the gas. This energy must be deposited in a time that is short as compared to the time require for the vibrational stored energy to relax via VT and VVT processes. For the pulse system, an additional constraint is that the pulse duration must be short as compared to an acoustical transit time in the optical cavity in order to assure that the density perturbations originating at the boundaries of the excited region, and particularly at the electrodes, do not degrade the optical quality of the medium during optical extraction. For typical geometries, this means that the excitation pulse must be on the order of 100 μ sec or less. The high pumping rates implied by these considerations are extremely difficult to realize in self-sustained discharges. At low temperatures, the problems associated with thermal instabilities are particularly severe, since the rate of change of density varies inversely with the square of the temperature, and the rate of diffusion (which tends to stabilize the discharge) decreases as the square root of temperature. A direct approach to satisfying these constraints is the use of the electron beam stabilized discharge technology previously employed for CO_2 laser. [76,77]

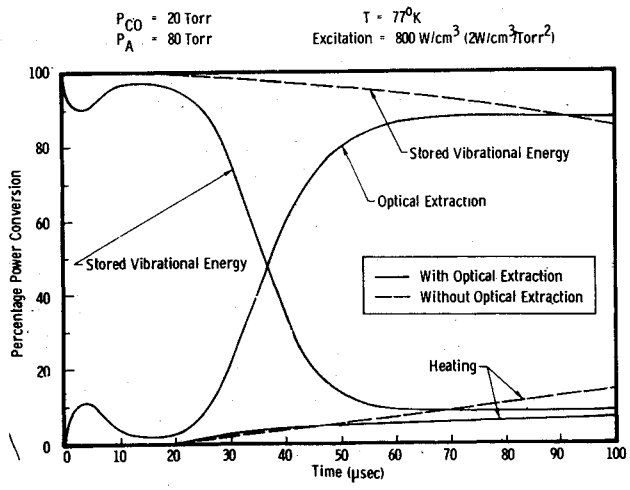

Fig. 21 Effect of optical extraction on CO laser kinetics.

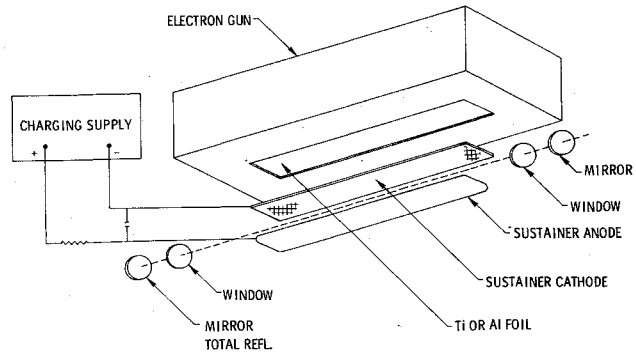

Fig. 22 Experimental configuration.[78]

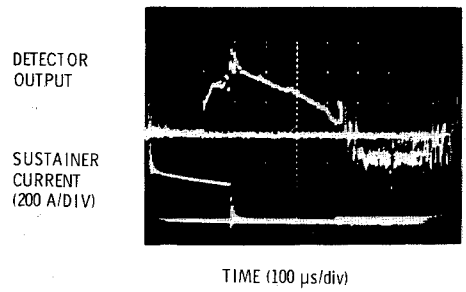

Fig. 23 Pulsed CO laser output: pressure = 1 atm, P(CO); $P(N_2)$-= 1:2, sustainer voltage = 8 kV(1.6 kV/cm), sustainer current = 300 A (1.0 A/cm²), E-beam voltage = 160 kV, E-beam current density = 0.5 mA/cm², output energy = 1.55 (5J/ℓ).

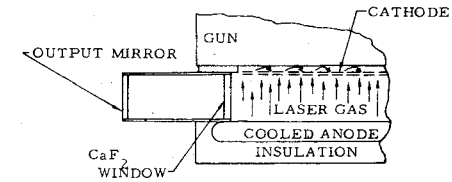

Fig. 24 Schematic cross section of cryogenic electron beam CO EDL.

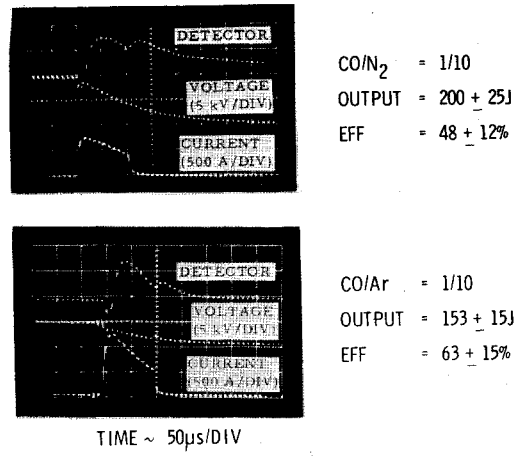

Fig. 25 Pulsed E-beam CO laser output: $T = 100$ K, $P = 100$ Torr, $i_{qun} \simeq 20$mA/cm², discharge vol = 2.0ℓ, optical = 1.5ℓ.

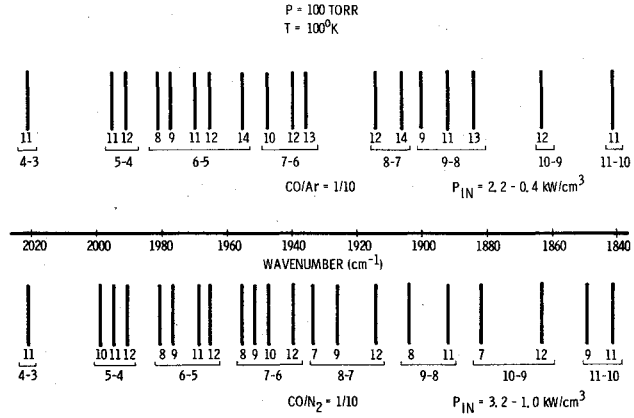

Fig. 26 Output spectra of pulsed E-beam CO laser.

