UCID- 19091

MASTER

A REVIEW OF NITROGEN LASER
RESEARCH 1963 - 1973

H. Garcia

July 1981

Lawrence
Livermore
Laboratory

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the Laboratory.

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under Contract W-7405-Eng-48.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

TABLE OF CONTENTS

INTRODUCTION	3
ACTUAL LASER SYSTEMS - A HISTORY OF EXPERIMENTS	4
MODELS OF THE PULSED, MOLECULAR NITROGEN LASER	19
INVERSION MECHANISMS	29
APPLICATIONS	33
SUPER RADIANT NITROGEN LASERS	34
Molelectron UV-Series Pulsed Nitrogen Lasers	34
Model UV-1000 and UV-600	34
Model UV-300	35
Dye Laser Pumping	35
Peak Power vs. Average Power	36
Design Features	37
DL-Series Dye Laser	38
Laser Spectroscopy Detector System	38
APPENDIX I: SPECIFICS OF LASER SYSTEMS DISCUSSED	40
Mathias and Parker (1) 1963	40
Mathias and Parker (2) 1963	41
Heard (1) 1963	42
Heard (2) 1963	43
Leonard 1965	43
Geller, Altmann, DeTemple 1966	45
Shipman 1967	46
Geller, Altmann, DeTemple 1968	47
APPENDIX II: A DISCUSSION OF THE TERMS OSCILLATION AND SUPERRADIANCE	48
REFERENCES AND FOOTNOTES	49
DISTRIBUTION	51

FIGURES

<u>Figure 1:</u> Energy Level Diagram of N_2 Molecule	7
<u>Figure 2:</u> Crossed Field Laser	12
<u>Figure 3:</u> Crossed Field Laser Beam Profile	12
<u>Figure 4:</u> Crossed Field Laser Power Output	14
<u>Figure 5:</u> Coaxial Transmission Line Gas Laser	14
<u>Figure 6:</u> Coaxial Line Laser: Ionization Wave Speed	15
<u>Figure 7:</u> Coaxial Line Laser: Discharge Voltage, Current vs Time ...	15
<u>Figure 8:</u> Blumlein Pulse Generator - Transverse Laser	15
<u>Figure 9:</u> Blumlein Pulse Generating Circuit Diagram	18
<u>Figure 10:</u> Sketch of Blumlein Pulsed Transverse Laser	18
<u>Figure 11:</u> Sketch of Blumlein Pulsed Transverse Laser	18
<u>Figure 12:</u> N_2 Excitation Channels via Shape & Feedback Resonances ...	31
<u>Figure 13:</u> Radiation Type vs. Time - N_2 Discharge	32

TABLES

Table 1: Stimulated Emission Lines of the First Positive System	8
Table 2: Stimulated Emission Lines of the Second Positive System	11

INTRODUCTION

This work was undertaken as an attempt to respond to the question:⁽¹⁾ "What would one consider if he wanted to construct a nitrogen laser?" The answer to this question is rather complicated, for the physics of the situation is not as well formulated as the techniques for the construction of an operational device.

This report is broken up into seven sections. The body begins with a description of exploratory, experimental nitrogen lasers; this description is done chronologically. Physical insights gained during the course of these experiments are also introduced chronologically so as to aid the reader in appreciating the improvements and disadvantages of successive approaches to the problem. Following this history of machine and idea proliferation, we give a review of previously accepted models of this laser. We shall show that the second model presented is a refinement of the first, though not necessarily an improvement. The models presented are based on assumed inversion mechanisms which have recently been called into doubt. This would normally be disturbing because the models were very accurate in their prediction of certain output characteristics. However, if one accepts the view that an accurate physical picture will ultimately yield correct engineering results, then an investigation into the actual inversion mechanisms should become the dominant area of interest. Hence, we discuss possible factors causing inversion and disprove some of the old assumptions employed; however, a unified theory has yet to be presented. The fifth section of this report is a short one on the uses of the pulsed nitrogen laser; the sixth is the

DISCLAIMER

appendix where the details of devices discussed are summarized. If one were to actually build a nitrogen laser, the best approach, short of solving the problem theoretically first, would be to peruse the appendix to get an idea of what would be involved and what to expect. The seventh section of this report is scattered about; it consists of the figures which give many of the numbers not discussed explicitly in the text, nor adequately displayed in the appendix. The first section, by the way, is this one.

ACTUAL LASER SYSTEMS - A HISTORY OF EXPERIMENTS

The first pulsed, electrically excited, molecular gas laser, was that reported by Mathias and Parker⁽²⁾ in 1963. This laser was very similar to the helium-neon laser in its construction. In a cavity consisting of two near confocal mirrors was set a separate, sealed, discharge tube. This discharge tube contained the axial discharge produced by two end electrodes; the ends of the tube were Brewster windows. The fill gas in the discharge tube was nitrogen and the oscillation produced was off the band systems of the $B^3\Pi_g \rightarrow A^3\Sigma^+_u$ transition, or the First Positive System. The output radiation was infrared, and in the range of 8 to 1.2 microns. Later that year, Heard⁽³⁾ reported on his success in constructing a pulsed nitrogen laser with ultraviolet (UV) output radiation. The oscillations produced here were off the Second Positive System, or the $C^3\Pi_u \rightarrow B^3\Pi_g$ transition. Heard's laser was very similar in construction to that of Mathias and Parker, and he could retrieve their observations by lowering his discharge voltage.

At this point it would do well to briefly review the structure of dia-

tomic nitrogen by perusing Fig. 1 (pg. 7), an energy level diagram taken from Herzberg⁽⁴⁾. T. Kasuya and D.R. Lide, Jr.⁽⁵⁾ in 1967 and C.A. Massone, M. Garavaglia, M. Gallardo, J.A.L. Calatroni and A.A. Tagliaferri⁽⁶⁾ in 1972 measured the stimulated emission lines of the first and second Positive Systems of Nitrogen. The results of this latter work on pages 8, 9, 10, and 11, of this document. Unless otherwise noted, we shall henceforth restrict ourselves to UV nitrogen lasers.

By 1965⁽⁷⁾ it was evident that the inversion produced in the N₂ laser was of a highly transient nature. For any laser of engineering dimensions the spontaneous emission to be amplified would have time enough to make only one or two passes through the discharge tube before the inversion was spoiled. In 1965, Leonard⁽⁸⁾ re-examined Heard's experiment, and he too produced ultraviolet radiation at 3371 Å from nitrogen gas using a fast rising high-current, high voltage discharge. Output from a 30 cm active length near confocal cavity was found to be approximately 10 watts (w); however, the spontaneous emission from the same transition perpendicular to the discharge tube axis was many kilowatts.

Leonard found that by

"sending the output beam from an oscillator of this type (i.e., the aforementioned 30 cm laser) through a synchronized open-ended amplifying section of relatively short length, consisting of a similar discharge tube, it has been possible to drive this high gain transition into saturation and obtain output powers approaching the spontaneous emission power level."⁸

In terms of experimental implementation of this new insights, Leonard introduced transverse electrical excitation and a cavity with one plane mirror. The first improvement was aimed at increasing the local electric field intensity in the discharge volume. This increased the average energy gained by an electron between collisions; or in the context of gas discharges, increased $(E/P)^{(9)}$. The second improvement was the removal of a nearly useless, if not detrimented optical cavity, replacing it with a plane mirror at one end. This arrangement allowed for maximum power output by doubling the effective length of the active medium. The essence of this last statement is that the laser was amplifying spontaneous emission originating at one end of the discharge tube. The construction of Leonard's laser allowed for an arbitrary active length, a characteristic which be used to good purpose in determining the saturation power density (for more details see the appendix and the figures on page 12).

The $C^3 \text{ IIu} \rightarrow B^3 \text{ IIg}$ transition of nitrogen is recognized to be a self terminating laser system because the radiative lifetime of $C^3 \text{ IIu}$ is 40 nsec and that of $B^3 \text{ IIg}$ is approximately 10^{-5} (or 10 μsec) sec. For maximum efficiency the rise time and length of the excitation current pulse should be as short as possible. When large power is required, the necessarily large values of initial current rise (variously estimated as $\sim 10^{11}$ A/sec⁽¹⁰⁾ and 10^{12} A/sec⁽¹¹⁾) impose severe restrictions on the circuit inductance. Geller, Altmann and DeTemple attempted, in 1966⁽¹⁰⁾ and 1968⁽¹¹⁾, to minimize this inductance. Their first scheme was to construct the entire circuit, including the plasma tube, in the form of a coaxial transmission line (see pages 14, and 15 for illustrations of the device and measured quantities). This arrangement means

ENERGY LEVEL DIAGRAM OF H_2 MOLECULE

Figure 1

Energy Level Diagram of the H_2 Molecule. The heavy (full) horizontal lines give the electronic states; the short thinner lines give the vibrational levels in each of them. The four levels u , v , x , y whose heights above the ground state are not known are indicated by broken lines. The light broken horizontal lines ending in heavier lines at the right indicate dissociation limits. The short heavy horizontal arrows designated P_r give the positions of observed predissociation limits. For the dissociation energy the value $D_0(N_2) = 7.373$ has been assumed (see text). Two ionization limits are given (heavy broken horizontal lines across whole figure) corresponding to the two states $^1\Sigma_g^+$ and $^3\Sigma_g^+$ of N_2^+ . To avoid overcrowding of lines the higher members of the Rydberg series leading to the two ionization limits have been omitted as have the $s = 1$ vibrational levels observed for the Worsley-Jenkins series [see Tanaka and Takamine (1457)]. An emission Rydberg series [Hopfield (331) and Takamine, Suga and Tanaka (600a)] has been observed very close to Hopfield's Rydberg series. The upper states of this series (probably $^1\Sigma_g^+$) are not shown.

