

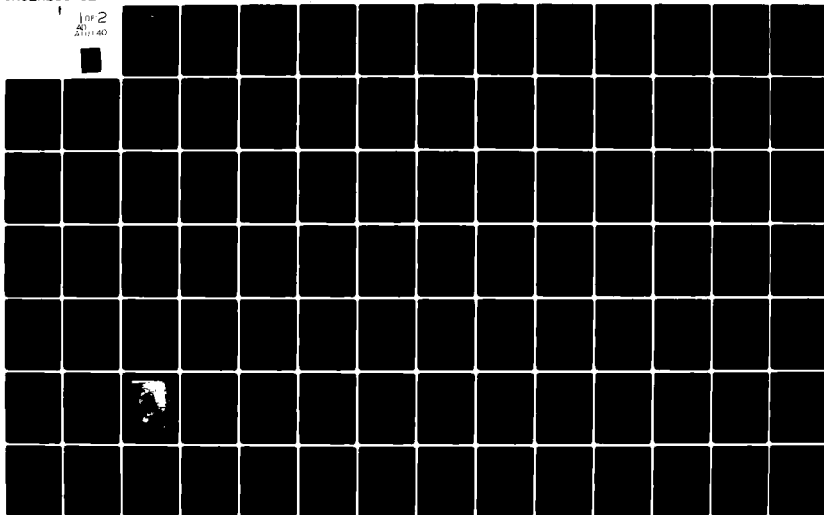
AD-A111 148

AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOO--ETC F/G 28/5
CHARACTERIZATION OF AN HF-PUMPED CO2 LASER.(U)
OCT 81 S P PERRAM
AFIT/SEP/PH/810-7

UNCLASSIFIED

NL

1 of 2
21
21/1/40



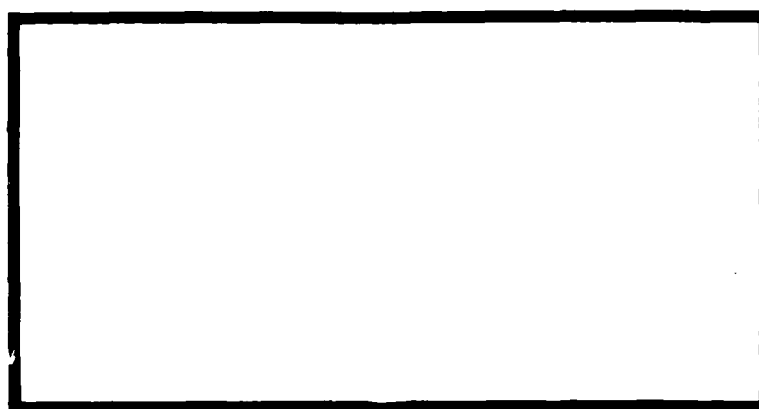
LEVEL II

(1)

AD A11140



DTIC
FEB 19 1982
E



UNITED STATES AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY
Wright-Patterson Air Force Base, Ohio

DTIC FILE COPY

This document has been approved
for public release and sale; its
distribution is unlimited.

82 02 18 067

II

①

CHARACTERIZATION OF AN
HF-PUMPED CO₂ LASER

THESIS

AFIT/GEP/PH/81D-7

Glen P. Perram
2nd Lt USAF

Approved for release
by NSA on 05-10-2013
dissemination code: A

CHARACTERIZATION OF AN
HF-PUMPED CO₂ LASER

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

Accession For	
NTIS	X
DTIC	
USCIB	
AD	
AS	
CS	
DA	
DD	
DM	
DR	
DS	
DT	
DU	
DX	
EA	
EB	
EC	
ED	
EE	
EF	
EG	
EH	
EI	
EJ	
EK	
EL	
EM	
EN	
EO	
EP	
EQ	
ER	
ES	
ET	
EU	
EV	
EW	
EX	
EY	
EZ	
FA	
FB	
FC	
FD	
FE	
FF	
FG	
FH	
FI	
FJ	
FK	
FL	
FM	
FN	
FO	
FP	
FQ	
FR	
FS	
FT	
FU	
FV	
FW	
FX	
FY	
FZ	
GA	
GB	
GC	
GD	
GE	
GF	
GG	
GH	
GI	
GJ	
GK	
GL	
GM	
GN	
GO	
GP	
GQ	
GR	
GS	
GT	
GU	
GV	
GW	
GX	
GY	
GZ	
HA	
HB	
HC	
HD	
HE	
HF	
HG	
HH	
HI	
HJ	
HK	
HL	
HM	
HN	
HO	
HP	
HQ	
HR	
HS	
HT	
HU	
HV	
HW	
HX	
HY	
HZ	
IA	
IB	
IC	
ID	
IE	
IF	
IG	
IH	
II	
IJ	
IK	
IL	
IM	
IN	
IO	
IP	
IQ	
IR	
IS	
IT	
IU	
IV	
IW	
IX	
IY	
IZ	
JA	
JB	
JC	
JD	
JE	
JF	
JG	
JH	
JI	
JJ	
JK	
JL	
JM	
JN	
JO	
JP	
JQ	
JR	
JS	
JT	
JU	
JV	
JW	
JX	
JY	
JZ	
KA	
KB	
KC	
KD	
KE	
KF	
KG	
KH	
KI	
KJ	
KK	
KL	
KM	
KN	
KO	
KP	
KQ	
KR	
KS	
KT	
KU	
KV	
KW	
KX	
KY	
KZ	
LA	
LB	
LC	
LD	
LE	
LF	
LG	
LH	
LI	
LJ	
LK	
LL	
LM	
LN	
LO	
LP	
LQ	
LR	
LS	
LT	
LU	
LV	
LW	
LX	
LY	
LZ	
MA	
MB	
MC	
MD	
ME	
MF	
MG	
MH	
MI	
MJ	
MK	
ML	
MM	
MN	
MO	
MP	
MQ	
MR	
MS	
MT	
MU	
MV	
MW	
MX	
MY	
MZ	
NA	
NB	
NC	
ND	
NE	
NF	
NG	
NH	
NI	
NJ	
NK	
NL	
NM	
NN	
NO	
NP	
NQ	
NR	
NS	
NT	
NU	
NV	
NW	
NX	
NY	
NZ	
OA	
OB	
OC	
OD	
OE	
OF	
OG	
OH	
OI	
OJ	
OK	
OL	
OM	
ON	
OO	
OP	
OQ	
OR	
OS	
OT	
OU	
OV	
OW	
OX	
OY	
OZ	
PA	
PB	
PC	
PD	
PE	
PF	
PG	
PH	
PI	
PJ	
PK	
PL	
PM	
PN	
PO	
PP	
PQ	
PR	
PS	
PT	
PU	
PV	
PW	
PX	
PY	
PZ	
QA	
QB	
QC	
QD	
QE	
QF	
QG	
QH	
QI	
QJ	
QK	
QL	
QM	
QN	
QO	
QP	
QQ	
QR	
QS	
QT	
QU	
QV	
QW	
QX	
QY	
QZ	
RA	
RB	
RC	
RD	
RE	
RF	
RG	
RH	
RI	
RJ	
RK	
RL	
RM	
RN	
RO	
RP	
RQ	
RR	
RS	
RT	
RU	
RV	
RW	
RX	
RY	
RZ	
SA	
SB	
SC	
SD	
SE	
SF	
SG	
SH	
SI	
SJ	
SK	
SL	
SM	
SN	
SO	
SP	
SQ	
SR	
SS	
ST	
SU	
SV	
SW	
SX	
SY	
SZ	
TA	
TB	
TC	
TD	
TE	
TF	
TG	
TH	
TI	
TJ	
TK	
TL	
TM	
TN	
TO	
TP	
TQ	
TR	
TS	
TT	
TU	
TV	
TW	
TX	
TY	
TZ	
UA	
UB	
UC	
UD	
UE	
UF	
UG	
UH	
UI	
UJ	
UK	
UL	
UM	
UN	
UO	
UP	
UQ	
UR	
US	
UT	
UU	
UV	
UW	
UX	
UY	
UZ	
VA	
VB	
VC	
VD	
VE	
VF	
VG	
VH	
VI	
VJ	
VK	
VL	
VM	
VN	
VO	
VP	
VQ	
VR	
VS	
VT	
VU	
VV	
VW	
VX	
VY	
VZ	
WA	
WB	
WC	
WD	
WE	
WF	
WG	
WH	
WI	
WJ	
WK	
WL	
WM	
WN	
WO	
WP	
WQ	
WR	
WS	
WT	
WU	
WV	
WW	
WX	
WY	
WZ	
XA	
XB	
XC	
XD	
XE	
XF	
XG	
XH	
XI	
XJ	
XK	
XL	
XM	
XN	
XO	
XP	
XQ	
XR	
XS	
XT	
XU	
XV	
XW	
XX	
XY	
XZ	
YA	
YB	
YC	
YD	
YE	
YF	
YG	
YH	
YI	
YJ	
YK	
YL	
YM	
YN	
YO	
YP	
YQ	
YR	
YS	
YT	
YU	
YV	
YW	
YX	
YY	
YZ	
ZA	
ZB	
ZC	
ZD	
ZE	
ZF	
ZG	
ZH	
ZI	
ZJ	
ZK	
ZL	
ZM	
ZN	
ZO	
ZP	
ZQ	
ZR	
ZS	
ZT	
ZU	
ZV	
ZW	
ZX	
ZY	
ZZ	

by

Glen P. Perram, B.S.
2nd Lt USAF
Graduate Engineering Physics
October 1981

Preface

The purpose of this study was to characterize the performance of an optically pumped molecular laser and determine the effect of pump frequency on output power. Specifically, the $P_2(6)$ transition in a chemical HF laser is used to pump $^{12}\text{C}^{18}\text{O}_2$ molecules from the ground state to the 101 vibrational energy level. A population inversion is established between the 101 and 100 energy levels and lasing action is achieved at 4.3 microns. The results of a theoretical analysis and an experimental study are used to maximize the system's performance, clarify the principles of operation, and to resolve discrepancies between theory and prior experimental observations.

I would like to acknowledge the support of the Avionics Laboratory, AFWAL, WPAFB, OH in conducting this study, particularly Dr. W. Schuebel for sponsoring the project and J. Brandelik for his advice, instruction, and guidance. The support of my AFIT thesis advisor, Dr. E.A. Dorko, and thesis committee members, Major J.H. Erkkila and Dr. W.B. Roh was greatly appreciated, as were the discussions and information provided by Capt. R.J. Cook, AFIT/ENP, and Capt R. Walters, AFWL. The technical support provided by C. Shortt, AFIT Shop supervisor, A.M. Becraft, Avionics Lab, R. Wade, Glassblower-Avionics Lab, S. Derby, Avionics Lab, J.R. Gabriel, AFIT, and particularly, P. Dunigan and M. Lovingshimer, TSSI contractors-Avionics Lab, is gratefully acknowledged.

Contents

	Page
Preface.....	ii
List of Figures.....	iv
List of Tables.....	vii
Notation.....	viii
Abstract.....	xii
I. Introduction.....	1
II. Background Theory.....	4
HF Laser Spectroscopy.....	4
Kinetic Model of $\text{SF}_6 + \text{H}_2$ in the Electric Discharge.....	12
Optical Pumping and the CO_2 Laser	31
III. Experiment.....	55
HF Laser Description.....	55
HF Laser Modifications.....	68
HF Laser Operation.....	78
HF Laser Performance Characterization.....	79
Optical Pumping.....	82
Power-Frequency Experiment.....	83
IV. Results and Conclusions.....	90
HF Laser Characterization.....	90
Pulse Shapes.....	103
Optical Pumping.....	106
Instability.....	108
Conclusions and Recommendations.....	113
Bibliography.....	118
Appendix A: Rate Constants for the $\text{SF}_6 + \text{H}_2$ / Electric Discharge Laser.....	125
Appendix B: Numerical Solution of the HF Laser Kinetic Model Equations.....	134
Appendix C: HF Laser Operating Instructions.....	142
Appendix D: HF Beam Propagation.....	143

List of Figures

<u>Figure</u>		<u>Page</u>
1	Energy Level Diagram for HF.....	6
2	Electron Discharge Model.....	14
3	Predicted HF Power Pulse Shape.....	30
4	Optical Pumping Schemes.....	31
5	CO ₂ Energy Level Diagram.....	32
6	¹² C ¹⁸ O ₂ Energy Level Diagram.....	34
7	HF and CO ₂ Line Broadening.....	36
8	CO ₂ Absorption versus CO ₂ Pressure..... (Theory)	40
9	CO ₂ Power versus HF Frequency..... (Theory)	41
10	Three Level CO ₂ Model.....	43
11	CO ₂ Gain for 3 HF Pump Frequencies (Theory)	47
12	CO ₂ Gain versus HF Frequency..... (Theory)	50
13	HF Laser Specifications.....	55
14	SF ₆ + H ₂ Electric Discharge Laser.....	56
15	HF Optical Cavity.....	57
16	HF Laser Discharge Circuit.....	58
17	HF Laser External Gas Flow.....	62
18	Flow Rate Calibration Charts.....	64
19	HF Laser Internal Gas Flow.....	65
20	HF Output Power versus Temperature.....	67
21	HF Laser Cooling System.....	69
22	Modified HF Optical Cavity.....	69

List of Figures
(Continued)

<u>Figure</u>	<u>Page</u>
23 PZ Voltage as a function of Time.....	70
24 Interferrometer Test of PZ Crystal Motion.....	71
25 Diode I - V Characteristic.....	74
26 Trigger Circuit.....	75
27 By-Pass Valve Modification.....	77
28 Experimental Coordinate Axes.....	80
29 Redesigned CO ₂ Cell.....	82
30 CO ₂ Gas Pumping System.....	86
31 Optical Set-up for Frequency Experiment.....	87
32 Electrical Wiring Diagram.....	88
33 HF Multiline Energy versus SF ₆ /SF ₆ +H ₂ Mixture.....	91
34 HF Output Power versus Cavity Pressure.....	93
35 HF Output Power versus Discharge Voltage.....	93
36 HF Energy versus Repetition Rate.....	94
37 HF Average Power versus Repetition Rate.....	94
38 Energy/Pulse versus Aperture Diameter.....	96
39 HF Spot Shape:Multimode-Vertical.....	98
40 HF Spot Shape:Multimode-Horizontal.....	98
41 HF Spot Shape:P ₂ (6)-Vertical.....	99
42 HF Spot Shape:P ₂ (6)-Horizontal.....	99
43 HF Spot Shape:Focused-Vertical.....	100
44 HF Spot Shape:Focused-Horizontal.....	100
45 HF Beam Divergence:Multimode.....	101
46 HF Beam Divergence:P ₂ (6).....	102
47 HF Pulse Shape (Experimental).....	105

List of Figures
(Continued)

<u>Figure</u>	<u>Page</u>
48 CO ₂ Pulse Shape (Experimental).....	105
49 HF Pulse Shapes (Experimental and Theory).....	106
50 CO ₂ Absorption of HF P ₂ (6).....	107
51 HF Power Instability.....	108
52 HF Frequency Instability.....	110
53 Power Instability versus Rep Rate.....	111
54 Power Instability versus Discharge Voltage.....	112
55 Power Instability versus Pressure.....	112
56 Discharge Current Pulse Shape.....	135

List of Tables

<u>Table</u>	<u>Page</u>
I CO ₂ Gain and HF Frequency.....	49
II HF Line Identification.....	81
III Boxcar Time Settings.....	85
IV Beam Divergence.....	103
V SF ₆ +H ₂ /Electric Discharge Rate Constants.....	125
VI Electron Number Density.....	139
VII Hydrogen and Fluorine Concentration.....	140
VIII HF Concentration and Population Inversion.....	141

Notation

<u>Symbol</u>	<u>Variable</u>
C	speed of light
K	boltzman constant
h	planck constant
R_U	universal gas constatnt
X	horizontal spatial coordinate
Y	vertical spatial coordinate
Z	axial spatial coordinate
V	volume
A	area
L	length
q	axial mode number
u	vibrational quantum number
J	rotational quantum number
β	rotational constant
A_{21}	Einstein coefficient for spontaneous emission
B_{12}, B_{21}	Einstein coefficient for stimulated emission
η	ratio of specific heats,
C_P	heat capacity at constant pressure
C_V	heat capacity at constant volume
ν	frequency
ν_0	linecenter frequency
δ	offset frequency, HF frequency - CO ₂ linecenter freq
$\bar{\nu}$	wave number
λ	wavelength
λ_0	linecenter wavelength

Notation

(Continued)

<u>Symbol</u>	<u>Variable</u>
γ	gain coefficient
γ_{TH}	threshold gain coefficient
α	absorption coefficient
α_0	distributed loss coefficient
σ	absorption crosssection
σ_{AB}	collisional crosssection
G	lineshape factor
$\Delta \nu_N$	natural linewidth
$\Delta \nu_C$	collisional linewidth
$\Delta \nu_D$	doppler linewidth
$\Delta \nu_T$	total linewidth
ω	beam spot size
$\theta_{1/2}$	beam divergence, half angle
R	complex radius of curvature
T	absolute temperature
M	mass
$M_{\#}$	Mach number
ϵ	energy/mole
ϵ_D	dissociation energy/mole
E	energy
V	potential
N	total number
N_{ϕ}	total photon number
η	number density

Notation

(Continued)

<u>Symbol</u>	<u>Variable</u>
$[]$	concentration
Δ	population inversion
P	power
I	intensity
I_0	incident intensity
I_S	saturation intensity
I_ν	intensity as a function of frequency
D	atomic diameter
U	velocity
a_S	speed of sound
a	radius
Λ	mean free path
ρ	reflectivity
R	radius of curvature
r	repetition rate
T	characteristic time
T_R	radiative lifetime
τ_c	cavity photon lifetime
K	rate constant
H	Hamiltonian
ψ	wavefunction
μ	dipole moment or viscosity
P	pressure
E	electric field

Notation

(Continued)

<u>Symbol</u>	<u>Variable</u>
S	strain
ξ	piezoelectric constant
i	current

Abstract

Optical pumping of the $000 - (10^0 1)_{\text{II}}$ transition in $^{12}\text{C}^{18}\text{O}_2$ by the $P_2(6)$ transition of an $\text{SF}_6:\text{H}_2$ electric discharge HF chemical laser was used to establish a population inversion between the $(10^0 1)_{\text{II}}$ and $(10^0 0)_{\text{I}}$ levels of $^{12}\text{C}^{18}\text{O}_2$ and lasing at 4.3 microns.

The HF pump laser was characterized and maximum power achieved at 79% SF_6 / 21% H_2 , 88 torr total pressure, a 12kV discharge voltage, and 300 pulses/sec. Lasing on the $P_2(4)$, $P_2(5)$, and $P_2(6)$ transitions was observed with a beam divergence of 9 mrad. A pulse-to-pulse variation in output power of a factor of six and a frequency instability greater than 200 MHz/msec. was observed. A 156 micro-Joule, 106 nsec pulse was observed multiline.

The $P_2(6)$ TEM 00 HF beam at 37.5 micro-J was coupled into a .5 inch diameter pyrex cell with 7 torr $^{12}\text{C}^{18}\text{O}_2$ with a 25 cm focal length CaF_2 lens. A 26 nsec CO_2 pulse was observed in the forward propagating direction. CO_2 lasing was erratic, due to near threshold pumping conditions.

A theoretical model of the kinetics of the $\text{SF}_6 + \text{H}_2$ / electric discharge was established. Pulse widths predicted by this theory and those observed experimentally agree well. The predicted power amplitude is larger than observed, due to losses not included in the model.

The dependence of CO_2 output power on HF frequency was not observed experimentally. The contradiction between established theory and previous experimental results was explained, however.

Introduction

Background

Laser sources are needed across a wide portion of the electromagnetic spectrum. The infrared region is particularly important for several laser applications: (1) multi-photon IR beam photochemistry, (2) laser isotope separation, (3) laser methods for obtaining pure materials, and (4) military applications [1:1317]. Several molecular lasers, including CO_2 , CO, N_2O , HF and DF, operate in the mid-infrared region, but do not adequately cover this band. Resonant frequency conversion can be used to increase the number of sources in the mid-IR by using one of the molecular lasers to optically pump a second laser medium. One advantage of such systems is the high power obtainable [2:68].

A CO_2 laser optically pumped by an HF laser was developed for the Avionics Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio by the Raytheon Corporation [3]. Many characteristics of this laser are unknown and few studies for optimization of the system have been completed. Several aspects of the laser's operation are not well understood and previous experimental investigations appear to contradict established theory.

Problem Definition

This investigation will characterize the performance of this HF-pumped CO_2 laser system in an attempt to maximize

its performance, clarify the principles of operation, reproduce the work of reference [3], and study discrepancies between theory and prior experimental results. Output power, beam quality, and stability of the HF laser will be examined. The CO_2 lasing system will be studied to maximize output power. In particular, optical pumping and the effect of HF laser frequency on the CO_2 output power will be studied and the results compared with previous investigations and theoretical predictions. HF and CO_2 power pulse shapes will be experimentally observed and explained in terms of the kinetics of the HF reaction and the optical pumping scheme.

In the Raytheon study, no significant variation in the CO_2 output power was observed with changes in the HF laser frequency over a 300 MHz range [3:64-65]. A substantial variation would be expected on theoretical grounds, however. The main effort of this thesis will be to explain this discrepancy between theory and experiment.

Presentation

Background theory on the operation of the HF pump laser and on the optically pumped CO_2 laser will be presented in Chapter II. A kinetic model of the HF laser will be established. A model of the effect of HF frequency on CO_2 power will also be established. Chapter III will describe the HF and CO_2 lasers, as well as the experimental set-up for studying the frequency - power relation.

Finally, Chapter IV will present the results of characterizing the HF pump laser, studying the optically-pumped CO₂ laser, and of the power-frequency experiment. Conclusions concerning the laser system and the frequency effect will be drawn. Recommendations for improvement of the lasing system and for future studies are then made.

Background Theory

Three main topics will be presented in this chapter: (1) spectroscopy of the HF laser, (2) a kinetic model of the $\text{SF}_6 + \text{H}_2$ in the electric discharge, with a derivation of the population inversion and power pulse shape, and (3) the theory of the CO_2 laser and the optical pumping scheme, including a derivation of the dependence of CO_2 output power on HF frequency.

HF Laser Spectroscopy

An HF chemical laser was first demonstrated by Kompa and Pimentel with lasing from the $\nu=2$ to $\nu=1$ vibrational energy levels [4]. The first cw HF laser was reported by Spencer et al [5]. SF_6 was used as a fluorine donor and lasing was observed for three different rotational transitions within the $\nu=2$ to $\nu=1$ band. Electric discharge initiated HF chemical lasers were also demonstrated early [6,7]. Since then a number of cw and pulsed HF lasers using SF_6 and H_2 have been demonstrated [8-17]. Electric discharge, electron beams, electric arcs, and N_2 - SF_6 collisions at high temperature have been used to dissociate SF_6 to produce atomic fluorine. It is an electric discharge, SF_6 type HF laser that is used in this study.

The HF chemical laser produces vibrationally excited HF molecules by direct reaction of hydrogen with fluorine. A chain reaction can be established and thus high efficiencies

are obtainable. The optical gain of HF lasers is high and can reach 100% per centimeter in pulsed operation [18]. Large amounts of energy are released during the chemical reaction and many vibrational levels can be populated. The cascading of transitions from upper vibrational levels to the ground state can yield a large number of lasing lines in a single system. Forty different lines for HF lasing in the 2.6 to 3.4 micron range have been summarized in reference [19:404].

HF lasers operate on transitions between vibrational-rotational levels of the HF molecule. The vibrational energy diagram for HF is shown in figure 1. A set of rotational energy levels is associated with each vibrational energy level. The notation $P_v(J)$ denotes the transition $v=v_1$, $J=J_1-1$ to $v=v_1-1$, $J=J_1$. The $P_2(6)$ transition is shown in figure 1 and is used to optically pump the isotope $^{12}\text{C}^{18}\text{O}_2$. The frequency of the $P_2(6)$ transition has been measured by several authors [6,20-23]. The best experimental value is $\bar{\nu} = 3531.3 \pm .12 \text{ CM}^{-1}$ [6]. Buchwald reports a value of $\bar{\nu} = 3531.175 \text{ CM}^{-1}$ based on the absorption of the $P_2(6)$ transition in $^{12}\text{C}^{18}\text{O}_2$ [23]. The wavelength is

$$\lambda = \frac{1}{\bar{\nu}} = 2.8319 \mu\text{m} \quad (1)$$

The linewidth of the HF $P_2(6)$ line is important, for it will determine the range over which the HF laser can be tuned and the amount of HF power absorbed by the CO_2 gas.

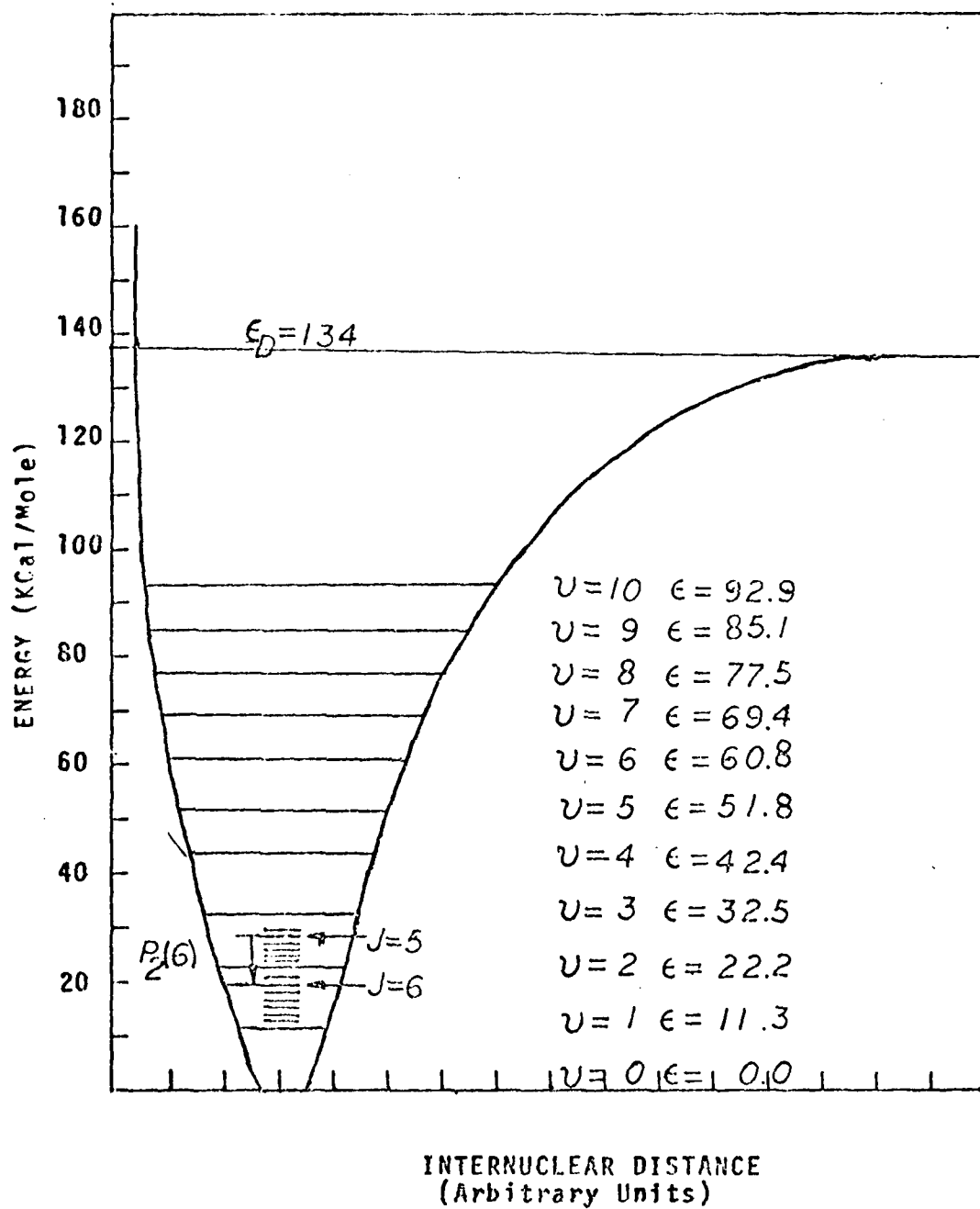


Figure 1.
Energy Level Diagram for HF
"Morse-type" Potential

The three main broadening mechanisms are natural, collisional, and Doppler.

The natural linewidth (FWHM) is

$$\Delta \nu_N = \frac{1}{2\pi\tau_R} \quad (2)$$

where τ_R is the radiative lifetime of the upper laser level [24:57]. Peterson has measured the natural linewidth for the $P_2(J)$ transitions as 3 MHz [25]. The $P_2(6)$ transition will be assumed to have a similar linewidth. Collisional and Doppler broadening will be shown to be much greater than 3 MHz and natural broadening will be neglected.

Collisional broadening arises from collisions between the active molecule (HF) and all other molecules. Its magnitude depends on the physical properties of the collision partners and on their partial pressures. The linewidth is

$$\Delta \nu_C = \frac{1}{\pi} \sum_B 2\eta_B \sigma_{AB} \sqrt{\frac{2KT}{\pi} \left(\frac{1}{M_A} + \frac{1}{M_B} \right)} \quad (3)$$

where

$$\sigma_{AB} = \pi \left(\frac{D_A + D_B}{2} \right)^2 \quad (4)$$

is the collisional crosssection, D_A and D_B are the molecular diameters of particles of type A (HF) and type B (HF collision partners), M_A and M_B are the masses of the particles, η_B is the number density of type B particles, and T is the absolute temperature [34]. The summation is taken over all collision partners, B, including the self collisions with other type A particles.

To evaluate this expression for the HF laser, the

following analysis is performed:

Introduce the ideal gas law and total pressure

$$P_B = n_B K T \quad P = \sum_B P_B \quad (5,6)$$

and

$$n_B = \frac{P_B}{KT} = \left(\frac{P_B}{P}\right) \frac{P}{KT} \quad (7)$$

Substitute equation (7) into equation (3):

$$\begin{aligned} \Delta \nu_C &= \frac{1}{\pi} \sum_B 2 \left(\frac{P_B}{P}\right) \frac{P}{KT} \sigma_{AB} \sqrt{\frac{2KT}{\pi} \left(\frac{1}{M_A} + \frac{1}{M_B}\right)} \\ &= \frac{2}{\pi} \sqrt{\frac{2}{\pi KT}} P \sum_B \left(\frac{P_B}{P}\right) \sigma_{AB} \sqrt{\left(\frac{1}{M_A} + \frac{1}{M_B}\right)} \end{aligned} \quad (8)$$

Let P be in torr, atomic radii in angstroms, and mass in kg/kgmole, then, at $T=300^\circ K$:

$$\Delta \nu_C = (.225 \text{ MHz}) P \sum_B \left(\frac{P_B}{P}\right) \frac{\pi}{4} (D_A + D_B)^2 \sqrt{\frac{1}{M_A} + \frac{1}{M_B}} \quad (9)$$

To evaluate this equation for the HF laser used in this study, take $P=80$ torr and a gas mixture of $\text{SF}_6:\text{H}_2=4:1$. The partial pressure of HF is set to zero. The atomic diameters are

$$D_{\text{HF}} = 4.3 \text{ \AA} \quad D_{\text{H}_2} = 2.7 \text{ \AA} \quad D_{\text{SF}_6} = 4.4 \text{ \AA}$$

from references [27,28] Then,

$$\Delta \nu_C = 322 \text{ MHz} \quad (10)$$

Doppler broadening arises from the distribution of particle velocities and the linewidth is

$$\Delta \nu_D = \frac{2}{\lambda_0} \sqrt{\frac{2KT/\ln 2}{M}} \quad (11)$$

where λ_0 is the line-center wavelength, T is absolute temperature, and M is the mass of the active molecule. For the $P_2(6)$ transition in HF at 300°K, $\Delta\nu_D = 294 \text{ MHz}$.

