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HIGH-ENERGY, SHORT-PULSE GAS LASER SYSTEMS*

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I. INTRODUCTION

Interest in investigating the feasibility of producing thermonuclear fusion reactions through the use of lasers has spurred the research and development of high-energy, short-pulse laser systems. This problem has been much studied and the results indicate that laser systems capable of delivering energy in the range of 1,000 to 100,000 joules on a subnanosecond time scale will be required. At the present time, only three laser systems are known which may have such potential, these being the solid state Nd:glass system, the electrically-excited, high-pressure CO₂ system, and the photo-dissociation atomic iodine system.

The Nd:glass laser was the first system to be considered for this application and while it is not the present purpose to make invidious comparisons between the solid state medium and systems based upon a gaseous medium

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MASTER

directly pumped by an electric discharge, it should be pointed out that the questions of efficiency, cost, medium damage and extrapolation to very large scale provided the incentive for considering these latter systems.

In the following, the status of the high pressure CO_2 laser, will be discussed in detail and some comparison made with the other two systems.

High-energy, short-pulse laser systems have a configuration as shown in Fig. 1 which is known as a master oscillator-power amplifier or MOPA configuration. In this configuration, the oscillator, through use of the technique of modelocking, produces a very short optical pulse which is then amplified as it passes through the successive amplifier stages. The generation of short duration pulses with good optical quality cannot be accomplished over very large volumes or at very high intensities so that the two processes, short pulse generation and short pulse amplification, must be carried out independently. Accordingly, the discussion of such systems can be conveniently divided into three areas: 1) the pumping mechanisms for the production of a population inversion in both the oscillator and amplifier, 2) short pulse generation by the oscillator, and 3) the extraction of the stored energy from the amplifier stages by short pulse amplification.

II. PUMPING MECHANISMS

The CO_2 laser first reported by Patel¹ in 1964 operates on a population inversion between vibrational molecular energy levels. Figure 2 shows an energy level diagram for this molecular system. In electrically-excited lasers, these levels are pumped through inelastic collision between electrons and molecules, the population inversion arising from both different excitation rates for the upper and lower levels as well as the faster relaxation rate of

the lower level. The collisional relaxation rate of the upper level is ~ 10 times slower than the lower level in typical CO_2 laser gas mixtures.

Initially, CO_2 laser systems were pumped using low pressure (~ 5 Torr), self-sustaining glow discharges. Such low pressure discharges are stable and can provide large volume discharges with electron temperatures suitable for efficient pumping (~ 1 eV). However, the number density of lasing molecules is correspondingly small and, as is well known, any attempt to increase the pressure and current to high values results in an unstable discharge which quickly degenerates into a low-impedance constricted arc not suitable for laser pumping.

The stored optical energy density in such low pressure systems is ≈ 0.05 joules/liter which should be compared to the corresponding values for Nd:glass of ≈ 350 joules/liter. For any competitive high-energy amplifier system then, it is necessary to increase the number density of lasing molecules several orders of magnitude to as high a value as feasible to provide large energy storage, which means operation at high pressure. (High pressure operation is also indicated for short pulse generation and efficient amplification as will be discussed below.) Thus the problem of pumping high-energy CO_2 lasers becomes a problem of producing uniform, large volume, stable electrical discharge at high pressures.

Two solutions to this pumping problem have been developed using rather different techniques. The first is based upon a self-sustained discharge in which the over-volted discharge is produced on a time scale shorter than arc-formation times with volume distribution accomplished by multiple electrode geometries. The first report of atmospheric pumping of CO_2 using such techniques was reported by Beaulieu in 1971.² Figure 3 shows this basic configuration.

Considerable improvements to this technique have been made by the use of improved geometries and auxiliary circuitry to provide preionization to the discharge which enhances stability and uniformity of the discharge.^{3,4} The first such improvement was reported by Dumanchin and Fig. 4 shows this configuration. The fast preionization discharge is produced between the glass encapsulated trigger wires and the cathode. The main discharge is subsequently produced between the main electrode. A second approach (due to Lamberton and Pearson) to the problem is shown in Fig. 5. Trigger wires running parallel to the main electrodes are used to provide a fast preionization discharge between them and one of the electrodes and subsequently the main discharge between the electrodes is produced.