TABLE 1. Stimulated Emission Lines of the First Positive System

Band	λ_{air} (Å)	σ_{-1} (cm)	σ_{spont}^a (cm ⁻¹)	Intensity	Band	λ_{air} (Å)	σ_{-1} (cm)	σ_{spont}^a (cm ⁻¹)	Intensity
4-2	7482.187	13361.40	13361.37: $^4R_{12} - 1$	1		7504.598	13321.50	13321.48: $P_1 - 3$	5
	7485.941	13354.70		3		7504.768	13321.19	13321.25: $P_1 - 1$	3
	7486.135	13354.35	13354.30: $^4Q_{11} - 3$	4				13321.37: $P_1 - 2$	
	7486.413	13351.86	13353.91: $P_1 - 4$	1				13321.23: $^4R_{12} - 4$	
	7486.253	13352.36	13352.32: $^4Q_{11} - 4$	4		7505.113	13320.54	13320.50: $^4R_{12} - 2$	2
	7487.409	13352.08	13352.05: $Q_1 - 9$	4		7505.710	13319.52		4
			13352.11: $P_1 - 5$			7505.803	13319.18		3
	7488.046	13350.54		4		7506.063	13318.40		4
	7488.246	13350.58	13350.54: $P_1 - 6$	5		7506.356	13318.38	13318.30: $^4P_{11} - 10$	1
			13350.58: $^4Q_{11} - 5$			7508.145	13315.20	13315.16: $^4P_{11} - 11$	1
	7489.107	13349.05	13349.04: $^4Q_{11} - 6$	3		7509.860	13312.11		3
	7489.626	13348.13	13348.12: $Q_1 - 8$	1		7510.133	13311.68	13311.67: $^4P_{11} - 3$	5
	7489.809	13347.80	13347.76: $P_1 - 13$	4		7510.923	13311.28		3
			13347.78: $^4Q_{11} - 7$			7511.592	13309.09	13309.06: $^4P_{11} - 4$	4
	7490.096	13347.29	13347.28: $P_1 - 12$	1		7512.799	13306.96		3
	7490.317	13346.79	13346.70: $^4Q_{11} - 8$	3		7513.003	13306.59	13306.58: $^4P_{11} - 5$	5
	7491.510	13344.77		3		7513.569	13305.59		2
	7491.705	13344.42	13344.40: $Q_1 - 7$	5		7514.357	13304.20	13304.18: $^4P_{11} - 6$	4
	7492.379	13343.22	13343.17: $^4P_{11} - 4$	0		7515.079	13302.92		3
	7493.082	13341.97	13341.98: $^4R_{12} - 6$	1		7515.446	13302.27		3
	7493.716	13340.84	13340.81: $Q_1 - 6$	4		7515.650	13301.91	13301.89: $^4P_{11} - 7$	5
	7493.910	13340.50		3		7517.728	13298.23	13298.27: $^4Q_{11} - 8$	3
	7495.086	13338.40	13338.39: $^4P_{11} - 5$	2		7518.013	13297.73	13297.71: $^4P_{11} - 9$	4
	7495.465	13337.73		0					
	7495.660	13337.38	13337.35: $Q_1 - 5$	4	3-1	7586.439	13177.79	13177.76: $Q_1 - 9$	0
	7496.024	13336.73		3		7587.693	13175.61	13175.62: $Q_1 - 7$	0
	7497.256	13334.54		5		7603.477	13148.26		3
	7497.524	13334.07	13334.04: $Q_1 - 4$	5		7606.374	13143.25	13143.28: $^4Q_{11} - 2$	1
	7497.728	13333.70		4		7607.626	13141.09	13141.08: $^4Q_{11} - 3$	5
	7498.598	13331.62		2		7608.801	13139.08	13139.03: $^4Q_{11} - 4$	5
	7499.043	13331.42		3				13139.02: $Q_1 - 9$	
	7499.327	13330.86	13330.85: $Q_1 - 3$	5		7609.853	13137.24	13137.23: $^4Q_{11} - 5$	5
	7499.593	13330.39		5		7610.759	13135.68	13135.66: $^4Q_{11} - 6$	4
	7499.835	13329.97	13329.92: $P_1 - 13$	1		7611.082	13135.12	13135.12: $Q_1 - 8$	4
	7500.071	13329.54	13329.52: $^4P_{11} - 7$	4		7611.514	13134.38	13134.37: $^4Q_{11} - 7$	5
			13329.50: $^4Q_{11} - 12$			7612.105	13133.36	13133.35: $^4Q_{11} - 8$	0
	7500.646	13328.51		2		7612.528	13132.63	13132.62: $^4Q_{11} - 9$	3
	7500.734	13328.36		2		7613.260	13131.36	13131.36: $Q_1 - 7$	5
	7501.056	13327.79	13327.77: $Q_1 - 2$	5		7615.347	13127.75	13127.75: $Q_1 - 6$	5
	7501.295	13327.36		4		7616.994	13124.93	13124.92: $^4P_{11} - 5$	2
	7501.494	13327.17		4		7617.337	13124.30	13124.29: $Q_1 - 5$	5
	7501.553	13326.90		4		7619.288	13120.97	13120.96: $Q_1 - 4$	4
			13326.90: $P_1 - 11$			7620.844	13118.30		3
			13326.88: $^4Q_{11} - 10$			7620.943	13118.13		3
	7502.139	13325.86	13325.85: $^4Q_{11} - 9$	3		7621.161	13117.75	13117.74: $Q_1 - 3$	5
	7502.729	13324.82	13324.83: $Q_1 - 1$	1		7622.235	13115.90	13115.90: $^4P_{11} - 7$	4
	7502.768	13324.75	13324.66: $P_1 - 9$	2		7622.565	13115.33		3
	7503.035	13324.27	13324.25: $^4Q_{11} - 7$	5		7622.959	13114.66	13114.65: $Q_1 - 2$	5
	7503.371	13323.67	13323.66: $^4Q_{11} - 6$	5				13114.69: $^4Q_{11} - 11$	
	7503.418	13323.59	13323.58: $^4P_{11} - 8$	5		7623.256	13114.15		4
	7503.642	13323.19	13323.20: $^4Q_{11} - 5$	5		7623.311	13114.05		4
	7503.669	13323.15		5		7623.582	13113.58	13113.51: $^4Q_{11} - 10$	3
	7503.697	13323.10	13323.07: $P_1 - 7$	5		7623.686	13113.41		3
	7503.834	13322.85	13322.82: $^4Q_{11} - 4$	4		7623.918	13113.01		3
			13322.77: $^4R_{12} - 7$			7624.220	13112.49	13112.48: $^4Q_{11} - 9$	1
	7503.960	13322.61	13322.57: $^4Q_{11} - 3$	5		7624.690	13111.68	13111.69: $Q_1 - 1$	5
	7503.984	13322.57	13322.59: $^4Q_{11} - 2$	4				13111.64: $^4Q_{11} - 8$	
	7504.106	13322.37	13322.39: $^4Q_{11} - 1$	5		7624.924	13111.28	13111.28: $P_1 - 9$	5
	7504.160	13322.27	13322.27: $^4Q_{11} - 1$	5		7625.115	13110.95	13110.95: $^4Q_{11} - 7$	5
	7504.184	13322.23	13322.18: $^4P_{11} - 6$	5		7625.445	13110.38	13110.37: $^4Q_{11} - 6$	5
	7504.274	13322.07	13322.04: $Q_1 - 0$	4		7625.709	13109.83	13109.83: $^4Q_{11} - 5$	3
			13322.04: $P_1 - 5$						

TABLE 1 (continued)