The effects of collisional and Doppler broadening can be convolved to give a total lineshape with the use of a Voigt profile. Assuming that collisional broadening is independent of particle velocity, the total lineshape at any wavelength is simply the convolution of the Lorentzian (collisional) and Gaussian (Doppler) lineshapes. The total lineshape is given by the summation over all frequency:

$$G(\lambda) = G(\lambda_0) \int_{-\infty}^{\infty} \frac{e^{-\chi^2}}{\zeta^2 + (\varphi - \chi)^2} d\chi \quad (12)$$

where $G(\lambda)$ is the total gain lineshape factor as a function of wavelength, λ , λ_0 is the line-center wavelength,

$$\zeta = \frac{\Delta\nu_C}{\Delta\nu_D} \sqrt{\ln 2} \quad (13)$$

$$\varphi = \frac{(\lambda - \lambda_0) c}{\lambda^2} \frac{1}{\Delta\nu_D} 2\sqrt{\ln 2} \quad (14)$$

$$\chi = \frac{(\lambda' - \lambda_0) c}{\lambda^2} \frac{1}{\Delta\nu_D} 2\sqrt{\ln 2} \quad (15)$$

and λ' is the variable wavelength of integration [29:128].

This integral is the Voigt integral and has been evaluated numerically [30]. For $\frac{\Delta\nu_D}{\Delta\nu_C} = \frac{294}{322} = .913$, the linewidth (FWHM) is 506 MHz, $\Delta\nu_T = 506 \text{ MHz}$.

Several studies of line broadening in HF lasers have been completed [31-32]. These studies have dealt mainly with the $P_1(J)$ transitions and HF - HF collisions. Broadening of the $\nu=2$ to $\nu=1$ transition due to HF - HF collisions is 7.9 MHz/Torr HF [31:1575]. Collisional broadening of the

$P_1(5)$ transition at 50 torr and 100°C has been measured as 672 MHz [32:1117]. No studies of the $P_2(6)$ transition with SF_6 collision partners were found. The value $\Delta\nu_T = 506\text{MHz}$ will be used in this study.

Axial modes in a laser are given by

$$\nu_q = \frac{qC}{2nL} \quad (16)$$

and the free spectral range by

$$\Delta\nu_q = \frac{C}{2nL} \quad (17)$$

where L is cavity length, n is the index of refraction of the lasing medium, and C is the speed of light. q is an integer specifying the axial mode number. For $nL = .56\text{M}$ (see the experimental section for a description of the optical cavity), $\Delta\nu_q = 268\text{MHz}$. Note that $\frac{\Delta\nu_T}{\Delta\nu_q} = 1.89$ and thus, one or two axial modes will exist depending on the exact value of L . The frequency of the laser can be changed by varying the cavity length. The relation between frequency change and length change is

$$\delta\nu_q = -\frac{qC}{2nL^2} \delta L = -\frac{C}{\lambda L} \delta L \quad (18)$$

To vary the laser frequency across its full width of 506 MHz, the length of the cavity must be varied by $2.6\text{ }\mu\text{m}$.

This length change is easily achieved with a piezo-electric crystal. The converse piezo-electric effect states an applied electric field produces a proportional strain in the crystal

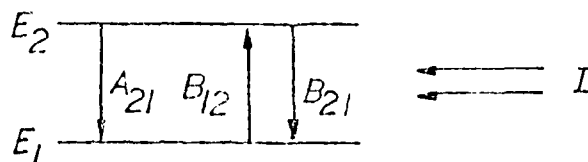
$$S = \frac{\Delta L}{L} = \xi E \quad (19)$$

where S is strain, ξ is the piezo-electric constant, and

E is the electric field. The magnitude of ξ for many piezo-electric materials is sufficient to provide a $2.6 \mu\text{m}$ deflection under the application of a 1 kV voltage. A BaTiO_3 crystal was used to vary the HF laser frequency and is described in the experimental section.

One last parameter is required to specify the energy levels and transitions. The transition rate between energy levels affects the population inversion and output power.

These transition rates are given by the Einstein coefficients. Take the following two level system:



E_2 is the upper energy level and E_1 is the lower level. I is the incident photon intensity and A_{21}, B_{12}, B_{21} are the Einstein coefficients defined as

A_{21} = the probability of a molecule spontaneously decaying from the upper energy level to the lower level per unit time. $\tau = 1/A_{21}$, the radiative lifetime from the upper to lower energy level.

$B_{12}I$ ($B_{21}I$) = the probability per unit time of a molecule being stimulated to transition to the other energy level by the incident photon intensity, I .

The Einstein coefficients are related by

$$A_{21} = \frac{2hC}{\lambda^3} B_{21} = \frac{2hC}{\lambda^3} B_{12} \quad (20)$$

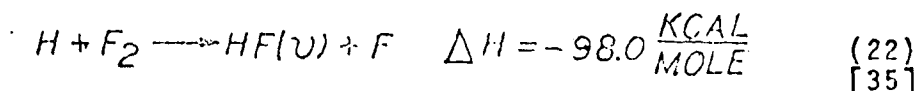
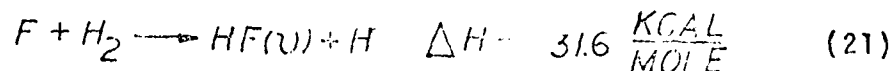
[34:2-18]

The Einstein coefficient, D_{21} , for the $P_2(6)$ transition in HF is $1.372 \times 10^{14} \text{ cm}^2/\text{J sec}$ [19:483]. The radiative lifetime is then .4 seconds.

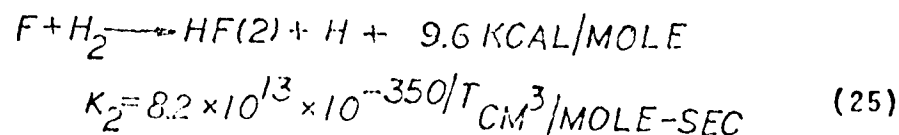
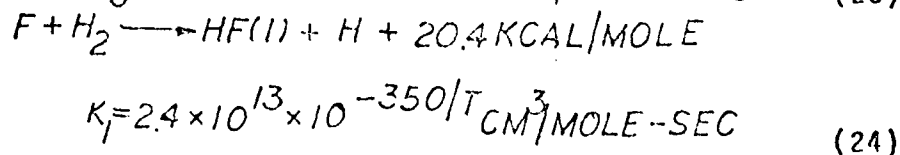
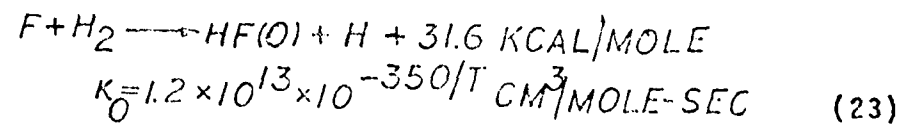
The spectroscopy of the HF lasing transition has been established. The mechanism for establishing the population inversion will now be examined.

Kinetic Model of $\text{SF}_6 + \text{H}_2$ in the Electric Discharge

HF chemical lasers establish a population inversion of the vibrational-rotational levels of HF through chemical reactions involving H , H_2 , F , and F_2 . The pumping processes are chemical reactions whose products are vibrationally excited HF molecules. The two major reactions are



Reaction (21) is termed the cold reaction, due to its lower ΔH . Population of the $\nu=0$ to $\nu=3$ levels are possible, with the $\nu=2$ state preferred:



cortical processes in the two cases which reflect the accompanying psychic events are quite different. It would be erroneous to conclude, however, that the ergotropic downward discharges are not subject to adaptive changes. That fundamentally different types of ergotropic discharges occur is evident from the increased excretion of noradrenaline (without that of adrenaline) and vice versa. Moreover, adjustments take place even within the autonomic-somatic components of the ergotropic downward discharge, as illustrated by the fundamental differences in the rates of excretion of noradrenaline and adrenaline in acute and chronic states of exposure to cold and in the absence of shivering in the cold-adapted organism.

VIII

Internal Secretions and the Ergotropic and Trophotropic Systems

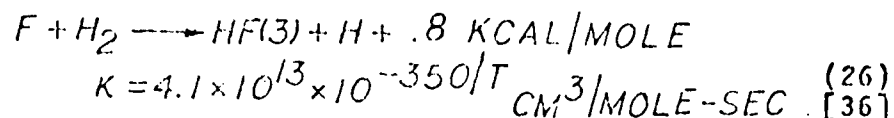
THAT increased ergotropic activity enhances the secretion of adrenocortical hormones as reviewed in the preceding chapter is but one example of ergotropic-hormonal relations. The reader will remember that conditioning and other forms of stress associated with augmented ergotropic discharges were shown to cause an increased secretion of adrenocortical steroids (Chapter III). These and numerous related investigations constitute an important part of neuroendocrinology, the discussion of which is obviously beyond the scope of this book, but in order to illustrate further the dependence of internal secretions on the ergotropic and trophotropic systems and vice versa, a brief survey of the influence of hypothalamus on the activity of several endocrine glands is presented in this chapter.

1. THE THYROID GLAND*

Clinical observations on Graves' disease and early physiological studies on prolonged stimulation of the cervical sympathetic nerves suggested but did not prove an influence of the ergotropic system on the activity of the thyroid gland. However, recent work involving the study of hypothalamic stimulations and lesions has finally established this relation.

The basic facts may be summarized as follows. In animals previously injected with radioactive Iodine the difference in radioactivity between the venous and the arterial blood of the thyroid gland increases on stimulation of the anterior hypothalamus, the median eminence, or the tuber cinereum anterior to the median eminence, whereas stimulation of either hypothalamic sites is without effect (143). These results can be matched by the injection of thyrotropin (TSH). Furthermore, in rats (144) (in cage) likewise show an increase in thyroid activity on stimulation; radioactive Iodine is released in increased amounts from the thyroid gland while the plasma protein-bound Iodine (PBI%) rises (429). In the rat, multiple

*For the literature see 114, 186, 642, 818, and 932.



Reaction (22), the hot reaction, populates the $v=0$ to $v=1/2$ states, with the $v=5$ or 6 state preferred [19:591]. Note that the set of reactions (21) and (22) form a chain mechanism. As a result, efficiency based on output power versus electrical input can be substantially greater than 100%. The length of the average chain has been estimated as 20 cycles [14]. Systems operating on both reactions should have larger output powers than those utilizing only one reaction.

To initiate reaction (21) and/or (22), donors for F , F_2 , H , and H_2 must be provided. As noted earlier, SF_6 and H_2 have been used in a number of operating HF lasers and are used in this Raytheon HF laser.

H_2 gas is readily available and can be dissociated to provide H atoms. If only H_2 were provided with no dissociation, both reaction (21) and (22) could still operate, since hydrogen is produced in reaction (21).

The complication in the kinetics arises from the SF_6 donor for fluorine. SF_6 is used because it is inert and more easily handled than fluorine gas. Before examining the processes for the production of F and F_2 from SF_6 , the structure and properties of SF_6 should be examined.

Sulfur hexafluoride (SF_6) has an octahedral structure

with six σ -bonds between fluorine atoms and the sulfur atom. Fluorine has one empty p-orbital ($1s^2 2s^2 2p^5$) and sulfur has six electrons in its outer shell ($1s^2 2s^2 2p^6 3s^2 3p^4$). The six fluorine atoms each share one of the outer electrons with the sulfur atom to form d^2sp^3 hybrid orbitals [28:99]. The S - F bond energy is slightly less than 78 kcal/mole (3.3 eV/molecule) and the bond length is approximately 1.4 angstroms [37:534-539, 38:F202].

SF_6 is very stable and reacts only under extreme conditions. This HF laser uses an electric discharge (12kV, 350 Amps) to produce the fluorine from SF_6 . H_2 is also dissociated in the discharge.

The energy of the electrons in the discharge is important to the nature of $e^- - SF_6$ reactions. An estimation of electron energies can be obtained with the model of figure 2.

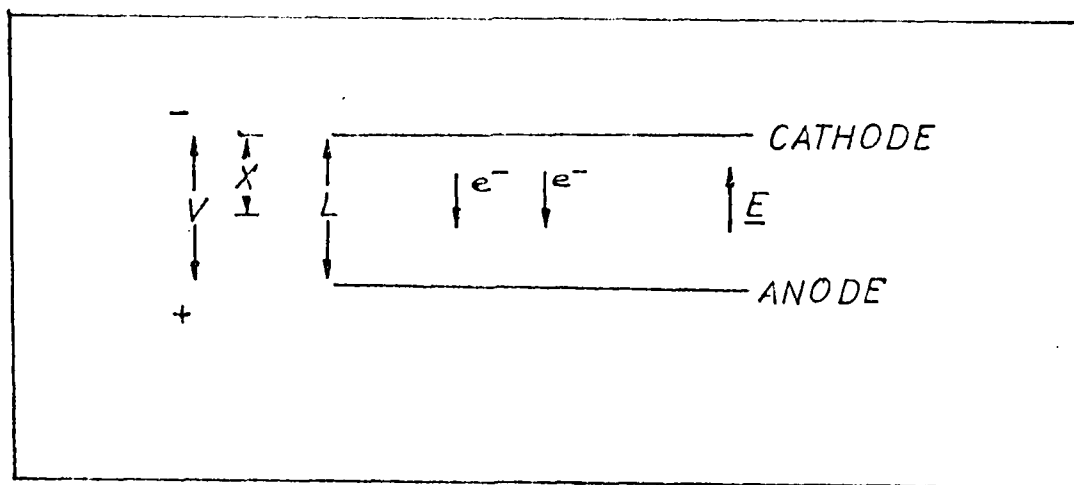


Figure 2.
ELECTRON DISCHARGE MODEL

The electrons at the cathode have a potential energy

of eV , where e is the charge of an electron and V is the voltage applied across the cathode/anode structure. For a uniform electric field, this potential energy will vary linearly across the gap to zero at the anode. From energy conservation, the decrease in potential energy of an electron as it moves to the anode is equal to the increase in the electron's kinetic energy. The electron is originally at rest and the kinetic energy of an electron at distance X from the cathode is

$$E = eV \frac{X}{L} \quad (27)$$

The average kinetic energy at collision is then

$$\langle E \rangle = eV \frac{\langle X \rangle}{L} = eV \frac{\Lambda}{L} \quad (28)$$

where Λ is the average distance an electron will travel before collision with a gas molecule, or the electron's mean free path. If it is assumed that an electron gives all its energy to the gas molecule upon collision, then the average electron energy throughout the gas, in electron volts, will be

$$\langle E \rangle = \frac{\Lambda}{L} 12 \text{ KeV} \quad (29)$$

for a 12 kV applied voltage. L is about 1 cm.

A very rough estimate of the mean free path can be obtained from a hard sphere model of collisions

$$\Lambda = \frac{4}{\pi n d^2} \quad (30)$$

where n is the number density of SF_6 , d is the diameter

of SF_6 and the equation is valid for light-heavy particle interactions. Taking $d = 2.8\text{\AA}$ (twice the S-F bond length) and using the ideal gas equation for number density

$$n = \frac{P}{KT} = \frac{(1\text{ATM}) \times (10^5 \text{N/M}^2)}{(1.38 \times 10^{-23}) (300) \text{JOULE}} \text{TORR} \quad (31)$$

Then, $n = 2.6 \times 10^{24} \text{ 1/M}^3$ and $\Lambda = 6.4 \mu\text{m}$.

This estimate is crude, for it completely neglects the electric field interaction. A more accurate value for Λ is obtained from a measurement of the $e^- - \text{SF}_6$ crosssection. This crosssection has been measured as $\sigma = 2.2 \times 10^{-19} \text{ m}^2$.

Thus,

$$\Lambda = \frac{1}{\sigma n} = 1.79 \mu\text{m}. \quad (32)$$

This slightly smaller mean free path will be used for further calculations.

The average electron energy from equation (29) is

$$E = \frac{\Lambda}{L} 12 \text{keV} = \left(\frac{1.79 \times 10^{-6}}{.01} \right) 12 \text{keV} = 2.2 \text{eV} \quad (33)$$

The average electron velocity is about 10^6 m/sec .

The mean free path is small compared to the anode-cathode separation and the electrons will suffer many collisions before clearing the discharge volume. The large number of electron collisions and low average energy suggests some sense of equilibrium may be obtained, and the electrons could be characterized by a temperature T , such that

$$\langle E \rangle = \frac{3}{2} KT \quad (34)$$

The temperature at 2.2 eV is then 25,500 °K.

The actual distribution of electron energies is potentially

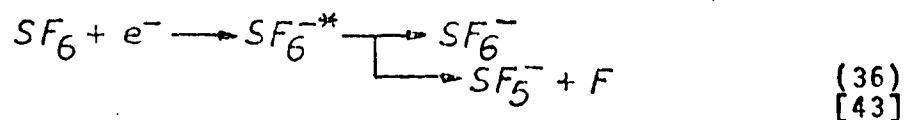
complex. There exists a large electric field, accelerating the electrons. There also exists a number of collision partners that could selectively depopulate particular energy electrons from the distribution. A steady state solution of the Boltzman equation for a system with an 18 kV/cm electric field was computed [41] and modified for an $\text{SF}_6\text{-H}_2$ mixture [42]. Results indicate a distribution that does not vary from a Maxwellian distribution by more than a factor of two over the 0 - 50 eV energy range. Thus, a Maxwellian distribution of electron energies will be assumed, with an average energy of 2.2 eV or temperature of 25,500°K.

A number of authors have investigated the kinetics of $\text{SF}_6 + e^-$ [14, 43-45]. Simply from the structure of SF_6 , it would be expected that only atomic fluorine would be produced. To produce F_2 , two, adjacent S-F bonds would need to be broken and the F-F bond created. The production of F_2 is much more likely from the process



and will be discussed later.

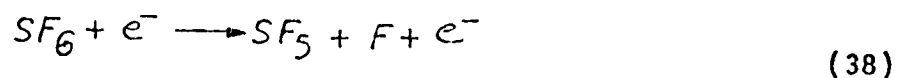
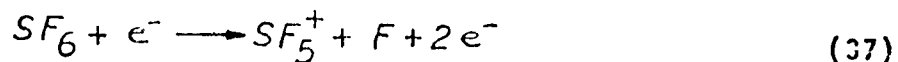
The production of atomic fluorine is based on the mechanism



The low energy, "thermalized" electrons attach to the SF_6 molecule to produce an excited state SF_6^{-*} , which decays very rapidly to either SF_6^- or $\text{SF}_5^- + \text{F}$. Since the second reaction

rates are so rapid, the final products may be considered the products of $SF_6 + e^-$.

Bashkin reports major fluorine production from the reactions

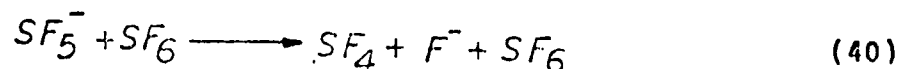


as well. These reactions have been investigated by Ahearn [46] and Assundi [47]. The reaction



is described by Curran [48] and included in a model of $SF_6 + H_2$ in an electric discharge developed by Lyman [42]. In this article by Lyman, pulse shapes for an $SF_6 + H_2$ electric discharge laser with a μ sec duration have been theoretically computed.

After these processes are initiated, further fluorine production from a reaction proposed by McGeachan [45] is possible:



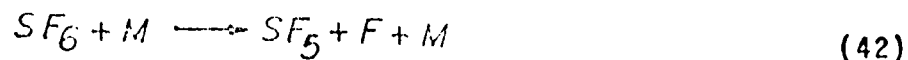
This reaction depends greatly on the ratio of electric field to number density (a measure of average electron energy) and is only important if $E/\eta \geq 3 \times 10^{-15} \text{ VOLT-CM}^2$.

The Raytheon laser has a 12 kV voltage applied across a 1 cm gap with 80 torr total pressure, and thus

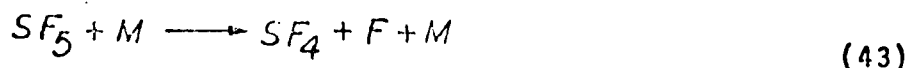
$$E/\eta = 2 \times 10^{-15} \text{ VOLT-CM}^2 \quad (41)$$

The production of F_2 from reaction (40) will be neglected.

Reactions such as



and



have such high activation energies (76 kcal/mole and 66kcal/mole) that they may be neglected. SF_6 may also be collisionally dissociated to produce ground state HF by



This reaction will be discussed later in conjunction with the pumping reactions.

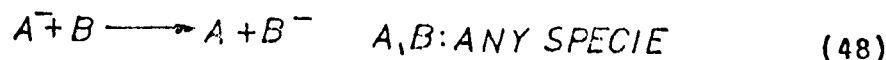
Hydrogen gas is also dissociated in the electric discharge. Collisional dissociation is again small, due to the high activation energy. Hydrogen dissociation is given by the reaction



Hydrogen may also be ionized by the electrons:

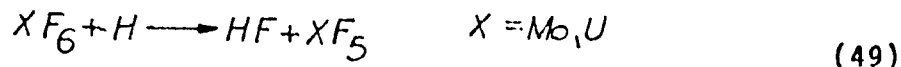


Charge transfer such as



can alter the concentrations H_2^+ , H^+ , F , F^- , and other species. The effect of these charge transfer equations will be addressed after presenting the pumping, recombination, and depopulating processes.

The pumping reactions have been presented in reactions (21) and (22). Several additional sources of HF should be considered. The decomposition of SF_6 by H to produce HF by reaction (44) was studied by Fenimore [49] and lasing with the reaction



important to the production of HF was studied by Dolgave [75]. The rate constant for reaction (44) is about 10^{20} smaller than the rates for reactions (21) and (22) and the reaction may be completely neglected. (See Appendix A for rate constants)

The direct production of HF by



is a moderately slow reaction, with a rate constant on the same order as for reaction (35) and may be important to the production of ground state HF. Reaction (50) will be analyzed in conjunction with the recombination of fluorine, reaction (35).

The importance of the hot reaction (22) depends on the quantity of diatomic fluorine available for reaction. Many $\text{SF}_6 + \text{H}_2$, electric discharge experiments indicate reaction (22) is not important [5,8,9,14,16,20]. In such cases, no vibrational transitions from levels higher than $v=3$ are observed and power is relatively low. Bashkin observed an increase in power by a factor of 20 when F_2 was added to the $\text{SF}_6 + \text{H}_2$ mixture under conditions very similar to this investigation [14]. It might be expected that the production of F_2 in this Raytheon laser is also small.

To establish the rate of production of F_2 , reaction (35) must be examined, for it is the sole source of F_2 .

The rate of formation of products can be characterized by the time interval required to reduce the concentration of reactants to a fixed percentage of the initial concentration, say .5 or .37. By comparing the magnitudes of these characteristic times to the gas flow rate, discharge pulse width, and other reactions, the importance of each reaction can be established. To make these comparisons, the gas flow rate and discharge duration must be examined.

The most important features of the HF laser in determining the flow rate are the discharge dimensions and the volume capacity of the gas recirculating fans. The gas flow velocity is about 250 ft/sec and the discharge structure's width is .166 inch (See experimental section). The time interval during which the products remain in the cavity is

$$\tau = L/U = 55 \mu S \quad U = 250 FT/S \quad L = .166 IN. \quad (51)$$

The effects of thermally caused pressure waves as described in the experimental section increase this time by a factor of 2-5, or to about 200 μ sec. Reactions with characteristic times greater than 200 μ sec may be neglected.

Another important factor of the laser design is the time width of the electric discharge, because it will determine the time interval during which atomic fluorine is produced.

This pulse width is about 100 nsec. The cold reaction is fast and has a characteristic time of about 100 nsec (See Appendix A). Thus, atomic fluorine is produced and consumed on a time scale of 100 nsec. After this time, little excited HF is produced. Since the HF output power pulse is the quantity of interest, only those reactions with characteristic times on the order of 100 nsec need be considered.

With this information, all the reactions of the SF_6 and H_2 system can be analyzed. An example calculation of characteristic times for the cold reaction and recombination of fluorine will be presented here. The characteristic times for the remainder of the reactions is presented in Appendix A.

The reaction



implies the rate equation

$$\frac{d[\text{F}]}{dt} = -K_{\text{r}}[\text{F}]^2[\text{M}] \quad (52)$$

where $[\text{F}]$ and $[\text{M}]$ are the concentrations of fluorine and the arbitrary collision partner M .

The characteristic time for the reaction will be taken as the time required for 63% of the reactants to be consumed. This percentage is used to facilitate the comparisons of characteristic times to the bimolecular reactions whose concentrations decay exponentially in time. An expression for this time is established by considering the concentration of M constant:

$$\int d[\text{F}]/[\text{F}]^2 = -K_{\text{r}}[\text{M}] \int dt \quad (53)$$

$$-2\left(\frac{1}{[F]} - \frac{1}{[F_0]}\right) = -K_1[M]t \quad (54)$$

$t = \tau_1$ for $[F] = .37[F_0]$. $[F_0]$ is the concentration of F at $t=0$.

Thus,

$$\tau_1 = \frac{3.4}{K_1[M][F_0]} \quad (55)$$

Likewise, the characteristic time for the cold reaction



is obtained by considering the rate equation

$$\frac{d[F]}{dt} = -K_2[H_2][F] \quad (56)$$

$$\int \frac{d[F]}{[F]} = -K_2[H_2] \int dt \quad (57)$$

$$[F] = [F_0] e^{-K_2[H_2]t} \quad (58)$$

and

$$\tau = \frac{1}{K_2[H_2]} \quad (59)$$

To evaluate these characteristic times, the rate constants presented in the appendix are needed. For the cold reaction $K_2 = 10^{13} \text{ CM}^3/\text{MOLE-SEC}$ and for the fluorine recombination $K_1 = 10^{16} \text{ CM}^3/\text{MOLE-SEC}$. The initial concentration of H_2 is ($P = 18 \text{ TORR}$)

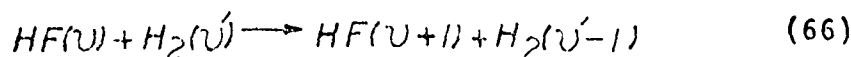
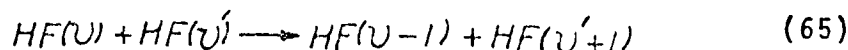
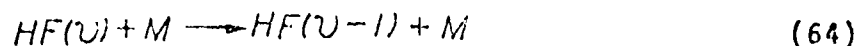
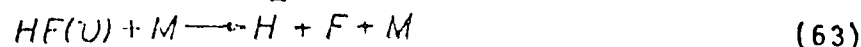
$$[H_2] = \frac{P}{KT} = 5.8 \times 10^{23} \frac{1}{\text{M}^3} \cong 10^{24} \frac{\text{MOLE}}{\text{CM}^3} \quad (60)$$

Then $\tau_2 = 100 \text{ NS}$, as quoted before. The exact concentration of F_0 depends on the electron attachment reactions. An upper limit for F_0 would certainly be the initial concentration of SF_6 , since only one fluorine atom is produced from each SF_6 molecule. Then, the characteristic time for fluorine

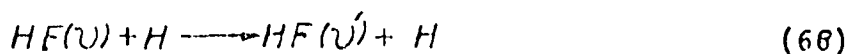
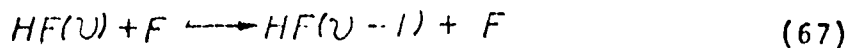
recombination is 17 μ sec or greater for a 4:1 $\text{SF}_6 : \text{H}_2$ mixture. Since $T_1 \gg T_2$, most of the atomic fluorine will be consumed by the cold reaction and the recombination of fluorine may be neglected. Note that fluorine atoms would recombine during the time they remain in the cavity (200 μ sec) if they did not react in reaction (21).

Similar arguments for the recombination process (50) indicates it too may be neglected. The characteristic time is 20 μ sec.

A number of process can reduce the concentration of excited HF by depopulation or recombination. These reactions include:



The laser is designed to convect the reaction products away from the optical cavity before processes (61-66) affect the laser output power. The same characteristic time analysis for these reactions is completed in Appendix A. The only significant reactions leading to excited HF depopulation are:



The reaction rates for the charge transfer equations are very fast. The ion concentration is very low, however. This ion concentration is specified by the discharge current of 350 Amps:

$$I = dq/dt \quad q = I \Delta t = (350)(100 \times 10^{-9}) \text{ COUL.} \quad (69-70)$$

The number of charges in the 8cm^3 volume is then

$$n_{e^-} = q/e = 4.4 \times 10^{-11} \frac{\text{MOLES}}{\text{CM}^3} \quad (71)$$

The total production of positive ions is of the same order as the electron concentration. If the concentration of any ion is taken as 10^{-10} moles/cm³, the characteristic time is

$$\tau = \frac{1}{k n_{e^-}} \approx 1 \text{ mS} \quad (72)$$

This time interval is four orders of magnitude greater than the discharge pulse width of 100 nsec. Thus, charge transfer depending on an ion concentration may be neglected. The reaction

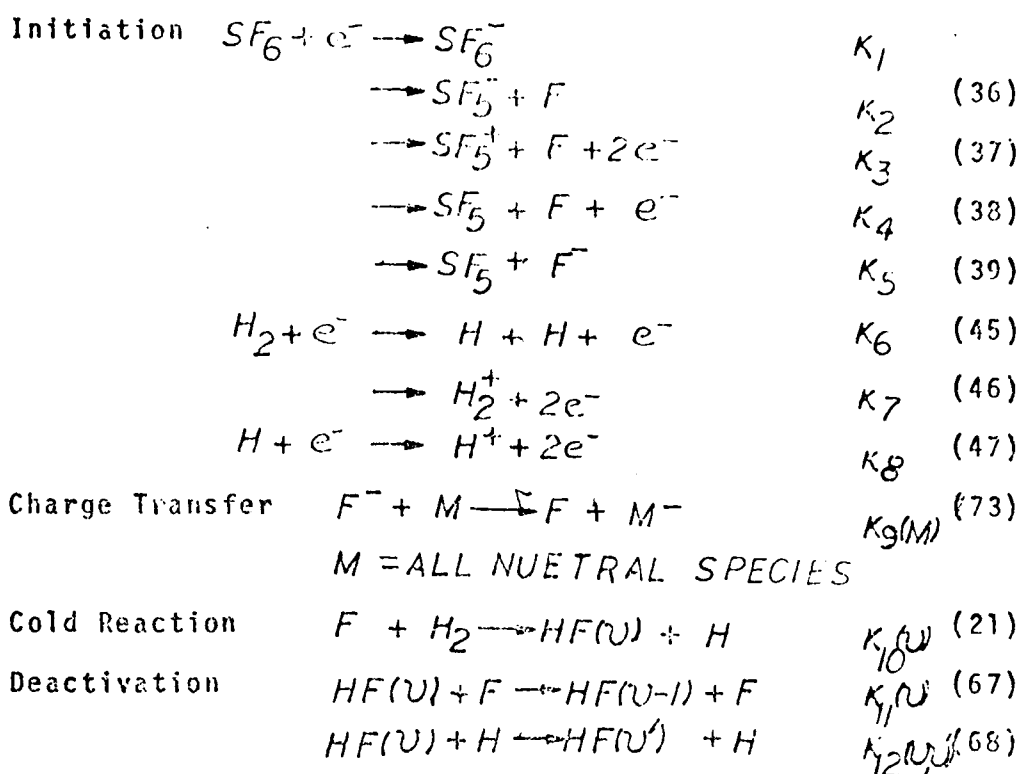


may be significant, however. Here

$$\tau = \frac{1}{k[M]} = 20 \text{ nS} \quad (74)$$

which is a very short characteristic time. This is the only charge transfer equation that will be considered.

