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DESIGN STUDY OF HIGH AVERAGE POWER (20-100 WATTS)
PULSED NITROGEN LASERS AT $\lambda = 3371 \overset{0}{\text{\AA}}$

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POWER (20-100 WATTS) PULSED
NITROGEN LASERS AT $\lambda = 3371 \text{ \AA}$

by

G. Dzakowic, T. Kan, R. Kuenning, and L. Schlitt

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Summary

Laser Modeling

A nitrogen kinetic model has been developed to predict the parametric behavior of N_2 laser devices. The model includes plasma and external circuit parameters to identify interactions between the laser and driver circuit. A comparison with experimental data taken from the available literature shows that the model predicts the performance to within 30% in four out of seven cases. The three lasers which do not agree with our predictions all report energies a factor of 3-4 higher than model calculations. A thorough modeling of this system is hampered at the present time by the lack of good data on electron impact cross-sections of the relevant levels and lack of a complete and consistent set of experimental parameters over a large portion of the laser parameter space for comparison.

The physical and electrical parameters which limit laser performance are fairly clear. Both the C and B states are pumped by the tail of the electron distribution. During the initial stages of gas breakdown when the gas resistivity and E/P are high, the C state is being pumped by electrons with an average electron temperature of about 4 eV which leads to an instantaneous laser efficiency of $\sim 1/2\%$. The electron temperature however drops by a factor of two while the instantaneous efficiency falls to 0.1% in a few nanoseconds as the electron density in the plasma increases and the plasma resistivity falls. The rapid decline of the plasma away from the optimum pumping conditions is responsible for an overall low laser efficiency and eventually for termination of the laser pulse 10 ns after it commenced.

The parametric performance of the nitrogen laser is a decreasing function of the parameters Z (line impedance), τ_r (voltage pulse rise time) and L (tube inductance). Practical lower limits on the values of these parameters are set respectively by the life of the PFL (pulse forming line), switch technology, and flow requirements.

Mode Control and Optical Energy Extraction

Conditions have been derived for the onset of superfluorescence in high gain lasers. Application of these results to nitrogen indicate that typical N_2 lasers achieve very efficient ($> 80\%$) extraction of the available energy for laser lengths exceeding ~ 60 cm. However, the unpredictable spatial intensity distribution and large beam divergence of superfluorescent emission is incompatible with LIS applications.

On the other hand near-diffraction-limited mode controlled energy extraction can be achieved with a MOPA (master-oscillator power amplifier) configuration in which a short unstable oscillator drives a series of amplifiers. The oscillator energies required are very modest since the saturation energy in nitrogen is low ($\approx 4 \mu\text{J}/\text{line}$ in the Doppler limit). The MOPA configuration requires temporal and spectral matching between the oscillator and amplifier to suppress superfluorescence. Temporal matching can be achieved with low jitter electrical circuitry (± 2 ns typical). Spectral matching requires knowledge of the detailed properties of the laser medium including the effects of buffer gases, like helium, on line width and collisional relaxation.

Electrical Pulser Design

For high average power operation of N_2 lasers, efficient electrical excitation can be achieved using the technology of fast pulse Blumleins. The requirement for a minimum line impedance implies a dielectric material with a maximum value of $\sqrt{\epsilon_r} E_{op}$. Of all the dielectrics (gases, liquids and solids) considered, Mylar and Kapton appear to be best suited for low impedance lines and high average power service. A lifetime of 10^8 pulses is expected for an operating stress in the dielectric of 1 kV/mil. High average power Blumleins have not heretofore been operated. Consequently an investigation of thermal loadings, cooling techniques, line failure modes and edge grading methods must be done for successful operation of the pulser in the high prf regime.

Electrical designs of the laser channel for the two possible directions of gas flow--parallel to the electric field (through the electrodes) and perpendicular to the electric field (through the pulse forming line)--have been made. Flow through the electrodes is preferred from the standpoint of less complexity and less demanding requirements on the insulator structures. In either case resistive coatings for the insulator surfaces, which provide field grading and prevent charge accumulation, must be developed for high prf operation.

The switch inductance required for near optimum switching of the pulse forming line is not known at the present time. Parallel combinations of thyratrons can be used to achieve inductances of 10 nh per laser module and repetition rates of 5-10 kHz, however much lower inductances and faster switching rates will require development of plasma switches.

Gas Transport

The flow considerations for the N_2 laser have been directed at determining the maximum electrical power dissipation in the gas for subsonic flow in directions parallel and perpendicular to the electric field. The two factors which determine the maximum attainable prf are the minimum clearing volume required to remove residual ionization before the next pulse, and the maximum gas inlet velocity set by thermal choking at the flow exit. These considerations indicate the need for a helium diluent to limit the gas temperature rise in order to attain high prf's (5-10 kHz). A flow dominated maximum power dissipation of 200 Kw/meter has been calculated for a laser with a 0.5 cm x 2 cm aperture at an inlet gas (mainly He) velocity of 3×10^4 cm/sec (Mach 0.25) at 7.7 kHz. This power dissipation limit is a conservative estimate based upon the assumption of a total conversion of electrical energy into gas heating within the laser channel. Careful design of the laser cavity and flow structures will be required to insure medium optical homogeneity and to accommodate thermal loadings.

20-100 Watt Nitrogen Lasers

The conclusion reached by this design study is that 20-100 watt average power mode-controlled nitrogen lasers are feasible with state of the art technology but that experimental work must be initiated to obtain the necessary data and develop the high power configurations and pulse forming line designs.

Introduction

The $\lambda = 3371 \text{ \AA}$ $C^3\Pi_u \rightarrow B^3\Pi_g$ laser transition in N_2 is a prime pumping source for dye lasers in the UV-blue spectral region where the ability to achieve high average powers (10-100 watts) would find immediate applications in Laser Isotope Separation.

The stimulated emission spectrum of the " $\lambda = 3371 \text{ \AA}$ " laser is very complex because the laser is actually composed of some 30 rotational transitions¹ between the $v = 0$ vibrational level of the upper $C^3\Pi_u$ electronic state and the $v = 0$ vibrational level of the lower $B^3\Pi_g$ electronic state, Fig. (1). Excitation of the C and B levels in the traditional glow discharge type laser occurs via direct electron impact excitation from the ground electronic state. Fig. (2) shows representative electron impact cross-sections² for the triplet levels of the nitrogen molecule which are of importance for laser considerations. There are experimental discrepancies between measured values of the cross-sections³⁻⁷ especially for the B state, and a lack of good agreement between the experimental and theoretical^{2,8} shapes.

The radiative lifetimes and excitation cross-sections of the C and B states essentially determine the laser properties and dictate the method of excitation. With a fully allowed radiative lifetime of 40 ns for the C state and a much slower 1 μ s lifetime for the B state, the laser transitions have extremely high gain (100-300 dB/m) and are self-terminating.⁹ This latter fact together with the requirement for a high plasma electron temperature ($T_e \sim 5 \text{ eV}$) to pump the upper level efficiently dictates rapid pulse excitation methods for the laser. The excitation circuits which seem most efficacious for satisfying the pulse excitation requirement are low inductance

N_2 LASER LEVEL STRUCTURE

Fig. (1a)

$N_2\ C\ 3\pi_u \rightarrow B\ 3\pi_g\ (0,0)$ High Gain Transitions

Fig. (1b)

CALCULATED N_2 TRIPLET ELECTRON EXCITATION CROSS SECTIONS REF. 2

Fig. (2)

pulse transmission-line circuits shown in Fig. (3) where a rapidly rising voltage pulse is developed across the laser tube, transverse to the optic axis, by the voltage wave created by switch closure. The high gain and transient inversion of the laser make conventional resonators useless. Nitrogen lasers therefore have operated exclusively as superfluorescent devices in which the pulse-line geometry can be configured in several ways to create a traveling-wave excitation pulse¹⁰ along the laser channel. This technique creates a unidirectional output beam for long laser structures where the optical transit time through the medium approaches the time duration of the inversion. Table (I) summarizes the performance figures and features of some high power nitrogen lasers which have been reported in the literature.¹⁰⁻²⁰

The development of the nitrogen laser since its inception has been directed primarily towards larger single pulse energies and higher peak powers except for two incursions into the regime of high pulse repetition frequencies.^{21,22} High average power nitrogen lasers (10-100 watts) require above all the development of a high pulse repetition frequency gas transport capability for this system. Furthermore the utility of this laser for the LIS mission depends upon the simultaneous synthesis of rapid pulse excitation, gas transport, and mode-controlled optical energy extraction in a single device with a minimum of compromise in the parameters which determine the laser performance in each of the three areas. The nitrogen C $\rightarrow$ B transition has also been pumped by electron beams utilizing return current excitation^{23,24} and collision energy transfer from argon metastables.^{25,26} Among all the excitation methods, only the glow discharge mechanism is well enough understood and the excitation technology mature enough to construct high average power devices for near term LIS applications.

FLAT PLATE BLUMLEIN

TRANSMISSION LINE PULSERS

Fig. (3)

	Energy/Pulse, U millijoules	Peak Power, P MW	Pulse Width, τ ns (FWHM)	Length, L cm	Discharge Height, h cm	Discharge Width, w cm	U/hL $\mu\text{j}/\text{cm}^2$	N_2 Pressure Torr	
Levatter ¹¹	20	3	6	120	1.2	0.6	139	200	Double triangular Blumlein, single plasma switch
Woodward ¹²	13	1.1	12	120	3	---	36	60	Multiple cables, thyatron
Geller ¹³	12.5	2.5	5	100	2.5	0.3	50	35	Rectangular PFL, 20 plasma switches
Tarasenko ¹⁴	10	1.4	--	100	2.4	0.3	42	40	Ceramic stripline, 10 plasma switches
Shipman ¹⁰	10	2.5	4	183	10	0.3	5.5	---	Rectangular Blumlein, 6 solid dielectric switches
Nagata ¹⁵	7	1	7	50	4	0.25	35	70	Ceramic stripline, single plasma switch
Cubeddu ¹⁶	6	0.5	12	60	5	---	20	30	Water capacitor, thyatron
Targ ¹⁷	3	0.3	10	80	4	---	9	$\approx$ 30	Capacitor discharge, thyatron
Basting ¹⁸	2.4	1.2	2	30	1.5	0.6	53	100	Double triangular Blumlein, single plasma switch
Bergmann ¹⁹	0.5	0.2	2.2	45	1	---	11	130	
Andersson ²⁰	0.3	0.05	6	30	2.5	0.2	4	60	

Table I

The purpose of this design study is to assess the feasibility of building high average power nitrogen lasers with a goal of identifying data which must be obtained and technology which must be developed for the venture to succeed. The report consists of four sections which treats respectively; (I) laser modeling, (II) mode-control and energy extraction, (III) electrical pulser technology, and (IV) gas flow. Our conclusion is that the feasibility of high average power nitrogen lasers is very positive. Conceptual designs for 20 and 100 watt nitrogen lasers are presented in (V).