Band	λ_{air} (Å)	σ_{-1} (cm)	σ_{spont}^a (cm ⁻¹)	Intensity
	7623.770	13109.82		3
	7623.812	13109.75	13109.77: $P_1 - 7$	4
	7623.906	13109.59	13109.58: $^oQ_{11} - 4$	4
	7626.007	13109.41	13109.46: $^oP_{11} - 7$	3
	7626.014	13109.35	13109.35: $^oQ_{11} - 3$	1
	7626.114	13109.23	13109.20: $P_1 - 6$	1
	7626.180	13109.12	13109.16: $^oQ_{11} - 2$	5
	7626.207	13109.07	13109.04: $^oQ_{11} - 1$	1
	7626.360	13108.81	13108.78: $P_1 - 5$	5
	7626.560	13108.46	13108.46: $P_1 - 4$	1
	7626.700	13108.22	13108.25: $P_1 - 3$	5
	7626.749	13108.14	13108.12: $P_1 - 1$	5
			13108.14: $P_1 - 2$	
	7626.826	13108.01	13107.98: $^oP_{11} - 9$	1
			13107.98: $^oR_{11} - 4$	
			13104.47: $^oP_{11} - 10$	2
	7628.854	13104.52		0
	7629.102	13104.10		1
	7630.365	13102.03		3
	7631.880	13099.33		5
	7632.446	13098.36	13098.34: $^oP_{11} - 3$	
			13098.35: $^oP_{11} - 12$	3
	7633.348	13096.81		5
	7633.983	13095.71	13095.69: $^oP_{11} - 4$	
			13095.74: $^oP_{11} - 13$	1
	7634.546	13094.75		0
	7634.779	13094.35		5
	7635.474	13093.16	13093.15: $^oP_{11} - 5$	4
	7636.126	13092.04		3
	7636.904	13090.71	13090.69: $^oP_{11} - 6$	3
	7637.586	13088.54		5
	7638.274	13088.36	13088.35: $^oP_{11} - 7$	2
	7639.571	13086.14	13086.13: $^oP_{11} - 8$	0
	7639.715	13085.89		3
	7640.353	13084.75		5
	7640.794	13084.04	13084.04: $^oP_{11} - 9$	0
	7641.020	13082.10	13082.12: $^oP_{11} - 10$	0
	7642.478	13081.16		0
	7644.612	13077.51		1
2-0	7743.859	12909.91	12909.86: $Q_1 - 5$	5
	7752.354	12895.76	12895.76: $P_1 - 8$	1
			12895.75: $^oQ_{11} - 6$	1
	7753.652	12893.60	12893.58: $P_1 - 2$	1
			12893.60: $P_1 - 1$	0
2-1	8609.223	11531.89	11531.90: $Q_2 - 9$	0
	8671.332	11529.09	11529.10: $Q_2 - 7$	0
	8692.580	11500.91	11500.87: $^oP_{11} - 1$	3
	8696.366	11495.90	11495.96: $^oQ_{11} - 2$	3
	8697.945	11493.81	11493.79: $^oQ_{11} - 3$	4
	8698.263	11493.39	11493.40: $Q_1 - 9$	4
	8699.397	11491.89	11491.88: $^oQ_{11} - 4$	4
	8700.670	11490.21	11490.20: $^oQ_{11} - 5$	5
	8700.684	11490.19	11490.20: $^oQ_{11} - 5$	5
	8701.481	11489.14	11489.15: $Q_1 - 8$	5
	8701.718	11488.83	11488.82: $^oQ_{11} - 0$	4
	8702.541	11487.74	11487.75: $^oQ_{11} - 7$	5
	8702.681	11487.56	11487.55: $^oP_{11} - 3$	0
	8703.093	11487.01	11486.98: $^oQ_{11} - 8$	0
	8703.457	11486.53	11486.54: $^oQ_{11} - 9$	3
	8704.540	11485.09	11485.10: $Q_1 - 7$	5
	8707.478	11481.23	11481.23: $Q_1 - 6$	5
	8710.118	11477.75	11477.75: $^oP_{11} - 5$	4
	8710.273	11477.54	11477.53: $Q_1 - 5$	5
	8742.950	11474.01	11474.01: $Q_1 - 4$	5
	8713.533	11473.25	11473.25: $^oP_{11} - 0$	1
			11473.20: $^oQ_{11} - 13$	
	8715.519	11470.64	11470.63: $Q_1 - 3$	5
	8716.718	11469.06	11469.06: $^oP_{11} - 7$	5
	8717.377	11468.19	11468.21: $P_1 - 11$	3
	8717.070	11467.41	11467.41: $Q_1 - 2$	5
	8718.571	11466.62	11466.67: $P_1 - 10$	3
	8718.654	11466.51	11466.52: $^oQ_{11} - 9$	4
	8719.537	11465.35	11465.39: $^oQ_{11} - 8$	4
	8719.562	11465.32	11465.32: $P_1 - 9$	5
	8719.562	11465.29		4
	8719.791	11465.02		3
	8720.251	11464.41	11464.42: $^oQ_{11} - 7$	5
	8720.284	11464.37	11464.36: $Q_1 - 1$	5
	8720.308	11464.34		4
	8720.419	11464.19	11464.20: $P_1 - 8$	5
	8720.848	11463.63	11463.62: $^oQ_{11} - 6$	4
	8721.155	11463.22	11463.24: $P_1 - 7$	5
	8721.327	11463.00	11462.99: $^oQ_{11} - 5$	4
	8721.718	11462.48	11462.45: $P_1 - 6$	5
			11462.47: $^oQ_{11} - 4$	
	8721.971	11462.15		4
	8722.007	11462.10	11462.10: $^oQ_{11} - 3$	5
	8722.220	11461.82	11461.84: $P_1 - 5$	5
			11461.82: $^oQ_{11} - 2$	
	8722.341	11461.67	11461.68: $^oQ_{11} - 1$	5
	8722.569	11461.37	11461.35: $P_1 - 4$	3
	8722.836	11461.01	11461.00: $P_1 - 3$	4
	8723.037	11460.72	11460.76: $P_1 - 1$	0
	8726.393	11456.42	11456.40: $^oP_{11} - 1$	1
	8728.430	11453.67	11453.66: $^oP_{11} - 2$	0
	8730.453	11451.02	11451.01: $^oP_{11} - 3$	4
	8732.394	11448.47	11448.45: $^oP_{11} - 4$	3
	8734.247	11446.04	11446.04: $^oP_{11} - 5$	5
	8735.995	11443.75	11443.74: $^oP_{11} - 6$	4
	8737.644	11441.59	11441.59: $^oP_{11} - 7$	5
	8739.162	11439.60	11439.61: $^oP_{11} - 8$	2
	8740.559	11437.78	11437.78: $^oP_{11} - 0$	3
	8742.917	11434.69	11434.72: $^oP_{11} - 11$	1
1-0	8845.349	11302.27	11302.28: $^oR_{11} - 1$	1
	8856.271	11288.34	11288.33: $Q_2 - 9$	0
	8858.470	11285.53	11285.53: $Q_2 - 7$	0
	8880.521	11257.51	11257.49: $^oR_{11} - 1$	1
	8884.527	11252.43	11252.40: $^oQ_{11} - 2$	1
	8886.204	11250.31	11250.29: $^oQ_{11} - 3$	3
	8886.378	11250.09	11250.07: $Q_1 - 9$	1
	8887.750	11248.35	11248.32: $^oQ_{11} - 4$	3
	8889.111	11246.63	11246.60: $^oQ_{11} - 5$	4
	8889.738	11245.84	11245.82: $Q_1 - 8$	1
	8890.243	11245.20	11245.18: $^oQ_{11} - 6$	2
	8891.133	11244.07	11244.06: $^oQ_{11} - 7$	3
	8891.769	11243.27	11243.24: $^oQ_{11} - 8$	1
	8892.140	11242.79	11242.77: $^oQ_{11} - 9$	1
			11242.83: $^oQ_{11} - 11$	
	8892.040	11241.70	11241.76: $Q_1 - 7$	3
	8896.001	11237.92	11237.90: $Q_1 - 6$	3
	8898.930	11234.22	11234.19: $Q_1 - 5$	3

TABLE 1 (continued)

Band	λ_{lab} (Å)	σ_{lab} (cm ⁻¹)	σ_{spont}^a (cm ⁻¹)	Intensity
	8800.078	11234.04	11234.04: $^2P_{11} - 5$	2
	8901.733	11230.68	11230.66: $Q_1 - 4$	3
	8902.711	11229.45	11229.43: $^2P_{11} - 6$	0
	8904.419	11227.30	11227.27: $Q_1 - 3$	4
	8906.097	11225.18	11225.17: $^2P_{11} - 7$	3
	8906.649	11224.49	11224.46: $P_1 - 11$	1
	8906.994	11224.05	11224.03: $Q_1 - 2$	2
	8907.920	11222.88	11222.86: $^2Q_{11} - 9$	1
	8908.808	11221.77	11221.76: $^2Q_{11} - 8$	2
	8908.878	11221.68	11221.65: $P_1 - 9$	3
	8909.451	11220.90	11220.94: $Q_1 - 1$	3
	8909.527	11220.80	11220.83: $^2Q_{11} - 7$	3
	8909.750	11220.58	11220.56: $P_1 - 8$	0
	8910.132	11220.10	11220.08: $^2Q_{11} - 6$	2
	8910.480	11219.66	11219.64: $P_1 - 7$	3
	8910.612	11219.49	11219.47: $^2Q_{11} - 5$	3
	8911.001	11219.00	11218.98: $^2Q_{11} - 4$	3
	8911.063	11218.93	11218.88: $P_1 - 6$	3
	8911.280	11218.65	11218.63: $^2Q_{11} - 3$	3
	8911.502	11218.37	11218.37: $^2Q_{11} - 2$	3
	8911.638	11218.33	11218.30: $P_1 - 5$	3
	8911.608	11218.24	11218.21: $^2Q_{11} - 1$	3
	8911.808	11217.88	11217.85: $P_1 - 4$	0
	8912.139	11217.57	11217.57: $^2P_{11} - 9$	4
			11217.52: $P_1 - 3$	
	8918.033	11210.16	11210.13: $^2P_{11} - 2$	0
	8920.184	11207.45	11207.43: $^2P_{11} - 3$	2
	8922.240	11204.80	11204.83: $^2P_{11} - 4$	2
	8924.223	11202.38	11202.36: $^2P_{11} - 5$	3
	8926.099	11200.03	11199.99: $^2P_{11} - 6$	2
	8927.865	11197.81	11197.79: $^2P_{11} - 7$	4
	8929.309	11195.75	11195.73: $^2P_{11} - 8$	1
	8931.019	11193.86	11193.82: $^2P_{11} - 9$	3
	8933.580	11190.65	11190.62: $^2P_{11} - 11$	1
3-3	9653.80	10355.68	10355.67: $P_1 - 11$	1
			10355.69: $^2Q_{11} - 5$	
	9658.46	10350.78	10350.75: $Q_1 - 7$	2
	9665.99	10342.72	10342.74: $Q_1 - 5$	4
	9672.70	10335.54	10335.53: $Q_1 - 3$	3
	9677.53	10330.33	10330.33: $^2Q_{11} - 7$	2
	9679.43	10328.35	10328.36: $^2Q_{11} - 5$	4
	9680.61	10327.10	10327.12: $^2Q_{11} - 3$	3
	9685.52	10311.21	10311.18: $^2P_{11} - 5$	1
	9698.79	10307.74	10307.73: $^2P_{11} - 7$	0

* Calculated from Dicke and Heath¹² level scheme.