The first experimental studies of electron beam stabilized electric discharge CO lasers were reported by Mann et al.[78] The configuration is shown in Fig. 22. The device was approximately 1 m long and had a cross section of approximately 3×4 cm for a nominal volume of 1 ℓ. The electron beam current density was approximately 0.5 mA/cm². The optical volume was approximately ½ ℓ. Figure 23 shows the results of an experiment at room temperature and atmospheric pressure. Threshold was reached approximately 200 μsec after the initiation of discharge, and laser action continued for several hundred microseconds after the termination of the discharge. With the optical volume restricted to about ½ ℓ, the output was about 1.5 J, representing an efficiency of less than 1%. Subsequently, the device was modified to provide for cryogenic operation. The modified device is shown schematically in Fig. 24. Gas that was precooled inititally by a LN_2 heat exchanger passed through a trimming heat exchanger in the anode itself. The gas then flowed through a porous distribution screen on the anode surface, across the discharge region, and was extracted by a pair of manifolds between the cathode and gun. The ends of the discharge section were isolated thermally by vacuum insulated cells terminated by CaF_2 antireflection coated windows. In addition to providing thermal isolation, the CaF_2 windows also confined the discharge, thereby minimizing problems associated with nonuniform excitation of the medium, which would otherwise result from electron beam scattering and field fringing at the ends. The discharge volume was nominally 2 ℓ with the optical volume restricted to about 1.5 ℓ. The electron gun had a nominal operating voltage of 175 kV, with an output current density in the order of 10-40 mA/cm².

Some typical experimental results are shown in Fig. 25. The upper trace is the sustainer voltage and the lower trace the sustainer current. The upper figure shows the results for an CO:N_2 mix of 1:10. In this case the output was output was approximately 200 J, with an efficiency of approximately 48%. The lower trace shows the results for CO:Ar. In this case the output was 150 J for efficiency of approximately 63%. The trend indicated here was generally observed. The efficiency

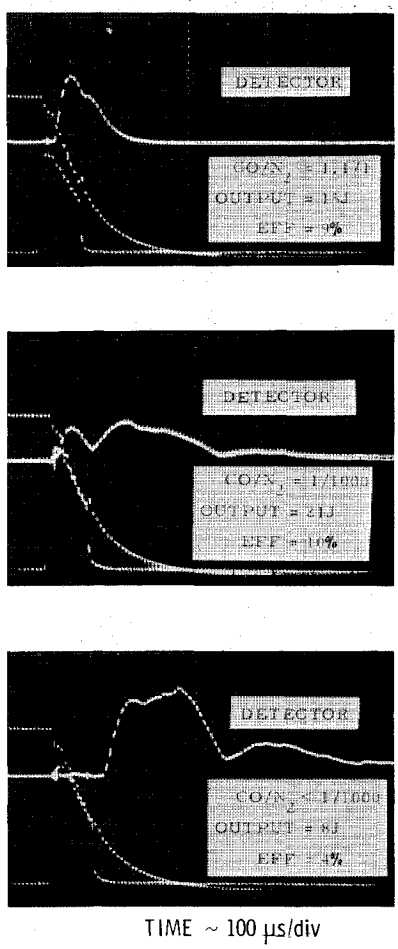

Fig. 27 Pulsed E-beam CO laser output: $T \simeq 100$ K, $p \simeq 100$ Torr, $i_{qun} = 20$ mA/cm^2, Vol = 2.0 ℓ, time ~ 100 μsec/DIV.

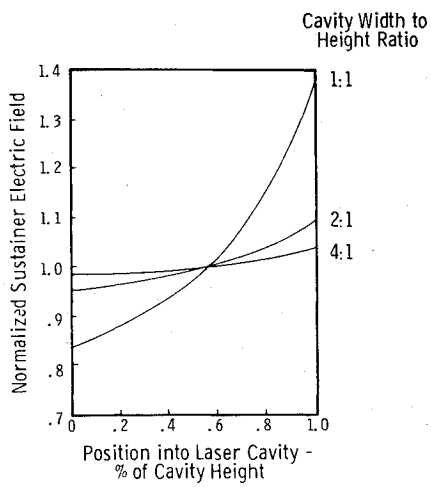

Fig. 28 Substainer field variation for cavities of different aspect ratios: electron beam energy = 200 keV; pressure = 200 Torr; temp. = 77 K; gas = CO,N_2

for Ar diluents was generally higher, since the energy that is deposited in the form of N_2 vibrational excitation can be only partially recovered. However, the energy that could be deposited with the N_2 diluent was higher, resulting in higher output energies. The observed spectra for the two cases are quite similar, as indicated in Fig. 26. The effect of N_2 diluents can be seen more dramatically in Fig. 27. The output pulses have a very characteristic form, with a primary pulse occurring during the excitation period and the secondary pulse occurring after the termination of the excitation. As the percentage of N_2 is increased, the primary pulse becomes less significant with increasing amounts of the output appearing in the tail. Finally, for very dilute mixtures, the primary pulse dissappears altogether with threshold for lasing occurring only well after the termination of the excitation, with the laser output continuing for a period on the order of a millisecond thereafter. The summary of the performance of the 2-ℓ device is given in Table 5.[79] Most of the low temperature experiments in this device were performed at relatively low pressure because of the electron-beam-scatter-induced pumping nonuniformities which became severe at higher pressure. Figure 28 shows the sustainer field variations due from electron scatter.[80] For the square geometry utilized for this device, it is apparent that the problem is already severe at a pressure of over 200 Torr. The other two curves show how the problem can be mitigated by changing the geometry to a more under square form.

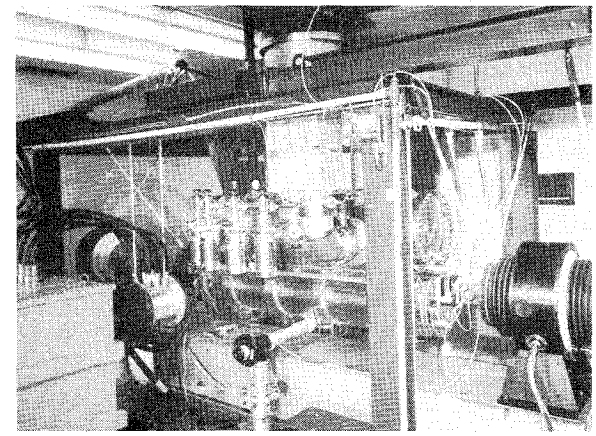

Fig. 29 Ten-liter electron beam stabilized CO EDL.