I. Laser Modeling

(A) KINETIC MODEL

A kinetic model of the nitrogen laser has been constructed which closely resembles that previously described by Gerry²⁷ and Ali, Kolb and Anderson.²⁸ In this model the laser medium is coupled to an external electrical circuit and equations of motion for the circuit voltage, circuit current, electron density, excited state density, and electron temperature are followed. The electrical circuit used is shown in Fig. (4) where the laser medium is incorporated in the form of a time varying resistance, and the applied voltage is allowed to have a finite risetime which is determined by the switch inductance. Both capacitor discharge and transmission line circuits can be modeled by appropriate choices for circuit capacitance C and impedance Z . For the case of a capacitor discharge the inductance L is the total circuit inductance while for the transmission line case the inductance between the laser discharge and the transmission line is to be used.

The excitation rates which were used in the laser rate equations are those given by Ali²⁹ and Ali, Kolb, and Anderson²⁸ with an additional rate for excitation of the A state which was evaluated by assuming a cross-section with the same shape as the C state cross-section but with a threshold at 6 eV and with a relative magnitude given by the calculations of Cartwright.² Only the (0,0) transition at 3371 Å was considered and the complexities of the three multiplets and of rotational structure within the $v = 0$ levels were ignored.

$$L\left(\frac{dI}{dt}\right) + [Z + R(t)]I = v_0 - \int_0^t (I/C)dt'$$

CIRCUIT PLASMA COUPLING

Fig. (4)

The C and B excited state densities, which determine the laser output, were calculated with an equation of motion which includes: excitation rates as a function of electron density and temperature, radiative decay, collisional de-activation of the C state by ground state N_2 , and the mixing of the C and B states by electron collisions. These processes are shown in Fig. (5). A Maxwellian distribution in the electron energy was assumed in deriving all excitation rates. The electron temperature is determined by energy balance in the plasma with ohmic heating and super-elastic electron collisions as heating terms and excitation of the electronic A, B, C states and vibrational levels as inelastic losses. The electron density is determined in turn by temperature dependent rates for ionization and recombination. A flow diagram of the couplings between the different equations of motion is shown in Fig. (6). The discharge resistivity, which couples the circuit with the plasma, is obtained from the data of Wagner and Raether³⁰ and Frommhold³¹ giving the electron drift velocity as a function of the electric field strength to neutral particle density ratio E/n .

Nearly all the calculations were carried out in the saturation approximation, that is, the difference between the populations of the C and B excited states are assumed to be small compared with the individual excited state densities. In this case, only a single equation for the excited state density need be used. When the saturation approximation was not used, the C and B densities were followed separately.

(B) PHYSICS OF A TYPICAL CASE

The fundamental processes occurring in the nitrogen laser are summarized in Figs. (8-14). The specific example considered is described in Fig. (7)

Fig. (5)

FLOW DIAGRAM FOR KINETIC
CALCULATIONS

Fig. (6)

$$w = 1 \text{ cm}$$

$$h = 1 \text{ cm}$$

$$l = 100 \text{ cm}$$

$$P = 90 \text{ torr}$$

$$z = 0.1 \Omega$$

$$L = 0.3 \text{ nh}$$

$$\tau_r = 15 \text{ ns}$$

$$v = 18 \text{ kV}$$

Fig. (7)

which shows both the laser parameters as well as the geometry of the double Blumlein device which was modeled. Fig. (8) shows that as the voltage on the line increases the electron temperature rises. When the electron temperature becomes greater than about 5 eV the exponentiation time for the electron density becomes approximately 200 ps. The electron density therefore grows at a rate of between two and three orders of magnitude per nanosecond and is accompanied by similar buildups in excited state density and inversion as shown in Fig. (9). This rapid buildup of electron density is also accompanied by a similarly rapid decrease in the resistance of the discharge shown in Fig. (10). Once the discharge resistance becomes comparable to the line impedance, which is 0.1Ω in this example, the discharge begins to load down the transmission line and the voltage across the discharge drops. This decrease in voltage is accompanied by a drop in electron temperature and a consequent drop in the ionization rate as the discharge approaches a quasi-steady state for the duration of the laser pulse.

As the electron temperature falls, the C state excitation rate falls. The C state deactivation rate however, which is proportional to the combined electron and ground state N_2 densities, remains high since the electron density is still high. This situation leads to a termination of the laser emission. This behavior is illustrated in Fig. (11) which shows the power flow into the laser as well as the power flow into each of the loss processes as a function of time.

A consequence of the plasma discharge behavior described above is the relative independence of the laser output on the width of the discharge as shown in Fig. (12). The reason for this effect lies in the fact that the

plasma electron density increases until the discharge resistance achieves a value approximately equal to the line impedance. A narrower discharge requires a lower resistivity and hence higher electron density to reach a given resistance. The required electron density is inversely proportional to the discharge width therefore the total number of electrons becomes independent of width. Since the C state excitation rate is proportional to the electron density, the integrated C state density and hence the laser energy depends to first order on the integrated electron density and is therefore insensitive to the discharge width. The only qualification to the above statement is that collisional mixing of the C and B states, which is a quenching process for the C state, is proportional to the product of the electron and excited state densities and therefore becomes a dominant nonlinear effect at the high densities associated with widths much less than 1 cm.

The laser pulse produced for the conditions shown in Fig. (7) contains 6.3 mJ of energy, has a pulse length of 5.3 ns FWHM and is produced with an efficiency of 1.4×10^{-3} . This efficiency is defined as the ratio of the laser output energy to the total electrical energy dissipated during the course of the laser pulse. The reason for this low efficiency is explained in Figs. (13, 14) which shows the fraction of the electrical input energy which goes into the different inelastic processes occurring in the laser medium as a function of electron temperature under steady state conditions. At temperatures in excess of 5 eV, five percent of the discharge energy goes into populating the C state. However, only about 15% of this energy can be extracted by stimulated emission when the quantum efficiency of the transition and the metastability of the B state is taken into account. Unfortunately,

Fig. (8)

Fig. (9)

Fig. (10)

LOSS PROCESSES RESPONSIBLE
FOR LASER TERMINATION

Fig. (11)

LASER ENERGY DEPENDENCE
ON DISCHARGE WIDTH

Fig. (12)

Fig. (13)

Fig. (14)

at these high values of electron temperature, the ionization of the medium is extremely rapid causing the rapid collapse of plasma resistance discussed previously. The laser medium therefore spends very little time at high values of electron temperature where the C state excitation is fairly efficient as shown by the super-imposed time versus electron temperature curve of Figs. (13, 14). In fact, the discharge spends most of its time at electron temperatures in the range from 2.5 to 3.0 eV where only one to two percent of the discharge energy is going into the C state. Even if the discharge could be maintained at electron temperatures of 5 eV, the maximum attainable efficiencies would still only be about 0.7%. This efficiency could be improved by a factor of two if a mechanism for removing the B state population could be found.

(C) COMPARISONS WITH PUBLISHED LASER CHARACTERISTICS

Seven examples of lasers operating at their respective optimum conditions were selected from published data and comparisons made between the measured laser parameters and the calculations of the kinetic model. The examples were selected on the basis of the completeness of the description of critical laser parameters. Results of the comparisons are summarized in Table II which shows agreement to within 30% between the model and measured characteristics for four out of the seven cases. In addition to the important laser characteristics, agreement was obtained with discharge voltage and current characteristics for these four cases where this data was available. A comparison of output power versus pressure was made for the laser of Bastings, et al. and the results are presented in Fig. (15).

LASER	Energy (mJ)		Power (Mw)		Pulse length (ns)	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
Geller ¹³	17	12.5	2.8	2.5	6	5.1
Bastings ¹⁸	2.9	3.2	1.2	1.1	2.4	2.7
Andersson ²⁰	.17	.21	0.06	0.06	3	3.6
Levatter ¹¹	18	6.4	3	1.4	6	4.7
Fitzsimmons ³²	2	2.5	0.5	0.45	4	5.7
Woodward ¹²	12	3.57	1	0.37	12	
Molelectron ³³	13	4.17	1.2	0.6		

Table II

COMPARISON OF CALCULATED AND
MEASURED LASER POWER DEPENDENCE
ON NITROGEN PRESSURE

Fig.(15)

There are two major shortcomings of the model; first, the substantial lack of agreement with the laser performance reported by Levatter and Lin,¹¹ Woodward¹² and Molelectron,³³ and second, the failure of the model to predict the substantial roll-off in output power at higher than observed optimum pressures. The laser of Levatter and Lin is a double triangular Blumlein device driven by a single plasma switch at the apex of the line while the Woodward and Molelectron lasers are multi-cable transmission line devices switched by a hydrogen thyratron (HY-5). A significant amount of effort has been spent trying to resolve the discrepancy between the calculations and the measurements of Levatter and Lin. Changes in the rate constants used in the model are certainly capable of removing the discrepancy but at the expense of introducing a similar discrepancy with the other four examples. There is only one feature of the Levatter and Lin laser which has not been duplicated in lasers constructed by other workers; that is, the inclusion of a third "pre-ionization" electrode. In order to assess the importance of this feature, another kinetic model was constructed which allowed, in addition to the processes already mentioned, an additional source of ionization whose strength and timing could be varied. Although the initiation of breakdown in the laser could be controlled with this supplemental source, no significant increase in laser output could be obtained and the source of the discrepancy therefore remains unknown. The discrepancy between calculations and the two other devices which use thyratrons and have fairly slow risetimes (70 ns) indicates that the code is under-predicting laser behavior at slow voltage risetime conditions.

The disagreement at high pressure could be due to several causes;

- a) other workers frequently note the breakup of the discharge into filaments at high pressures which could interfere with the laser action,
- b) the ionization of excited states by electrons (especially the A state) would be more severe at high pressure and would result in a greater impedance collapse accompanied by lower pumping rates (this in fact may be the cause of observed filamentation; and c) as the pressure is increased the laser pulse becomes shorter and the laser length-dependent transit time effects to be discussed in section (G) could become important.

The examples selected from Table I include a wide range of laser parameters. Length of the lasers range from 30 to 120 cm, pressures from 35 to 175 torr, line impedances from 0.08 to 5 Ω , and the E/P measured in terms of the open circuit voltage developed across the laser discharge range from 170 to 340 V/cm-Torr. Although the discrepancy between the model and measured laser characteristics at high pressures might be resolved by a more sophisticated model, there does not appear to be a direct approach with data we have available to resolve the discrepancy with the results of Levatter, Woodward and Molelectron. The code consistently underpredicts the laser energy for certain devices therefore the device parametric studies of section (E) should be viewed as a predictor of general parametric laser behavior rather than as an absolute guide for laser design.

(D) SENSITIVITY ANALYSIS

The model was checked for its sensitivity to the important rates assumed in the model. The laser output is, of course, a strong function of

the magnitude of the rate for the excitation of the C state. If the laser were to operate at higher electron temperatures (say in the range of 4 or 5 eV) the laser output would be relatively insensitive to the B state excitation rate. However, because the discharge is operating at very low electron temperatures during the bulk of the laser pulse where the excitation rate for the B state is a significant fraction of that for the C state, the laser output is also sensitive to the B state rate. The elimination of either the neutral deactivation of the C state, or the electron collisional mixing of the B and C states, or a doubling of the radiative lifetime of the C state, would each lead to increases in laser output of 20% to 30% appearing principally as an increased laser pulse length. A combination of these effects could result in considerably higher output energies. However this would be inconsistent with some of the observed characteristics summarized in Table II. Certainly the most critical assumptions of the model are the rates for the excitation of the C and B states.