The system of kinetic equations, or mechanism, for the production of vibrationally excited HF that results from this complete presentation is:



The system of rate equations modeling the discharge is

$$\frac{d[SF_6]}{dt} = -(K_1 + K_2 + K_3 + K_4 + K_5) n_e [SF_6] \quad (75)$$

$$\frac{d[H_2]}{dt} = -K_6 n_e [H_2] - \sum_V K_{10}(V) [F] [H_2] \quad (76)$$

$$\frac{d[H]}{dt} = 2K_6 [H_2] n_e - K_8 n_e [H] + \sum_V K_{10}(V) [F] [H_2] \quad (77)$$

$$\frac{d[F]}{dt} = +(K_2 + K_3 + K_4) n_e [SF_6] + \sum_M K_9(M) [F^-] [M] - \sum_V K_{10}(V) [F] [H_2] \quad (78)$$

$$\frac{d[F^-]}{dt} = +K_5 n_e [SF_6] - \sum_M K_9(M) [M] [F^-] \quad (79)$$

$$\begin{aligned} \frac{d[HF(V)]}{dt} = & +K_{10}(V) [F] [H_2] - K_{11}(V) [HF(V)] [F] \\ & + K_{11}(V+1) [HF(V+1)] [F] - \sum_{V' < V} K_{12}(V, V') [HF(V)] [H] \\ & + \sum_{V' > V} K_{12}(V, V') [H] [HF(V')] \end{aligned} \quad (80)$$

with the initial values

$$\left[H \right]_0 = \left[F \right]_0 = \left[\bar{F} \right]_0 = \left[HF \right]_0 = 0 ; \left[\frac{d}{dt} \right]_0 = 4 \left[\frac{d}{dt} \right]_0 = 4 \times 10^{-6} \frac{14 \text{ eV}}{\text{cm}^3} \quad (81)$$

The current forcing function is

$$\eta_c = \frac{1}{e} \int_{t_1}^{t_2} I(t) dt \quad (82)$$

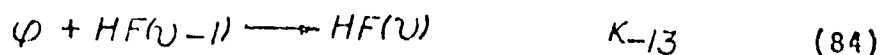
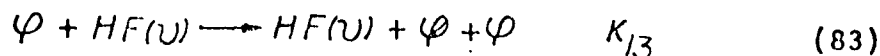
The current pulse is given in Appendix B and is taken from the observations of the Raytheon study [3:36].

The limits of integration on the current forcing term are taken as $t_2 - t_1 = 20 \text{ nS}$. The average electron energy at collision is, from equation (33), 2.2 eV, and the velocity corresponding to this energy is $8.8 \times 10^5 \text{ m/s}$. The electron's energy increases linearly after each collision; the average energy is 1 eV and the average velocity is $6.2 \times 10^5 \text{ m/s}$. The electrons take 16 nsec to traverse the cathode/anode gap. The system of rate equations is solved numerically in Appendix B with a step-by-step integration method. A 20 nsec time interval is used for this integration as well.

The rate constants $K_1 - K_{10}$ are listed in Appendix A.

Optical processes have not yet been considered.

Spontaneous emission may be neglected, due to the long radiative lifetime of HF (.4Sec) (See p12). Stimulated emission is certainly of prime importance and does affect the population of excited HF levels. The stimulated processes are



where φ is the symbol for photons of energy $h\nu = hc/2.8\mu m$. The number density of photons is given by the implied rate equation

$$\frac{d n_{\varphi}}{dt} = K_{13} n_{\varphi}[HF(v)] - K_{-13} n_{\varphi}[HF(v-1)] \quad (85)$$

The reactions (83) and (84) would affect the rate equation (80), adding a term of

$$-K_{13} n_{\varphi}[HF(v)] + K_{-13} n_{\varphi}[HF(v-1)] \quad (86)$$

The rate constants for reactions (83) and (84) are calculated in Appendix A and are related to the Einstein coefficient of page 12 by

$$K_{13} = K_{-13} = Ch\nu B_{21} = 1.2 \times 10^{-4} \frac{CM^3}{SEC-PARTIC} \quad (87)$$

The characteristic time for the term (86) is then

$$\tau = \frac{1}{n_{\varphi} K_{13}} \quad (88)$$

where

$$n_{\varphi} = \frac{ENERGY PULSE/h\nu}{BEAM VOLUME} = \frac{E_p/h\nu}{\pi W^2 C t_p} = 6.5 \times 10^{11} \frac{1}{CM^3} \quad (89)$$

and then, $\tau = 12 NSEC$.

Rather than include the reactions (83) and (84) in the system of equations on page 26, the model will be simplified by assuming that stimulated emission is very fast compared to the pulse width $12 NSEC \ll 100 NSEC$. With this assumption, all the excited HF molecules in the upper laser level, N_2 , created during the integration interval of 20 nsec will be stimulated to emit a photon.

Once a photon is created, it leaves the optical cavity very quickly, due to low mirror reflectivity. The photon

lifetime is given by

$$\tau_c = \frac{1}{c(\alpha_0 + \frac{L}{2L} \ln \frac{1}{R})} \quad (90) \quad [50:79]$$

where α_0 is the distributive loss coefficient, L is the cavity length, and R is the output mirror reflectivity.

Assuming $\alpha_0=0$ and evaluating equation (90) for the Raytheon laser ($L = .56 M$, $R = 30\%$), $\tau_c = 3.1 NSEC$.

Therefore, most of the photons created in the 20 nsec integration interval will leave the cavity. The output power is then

$$P = [HF(2)] V \frac{h\nu}{\Delta t} \quad \Delta t = 20 NSEC \quad (91)$$

where $[HF(2)] V$ is the total number of $\nu=2$ HF molecules created in the 20 nsec interval.

The solution to the system of differential equations on page 26 with these assumptions on the optical processes is detailed in Appendix B. Several of the equations can be decoupled from the rest of the system and solved directly. The remaining equations form two sets; one involving H_2 , H , F , and F^- , and the second involving the vibrational levels of HF and the output power. These two sets are solved numerically by a step-by-step integration method. The resultant power pulse shape is plotted in figure 3.

The HF pump laser has been discussed in these first two sections. The final section of this chapter will analyze the optical pumping and CO_2 laser.

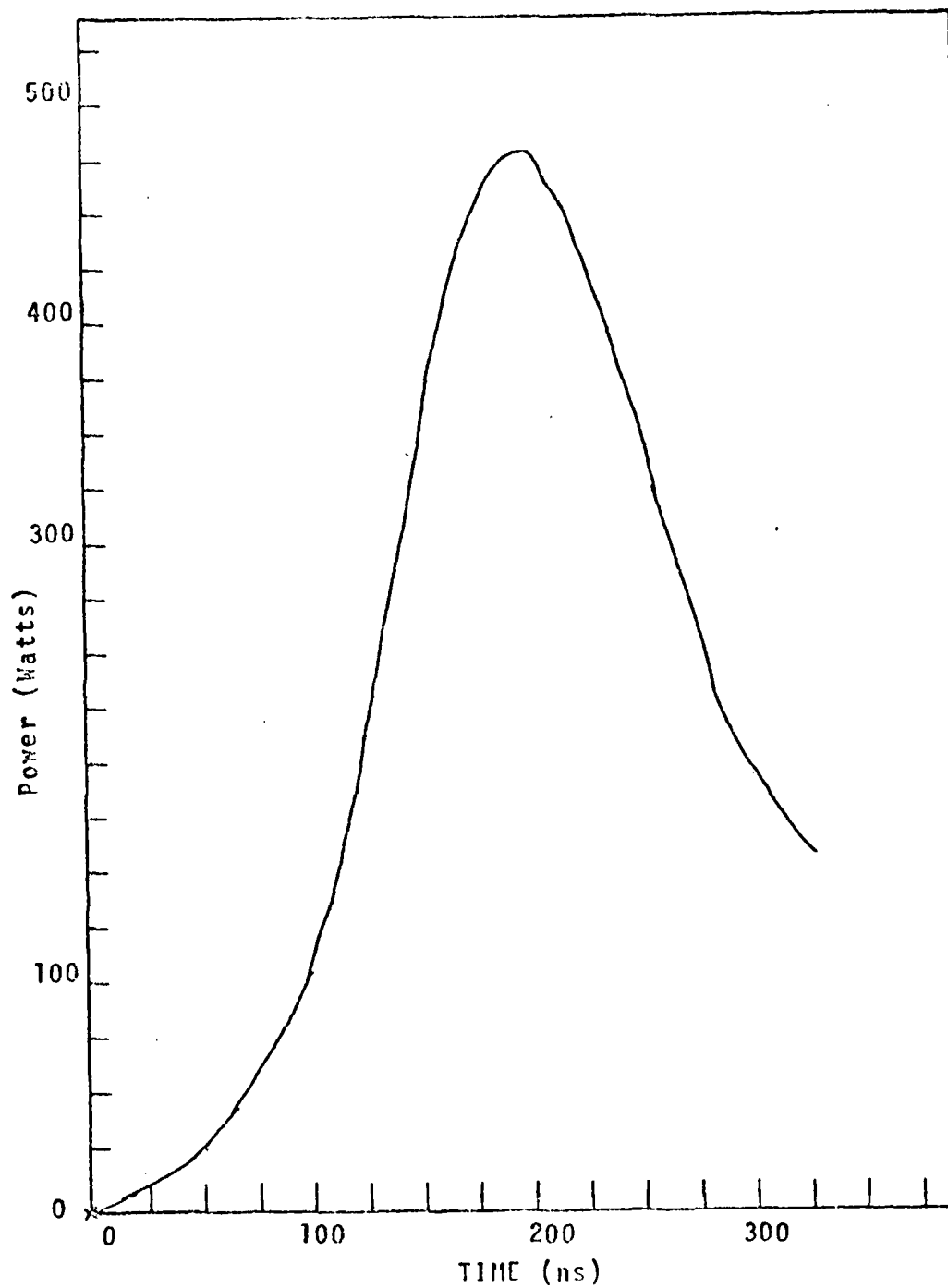


Figure 3.
Predicted HF Power Pulse Shape

Optical Pumping and the CO₂ Laser

Various pumping techniques may be used to establish a population inversion within a lasing medium. Optical pumping, using a high energy IR laser to pump a second laser medium, can be advantageous. Most of the energy can be efficiently coupled into the lasing medium. No pumping of the lower laser level occurs, due to the narrow energy band of the pump. Optical pumping in this case is used to convert a laser beam to a longer wavelength.

Several types of optical pumping are possible [51,2]. Figure 4 illustrates five different optical pumping schemes.

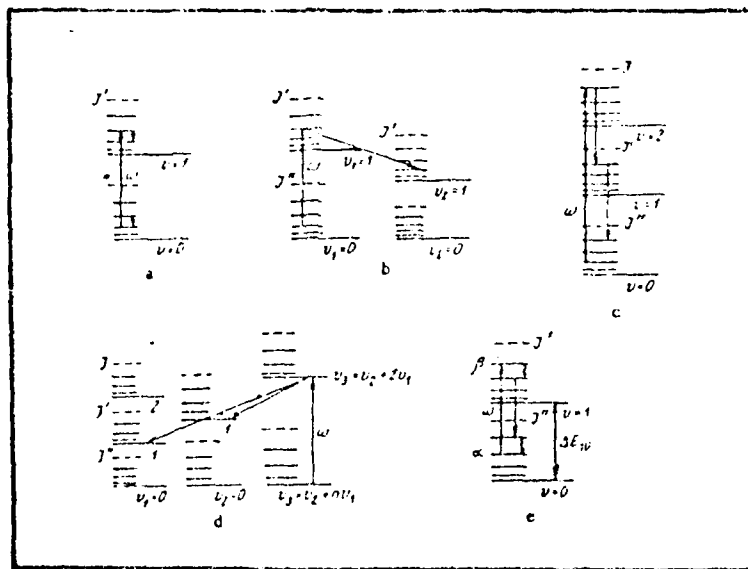


Figure 4.

Optical Pumping Schemes [51]

Diagrams a, c, and e illustrate pumping and lasing occurring on the same fundamental band. One example is to pump on an R transition and lase on a P transition. Diagram b shows pumping to a fundamental level and lasing within a difference

band to a lower level. Finally, diagram d illustrates pumping to a combined vibrational level of the molecule (such as 101 in CO_2) and lasing on a hot band.

A number of lasers based on these processes have been demonstrated [2,52]. Investigations of HF pumped media [2,52] and optical pumping of CO_2 [53-56,25] have been performed. Raytheon searched for a laser source at 4.3 - 5 μm compatible with the HF/DF laser design and found no "priciple" laser source [3:56]. Isotopic species of CO_2 [2,23] and H_2O [2,52] appeared to satisfy the requirements for optical pumping by the HF laser and were investigated [3:56-57]. No lasing was achieved with H_2O , but three isotopes of CO_2 , including $^{12}\text{C}^{18}\text{O}_2$, did establish lasing. One other HF pumped CO_2 laser has been reported [23].

The isotope $^{12}\text{C}^{18}\text{O}_2$ was used in this experiment and the HF $\text{P}_2(6)$ transition was used to pump the CO_2 101 vibrational level. An inversion is created between the 101 and 100 levels and is of the type of optical pumping shown in figure 4d. The 001 CO_2 level is nearly resonant with the lasing transition and some self absorption will occur. The lower laser level decays mainly to the 010 vibrational level.

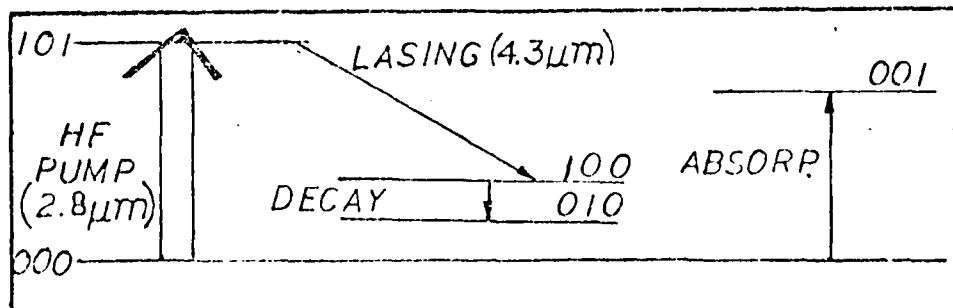


Figure 5
 CO_2 Energy Level Diagram

A first order calculation of transition frequencies can be made from the fundamental vibrational modes:

$$\bar{\nu} = (\nu_1 + 1/2) \bar{\nu}_1 + (\nu_2 + 1/2) \bar{\nu}_2 + (\nu_3 + 1/2) \bar{\nu}_3 \quad (92)$$

$$\bar{\nu}_1 = 1330.0 \text{ CM}^{-1} \text{ SYMMETRIC}$$

$$\bar{\nu}_2 = 667.3 \text{ CM}^{-1} \text{ ANGLE BEND}$$

$$\bar{\nu}_3 = 2349.3 \text{ CM}^{-1} \text{ ANTI-SYMM}$$

[57]

From equation (92) the transitions are:

$$000-101$$

$$\Delta \bar{\nu} = \bar{\nu}_{101} - \bar{\nu}_{000} = \bar{\nu}_1 + \bar{\nu}_3 = 3679.3 \text{ CM}^{-1} \quad (93)$$

$$101-100$$

$$\Delta \bar{\nu} = \bar{\nu}_{101} - \bar{\nu}_{100} = \bar{\nu}_3 = 2349.3 \text{ CM}^{-1} \quad (94)$$

$$001-000$$

$$\Delta \bar{\nu} = \bar{\nu}_{001} - \bar{\nu}_{000} = \bar{\nu}_3 = 2349.3 \text{ CM}^{-1} \quad (95)$$

Due to the requirement for nearly resonant pumping, a much more exact spectroscopic study is required. Rotational levels must be considered and more precise, experimental measurements of the energy levels are needed.

A first calculation of rotational levels, shows a large separation between adjacent J levels:

$$E_J = \beta J(J+1)hC \quad \Delta J = \pm 1 \quad (96)$$

$$\Delta E = E_{J+1} - E_J = 2\beta(J+1)hC \quad (97)$$

The separation between lines is

$$\Delta E' - \Delta E = 2\beta \quad \beta \approx .387 \text{ CM}^{-1} \quad [76] \quad (98)$$

and, then

$$\Delta E' - \Delta E = .774 \text{ CM}^{-1} \quad \Delta \nu = C(.774) = 23.2 \text{ GHz} \quad (99)$$

The exact rotational-vibration transitions are given in figure 6

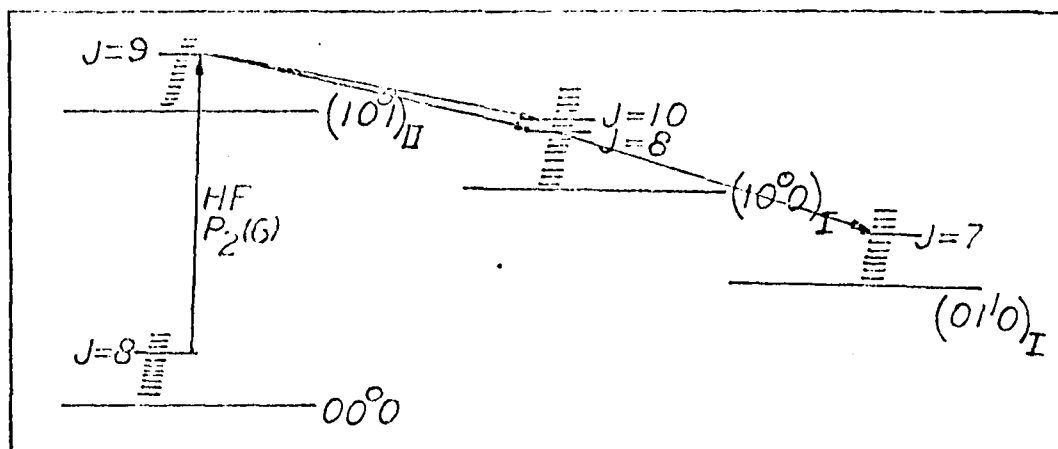


Figure 6.

$^{12}\text{C}^{18}\text{O}_2$ Energy Level Diagram [22]

It is important to note the degeneracy of the angle bend mode, denoted by the angular momentum quantum number superscript, and the nuclear spin, denoted by the subscript, to obtain the very exact transition frequencies required.

Many studies of the 10.6 μm band of CO_2 are available as a result of high energy CO_2 laser research [58,59], but less data is available for the 2.8 - 4.3 μm region, particularly for certain isotopes of CO_2 . The 2.8 μm band for $^{12}\text{C}^{16}\text{O}_2$, $^{13}\text{C}^{16}\text{O}_2$, and $^{12}\text{C}^{16}\text{O}^{18}\text{O}$ are known to an accuracy of .005 cm^{-1} [60] and for $^{12}\text{C}^{18}\text{O}_2$ to .03 cm^{-1} [61]. Such accuracy is inadequate to compare the separation of the $\text{P}_2(6)$ HF line and the $(00^\circ 0) - (10^\circ 1)_{\text{II}}$ CO_2 transition. Buchwald gives a separation between the HF $\text{P}_2(6)$ line and the CO_2 absorption transition of $\Delta \bar{\nu} = .007 \text{ cm}^{-1}$, based on direct laser pumping observations [23]. This yields $\Delta \nu = \Delta \bar{\nu}(c) = 210 \text{ MHz}$.

Note that this separation is much less than the 23 GHz between rotational levels of CO_2 and thus only one rotational level need be considered.

Finally, a study of line broadening is required. Collisional broadening is given by equation (9)

$$\Delta\nu_C = (.225 \text{ MHz}) P \sum_B \left(\frac{P_B}{P} \right) \frac{\pi}{4} (D_A + D_B)^2 \sqrt{\frac{1}{M_A} + \frac{1}{M_B}} \quad (9)$$

For pure $^{12}\text{C}^{18}\text{O}_2$ at 7 torr total pressure and 300°K and using the C-O bond length of 1.2 angstroms to give a 2.4 angstrom diameter for CO_2 , then

$$\Delta\nu_C = 5.82 \text{ MHz} \quad (100) \quad [38:F202]$$

Doppler broadening is given by equation (11)

$$\Delta\nu_D = \frac{2}{\lambda_0} \sqrt{\frac{2KT \ln 2}{M}} \quad (11)$$

and at 300°K for $^{12}\text{C}^{18}\text{O}_2$ at 2.8 μm , and 4.3 μm ,

$$\begin{array}{ll} \Delta\nu_D = 192 \text{ MHz} & \Delta\nu_D = 125 \text{ MHz} \\ 2.8 \mu\text{m} & 4.3 \mu\text{m} \end{array} \quad (101)$$

The total linewidth, $\Delta\nu_T$, based on the Voigt Profile as given by equation (12), is for $\frac{\Delta\nu_D}{\Delta\nu_C} = \frac{192 \text{ MHz}}{5.82 \text{ MHz}}$

$$\begin{array}{ll} \Delta\nu_T \cong 196 \text{ MHz} & \Delta\nu_T \cong 129 \text{ MHz} \\ 2.8 \mu\text{m} & 4.3 \mu\text{m} \end{array} \quad (102)$$

The CO_2 transition for absorption and the HF $P_2(6)$ transition are shown in figure 7.

As the HF frequency is increased, more of the HF pulse is absorbed, a greater CO_2 population inversion is created and a greater output power should be obtained. In this rough way, CO_2 power should depend on HF frequency. Two calculations of this dependence follow. The first is based

GAIN (Arbitrary Units)

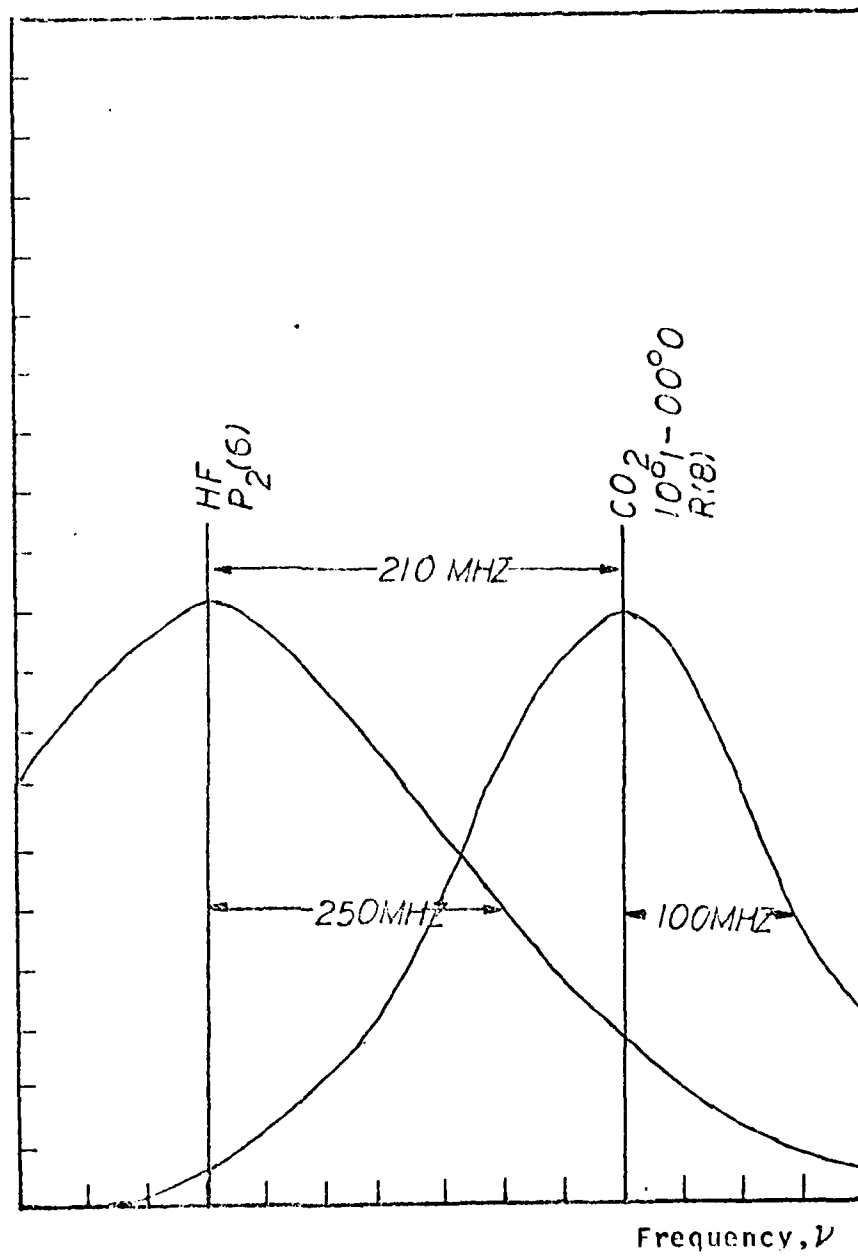


Figure 7.

HF and CO₂ Line Broadening

on figure 7. The second is based on a derivation of the CO₂ gain curve and its dependence on HF frequency.

First Calculation

The CO₂ absorption curve is Doppler broadened and the lineshape function is

$$G(\nu) = \frac{1}{\pi \sqrt{\frac{\ln 2}{\pi}}} \exp\left(-4 \ln 2 \frac{(\nu - \nu_0)^2}{(\Delta \nu_T)^2}\right) \quad (103)$$

$$\Delta \nu_T = 200 \text{ MHz} \quad [24:167]$$

where

$$\nu_0 = c/\lambda ; \quad \lambda = 2.8 \mu\text{m} \quad (104)$$

and let

$$\delta = \nu - \nu_0 ; \quad \delta \text{ IN } 100 \text{ MHz} \quad (105)$$

Then

$$G(\delta) = (7.8 \times 10^{-10} \text{ SEC}) \exp\left(-\left(\frac{\delta}{1.2}\right)^2\right) = T_1 \exp\left(-\left(\frac{\delta}{1.2}\right)^2\right) \quad (106)$$

The absorption coefficient is related to this lineshape function by

$$\alpha(\delta) = \frac{h\nu B_{12}}{4\pi} \left(n_1 - \frac{g_1}{g_2} n_2 \right) G(\delta) \quad (107)$$

where $\nu \approx \nu_0$, n_1 and n_2 are the number densities of molecules in the lower and upper CO₂ laser levels, B_{12} is the stimulated Einstein coefficient, and α is the absorption coefficient as in Beer's Law

$$I = I_0 e^{-\alpha Z} \quad (108)$$

Since the number of photons incident is proportional to the incident intensity, I , then

$$N_\varphi = N_{\varphi_0} e^{-\alpha Z} \quad (109)$$

where N_φ is the number of photons remaining in the HF pump

beam as a function of the propagation distance, Z , and N_{ϕ_0} is the number of incident photons.