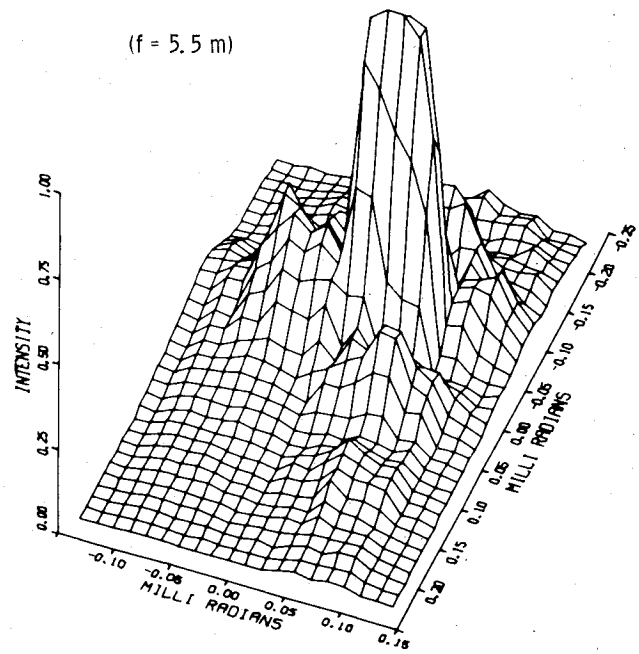

Fig. 30 3-D geam profile and focal plane.

One of the most critical problems associated with high pressure CO EDL's is medium uniformity. Because of the high density and high index associated with the cryogenic gas, temperature uniformity is critical for good optical performance. In order to obtain diffraction limited performance, ordered, noncorrectable, disturbances must be held to within a few hundredths to a few tenths of a degree C/cm, depending on the gas constituency and form of the disturbance.

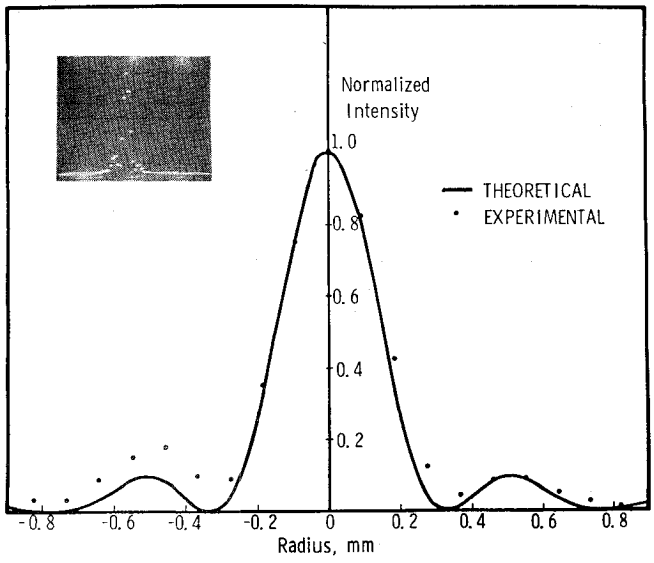

Fig. 31 Pyroanalyzer trace of laser intensity profile at the focus compared with the theoretical profile.

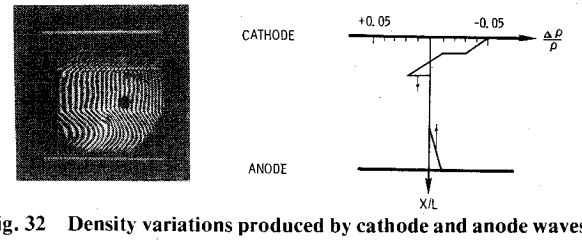

Fig. 32 Density variations produced by cathode and anode waves.

Table 6 Plasma diode CO laser spectrum[85]: T_g = 170 K, P_{N_2} = 193 Torr

Observed wavelength, μm	Transition	Transition wavelength
Strong lines		
5.022	4→3 P18	5.021
5.075	5→4 P17	5.076
5.155	6→5 P18	5.154
5.225	7→6 P18	5.222
Weak lines		
5.085	5→4 P18	5.087
5.125	4→3 P27	5.125
	7→6 P9	5.124
5.165	6→5 P19	5.165
5.200	7→6 P16	5.200
	6→5 P22	5.200
5.275	9→8 P10	5.274
	6→5 P28	5.274
5.305	9→7 P19	5.305
5.345	9→8 P16	5.341
5.430	9→8 P20	5.389

To demonstrate that diffraction limited performance was possible, a larger device was constructed which was designed to maintain these tolerances. A photograph of this device is shown in Fig. 29. The conceptual design of this device was similar to the smaller one, with a multitube anode heat exchanger, cryogenically cooled walls, and vacuum isolated end windows. The device is $10\times10\times100$ cm, giving a discharge volume of approximately 10 ℓ, while the optical volume is restricted to 7. The mass flow was in the order of 10-50 g/sec, which was adequate to minimize boundary-layer growth and eliminate buoyancy effects. The electron gun had a maximum output current density of approximately 140 mA/cm^2. An output of 506 J at 40% efficiency was obtained with a 1:7.5:9 CO:N_2:Ar mixture at 175 Torr. Near-diffraction-limited performance was obtained by use of an unstable resonator with a magnification of 2.5. Figure 30 shows the beam profile observed in the focal plane of a 5.5-m mirror as imaged on a pyroelectric detector array (Fig. 31). Comparison with a theoretical beam profile (Fig. 31) shows that the beam quality was approximately 1.2 × the diffraction limit.[81]

By observing the magnitude and velocity of density perturbations (Fig. 32) following the discharge pulse, it was possible to estimate the heating rate.[41] It was found, consistent with theoretical predictions, that for most conditions of interest less than 10% of the input power went into heat. These results also were consistent with earlier measurements of the rotational structure of the visible fluorescence of N_2 (Ref. 82), as well as data obtained recently from measurements of the downstream Mach number in a supersonic flow laser.[11,12]

Center[9] has reported the highest energies so far obtained in a CO EDL. His device is shown schematically in Fig. 33. Precooled gas is injected at the cathode, flows parallel to the discharge direction, and is exhausted through a porous anode; the volume is approximately 20 ℓ. Figure 34 shows the output energy and efficiency obtained with a 1:3 CO:N_2 mixture, a pressure of 150 Torr, and a nominal temperature of 100 K. The maximum energy was 1.2 kJ with an efficiency of 15%. The reason for the low efficiency as compared to the experiments previously discussed is not clear. However, it appears that thermal nonuniformities in the medium may be responsible for the degraded performance.