There has been a recent report of evidence for possible B state quenching effects with SF_6 additive in a nitrogen laser.⁹ The effects of a hypothetical B state quencher on the laser pulse length, should one become available, is presented in Fig. (16) as a function of the effective B state decay time.

(E) PARAMETRIC STUDIES

Comprehensive parametric studies for three proposed laser configurations were carried out and the results are presented in Figs. (17-31).

All cases utilize a double Blumlein excitation device 100 cm long. The first two cases model a laser with a cross section of 1 cm x 1 cm and the third

Fig. (16)

case models a cross section of 0.5 cm x 2 cm with the long dimension oriented along the applied electric field. The first case for the square cross-section laser assumes optimistic values for the voltage risetime and laser tube inductance. The third case of rectangular cross-section is based on conservative choices for these parameters appropriate to that geometry.

For the first case, Fig. (17) shows the variation of laser characteristics as a function of transmission line impedance. Both the power and total energy of the laser are strong functions of this parameter. The enhanced output at decreasing line impedance is due to the fact that a lower circuit impedance will allow a lower plasma resistance to be reached before the plasma E/P decreases. The lower plasma resistivity implies a higher electron density and a correspondingly higher excitation rate for the upper laser level. Although the laser performance becomes more attractive as the line impedance decreases (keeping a fixed voltage), a lower limit on Z is set by the maximum electric stress consistent with a desired PFL lifetime. The assumed value of dielectric stress (1 kV/mil) in all three cases modeled when this parameter is not explicitly varied is consistent with high repetition rate operation (10^8 shot life). Similarly, the variation of laser output with voltage shown in Fig. (18) indicates the advantages of operating at higher voltage. The maximum voltage is again limited by electric stress.

The variation of laser characteristics with pressure is presented in Fig. (19). The single pulse energy peaks at 46 Torr while the pulse length and efficiency decreases with the nitrogen pressure. Fig. (20) indicates the importance of minimizing the laser tube inductance. The lower limit on tube

Parametric Behavior of 1 cm x 1 cm x 100 cm Laser

Standard Conditions $p = 90$ Torr

$$z = 0.1 \text{ } \Omega$$

$$L = 0.3 \text{ nh}$$

$$\tau_r = 15 \text{ ns}$$

$$V = 18 \text{ kV}$$

The parameters which are held fixed in each parametric analysis are the standard conditions

$$P = \text{Laser Power (Mw)}$$

$$E = \text{Laser Energy (mJ)}$$

$$\eta = \text{Efficiency}$$

$$= \frac{\text{Laser Energy}}{\text{Electrical Energy Dissipated}}$$

$$\tau = \text{Pulse Width (FWHM)(ns)}$$

LINE IMPEDANCE

1 cm x 1 cm x 100 cm

Fig. (17)

VOLTAGE

1 cm x 1 cm x 100 cm

Fig. (18)

N₂ PRESSURE

1 cm x 1 cm x 100 cm

Fig. (19)

TUBE INDUCTANCE

1 cm x 1 cm x 100 cm

Fig. (20)

VOLTAGE RISE TIME

1 cm x 1 cm x 100 cm

Fig. (21)

inductance is set by the minimum tube insulator length required to prevent insulator breakdown. Reductions significantly below the values chosen in this case do not appear feasible. The importance of achieving fast voltage risetimes is shown in Fig. (21). The 15 ns risetime chosen for this calculation is a desirable goal but further decreases in risetime are of little significance because the laser tube inductance then becomes the limiting factor.

The same set of calculations was performed for the square cross section laser with more conservative values for tube inductance and voltage risetime. The results of these calculations are shown in Figs. (22-26). Although there are quantitative differences between this case and the previous case, the same qualitative variations were obtained and thus the same conclusions may be drawn. This more conservative choice of parameters leads to a reduction in laser output energy by more than 30%.

Similar calculations for the third case, that of a discharge with a rectangular cross section are presented in Figs. (27-31). This geometry leads to an increase in energy output over that of the first case by about 15%.

These parametric studies lead to the conclusion that the maximum voltage and minimum transmission line impedance consistent with dielectric lifetime should be used and that voltage risetime and tube inductance should be minimized to the point indicated by the model.

(F) SKIN DEPTH

There have been many reports in the nitrogen laser literature of plasma constrictions which cause the laser radiation to be emitted only over the

Parametric Behavior of 1 cm x 1 cm x 100 cm Laser

Standard Conditions $p = 90$ Torr

$$z = 0.1 \text{ } \Omega$$

$$L = 0.5 \text{ nh}$$

$$\tau_r = 30 \text{ ns}$$

$$V = 18 \text{ kV}$$

The parameters which are held fixed in each parametric analysis are the standard parameters

P = Laser Power (Mw)

E = Laser Energy (mJ)

η = Efficiency

$$= \frac{\text{Laser Energy}}{\text{Electrical Energy Dissipated}}$$

τ = Pulse Width (FWHM)(ns)

LINE IMPEDANCE

1 cm x 1 cm x 100 cm

Fig. (22)

VOLTAGE

1 cm x 1 cm x 100 cm

Fig. (23)

N₂ PRESSURE

1 cm x 1 cm x 100 cm

Fig. (24)

TUBE INDUCTANCE

1 cm x 1 cm x 100 cm

Fig. (25)

VOLTAGE RISE TIME

1 cm x 1 cm x 100 cm

Fig. (26)

Parametric Behavior of 0.5 cm x 2 cm x 100 cm Laser

Standard Conditions $p = 90$ Torr

$$z = 0.2 \text{ } \Omega$$

$$L = 1.2 \text{ nh}$$

$$\tau_r = 30 \text{ ns}$$

$$V = 36 \text{ kV}$$

The parameters which are held fixed in each parametric analysis are the standard parameters

P = Laser Power (Mw)

E = Laser Energy (mJ)

η = Efficiency

$$= \frac{\text{Laser Energy}}{\text{Electrical Energy Dissipated}}$$

τ = Pulse Width (FWHM)(ns)

LINE IMPEDANCE

0.5 cm x 2 cm x 100 cm

Fig. (27)

VOLTAGE

0.5 cm x 2 cm x 100 cm

Fig. (28)

N₂ PRESSURE

0.5 cm x 2 cm x 100 cm

Fig. (29)

TUBE INDUCTANCE

0.5 cm x 2 cm x 100 cm

Fig. (30)

VOLTAGE RISE TIME

0.5 cm x 2 cm x 100 cm

Fig. (31)

periphery of the discharge cross-sectional area. A skin depth phenomena could be responsible for such discharge and laser behavior.

A conducting medium has a characteristic time associated with the diffusion of gradients in current (equivalently magnetic or electric fields) through the medium. For a fixed time the current can diffuse a characteristic distance in the medium. Because the plasma current is being fed from the edges of the line, Fig. (32), the skin depth problem translates into the following question. Can the discharge current and hence the laser excitation propagate the full width of the discharge in the direction perpendicular to the applied electric field within the breakdown time of the gas. The consequence of this effect cannot be simply estimated since the plasma conductivity is a rapidly varying function of time and the laser output cannot be simply related to the current flow in the medium. In order to treat this problem, the kinetic model described above was extended to include the time dependent diffusion of current in the laser medium. The diffusion was assumed to be one-dimensional in the direction perpendicular to the applied electric field and was assumed to obey the current diffusion equation.

$$\nabla^2 \left(\frac{J}{\sigma} \right) = \mu_0 \frac{\partial J}{\partial t} \quad (1)$$

This diffusion equation was approximated with finite differences by dividing the discharge width into ten segments. The full set of kinetic equations describing laser action was then solved for each of the resulting discharge

SKIN EFFECT - CURRENT FLOW

Fig. (32)

segments. In the hope that the skin depth could be counteracted by appropriately shaping the electrodes, the spacing between the electrodes was allowed to be a function of the distance transverse to the electric field.

The results of these calculations are presented in Figs. (33-35). The laser parameters chosen are the same as those used in Section (B). A double Blumlein discharge is assumed and the problem is solved for one-half of the discharge width. The laser power and energy per segment as a function of transverse distance x measured from the outer edge of the discharge is plotted in Fig. (33). For plane parallel electrodes there is a three-fold variation in laser output across the discharge. If a very slight convex shape is added to the electrodes, the laser output can be made uniform. The shape used to achieve this uniformity is shown in Fig. (34). It involves a change of only about 2.5% in the electrode spacing between the center and the edge. Careful examination of the laser characteristics for the convex electrodes shows that the gas breaks down in the center first, followed by the propagation of the breakdown toward the outer edges of the discharge region. The propagation of breakdown is accompanied by propagation of laser excitation but the spatial uniformity of laser emission is achieved at the expense of a small temporal non-uniformity, as shown in Fig. (35). However, note that even in the case of uniform electrodes the peak in laser output occurs earlier in the center of the discharge. This effect is only exaggerated by the shaping of the electrodes. Whether or not shaping of the electrodes to improve spatial uniformity in laser output at the expense of temporal uniformity is a viable solution to the skin depth problem, depends upon the application being considered.

NON-UNIFORM LASER EMISSION DUE TO SKIN EFFECT

Fig. (33)

UNIFORM ELECTRODE PROFILE

Fig. (34)

Plane Electrodes

Shaped Electrodes

TEMPORAL EFFECT OF ELECTRODE SHAPING ON LASER PULSE

Fig. (35)

(G) TRANSIT TIME ABSORPTION EFFECTS

So far, the calculations have ignored the finite time required for laser energy to propagate along the length of the laser. Since the laser medium becomes absorptive following the termination of lasing action, a laser which is excited uniformly in time along its entire length may have a portion of the available laser energy absorbed before it can propagate to the end of the device. This fact becomes important for lasers where the one-way transit time for light approaches the inversion lifetime. This effect can be counteracted with traveling-wave (TW) excitation by arranging the electrical excitation pulse to propagate along the length of the device with the velocity of light. Traveling-wave excitation can be approximated in practice by segmenting the laser and appropriately phasing the excitation of each segment. This approach was incorporated into the model to determine the maximum length of an individual segment and the timing requirements between segments needed to minimize self-absorption. The model divided a laser into segments along the optic axis. The total laser output was integrated along the length of the device (summed over the sub-segments) with the local power output evaluated at the appropriate retarded time. The results of this modeling are presented in Figs. (36) and (37). Fig. (36) shows the resulting output characteristics of a non-TW excited laser as a function of the module length assuming single pass energy extraction in one direction only. The finite propagation time for the laser pulse and the eventual absorption of the laser medium causes the laser energy and pulse length to saturate as the length of the laser module is increased. The calculation indicates that a module length of 2. meters is capable of delivering 85% of its available energy for the conditions modeled. If the laser is

LASER OUTPUT AS A FUNCTION OF LENGTH - NON-TW DEVICE

Fig. (36)

Fig. (37) LASER OUTPUT DEPENDENCE
ON INDIVIDUAL MODULE
TIMING ACCURACY

operated at lower pressures where the pulse length is longer, an even longer module would be possible.