The exact mechanism by which the preionization discharge operates to promote uniformity and stability is not well understood but streak photographs of the growth of the main discharge in the Lamberton-Pearson device indicated that volume photoionization was involved. Several workers^{5,6} investigated this effect using the geometries of Figs. 6 and 7. In these geometries the preionization circuit illuminates the gas volume with ultraviolet radiation from an arc. These experiments showed that volume ionization of the discharge is involved in the discharge mechanism, however, more work needs to be completed to understand the phenomenon fully.⁷ Notwithstanding this need for further study, impressive performance has been achieved with this technique and the results are summarized in Table I.

A technique reported by workers at Los Alamos⁸ and the Avco Everett Research Laboratory⁹ in this country and by N. G. Basov¹⁰ at the Lebedev Institute, Moscow, is based upon a discharge in which the electron-ion production is made independent of the applied electric field through the use of an external ionizing agent, a high-energy electron beam, which produces the requisite

charge carriers. This technique is known variously as an electron-beam-controlled discharge, an e-beam sustained discharge, or an electroionization discharge.

That such decoupling of the charge production from the electric field transport processes would produce a stable discharge was indicated in Persson's work¹¹ on the brush cathode and the essence of his argument is repeated here. A necessary condition for a steady state stable discharge is that the charge balance equation be satisfied:

$$D_a \nabla^2 n + S = \alpha n^2 \quad (1)$$

where D_a is the ambipolar diffusion coefficient, S is the source function for generation of electron-ion pairs, α is the volume recombination coefficient, and n the electron number density. Persson pointed out that in an electromagnetically generated discharge D_a , α , and S ($= \nu_i n$, ν_i being the ionization frequency) are strong functions of the electric field and that stable solutions exist for unique electron temperature, electric field, and electron number density. Departures from these values lead to solutions exhibiting spatial structure and instabilities. The additional degree of freedom added to this condition by making S independent of the electric field through the use of an external ionizing agent, a high-energy electron beam, allows stable solutions to the equation and in Ref. 11 solutions are given for the diffusion-dominated case and the volume recombination-dominated case as well as the general case for these loss mechanisms. This argument and these solutions are summarized in Figs. 8 and 9. While Persson's work was directed at producing and understanding low pressure, stable uniform plasmas, experimental work at Los Alamos established

that the argument applied to high pressure discharges as well. For the special case of electric discharge laser pumping, the time scales are such ($\sim 10 \mu\text{sec}$) that diffusion can be neglected and volume recombination is the dominant loss mechanism (electron attachment is negligible) so that the time history of the number density assumes a simple and now well-known form, as shown in Fig. 10:

$$\begin{aligned}
 \dot{n} &= S - \alpha^2 n \\
 n &= n_0 \tanh \sqrt{S\alpha} t & S = S_0 \neq 0 \\
 n &= \frac{n_0}{1 + n_0 \alpha t} & S = 0 \\
 n &= \sqrt{S/\alpha}
 \end{aligned} \tag{2}$$

and in the presence of an applied electric field a current density

$$j = ne v_d(\vec{E}) \tag{3}$$

will be established where v_d is the electron drift velocity, a function of the field.

It is instructive to estimate the values of these parameters for a representative discharge in a CO_2 laser gas mixture. A high-energy electron beam (100 - 200 keV) loses about 3 kV/cm of path in an atmospheric pressure gas of this density ($\sim 1 \text{ mg/cm}^3$) producing about 100 ion pairs per centimeter resulting in an effective range of $\sim 10 - 20 \text{ cm}$. For a 0.100 A/cm^2 beam then $S \approx 6 \times 10^{13} \text{ ion-pairs/cm}^3\text{-sec}$, recombination coefficients are $\approx 10^{-7} \text{ cm}^3/\text{sec}$ which gives an $n_0 = 3 \times 10^{13}/\text{cm}^3$. For an applied field of $\approx 5 \text{ kV/cm}$, $v_d \approx 5 \times 10^6 \text{ cm/sec}$ so that $j \approx 25 \text{ A/cm}^2$. Several hundred joules per liter-atmosphere can thus be deposited in the time of interest ($\sim 10 \mu\text{sec}$). The

ratio of energies, primary beam energy deposition to energy deposited by the applied field is $\approx 1 - 5\%$.