There have been theoretical analyses[28,83] that suggest that it should be possible to obtain efficient operation of a CO laser at room temperature at high energy loadings (on the order of 1 kJ/ℓ-atm). This possibility was examined experimentally by Thweatt et al.[84] by using a high current cold cathode electron gun. Energies in excess of 1 kJ/ℓ-atm were loaded into atmospheric pressure gas mixtures of 1 part CO to 3 parts He, Ar, and N_2. With the He diluent, the maximum energy input was approximately 500 J/ℓ-atm, while more than 1 kJ/ℓ-atm was put into the CO:N_2 mix. In all cases, the laser action was not initiated until several microseconds after the termination of the discharge pulse, and the output pulse extended for a few tens of microseconds for CO:He and all the way up to 90 μ sec for CO:N_2. The output spectra consisted of transitions from 12-11 to 15-14. The maximum conversion efficiency was

Table 7 Spectral distribution of laser output[88]

Vibrational band	Uncooled rotational transitions	Normalized band intensity	Rotational transitions	Cooled normalized band intensity	Wavelength range, μ
V=3-2	...	...	P(8)-P(10)	0.6	4.857-4.877
V=4-3	P(9)-P(11)	0.60	P(7)-P(10)	0.8	4.910-4.949
V=5-4	P(9)-P(12)	1	P(7)-P(11)	1	4.974-5.024
V=6-5	P(8)-P(11)	1	P(7)-P(10)	1	5.039-5.079
V=7-6	P(7)-P(10)	0.6	P(6)-P(10)	0.8	5.095-5.136
V=8-7	P(7)-P(10)	0.3	P(6)-P(9)	0.6	5.233-5.265
V=9-8	P(7)-P(9)	0.15	P(6)-P(9)	0.2	5.163-5.205
V=10-9	P(6)-P(8)	0.05	...	...	...

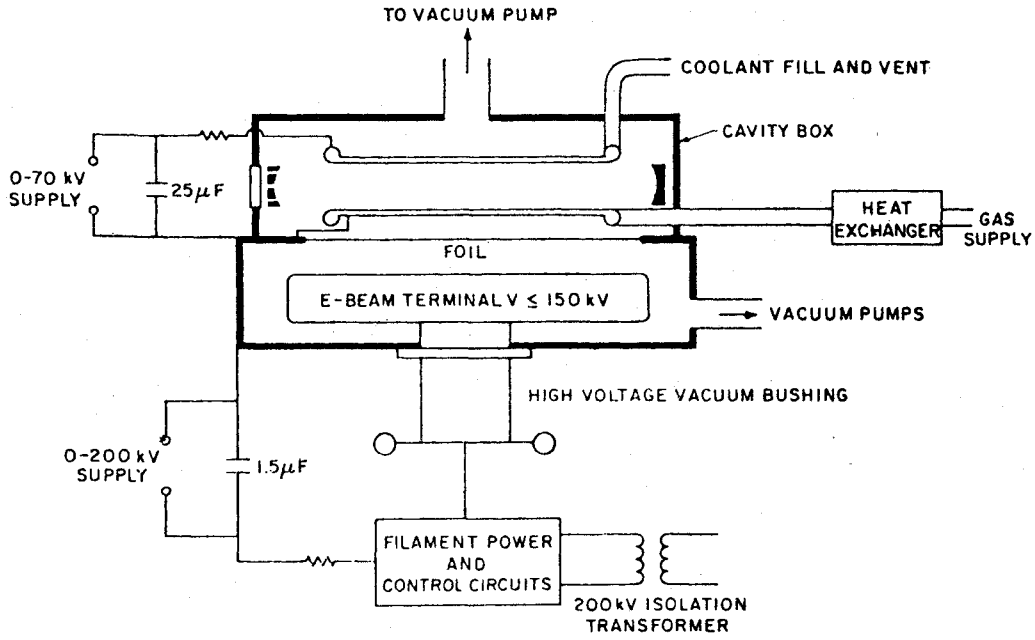

Fig. 33 Schematic of high-pressure electrical CO laser.[9]

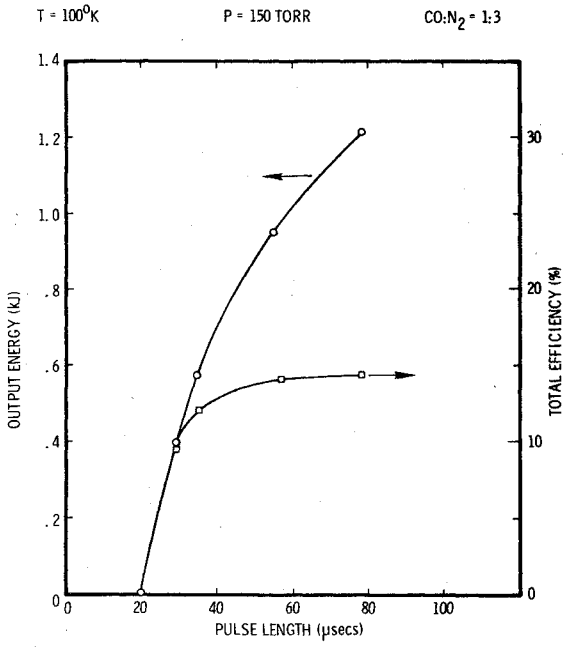

Fig. 34 Laser pulse energy and total efficiency vs discharge pulse length.[9]