Timing constraints of excitation pulses applied to two modules was computed for two 1 m long modules each excited uniformly in time, but with a variable delay time between them. The results are shown in Fig. (37) where the energy and power output of the laser is plotted as a function of the delay time. In this figure a positive delay time refers to the first module being fired before the second and the optimum delay timing is $\tau_d = 3.3$ ns which is to be the transit time for light through one of the modules.

The calculation indicates that a switch timing jitter of ± 2 ns is not unreasonable. Note that for $\tau_d > 3.3$ ns, a total of 12 mJ will appear at the output. However, if an oscillator is used to control the beam quality of an amplifier system, absorption in the first amplifier for $\tau_d > 3.3$ ns will prevent the penetration of the oscillator pulse through the first amplifier and a portion of the emission from the second amplifier module will therefore not be controlled by the oscillator. Fig. (37) includes only that portion of the output energy which is capable of being controlled by an input oscillator signal. For this reason the calculation shows that the controlled energy output decreases with the increasing τ_d for values of τ_d greater than optimum.

II. Energy Extraction

The nitrogen laser has two applications in LIS; as a dye laser pump source to generate tunable radiation, and as a photoionization source for schemes which apply this technique. For the former application good beam quality in the nitrogen laser spatial beam dimension normal to the dye laser optic axis, Fig. (38), is most important while for both applications uni-phase near-diffraction-limited beams which can be propagated and manipulated would be useful. These requirements imply the need to achieve mode control a feature which has heretofore not been demonstrated for this system.

Mode control for this laser and other transient very high gain systems is difficult to achieve because the large specific gains (300 dB/m) and short inversion lifetimes ($\lesssim 10$ ns) make conventional resonators useless for high power devices. All nitrogen lasers operate as single-pass or double-pass superfluorescent³⁴ (amplified spontaneous emission) devices in which the beam divergence is determined primarily by the geometry of the cavity Fig. (39). For a slit beam of width $w = 0.5$ cm, the laser length L required to produce an angular divergence equal to three times the diffraction limit is $L \approx 20$ meters. The essence of mode control in the nitrogen laser is therefore the suppression of superfluorescence and achievement of efficient extraction of the available energy with the desired beam qualities.

The most attractive scheme for achieving mode control is to use a MOPA (master-oscillator power-amplifier) configuration in which a mode-controlled oscillator is used to drive a series of amplifiers Fig. (40). The over-riding consideration which determines the oscillator characteristics and oscillator-

BEAM DIVERGENCE OF SUPERFLUORESCENT LASER

Fig. (39)

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N₂ MOPA SYSTEM

Fig. (40)

amplifier synchronization requirements is the need to slave the amplifiers to the oscillator. These considerations will be developed below by first considering the magnitude of the superfluorescence effects, its implications for the various components in the oscillator-amplifier chain and finally the configuration and parameters of the requisite oscillator.

(A) SUPERFLUORESCENCE

The oscillator requirements are set by the need to overcome superfluorescence. We therefore seek a condition on the oscillator input flux required to force the amplifier to radiate its energy into the stimulated emission field provided by the oscillator rather than superfluorescence. It is clear that the above condition will result if at the entrance to the first amplifier the stimulated emission rate due to the oscillator field on each inverted rotational transition exceeds the total rate of spontaneous emission from the upper level of that transition.

$$\sigma \left(\frac{I_0}{h\nu} \right) > \frac{1}{\tau_s}$$

$$I_0 > I_s = \frac{h\nu}{\sigma\tau_s} \quad (2)$$

In Eq. (2) I_0 is the injected oscillator intensity, I_s the saturation intensity ($\epsilon_s = \frac{h\nu}{\sigma}$ the saturation energy), τ_s the spontaneous emission lifetime³⁵ and σ the stimulated emission cross-section. At low pressures where the line is Doppler broadened: $I_s \approx 110 \text{ w/cm}^2$, $\epsilon_s \approx 4.5 \times 10^{-6} \text{ J/cm}^2$.

With the addition of the helium buffer gas required for gas transport considerations, the values of I_s and ϵ_s will increase as the linewidth of the transition increases. The collision broadening of the C $\rightarrow$ B transition by He is not known but at sufficiently high He pressures (probably a few hundred Torrs) I_s and ϵ_s will be proportional to p_{He} .

The condition imposed on the oscillator flux in Eq. (2) is an over estimate of the required amplifier input flux to suppress superfluorescence. Since spontaneous emission is emitted into a 4π solid angle and only a small fraction is directed into the solid angle of the laser aperture, a lower limit on the requisite oscillator flux is set by the requirement that the injected oscillator flux build up to saturation more rapidly than the superfluorescence. To estimate the magnitude of superfluorescence we use the results of Kogelnik and Yariv³⁶ for the total spontaneous emission power emitted between the frequency range ν and $\nu + \Delta\nu$, passing through area A and radiated into a solid angle Ω in the limit of no saturation.

$$P = 2h\nu \Delta\nu \frac{n_2}{n_2 - n_1} \frac{g_2}{g_1} (e^{aL/\cos\theta} - 1) \frac{A\Omega}{\lambda^2} \quad (3)$$

For a cavity with non-reflecting walls we will assume that the amplified spontaneous emission will begin to saturate the medium when

$$I = \frac{P}{A} > I_s = \frac{h\nu}{\sigma\tau_s} \quad (4)$$

Equations (3) and (4) predict the gain length ℓ required for the buildup of superfluorescence in this approximation.

Figure (41) gives the gain distribution $\alpha(j)$ at peak gain among the P branch rotational transitions for the optimum laser parameters of case two Figs. (22-26). The gains were calculated assuming a Boltzmann distribution within the rotational manifold and an equipartition of the inversion between the three $3\Pi_{0,1,2}$ multiplets.

$$\alpha(j) = \sigma \Delta n(j) = \sigma [n_C(j) - n_B(j-1)]$$

$$\Delta n(j) / \sum_j \Delta n(j) = \frac{2}{3} \frac{hcB}{kT} 2^m (2j+1) \exp - \left[\frac{hcB}{kT} j(j+1) \right] \quad (5)$$

The factor m is 0 or 1 depending upon whether j is odd or even. The peak values of gain shown in Fig. (41), which were calculated in the Doppler limit, are comparable to experimentally determined values.³⁷ Equations (3), (4) and (5) give the gain length $\ell(j)$ required for onset of super-fluorescence from each transition. The result is shown in Fig. (42). It is obvious that N_2 lasers with high specific gains ($\alpha \gtrsim 0.2 \text{ cm}^{-1}$) achieve greater than 80 percent extraction of the available energy for single pass lengths greater than $\sim 60 \text{ cm}$ and double path lengths of $\sim 30 \text{ cm}$.

For an oscillator amplifier system the oscillator begins to dominate the amplifier emissions when the oscillator input flux $I_0(j)$ on each transition just saturates the transition at the same position $\ell(j)$ in the amplifier that

ROTATIONAL GAIN DISTRIBUTION IN N_2

Fig. (41)

PATH LENGTH REQUIRED BY INDIVIDUAL
 N_2 LASER TRANSITIONS TO REACH SUPERFLUORESCENCE

Fig. (42)

defines the onset of superfluorescence. Figure (43) gives the values of the normalized oscillator flux $I_o(j)/I_s$ required at the cross-over condition. The total oscillator power on all transitions for the condition of Fig. (43) is merely $\sum_j I_o(j) = 3 \times 10^{-3} I_s \approx 0.3 \text{ watts/cm}^2$. For an oscillator pulse 10 ns long the laser energy required is only 3 nJ/cm^2 , an almost insignificant quantity. Many orders of magnitude more energy can be obtained from a small nitrogen-laser oscillator so the energy requirement to suppress superfluorescence should be easy to satisfy.

(B) OSCILLATOR-AMPLIFIER SYNCHRONIZATION

While the results indicated above demonstrate that very modest oscillator fluxes will force the amplifier to radiate into the oscillator field, suppression of superfluorescence will also require that the amplifier medium becomes inverted only in the presence of oscillator flux at all points along the medium.

In the case where true traveling-wave excitation of the amplifier can be achieved, the above requirement translates simply into the need to delay the excitation of the amplifier with respect to the arrival of the oscillator pulse in the manner shown in Fig. (44). The requisite delay τ_d is determined by two conditions; first an adequate oscillator flux $I_o(\tau_o)$ at the entrance of the amplifier in accordance with the previous considerations of superfluorescence and second the accommodation of the timing jitter between the oscillator and amplifier.

For TW excitation of the amplifier therefore, the oscillator pulse length τ_{osc} must satisfy $\tau_{osc} > \tau_i + \tau_d = \tau_i + \tau_o + \tau_j$ to extract all the energy

Fig. (43)

OSCILLATOR AMPLIFIER SYNCHRONIZATION
TW AMPLIFIER

Fig. (44)

OSCILLATOR AMPLIFIER SYNCHRONIZATION
NON-TW AMPLIFIER

Fig. (45)

in the amplifier where τ_j is the switch jitter and τ_i the time the amplifier is inverted.

If the amplifier is excited simultaneously along its entire length, then the oscillator pulse must fill the entire amplifier before it is excited. This case is illustrated in Fig. (45). The oscillator pulse length must now satisfy $\tau_0 > \tau_i + \tau_0 + \tau_j + L/C$ for efficient energy extraction. These requirements indicate that amplifier modules which are not TW excited must be no longer than about 2 meters and switch jitter of 1-2 nanoseconds are desired.

(C) MODE-CONTROLLED OSCILLATOR

The oscillator is the key component in the scheme to achieve mode-control. It must provide a low divergence mode-controlled beam with sufficient single pulse energy to dominate the output characteristics of the amplifier. For this application unstable resonator optics are best suited to generate single mode low divergence beams from cavities with very large fresnel numbers ($200 < N < 1000$) characteristic of nitrogen laser oscillators.

Unstable resonators have the desirable property of providing near diffraction-limited beams independent of the cavity aperture dimension and therefore fresnel number. Recent numerical computations³⁸ indicate that an unstable resonator will always oscillate in a single mode and verifies the above assertion for fresnel numbers $N < 60$. A striking experimental verification of these characteristics has been provided by the report of near diffraction limited beams from a two dimensional unstable resonator at $\lambda = 1.06 \mu$ with a fresnel number of $N \approx 56,000$.³⁹ These properties

of the unstable resonator are ideal for applications in a nitrogen oscillator provided certain gain conditions are satisfied. Because the characteristics of the N_2 laser medium and the dye pumping requirements both favor rectangular beam geometries, a two dimensional unstable resonator will be considered with the parameters shown in Fig. (46). The double-slit output beam pattern could either be combined in the near field or propagated into the far field to provide a suitably matched input beam to feed the amplifiers, Fig. (47).

In the context of the N_2 unstable resonator oscillator, certain requirements are placed upon the output coupling fraction, cavity length, and medium optical gain in order to satisfy the mode control function. These parameters are determined to first order by the need to have sufficient round trip transits within the limited inversion lifetime to build-up a definite cavity mode and sufficient gain to achieve saturation of the oscillator medium.