TABLE 2. Stimulated Emission Lines of the Second Positive System

Band	λ_{air} (Å)	σ (cm ⁻¹)	σ spont ^a (cm ⁻¹)	Intensity
0-0	3371.429	29652.50	29652.43: P ₂ ' - 8	5
	3371.421	29652.57	29652.44: P ₂ - 9	5
	3371.392	29652.82	29652.78: P ₂ - 7	5
	3371.366	29653.05	29652.96: P ₂ ' - 10	4
	3371.307	29653.57	29653.49: P ₂ ' - 6	6
	3371.266	29653.93	29653.83: P ₂ - 11	1
	3371.172	29654.76	29654.67: P ₂ - 5	5
	3371.143	29655.01	29654.95: P ₂ ' - 9	5
	3371.135	29655.08	29654.98: P ₂ - 10	3
	3371.121	29655.21	29655.05: P ₂ ' - 12	1
	3371.113	29655.28	29655.24: P ₂ - 8	2
	3371.082	29655.55	29655.47: P ₂ - 11	0
	3371.075	29655.61	29655.51: P ₂ ' - 11	1
	3371.037	29655.94	29655.93: P ₂ ' - 7	5
	3370.986	29656.39	29656.33: P ₂ ' - 4	5
			29656.34: P ₂ - 12	
	3370.919	29656.98	29656.84: P ₂ - 6	5
	3370.820	29657.80	29657.65: P ₂ - 10	1
	3370.816	29657.80	29657.75: P ₂ - 11	2
	3370.812	29657.92	29657.85: P ₂ ' - 10	2
	3370.797	29658.06	29657.98: P ₂ - 9	3
	3370.782	29658.19	29658.13: P ₂ ' - 9	1
	3370.758	29658.40	29658.36: P ₂ ' - 5	5
	3370.749	29658.48	29658.38: P ₂ ' - 12	5
	3370.726	29658.68	29658.64: P ₂ - 8	2
	3370.714	29658.79	29658.73: P ₂ ' - 8	4
	3370.677	29659.10	29658.99: P ₂ - 13	0
	3370.619	29659.62	29659.58: P ₂ - 7	4
	3370.608	29659.72	29659.66: P ₂ ' - 7	2
	3370.562	29660.12	29660.00: P ₂ - 4	4
	3370.555	29660.19	29660.18: P ₂ - 14	4
0-1	3370.474	29660.90	29660.83: P ₂ - 0	1
	3370.466	29660.97	29660.94: P ₂ ' - 0	3
	3370.312	29662.32	29662.19: P ₂ ' - 3	3
	3370.295	29662.47	29662.41: P ₂ - 5	3
	3370.288	29662.54	29662.48: P ₂ ' - 5	1
	3370.081	29664.36	29664.32: P ₂ - 4	2
	3370.075	29664.41	29664.40: P ₂ ' - 4	3
	3370.027	29664.83	29664.83: P ₂ - 2	1
	3369.835	29666.52	29666.46: P ₂ - 3	2
	3369.823	29666.63	29666.55: P ₂ ' - 3	1
	3369.552	29669.01	29668.95: P ₂ ' - 2	1
	3369.541	29669.11	29669.08: Q ₂ ' - 2	2
	3570.955	27948.76	27948.82: P ₂ - 7	5
			27948.80: P ₂ ' - 8	
	3570.899	27949.20	27949.21: P ₂ - 9	5
			27949.26: P ₂ ' - 6	
	3570.778	27950.15	27950.10: P ₂ - 5	2
			27950.08: P ₂ ' - 10	
	3570.613	27951.43	27951.44: P ₂ - 11	3
			27951.43: P ₂ - 9	
			27951.38: P ₂ - 8	
			27951.45: P ₂ ' - 9	
			27951.42: P ₂ ' - 8	
	3570.571	27951.76	27951.74: P ₂ - 7	2
			27951.79: P ₂ ' - 7	
	3570.320	27953.72	27953.74: P ₂ - 5	2
			27953.79: P ₂ ' - 5	
	3570.250	27954.27	27954.28: P ₂ - 9	2
	3570.194	27954.71	27954.78: P ₂ - 11	2
	3570.980	27956.38	27956.34: P ₂ - 6	2
			27956.42: P ₂ ' - 6	

^a Calculated from Dieke and Heath¹⁰ level scheme.

CROSSED FIELD LASER

FIGURE 2

Schematic of apparatus in which the electric field is perpendicular to the stimulated emission. Circuit parameters were typically: $L = 100 \text{ nH}$; $C = 0.03 \text{ }\mu\text{F}$; initial capacitor voltage 15 to 25 kV.

CROSSED FIELD LASER BEAM PROFILE

FIGURE 3

Photographs of the output beam from the crossed field laser. The beam divergence of 10^{-3} rad is determined by the geometrical aperture of the discharge channel.

that the discharge is axial and results in a finite volume rate of excitation which causes the laser pulse to begin 30 to 50 nsec. after the current pulse. Gaseous breakdown and excitation do not occur simultaneously throughout the tube; the initial breakdown is at the high voltage terminals and travels down the axis of the tube towards the ground terminal. The velocity of this pressure dependent excitation wave was measured by Geller, Altmann, and DeTemple. The reason for the positioning of the laser tubes into two sections was to ensure excitation of the entire laser medium within a 40 nsec. time span. Leonard, via a transverse discharge, attained a large volume excitation rate independent of a slow ionization wave velocity. This was also experimentally demonstrated by Shipman⁽¹²⁾ who found that the time delay between the current pulse and light output was not measurable (< 1 nsec.) with transverse excitation. His experimental device consisted of a flat-plate Blumlein pulse line circuit containing a laser cavity (see page 16). This circuit was employed in an effort to cut down on the inductance. In an attempt to improve the coherence and unidirectionality of the laser output, Shipman inverted the plasma by a traveling wave of excitation current starting from one end of the laser tube and progressing toward the other with a velocity equal the velocity of light. The plasma at the 'cold' end would emit spontaneous radiation isotropically, but subsequent elements would be preferentially stimulated to emit toward the output end by the amplified emission of these finite elements, before having time to emit very much spontaneous radiation in other directions. This wave could be generated by a sequential firing of solid dielectric switches (see figure 8) or by having graduated length cables connected to the laser tube and fed by one switch. By this method, Shipman

CROSSED FIELD LASER POWER OUTPUT

FIGURE 4

Laser power output vs active discharge length. The calibrated photomultiplier and the "rat's nest" calorimeter

measurements of the maximum power output agree to within 50%. The average of the two measurements is 200 kW.

COAXIAL TRANSMISSION LINE GAS LASER

FIGURE 5

COAXIAL LINE LASER: IONIZATION WAVE SPEED

FIGURE 6

Velocity of luminous front of the ionization wave in nitrogen

COAXIAL LINE LASER: DISCHARGE VOLTAGE, CURRENT VS TIME

FIG. 7 Open-circuit
voltage as a function of
time

SWEEP SPEED 20 NS/CM

VERTICAL SENSITIVITY 18,000 VOLT/CM

SWEEP SPEED 20 NS/CM

VERTICAL SENSITIVITY 1780 AMPERES/CM

FIGURE 7

Two consecutive exposures of current as a function of time. The upper curve has the coaxial return as shown in Fig. 1. The lower curve has the current return through a separate noncoaxial lead. Stimulated emission was observed only for the former, i.e., the faster rising current pulse.

BLUMLEIN PULSE GENERATOR - TRANSVERSE LASER

FIGURE 8

Schematic of the Blumlein pulse generator with flat-plate transmission lines used to pump molecular nitrogen and neon lasers. Bottom plate: 183-cm wide and 366-cm long. Dielectric: 0.15-cm thick Mylar submerged in water. Generator impedance: 0.5 Ω ; voltage applied to top plates: ~75 kV.

achieved a 10:1 power output ratio between the two ends of the laser cavity and a 2.1 Mw, 4 nsec. pulse of 3371 Å radiation at the high power end.

Upon reflection we realize that in order to maximize the power output from our laser we would want to create the largest inversion possible, and then lase before radiative decay sets in. We would like to produce as large a number of exciting electrons, in as short a time as possible. To do this, we want nitrogen to breakdown at very high voltages and to produce very high currents ($\sim 10^4$ A/cm² current density⁽¹¹⁾, $\sim 10^{12}$ A/sec current rise⁽¹¹⁾). The desired macroscopic circuit behaviour is only a reflection of a vast number of microscopic ionization and excitation events. Our laser gas remains nonconducting until breakdown, when it becomes very conducting and where the amount of current that the gas will conduct is controlled only by the external circuit. Any improvement we make to the circuit conductivity will result in a higher power, more efficient laser.

Most of the experiments in nitrogen UV lasers since Heard can be evaluated in the context of power maximization through circuit optimization. Geller, Altmann, and DeTemple have explicitly and repeatedly addressed themselves to the specific problem of circuit impedance reduction. In 1968⁽¹¹⁾ they considered two effects:

- 1) a laser under certain circumstances can do its own switching thereby eliminating additional inductances associated with extra switches,
- 2) the maximum power results (for a parallel plate transmission line, see page 18) when the thickness of the insulation of the pulse forming line is at a minimum value consistent with that necessary

to avoid dielectric breakdown at the voltage at which the laser gas discharges.

For the transmission line connected to the laser tube to also serve as a pulse forming line, some switching is necessary to allow for the necessary voltage buildup before discharging through the laser gas. All switches add inductance; however, in the design of Geller, Altmann and DeTemple, the pulse forming line is pulse charged through the spark gaps from a storage element, and the finite amount of time which elapses between the sudden application of voltage to the laser gas and the occurrence of breakdown (the breakdown time) permit charging the pulse forming line to a voltage much larger than the D.C. breakdown value of the gas. In the sense that the gas remains nonconducting until the discharge begins, the gas acts as its own switch. Furthermore, if the two-way transit time of the pulse forming line is larger than the time associated with the important excitation processes, the laser is to or first approximation independent of the inductance of the pulse charging switch. Thus for any value of breakdown voltage, the initial current rise is larger when the spark gap switch is in the charging circuit than when it is adjacent to the laser tube.

For minimum impedance, or maximum laser current, the dielectric between the plates should be no thicker than required to withstand the maximum voltage applied to the line in the self-switching configuration; this is the breakdown voltage.

BLUMLEIN PULSE GENERATING CIRCUIT DIAGRAM

FIGURE 9

Schematic diagram of a pulsed nitrogen laser.

SKETCH OF BLUMLEIN PULSED TRANSVERSE LASER

FIGURE 10

laser tube and its power source. Component values are: storage line length, 170 cm; width, 107 cm; impedance, 0.10 Ω . Pulse forming line impedance was varied between 0.080 Ω and 0.27 Ω . Storage line transit time, 10 nsec; pulse forming line transit time, 3.5 nsec; switch inductance, 20 nH (estimated).

SKETCH OF BLUMLEIN PULSED TRANSVERSE LASER

FIGURE 11

Details of construction of pulse forming line and laser tube.

MODELS OF THE PULSED, MOLECULAR NITROGEN LASER

Gerry⁽¹²⁾; Ali, Kolb, and Anderson⁽¹⁴⁾; and Ali⁽¹⁵⁾ have constructed theoretical models of the pulsed nitrogen laser. These models differ only in the number and type of initial and simplifying assumptions, but all predict characteristics that are fairly well matched to existing laser systems. The inversion mechanisms postulated appear to be in error because recent research has indicated some of the conceptions of these authors to be in error and has brought to light the fundamental nature of certain neglected phenomena. The questions of inversion mechanisms will be discussed in the following section.