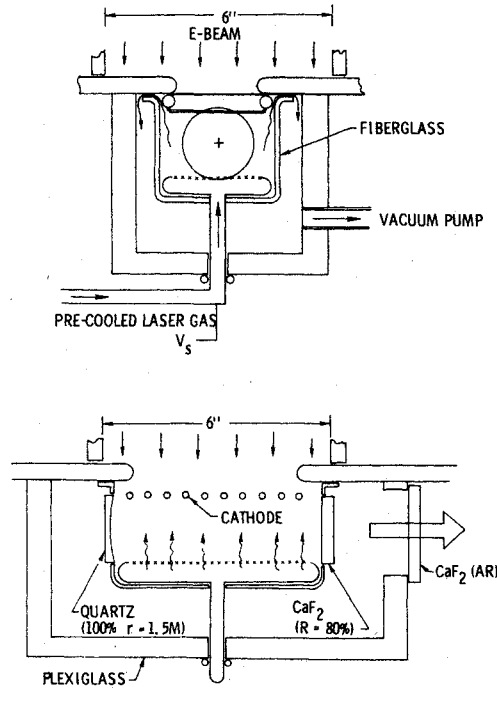

Fig. 35 Plasma diode CO laser configuration.[85]

2%, as compared to the 50% predicted by theory. The reason for the considerable disparity between theory and experiment which consistently occurs in high temperature experiments is poorly understood.

O'Brien[85] has reported on a small electron beam stabilized electric discharge laser, which employs a cold cathode plasma-type electron gun.[86] The device is shown schematically in Fig. 35. The flow system was conceptually similar to that used for the hot cathode electron beam stabilized lasers discussed previously. Typical performance characteristics are indicated in Fig. 36. The laser produced relatively short pulse (approximately 20 μsec) multiline radiation with powers in excess of 0.5 MW (pulse energy up to 13 J). The excited volume was 13 cm long by 4.35 cm in diam. With a $CO:N_2$ mixture at 0.58 Amagat density, the maximum electrical pumping was 45 kW/cm^3, corresponding to 0.6 J/cm^3 energy deposition. The typical output spectrum (Table 6) consisted of a number of lines between 5.02 and 5.43 μ. The efficiency was approximately 11%.

Supersonic Electric Discharge Lasers

Supersonic expansion is an alternative approach to cryogenic gas conditioning which offers several potential advantages. Large volumes of gas can be cooled without the use of complex heat exchangers or cryogens. The residual stored vibrational energy that remains in the active gas after optical extraction can be removed from the optical cavity in a short time compared to the characteristic time associated with the decay of the vibrational energy into heat. The bulk of the gas heating then occurs downstream of the optical cavity and does not influence the performance of the laser. In addition, for a

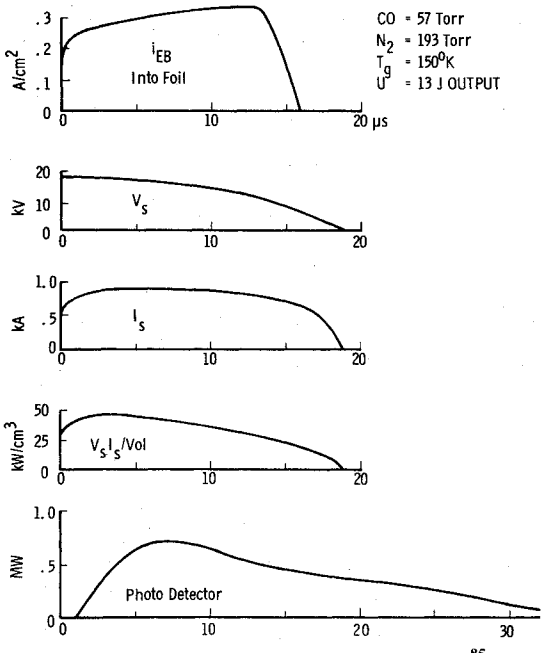

Fig. 36 Plasma diode CO laser performance.[85]

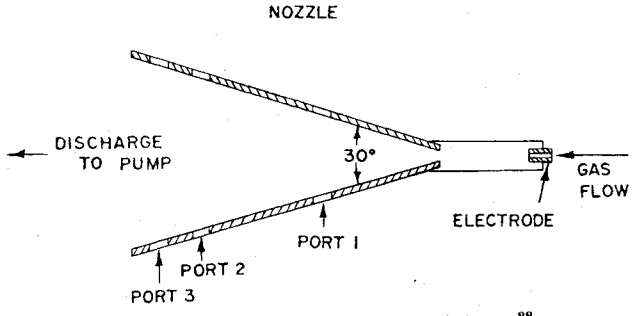

Fig. 37 Electrical-discharge gas-dynamic laser.[88]

given temperature rise in the gas, the thermally induced medium perturbations are reduced as compared to the subsonic case. Previous experiments[7,8] have demonstrated the sensitivity of the device performance, and particularly the spectral characteristics, to temperature. Supersonic expansion provides a convenient mechanism for attaining temperatures below those practically realizable by cryogenic techniques. On the debit side are problems associated with flow induced density perturbations and warm boundary layers.

The earliest experiments with a supersonic CO EDL were reported by Rich et al.[87] and by Kan et al.[88] The device employed in the latter work is shown in Fig. 37. CO:N_2:He mixtures at pressures of 100 to 150 Torr were excited by electric discharge in the plenum section, which was connected to a two-dimensional 30° nozzle. Three mirror stations were located in the sidewalls, permitting the flow to be probed at geometric area ratios $A/A^* = 7.2$, 10.6, and 12.2. The gas mixture undergoes a 75:1 expansion before reaching to the first mirror station. A resonator established at Station 1 yielded a maximum power of 16 W, representing a 2% conversion efficiency of electrical power into laser output. By precolling the gas to 196 K, the output power was increased by a third and the spectrum shifted to lower V bands. The spectra observed for the uncooled and cooled cases are summarized in Table 7, and it is evident that, particularly for the cooled case, the spectral output is concentrated in the region below 5.1 μ.