The cavity length L is set by the number of round trip transits required to establish a stationary mode amplitude and phase distribution within the lifetime of the inversion. Numerical computations³⁸ indicate that only 5-10 round trip transits are required for the mode to stabilize. The existence of single mode solutions in unstable resonator configurations found in the results of Ref. 38 can be understood in the following way. In the geometric limit the round trip fractional power loss for the modes of a two dimensional unstable resonator can be approximated by the expression⁴⁰ below in which m is the resonator magnification.

$$f_n = 1 - \frac{1}{|m^{2n+1}|} \quad (6)$$

$$\text{Magnification } m = a_1/a_2$$

$$\text{Fresnel Number } N = a_1^2/L\lambda$$

$$\text{Equivalent Fresnel Number } N_{eq} = \frac{m-1}{2m^2} N$$

$$\text{Output Coupling } C = 1 - 1/m$$

TWO DIMENSIONAL UNSTABLE RESONATOR

Fig. (46)

OSCILLATOR BEAM SHAPING TO FEED AMPLIFIERS

Fig. (47)

The discrimination between the two lowest order modes $n = 0$ and 1 after q roundtrip transits is given by $r = (f_1/f_0)^q$ and is a function of the magnification m . For $q = 10$ and $m < 2$, $r < 3.6 \times 10^{-3}$. The higher order modes should therefore contain less than 1% of the total energy. If the inversion lifetime of the medium is τ_i , the maximum cavity length is therefore set by the condition

$$L_m \approx \frac{c\tau_i}{2q}$$

The requirement for oscillator pulses which are longer than the amplifier inversion time favors operation of the oscillator at low N_2 pressures. If we operate the oscillator at $P_{N_2} \approx 15$ Torr, the inversion lifetime from the parametric analysis is $\tau_i \approx 10$ ns. To obtain 10 round trip transits requires a cavity length $L_m = 15$ cm.

The second requirement for the oscillator to satisfy the mode-control function is to provide adequate energy to drive the amplifier on as many transitions as possible. To achieve maximal energy extraction, the specific gain of the oscillator medium must be adequate to allow buildup of oscillations from noise to saturation within the lifetime of the inversion. The requisite buildup time τ^* from noise to saturation can be estimated from Eq. (3) as

$$\begin{aligned} \tau^* &\approx \frac{1}{(\alpha' - \beta)c} \ln \left[\frac{A}{2h\nu\Delta\nu} \frac{n_2 - n_1 \frac{g_2}{g_1}}{n_2} I_s \right] \\ &\approx \frac{23}{(\alpha' - \beta)c} \end{aligned} \quad (7)$$

where $\alpha' = \alpha(\frac{\ell}{L})$ and β is the distributed cavity loss parameter. To achieve maximal energy extraction, $\tau^* < \tau_i$. This condition implies a minimum specific gain α given by

$$\alpha' - \beta > \frac{23}{c\tau_i} \quad (8)$$

For given pumping conditions, Eq. (8) determines those rotational transitions from which energy will be extracted. For an oscillator operated at $P_{N_2} \approx 15$ Torr where $\tau_i \approx 10$ ns, $\alpha' - \beta > 0.08 \text{ cm}^{-1}$. The specific gains $\alpha(j)$ under the above laser conditions are approximately one half the value of the gains presented in Fig. (41). If a cavity with $\ell = 13$ cm, $L = 15$ cm and $m < 2$ is utilized, energy will be extracted from rotational transitions $3 < j < 17$, and will contain greater than 80% of the available energy in the rotational distribution. From the modeling results shown in Fig. (29) the maximum extractable energy from the 15 cm long oscillator operated at 15 Torrs on all lines is $E = \sum_j E(j) \approx 600 \text{ } \mu\text{J}$ per cm^2 of aperture. The outer-most lines $j = 3$ and 17 contain about 4% of the total energy or $24 \text{ } \mu\text{J}/\text{cm}^2$. This is five times the low pressure saturation energy.

(D) INFLUENCE OF He DILUENT

While most of the preceding considerations have been based upon lasers operating at low pressures and pure N_2 gas for which numerical and experimental data exists, the analysis of gas transport requirements for high average power devices presented in IV indicates the need for He diluent to limit the temperature rise. Although there is evidence^{32,41} that He, at partial pressures up to one

atmosphere, does not alter the gross amount of energy which is emitted from the nitrogen lasers, the presence of helium could alter the characteristics of mode-controlled energy extraction by a reduction of gain through line broadening, and by thermalization effects among the various population distributions during energy extraction.

The detailed distribution of population in the C and B states--among the three spin orbit multiplets $^3\Pi_{0,1,2}$, between the rotational levels within each multiplet, and among each Λ doublet--is not known, even under conditions of low pressures. Parks⁴² reports roughly a 7:4:3 intensity ratio between the three spin multiplets in stimulated emission while Andersson and Borgstrom²⁰ report roughly an equipartition of energy. Although the rotational transitions have been analyzed⁴³⁻⁴⁶ for wavelength content in stimulated emission, no accurate intensity distribution study has been reported. Furthermore, disagreement still exists in the literature concerning whether one or both components of the Λ doublet are stimulated. Since energy extraction in N_2 is very sensitive to the magnitude of the gain and therefore the level populations, collisions which can alter the level distributions are important. Besides this influence on the static value of the gain distribution, collisions can influence the gain distribution dynamically by a cross-coupling between the levels during optical extraction as in the case of the CO_2 laser where one or a few transitions are responsible for draining the entire manifold. A dynamical coupling effect promoted by He would perhaps simplify energy extraction considerations by reducing the number of frequencies which the oscillator must generate. But unlike the case of CO_2 one must still contend with the problem of superfluorescence on lines which are not being stimulated directly. The

influence of these collision effects depends upon the magnitude of collision cross-relaxation times in relation to the pulse length. Unfortunately no information of this kind exists which would allow reasoned estimates.

The second effect of He which alters the gain, that of collision broadening, is also unknown. In the oscillator, gain reduction would reduce the number of potential transitions which can be utilized to drive the amplifier. In the amplifier line broadening will decrease the gain and increase the saturation flux. These two effects influence both the process of amplification and superfluorescence.

III. Electrical Design

Line impedance, tube inductance and voltage risetime are important for nitrogen lasers. Although there is quantitative uncertainty concerning the code predictions, there is ample experimental and computational information to indicate the desirability of minimizing these three parameters for efficient laser performance. While the electrical design of the laser-PFL structure must strive to achieve these desired characteristics, it must also satisfy the requirements placed upon the electrical design by gas flow and high average power dissipation. The configuration and design of the laser tube, PFL, and switch necessary to meet all the above requirements simultaneously will be explored below.

(A) LASER TUBE

The overall configuration of the laser tube is determined primarily by the direction of gas flow. The two possible classes of configurations correspond to gas flow parallel to the electric field (through porous electrodes) and perpendicular to the electric field (through porous PFL structures).

(1) Flow Parallel to Electric Field

Consider first the case for flow parallel to the electric field, Fig. (48). In this case the important considerations are the tube inductance and insulator requirements. For this configuration the inductance L of the laser tube is a sum of the two inductances; L_i associated with the area A_i between the discharge and the ground plane and the inductance L_d of the discharge area A_d itself. In Eq. (9) L has units of nanohenries if A is in cm^2 and the tube length ℓ is in

LASER TUBE DESIGN
FLOW PARALLEL TO ELECTRIC FIELD

Fig. (48)

$$L = L_i + L_d = \frac{0.13}{\ell} (A_i + \frac{A_d}{3}) \quad (9)$$

meters. L_i assumes a negligible reluctance in the magnetic flux path outside the current return path which is reasonable for devices with discharge lengths ℓ much greater than the transverse dimensions and L_d assumes a uniform current density distribution. For a double Blumlein device in which Fig. (48) represents one symmetrical half, the inductance L is the value for one side.

For a given discharge geometry $w \times h$, the minimum tube inductance is determined by the minimum insulator length h_i required to prevent insulator surface breakdown. Since the insulator is electrically in parallel with the gas discharge, the insulator voltage is set by the discharge voltage which, although dynamically limited by gas breakdown, can reach about twice the static breakdown voltage transiently. The laser code indicates that a value of $h_i = 1.3 h$ results in a ratio of current density of 10^{-7} at the insulator surface as compared to the center of the discharge. This large ratio of current densities is due to the very sensitive dependence of the plasma current e-folding time on E/P . This fact indicates that under uniform field conditions, an insulator height $h_i > 1.3 h$ will allow gas discharge breakdown to beat insulator surface breakdown. Using this value of h_i , the minimum tube inductance for discharge dimensions of 1 cm x 1 cm and 1/2 cm x 2 cm are approximately 0.4 and 0.8 nanohenries per meter of length.

A resistive coating on the insulator surface is required for field grading and charge dissipation. In the absence of such a coating, the electric field on the insulator surface would be quite non-uniform due to the proximity of the

ground plane. Ionization buildup at points of high local fields can thus occur. Furthermore the accumulation of charge from the plasma and UV irradiation from the discharge could further distort the field and accelerate breakdown by secondary electron emission. The resistivity of the coating must be low enough to charge the capacitance of the coating (with respect to the ground plane) in a small fraction of the laser tube voltage risetime. For risetimes of interest in N_2 laser devices, a resistivity of about 10^4 ohms/cm² is required. Aquadag looks promising for this application because it has the requisite resistivity and also has a low secondary emission coefficient.⁴⁷

The insulator itself should be an inorganic refractory material such as alumina which would be resistant against deterioration from exposure to UV radiation. The insulator and the entire laser tube structure will have to be thermally cooled for sustained operation at high average power dissipation conditions.

(2) Flow Perpendicular to Electric Field

For large aspect ratio discharges where the short dimension is perpendicular to the electric field, flow across the field entails shorter distances across the plasma. The insulator structure and resistive coating requirements however become more complex since the gas must now pass through the PFL. Multiple low inductance electrical connections must be made between the ground planes on opposite sides of the discharge channel to form a porous PFL structure. Two such configurations were analyzed. Fig. (49) shows an insulated ground return path structure composed of multiple rods and Fig. (50) shows an uninsulated screen ground return path design. Consider the rod structure first.

LASER TUBE DESIGN
INSULATED GROUND RETURN PATH
FLOW PERPENDICULAR TO ELECTRIC FIELD

Fig. (49)

LASER TUBE DESIGN
UNINSULATED GROUND RETURN PATH
FLOW PERPENDICULAR TO ELECTRIC FIELD

Fig. (50)

The capacitance from the resistive coating to the inner rods depends upon the thickness and diameter of the insulating tube. The capacitance in this geometry will be high, and the resistive coating must therefore have a low surface resistance to hold the electric fields uniform during the rise-time of the voltage pulse. Enough electrical energy is then dissipated in the coating to require liquid cooling. The fringing fields which extend outward from the resistive coating on the side opposite the discharge, and which scales with the length of the rods, would require the gas to flow a longer distance between successive pulses to clear the fringing fields at the downstream electrodes. The downstream fringing fields can be eliminated by using only a single sided line with rods upstream of the flow but at the expense of asymmetry and an increase in the line impedance.