The number of photons absorbed, $N_{\phi_0} - N_{\phi}$, is identical to the number of CO_2 molecules pumped to the 101 energy level:

$$N_2 = N_{\phi_0} - N_{\phi} = N_{\phi_0}(1 - e^{-\alpha Z}) \quad (110)$$

The incident photon number is estimated assuming a uniform number of photons in time:

$$N_{\phi_0} = \frac{\text{PULSE ENERGY}}{h\nu} = \frac{15611\text{J}}{7.1 \times 10^{-20}\text{J}} = 2.2 \times 10^{15} \quad (111)$$

If a small total absorption is assumed, then there will exist a uniform population inversion within the length of the CO_2 gas cell ($L = 33\text{CM}$) and the population inversion $\eta_1 - \frac{8}{3}\eta_2 \approx \eta_1$. A characteristic time can then be defined as

$$1/T' = \frac{h\nu}{4\pi} B_{12} (\eta_1 - \frac{8}{3}\eta_2) \Delta Z \quad (112)$$

$$= \frac{hC}{4\pi\lambda} \eta_1 L B_{12} \quad (113)$$

$$= \left(\frac{hC}{4\pi\lambda}\right) \left(\frac{PL}{KT}\right) B_{12} \quad (114)$$

where

$$\left(\frac{hC}{4\pi\lambda}\right) = 5.56 \times 10^{-21} \text{ JOULES} \quad (115)$$

$$\left(\frac{PL}{KT}\right) = (1.05 \times 10^{22}) P_{\text{TORR}} \frac{L}{M^2} \quad (116)$$

and from [62], $A_{21} = .63\text{S}^{-1}$ and from eq (20), $B_{12} = 3.5 \times 10^7 \frac{M^2}{J-S}$

The characteristic time is then

$$T' = 7.0 \times 10^{-11} \text{ SEC AT } 7 \text{ TORR} \quad (117)$$

From equation (107) and (110), the 101 level population is

$$N_2 = N_{\phi_0} \left[1 - \exp\left(-\frac{T_1}{\tau} \exp\left(-\left(\frac{\delta}{1.2}\right)^2\right)\right) \right] \quad (118)$$

Assuming no losses, the pulse energy is

$$E = h\nu N_{\phi_0} \left[1 - \exp\left(-\frac{T_1}{\tau} \exp\left(-\left(\frac{\delta}{1.2}\right)^2\right)\right) \right] \quad (119)$$

or

$$E = 102 \mu\text{J} \left[1 - \exp\left(-1.59 P_{\text{TORR}} \exp\left(-\left(\frac{\delta}{1.2}\right)^2\right)\right) \right] \quad (120)$$

The absorption, from equation (109) is

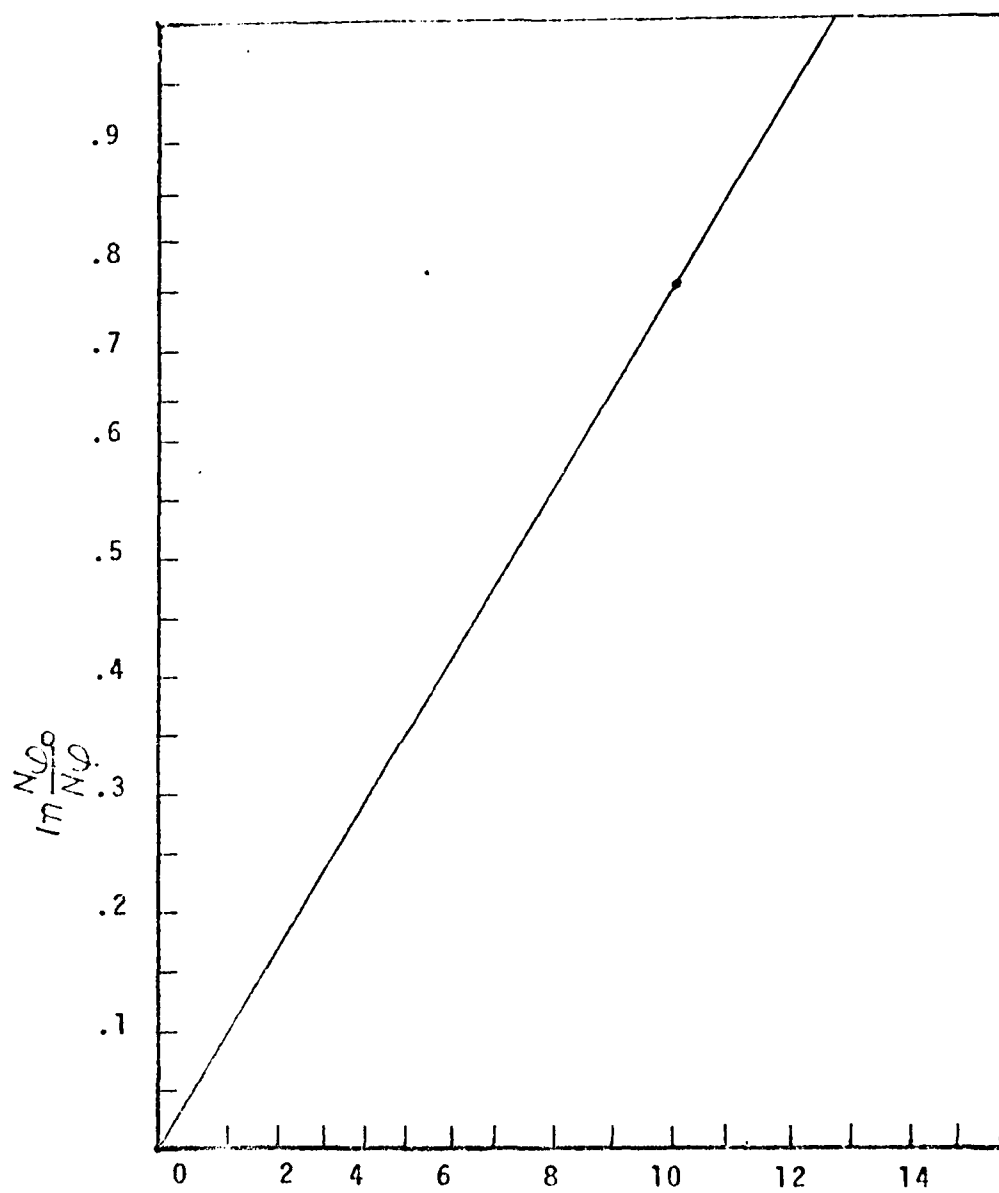
$$N_{\phi} = N_{\phi_0} \left[\exp\left(-1.59 P_{\text{TORR}} \exp\left(-\left(\frac{\delta}{1.2}\right)^2\right)\right) \right] \quad (121)$$

or

$$\frac{L}{L_0} \frac{N_{\phi_0}}{N_{\phi}} = .0023 \text{ CM}^{-1} P_{\text{TORR}} \quad (122)$$

HF power was assumed not to vary with HF frequency in this derivation. The HF transition has a large collisional, or homogeneous, broadening. For a cw, homogeneously broadened laser, the gain is "pegged" at the threshold level. Under such conditions, $\gamma = \gamma_{TH}$, and the power is held relatively constant with changes in frequency. The time interval before the gain returns to threshold level is basically the time required to reach a steady state solution of the laser rate equations. This is a relatively fast process and is basically determined by the photon lifetime. From equation (90) the photon lifetime is 3.1 nsec. Since the pulse time of 100 nsec is much longer than this lifetime, it may be assumed that HF power does not vary significantly with HF frequency.

A plot of CO_2 absorption versus CO_2 pressure (eq 122) is given in figure 8 and CO_2 power versus HF frequency in figure 9.



Pressure (Torr)

Figure 8.

CO₂ Absorption versus CO₂ Pressure

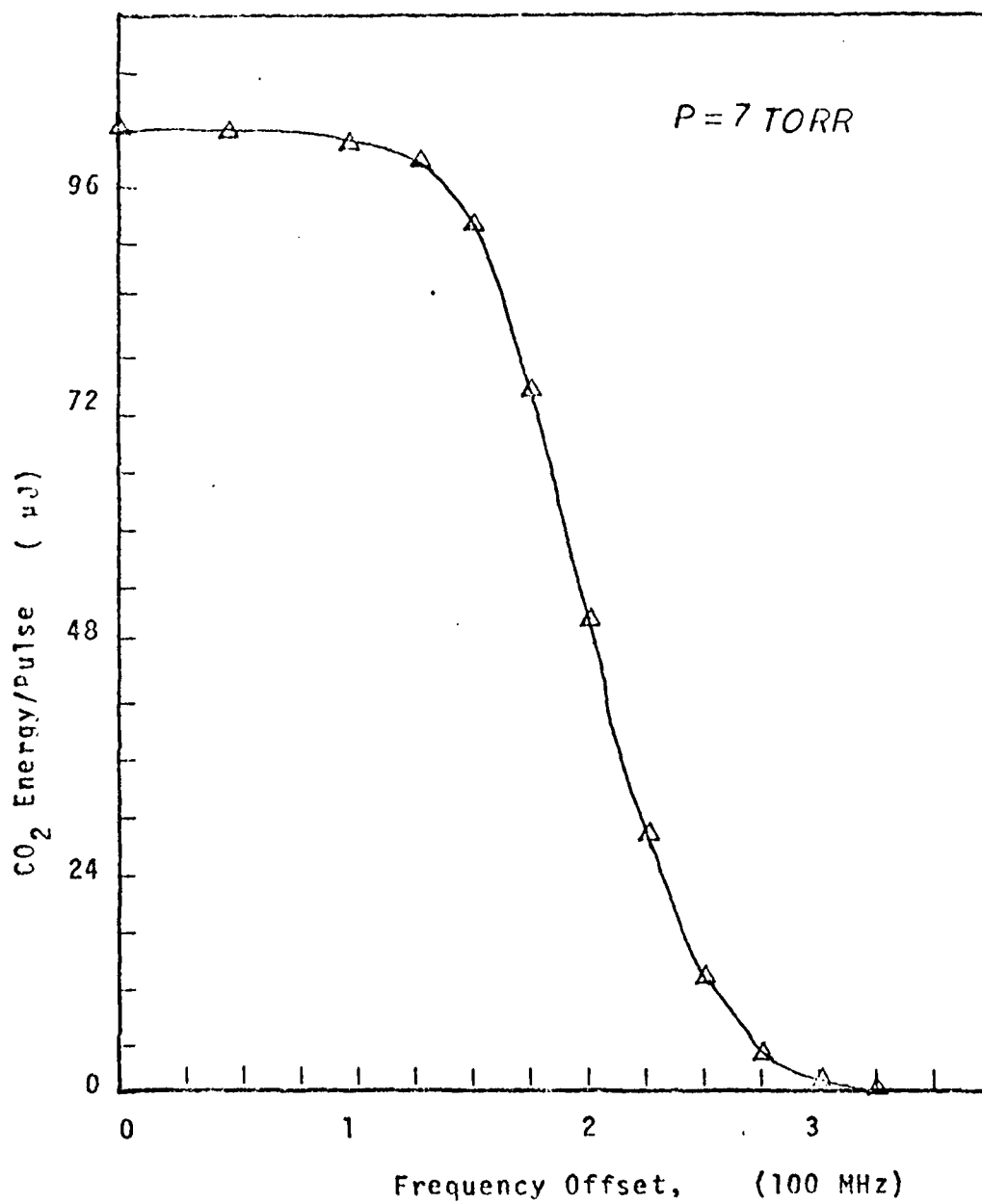


Figure 9.

CO₂ Power versus HF Frequency

Several general remarks concerning these theoretical results can be made. First, CO_2 power is very sensitive to the offset frequency, $\delta = \text{HF frequency} - \text{CO}_2 \text{ line-center}$, and is a maximum for zero offset. Pumping directly on the CO_2 linecenter is most efficient and efficiency drops off rapidly with offset frequency, as expected.

Secondly, power increases with increasing CO_2 pressure. This is reasonable, for the number of absorbers is increasing and thus output power increases. Note that the increase in power is not a result of increased linebroadening, because the transition is Doppler broadened. This second effect would be important above 70 torr, or so. In such cases the model would require revision to include collisional broadening.

The theory does not predict a maximum operating pressure, but rather, power increases continuously with pressure. This is clearly not physical. The model assumed small total absorption, but as pressure increases so does total absorption. The small absorption assumption fails at high pressures. Even at 1 torr, 80% of the HF beam is absorbed.

Finally power increases with increasing T_1 , or increased Doppler broadening, as expected. T_1 is basically a constant of the transition in question. The actual output power is rather sensitive to inaccuracy in this number, however.

This calculation of CO_2 power as a function of HF frequency has neglected the effects of coherent pumping. Two photon processes can affect the gain spectrum [63,64] and saturation [65-67] of laser excited lasers. In the

Raytheon study, the CO_2 gain curve was derived including these effects and evaluated for different HF frequencies [3:63-66].

Second Calculation

This derivation is based on the work of Feld and Javan, who studied the line shape of a Doppler broadened transition in the presence of a laser field resonating with a second doppler broadened transition sharing a common energy level [64]. The derivation is valid for two Doppler broadened transitions if one of the fields fully saturates its transition and the second field is weak. The intense field must be detuned from linecenter and the difference between transition frequencies greater than the natural linewidth of the medium.

The three level system is as shown in figure 4d, and in terms of the CO_2 energy levels is as shown in figure 10.

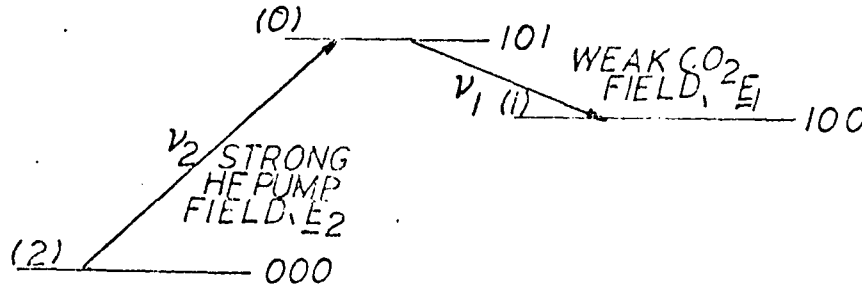


Figure 10.

Three Level CO_2 Model

The three level system consists of the strong HF pump field resonant with the 000 - 101 CO_2 transition and the lasing transition (weak field) is the 101 - 100 transition, with the shared level being the 101 level.

A single, inhomogeneously broadened gain curve will

demonstrate hole burning in the presence of a laser field. That is, molecules with a velocity such that their doppler shifted observed frequency matches the laser frequency, will be selectively depopulated from the upper laser level. A second transition sharing one of these selectively depopulated energy levels has its own doppler curve altered. The gain of the first transition is

$$\gamma_1 = \sigma_1 \Delta_1 = \sigma_1 (N_0 - N_1) \quad (123)$$

and of the second transition is

$$\gamma = \sigma_2 \Delta_2 = \sigma_2 (N_0 - N_1) \quad (124)$$

where γ is the gain coefficient, σ the absorption crosssection and N_i the total population of the i^{th} energy level. Thus, holeburning in one gain curve affects N_0 which in turn affects the second transition's gain.

The gain curve for a single, hole-burned doppler transition is symmetric, but this need not be the case for the coupled transition. This assymetry will produce a directional dependance on gain. A beam of radiation from the second transition will be more intense when it propogates with the pump beam than when propogating in the opposite direction. This issue will be discussed again in conjunction with the amplified spontaneous emission nature of the CO_2 cavity.

There are actually two distinct processes that affect the shape of the gain curve of the weak field. First, there is the single quantum affect already discussed in which one field affects the rate of stimulated emission in the second field. The second process involves the exchange of a photon

with each of the fields and is a two photon process. Both of these processes can be analyzed by establishing the transition rates with a semi-classical, perturbational approach.

This derivation involves ten major steps:

- (1) Express the electric fields classically with the appropriate frequencies, ν_2 for HF and ν_1 for the 4.3 μm CO₂ transition.
- (2) Transform to a coordinate frame at rest with respect to the particles of velocity U . Frequencies must be transformed according to the doppler effect, $\nu = \nu_0(1 + U/c)$
- (3) Express the Hamiltonian as the sum of the strong field and weak perturbing field potentials,

$$H = H_0 - \mu_2 E_2 + V$$
 where $V = -\mu_1 E_1$ is the perturbing potential of the weak field E_1 , E_2 is the strong field, and μ is the dipole moment.
- (4) Expand the wavefunction, $\Psi(r, t)$, in terms of the stationary states, $\Psi(r, t) = \sum_n c_n(t) \psi_n(r)$
- (5) Apply the time-dependent Schrodinger Wave Equation to $\Psi(r, t)$. $H\Psi = i\hbar \frac{\partial \Psi}{\partial t}$
- (6) Integrate over all space and transform to the Heisenberg interaction picture ($c_j, \dot{c}_j$)
- (7) Establish the equations of motion in terms of the time derivatives of the wavefunction expansion coefficients ($\dot{c}_j$) and add term appropriate for spontaneous decay, $1/\tau_j$.

$$\dot{c}_i = \sum_j b_{ij} c_j \quad ; \quad b_{ij} = a_{ij} \exp\left[\left(\frac{i}{\hbar} E_j - \frac{1}{\tau_j}\right)t\right]$$

$$a_{ij} = -\frac{i}{\hbar} \langle i | -e r | j \rangle \exp\left[\left(\frac{E_i - E_j}{\hbar}\right)t\right] (E_1 + E_2)$$
- (8) Solve the system of equations with a perturbational method
- (9) Calculate the transition rates, given by $|d_{ij}|^2$. Total power is $P = \eta_2 J_{21} + \eta_0 J_{01} - \eta_1 (J_{10} + J_{12})$ where η_i is the population of level i and J_{ij} is the transition rate.

- (10) Take an ensemble average of velocities, directly related to the frequency by the doppler effect,

Then, gain is

$$G(\nu_1) = \frac{1}{\pi} \frac{\nu_0}{c} \eta_2 \frac{h^2}{h} \frac{\nu_2^2 E_2^2}{4 h^2} I_M \left\{ \int_{-\infty}^{\infty} \left[\frac{1}{\sqrt{2KT/M}} \exp\left(-\frac{U^2}{2KT/M}\right) \right] \times \right. \\ \left. \left[\frac{\nu_2(1-\frac{U}{c}) - \nu_{02} + \frac{1}{2\pi T_{20}} + 2\frac{T_0}{T_{20}} \left(\nu_2(1-\frac{U}{c}) - \nu_{02} - \nu_1(1-\epsilon\frac{U}{c}) + \nu_{01} - \frac{1}{2\pi T_2} \right) \right]}{\left(\nu_2(1-\frac{U}{c}) - \nu_{02} \right)^2 + \frac{1}{4\pi^2 T_{20}} + \frac{h^2 E_2^2}{4\pi^2 h^2} \frac{T_0 T_2}{T_{20}^2}} \right] \times \\ \left. \left[\frac{dU}{\left(\frac{h^2 E_2^2}{16\pi^2 h^2} \right) - \left(\nu_1(1-\epsilon\frac{U}{c}) - \nu_{01} - \frac{1}{2\pi T_{10}} \right) \left(\nu_2(1-\frac{U}{c}) - \nu_{02} - \nu_1(1-\epsilon\frac{U}{c}) + \nu_{01} - \frac{1}{2\pi T_2} \right)} \right] \right\}$$

[125]

Where,

$M = 48 \text{ AMU}$; MOLECULAR WEIGHT OF CO_2

$K = \text{BOLTZMAN CONSTANT}$; $h = \text{PLANCK CONSTANT}$

$T = \text{ABSOLUTE TEMP}$; $c = 3 \times 10^8 \text{ M/S}$

$\eta_2 = \text{CO}_2 \text{ GROUND STATE NUMBER DENSITY}$

$\nu_{01} = \text{CO}_2 \text{ 101-100 LINECENTER FREQ.}$

$\nu_{02} = \text{CO}_2 \text{ 000-101 LINECENTER FREQ.}$

$T_0 = \text{SPONT. DECAY TIME FROM 101}$

$T_1 = \text{" " " " 100}$

$T_2 = \text{" " " " 000}$

$T_{10} = \text{POLARIZATION "DECAY" 100-100}$

$T_{20} = \text{" " " " 101-000}$

$T_2 = \text{RAMAN COHERENCE DECAY 000-100}$

$\epsilon = \pm 1 \text{ (CO/COUNTER-PROPAGATION)}$

This expression for gain was evaluated numerically in reference [3] under various conditions. Of particular interest are the results for HF power = 100 kW/cm^2 (.7 mJ per pulse coupled into a 3mm diameter tube), CO_2 pressure = 10 torr, and three different HF pump frequencies [3:66]. The results for these conditions are given in figure 11.

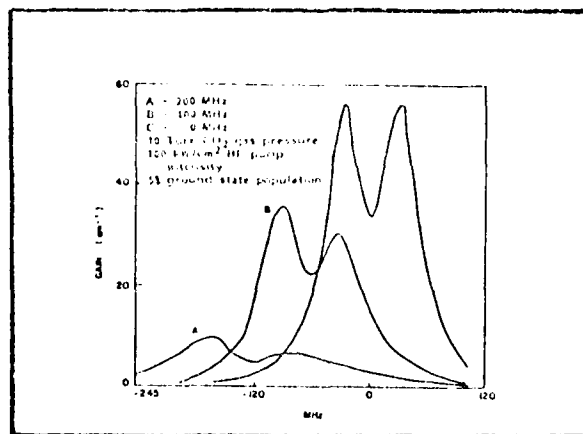


Figure 11.

CO_2 Gain for 3 HF Pump Frequencies [3:65]

From these curves, CO_2 output power as function of frequency can be established. First, the nature of the CO_2 cavity will be addressed.

The CO_2 laser is simply a pyrex cell with CaF_2 windows; no mirrors are used and sufficient gain is established in a single pass to produce lasing. That is, the CO_2 laser operates in an amplified spontaneous emission mode (ASE). Typical ASE operation does not exhibit a preference for forward or backward propagating beams. The HF pumped CO_2 laser has a forward to backward power ratio of 12, however [3:73].

This ratio is partially explained by the previous arguments concerning the coupling of the two doppler curves. The

optical pumping also establishes a population gradient within the cell due to the variable intensity of the HF beam as it propagates through the CO_2 gas. The HF beam also requires a finite time to pass through the cell and the population inversion at one end is established before it is at the other end. A detailed rate equation investigation would be required to explain the details and size of the forward to backward power ratio.

Such a directional nature to gain is often associated with superradiance [68-70]. It is probable that this system is not superradiant and simply operates in an ASE mode. The Raytheon report states the CO_2 laser operates in ASE mode without explanation [3:70]. Superradiant operation usually entails very short time scales, on the order of picoseconds. In a superradiant mode, the molecules in a volume whose dimensions are much less than the size of a wavelength are coupled and power is proportional to the number of excited states squared, rather than linearly proportional to population inversion, as in ASE. Since the same energy is available, but the pulse is much greater in magnitude, the pulse must be narrow in time [71]. The CO_2 pulses do not exhibit this nature, but rather, they follow the HF pump pulse rather closely [3:74]. No conclusive statement concerning superradiance can be made from the data obtained in this experimental study, but the process is probably not important.

Since the CO_2 laser operates without a "cavity", the determination of axial modes from the usual criterion of waves constructively interfering does not apply. Rather,

there exists a "natural" cavity length, L , determined by the gain curve. The system will tend to operate at the maximum in the gain curve for ASE operation.

Now, returning to the gain curves, the CO_2 power as a function of HF frequency can be obtained from the maximum gain of each curve in figure 11, as shown in Table I.

Table I.
 CO_2 Gain versus HF Frequency

δ (100MHZ)	γ (CM^{-1})	$\gamma/\gamma(\delta=0)$
0	55	1.0
1	35	.64
2	10	.18

Power is proportional to gain. If $\gamma = \gamma^0$ and $P = P^0$ for $\delta = 0$, then $\frac{\gamma}{\gamma^0}$ or $\frac{P}{P^0}$ can be plotted as a function of HF frequency, as is shown in figure 12. A value for P^0 will be calculated after considering gain saturation.

In the Raytheon investigation, no variation of CO_2 power with changes in HF frequency were observed. Saturation was suggested as a possible explanation [3:75]. Saturation in two senses can be considered. First, a total inversion is possible for very high pump energies. If one-half of the CO_2 molecules are raised from the 000 state to the 101 state, then absorption goes to zero. More intense HF beams

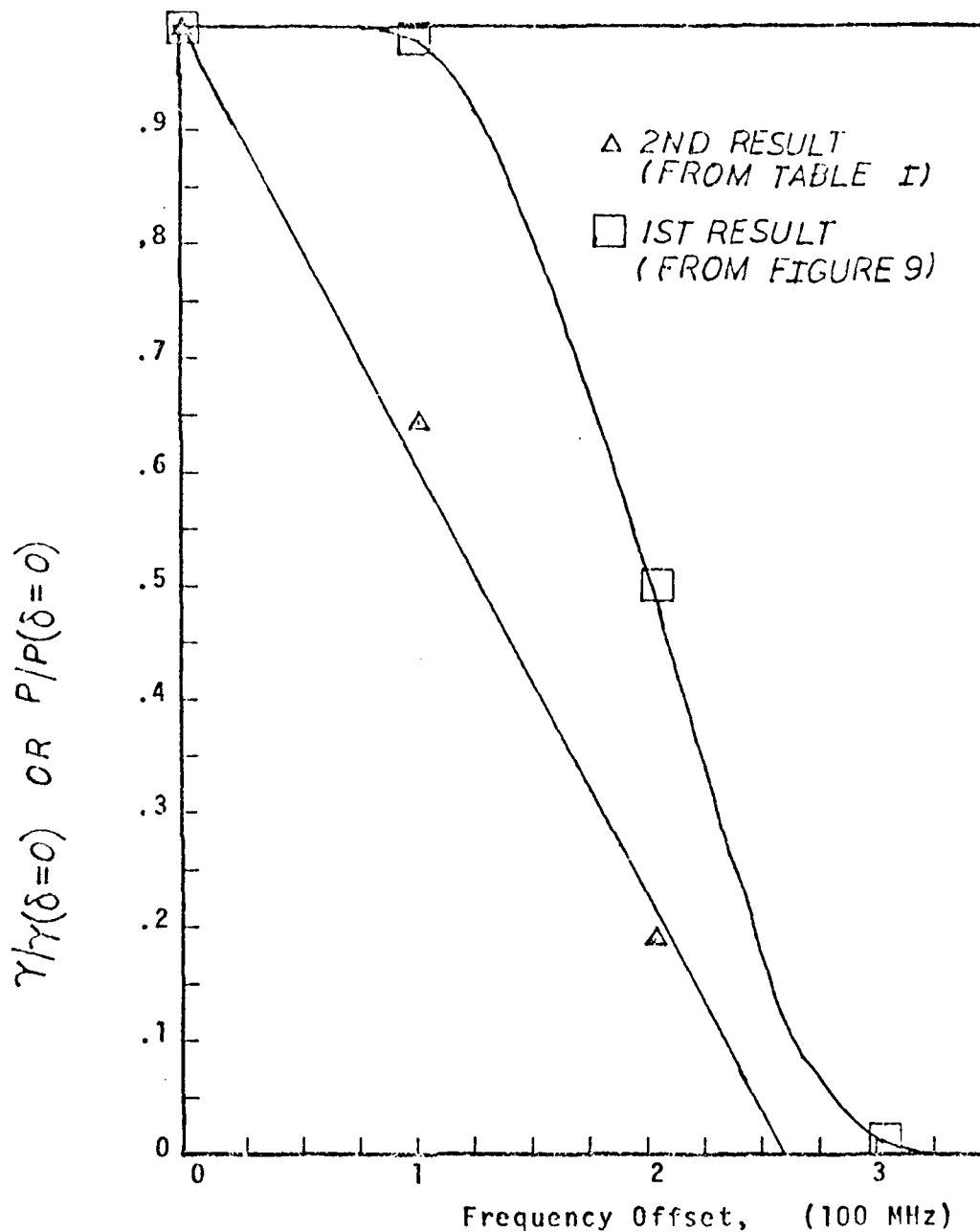


Figure 12.

CO₂ Gain versus HF Frequency

will simply be transmitted by the CO_2 gas. Secondly, the laser field created by the population inversion decreases the inversion and thus, decreases gain and power. That is, gain depends on the field intensity.

Under no circumstance is the CO_2 system completely inverted. Assuming a Boltzmann distribution of molecules among the rotational states of the ground vibrational level, only 5 % of the total number of CO_2 molecules populate the $J = 8$ level and are accessible for transition to the 101 vibrational level. Buchwald found the characteristic time for equilibration of the ground state rotational levels to be 90 ns-atm, or .8 ns at 7 torr [23]. This equilibration time is much shorter than the pump pulse duration of 100 ns. Many of the ground state CO_2 molecules will fill the $J = 8$ level as the HF pump pulse depletes them. Five percent of the total CO_2 number is a very conservative value for considering total inversion and will be used.

The number of CO_2 molecules available for transition are

$$.05N = .05\left(\frac{PV}{KT}\right) = 4 \times 10^{17} \quad (126)$$

for $V=37\text{CM}^3$, $T=300^\circ\text{K}$, $P=7\text{TORR}$. The incident

number of HF photons is from equation (111) $22 \cdot 10^{15}$

Even if every photon is absorbed and only 5 % of the CO_2 molecules are available for pumping, $\frac{N_0}{.05N} = 55 \times 10^{-3}$.

and a total inversion is impossible. Raytheon used a smaller cell (2.3 cm^3) and a higher pump energy (.8 mJ). For these conditions, $N_0/.05N = .45$ and $N_2 \approx N_1$. A total inversion

is possible if all the photons are absorbed and no equilibration of rotational levels occur. This is not the case and the system would only approach the criteria for a total inversion.

Saturation from the laser field intensity reduces the gain of the system according to

$$\gamma = \frac{\gamma_0}{1 + \frac{I_\nu}{I_S}} \quad (127) \quad [24:168]$$

where

$$\gamma_0 = \frac{\chi^2 G(\nu)}{8\pi} A_{21} \Delta \quad (128)$$

$$I_\nu = \frac{c E^2}{2} \quad (129)$$

$$I_S = \frac{4\pi h \nu A_{21}}{6(\nu) K T_{\text{INVERSION}}} \quad (130)$$

This gain saturation relationship is strictly valid for a steady state operation. The cavity photon lifetime is very short for the CO_2 laser since there are no mirrors on the cavity. The arguments of page 39 can again be used to justify the use of equation (127).

To evaluate I_S from equation (129), the lineshape from equation (106) and an Einstein coefficient of $A_{21} = 200\frac{1}{5}$ [3:60] is used. Approximating the inversion lifetime, T , as the pulse width (100 ns),

$$I_S = 5.6 \times 10^3 \frac{\text{J}}{\text{CM}^2 \cdot \text{s}} \quad (131)$$

The HF pump intensity is

$$I_\nu = 1.3 \times 10^3 \frac{\text{J}}{\text{CM}^2 \cdot \text{s}} \quad (132)$$

A beam spot size of $\omega = .6 \text{ CM}$ is used in this calculation.

The CO_2 field intensity is some fraction of the HF intensity

$$I_{CO_2} = \beta I_{HF} \quad (118)$$

$\beta < 1$ and $\sim .1$. Under these conditions the transition is not saturated.

For the Raytheon studies, $E_p = 0.8 \text{ mJ}$ and $A = \pi (0.15)^2 \text{ cm}^2$ giving $I_{HF} = 1.1 \times 10^7 \frac{1}{\text{cm}^2 \text{ s}}$, and the 101-100 transition is certainly saturated.

Now that saturation has been examined, a value of P^0 for page 49 and figure 12 can be calculated. From equations (131) and (132), the relation between small signal and saturated gain is

$$\gamma = 5.6 \times 10^{-3} \gamma_0 \quad (133)$$

Gain is related to inversion by

$$\gamma = \sigma \Delta \quad \text{SEE EQ 123} \quad (134)$$

and inversion to energy per pulse, assuming no losses, by

$$E_p = h\nu \Delta V \quad (135)$$

where Δ is the population inversion per volume and σ is the optical crosssection related to transition rate by

$$\sigma = \frac{\sum A_{21} G(\nu)}{8\pi} \quad (136)$$

Again using $G(\nu) = 7.6 \times 10^{-11} \text{ s}$ and $A_{21} = 200 \frac{1}{\text{s}}$, then

$$\Delta = 2.8 \times 10^{14} \text{ cm}^{-3} \quad (137)$$

and energy is

$$E_p = 30 \mu\text{J} \quad P = 300 \text{ W} \quad (138)$$

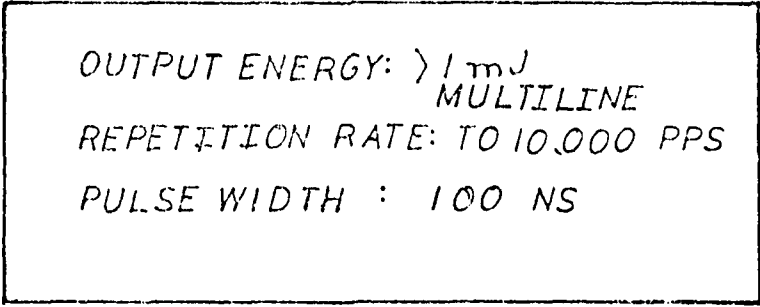
The theory of the HF pump laser, a kinetic model for the $\text{SF}_6 + \text{H}_2$ in an electric discharge, and the theory of optical pumping and the CO_2 laser has been presented. To compare these predictions with the performance of the actual system, an experiment has been designed and is described in the next section.

Experiment

This experiment was designed to characterize the performance of the HF pumped CO₂ laser and study the dependance of CO₂ power on HF frequency. First, the HF laser developed by the Raytheon Corporation [3] and the modifications made to this laser will be described. Next, the experiments to characterize the HF laser's performance are outlined. The HF pumped CO₂ system is then analyzed, including the coupling of the HF beam into the CO₂ cell. Finally, the experimental set-up and procedure for the frequency investigation is presented.

HF Laser Description

The molecular laser used to pump the CO₂ laser is an SF₆ + H₂/D₂, electric discharge, high repetition rate HF/DF laser. Only hydrogen will be used in this experiment. The laser's specifications, as presented in reference [3] are listed in figure 13.



OUTPUT ENERGY: $> 1 \text{ mJ}$
MULTILINE
REPETITION RATE: TO 10,000 PPS
PULSE WIDTH : 100 NS

Figure 13.

HF Laser Specifications

A picture of the laser, without the high-voltage electrical connections or exhaust pump, is shown in figure 14 [3:29].