This simple model which describes the main features of the discharge remarkably well has been studied and verified in extensive parametric studies on CO₂ laser gas mixtures.¹² Representative results are given in Fig. 11 showing the time history of the current and corresponding small signal gain coefficient. Figure 12 gives representative values in CO₂ laser discharges.

This technique, which has been shown to be successful in the production of high pressure, large volume, stable discharges with high rates of energy deposition into the gas, has several features which distinguish it from the self-sustained discharge and they should be emphasized.

First the electric field, which for a given gas and neutral number density determines the electron energy of the discharge, can be varied to optimize the excitation rate of the pertinent vibrational levels and thus optimize the pumping. Figure 13 shows this effect dramatically. Second, the pumping rate for a given field can be varied by varying the current through the electron number density and in addition the stability achieved permits one to produce long, essentially steady-state discharges over a wide value of current, field strength and gas mixtures. This degree of control allows one to investigate and understand the discharge because of the ability to vary these parameters of the discharge independently.

Just as improvements to the self-sustained discharge have been made, various techniques to improve this pumping method have been suggested. The first of these was the development of large area ($\sim 1000 \text{ cm}^2$), long pulse ($\sim 5 \text{ } \mu\text{sec}$), high current (10 A/cm^2) cold cathode electron guns to replace the heated cathode systems which can provide much higher current densities and hence faster pumping rates.

A suggestion of a more fundamental nature has been made by Javan and Levine¹³ which considers the feasibility of producing the volume ionization in the gas by seeding it with a molecule of low ionization potential and using near UV ($\sim 3000 \text{ \AA}$) radiation from flashlamps. In this approach, both single-step and two-step ionization processes are considered. The advantage of this approach is that the absorption depth of the UV photons can be varied independent of the total gas pressure, allowing ultra high pressure operation and in a two-step process relatively long wavelength radiation is involved simplifying the flashlamp technology. Their experiments have shown that number densities of $\sim 10^{13}/\text{cm}^3$ can be achieved and have produced laser pumping in CO_2 . Much remains to be done to completely understand the process but if feasible, it could change present laser design significantly.

Having briefly outlined the principal features of a laser pumping process which is capable of depositing large energies into gas mixtures on an appropriate time scale, the discussion now turns to its application to high-energy, short-pulse amplifier systems.

III. HIGH-ENERGY, SHORT-PULSE AMPLIFIER SYSTEMS

For high-energy, short-pulse amplifier systems, the figure of merit is the instantaneously stored energy in the population inversion and the efficiency for such storage. This is in contrast to the figure of merit for high-power, long-pulse laser oscillators in which output energy density (joules/liter) is the meaningful parameter. For oscillators, this number can be maximized by long pumping/lasing times so that energy stored in other vibrational levels with long relaxation times, e.g., the N_2 ($v = 1$), level can be extracted. In addition, relaxation of the lower level can increase this laser output. Long pulse laser oscillations are thus power converters.

For short pulse amplifiers (~ 1 nanosecond) only that vibrational energy available on this time scale, which is much faster than vibrational energy transfer times under usual conditions, can contribute to the output. One can see that there will be considerable decrease in efficiency for these short pulse systems, therefore, from this consideration as well as from the physics of the gain storage process itself. Considering a very simple case in which the population inversion is being produced against a constant relaxation process; if R is the pumping rate and t the relaxation time, then at the time that 90% of the asymptotic value Rt is reached, $2.3 Rt$ molecules have been pumped of which only $.9 Rt$ are available at the time of amplification, the rest having decayed by collisional deactivation. In a laser oscillator operating for the same time duration all of these molecules would be available to provide optical energy output. The pumping mechanism is of course much more complicated than this and includes such effects as temperature dependent effects on relaxation processes but this simple first order model shows that efficiencies for short pulse amplifiers will diminish by a factor of 2 to 3 from that of an oscillator.