In the uninsulated screen geometry, the insulators are subjected to only half the voltage experienced in previous examples because the ground plane will nominally assume a voltage which is one half the voltage appearing between the electrodes. A resistive coating on the electrodes however cannot be used with a Blumlein circuit since in this insulator geometry the charging voltage also appears across the insulator. The charging voltage, which lasts three orders of magnitude longer than the pulsed voltage, would cause excessive energy dissipation in the resistive coating. Without a resistive coating the fields along the insulator will not be uniform and the criteria for insulator length developed before does not apply. The necessary insulator length and therefore the minimum gas flow distance and tube inductance will have to be determined experimentally.

(B) PULSE FORMING LINE

(1) Geometry and Risetime

Many different PFL designs have been used for nitrogen laser excitation. Historically the excitation source has evolved from a PFL consisting of multiple cables through rectangular lines with single or multiple switches and then to shaped (parabolic⁴⁸ and trapezoidal¹⁸) lines designed specifically to produce TW excitation from a single switch. There is no definitive information at the present time to prefer any one geometry over another. With few exceptions, most lines which have been used for laser excitation utilize switches with sufficient inductance to cause the voltage risetime to exceed the line one-way electrical transit time substantially. This fact implies that voltage reflections from different parts of the line will influence and modify the time history of the voltage appearing at the laser channel. The voltage wave at the laser channel will therefore depend upon the exact geometry of the switch and PFL in some complicated way which would require a two-dimensional PFL code to model. Such an analysis, which was not done as part of this study, would be useful to clarify the requirements for TW excitation and in determining the exact dependence of PFL geometry on laser output. This question of PFL shape is important from the standpoint of maximizing total laser efficiency since considerable energy remains in the line after the laser has terminated.

Irrespective of the exact PFL geometry, the concept of the double or folded Blumlein introduced by Bastings et al.,¹⁸ and shown in Figs. (7,51) is preferred for high power lasers. This geometry has the advantage of providing half the impedance of a single line and symmetrical current delivery to the discharge which reduces possible skin depth effects by a factor of two.

DOUBLE FOLDED BLUMLEIN

Fig. (51)

The Blumlein circuit, whether single or double, is essentially an L-C reversal circuit which develops a voltage equal to the initial charge voltage across a matched load and twice the initial charge voltage to an open circuit as in the case of the N_2 laser prior to gas breakdown. In the normal regime of switch inductance where the reversal time of the Blumlein is several times the one-way line transit time, the charging of the laser channel can be approximated by a lumped line capacitance C . For this approximation the equivalent linear risetime for full voltage reversal (open circuit voltage risetime) is given by $2\sqrt{L_s C}$ where L_s is the switch inductance.

(2) Dielectric and Edge Grading

The desire for minimum line impedance consistent with a fixed life (number of pulses) dictates a dielectric with a maximum value of $\sqrt{\epsilon_r} E_{op}$ where ϵ_r is the relative dielectric constant and E_{op} the allowable operating field. Of all the dielectrics considered which included gases, liquids and solids, Mylar or Kapton seem to be the best material from the above viewpoint and from considerations of suitability for high repetition rate service. The life of Mylar in pulsed service varies inversely as the 7.5 power of the electric field, starting from a life of 10^3 pulses at 1.75 MV/cm stress to 10^8 pulses at 0.38 MV/cm (0.96 kV/mil). The latter value of stress was used to determine the line impedance in the laser computations of Section I.

The weak point of stripline insulation is actually at the periphery of the PFL, where the usual field enhancement at the edges of a conductor causes the field to exceed that in the dielectric. Field enhancement can have several serious effects. First, flashover around the edge of the line insulation is probable if the edge fields are not reduced. Second, electric fields in air

adjacent to the edge will greatly exceed the corona starting voltage of 100 volts/mil unless special precautions are taken. High levels of corona will rapidly deteriorate organic insulation like Mylar and it is important for this same reason to exclude air from between the layers of insulation within the line itself. The edge of the PFL conductor therefore needs careful treatment in devices intended for high repetition frequencies and long life.

One solution to reduce edge fields is to gradually increase the thickness of the dielectric near the conductor edge and simultaneously increase the conductor spacing to reduce the electric field to allowable levels, Fig. (52). Another solution is to use resistive grading at the edges of the line to gradually reduce the voltage across the line insulation in order to keep the fields below the corona threshold, Fig. (53). For transient voltages on the line, the resistive layers act as distributed RC filters whose resistance must be set at an appropriate value to provide an RC time constant which will allow the distribution of the voltage along the layer on a time scale shorter than the time scale of the voltage change. The voltage changes generated by Blumlein voltage reversal, which occurs on the order of tens of nanoseconds, requires a resistivity on the order of 10^4 ohms/cm². This is the low resistance area of Fig. (53). Voltage variations generated by charging of the line from the power supply, which occurs on a time scale of 10 microseconds or less, requires a resistivity of 10^7 ohms/cm². This is the high resistance area on the line.

An additional mechanism of dielectric failure is dielectric heating at high average power operation due to various dielectric losses. Estimates of

✓

Fig. (52)

RESISTIVE EDGE GRADING

Fig. (53)

the loss processes for Mylar which include dielectric relaxation, I^2R losses and a finite dissipation factor indicates that about an upper limit of 30% of the energy stored in the line can be dissipated in the dielectric. For the 0.5 cm x 2 cm aperture laser represented by case three of Section I, approximately 0.2 watts/cm² will be dissipated in the dielectric for every kilohertz increase in the pulse repetition rate.

An 0.1 Ω PFL for a nitrogen laser with a 0.5 cm x 2 cm cross-sectional discharge area would contain a total thickness of 18 mils of Mylar. For nine individual layers each 2 mils thick, the steady-state temperature rise at a prf of 2 kHz is less than 30°C, assuming heat transfer to ambient temperature PFL conductor surfaces. A better dielectric for higher power dissipation would be Kapton which seems to have the same electrical properties as Mylar at room temperature but maintains these properties at higher temperatures.

(C) SWITCHING

The discrepancy between the code predictions and reported laser characteristics discussed in I(C) leaves the question of switch requirements unclear. Table I indicates similar performances from lasers driven with thyratrons and single or multiple plasma switches although it is not clear in these examples whether other device parameters are equivalent. The major difference between thyratrons and plasma switches lies in the fact that plasma switches have the potential of being developed to be much less inductive if low switch inductance appears desirable. The advantage of thyratrons rests in their proven capability to operate at multi-kilohertz rates. A plasma switch does not exist commercially and must undergo some development to operate reliably in this region.

Large hydrogen thyratrons like the HY-5 or the KU275C are rated at 5 kAmps peak current and have inductances on the order of 50 nh. The total charge switched by a Blumlein shorting switch (two lines, complete reversal) is $Q = 4 \text{ CV}$. For a 0.5 cm x 2 cm x 100 cm laser driven by a $Z = 0.1 \Omega$ rectangular Blumlein, the total charge transfer is $Q \approx 4 \times 10^{-3}$ coulombs. The equivalent linear voltage risetime for this circuit is $\tau_r = 2\sqrt{LC} = 155/\sqrt{n} \text{ ns}$ and the total peak current is $I_p = Q/\tau_r \approx 2.6\sqrt{n} \times 10^4$ amps where n is the number of thyratrons used. Six thyratrons gives a peak current of 10 kAmps each and this value is probably not sufficient over current to reduce the thyatron life appreciably. The 2 nanosecond jitter required to synchronize individual modules can be obtained from the thyratrons with careful engineering.

IV. Gas Flow

The operation of nitrogen lasers at repetition frequencies of 1-10 kHz required to generate high average powers (10-100 watts) and achieve a good coupling efficiency to the separation process requires the development of gas flow capability for this laser. While high repetition frequency nitrogen lasers have been investigated previously,^{21,22} the excitation techniques used do not conform to the requirements of high pulse energies. Only by combining the excitation technology developed for high peak powers with gas flow will high average power devices become possible.

The problem of flow for the nitrogen laser is substantially different than for other high prf laser systems in that the flow solution must be developed within the constraints of the desired PFL geometry and the requirement for maximum compactness of the laser tube structure needed to reduce inductance and maintain high pulse energy and efficiency. The gas flow study is aimed at; defining optimum gas flow configurations for nitrogen lasers consistent with strip line excitation, determining the power dissipation limits for the various geometries, and defining the flow passage design requirements needed to preserve medium optical quality.

The gas transport analysis which follows is based upon several assumptions. They are: 1) ideal gas, 2) subsonic flow, 3) constant mass flow rate or no mass accumulation volume, 4) no significant boundary layer effects, and 5) no regions of stagnant gas flow or reverse flow. Supersonic flows permit a higher pulse repetition rate than is possible with subsonic flow. However the additional complexity involved does not appear necessary for devices

in the 10-100 watt category and therefore will not be considered in the scope of this study. The constant mass flow rate assumption is based upon the belief that the gas will clear the discharge region if steady flow prevails rather than the acceleration-deceleration processes that would occur if a mass flow rate limit is encountered when the gas is heated. As for the boundary layer effect, a laminar boundary layer such as that formed on a flat plate can lead to a slower removal of the gas in the laser by diffusion rather than by convection. A detailed evaluation of the importance of boundary layers on each configuration must be made in any final design. The importance of no stagnation regions in the vicinity of the electrodes is essential to effective removal of residual ionization. This assumption includes suitable flow conditioning upstream of the electrodes, perhaps flow area contraction at the electrodes to minimize eddy and boundary layer influence. The proper amount of flow conditioning is determined by the eventual use of the laser and the constraints on medium homogeneity.

(A) MAXIMUM PULSE REPETITION FREQUENCY

The power dissipation limit for the nitrogen laser is set predominantly by the value of the maximum permissible pulse repetition frequency $(prf)_{max}$. This value can be defined as

$$(prf)_{max} = \frac{1}{\tau_c} = \frac{v_{max}}{CR W} \quad (10)$$

where τ_c is the clearing time, v_{max} is the maximum allowable gas inlet velocity, W the discharge dimension in the direction of gas flow, and CR is the

clearing ratio defined as the number of multiples of the gas discharge volume which must be convected to produce a stable glow discharge in successive pulses. We derive below general expressions for CR and $v_{\max}$ which will then be applied to the specific case of the nitrogen laser configurations.

(1) Clearing Ratio - Ionization Removal Criterion

When heating takes place as a result of electrical energy deposition, gas inertia produces a region of high pressure which expands generating shock and expansion waves, until pressure equilibrium is established. The results of this expansion are 1) ionized gas has expanded upstream of the discharge region and must be convected back through the discharge region in order to remove residual ionization before the next pulse, and 2) shock waves propagate until dissipated or reflected from the region. The removal of residual ionization from the discharge region between successive pulses is important to promote discharge stability and to maintain a high resistivity gas before gas breakdown to insure efficient laser excitation.

To account for ionization that has expanded upstream it is convenient to introduce the clearing ratio (CR) as the number of multiples of the gas discharge volume which must be removed to produce a stable glow discharge in successive pulses. In practice values of clearing ratio between 1.5 and 5 are typical.