Using insights gained from Leonard's research and in an attempt to match his data, Gerry constructed a simple theory of a pulsed, collisionally pumped, three level laser. He assumed that the $C^3 \Pi_u n = 0$ state was overpopulated by direct electron impact from groundstate nitrogen ($X^1 \Sigma_g^+$), and that the excitation function (cross-section) was that measured by Steward and Gabathuler⁽¹⁶⁾. Since he could not find a measured excitation function for $B^3 \Pi_g n = 0$, he assumed that the ratio of $B^3 \Pi_g$ to $C^3 \Pi_u$ cross section was equal to the ratio of the Frank-Condon factor for overlap of the $B^3 \Pi_g$ and $C^3 \Pi_u$ states with the ground state. This yielded a smaller cross section by a factor of ten. The shape was assumed to be similar since both overlaps involved singlet-triplet excitation. These cross sections, and an ionization cross section taken from Brown⁽¹⁷⁾, were all integrated over an electron Maxwellian velocity distribution to obtain excitation and ionization rates as a function of electron temperature. The circuit was assumed to include a capacitance C originally

charged to a voltage V_C , a switch closing at $t = 0$, an inductance L , and a time varying resistance $R(t)$ representing the discharge plasma resistance (calculated from mobility data). Gerry's equations are circuit equations:

$$V_C = LA \frac{dj}{dt} + \frac{V_C^2}{j} \quad (1)$$

$$\frac{dV_C}{dt} = \frac{-jA}{C} \quad (2)$$

ionization rate equation:

$$\frac{dN_e}{dt} = N_e N_0 \overline{\sigma_i V_e} \quad (3)$$

excitation rate equations:

$$\frac{dN_C}{dt} = N_e N_0 \overline{\sigma_{0C} V_e} - \frac{N_C}{T_C} - P \quad (4)$$

$$\frac{dN_B}{dt} = N_e N_0 \overline{\sigma_{0B} V_e} + \frac{N_C}{T_C} + P - \frac{N_B}{T_B} \quad (5)$$

electron energy equation:

$$\frac{d}{dt} \left\{ \frac{3}{2} N_e k T_e \right\} = \rho j^2 - N_e N_0 \overline{\sigma_i V_e} E_i - \sum_k N_e N_0 \overline{\sigma_{Xk} V_e} E_k \quad (6)$$

where:

V_C = voltage on the capacitor,

- j = current density,
 $\rho = \rho(kT_e, n_e)$ plasma resistivity,
 L = discharge length,
 A = discharge area,
 v_e = electron speed
 n_e = electron density,
 n_0 = H_2 ground state density (which is assumed constant),
 n_C = density of H_2 in the $C^3\Pi_u$ state,
 n_B = density of H_2 in the $B^3\Pi_g$ state,
 τ_C = radiative lifetime of $C^3\Pi_u$ (~ 40 nsec.),
 τ_B = radiative lifetime of $B^3\Pi_g$ (~ 10 sec.),
 P = laser power density in photons/cm² sec,
 I_i = ionization energy for the H_2 molecule,
 I_L = energy loss for miscellaneous excitations,
 Bar quantities are the averages described earlier.

Gerry's simplifying assumptions were:

- a) to include only excitation to $B^3\Pi_g$, $C^3\Pi_u$ and ionization as energy loss processes;
- b) to consider a large enough system so that the transition is saturated, $n_C - n_B \ll n_B$.

Gerry computed P for saturation conditions by setting $n_C = n_B \equiv n$ in the excitation rate equations (4) and (5); taking their sum and difference to obtain two equations:

$$\frac{dn}{dt} + \frac{n}{2\tau_B} = \frac{1}{2} \left\{ n_e n_0 \overline{\sigma_{oB} v_e} + n_e n_0 \overline{\sigma_{oC} v_e} \right\} \quad (7)$$

$$P = \frac{1}{2} \left\{ N_e N_0 \overline{\sigma_{oc} V_e} - \frac{2 - (T_c/T_B)}{T_c} N - N_e N_0 \overline{\sigma_{ob} V_e} \right\}. \quad (8)$$

These equations were solved numerically using circuit parameters and densities N_0 characteristic to one of Leonard's laser amplifiers. Curves of saturated power density and current density versus time were in good agreement with experiment, efficiency was not, viz.:

	<u>THEORY</u>	<u>EXPERIMENT</u>
<u>Peak Power</u> <u>Density (KW/cm²)</u>	2.1	2.
<u>Efficiency</u> <u>Formula</u>	energy at $\frac{\int n j^2 dt}{\text{pulse}}$	$\frac{2 \times 10^3 \Delta t}{\int_0^{T_{\text{Pulsed}}} j \cdot E dt}$
<u>Efficiency</u>	2.1%	.6 - .9%

Because of the large number of energetic electrons in the 10 eV range, and the significant amount of inversion in the N_2 laser plasma, electron-molecule collisions for deexcitation and ionization from $C^3\Pi_u$ and electron-molecule vibrational excitation collisions with $X^1\Sigma_g^+$ should not be ignored; the cross sections are far from zero. Ali, Kolb, and Anderson performed a refined version of Gerry's analysis in which:

- collisional deexcitation ("mixing") and collisional ionization from $C^3\Pi_u$ were considered,
- calculations of the power density were made with and without the saturation assumptions.

The general rate equations for the laser system are:

$$\begin{aligned} \frac{dN_2}{dt} = & X_{13} N_1 + X_{23} N_2 - \left\{ Y_{31} + Y_{32} + T_{31}^{-1} + T_{32}^{-1} \right\} N_3 \\ & - R_{32}^{-1} \left[N_3 - \frac{g_3}{g_2} N_2 \right] \end{aligned} \quad (9)$$

$$\begin{aligned} \frac{dN_2}{dt} = & X_{12} N_1 + \left\{ T_{32}^{-1} + Y_{32} \right\} N_3 - \left\{ T_{21}^{-1} + Y_{21} + X_{23} \right\} N_2 \\ & + R_{32}^{-1} \left[N_3 - \frac{g_3}{g_2} N_2 \right] \end{aligned} \quad (10)$$

$$\frac{dN_1}{dt} = - \left\{ X_{12} + X_{13} \right\} N_1 + \left\{ T_{21}^{-1} + Y_{21} \right\} N_2 + \left\{ T_{31}^{-1} + Y_{31} \right\} N_3 \quad (11)$$

where

- N_3 = upper laser level ($C^3 \Pi_u$) density,
- N_2 = lower laser level ($B^3 \Pi_g$) density,
- N_1 = ground state ($X^1 \Sigma_g^+$) density,
- X_{ij} = rate of collisional excitation by electron impact from level i to j , ($i < j$),
- Y_{ji} = rate of collisional deexcitation from j to i ,
- T_{ji}^{-1} = rate of radiative decay from j to i ,
- R_{ji}^{-1} = rate of induced emission from j to i ,
- g_3 = degeneracy (statistical weight) of $C^3 \Pi_u$,
- g_2 = degeneracy (statistical weight) of $B^3 \Pi_g$.

For the UV nitrogen laser $g_3 = g_2 = 1$ as we only consider the 0-0 band (3371 Å), the more intense of the two observed. Ali, Kolb, and Anderson made the following simplifying assumptions:

- a) induced emission and absorption rates, and collisional deexcitation rates from the laser levels to the ground state were neglected,
- b) $T_{31} \gg T_{32}$,
- c) $X_{13} > X_{12}$,
- d) $T_{21} \gg T_{32}$.

b) and d) are a consequence of the metastability of $B^3 \Pi_g$; $T_{21} \sim 10 \mu\text{sec}$, $T_{32} \sim 40 \text{ nsec}$. c) is Gerry's old assumption that electron impact excitation of $C^3 \Pi_u$ is favored over $B^3 \Pi_g$. Using these assumptions one can sum the rate equations for the laser levels to get ((9) + (10)):

$$\frac{d}{dt} \{N_3 + N_2\} = X_{13} N_1. \quad (12)$$

Assuming, as Gerry did, that N_1 and the pumping rate are constant:

$$N_3 + N_2 = X_{13} N_1 t. \quad (13)$$

Using the rate equation for N_3 (9) modified by the conditions stated, and equation (13):

$$\frac{dN_3}{dt} = X_{13} N_1 + [X_{13} N_1 t - N_3] X_{23} - [T_{32}^{-1} + Y_{32}] N_3. \quad (14)$$

The solution of equation (14) is:

$$N_3 = \frac{N_1 X_{13} (Y_{32} + T_{32}^{-1})}{(T_{32}^{-1} + Y_{32} + X_{23})^2} \left\{ 1 - e^{-[T_{32}^{-1} + Y_{32} + X_{23}]t} \right\} + \frac{N_1 X_{13} X_{23} t}{T_{32}^{-1} + Y_{32} + X_{23}}. \quad (15)$$

For small times one can write equations (15) by expanding the exponential up to terms in t^2 as:

$$N_3 = N_1 X_{13} t - N_1 X_{13} \left\{ Y_{32} + T_{32}^{-1} \right\} \frac{t^2}{2} . \quad (16)$$

Using this last equation and equation (13) relating N_1 , N_2 , N_3 , we get an expression for N_2 in terms of N_1 :

$$N_2 = \frac{1}{2} N_1 X_{13} \left\{ Y_{32} + T_{32}^{-1} \right\} t^2 . \quad (17)$$

For this three level laser, the inversion or threshold criterion is that

$$N_3 > N_2 . \quad (18)$$

For this to be true, equations (16) and (17) dictate:

$$\frac{2}{Y_{32} + T_{32}^{-1}} > t \quad (19)$$

or, inversion takes place in a time small compared to $\left\{ Y_{32} + T_{32}^{-1} \right\}^{-1}$. For a negligible collisional mixing rate the criterion becomes:

$$\frac{2}{T_{32}^{-1}} > t$$

$$2 T_{32} > t \quad (20)$$

or, inversion takes place in a time small compared to the radiative decay time of $C^2 H_4$. It is evident that for high electron densities ($> 6 \times 10^{14}$

cm^{-3} as estimated by Ali, Kolb, and Anderson) γ_{32} will exceed the radiative decay rate τ_{32}^{-1} .