So that it should be emphasized again for the system under consideration, the instantaneous (instantaneous on a time scale comparable to the pulse length) population inversion is the figure of merit. This population inversion is of course directly related to the small signal gain coefficient which through the relation

$$g_0^{J,J'} = \frac{\lambda^2}{4\pi^2} \frac{1}{t_{sp}} \frac{1}{\Delta\nu} \left(n_u^J - n_l^{J'} \right) \quad (4)$$

where λ is the wavelength, t_{sp} the radiative lifetime, $\Delta\nu$ the full line width at half maximum and n_u^J , n_l^J are the respective upper and lower laser levels. Degeneracy factors have been neglected in this case.

For the pumping technique described, the electron-beam-controlled discharge, in CO₂ laser mixtures, gain coefficients $> 6\% \text{ cm}^{-1}$ have been produced and for the values of $\lambda^2/4\pi^2 t_{sp} \Delta\nu$ at the operating conditions ($\approx 1 \times 10^{-18} \text{ cm}^2$) this value implies a stored energy density $\Delta N h\nu$, (where $\Delta N = \sum_J n_u^J$ which includes all rotational levels of the upper state) of $\approx 10 \text{ joules/liter-atm}$. This storage is accomplished with an efficiency (stored energy/electrical energy input) of $\approx 10\%$. For any operating system, two factors must be applied to this efficiency, the first being the efficiency for energy extraction from these J levels of the upper state for short pulses and second engineering efficiencies, i.e., pumped volume to useful optical volume. This energy extraction problem will be discussed later. At this point, the application of this pumping technique to large systems will be discussed.

Figure 14A shows a cross section and 14B a perspective view of an amplifier stage which has been described previously.¹⁴ In brief, the electron gun for this laser amplifier is a hot cathode planar diode 8 cm x 100 cm in extent using 100 thoriated tungsten filaments spaced at 1 cm operating in a vacuum of $\approx 10^{-7}$ Torr. The electron accelerating voltage of 125 kV is supplied from a 3 stage Marx bank. The vacuum window is a nominal 25 μ thick titanium foil supported upon a grid structure. The electron transmission of this window and support is $\approx 50\%$. The electron energy loss in the foil is $\approx 25 \text{ keV}$. The energy for the gas discharge in the optical chamber is a rundown capacitor bank which supplies the current at a field strength $\approx 4 \text{ kV/cm-atm}$. The detailed operating performance of this system has also been presented in Ref. 14.

Using this geometry, a four-stage CO₂ amplifier system has been built. The configuration and design parameters are given in Fig. 15.

IV. SHORT PULSE GENERATION

It is not the intent to treat short pulse generation in detail in this article but only to give general considerations which determine the performance of modelocked CO₂ laser oscillators.

Reliable, repeatable modelocking has been accomplished in atmospheric pressure CO₂ oscillators and many articles describing the technique are available. Straightforward techniques are used; because the output power is limited by optical damage to cavity elements and because generally good optical quality Gaussian fundamental spatial mode structure is desired, only small volumes of active medium are required and these can readily be produced by any of the variety of TEA (self-sustained discharge) lasers. Modulation is accomplished with acousto-optic transducers using germanium. Such modulators are capable of depths of modulation of $\approx 20 - 50\%$ with relatively low RF power input ($\sim$ watts). The parameters which determine pulse duration have been developed by Siegman and Kuizenga¹⁵ with the result that for a steady state homogeneously broadened gain medium

$$\Delta\tau_p \approx \frac{\sqrt{\ell n^2}}{\pi} \left(\frac{2\alpha}{\delta} \right)^{1/4} \frac{1}{(f_m \Delta f)^{1/2}} \quad (5)$$

(Fig. 16)

where $\Delta\tau_p$ is the full width of a Gaussian pulse, α is the resonator loss coefficient, Δf is the gain bandwidth (FWHM), f_m is the modulation frequency = $\frac{c}{2L}$.