A simplified calculation of the clearing ratio can be obtained for subsonic flow of ideal gas. Figure (54) depicts the gas expansion (puffing) process and shows the spatial and temporal positions of pressure waves and adulterated gas for the time period immediately following the glow discharge.

GAS PUFFING MODEL

Fig. (54)

For simplicity in the model the energy deposition time is assumed negligible when compared with the gas displacement time in the $X - \tau$ plot on the figure.⁴⁹

A shock wave is formed because the inertia of the gas allows a constant density pressure rise during the rapid uniform heat input to the gas. A shock wave pressure discontinuity appears at the interface between pulsed and non-pulsed gas (called the contact surface). This shock wave separates from the contact surface and moves away from the heated region with a speed greater than sonic. The contact surface also moves out ("puffs") into the low pressure region, but with a speed which is slightly less than sonic, and stops its outward movement when expansion (rarefaction) waves moving at sonic velocity in the adulterated gas overtake the contact surface. For clarity in the figure, only the leading edge of the rarefaction is shown.

The adulterated gas is displaced a distance X_1 into the surrounding gas in a time τ ($\sim 100 \mu s$). In order to clear the inter-electrode region of ionization in preparation for the next pulse, the adulterated gas which puffed upstream has to be convected back to the gap at reduced velocity v/β then through the gap at velocity v and finally a distance X_2 downstream at velocity v/β . β is the ratio of upstream to interelectrode flow cross-sectional areas. If the PRF is a few kHz, v will be subsonic and τ will be negligibly small compared to the total clearing time, τ_c . For this condition τ_c is, to a good approximation, given by the following equation:

$$\tau_c = \frac{W}{V} + \frac{\beta}{V} (X_1 + X_2) \quad (11)$$

The displacement X_2 must be about half the interelectrode spacing, h , thus

$x_2 \approx h/2$. To approximately predict the displacement x_1 , an equilibrium position for the expansion of the adulterated gas is calculated for a one-dimensional gas displacement represented by a two-step process depicted on a pressure-volume diagram as shown in Fig. (55). Process 1-2 is the constant volume heat addition to the gas during the glow discharge and process 2-3 represents the puffing, that is, the isentropic expansion of the heated gas following the pulsed discharge. x_1 , which is determined by the volume expansion experienced by the gas in the two step process $1 \rightarrow 2 \rightarrow 3$, can be calculated by using the equations of: state $P_2/P_1 = T_2/T_1$, energy $(\gamma - 1)\Delta E/P_{\text{tot}} \text{Vol} = (T_2/T_1) - 1$, and isentropic expansion $(P_3/P_2)^{\frac{\gamma-1}{\gamma}} = T_3/T_2$. ΔE is the amount of energy deposition which appears as translational heating. The value of x_1 calculated in this manner can then be inserted into Eq. (11) and (10) to give an expression for the gas clearing ratio for gas flow between solid electrodes.

$$CR_1 = 1 + \frac{\eta\beta}{2} + \frac{\beta}{2} [(1 + \epsilon_v)^{1/\gamma} - 1] \quad (12)$$

where $\epsilon_v = \frac{\Delta E(\gamma - 1)}{P_{\text{tot}} \text{Vol}} = \text{normalized energy density at constant volume}$

$\eta = h/\omega$ = ratio of interelectrode spacing to discharge dimension in direction of gas flow.

β = ratio of approach to interelectrode flow areas

$\gamma = c_p/c_v$ = ratio of specific heat capacities

If the gas expansion occurs freely in two dimensions, e.g. for gas flow entering and leaving through or across highly porous electrodes as opposed to the one dimensional expansion as shown in Fig. (54), then the expression for clearing ratio becomes

PRESSURIZATION-EXPANSION PROCESSES FOR
GAS SUBJECTED TO A PULSED GLOW DISCHARGE

Fig. (55)

$$CR_2 = 1 + \frac{\eta\beta}{2} + \frac{\beta}{4} (\alpha + 1) \left\{ \left[1 + \frac{4\alpha}{(\alpha + 1)^2} \{(1 + \epsilon_v)^{1/\gamma} - 1\} \right]^{1/2} - 1 \right\} \quad (13)$$

where $\alpha = 1/\eta$ for flow parallel to electric field
 $= \eta$ for flow transverse to electric field

For low values of clearing ratios ($CR \approx 1.5$) boundary layer diffusion processes may determine the clearing ratio rather than the gas expansion process depicted here.⁵⁰

(2) V_{max} - Rayleigh Gas Heating Limit

When a steady flow of gas is passed through the interelectrode space and the gas is heated by the electric discharge, the gas velocity at the exit will tend toward sonic. This effect is a consequence of conservation of mass and momentum. The locus of state points allowed defines a Rayleigh line which in turn determines the gas heating that is permitted before a sonic exit velocity is reached (point of maximum entropy) and flow redistribution occurs. If the incoming gas velocity exceeds that allowable by Rayleigh heating the incoming flow velocity will be reduced so that the sonic velocity conditions remain satisfied at the exit. This effect sets the maximum inlet velocity and therefore the maximum pulse repetition rate.

The maximum inlet Mach number, M , permitted by the above condition can be related to stagnation temperature rise to define an upper limit to incoming gas velocity. The stagnation temperature rise is related to Mach number by the following expression⁵¹

$$\frac{T_0}{T_0^*} = \frac{2(\gamma + 1)M^2(1 + \frac{\gamma - 1}{2} M^2)}{(1 + \gamma M^2)^2} \quad (14)$$

where T_o is the stagnation temperature at the inlet and T_o^* the stagnation temperature at $M = 1$. The stagnation temperature rise is also related to the energy deposition by

$$\frac{T_o}{T_o^*} = (1 + \epsilon_p)^{-1} \quad (15)$$

where

$$\epsilon_p = \frac{(\gamma - 1)\Delta E}{[P_{tot}(\text{vol})\gamma]} = \frac{1}{\gamma} \epsilon_v \quad (16)$$

Equations (14) and (15) can be combined to give an expression for inlet Mach number in terms of input energy.

$$\frac{T_o^*}{T_o} = 1 + \epsilon_p = \frac{1}{2(\gamma + 1)} \left[\frac{1}{M^2} + \frac{3}{2}\gamma + \frac{1}{2} + \left(\frac{1}{4}\gamma^2 - \frac{1}{2}\gamma - \frac{1}{4}\right)M^2 + (0)M^4 + \dots \right] \quad (17)$$

It is worthwhile to investigate the magnitude of ϵ_p for the proposed N_2 laser in order to define the important gas properties and optimize them. $\epsilon_p = 1$ represents an amount of gas heating by the discharge which equals the thermal energy contained in the incoming gas stream and corresponds to 0.47 Joules/(liter-Torr) for pure N_2 . For a 100 Torr N_2 laser which deposits 300 j/liter into the gas translationally, $\epsilon_p \approx 6$, which implies that the gas temperature will rise six times its initial temperature ($\sim 2000^\circ \text{K}$). This temperature rise, should it occur, will require extensive cooling of insulators and support structures and sets a maximum inlet velocity for the gas of $M = 0.17$.

A more viable approach to limit the temperature rise is to seek a diluent gas with a large heat capacity to absorb the inefficiencies of the excitation process. Helium has been considered as a diluent for the nitrogen laser in this study because it is reported to have minimum influence on the laser and electric discharge characteristics.^{18,32} A value of $\epsilon_p = 1$ in helium corresponds to 0.33 j/(l-Torr). Because there is no apparent pressure constraint on helium, the optimum helium pressure will be specified (arbitrarily) by some other system requirement. A 1 atm laser cell (100 Torr N_2 + 660 Torr He) gives an $\epsilon_p \approx 1.1$ at 300 j/l electrical energy input and a gas temperature rise of about 300°K. The corresponding maximum inlet Mach number is now $M > 0.5$. The higher sonic velocity of helium together with a higher inlet Mach number allowed by the reduced temperature rise implies a much higher $(prf)_{max}$ with helium dilution than for low pressure nitrogen alone and results in substantially increased power handling capability.

(B) POWER DISSIPATION LIMIT

The maximum power into the discharge that can be accommodated by gas flow is

$$\underline{P} = (PRF)_{max} \frac{(\Delta E)}{(\text{vol})} \text{ vol} \quad (18)$$

To account for the effect of flow obstructions necessitated by the laser design and discussed in Section III, the value of $(PRF)_{max}$ will be reduced by the fraction of flow area which is blocked in the downstream direction. Inserting Eqns. (10), (12), (13), (16), and (17) into Eqn. (18) and casting Eqn. (18) into a non-dimensional form gives

$$P = \frac{P(\gamma - 1)}{P_{\text{tot}} a h l f} = \frac{\epsilon_v M}{CR} \quad (19)$$

where P is a dimensionless power, a is the sound speed, l the discharge length and f the fraction of the downstream flow area which is unobstructed.

or

$$P = \frac{\epsilon_v}{\left\{1 + \frac{\eta\beta}{2} + \frac{\beta}{2} [(1 + \epsilon_v)^{1/\gamma} - 1]\right\} \left\{2(\gamma + 1) \epsilon_p + \frac{\gamma + 3}{2}\right\}^{1/2}} \quad (20)$$

The criteria for maximum power into the discharge can be determined by equating the derivative $\frac{dP}{d\epsilon_v}$ equal to zero. The resulting expression for the optimum value ϵ_{vopt} of ϵ_v is

$$\frac{\beta}{2\gamma CR_{\text{opt}}} (1 + \epsilon_{vopt})^{\frac{1-\gamma}{\gamma}} + M_{\text{opt}}^2 (\gamma + 1) = \frac{1}{\epsilon_{vopt}} \quad (21)$$

where

$$CR_{\text{opt}} = 1 + \frac{\eta\beta}{2} + \frac{\beta}{2} [(1 + \epsilon_{vopt})^{\frac{1}{\gamma}} - 1]$$

$$M_{\text{opt}} = \left\{2(\gamma + 1)(\epsilon_{vopt} + 1) - \frac{3\gamma + 1}{2}\right\}^{-1/2}$$

$$\epsilon_{vopt} = \gamma \epsilon_{vopt}$$

Eq. (20) is presented in graphical form in Fig. (56). Each curve presents the relationship between the input energy and the maximum input power based upon the ion removal and gas heating flow limitations parametric in the geometry factor, β . The maximum value of P for constant β corresponds to those values predicted by Eq. (20). Power values for $\beta = 1$ represents an upper limit based on practical geometrical constraints for the gas flow; i.e., for $\beta \leq 1$ boundary layer separation occurs and will not properly clear the discharge region of residual ionization.

(C) TRANSLATIONAL HEATING

For order of magnitude estimates we have assumed that the total electrical energy deposition appears as gas heating instantaneously. The actual translational temperature rise of the gas following the discharge pulse, which determines the flow limits, is determined by the relative time scales for the relaxation of the various excited states in comparison to the time scale for gas flow through the laser structure.

The kinetic model indicates that the bulk of the electrical energy dissipated in the plasma is partitioned approximately in the following way: A state (50%), vibration (45%), and ionization (5%). The energy stored in the plasma in the form of charged particles comes out very quickly. With a recombination coefficient of $\alpha \sim 10^{-7}$ and electron densities of 10^{15} cm^{-3} , the decay of the plasma density follows the form $n_e/n_0 = (1 + 10^8 t)^{-1}$. The charged particle energy therefore is deposited in less than 100 ns and can be assumed to be funnelled into the translational bath instantaneously on the time scale of gas flow.