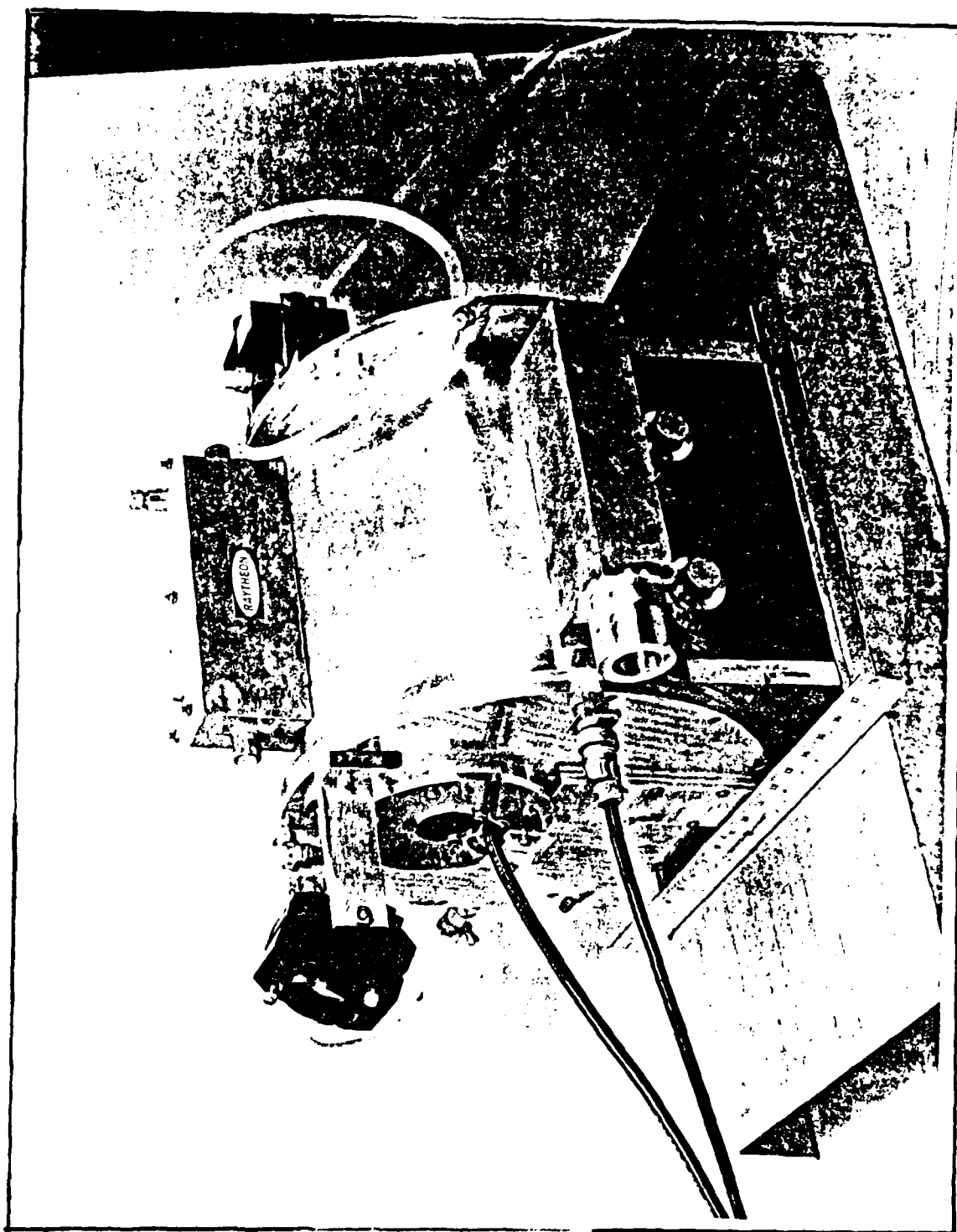


Figure 14.
 $\text{SF}_6 + \text{H}_2$ Electric Discharge Laser

The cathode (8" x 1 3/4" x 3 1/2") is situated above the cylindrical body (13 1/4" x 14 1/2" dia) directly above the optical cavity (gas volume: 17 1/2" x 1 1/8" dia.). The grating (left) and output coupler (right) extend the cavity to .5 meters. The remainder of the cylinder houses the gas recirculating and cooling systems, and the thyatron.

Details of the laser and its four subsystems will be discussed in the following sections.

Optical Cavity

The reacting gases are sealed within the cylindrical laser housing. The optical path is formed by two CaF windows (1 3/8" dia.) at Brewster's angle, 55°, separated by 17 1/2". The cavity is established by a copper and a germanium mirror, as shown in figure 15.

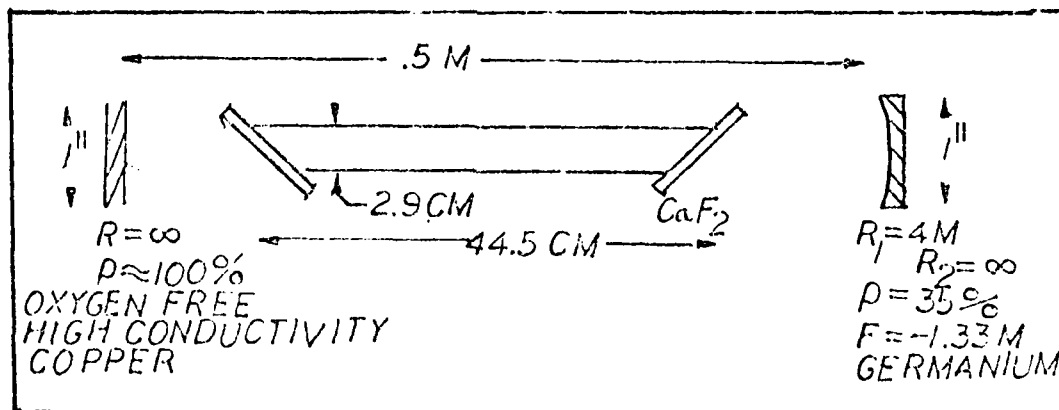


Figure 15.

HF Optical Cavity

A 300 gr/mm grating (1 3/4" x 1 3/4") can be exchanged for the copper mirror. The grating's normal is fixed at 39° to the optic axis. A 35 % output reflectivity was selected as the maximum output coupling based on the work with an HF

mini-TEA laser [3:10]. The active volume of the optical cavity is determined by the electrodes and is described in the next section.

Electric Discharge

The electrical circuit design is dictated by the requirements for a 350 Amp, 120 ns current pulse to initiate the chemical reaction at repetition rates of up to 10 kHz. The discharge circuit is shown in figure 16 and consists of three main components; (1) the voltage supply and doubler, (2) the trigger and thyatron, and (3) the laser cathode/anode structure.

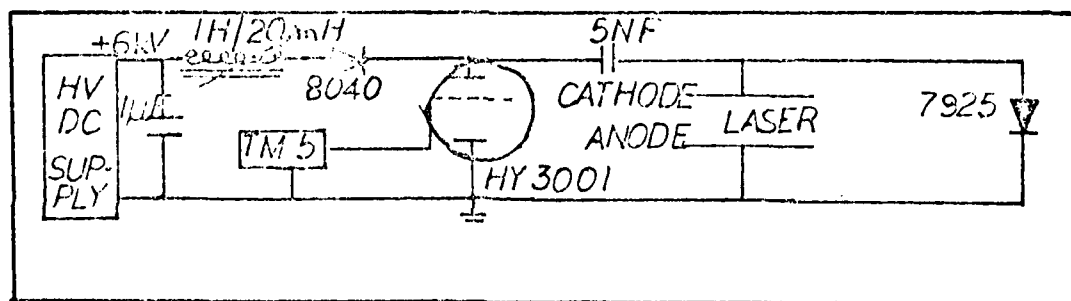


Figure 16.

HF Laser Discharge Circuit

The 6 kV supply charges the 5 nF capacitor through the diodes and inductor while the thyatron is open circuited. When the TM-5 trigger fires the thyatron, 12 kV is placed across the cathode/anode, a large current flows through the thyatron and from the anode to cathode. (Electrons flow from the cathode to the anode.)

The DC voltage supply is a 10kV, 5kW, Glow Discharge Power Supply, Electro Powerpacs Corp Model 1102. The high voltage diodes are manufactured by Solitron, but no specifications could be obtained. The saturable inductor is used to eliminate

the losses associated with resistive charging and to meet the 10 kHz repetition rate requirement. The high inductance required for charging the 5 nF capacitor would also cause the thyatron to "lock-on" during discharge, but the inductor reduces its value to 20 mH at saturation and the thyatron operates as designed.

The HY 3001 hydrogen thyatron switches the current through the cathode/anode. The thyatron consists of a cathode, anode, and high voltage grid. Electrons are accelerated from the cathode to the anode under the high voltage and collide with H₂ molecules, producing ions and electrons by the reaction



The current is increased by several orders of magnitude. The plasma neutralizes and the current pulse is terminated. As long as the grid voltage is held at a large negative voltage, no current flows. But, as its value is made less negative, electrons begin to leave the cathode and eventually acquire enough energy to ionize the hydrogen gas. Breakdown occurs and a sharp pulse is created. A photograph of an oscilloscope trace of this current pulse as observed by Raytheon is presented in Appendix B.

The trigger for the thyatron is an EG&G TM-5 trigger module with a HY 6004 hydrogen thyatron that produces a 25 A/ 2.5 kV and 500 nsec output pulse, with a variable repetition rate to 20 kHz.

The cathode consists of "68 molybdenum pins, .03 inch in diameter, sealed to a high density alumina body using 7052

Corning glass" [3:40]. A 220 Ohm, 10 Watt resistor is connected to each pin. The pins are arranged in three rows with .083 inch separation between rows and .33 inch separation between pins in the same row. The flat aluminum anode is .4 inch below the cathode. This anode cathode separation was chosen on the basis on tests that Raytheon conducted with the mini-TEA laser [3:41]. The total active volume is $7.5" \times .166" \times .4" = .5$ cubic inches = 8.16 cubic centimeters.

Gas Flow

This gas laser requires a flowing system for two reasons, (1) products of the chemical reaction must be removed from the cycle and fresh reactants supplied and (2) products of reaction and heat of reaction must be convected from the optical region. The system is not sealed and gases are recirculated many times before being exhausted.

For maximum operation, a fresh $SF_6 + H_2$ gas supply should be provided for each discharge duration. This establishes a requirement for flow velocity [72]. It is important that reaction products be removed from the optical cavity and two processes accomplish this: (1) recombination processes such as



and



and (2) convection of products from the active volume by high speed flows. Recombination processes are discussed in

the theory section on kinetics, pages 12-26. In general, these processes are slow and convection serves as the primary means for removing unwanted products.

If a uniform, constant gas flow is assumed, then the flow rate criteria yields

$$FLOW \text{ \%S} \approx VOLUME \times REP \text{ RATE} \quad (141)$$

The flow will not be laminar and uniform for three main reasons; (1) a boundary layer will form on the electrodes, (2) the flow will be very turbulent, as a result of the physical design of the gas recirculating system, and (3) sudden heating of the gases during the electric discharge will create pressure waves within the gas mixture.

Dzakowicz and Mutzke estimate the required increase in flow rate due to processes (1) and (3) to be a factor of 2 - 5. [72].

The speed of sound in the $SF_6 + H_2$ mixture may be calculated theoretically. The heat capacity of SF_6 at 300°K is 23.329 cal/mole °K [73]. Then, from an ideal gas approximation,

$$\eta = \frac{C_P}{C_P - R_u} \quad R_u = 2 \text{ CAL/MOLE } ^\circ K \quad (142)$$

and the speed of sound is

$$\alpha_s = \sqrt{\frac{\eta R T}{M}} = 136 \text{ M/S} \quad (143)$$

This establishes an upper limit on repetition rate for a subsonic, clean flow.

The flow of gases external to the HF laser is diagrammed in figure 17. Gases are stored in 100 lb. cylinders at 20 psig and fed by 3/4" plastic tubing to a control panel

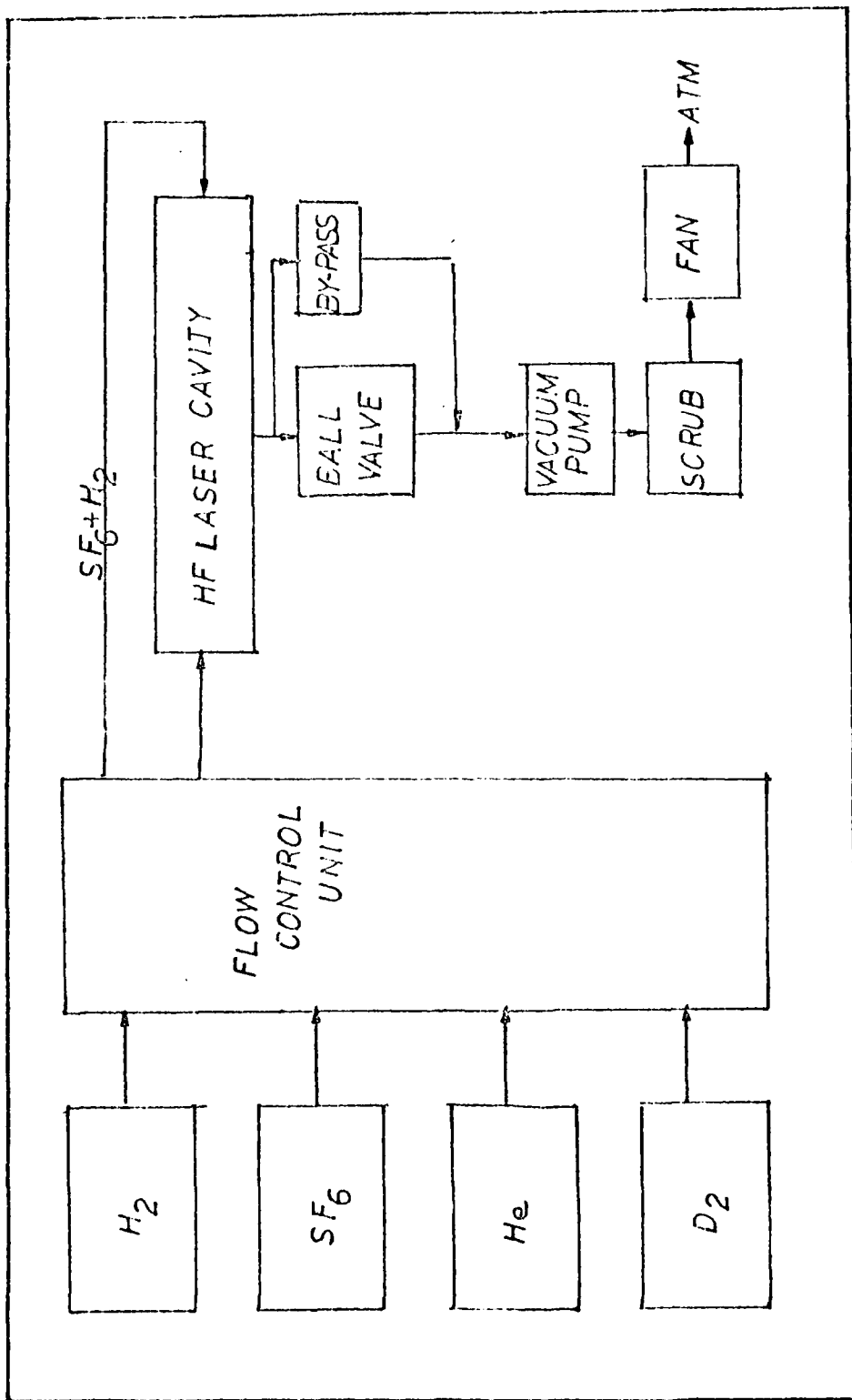


Figure 17.
HF Laser External Gas Flow

with Matheson 603 (H_2) and 605 (SF_6) flow meters to control the flow rate and mixture. Calibration charts for these flow meters are given in figure 18, from [3:88]. For the typical operating points of 20mm H_2 and 35 mm SF_6 , the flow rates are 1.4 l/min and 5.6 l/min, respectively. The $SF_6 + H_2$ mixture is introduced into the HF laser across the CaF_2 brewster windows. The flow of gases within the laser is illustrated in figure 19 and discussed below.

Gases are exhausted through a 1 1/2" Hayward PVC Ball Valve and an Alcatel ZT 1060C vacuum pump to a chemical scrubber and exhausted to the atmosphere through a roof fan. The ball valve controls total gas pressure in the laser cavity.

Once gas is in the cylindrical laser housing, it flows in a circle past the discharge area, through a sulfur precipitator, chemical scrubber and heat exchanger. For low repetition rates, two Rotron Propimax 3B Model 754D fans with a 62.8 l/s capacity each, are used to recirculate the gases. The flow velocity within the cavity is

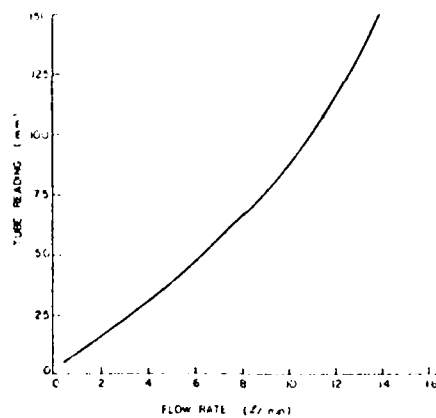
$$U = 2(62.8)(20 \text{ CMA}) = 649 \text{ MS} \quad (144)$$

The speed of sound from equation (143) is 136 m/s and then, the mach number is

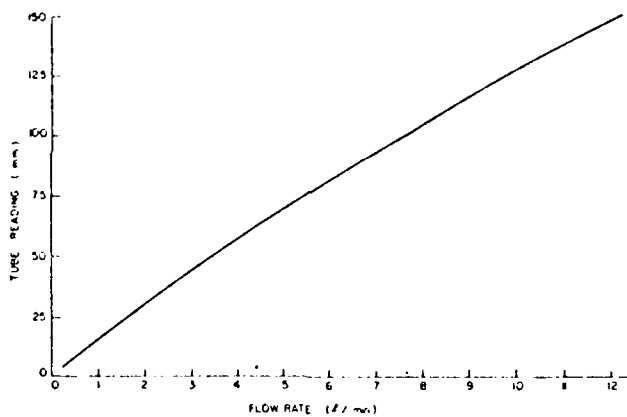
$$M = \frac{U}{a} = .48 \quad (145)$$

The fresh gas flow rate is 7 l/min or .12 l/sec and on the average the gas remains in the laser cylinder for 523 cycles.

With this large number of cycles before exhaust, many contaminants will build up in the gas flow. The kinetic model presented in the theory section was based on a single



Hydrogen at 20 psig. Matheson
603 tube, glass ball.



Sulfur hexafluoride at 20 psig.
Matheson 605 tube, glass ball.

Figure 18.

Flow Rate Calibration Charts [3:88]

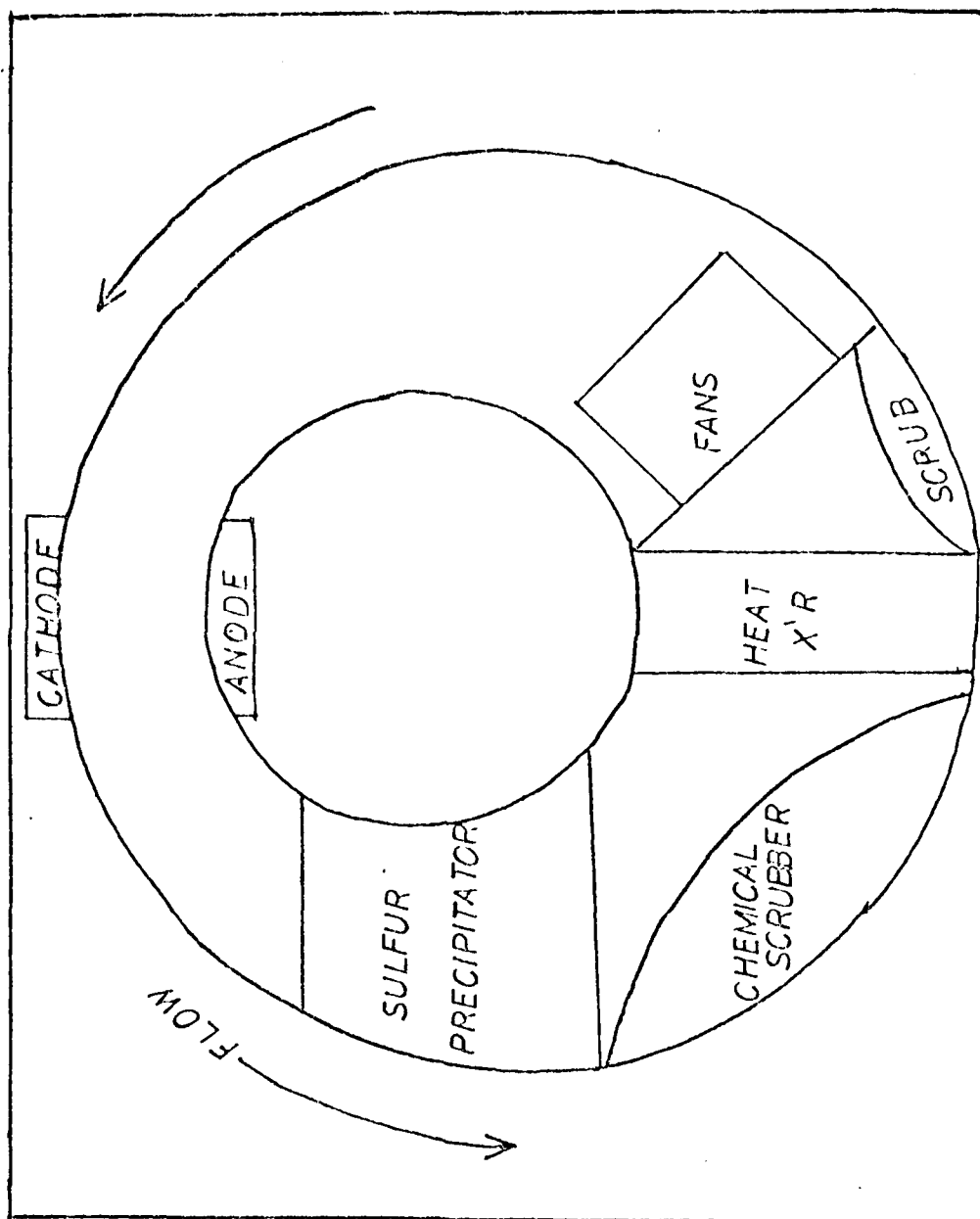


Figure 19.
HF Laser Internal Gas Flow

cycle and neglected the formation of S, H₂S, ground state HF, etc, which are formed downstream of the discharge volume after many cycles. In order to eliminate these unwanted products from the flow, a sulfur precipitator and chemical scrubber are included in the laser gas recirculating design. The sulfur precipitator is constructed of many, water cooled, aluminum plates. Two chemical scrubbers containing Linde 5A Molecular Sieves remove other contaminants. Note, as the laser is run for extended periods, particulates will build up on these collectors and their efficiency will be degraded. The odor of H₂S was noticed in the laser exhaust and it is assumed that the precipitator and scrubber do not efficiently remove contaminants from the flow.

Cooling System

The electrical energy input to the laser is rather high:

$$P_{AV} = IV = 21 \text{ W} \quad (\text{AVE. DISCHARGE POWER}) \quad (146)$$

$$P_P = IV = 4 \text{ MW} \quad (\text{PEAK DISCHARGE POWER}) \quad (147)$$

$$P_{FAN} = 600 \text{ W} \quad (\text{FAN'S POWER}) \quad (148)$$

This energy heats the gas, cathode, and other components. Output power is very sensitive to gas temperature, see figure 20 [3: 13]. To cool the gas flow a Lytron Model 5120 Heat Exchanger (39W/°F) is included in the design.

Extreme temperatures will also damage the electrical components. These elements are air, water, and oil cooled. The gas recirculating fans are cooled by the high speed gases flowing past them and should not be operated with less than 50 torr total pressure in the cavity. The saturable

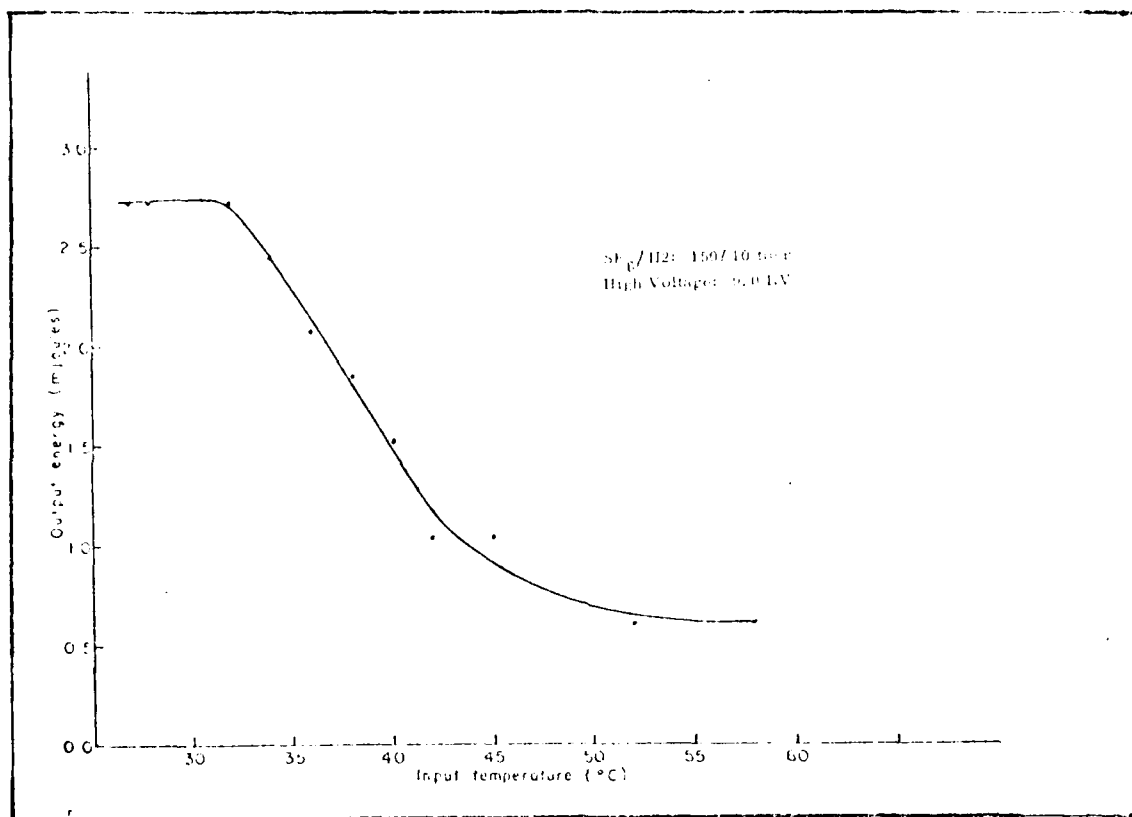


Figure 20.

HF Output Energy versus Temperature [3:13]

inductor and voltage doubling circuit is air cooled by a small fan. Gases are exhausted to atmosphere and convect heat from the laser.

The remaining cooling is completed by a water and oil (silicone, 20 cs viscosity) flow system as depicted in figure 21. Chilled water cools the heat exchanger and sulfur precipitator directly. The oil cools the cathode and thyatron in a closed flow system. The oil exchanges heat with the chilled water in a Young SSF-302-BY-2P heat exchanger and is pumped by a Little Giant Model 13 pump.

HF Laser Modifications

A number of modifications were made to the HF laser to complete the frequency investigation and to repair damaged components.

Optical Cavity

The power - frequency relations developed in the theory section were based on a single axial, TEM 00, $P_2(6)$ laser transition. The experiment also requires a controlled variation of HF frequency across the linewidth of 500 MHz. The HF laser normally operates multiline and multimode, however.

Two modifications to the optical cavity were made to solve these problems. An aperture was designed and installed to force the laser to the TEM 00 mode. A piezoelectric crystal was added to drive the output coupler mirror and control HF frequency. The $P_2(6)$ transition was selected with the grating replacing the OFHC copper mirror. A diagram of the modified optical cavity is shown in figure 22.

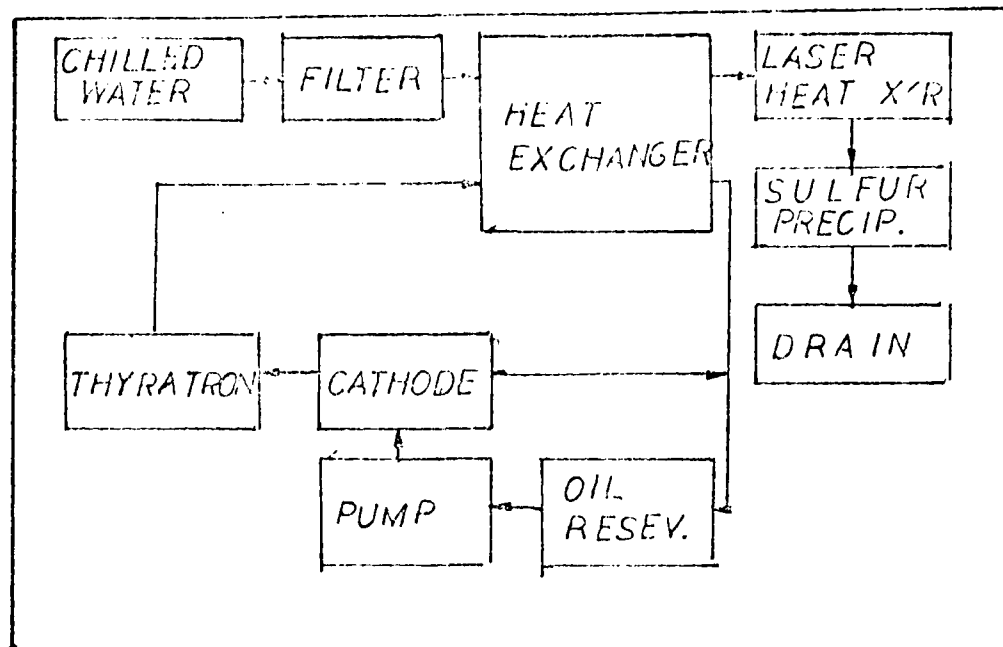


Figure 21.

HF Laser Cooling System

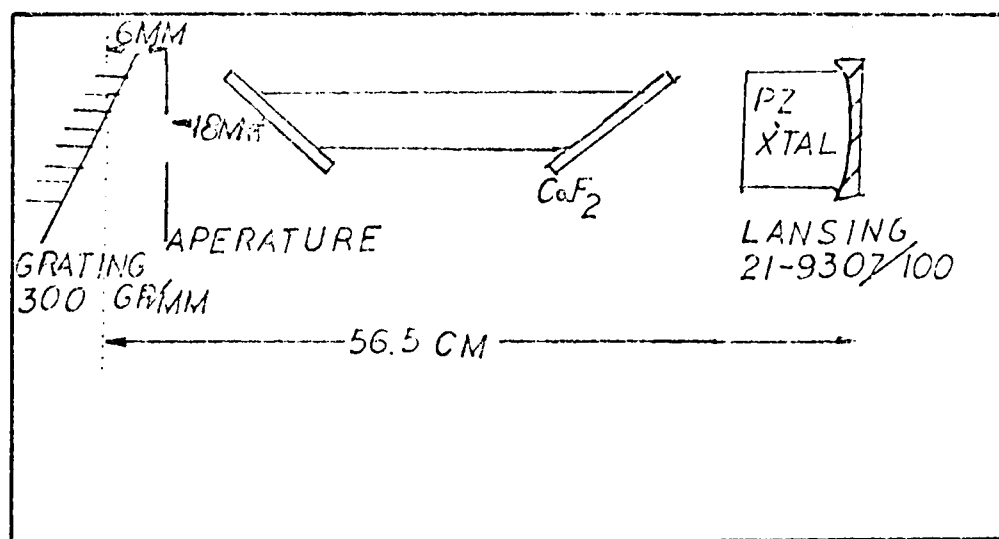


Figure 22.