For CO_2 mixtures, $\Delta f \approx 4 \times 10^9 \text{ M}_c$ so that $\Delta\tau_p \approx 1$ nanosecond at 760 Torr and at 10 atmospheres $\Delta\tau_p \approx 300$ psec. These considerations apply to all pressure-broadened molecular gas systems.

Single switched out nanosecond pulses with good contrast ratio can now be routinely produced.

V. ENERGY EXTRACTION EFFICIENCY

The last aspect of the high-energy, short-pulse laser amplifier system to be treated here is that of the energy extraction process. Pulsed energy extraction from a two-level laser system has been treated in detail by Franz and Nodvick¹⁶ and Letokhov¹⁷ and the results can be directly applied for a two-level case, given the parameters of the system.

In the CO_2 laser, the energy is not stored as in a simple two-level system. The upper and lower laser levels comprise a manifold of rotational sublevels over which the vibrational energy is distributed. These levels communicate with each other on a time scale of about one collision time ($\sim 10^{-9}$ sec STP). Lasing occurs between pairs of these levels according to the selection rules $\Delta J = \pm 1$ (P or R branch transitions, J being the angular momentum quantum number). Hence, the straightforward two-level energy extraction model must be modified to include this effect and, in general, the other molecular kinetic processes should be treated depending upon the time scale involved. The consideration of these kinetics includes the following vibrational energy transfer processes: V-V transfer between N_2 ($v = 1$) and CO_2 (001) levels;

V-V and V-T process for the (001) and (100) levels in CO_2 , as well as relaxation among the rotational levels of these states.

The N_2 ($v = 1$) and CO_2 (001) levels are in good resonance with a V-V rate about equal in both directions so that in steady state these levels partition the energy according to the mole fraction ratio. The rate at 1 atmosphere, however, is $\sim 1 \mu\text{sec}$, so that during the passage of a one nano-second pulse there is no time for this process to contribute to the energy extraction.

In most modelocked oscillators, the output pulse consists of but a single P-branch transition, the one with highest gain for the operating conditions unless a technique described below is employed. The stored energy in the upper level is distributed over a Boltzmann distribution of angular momentum values. For this situation then energy is extracted from the upper level only through this channel. The fractional energy stored in this single level is $\approx 6\%$ of the total and rotational relaxation among the other levels into this lasing transition determines the rate at which these remaining levels contribute to the amplification process. Fortunately, this rotational relaxation rate is quite fast, about one collision time, or ≈ 0.2 nanoseconds at atmospheric pressure, which is fast enough to allow substantial communication among the other levels but not fast enough to be considered infinitely fast on the time scale of the pulse.

A reasonable estimate of the energy extraction can be made using a strong signal rate equation approximation,¹⁸ that is amplification of an optical pulse with sufficient intensity to saturate the lasing transition so that the rotational relaxation rate into this level limits the rate of energy extraction. The result of this approximation is that the total available energy in the

system $\frac{\Delta N}{2} h\nu$ where ΔN is the total population inversion including all J levels is reduced by a factor

$$\left\{ 1 - \exp \left(- \frac{\tau_p^k}{\tau_r} \right) \right\} \quad (6)$$

with τ_p the pulse width, τ_r the rotational relaxation time, and k is the fraction of the distribution represented by the lasing transition (≈ 0.06). Thus the energy extraction efficiency for a one nanosecond pulse is approximately 30%. Figure 17 summarizes this effect for various pulse lengths and pressures.

Clearly the way to improve this factor is to increase the operating pressure. Additionally, if the incoming pulse contains more than one P-branch transition, the energy extraction will be enhanced. In this laboratory an oscillator has been devised, using an etalon to reduce competition effects among the P-branch transitions, whose output consists of four transitions. This combination of pressure and multiple transition oscillator recoups most of the loss due to finite rotational relaxation time. A more exact and detailed treatment of the energy extraction process can be found in the work of Schappert¹⁸ and the work of Stark, et. al.,¹⁹ gives some experimental results for comparison.

VI. CONCLUSION

Figure 18 summarizes the performance to date of the system under consideration. Information gained from this development program is presently being used to design a 10^4 joule system based upon eight optical beams to irradiate a target isotropically and it is believed that a factor of 10 higher in output energy will be feasible.