Fig. (56)

The A state and the vibrational levels are metastable since the former has a radiative lifetime (Vegard-Kaplan Bands) of 1 second and the latter does not radiate at all. The collisional decay times into the translational bath for these two energy reservoirs, which contain nearly all the energy, is more difficult to estimate accurately and could very well be impurity dominated. Extrapolation of high temperature ($> 2000^{\circ}\text{K}$) shock tube data⁵² for the processes $\text{N}_2^* + \text{N}_2 \rightarrow \text{N}_2 + \text{N}_2$ and $\text{N}_2^* + \text{He} \rightarrow \text{N}_2 + \text{He}$ indicate vibrational decay rates near room temperature of $p\tau = 1 \text{ sec-atm}$ and $4 \times 10^{-3} \text{ sec-atm}$ respectively. Near room temperature measurements⁵² for $\text{N}_2^* + \text{N}_2 \rightarrow \text{N}_2 + \text{N}_2$ gives a value of $p\tau \sim 4 \times 10^{-3} \text{ sec-atm}$ which is much faster than the high temperature extrapolation. It is not known whether this faster rate is impurity dominated. If we assume rates of $p\tau = 4 \times 10^{-3} \text{ sec-atm}$ for both processes then the vibrational energy will not contribute to gas heating until the gas has been convected out of the laser channel for discharge configurations which have been considered and flow velocities of interest for LIS. For example a laser using helium diluent at pressures less than an atmosphere, with a discharge cross-section of $0.5 \text{ cm} \times 2 \text{ cm}$, and operated at a repetition frequency of $f \text{ kHz}$ has a gas residence time within the laser channel of $t_r \sim (8/f) \times 10^{-4}$ seconds. For $f > 1$ the vibrational deactivation times are more than five times longer than the gas transit times. The effect of impurities will probably not affect these conclusions since their densities will be low.

The flow of energy from the A state is the least clear. The dominant deactivation process for this level is the pooling reaction $\text{N}_2(\text{A}) + \text{N}_2(\text{A}) \rightarrow \text{N}_2^*(\text{X}) + \text{N}_2^*(\text{Y})$ where X is the ground electronic state and Y can be either the B, C or E states. The total rate constant⁵³ for pooling is $k_T = 10^{-10} \text{ cm}^3/\text{sec}$

and is divided among the three states with a ratio of $k_B:k_C:k_E = 0.8:0.15:0.05$. The decay of the A state follows the relation $N_2(A)/N_2(A)_0 = (1 + k_T N_2(A)_0 t)^{-1}$. For $N_2(A)_0 \approx 10^{15} \text{ cm}^{-3}$ the time constant $[k_T N_2(A)_0]^{-1}$ is about 10 μsec so the $N_2(A)$ density decays instantaneously on the time scale of the flow. This rapid decay however does not imply that all the energy is funneled to translation at the same rate. Eighty percent of the deactivations $N_2(A) + N_2(A)$ produces a ground state $N_2(X)$ and a B state $N_2(B)$. The B state radiates back into $N_2(A)$ in about 1 μsec . Each deactivation therefore produces an energy defect of about 4.5 eV which must appear in the form of vibrational excitation or translational heating. Such a large energy defect however implies that a large fraction of the exothermicity probably resides in excited vibrations of the A and X states. Vibrational deactivation of the ground electronic state is slow but no information exists on vibrational deactivation of the A state. In any case the partitioning of the excess energy and the time scale for translational heating from the A reservoir is not known and must be determined experimentally.

From the above discussions we can conclude that a quantitative determination of translational heating must await experimental data but that a minimum of 45% of the electrical energy dissipated in the discharge (vibrations) does not contribute to gas heating within the laser channel itself at high ($> 1 \text{ kHz}$) prf conditions.

(D) LASER CAVITY FLOW DESIGN CONSIDERATIONS

High average power nitrogen laser configurations are shown in Figs. (57,61) For flow parallel to the electric field with a double stripline, Fig.(57), the gas flow enters between the inner conductors, pass through porous electrodes and exhausts through the downstream electrode between the downstream line conductors. Electrical switching of the line is best situated upstream of the discharge region in order that the switch and gas inlet area can be accomodated in the limited space between the interior line conductors. This configuration poses several constraints on the design of the electrodes. First, the flow wakes generated by the passage of gas through the inlet electrode must be dissipated in a small fraction of the discharge length along the flow direction to obtain an optically uniform medium. If we choose a criteria of 99% wake dissipation in the first 10% of the discharge height then the structural members in the upstream electrodes must not be larger than 0.07 mm typically. Such an electrode can be fabricated in a structurally rigid form from metal hexcel honeycomb material. The downstream electrode must have maximum open area (typically 70% or more) to prevent thermal choking of the flow. For a 20 watt nitrogen laser design as shown in Fig. (61), 0.5 kW of electrical power is deposited per centimeter along the laser channel. This thermal load will require extensive cooling of the downstream electrode, laser tube, and surrounding structures.

The two double PFL designs for flow transverse to the field are shown in Fig. (58) and (59). These configurations will generally have a higher inductance and require longer flow distances to clear the plasma from conducting regions than the configuration for flow parallel to the field. A variation of

ELECTRICAL FLOW CONFIGURATION FOR NITROGEN LASERS
FLOW PARALLEL TO ELECTRIC FIELD (DOUBLE STRIP LINE)

Fig. (57)

ELECTRICAL-FLOW CONFIGURATION FOR NITROGEN LASERS.
FLOW TRANSVERSE TO ELECTRIC FIELD (DOUBLE STRIP LINE)

Fig. (58)

ELECTRICAL-FLOW CONFIGURATION FOR NITROGEN LASERS
FLOW TRANSVERSE TO ELECTRIC FIELD

Fig. (59)

N₂ LASER WITH GAS FLOW TRANSVERSE TO ELECTRIC FIELD
(SINGLE STRIP LINE)

Fig. (60)

the transverse flow approach is the single sided stripline configuration with upstream graded insulators Fig. (60). The trade-offs between the two mutually orthogonal flow options must eventually be answered experimentally but transverse flow would become advantageous for N_2 lasers where the discharge height h becomes comparable to the transverse dimension of the entire PFL structure.

(E) POWER DISSIPATION LIMITS FOR VARIOUS N_2 LASER CONFIGURATIONS

The power dissipation limits derived from gas heating limitations upon the gas flow have been applied to several N_2 laser geometries and the results are summarized in Table III. The pulser circuit used for flow parallel to the electric field is a double triangular Blumlein whereas a single (one-sided) triangular Blumlein was considered for flow perpendicular to the field. In each case a one meter long laser channel is assumed where the energy stored in the line corresponds to a dielectric stress for Mylar of 1 kV/mil and corresponds to a 10^8 shot life. The power dissipation limits derived are absolute lower limits obtained by assuming that the total energy stored in the line is dissipated as translational heating within the laser channel. The dimensionless energy term ϵ_v represents the relative magnitude of the temperature rise to be experienced in the immediate vicinity of the discharge ($\epsilon_v = 1$ corresponds to a doubling of the incoming gas temperature).

TABLE III - GAS FLOW LIMITATIONS FOR CANDIDATE NITROGEN LASER
DISCHARGE CROSS SECTION DIMENSIONS⁺

Gas Flow Parallel to E Field Double Strip Line ¹							Gas Flow Transverse to E Field Single Strip Line ²					
Discharge Dimensions* (cm x cm)	ΔE (joules)	ϵ_v	M	CR	$\frac{P}{\text{P}}$ (kilowatts)	(PRF) _{max} (kHz)	ΔE (joules)	ϵ_v	M	CR	$\frac{P}{\text{P}}$ (kilowatts)	(PRF) _{max} (kHz)
1 x 1	13	1.63	0.37	1.34	252	19.4	6.5	0.81	.43	2.2	126	19.4
1/2 x 2	26	3.27	0.27	1.23	201	7.7	13	1.63	.27	17.3	166	12.8
1/4 x 4	52	6.53	0.20	1.12	163	3.1	26	3.26	.27	17.3	163	6.3
1/2 x 4	52	3.27	0.27	1.14	217	4.2	26	1.63	.37	9.8	197	7.6
1 x 4	52	1.63	0.37	1.14	296	5.7	26	.81	.43	5.2	214	8.2
1 x 2	26	1.63	0.37	1.23	274	10.6	13	.81	.43	3.2	174	13.4

+ 400 Torr mostly helium

1 $\beta = 2$ $\gamma = 1.67$ $a = 10^5 \text{ cm/sec}$ $\eta = 0$ $f = 0.7$

2 $\beta = 2$ $\gamma = 1.67$ $a = 10^5 \text{ cm/sec}$ $\eta = 1$ $f = 1$

* First dimension is discharge width, w,
second dimension is interelectrode spacing, h, and
third dimension is 100 cm along optical axis.

β = ratio of approach to inter-electrode cross-sectional areas.

$\gamma = C_p/C_v$

a = sound speed

f = fraction of downstream flow area which is unobstructed

V. Conclusions

The conclusion reached by this design study is that 20-100 watt average power mode-controlled nitrogen lasers are feasible with state of the art technology but that preliminary experimental work must be initiated to obtain the necessary data and develop the high power laser configurations and pulse forming line.

(A) 20 WATT LASER

A conceptual design of a 20 watt nitrogen laser based upon a conservative use of the conclusions of the study is shown in Fig. (61). The operating parameters were chosen to be well below any operating limits for flow or pulser technology identified in the study. The power amplifier shown can be either TW or non-TW excited and employs flow through the electrodes across the 2 cm dimensions. Switching of the double Blumlein can be accomplished with five thyratrons.

(B) 100 WATT LASER

There are several ways one could proceed to 100 watts. From the viewpoint of LIS application requirements, increasing the prf would be desirable. Table III indicates that the 20 watt amplifier can be operated at 5 kHz without stretching the pulse rate limit or exceed the thermal dissipation properties of the PFL. In this case a second 150 cm module added to the 20 watt system could be uprated to produce a 100 watt N_2 system without any change in components.

TWENTY WATT NITROGEN LASER OSCILLATOR-AMPLIFIER

OSCILLATOR

Double Blumlein

Discharge Dimensions:

1 cm x 2 cm x 13 cm

Gas:

15 Torr N_2 + 300 Torr (min) He

Laser Output:

0.5 mj/pulse in 10 ns

Pulse Rate:

2 KHz

Input Energy

6 j/pulse

Optics:

Unstable Resonator

Gas Velocity:

2×10^4 cm/sec (Mach 0.2)

Power Input:

12 Kw

Efficiency:

8×10^{-5}

AMPLIFIER

Double Blumlein

1/2 cm x 2 cm x 150 cm

50 Torr N_2 + 300 Torr (min) He

10 mj/pulse in 5 ns

2 KHz

45 j/pulse

None

2×10^4 cm/sec (Mach 0.2)

90 Kw

2×10^{-4}

Fig. (61)

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