Consider a nitrogen molecule as a lasing system coupled to an electrical circuit consisting of a capacitor C originally charged to voltage V_0 , and of fixed external resistance R_e and inductance L. The lasing media, as part of the electric circuit, acts as a variable resistance $R(t)$ which is the sum of resistances due to ion-electron (plasma) and electron-neutral collisions. Since neutral densities are by far superior to charged particle densities, electron-neutral collisions are the predominant contribution to laser media resistance. Our set of equations for the laser circuit is then: rate equations:

$$\frac{dN_3}{dt} = X_{13} N_1 + X_{23} N_2 - (\tau_{32}^{-1} + \gamma_{32}) N_3 - R_{32}^i (N_3 - N_2) \quad (21)$$

$$\begin{aligned} \frac{dN_2}{dt} = & X_{13} N_1 + N_3 (\tau_{32}^{-1} + \gamma_{32}) \\ & - (\tau_{21}^{-1} + X_{23}) N_2 + R_{32}^i (N_3 - N_2) \end{aligned} \quad (22)$$

$$\text{equation (11) for } \frac{dN_1}{dt} = 0 \text{ (} N_1 = \text{constant)}.$$

Note the similarity of these equations to Gerry's (4), (5). The energy density at the laser frequency can be expressed as:

$$\frac{1}{E_l} \frac{dp}{dt} = N_3 \tau_{32}^{-1} + R_{32}^i (N_3 - N_2) \quad (23)$$

where E_1 is the energy of a laser photon.

The ionization rate is:

$$\frac{dN_e}{dt} = N_1 N_e S \quad (24)$$

where S is the ionization rate coefficient (see equation (3)). The energy equation (rate at which electrons are heated) is

$$\begin{aligned} \frac{d}{dt} \left\{ \frac{3}{2} N_e T_e \right\} &= nI^2 R(t) - N_1 \{ X_{13} E_{31} + X_{12} E_{21} \} \\ &\quad - N_e N_1 S E_a - N_e N_1 \overline{\lambda_v E_v} \\ &\quad - E_{32} \{ N_2 X_{32} - N_3 Y_{32} \} \end{aligned} \quad (25)$$

where

E_{ji} = energies of transitions $j \rightarrow i$,

E_a = ionization energy from $X^1 \Sigma_g^+$,

T_e = electron temperature,

The electrons are assumed to be in a Maxwellian distribution E_{ji} , E_a , T_e are expressed in eV.

I = total current

λ_v = conversion factor to eV per unit volume

Equation (6) is very similar to this.

The circuit equation is:

$$L \frac{dI}{dt} + \{ R_e + R(t) \} I = V_0 \int_0^t \frac{Idt}{C} \quad (26)$$

(see equation (1) and (2)).

The rates and cross sections used by Ali, Kolb, and Anderson were found from the same sources or by the same techniques as Gerry; deexcitation rates were found by invoking detailed balancing. If the saturation assumptions are made so that:

$$a) \quad N_2 = N_2 \ll N_1 = N_3 = N_2 = N_1$$

$$b) \quad k_{32}^{-1} (N_3 - N_2) = P$$

and P is the saturation power output per unit volume. When the sum and difference of equations (21) and (24) are formed, we find:

$$\frac{dN_1}{dt} = \frac{N_1}{2\tau_{21}} - \frac{1}{2} \{ \lambda_{13} + \gamma_{12} \} N_1 \quad (27)$$

$$P = \frac{1}{2} \left\{ (\lambda_{13} - \gamma_{12}) N_1 + \frac{N_1}{\tau_{21}} \right\} = \{ \tau_{32}^{-1} + \gamma_{32} - \lambda_{23} \} N_1 \quad (28)$$

which are basically the same equations as (7) and (8). Ali, Kolb, and Anderson show that for a gas pressure of 30 TORR, saturation takes place in .3 nsec from the onset of the discharge, so the saturation approximation is a justifiable one. Calculations of saturation output power density were performed using data by Shipman, a comparison of results yields:

	<u>THEORY</u>	<u>EXPERIMENT</u>
<u>Peak Power</u> <u>Density (TW/cm²)</u>	26.2	26.
<u>Half Width of</u> <u>Power Pulse (nsec)</u>	3.9	3.2

when collisional ionization from $C^3 \Pi_u$ is also considered, the results are:

<u>Peak Power</u>	25.4
<u>Density (KW/cm²)</u>	
<u>Half Width of</u>	3.5
<u>Power Pulse (nsec)</u>	

INVERSION MECHANISMS

The originally assumed inversion mechanism for the infrared nitrogen laser was a two step process.(2,7) On breakdown of the gas, the impact of electrons with ground state molecules preferentially excites singlet states since there is no change in multiplicity. Many of these decay to the first excited ($a^1 \Pi_g$) state, which is both radiation trapped and weakly metastable. Collisions between molecules in this state and the ground state form molecules in the $B^3 \Pi_g$ triplet state; these decay to the $A^3 \Sigma^+u$ state emitting the first positive system. To summarize:

The inversion mechanism of the UV nitrogen laser was believed to be single step; collisional pumping of a preferential nature to the upper laser level. Recent work on nitrogen lasers summarized in C. A. Massone(6) et.al. and on electron-molecule resonance collisions summarized in Schulz(18) bring both of the previous inversion mechanisms into serious doubt.

The electron impact excitation of electronic levels $C^3 \Pi_u$, $B^3 \Pi_g$, $A^3 \Sigma^+u$

can proceed via several channels. Schulz(18) and McDaniel(19) show that the cross section for the formation of a negative ion N_2^- which can quickly decay ($\sim 10^{-13}$ sec) into one of the above states is appreciable. The cross sections for excitation of vibrational levels in $X^1 \Sigma_g^+$ via a $2\Pi_g$ resonance (see page 33, figure 12) is approximately $1\text{\AA}^2$.

Excitation of the $C^3 \Pi_u$ state would seem to be highly probable for electron energies of the order of 11 e.v. as there are several shape and Feshbach resonances in this range. This compound mechanism is a way in which a population inversion could be created between the $C^3 \Pi_u$ and $B^3 \Pi_g$ states.

Excitation cross section studies(6) for electronic states of nitrogen, show that the cross section of the $B^3 \Pi_g$ state is larger than that of the $C^3 \Pi_u$ state; it is not ten times lower as had previously been assumed. The $B^3 \Pi_g$ state is much more strongly excited by electron impact than the $A^3 \Sigma^+$ state, which implies that metastable species in the $A^3 \Sigma^+$ state are formed mostly by cascading from $B^3 \Pi_g$ or higher states and not by direct excitation. Molecular nitrogen in $A^3 \Sigma^+$ is also produced by volume recombination of nitrogen atoms.

Massone et.al.(6) observed the temporal behavior of powerfully pumped nitrogen discharge lasers, recording a series of radiative emissions from the laser gas. Just after the discharge was initiated, ($\sim 10^{-8}$ sec) spontaneous, superradiant and laser emission in the ultraviolet was observed. This was shortly followed (at $\sim 10^{-7}$ sec) by infrared emission. At later intervals of time (~ 70 psec) emission from atomic nitrogen transitions and ($\sim 10^4$ psec) transitions of the First Negative system of N_2^+ were observed.

N_2 EXCITATION CHANNELS VIA SHAPE & FESHBACH RESONANCE

FIGURE 12

Energy Level Diagram of N_2 and N_2^+ in Schematic Form. Energy levels in box marked N_2 and the compound states are divided into shape resonance and Feshbach resonances. Some, but not all, delay channels are listed by arrows. Grandparents of Feshbach resonances are connected by dashes.

RADIATION TYPE VS. TIME - N₂ DISCHARGE

Figure 13

The first ionization potential of molecular nitrogen is over fifteen electron volts; hence for electron energies of the order of 11 e.v. in a self sustaining discharge, a significant number of molecule-molecule ionization collisions must occur (the Penning effect⁽²⁾). By using short pulsed discharges for exciting molecules nitrogen, nitrogen atoms can be observed in the plasma, and after that, by volume atom-atom recombinations, nitrogen molecules in metastable states such as $a' \ ^1\Sigma^+u$, $A^3 \ ^3\Sigma^+u$, $3\Delta_u$. The interactions between excited molecules in these metastable states or electron impact with molecules in the $a' \ ^1\Sigma^+u$, $A^3 \ ^3\Sigma^+u$ and $3\Delta_u$ states is most probable via the formation of N_2^+ molecules. Consequently the ionization of the nitrogen molecule occurs after the ultraviolet laser emission of the $C^3 \ \Pi_u + B^3 \ \Pi_g$ transition is observed. For this reason it is not well justified to consider ionization (of $C^3 \ \Pi_u$) in the overpopulation mechanism of the $C^3 \ \Pi_u$ state. Hence, the inversion mechanism of the ultraviolet nitrogen laser is most probably via negative ion formation. Because of the many electron energy loss channels provided by N_2 , and because of its large density fraction, molecule-molecule collisions must be considered to permit self-sustained discharge operation. The bulk of (positive) nitrogen ions necessary for conducting the discharge

current pulse are created long ($10^4 \mu\text{sec}$) after lasing ($\sim 40 \text{ ns}$) occurs. These ions must recombine into neutrals before the pulse can be repeated. Thus, the duty cycle of a pulsed nitrogen laser is limited to 100 Hz ($10^4 \text{ ns} = 10^{-2} \text{ sec} \Rightarrow 100 \text{ Hz}$).

For the infrared nitrogen laser, the evidence (6) seems to indicate that direct electron impact excitation is the mechanism responsible for the overpopulation of the $B^3 \Pi_g$ state.

APPLICATIONS

The nitrogen laser can be employed where nanosecond pulses of kilowatt to megawatt ultraviolet power (10^{-6} to 10^{-2} joules or greater) at repetition rates of not greater than 100 cps and efficiencies of fraction of a percent are desired. (Atoms and molecular ions must recombine before being tapped again.)

One application of the nitrogen laser is as a pumping source of a dye cell for dye laser operation. The paper by Hansch⁽²²⁾ and figure 14 on pages 37, 38, 40, amply demonstrate this application. For the study of power dependent, nonlinear effects in crystals or other electric-optical materials, the nitrogen laser can be used, if pulsed output can be tolerated. Probably because of its low efficiency (and/or high input requirements) the nitrogen laser does not seem to have found a great deal of commercial applications.

SUPER RADIANT NITROGEN LASERS

Molectron UV-Series Pulsed Nitrogen Lasers

The Molectron Model UV-Series Pulsed Nitrogen Laser product line provides the highest peak power and pulse energy levels commercially available. The range of outputs offered are designed to satisfy a broad cross section of system requirements.

Model UV-1000 and UV-600

A state-of-the-art discharge channel design provides high peak power optimized for dye laser pumping while still retaining good performance at higher repetition rates. In this way the lasers offer the highest peak and RMS power levels commercially available.