Regarding the possibilities of other gas laser systems, it should be pointed out that other gases should be amenable to this technology, long pulse CO lasers operating at $5\ \mu$ have produced over 1000 joules in many μ sec. Figure 19 shows the discharge characteristics for hydrogen.

Two rather basic observations might be made: 1) considerable uncertainty exists in the understanding of CO_2 laser kinetics, even at this late date, specifically the values for the stimulated emission cross section and its temperature and pressure dependence as well as the values of the pertinent relaxation rates, mentioned above, and 2) the need to search for other gaseous laser systems which could be pumped efficiently with this technique.

In summary, Fig. 20 compares the present state of the three high-energy laser systems.

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High Energy—Short Pulse Laser System

Master—Oscillator—Power Amplifier Configuration

FIGURE 1

73-4255

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$\text{CO}_2\text{-N}_2$ ENERGY LEVELS

FIGURE 2

73-11106

TEA Pin Type¹

Self-sustained Discharge Configuration

1) A.J. Beaulieu , Appl. Phys. Letters, 16, 504 , (1970)

FIGURE 3

Self-Sustained Discharge Configuration (1)

- (1) R. Dumanchin et al., "High power per unit volume CO₂ lasers in continuous and pulsed operation," IEEE J. Quantum Electron. (Abstract), vol. QE-6, pp. 4-5, Jan. 1970.

FIGURE 4

SELF-SUSTAINED DISCHARGE CONFIGURATION

FIGURE 5

(PEARSON AND LAMBERTON, S.E.R.L. TECHNICAL JOURNAL, V.21, NO. 3, OCTOBER 1971)

73-4193

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SELF-SUSTAINED DISCHARGE CONFIGURATION

FIGURE 6

(SEGUN AND TULIP, APPL. PHYS. LETTERS V.21, NO 9, P.414, NOV. 1972)

73-4107

SELF-SUSTAINED DISCHARGE CONFIGURATION

FIGURE 7

(RICHARDSON, ALCOCK, LEOPOLD, AND BURTYN, IEEE J. QUANTUM ELECTRON V. QE-9, P.236, FEB. 1973)

TABLE I

Self-Sustained Discharge Performance & Parameters

Pressure $\approx$ 1 atmosphere

Electric Field $\approx$ 10-15 kV/cm-atm

Electrical Energy Input $\approx$ 300 J/liter-atm

Laser Energy Output $\approx$ 50 J/liter

Efficiency $\approx$ 10-15 %

Maximum Energy / Power Output $\approx$ 300 joules / 3 Gw

Small Signal Gain Coefficient $> 0.04 \text{ cm}^{-1}$ (260 J/liter-atm input)

Largest Aperture Uniformly Pumped $\approx 8\text{cm} \times 8\text{cm}$

Electron Beam Generated Plasma¹

Stability considerations

$$Da \nabla^2 n + S = \alpha n^2$$

For electromagnetically generated plasmas (self-sustained)

$$S = \nu_i n$$

$$\text{with } \nu_i = \nu_i(\vec{E}).$$

$$Da = Da(\vec{E})$$

so that simple solutions exist for unique $n, \vec{E}$

¹ Karl-Berger Persson, J. Appl. Phys. Vol. 36, 10, 3086, (1965)

Electron Beam Generated Plasma¹

For S independent of n ,

$$S + Da \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial n}{\partial r} \right) = \alpha n^2$$

and well behaved solutions exist.

a) For diffusion dominated case:

$$n = n_0 \left(1 - \frac{r^2}{R^2} \right)$$

$$n_0 = \frac{SR^2}{4Da}$$

b) In recombination limit:

$$n = \sqrt{\frac{S}{\alpha}}$$

¹ Karl-Berger Persson, J. Appl. Phys. Vol. 36, 10, 3086, (1965)