The configuration used by Rich et al. (Fig. 38) is basically similar to that of Kan. However, by injecting the gases through a choked slot in the anode either with the velocity parallel, or more recently perpendicular, to the discharge axis, Rich et al.[89] have been able to obtain stable discharges in

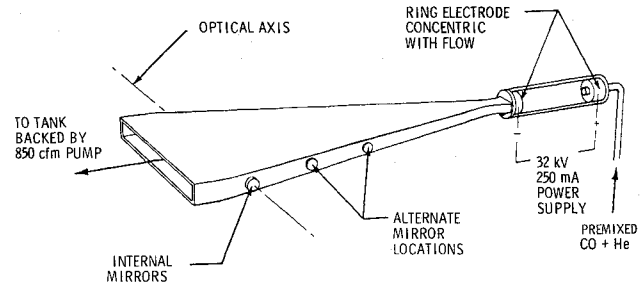

Fig. 38 Perspective sketch of the electrically excited supersonic flow CO laser.[89]

dilute CO:He mixtures at pressures up to 1.5 atm. This method of gas injection creates a radial flow velocity in the vicintiy of the anode, which promotes the rapid dissipation of incipient streamline arc filaments, and thereby increases the discharge stability. Optimum performance has been obtained with a discharge pressure of 684 Torr in a CO:He mix of 2.27. Maximum output power was 360 W, corresponding to a specific power of 14.5 kW/lb/sec, a power per unit volume of approximately 4.5 W/cm^3 and an efficiency of 11%. The cavity pressure was 2.5 Torr and the cavity temperature was 40 K. Of particular significance was the fact that more than 60% of the output power is distributed among approximately 15 lines of wavelengths from 4.819 to 5.084 μ. This is important, since a number of good atmospheric transmission windows exist within this spectral region.[90,91] Researchers at Calspan are exploring the possibility of extending the performance of the pre-excitation-type supersonic CO EDL by exploiting electron beam technology.[92] A schematic of an experimental Calspan device is shown in Fig. 39. In initial discharg experiments, power loadings as high as 200 kW/lb/sec corresponding to an energy input per CO molecule of approximately 0.6 eV have been obtained using a primary electron beam current of 10 mA/cm^2. These studies have revealed one of the important limitations to the pre-excitation approach. Since the excitation occurs at relatively high temperature and pressure in a region without optical extration, a relatively large fraction of the input power can go into translation and rotation, as opposed to vibrational excitation. For a room temperature discharge, as much as 60% of the input energy went into heat. By precooling the gas to 170 K, this value was reduced to approximately 34%. These losses limit the efficiency obtainable from a pre-excitation device.

A second approach to the supersonic EDL was investigated by Brunet and Mabru.[94,95] In their device (Fig. 40), N_2 was vibrationally excited in an electrical discharge and then mixed with cold CO during the process of supersonic expansion. N_2 was excited in the discharge upstream of the nozzle, and cold CO and O_2 were injected at a point approximately 1 cm upstream of the nozzle throat. The plenum pressure was typically less than 200 Torr. For the maximum laser output, the optimum mixture consisted of 24% CO, 36% N_2, 32% Ar, and 8% O_2 at a plenum pressure of 180 Torr. For this case, the pressure in the laser cavity was 2.5 Torr. When the gases were precooled to approximately -60°C before entering the discharge tube, the maximum laser power was 45 W. With precooling of the CO alone, the power was 36 W, and without any precooling the power was 16 W. The maximum power corresponded to a 4% conversion efficiency of electrical power into laser power. The translational temperature in the lasing region was estimated to be about 100 K. The specific power was approximately 20 W/g/sec (9 kW/lb/sec), and the author suggested that a specific power in excess of 20 kW/lb/sec should be obtainable with this type of device.

High efficiency and specific power are predicted for devices in which post expansion excitation is employed.[10,32,96] Disadvantages of this configuration include the fact that heat addition due to discharge excitation inefficiency will, in general,

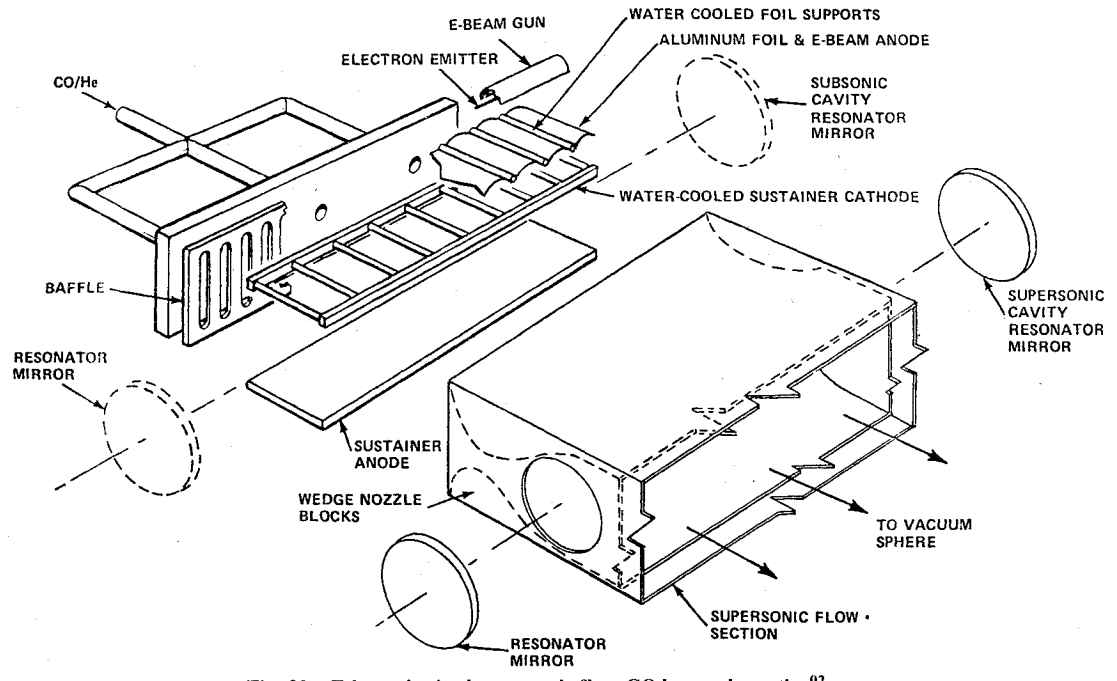

Fig. 39 E-beam ionized supersonic flow CO laser schematic.[92]