High peak current coupled with low electro-magnetic interference (EMI) is provided by a fully coaxial pulse system employing a ceramic hydrogen thyatron, low inductance storage capacitor and an extremely low impedance transmission line to the discharge channel.

Simplicity of operation together with maximum versatility is provided by a single panel including all controls for routine operations. Gas flow rate, pressure and voltage controls may be present and thereafter be automatically shut on and off by single pushbutton control. Adjustment to provide different performance characteristics may be accomplished at any time.

Model UV-300

The UV-300 Nitrogen Laser provides the highest peak power commercially available (with the exception of the UV-1000 and UV-600) in a well engineered, low-cost system.

The laser utilizes a hydrogen thyatron switched pulser with multiple coaxial cables feeding secondary energy storage capacitors at the discharge channel. The channel incorporates a low inductance electrode structure for rapid gas excitation.

A separate power supply provides a range of peak charging voltages and the system is completely safety interlocked.

Dye Laser Pumping

Power levels up to 1 MW permit the broadest possible tuning range and narrowest emission linewidths to be obtained for a wide variety of dyes and dye lasers. This performance can only be achieved at high peak power and

sufficiently low repetition rate to avoid dye and sample heating.

For example the Molelectron DL-Series Dye Lasers pumped with any of the Molelectron Nitrogen Lasers provide 0.001 nm resolution from 350 to 740 nm (frequency doubled down to 250 nm with the same resolution).

	UV-1000	UV-600	UV-300
Peak Power at 10 Hz	1 MW	600 kW	300 kW
Repetition Rate	1 - 50 Hz	1 - 50 Hz	1 - 50 Hz
RMS Power at 25 Hz	500 W	300 W	100 W
Average Power at 25 Hz	250 mW	150 mW	50 mW
Pulse Width	10 ns	10 ns	14 ns
Beam Dimensions	6 mm (vert) 25 mm (horiz)	6 mm (vert) 25 mm (horiz)	6 mm (vert) 32 mm (horiz)
Beam Divergence	< 1 mrad x < 7 mrad (half angle)		

Peak Power vs. Average Power

The single most significant factor governing dye laser range and resolution is the peak power of the pumping laser. Once above the dye threshold, the signal-to-noise ratio increases linearly with peak power (assuming that

dominant noise sources are in the detection system).

For repetitive pulses, once the dye is above threshold, the signal-to-noise ratio of the dye laser output increases linearly with RMS laser power and only as the square root of the average power as described by the function.

$$S/N \propto \text{RMS Power} = \sqrt{P_{\text{ave}}} \cdot P_{\text{peak}}$$

Molelectron Nitrogen Lasers are designed for maximum RMS power with low average power and correspondingly higher peak power to reduce side effects such as dye and sample heating.

Design Features

The laser head, power supply and trigger pulse generator units are mounted in a common console for the UV-1000 and UV-600. The UV-300 provides separate housings for these items.

Laser Head	* Flow control valves with pressure gauge and overpressure relief. * Thyatron-switched transverse discharge. * RF shielding. * No water cooling required.
Power Supply	* Enclosure and thyatron filament interlock protection. * High voltage interlock protection. * Voltage and current meters. * Input requirements: 115V 60 Hz, 20/30 A, 220V 50/60 Hz, 10/15 Amps.

- Trigger Pulse Generator
- * Manual: Single pulse with either local or remote pushbutton.
 - * Internal: 1-100 Hz rate variable.
 - * External: 1-100 Hz triggered by 1 μ s max rise, +5 to 30V pulse (50 k Ω input impedance).
 - * Input requirements: 115V 60 Hz, 1 Amp or 220V 50/60 Hz, 1/2 Amp.

DL-Series Dye Laser

The Molelectron DL-Series Dye Laser is a pulsed nitrogen laser pumped system based on the Mansch design*. Each unit in the series incorporates a grating sine drive, Invar stabilization and wavelength readout.

In its most sophisticated form the DL-400 offers 0.001 nm resolution from 250-740 nm. The unit may be automatically scanned with accurate wavelength indication provided by an extracavity etalon; dye cell interchange is totally automatic and the unit is completely computer compatible.

Laser Spectroscopy Detector System

The Molelectron LSDS is a modular instrument designed specifically for accurate laser pulse measurements. It is a complete system including detectors, preamplifiers, main amplifiers, gated integrators and channels multiplication or ratio units.

In operation, the unit provides 0.1% accurate pulse intensity measurements with vastly improved signal-to-noise ratios over those attainable with ungated dc techniques.

Adjustable gate widths and delays (or automatically scanned gate delays) permit recovery from noise of either repetitive pulses or waveforms.

APPENDIX 1
SPECIFICS OF LASER SYSTEMS DISCUSSED

Following is a summary of specific laser systems discussed in this report. All characteristics reported or calculable are included; however, the reader is advised that because of the type of device we are considering, such things as efficiency, gain, etc. can only be given realistically by measurement. Generally not enough information is reported for efficiency calculations, and these are dependent on pulse shapes anyway. Pulse shapes are not generally repeatable in these systems. Therefore, the best sources of laser parameters in lieu of a prior calculations are 1) this appendix, 2) the figures, 3) your own experiment, good luck.

MATHIAS AND PARKER (1) 1963

cavity

- 1) separate discharge tube; near confocal mirror system
- 2) mirrors silver coated, .1% transmission in $8 \rightarrow 1.2 \mu$ range

discharge tube

- 1) axial discharge, tungsten electrodes
 - 2) Brewster windows
 - 3) 7 mm inside diameter
- 40 cm discharge length

excitation pulse

- 1) d.c. pulses
- 2) 1 μ sec. pulse, 50 $\rightarrow$ 150 cps repetition rate

pressure and voltage, $\frac{E}{P}$

- 1) 1 TORR
- 2) 20 kV, peak voltage
- 3) 35 A, peak current
- 4) $\frac{E}{P} = 125 \frac{\text{volts}}{\text{cm TORR}} = \frac{\text{Imposed voltage}}{(\text{Discharged Length})(\text{Pressure})}$

output

- 1) infrared radiation
- 2) λ 's between .7 and 1.2 μ
- 3) .5 W output power, pulse - 1 μ sec - between $\frac{1}{2}$ power points
- 4) transition $1^2 \rightarrow 2^2 = 4^3 \text{ cm}^{-1}$ (band)

MATTHEIS AND PARKER (2) 1963

cavity

same except length and mirrors now multi layer dielectric

discharge tube

- 1) same except
- 2) 10 mm i.d.
- 3) 186 cm discharge length

excitation pulse

- 1) 1 μ sec. long, 65 cps repetition rate

pressure and voltage, $\frac{E}{P}$

- 1) 2 TORR
- 2) 40 kV
- 3) 90 A
- 4) $\frac{E}{P} = 107.5 \frac{\text{volts}}{\text{cm TORR}}$

output

- 1) infrared radiation, see page
- 2) $100 - 7500 \text{ Å}$
 $750 - 7700 \text{ Å}$
- 3) $> 100 \text{ W}$ power
- 4) transition $F^2 \text{ } ^3\text{P} \rightarrow A^3 \text{ } ^3\text{P}$ (band)

significant contribution

- 1) ^{15}N pulsed laser, ^{15}N molecular gas lasers

in ARD (1) 1963

cavity

- 1) separate discharge tube, confocal mirror system
- 2) mirrors: a) silver coated flint glass
b) radius of curvature $\sim 400 \text{ cm}$
c) one mirror heavily silvered, one 2.5% transmitting
- 3) 150 cm between mirrors

discharge tube

- 1) axial discharge, cold cathode excitation used
- 2) discharge length 40 in. $\sim 127 \text{ cm}$
- 3) flowster windows

excitation pulse

- 1) $\sim 1 \text{ msec. long}$

pressure and voltage, $\frac{E}{P}$

- 1) no pressure reported; only "room" temperatures
- 2) $100 - 150 \text{ kV}$

output

- 1) ultraviolet radiation

output (continued)

- 1) Lines 2, 3, 4, 4000 Å
- 2) 1 Å strongest line
- 3) 1 Å strongest variable line
- 4) 100 watt power summing over lines, 20 msec. pulse
- 5) 100 watt power summing

LICHARE 1963

1) 100 watt power summing, except now running conditions

output (continued)

- 1) 100 watt power summing
- 2) 100 watt power summing
- 3) 100 watt power summing
- 4) 100 watt power summing
- 5) 100 watt power summing
- 6) 100 watt power summing
- 7) 100 watt power summing
- 8) 100 watt power summing
- 9) 100 watt power summing
- 10) 100 watt power summing
- 11) 100 watt power summing
- 12) 100 watt power summing
- 13) 100 watt power summing
- 14) 100 watt power summing
- 15) 100 watt power summing
- 16) 100 watt power summing
- 17) 100 watt power summing
- 18) 100 watt power summing
- 19) 100 watt power summing
- 20) 100 watt power summing
- 21) 100 watt power summing
- 22) 100 watt power summing
- 23) 100 watt power summing
- 24) 100 watt power summing
- 25) 100 watt power summing
- 26) 100 watt power summing
- 27) 100 watt power summing
- 28) 100 watt power summing
- 29) 100 watt power summing
- 30) 100 watt power summing
- 31) 100 watt power summing
- 32) 100 watt power summing
- 33) 100 watt power summing
- 34) 100 watt power summing
- 35) 100 watt power summing
- 36) 100 watt power summing
- 37) 100 watt power summing
- 38) 100 watt power summing
- 39) 100 watt power summing
- 40) 100 watt power summing
- 41) 100 watt power summing
- 42) 100 watt power summing
- 43) 100 watt power summing
- 44) 100 watt power summing
- 45) 100 watt power summing
- 46) 100 watt power summing
- 47) 100 watt power summing
- 48) 100 watt power summing
- 49) 100 watt power summing
- 50) 100 watt power summing
- 51) 100 watt power summing
- 52) 100 watt power summing
- 53) 100 watt power summing
- 54) 100 watt power summing
- 55) 100 watt power summing
- 56) 100 watt power summing
- 57) 100 watt power summing
- 58) 100 watt power summing
- 59) 100 watt power summing
- 60) 100 watt power summing
- 61) 100 watt power summing
- 62) 100 watt power summing
- 63) 100 watt power summing
- 64) 100 watt power summing
- 65) 100 watt power summing
- 66) 100 watt power summing
- 67) 100 watt power summing
- 68) 100 watt power summing
- 69) 100 watt power summing
- 70) 100 watt power summing
- 71) 100 watt power summing
- 72) 100 watt power summing
- 73) 100 watt power summing
- 74) 100 watt power summing
- 75) 100 watt power summing
- 76) 100 watt power summing
- 77) 100 watt power summing
- 78) 100 watt power summing
- 79) 100 watt power summing
- 80) 100 watt power summing
- 81) 100 watt power summing
- 82) 100 watt power summing
- 83) 100 watt power summing
- 84) 100 watt power summing
- 85) 100 watt power summing
- 86) 100 watt power summing
- 87) 100 watt power summing
- 88) 100 watt power summing
- 89) 100 watt power summing
- 90) 100 watt power summing
- 91) 100 watt power summing
- 92) 100 watt power summing
- 93) 100 watt power summing
- 94) 100 watt power summing
- 95) 100 watt power summing
- 96) 100 watt power summing
- 97) 100 watt power summing
- 98) 100 watt power summing
- 99) 100 watt power summing
- 100) 100 watt power summing

output

- 1) infrared radiation as observed by Mathias and Farker; infrared radiation not observed in high voltage case
- 2) 100 watt power summing

output (continued)