Electron Beam Controlled Discharge Time History

Neglecting diffusion and attachment for time scales and gases of interest

$$\dot{n} = S - \alpha^2 n$$

$$n = n_0 \tanh \sqrt{S\alpha} t$$

$$S = S_0 \neq 0$$

$$n = \frac{n_0}{1 + n_0 \alpha t}$$

$$S = 0$$

$$n_0 = \sqrt{S/\alpha}$$

FIGURE 10

FIGURE 11

TIME, μ sec

Representative Values For CO₂ Laser Discharge

For electron energies of $E \approx 100 - 200 \text{ keV}$

$$j_{eb} \approx 0.100 \text{ A/cm}^2$$

and $\frac{dE}{dX} \approx 3 \text{ keV/cm}$

so that $S \approx 6 \times 10^{19} \text{ ion pairs/cm}^3\text{-sec}$

for $\alpha \approx 10^{-7} \text{ cm}^3/\text{sec}$

then $n_o = \sqrt{\frac{S}{\alpha}} \approx 3 \times 10^{13} / \text{cm}^3$

if $E \approx 5 \text{ kV/cm}$

$$v_d \approx 5 \times 10^6 \text{ cm/sec}$$

so that $j_{disch} = n_o e v_d \approx 25 \text{ A/cm}^2$

and the energy ratio $\frac{E_{\text{electron beam}}}{E_{\text{applied field}}} \approx 1 - 5 \%$

FIGURE 12

FIGURE 13

73-4105

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FIGURE 14a

FIGURE 14b

Component	Area, cm ²	L, cm	Gain	Pressure, Torr	Energy Out (Joules)
Oscillator					0.001
Stage 1	15	100	165	600	0.1
Stage 2	15	100	165	600	1.1
Stage 3	40	100	125	1800	17
Stage 4	500	200	10 ⁴	1800	500-700*

* Depends on final operating parameter and configuration.

FIGURE 15

Short Pulse Generation

Homogeneous mode-locking¹

$$\Delta t_p = \frac{\sqrt{\ln 2}}{\pi} \left(\frac{2\alpha}{\delta} \right)^{1/4} \frac{1}{(f_m \Delta f)^{1/2}}$$

δ = depth of modulation

α = loss coefficient of resonator

Δf = gain bandwidth (FWHM)

f_m = modulation frequency

For CO_2 $\Delta f \approx 5.7 \times 10^9$ Hz (CO_2 STP)
 $\approx 4 \times 10^9$ Hz (He/ N_2 / CO_2 mixture)

so that $\Delta t_p \approx 1$ nanosecond

and at 10 atm., single line operation

$$\Delta t_p \approx 300 \text{ psec}$$

¹A. Siegman, D. Kuizenga, IEEE/J.Q.E. Vol. QE-6, No. 11, Nov. 1970

FIGURE 17

Electron Beam-Controlled Discharge Performance & Parameters

Pressure 5-50 atmospheres

Electric Field ≈ 5 kV/cm-atm

Energy Output (Laser Oscillation) > 1000 joules at 50 J/liter
(long pulse)

Efficiency (short pulse) $\approx 2-3$ %

Efficiency (long pulse) > 25 %

Peak Power (to date) $\approx 10^5$ Gw (130 joules-1.2 nanosecond input pulse)

Small Signal Gain Coefficient > 0.05 cm⁻¹ (100 j/liter-atm input)

Largest Aperture ≈ 26 cm $\times$ 26 cm (1800 Torr)

FIGURE 18

75-11111

(11)

FIGURE 19

High-energy Short-pulse Laser System Comparison

	Nd:Glass	Iodine	CO ₂
$\lambda(\mu)$	1.06	1.31	10.6
$-\Delta\nu$ (torr)	2×10^{13} (inhomogeneous)	1.8×10^{10} (homogeneous)	4×10^9 (homogeneous)
τ_p (sec)	$10^{-12} - 10^{-9}$	3×10^{-10}	$\sim 10^{-9}$
$\sigma_{stim}(\text{cm}^2)$	1.2×10^{-20}	7×10^{-19}	10^{-18} (P-20)
Small signal gain coeff. (cm^{-1})	$\sim 20\%$	$\sim 20-40\%$	$\sim 5\%$
Energy storage (J/liter)	350	20-40	10
Efficiency	0.3 %	0.2-0.5 %	2-3 %
Medium breakdown (J/cm)	~ 20	≈ 30	>10

FIGURE 20