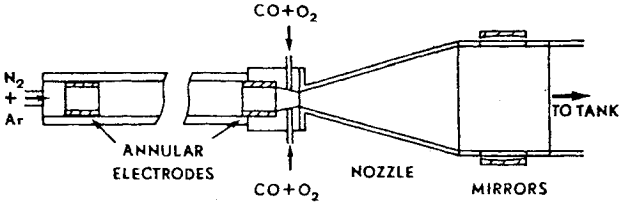

Fig. 40 Schematic of electrically excited CO gas-dynanic laser.[94]

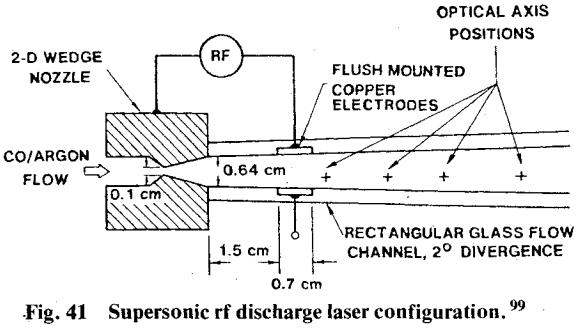

Fig. 41 Supersonic rf discharge laser configuration.[99]

affect the medium quality adversely. In addition, the warm boundary layer formed on the sidewalls can have a tendency to short the discharge. If the boundary layers become vibrationally excited as the result of electron scattering, optical losses may result, since the vibrationally excited warm gas may exhibit loss on transitions that have positive gain in the core. Additional problems can result from extraordinary growth of the boundary layers along the electrodes as the result of heat addition by the discharge, particularly at the cathode. Several discharge configurations have been used for postempansion excitation. Vallach et al.[97] employed a conventional resistively ballasted pin discharge. They observed an enhancement in gain of about a factor of 10 for pulse excitation in a supersonic flow as opposed to transverse excitation of stagnant room temperature gas at the same density. The gas temperature was estimated to be about 50°C. Weisbach has experimented with a similar configuration at the NASA-Ames Research Center, obtaining a conversion efficiency of approximately 0.3%. However, the low efficiency in this case was primarily the result of limitations in the electrical system which limited the input energy to approximately 0.02 eV/CO molecule, which is far below that required for efficient operation. This system has been upgraded recently so that an energy loading exceeding 1 eV/CO molecule can be obtained with reasonably uniform discharges.[98]

Shirley et al.[99] have observed emission on the 4-3, 5-4, and 6-5 vibrational transitions, using a low power rf excited discharge configuration, as shown in Fig. 41. The Mach number in their system was approximately 2.5, and the translational temperature was estimated to be approximately 100 K. The overall efficiency of this device was quite low, on the order of 0.07%. The lack of efficiency is in part attributable to the relatively weak pumping. The authors also suggest that the low value may be due to discharge power deposition in the boundary layer, which is supported by the fact that the measured Mach number was appreciably lower than the value predicted for isentropic flow.

One of the more promising approaches for obtaining efficient high power operation appears to be the use of an electron beam stabilized discharge coincident with the optical extraction region, downstream of the expansion nozzle. Within the past year, several groups have reported on experimental investigations of this type device. Jones et al.[10] have reported the results of experiments using the device shown in Fig. 42. Gas is supplied by a Ludwieg tube, which supplies a quasisteady supersonic flow for approximately 20 msec. The flow Mach number was approximately 3.5. The excitation period was several hundred microseconds, which exceeded the flow transit time, and therefore tends to simulate cw performance, although decreasing output power and discharge instabilities were observed as the excitation period was extended. The maximum laser output was obtained for a 10:90 CO:Ar mixture at a pressure of approximately 0.1 atm. By use of a 4.3-cm-diam stable resonator with 10% output coupling, the maximum output power was 31 kW. The electron beam current was limited to 1 mA/cm^2, consistent with foil heating limitation for true cw operation. The maximum electrical efficiency was 10% and the maximum energy input into the gas was 1240 J/ℓ-atm. The observed transition ranged from the 5-4 to the 8-7 bands, corresponding to a wavelength range from 4.95 μ to 5.19 μ. As mentioned previously, flow Mach number measurements showed that only 9% of the total power appeared as thermal energy in the gas.

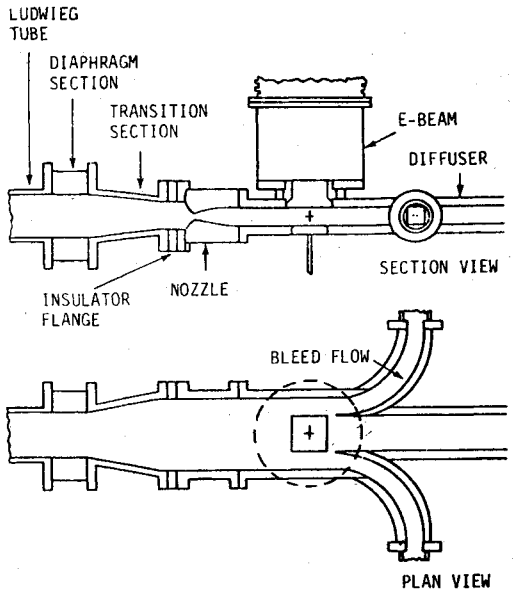

Fig. 42 Small supersonic CO CW laser.[10]

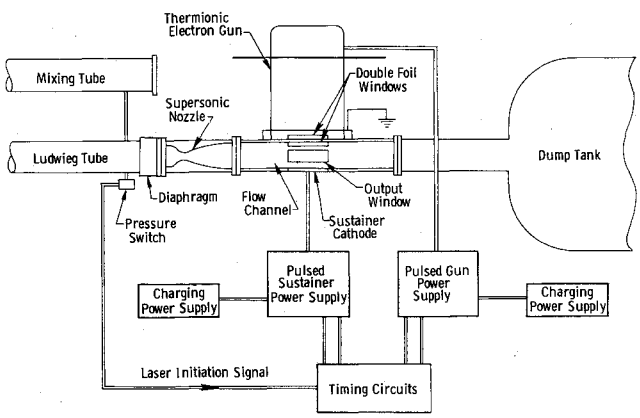

Fig. 43 Schematic of supersonic CW-CO laser.