Modified HF Optical Cavity

The variable aperture is continuously variable from .059 " to .709 ", with thirteen calibrated positions (.059, .086, .128, .159, .193, .221, .281, .328, .359, .406, .500, .709 inch). TEM 00 operation is achieved for aperture diameters of .221 inches or less. The aperture is mounted in an aluminum plate and fixed to the grating mount with a vertic position control and centered horizontally on the discharge volume.

The HF frequency, , is varied by changing the cavity length, , with a variable voltage, 0 - 1.3 kV, applied to the piezoelectric crystal. A Lansing 80-214 Lock-in Stabilizer is used to supply the high voltage to the crystal. In the slow scan mode, this supply provides a linear ramp of 0 to - 1.3 kV in 44 seconds. The crystal returns to its unperturbed length in less than one second. Figure 23 shows a plot of the voltage applied to the crystal as a function of time.

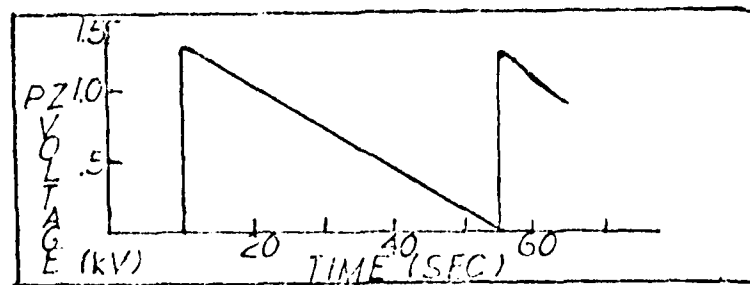


Figure 23.

PZ Voltage as a Function of Time

The crystal expands by 2.22 μm under a 1.3 kV applied voltage. This motion was detected with an Ealing Michelson interferometer as shown in figure 24.

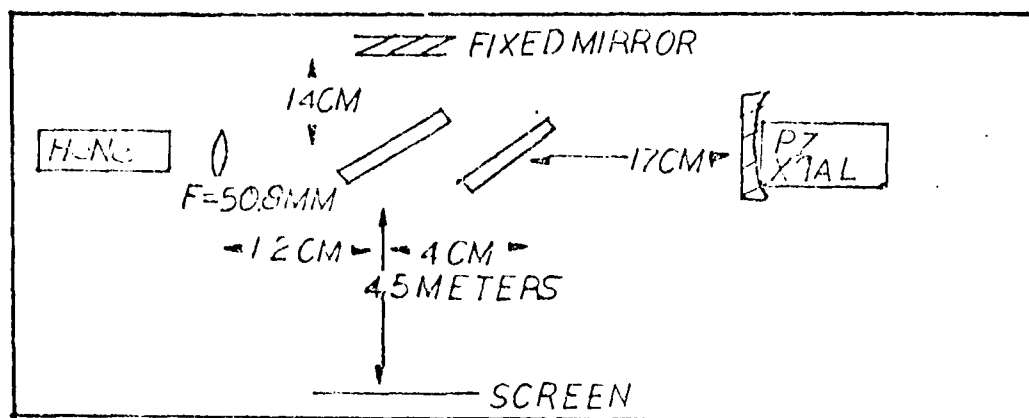


Figure 24.

Interferometer Test of PZ Crystal Motion

Fringes of 2.5 cm diameter were achieved at the screen and a shift of seven orders was observed as the voltage was varied from 0 to -1.3 kV. The length change of the crystal is

$$\Delta L = m \frac{\lambda}{2} = 22 \mu m$$

(149)

This nearly meets the requirement established by equation (18) for covering the 500 MHz linewidth of the HF gain curve.

The crystal was mounted on the laser with an adapter that screwed into the original mirror mount. The mirror was held to the adaptor by the same ring screw that originally held the mirror to the cavity.

The modified cavity length is 56.5 cm and from equation (17) the free spectral range is 268 MHz. The free spectral range is less than the linewidth and two axial modes will exist during extended periods of the piezoelectric crystal's sweep. Given the physical dimensions of the cylindrical housing, little can be done to increase the free spectral range.

When two axial modes exist, both will pump the CO_2 000 - 101 transition. The mode on the low frequency end of the gain curve will pump much less efficiently, however. It has an offset frequency of 265 MHz greater than the first mode. Based on the model of pages 37-42 and equation (121), the ratio of pumping efficiency for the two axial modes is

$$\frac{\ln N_{02}/N_0}{\ln N_{01}/N_0} = \text{EXP} - (\delta_1^2 - \delta_2^2) / 1.15 \approx 22 \times 10^{-3} \quad (150)$$

and the lower frequency mode may be neglected.

Frequency stability of any mode could be enhanced by increasing the number of axial modes. If the free spectral range were to be decreased to 170 MHz (3-4 axial modes), the ratio as calculated in equation (150) would increase to 10 % and the second mode's interaction could not be neglected. The theory would be significantly complicated in this case. Note also, that decreasing the free spectral range limits the range over which the frequency can be effectively varied. The effect on CO_2 laser power at large offset frequency, δ , would not be measureable. For these reasons, one or two axial modes is preferable.

The spot size of the HF beam is important, because the beam must be coupled into the CO_2 cell with sufficient intensity to establish the threshold population inversion. The HF beam is large and will be reduced with an optical system external to the HF cavity.

Several other problems were encountered with the optical cavity. Beam quality is rather poor due to aperturing, flow

turbulence, etc. Beam divergence is large, about 9 mrad. The control on optical alignment, particularly for the grating is poor. Finally, the output coupler was not truly flat on the external side, with a wedge angle of 7.3 mrad in the vertical direction and 14.6 mrad in the horizontal direction.

Electric Discharge

Repairs and modifications to the high voltage DC supply, high voltage diodes, and the thyatron trigger unit were required.

The DC voltage supply was modified to be included in the interlock system. This system prevents the laser from being run if the chilled water supply is off or if a five minute warm-up time for the thyatron is not provided. The DC supply was wired to this interlock system so that it could not be turned on if the interlock system was open circuit, or tripped. This HV DC supply require 240 Volt single phase power.

The high voltage diodes of figure 16 were unreliable and probably underrated (16-20 kV, required). The Solitron 8040 2A SLD - 30 diode failed twice during the investigation. Without this diode, the voltage doubling circuit does not function and the discharge is spatially nonuniform.

One replacement diode was available and was used to replace the first failure. The I - V characteristic for the defective and replacement diodes are shown in figure 25.

The second failure occurred after repeated arcing in the voltage doubling circuit and extreme heating of the diode.

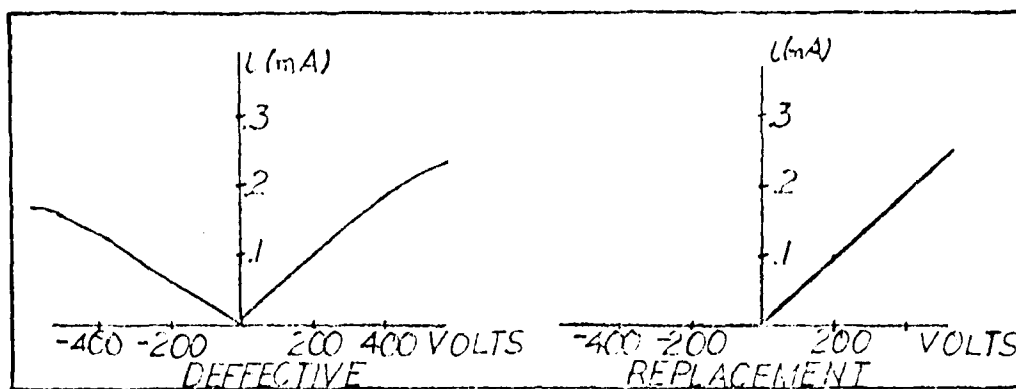


Figure 25.

I-V Characteristic of HV Diode (8040)

Three Varo VC 80 V diodes (8 kV, 2A, ea.) were used in series to replace the single Solitron diode.

Repeated problems in triggering the HY 3001 thyatron were encountered. Two distinct problems were involved. First, the EG&G TM-5 trigger unit with HY 6001 thyatron was inoperative and replaced. Secondly, the integrators and recording equipment require synchronization with the discharge pulse.

The EG&G TM-5 unit would provide a 2.5 kV, 500 nsec pulse (unloaded). Two components within this unit failed, however. A 2N4401 transistor was defective and replaced. The HY 6001 thyatron was defective, probably due to its mounting design. The thyatron was located on its side and the grid was likely warped. No replacement thyatron was available and a new trigger system was designed.

An EG&G TM-30 trigger was available and used to trigger the HY 3001 thyatron. To match the output impedance of the TM-5 unit, a 28 ohm, wire wound resistor was put in series with the grid output of the TM-30 unit. The rise

time of the trigger pulse was increased by a factor of two to $2 \mu\text{s}$ by the inductance of this wire wound resistor. The magnitude of the trigger pulse was 2 kV and was sufficient to fire the laser thyatron.

The final solution employed for the integrator synchronization problem involved using two pulse generators with variable delay. The circuit is shown in figure 26.

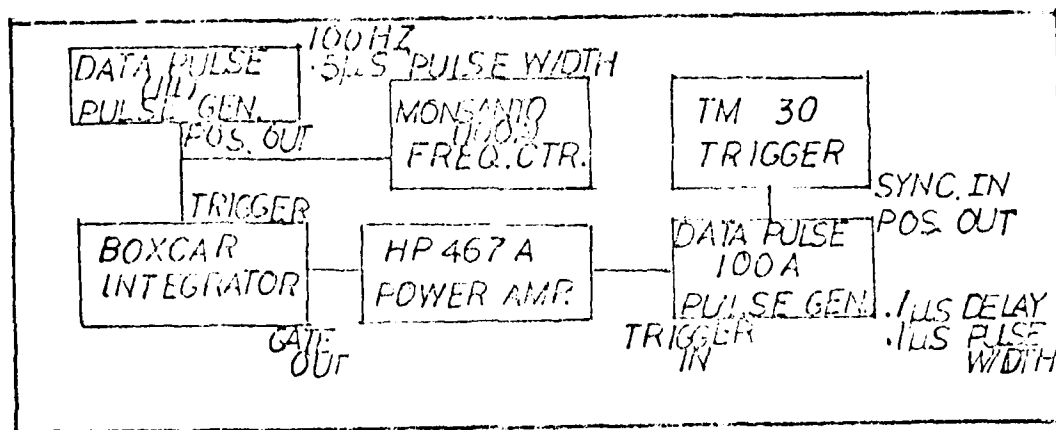


Figure 26.

Trigger Circuit

The first pulse generator is free-running and its variable repetition rate determines the discharge repetition rate. The positive output of this generator triggers the boxcar integrator, whose gate output is used to trigger a second pulse generator with variable delay control. In this way, the boxcar integrator gate and laser pulse may be synchronized.

Substantial space-charge buildup in the TM30 circuit required grounding the wire wound resistor temporarily before laser turn on.

Gas Flow

A limited supply of SF_6 was available for this study,

approximately 300 lbs. Gas consumption without recirculation is 100 lbs/ 1.5 min [3:30]. With gas recirculation of 500 cycles, the 100 lb cylinder should last 12.5 hours. Even at this rate, the supply will only last 37.5 hours.

To decrease the SF_6 gas usage and increase laser time, a modification to the flow system was made. In the original design a 1 7/8" inner diameter stainless steel pipe was used to exhaust gases from the laser through the ball valve and vacuum pump. This pipe size was used to accomodate the gas flow required at 10 kHz repetition rates. Repetition rates of about 100 Hz were used in this experiemnt to conserve gas, provide sufficient signal-to noise averaging , and maintain sufficient energy/pulse to pump the CO_2 laser. This rate requires a 100 times smaller flow rate and a smaller exhaust pipe may be used.

The average flow velocity (radial average) of a flow in a pipe is

$$U = \frac{dP}{dz} \frac{a^2}{4\mu} \quad (151) \quad [74]$$

where a is the pipe radius, μ the gas viscosity, and $\frac{dP}{dz}$ the pressure gradient, axially. The volume flow rate is then

$$\frac{dP}{dz} \pi a^4 \left(\frac{1}{4\mu} \right) \quad (152)$$

By reducing the pipe radius, much lower flow rates can be achieved. The same effect can be obtained by nearly closing the ball valve, but this adjustment becomes very sensitive for such slow rates.

On this basis, the modification of figure 27 was made. A cavity pressure of 1 torr was obtained with this modification

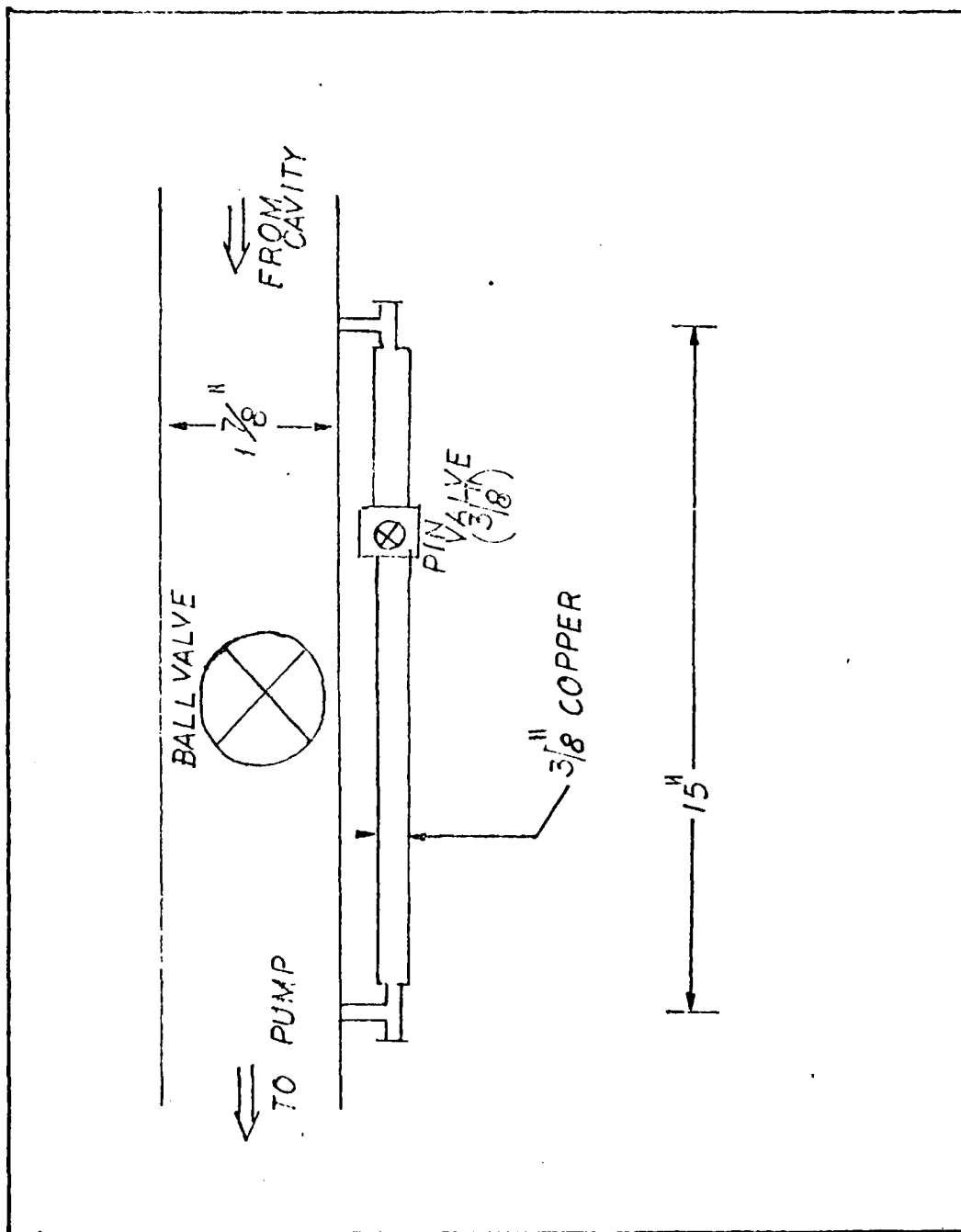


Figure 27.

By-Pass Valve Modification

and the ball valve closed. Two torr was maintained for several hours. The ball valve could not be completely closed when running the laser because a slightly greater flow rate was required. The pin valve was used as fine adjustment for flow rate.

HF Laser Operation, Safety, and Alignment

Appendix C lists the step-by-step procedure used for running the HF laser.

Several safety factors were considered. Deadly voltages and lethal energies are exposed during the operation of the laser. The trigger circuit, cathode area, and high voltage DC supply must be handled with extreme care. High voltage areas are clearly marked and shielded.

The interlock system was described on page 73.

The thyatron can "lock-on", continuously conducting current. If this occurs, the high voltage supply must be turned off within seconds to prevent damage to the power supply.

The gas recirculating fans are gas cooled and must not be operated with less than 50 torr total pressure in the laser cavity.

Several grounding wires are conveniently located for possible emergency use.

A gas detector (combustible products) was installed in the gas storage closet.

The safe eye exposure distance (SEED) is larger than the dimensions of the lab room:

$$SEED = \sqrt{\frac{2E_p}{\pi \theta_{1/2}^2 PEL}} \quad (153)$$

Evaluating equation (153) for

$$E_p = 1 \text{ mJ}$$

$$\theta_{1/2} = 6 \text{ mrad}$$

$$PEL \sim 10^{-7} \text{ J/cm}^2$$

yields

$$SEED = 200 \text{ M} \quad (154)$$

The required optical density for goggles is

$$D = \log \frac{E_0}{E_p} = 4.4 \quad (155)$$

Goggles with $D=4$ at $2.8 \text{ } \mu\text{m}$ were available and were used when operating the laser.

The HF cavity was aligned with a HeNe laser. The laser is high gain and alignment is not particularly difficult. Once lasing is achieved, the power can be maximized by adjusting each of the mirrors. To achieve single line operation, the copper mirror is removed and replaced by the grating. Once the grating is in place, lasing can be established by merely adjusting the grating angle.

HF Laser Performance Characterization

The first set of experiments characterized the performance of the HF laser. Power was measured as a function of pressure, SF_6/H_2 mixture, repetition rate, discharge voltage, aperture diameter, and time. Beam quality and divergence were also investigated. The laser was operated under both multiline and single line (including the $\text{P}_2(6)$ transition) conditions.

Multiline operation was achieved with the OFHC copper mirror. A Raytheon Au:Ge Infrared detector was used to measure the energy/pulse. Pulse shapes were observed on a

Tektronix 555 Oscilloscope. A Princeton Applied Research Model 160 Boxcar Integrator with a 50 μ s gate, 100 ms time base, and .3 ms time constant, was used to average the energy/pulse. The integrated output was displayed on a Fluke 8100A digital voltmeter. It is this averaged power that was measured as repetition rate, pressure, voltage, and mixture were varied.

Beam quality and divergence were investigated using the same set-up with the detector on a two degree of freedom (X,Y) translating mount. The detector was moved axially (Z) along the HF beam on a 90 cm optical rail. The coordinate axes are shown in figure 28.

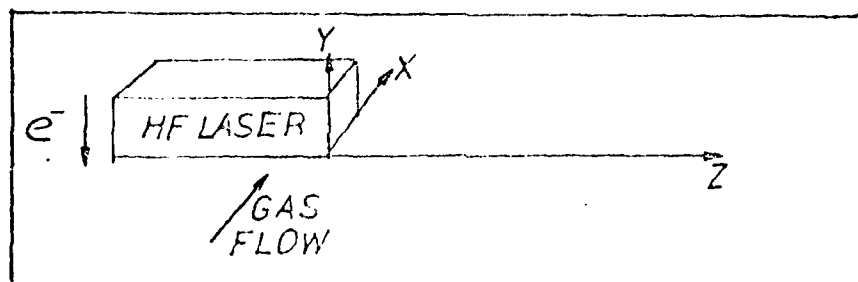


Figure 28.

Experimental Coordinate Axes

An absolute value for average energy/pulse was obtained with a Scientech Model 3604 Laser Power Meter thermal type energy detector with a sensitivity of 84.5 mV/W.

Single line operation was established with the 300 gr/mm grating replacing the copper mirror. A Lumonics Spex Mini-Mate monochromator with a 3 μ m blaze, 300 gr/mm grating and 2.5 mm slits was used to choose the HF $P_2(6)$ transition. The

monochromator was calibrated by observing the location of the zeroeth through fifth orders of HeNe transmission. Based on $\lambda_{\text{HeNe}} = 0.6328 \mu\text{m}$, the observed HeNe order separation of .5775 μm , and the observed zero order HeNe setting of -.008 μm , the relation between scale reading and actual wavelength is

$$\lambda_{\text{ACTUAL}} = 1.0958(\lambda_{\text{SCALE}} - .008 \mu\text{m}) \quad (156)$$

Three HF lines were observed at $\lambda_{\text{ACTUAL}} = 2.851$, 2.8074, and 2.7702 μm . These lines were identified as the $P_2(6)$, $P_2(5)$, and $P_2(4)$ transitions based on the comparisons of known wavelengths of the transitions, the separation between these wavelengths, and the observed transitions in the Raytheon study [3:13,46]. This information is summarized in Table II.

Table II.
HF Line Identification

Transition	$\lambda(\mu\text{m})$	[3] 9100m	Wavelength Difference	This Study	Wavelength Difference
$P_3(6)$	2.9643				
$P_3(5)$	2.9256	X			
$P_3(8)$	2.9111	X			
$P_2(11)$	2.9103				
$P_1(4)$	2.8889				
$P_3(7)$	2.8706	X			
$P_2(10)$	2.8657				
$P_2(6)$	2.8318	X	} .0365 } .0349	2.8510	} .0436 } .0372
$P_2(5)$	2.7953	X		2.8074	
$P_2(8)$	2.7826	X			
$P_2(4)$	2.7604	X		2.7702	
$P_1(7)$	2.7441	X			
$P_2(3)$	2.7275				
$P_1(6)$	2.7075	X			
$P_1(5)$	2.6730				
$P_1(4)$	2.6400				

AD-A111 148

AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL--ETC F/G 28/B
CHARACTERIZATION OF AN HF-PUMPED CO2 LASER.(U)

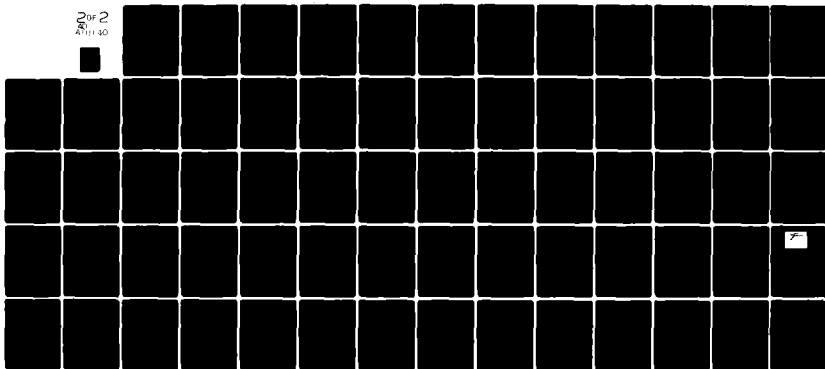
OCT 81 G P PERMAN

AFIT/SEP/PH/810-7

UNCLASSIFIED

NL

2 of 2
2
21-11-40



END

DATE

FILED

8-82

DTIC

Optical Pumping

After characterizing the HF laser and choosing the $P_2(6)$ transition, the HF beam was used to pump the CO_2 gas.

The results of the beam divergence measurements indicate the need for reducing the HF beam spot size. Originally, a telescope was used to couple the HF beam into the CO_2 cell with 4 mm diameter used by Raytheon in their study. With the optics available, this method did not reduce the HF beam size sufficiently.

To solve this problem, a 1 cm diameter CO_2 cell was designed and constructed as shown in figure 29. The HF beam was

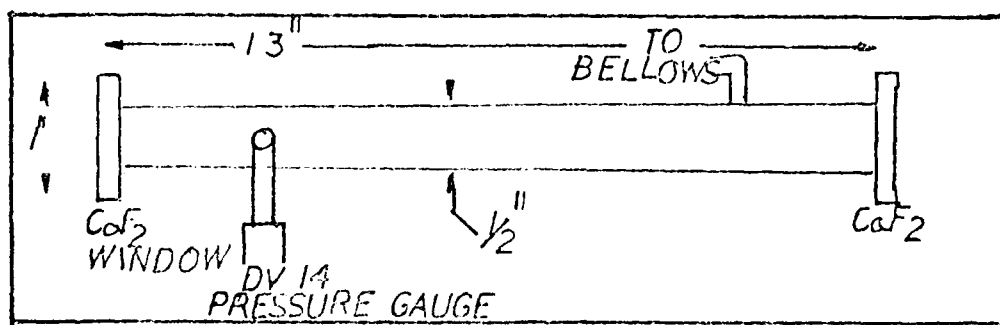


Figure 29

Redesigned CO_2 Cell

focused at the center of this cell with a one inch diameter CaF_2 lens. The two requirements of a small spot size and a collimation length of 40 cm led to the selection of a 250 mm focal length. (See Appendix D for the theoretical analysis used to make this selection.) This theoretical analysis predicted the 250 mm focal length lens would provide a spot size of less than 3.5 mm over a length of 40 cm at a distance of 14 - 54 cm from the lens. Experimentally, a spot size of less than 6 mm was observed over this 40

cm range.

To fill the CO_2 cells and control pressure of the $12\text{ }^{18}\text{O}_2$ gas, a pump system was designed (see figure 30). The two pyrex cells are connected to 1/4" piping by a flexible bellows. The $12\text{ }^{18}\text{O}_2$ is stored in a 1 liter cylinder that can be cooled in a liquid nitrogen bath. The cells can be evacuated to about 1 torr with a DuoSeal Model R1406 vacuum pump. To reduce the pressure to 100 μm , a Varian Vac Sorb molecular sieve is cooled in a liquid nitrogen bath. An adaptor was designed and built from a non-rotating mini-flange flat to connect the 1/4" piping to the molecular sieve.

Power-Frequency Experiment

The optical set-up for the CO_2 power as a function of HF frequency experiment is illustrated in figure 31. The propagation of the HF, CO_2 and HeNe alignment beams are shown.

The main CO_2 cell is pumped by the HF laser directly. The incident HF beam is split and detected by a HgCdTe detector, D2. The transmitted HF beam is observed at the Raytheon Au:Ge detector, D4. The monochromator is used to determine the HF lasing transition and to filter out the CO_2 beam.

The incident HF beam also travels through a second CO_2 cell. HF intensity is sufficiently low here that no lasing action is obtained and the absorbed HF beam is detected at a Santa Barbara Au:Ge detector, D1. There is a 2.8 μm filter in this leg of the optical path to remove the CO_2

The CO_2 cell lases and a forward and backward pulse is observed at D3 and D5 (InSb) detectors. A 4.3 μm filter

is used to eliminate the HF beam at D5. The second Lumonics monochromator is used to measure the CO₂ wavelength and select either the R(8) or P(10) 101-100 transition. This monochromator has a 150 gr/mm, 6 μ m blaze grating and 1.25 mm slits.

The CaF₂, $F=25$ CM, lens is used to focus the HF beam into the CO₂ cell, as described earlier. A CaF₂ lens focuses the HF incident beam on D2.

Finally, a HeNe, Spectra Physics Model 142 laser is used for alignment. After the absorption cell leg of the optical path was aligned, the HeNe laser was located as shown to align the main CO₂ cell and the monochrometers.

This set-up provided the necessary data for comparing the CO₂ power to HF frequency. The amount of HF absorption was obtained by comparing intensities of incident (D2) and transmitted (D4) HF pulses. CO₂ forward and backward pulses were observed at D3 and D5. Finally, the HF frequency was measured by observing the HF absorption through the second CO₂ cell. The absorption should vary with frequency according to a doppler broadened lineshape. From this variation in absorption, the variation in frequency was measured.

The transmittance for each of the optical elements was measured with a Wilks Miran I Variable Filter IR Analyzer with a Wilks Preamplifier. The three CaF₂ beam splitters transmitted 90% at 4.3 microns and 95% at 2.8 microns at 45 ° incidence. The Raytheon 90-90574 2.8 micron filter transmitted 8% at 4.3 microns and 90% at 2.8 microns at normal incidence. The 4.3 micron filter is a flat gold and copper Laser Optics 3.6 - 8 micron filter and transmits

less than .5% at 2.8 microns and 95% at 4.3 microns at normal incidence. During alignment, the CaF_2 , $F = 25 \text{ CM}$, lens transmittance was measured as 94% by detecting power with the thermal detector before and after the lens.

Each of the detected signals are amplified, displayed on an oscilloscope, averaged by a boxcar integrator, and recorded on an XY or strip chart recorder. The electrical wiring diagram for the entire experimental set-up is shown in figure 32.

The integrators are Princeton Applied Research CW-1 and 160 boxcar integrators. The gate widths were chosen to match the widths of the detected pulses. The faster PAR 160 integrators were used with the faster detectors (D2, D5). Time constants were chosen to reduce noise as plotted on the recorders. The settings for each integrator are listed in table III.