- 1) 100 watt power summing

LICHARE 1965

cavity

- 1) 100 watt power summing

discharge tube

- 1) transverse electric field, $\perp$ to direction of stimulated emission

- 2) length 2 meters = 200 cm (active length arbitrary)
- 3) electrodes: a) high voltage: 128, 1/2" aluminum segments separated by 1/8" lucite spaces
b) ground return: 'U' aluminum channel
- 4) discharge cavity 1/2" wide x 1" high; lucite walls along side
- 5) one plane mirror at one end; doubles effective length; i.e. reduces beam divergence by one half

excitation pulse

- 1) 100 cps repetition rate

res. freq. and voltage, $\frac{1}{f}$

- 1) $\frac{1}{f} = 1$ sec. repeated 200 $\frac{\text{volts}}{\text{cm TORR}}$
- 2) 1000 kv capacitor (energy storage element)
- 3) pressure range 1 - several 10's of TORR optimum pressure ~ 20 TORR

output

- 1) ultraviolet radiation
- 2) $\lambda = 3371 \text{ \AA}$
- 3) 200 kW, 20 nsec. pulses - output, have been produced
- 4) beam divergence at 5 meters with a plane mirror at one end is 1.77 radians, rectangular cross sections
- 5) power output depends on length
 - a) active length < 80 cm
 - power < 10 kW
 - gain 73dB/meters
 - 3×10^7 watts/meter
 - b) active length > 80 cm saturates, power $\propto$ length
saturates power $2 \times 10^3 \text{ W/cm}^3$
- 6) efficiencies reported:

$$\frac{\text{saturation power}}{\text{total electrical power per unit volume up to time laser pulse terminates}} = \frac{2 \times 10^3 (\Delta t)}{\int_0^{t_{\text{laser}}} j \cdot E dt}$$

= .6%
(significant contribution driving to saturation)
the external circuit is not well matched to the discharge tube so
the overall efficiency

$\frac{\text{laser output}}{\text{energy in capacitor}} = \sim .03\%$

7) transition $3\text{ } 2u \rightarrow 8\text{ } 1g$

GELLER, ALTMANN, DUTCHALL 1966

cavity

one with the discharge tube; plane mirror at one end; discharge tube
has Brewster windows, circular cross section

discharge tube

- 1) axial discharge
- 2) 60 cm actual length, in two sections, 3 electrodes
- 3) copper electrodes: a) outer 2 are high potential (+)
b) inner 1 is ground return (-)
- 4) laser tube is a continuation of a coaxial circuit
 - a) silver braid outside the tube, connected to center electrodes,
is the outer conductor - a ground return;
 - b) discharge plasma in the tube is the center conductor
 - c) inner and outer diameters of tubing are chosen so laser tube
impedance matches that of the cable

excitation pulse

- 1) 10,000 volts rise in 1 nsec.

pressure and voltage,

- 1) 2 to 10 Torr
- 2) peak 30 kV
- 3) peak $\sim 3390 \text{ \AA}$ when get superradiance

4) $\frac{E}{P} = 442 \cdot 88.4 \frac{\text{volts}}{\text{cm TORR}}$

output

- 1) ultraviolet radiation
- 2) 3371 Å; pulse ~ 10 nsec. wide
- 3) at $p = 6$ TORR:
 - a) $\frac{E}{P} = 147 \frac{\text{volts}}{\text{cm TORR}}$
 - b) peak power = 20 kW
 - c) total output power = 80 kW
 - d) pulse width ~ 10 nsec.

significant contributions

reduction of circuit impedance matching of laser tube impedance to that of circuit

SHIMAN 1967

cavity

one with discharge tube

discharge tube

- 1) .3 cm x 10 cm x 183 cm cavity in a plate conductor, effectively a gap between what becomes an anode and a cathode
- 2) transverse excitations (across 10 cm)

excitation pulse

- 1) as fast as 100 kA/4 nsec. (all switches fire simultaneously)
- 2) $dI/dt = 10^{14}$ Amp/sec.

pressure and voltage,

- 1) 30 TORR
- 2) 75 kV
- 3) $\frac{E}{P} = 250 \frac{\text{volts}}{\text{cm TORR}}$

output

- 1) ultraviolet radiation ~ 3371 Å

- 2) power output without using excitation wave 1.2 MW pulse, 5 nsec wide at 1/2 power point from early end

power output with excitation wave: 10: |ratio in power emitted from 2 ends, 2.5 MW, 4 nsec pulse 'hot' end

significant contributions

traveling wave excitation pulse

CELLER, ALTMANN, DETEMPLE 1968

cavity

- 1) 1 glass mirror

discharge tube

- 1) transverse discharge
- 2) aluminum, 1 meter large, .3 cm high, 2.5 cm wide
- 3) Brewster windows

excitation pulse

- 1) 13 kV by 30 nsec (from 0) at breakdown ~ 20 nsec wide at 1/2 peak point this breakdown value is 7 times the d.c. value of 1800 V
- 2) initial voltage capacitors 30 kV

pressure and voltage,

- 1) 35 TORR
- 2) 13 kV
- 3) $\frac{E}{P} = 148.5 \frac{\text{volts}}{\text{cm TORR}}$

output

- 1) ultraviolet radiation, $\lambda \sim 3371 \text{ \AA}$
- 2) maximum power 2.5 MW pulse, width ~ 10 nsec

significant contribution

- 1) minimize inductance, impedance of external circuits + maximize power

APPENDIX II

A DISCUSSION OF THE TERMS OSCILLATION AND SUPERRADIANCE

A laser is a cavity in which an oscillating signal, or standing wave, is amplified coherently. Hence the term 'oscillation' refers to laser emission produced by multiple passes of spontaneously emitted photons through a laser cavity. Superradiance refers to spontaneously emitted light that passes once through a coherently amplifying cavity, of very high gain. If one photon at end A of our 'laser' were to propagate through the inverted medium towards end B, being amplified coherently as it passed by relaxation of the inversion, and arrived at B with no inversion behind it, then this would be called superradiance. Superradiance can be considered to be a type of 'coherent fluorescence'.

REFERENCES AND FOOTNOTES

- (1). Posed by R. E. Miles.
- (2). L. E. S. Mathias and J. T. Parker, Applied Physics Letters, 3, 16 (1963).
- (3). H. C. Heard, Nature, 200, 667 (1963).
- (4). G. Herzberg, Spectra of Diatomic Molecules, second edition, D. van Nostrand Co., Inc. (1953).
- (5). T. Tasuya and D. R. Lide, Jr., Applied Optics, 6, 69 (1967).
- (6). C. A. Massone, M. Gallardo, M. Garavaglia, J. A. L. Calatroni, A. A. Tagliaferri, Applied Optics, 11, 1317 (1972).
- (7). W. R. Bennett, Jr., Applied Optics Supplement, 2, 3 (1965).
- (8). D. A. Leonard, Applied Physics Letters, 7, 4 (1965).
- (9). See for instance A. M. Howson, An Introduction to Gas Discharges, Pergamon Press (1965).
- (10). M. Geller, D. L. Altmann, T. A. DeTemple, Journal of Applied Physics, 37, 3639 (1966).
- (11). M. Geller, D. L. Altmann, T. A. DeTemple, Applied Optics, 7, 2232 (1968).
- (12). J. D. Shipman, Jr., Applied Physics Letters, 10, 3 (1967).
- (13). I. T. Gerry, Applied Physics Letters, 7, 6, (1965).
- (14). A. W. Ali, A. C. Kolb, A. D. Anderson, Applied Optics, 6, 2115 (1967).
- (15). A. W. Ali, Applied Optics, 7, 993 (1968).
- (16). D. T. Steward, L. Gabathuler, Proceedings of the Physical Society, 72, pg. 2, 287 (1958).
- (17). S. C. Brown, Basic Data of Plasma Physics, Technology Press and Wiley (1959).
- (18). G. J. Schulz, Reviews of Modern Physics, 45, 423 (1973).
- (19). E. W. McDaniel, Collisional Phenomena in Ionized Gases, pg. 225, J. Wiley and Sons (1964).

REFERENCE AND FOOTNOTES
(continued)

- (20). Pg. 28 of Howatson:
"Excitation energy can also be exchanged between neutral atoms. In particular, an excited atom can ionize by virtue of its excitation energy, if the latter is larger than the required ionization energy. Such a process is made more probable if the excited atom is in a metastable state and has thus a longer lifetime in which to undergo a collision. The process is then known as the Penning effect and can be an important ionizing agent for discharges in mixtures containing rare gases, the atoms of which have metastable states of high energy."
- (21). T. W. Hansch, Applied Optics, 11, 895 (1972).
- (22). Handbook of Chemistry and Physics, 48th edition, Chemical Rubber Company.
- (23). D. Halliday, R. Resnick, Physics, Part II, J. Wiley and Sons, (1967).