A 4.5-ℓ device (5 cm high × 50 cm wide × 15 cm in the flow direction) has been employed by Plummer et al.[11] for studies of postexpansion excitation. A stable resonator with an optical volume of 0.8 ℓ is employed. The resonator is centered approximately 11 cm from the beginning of the discharge. A power output of 28 kW at 4.7% efficiency has been obtained. The pulse duration was 900 μsec, which corresponded to 3 flow times, and is therefore indicative of cw operation. Higher power outputs up to 67 kW have been obtained for 300-μsec pulses corresponding to one flow time. The reason for the lower efficiencies and specific power output as compared to other devices of this type is not clear, but it is significant that measurements of heat addition in this case yielded values of approximately 25%, which is well in excess of the values obtained in other experiments.

Experimental investigations also are in progress on a similar device at Northrop (Fig. 43). This device has an active region 15 cm wide × 20 cm in the flow direction and discharge height of 5 cm. The sustainer cathode consists of a solid metal plate, and a foil is used for the anode to minimize medium perturbations, which could result from the use of an open structure for the electrode. Typical downstream conditions are a pressure of 0.1 atm and a temperature 0f 84 K. Using $CO:N_2:Ar$ in the ratio of 1:4:5, an output power of 110 kW was obtained for a period of 2 msec, which corresponds to approximately 5 flow times, and is therefore representative of cw performance. The efficiency was approximately 18%. The run time was limited by the energy limitations of the capacitor

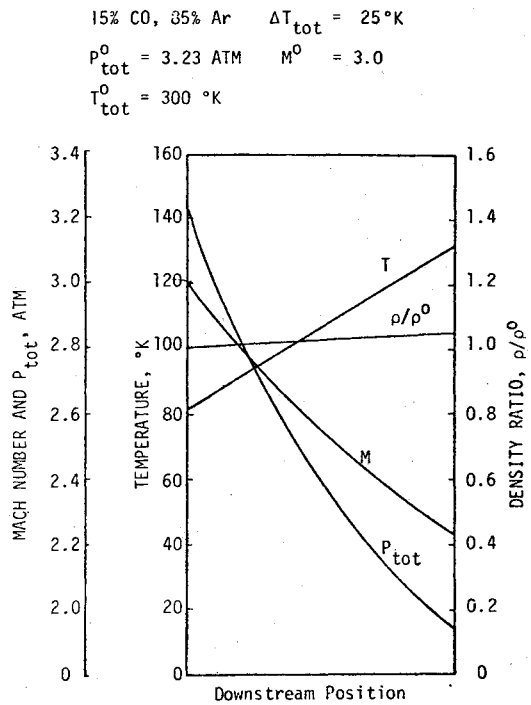

Fig. 44 Supersonic heat addition.[10]

storage systems employed to power the electron gun and sustainer. However, although the period of excitation was sufficient to establish a steady-state condition with relation to the laser kinetics, caution should be exercised in directly extrapolating the results to true cw operation, since steady conditions in the boundary layer and cathode fall regions probably were not attained. With higher pumping levels, the runs terminated in arcs befor the energy constraints were reached, suggesting the existence of stability limits dependent on both excitation rate and duration. Maximum powers as high as 250 kW were obtained for a shorter period before the discharge was terminated by an arc. It also should be noted that the electron gun current density used in these experiments ($\sim$2mA/cm^2) is almost twice the value that can be handled on a continuous basis by current electron gun foil window cooling technology.[100] Measurements of heating rate as determined from downstream Mach number in this device indicated that less than 10% of the input power was going in heat, consistent with previous experimental results.

Although no attempt has yet been made to obtain diffraction-limited performance, the results of calculations of medium uniformity, which are consistent with the measured heating rates, indicate that near-diffraction-limited performance should be obtainable in devices of reasonable size. Figure 44 shows the anticipated variation of flow parameters for typical excitation conditions. The variation in the medium density is less than 5%. Furthermore, it is only the departures from linearity which are of concern for beam quality. For the conditions indicated in the figure, an optical distortion of less than 1/10 fringe at the CO wavelength would result from a ½-m optical path.

The results of theoretical analysis[96] indicate that it should be possible to obtain efficiencies in excess of 60%, specific powers in excess of 100 kW/lb/sec, and volumetric power extractions in excess of 250 W/cm^3 from optimized devices. In addition, for typical flow conditions, pressure recovery to atmospheric pressure is possible.

The reason for the discrepancy between theoretical prediction and the small-scale experimental results to date is not well-understood. However, the short gain length and high reflectivity resonators employed for the smaller experimental devices makes them extremely susceptible to performance

degradation associated with intracavity loss, or any mechanism which tends to degrade the optical gain. Previous work also has shown that the device performance is extremely sensitive to the presence of impurities, which can enhance vibrational deactivation, influence the discharge properties, and result in optical absorption. [101,102]

Although most of the work thus far has been directed at investigating the cw mode of operation, the repetitively pulsed mode also is of interest, since it offers the possibility of circumventing some of the problems associated with spatial inhomogeneities (e.g., nonuniform spectral gain profile along the flow direction) and somewhat greater flexibility in adjusting the excitation rates. These advantages are countered by the additional complexity associated with this mode of operation and the possibility of reduced mass flow efficiency. The operation of repetitively pulsed, electron beam stabilized, supersonic CO EDL's currently is being investigated at Boeing. [103]

Summary

The theoretical and experimental work to date clearly has established the CO EDL as one of the most attractive candidates for efficient high power lasers. The efficiencies and specific powers already demonstrated exceed the performance of any other directly excited laser system, and further significant advances can be realistically anticipated. The operation of the CO laser appears to be qualitatively understood. Reasonably good quantitative agreement between theory and experiment also has been demonstrated, at least at low temperatures, although more work is required to eliminate the uncertainties in rates and cross sections before the models can be used confidently to predict laser performance. It may be reasonably predicted that, with the increased attention currently being focused on the development of CO laser technology, the next few years should show rapid advances and increased application of CO electric discharge lasers.

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