Table III
Boxcar Time Settings

Integrator	Model	Gate Width	Time Base	Time Constant
I2	PAR 160	500 ns	20 μs	.3 ms
I3	PAR 160	1.6 μs	2 μs	1 ms
I4	CW-1	10 μs	50 μs	.3 ms
I5	CW-1	10 μs	1 ms	3 ms

HF absorption was measured as the auxiliary cell was filled with $^{12}\text{C}^{18}\text{O}_2$ at pressures from 0 - 7 torr. Integrated

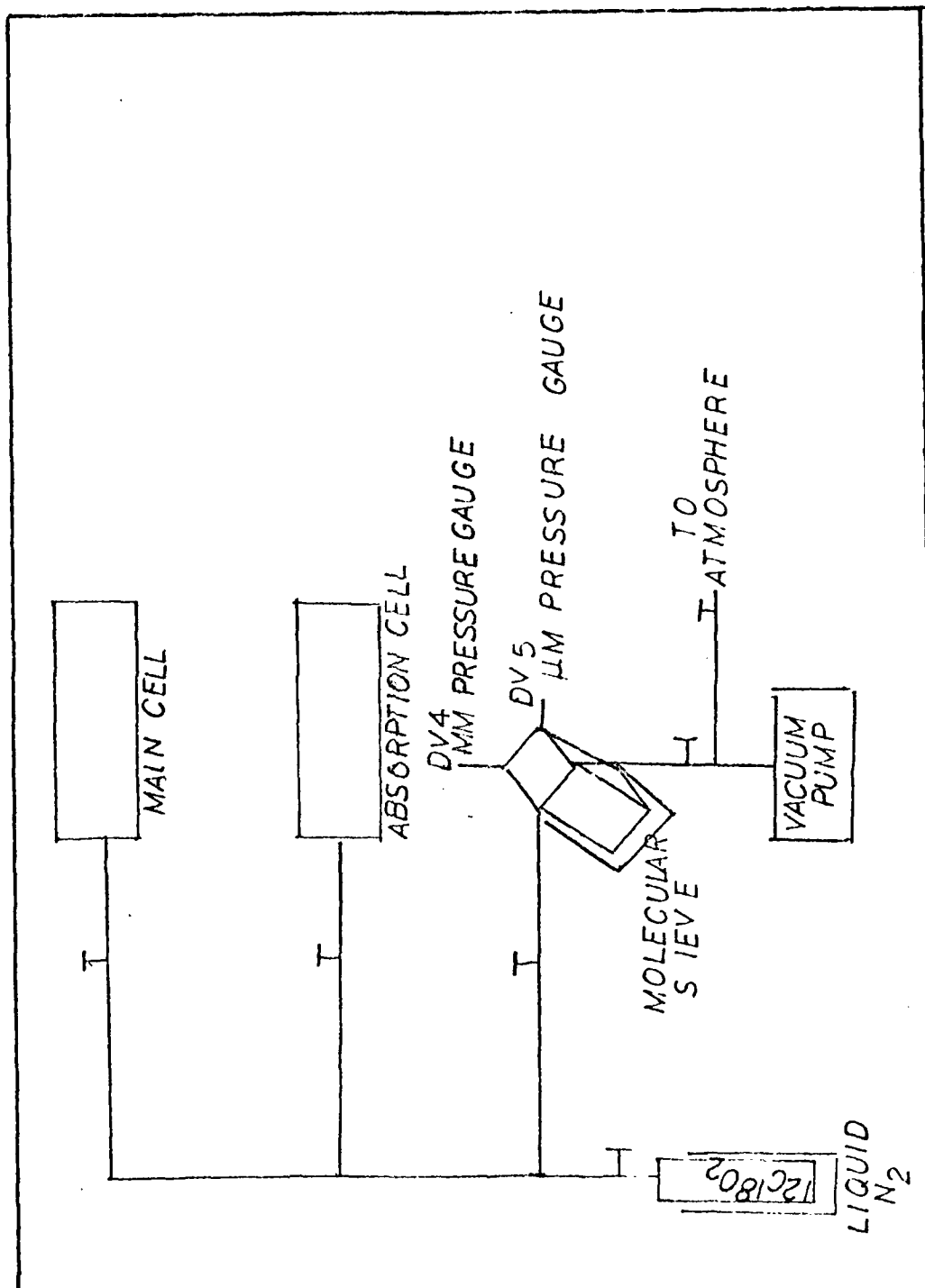


Figure 30.
CO₂ Gas Pumping System

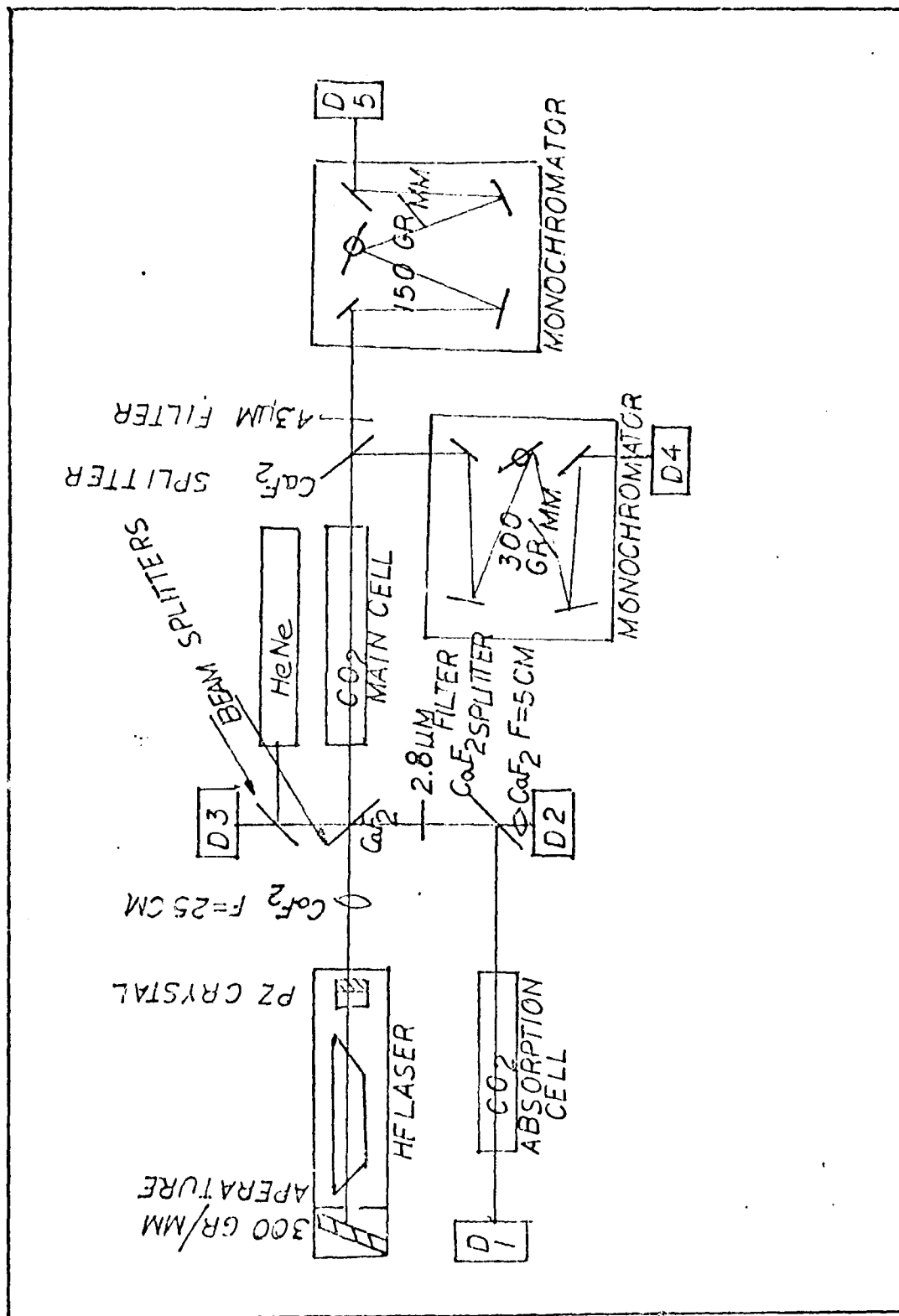


Figure 31.
Optical Set-up for Frequency Experiment

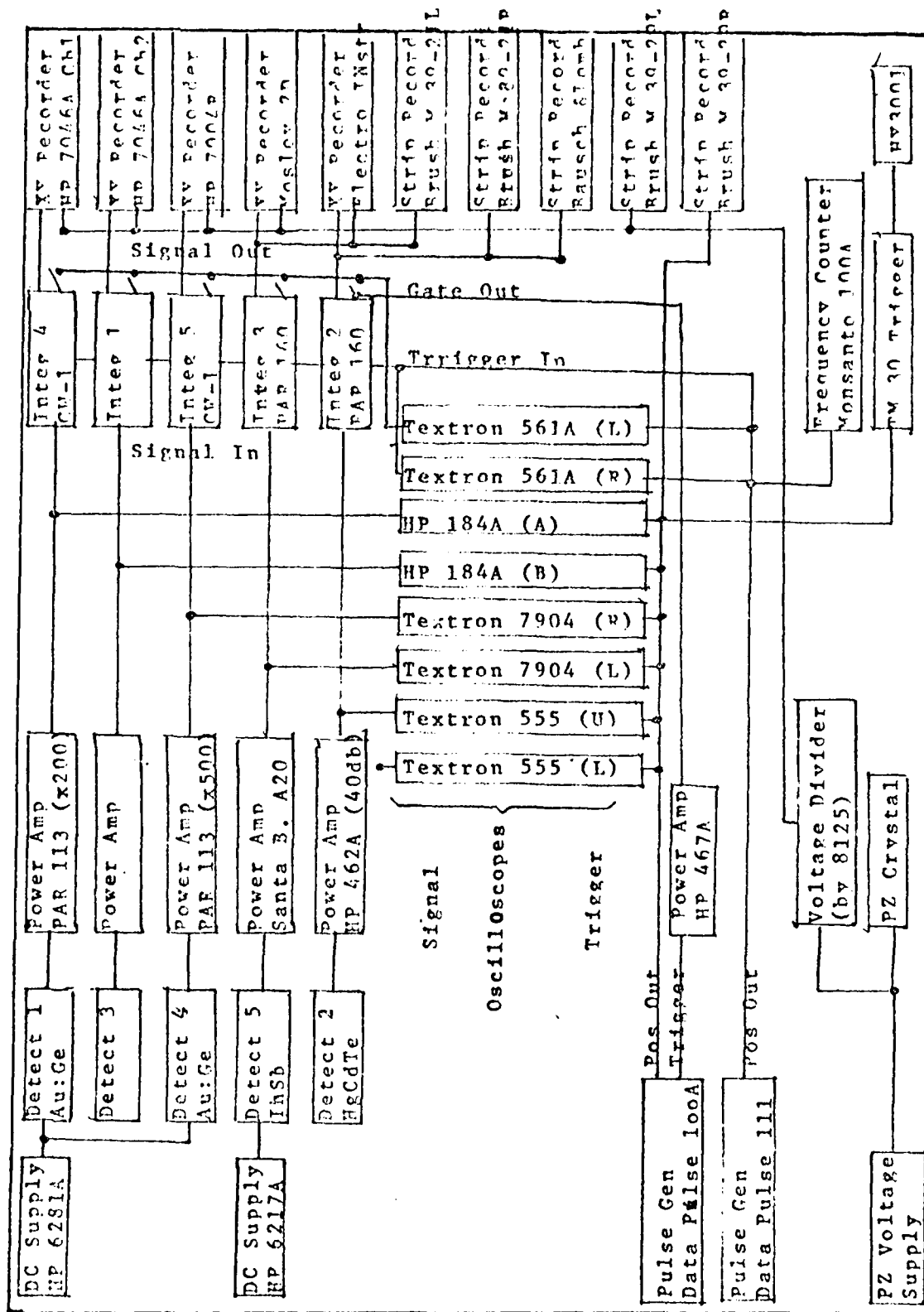


Figure 32
Electrical Wiring Diagram

power from detectors D1 and D2 were recorded on the HP 7046 XY recorder. Immediately after changing the pressure, the HF beam was blocked to mark the pressure reading.

The main CO₂ cell was then slowly filled with ¹²C¹⁸O₂. CO₂ lasing was observed at 7 torr. HF and CO₂ pulse shapes detected at D1, D2, D4, and D5 were photographed from oscilloscope traces. Detectors D2 and D4 were sufficiently fast to resolve 20-200 nsec pulse shapes.

From the oscilloscope traces, it was observed that CO₂ lasing was erratic. A CO₂ pulse was observed for every 3-5 HF pulses. The HF pulses varied considerably in magnitude from pulse to pulse and CO₂ lasing was achieved only on the stronger HF pulses. The pulse-to-pulse variation in HF power was measured by displaying multiple pulses from detector D2 on oscilloscope channel 1.

HF absorption was measured as the PZ crystal voltage was swept from 0 to - 1.3 kV in 44 sec. No correlation between power and PZ crystal voltage was observed, indicating a frequency instability in the HF laser pulse on a time scale small compared to the integration period of 1 ms.

The nature of the power and frequency instability was investigated and its dependence on repetition rate, discharge voltage, and pressure recorded.

The data and results of these experiments are presented in the following section. Conclusions and recommendations will be made after considering these results.

Results and Conclusions

The results of the experiments described in the previous section are now presented and compared to the theory established in the first section and to prior experimental studies. Conclusions concerning the system and its operation are drawn. Finally, a summary of the investigation, results, and conclusions is presented. The HF laser characterization, the pulse shape and kinetic model, and the optically pumped CO_2 laser will be discussed individually.

HF Laser Characterization

The experiments characterizing the HF pump laser studied the dependence of HF power on the $\text{SF}_6:\text{H}_2$ mixture, total cavity pressure, discharge voltage, repetition rate, and aperture size, and analyzed beam quality and beam divergence. Power and frequency stability are discussed in the section on the optically pumped laser.

Figure 33 illustrates the dependence of HF power on the SF_6 flow rate, for a fixed H_2 flow rate of 1.4 l/min. There is a slight decrease in power at lower SF_6 flow rates, indicating the reduction in atomic fluorine concentration and the resultant decrease in vibrationally excited HF concentration. Results from the Raytheon investigation are also shown in figure 33. These results indicate a reduction in HF power above 80% SF_6 , where hydrogen becomes the limiting specie in the cold reaction (21). Throughout this investigation, a 79% SF_6 mixture was used.

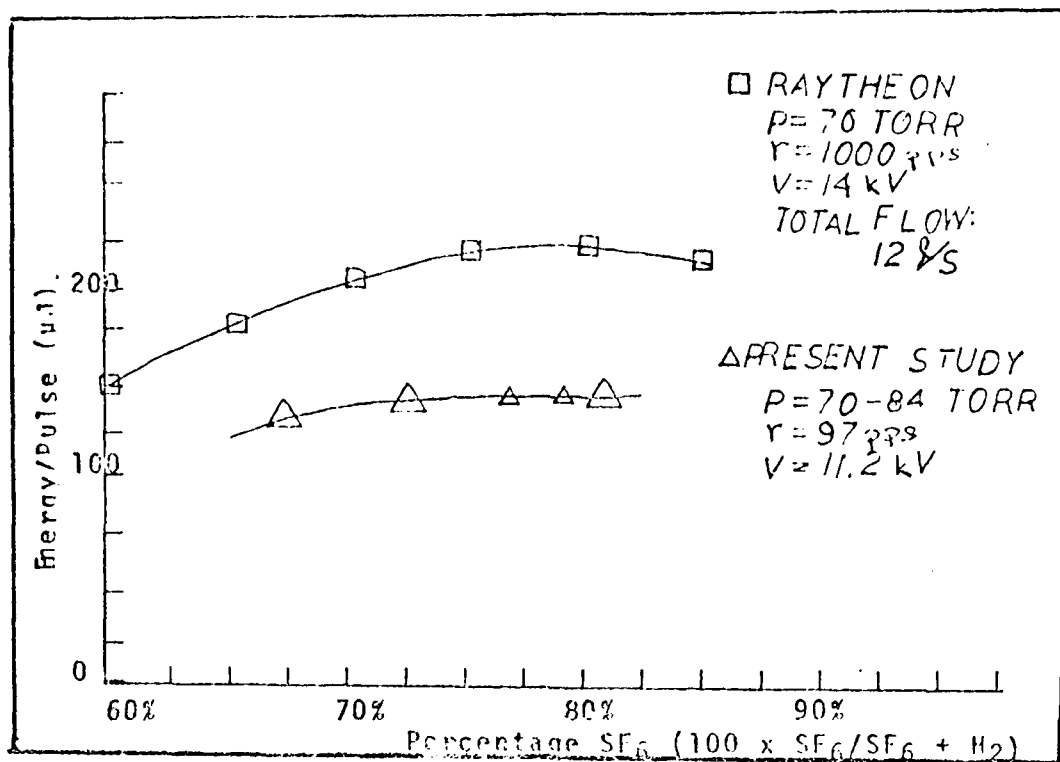


Figure 33.

HF Multiline Energy versus $\text{SF}_6/\text{SF}_6+\text{H}_2$ Mixture

Figure 34 depicts the HF output power - total cavity pressure relationship. At 11.2 kV discharge voltage, 97 pulses/sec repetition rate, and 79% SF_6 , no variation in power with pressure was observed over a 30 torr range. No study of this relationship was undertaken by Raytheon. Throughout this study, a total pressure of 70 - 90 torr was maintained.

Figure 35 illustrates the dependence of HF power on discharge voltage as observed in this experimental study at 100 pulses/sec and in the Raytheon study at 4000 pulses/sec. The peak in this curve depends on repetition rate and moves to higher voltages at lower repetition rates [3:42-43]. The peak occurs at 12 kV at 4000 pps, but no peak is observed at 100 pps. The 100 pps curve is very flat from 10 - 16 kV and the peak likely occurs above the 16 kV recommended

voltage limit. 11 - 12 kV was chosen as the operating point for the current experiments.

The input power is V^2/R , where V is the discharge voltage and R is the resistance of the gases between the cathode and anode. A larger discharge voltage provides a greater input power and current to dissociate SF_6 . Larger powers result. A larger discharge voltage also yields a greater average electron energy (see equation (28)). The reaction rates for electron attachment to SF_6 decrease as electron energy increases (see Appendix A). The associated reduction in fluorine reduces HF output power. These two effects are competitive.

At high repetition rates, the discharge circuitry can become power limited. In this case, current will be fixed and only the electron energy effect will be important. As repetition rate increases, current limiting occurs sooner and the peak shifts to lower voltages.

There is a voltage below which no discharge occurs. Since electron attachment increases with decreasing voltage, it is not ionization that limits the discharge, but rather the discharge circuit itself. At low voltages, the current reduction may reduce the population inversion below threshold conditions. A determination of which effect is dominant was not completed.

The energy per pulse and average power versus repetition rate are presented in figures 36 and 37. The average energy per pulse decreases linearly in the range 0 - 600 pps, and has a long shallow tail to 1000 pps. High repetition rates

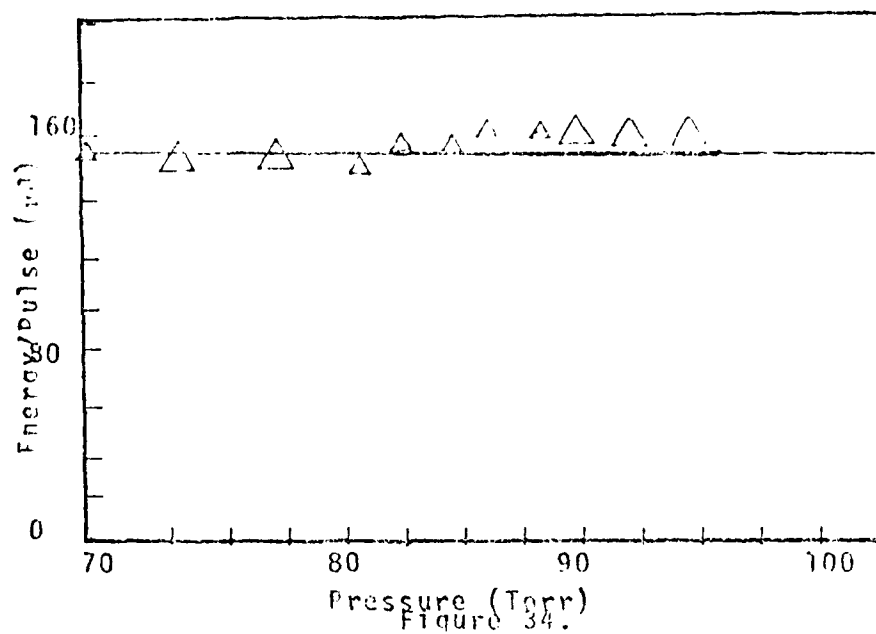


Figure 34.
HF Energy versus Cavity Pressure

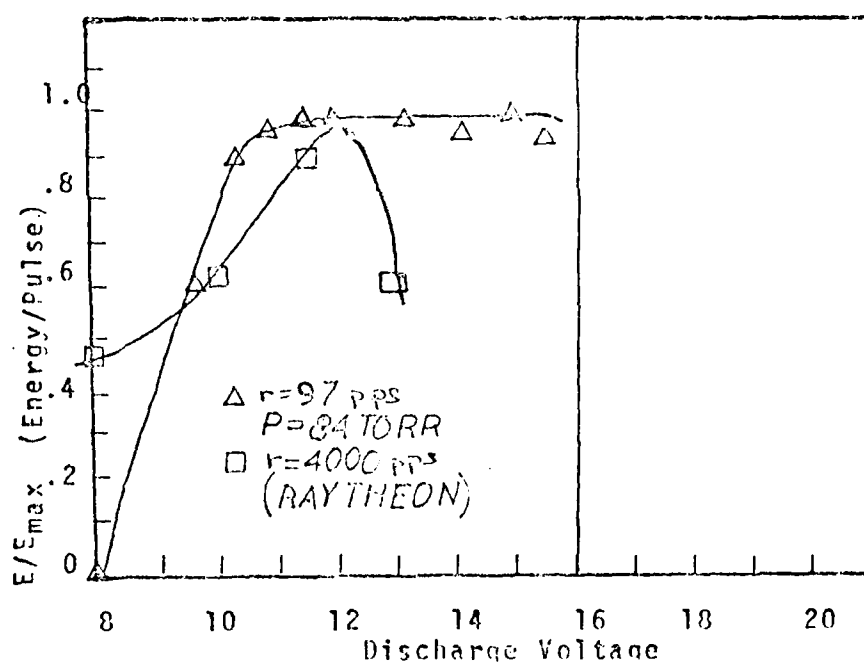


Figure 35
HF Energy versus Discharge Voltage

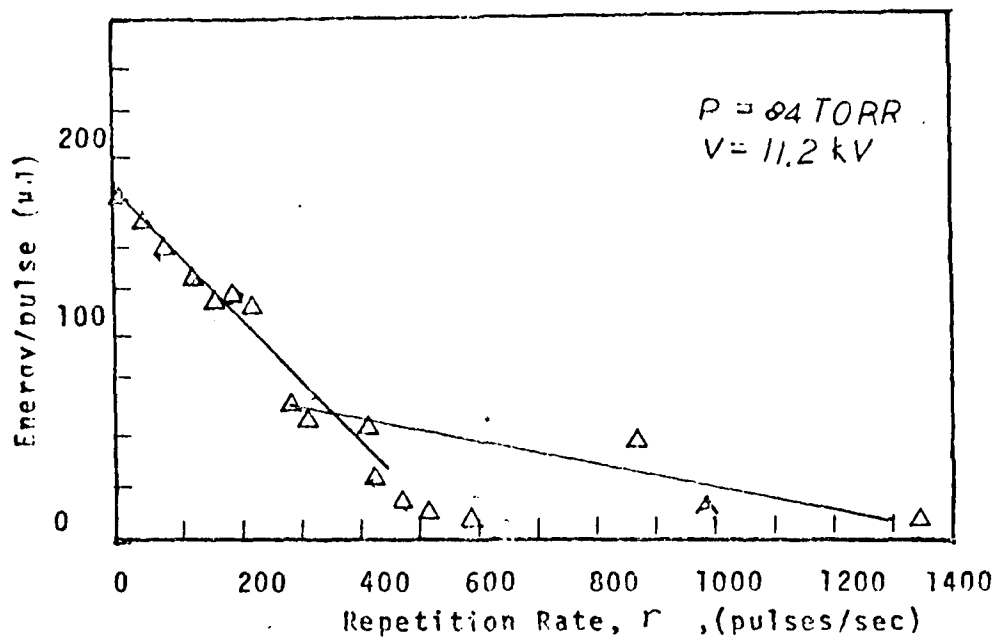


Figure 36.
HF Energy versus Repetition Rate

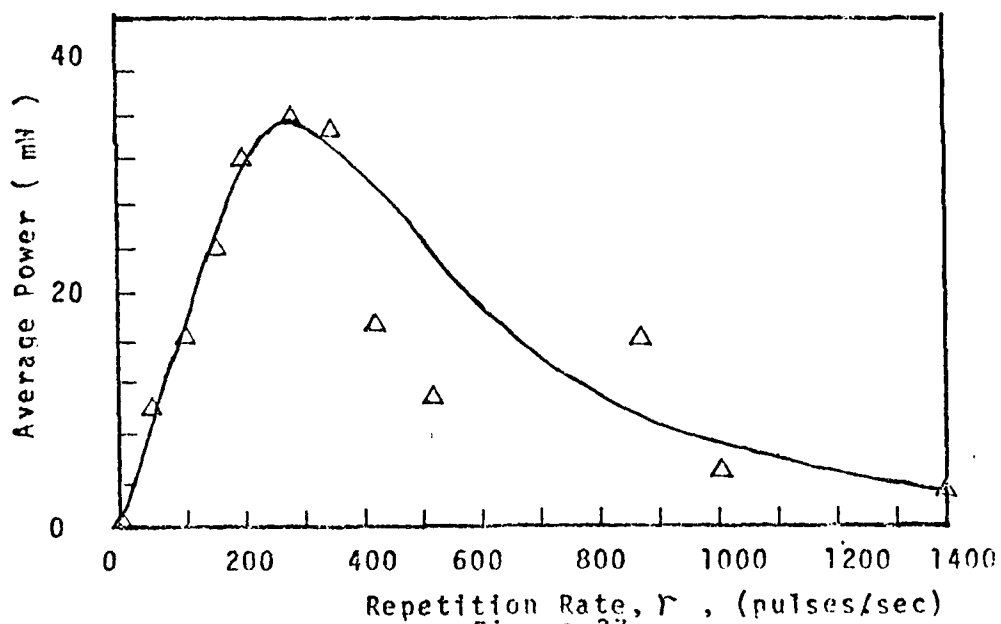


Figure 37.
HF Average power versus Repetition Rate

were not studied, due to the modifications for flow rate and limited gas supply.

Discharge voltage drops with increased repetition rate for a fixed DC supply because of increased loading. A constant 11.2 kV was maintained throughout this repetition rate study, however.

Average power is related to the energy per pulse by the repetition rate, γ ,

$$P_{AVE} = E_{PULSE} \times \gamma \quad (157)$$

Average power is plotted against repetition rate in figure 37. The results from the Raytheon study of power versus repetition rate indicate a much wider curve; over a 10,000 pps range with a peak at 3000 pps. These results appear to be obtained by maximizing power with respect to discharge voltage, pressure, mixture, and flow rate at each repetition rate.

Average power increases initially to 300 pps, simply due to the increased number of pulses per second. The average power falls above 300 pps largely due to increased contaminants (H_2O , H_2S) in the flow. Also, the chemical scrubber is less efficient at higher repetition rates [3:43]. The increased power input will also increase the gas temperature and decrease output power. The fixed flow rate will affect power only if an incomplete exchange of gases in the electrode volume occurs between pulses. This is not the case at these low repetition rates.

Three HF vibrational-rotational transitions were observed

to lase; the $P_2(6)$, $P_2(5)$, and $P_2(4)$ transitions (see page 81 and table II). The results already presented include all of these transitions. The total multiline energy per pulse observed was 156 μJ .

The $P_2(6)$ transition was studied by itself. 88 μJ was measured as the average energy per pulse. With a .221" diameter aperture, the measured average energy per pulse was 37.5 μJ . TEM 00 operation was achieved with this .221" aperture. A plot of energy/pulse versus aperture size is shown in figure 38.

No $U=1$ to $U=0$ transitions were observed. Raytheon observed no $P_1(J)$ transitions above 2000 pps, due to the decreased efficiency of the chemical scrubber [3:43]. It is likely that the chemical scrubber's performance has been degraded to the point that it will not remove sufficient ground state HF to establish a population inversion between the $U=1$ and $U=0$ levels even at 100 pps.

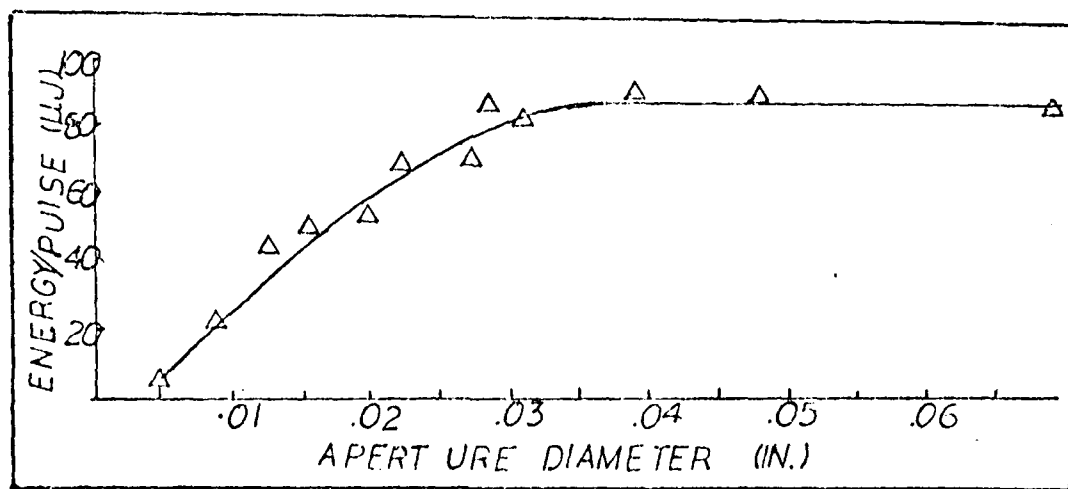


Figure 38.

Energy/Pulse vs Aperture Diameter

The spatial distribution of power within the HF beam was investigated for three cases: (1) multiline operation, (2) single $P_2(6)$ line, TEM 00 mode operation, and (3) with external focusing optics for the $P_2(6)$ TEM 00 case. No similar investigation was reported by Raytheon.

Figures 39 - 44 present representative spot shapes for the three cases. From the full set of spot size measurements as a function of axial distance, beam divergence was calculated and the spot sizes versus axial position are shown in figures 45 - 46. A time resolved study of the pulse shapes was not conducted.

The multiline HF beam profile is certainly non-Gaussian. This is not merely a result of higher order transverse modes. Spatial inhomogeneities in the lasing medium also contribute to the features of the beam profile. The uniformity of the discharge is important as well.

Turbulence within the gas flow and local nonuniformities in the concentrations of reactants and contaminants will affect the local gain. Purely random fluctuations will not persist and therefore will not be evident in the measured profiles, however.

Several persistent features in the profiles are observed. The multiline profiles exhibit a "flat top" across about one-half of the FWHM in the vertical direction. This is a result of aperturing by the cathode - anode structure. In the horizontal direction, the profiles exhibit a long tail in the up-flow direction. This is likely a result of a nonuniform electric discharge.

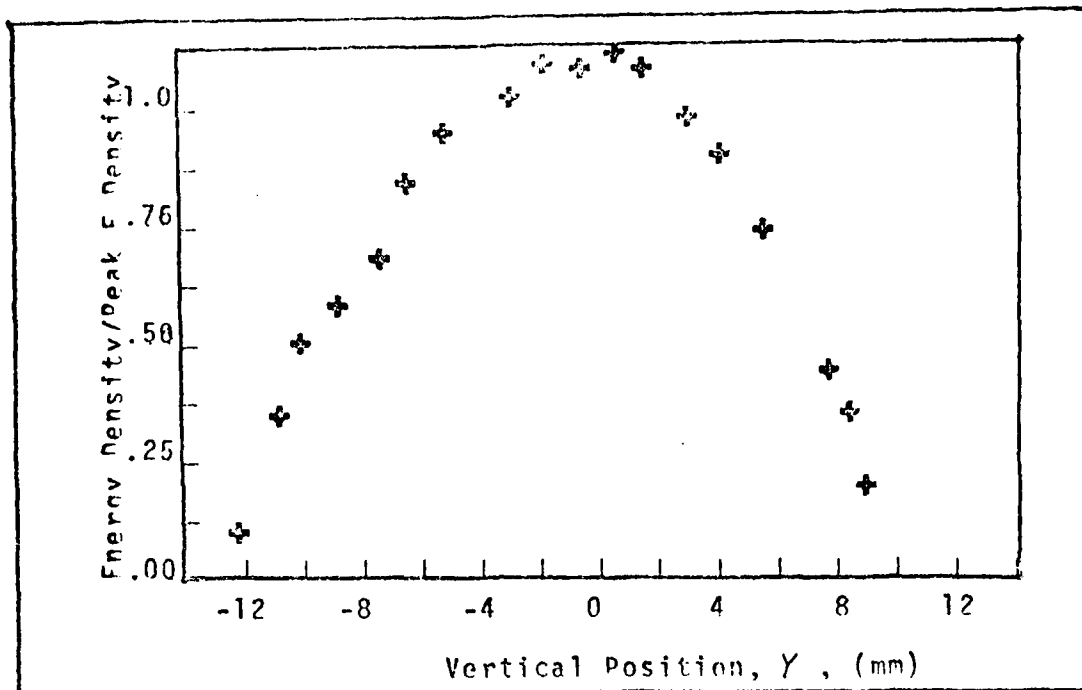


Figure 39
HF Spot Shape: Multiline - Vertical

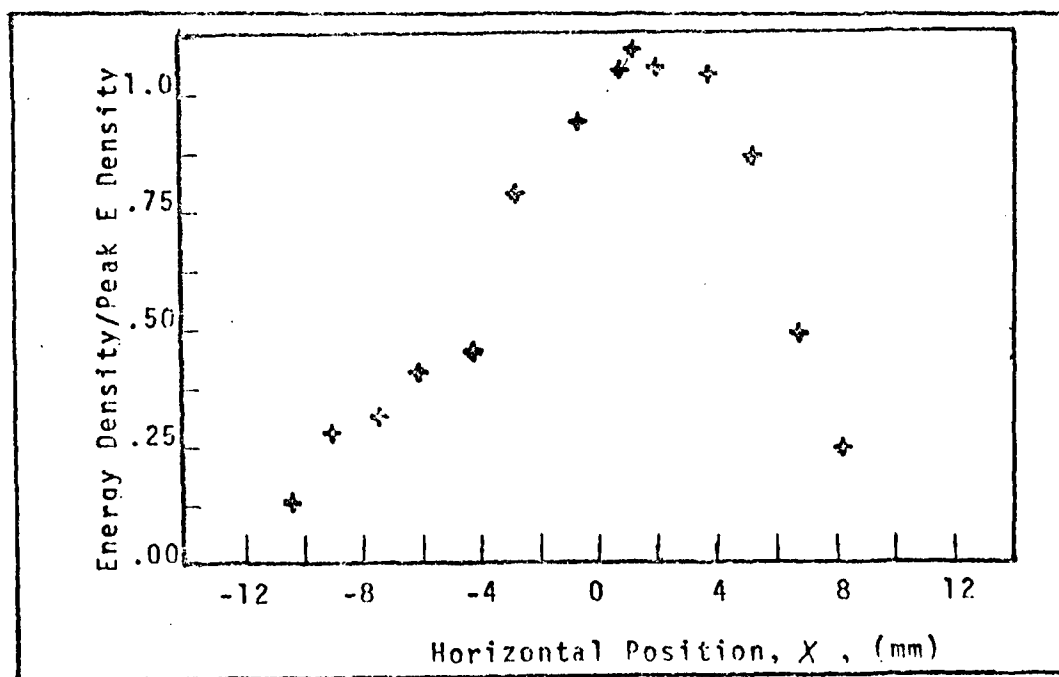


Figure 40.
IIF Spot Shape: Multiline - Horizontal

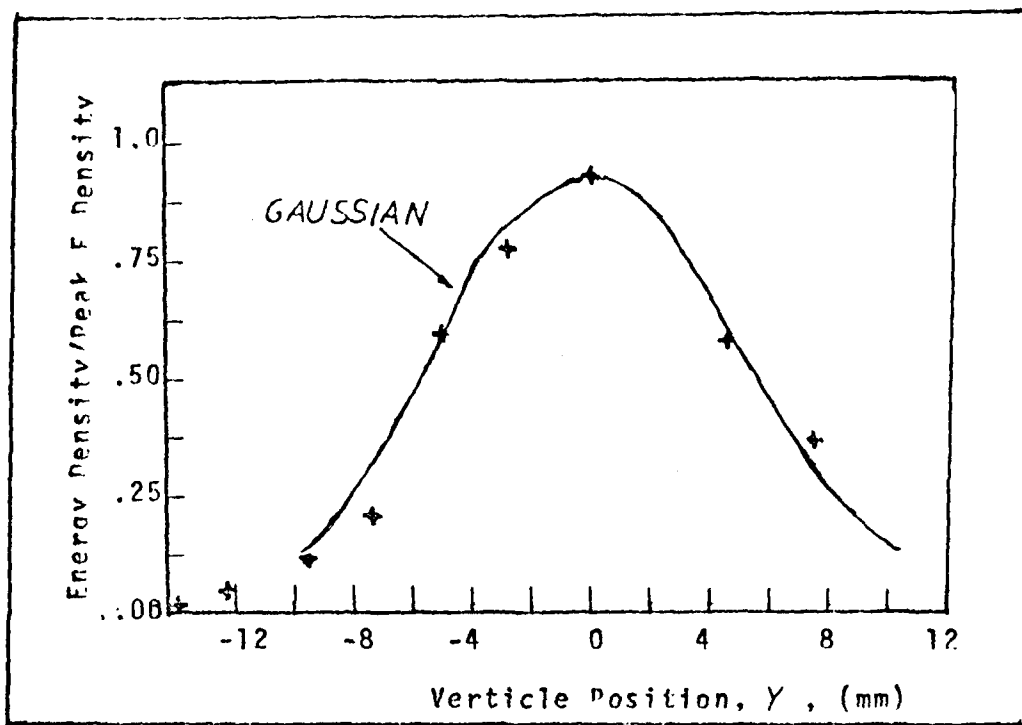


Figure 41.
HF Spot Shape: Sinoleline - Vertical

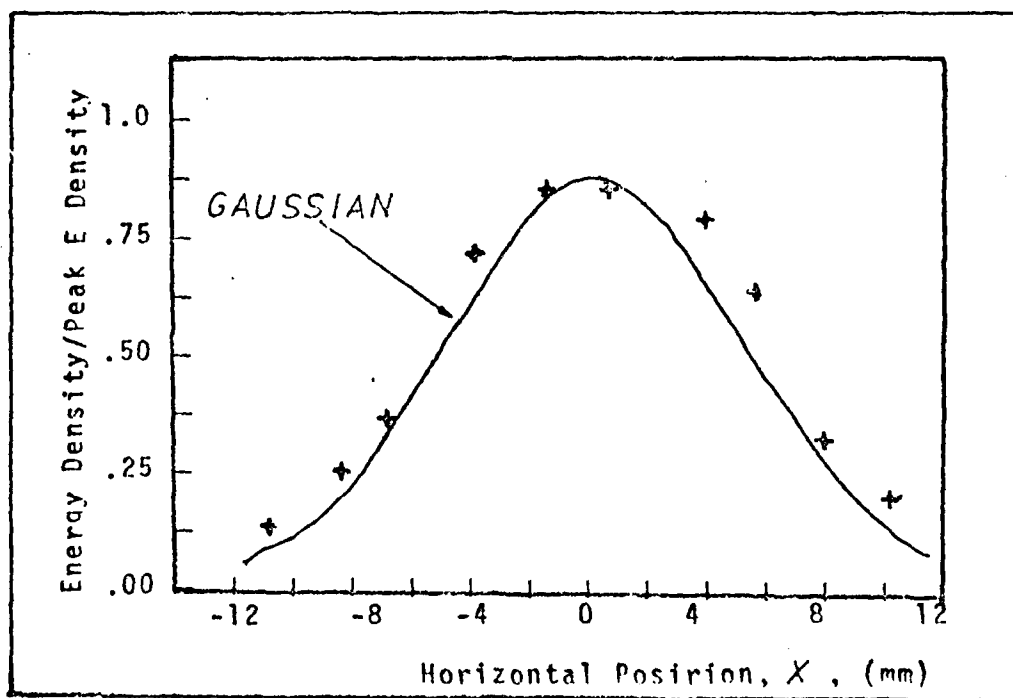


Figure 42.
HF Spot Shape: Sinoleline - Horizontal

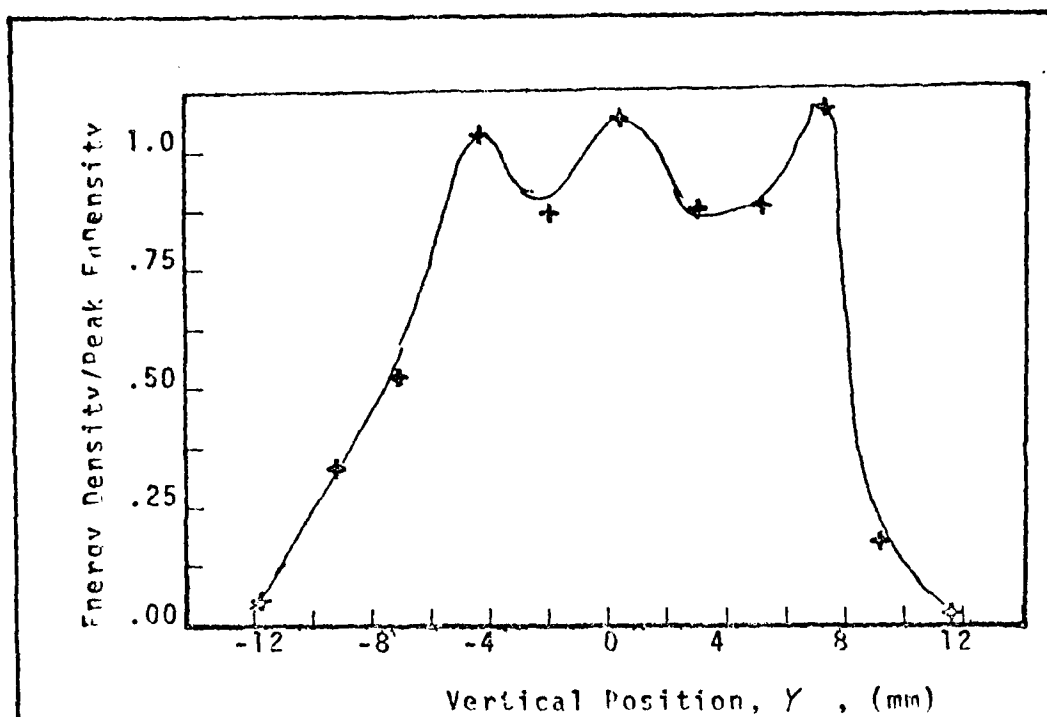


Figure 43.
HF Spot Shape: Focused-Vertical

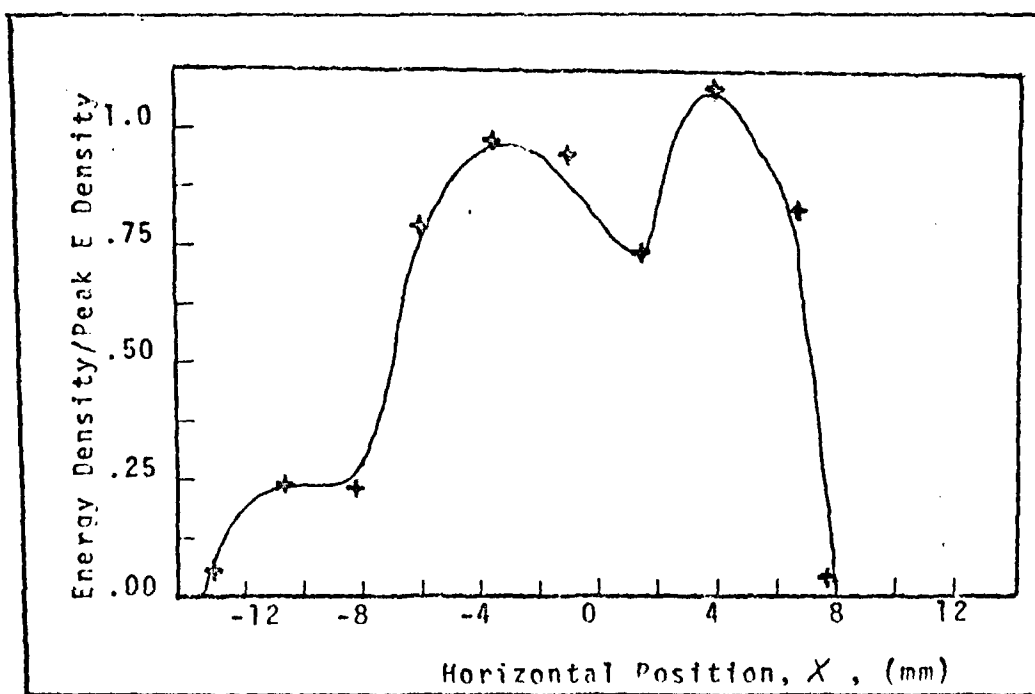


Figure 44.
HF Spot Shape: Focused - Horizontal

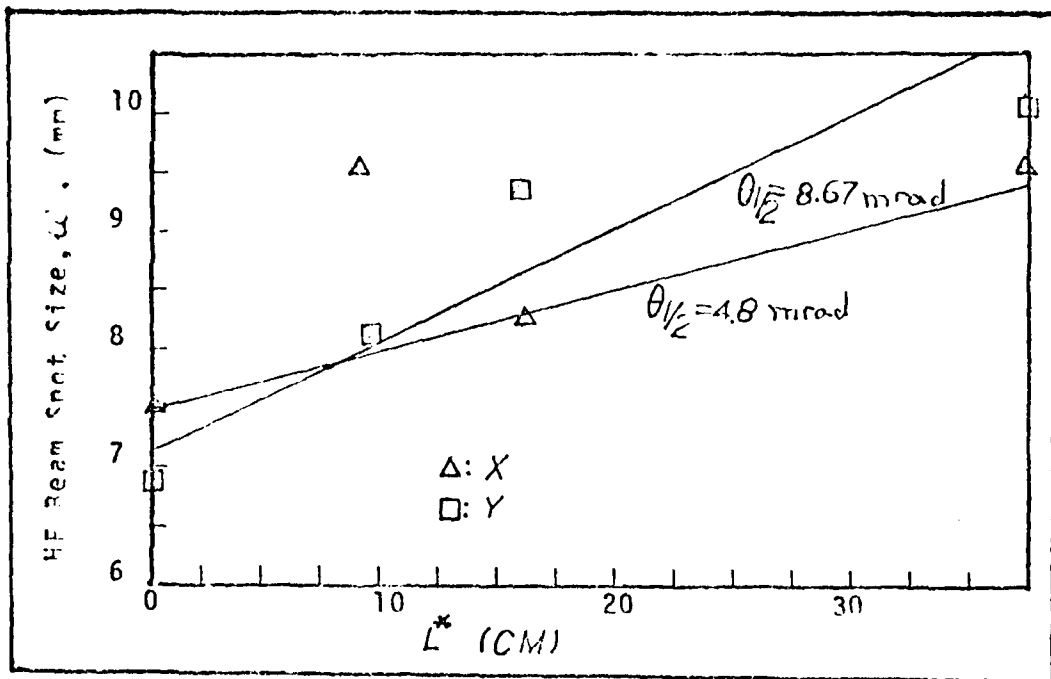


Figure 45.
HF Beam Divergence: Multiline

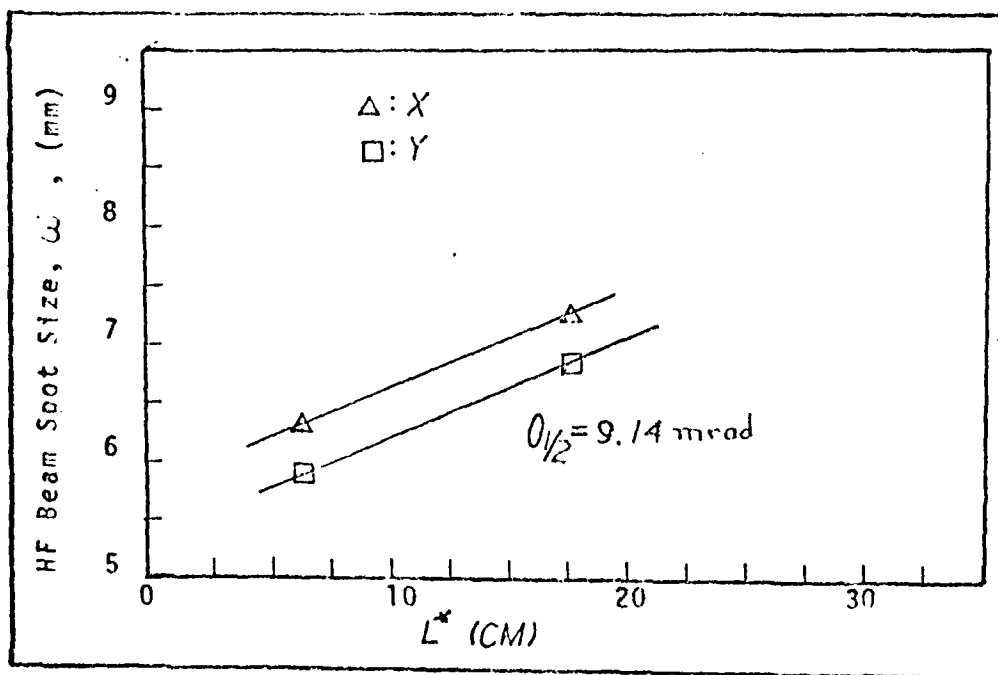


Figure 46.
HF Beam Divergence: $P_2(6)$ TEM 00

The single $P_2(6)$ transition with the .221" diameter aperture corresponds very nearly to a gaussian profile, indicating the TEM 00 mode.

The focused $P_2(6)$ beam has several peaks in its spatial energy distribution. This poor beam quality is probably due to imperfect lensing.

The full set of beam profiles at various axial locations were used to establish the beam divergence. The spot size was taken as the half-width at the 1/e power point of each profile.

The far field condition is

$$Z \gg \frac{\pi \omega_0^2}{\lambda} = 1.3 \text{ METERS} \quad (158)$$

where ω_0 is the beam waist, $\omega_0 = 1.09_{\text{mm}}$ [3:48]. None of the beam profiles were measured in the far field. In the near field, the spot size as a function of axial distance, Z , is

$$\omega = \omega_0 \sqrt{1 + \frac{\lambda Z^2}{(\pi \omega_0^2)^2}} \quad (159)$$

where ω_0 is the beam waist [34]. Then,

$$\delta \omega = \omega_0 Z \frac{\lambda}{\pi \omega_0^2} \quad (160)$$

Or,

$$\Delta \omega = \frac{\lambda}{\pi \omega_0} \Delta Z \frac{1}{\sqrt{1 + \frac{\lambda Z^2}{(\pi \omega_0^2)^2}}} \quad (161)$$

Let

$$L^* = \frac{Z}{\sqrt{1 + \frac{\lambda Z^2}{(\pi \omega_0^2)^2}}} \quad (162)$$

Then

$$\Delta \omega = \theta_{1/2} \Delta L^* \quad (163)$$

where $\theta_{1/2}$ is the far field beam divergence.

The plots in figures 55 and 56 are based on this new variable L^* , to find the far field beam divergence from the near field measurements. The resulting beam divergences are summarized in table IV.

Table IV.
Beam Divergence

Case		(mrad)
Multiline	Y	8.7
	X	4.8
$P_2(6)$ TEM 00	Y	9.1
	X	9.1

Raytheon gives a value of 1.4 mrad , based on a theoretical calculation and the cavity design [3:49].

Pulse Shapes

The power pulse shapes for HF and CO_2 are illustrated in figures 47-48. The data is taken from photographs of oscilloscope traces and the calibration from voltage to power, 60 W/Volt, is based on the total area under the power curve ,

$$E = \int P dt \quad (164)$$

equal to the average energy per pulse of 37.5 μJ .

For the HF pulse, the full-width at half-maximum is 106 ns, total energy, 37.5 μJ , and peak power .46 kW. For the CO_2 pulse, the FWHM is 26 ns. No total energy calibration

for the CO_2 curve was possible because the thermal energy detector was insufficiently sensitive to measure the lower power CO_2 signal. In contrast, Raytheon observed a 90 ns CO_2 pulse for a 100 ns, 1.8 mJ HF pump pulse.

The reduced CO_2 pulse width observed in this study is a result of reduced intensity of the HF pump pulse. Threshold lasing conditions for the CO_2 gas are reached only at the peak of the most intense HF pulses. The time interval over which threshold pumping is achieved is reduced to a small interval across the top of the HF pulse.

This conclusion is supported by several observations. The pulse-to-pulse variation in HF power is as large as a factor of six. CO_2 lasing was observed for one out of 3-5 HF pulses. The pulse shapes of figures 47 and 48 suggest a reasonable value for threshold pumping of 300 W/cm^2 .

Figure 49 compares the pulse shape predicted by the kinetic theory of figure 3 and the observed HF pulse normalized to a 1.5 mJ total energy. The zero of the time scale for the actual HF pulse is taken at 140nsec, to align the peaks of the two pulses. No measurement of the delay between electric discharge initiation and pulse initiation or of delays in the wiring or equipment were made.

The FWHM of the two curves agree very closely. The two curves diverge slightly at low power. No consideration of losses or threshold pumping was included in the kinetic model and this probably accounts for the divergence at lower powers.

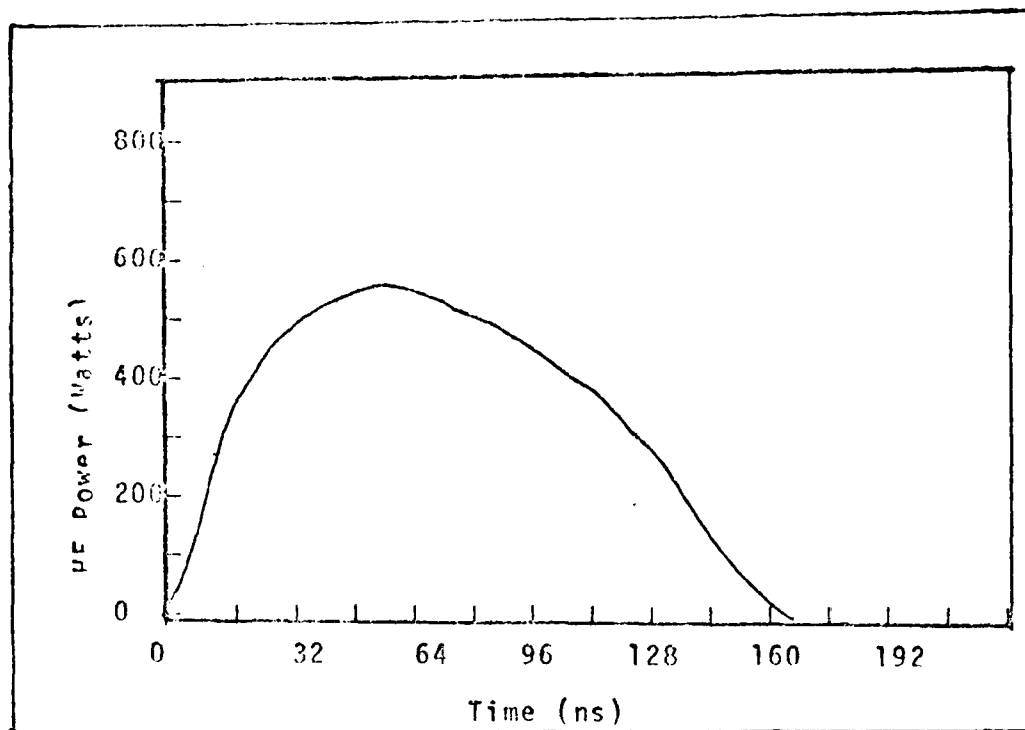


Figure 47.
HF Pulse Shape

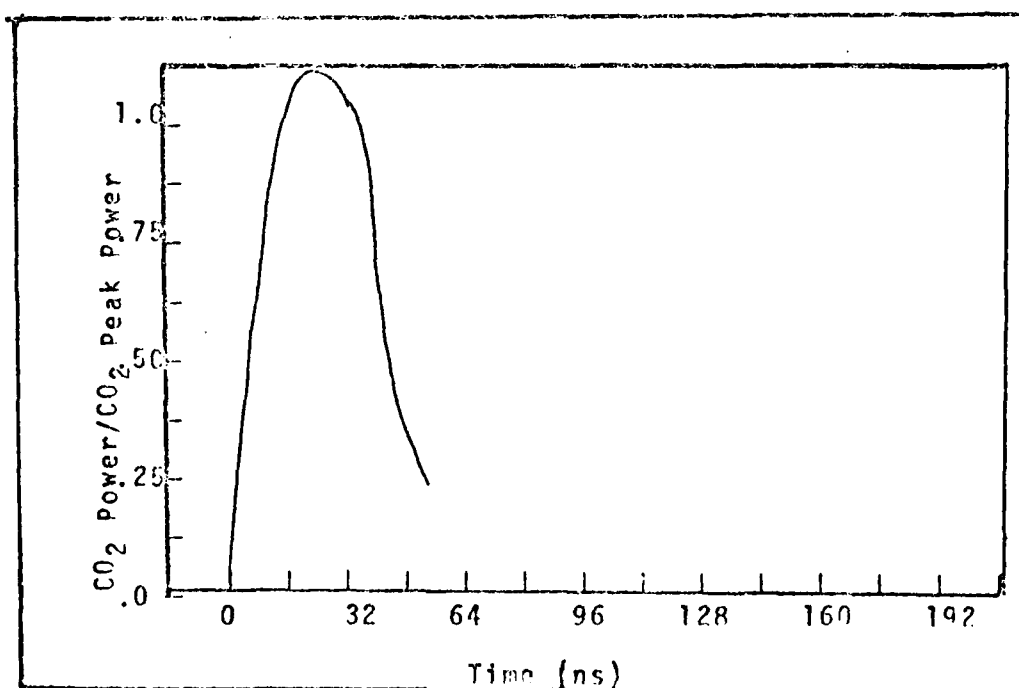


Figure 48.
CO₂ Pulse Shape

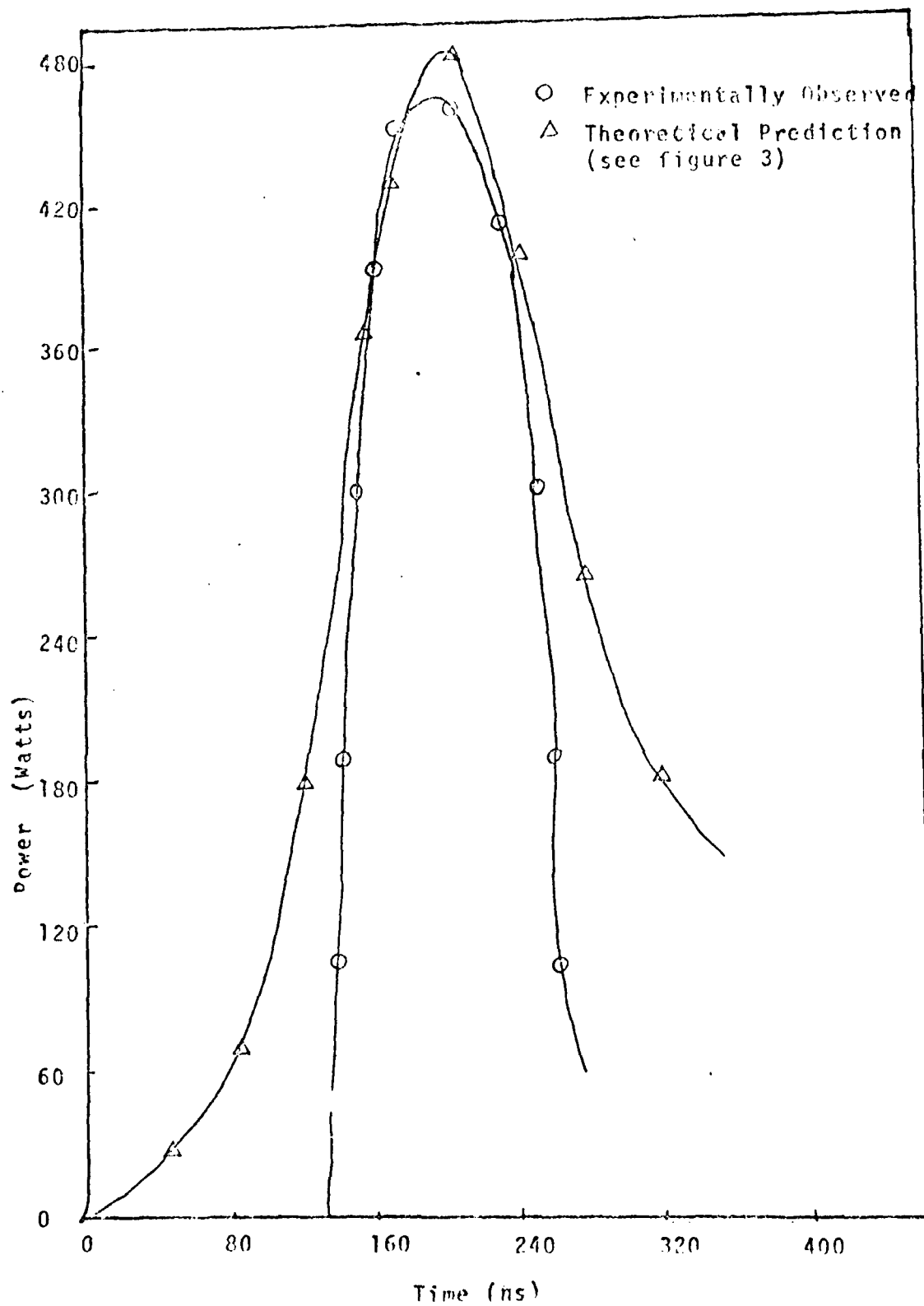


Figure 49.
HF Pulse Shapes

The HF pulse was normalized to 1.5 mJ total energy which is a factor of forty greater than observed in the current study. The difference in magnitude is a result of a number of factors. First, no losses were included in the theoretical model. Aperturing, scattering, and alignment losses were not considered. Certainly the aperture installed in the cavity to force the beam to the TEM 00 mode reduces the output power. Without the aperture, an energy of 88 μ J was measured. Secondly, the model neglected the formation of H_2S and other contaminants in the flow. H_2S is particularly efficient at depopulating excited HF molecules. This cause of reduced power may indeed be significant. Raytheon obtained an 1.8 mJ $P_2(6)$ pulse energy with clean chemical scrubbers.

Optical Pumping

The absorption of the HF $P_2(6)$ laser transition by the $^{12}C^{18}O_2$ molecules as observed experimentally (Δ), predicted theoretically ($\circ$), and as observed by Raytheon ($\square$) are presented in figure 50. The absorption coefficient is related to incident and transmitted power by

$$\alpha = \frac{1}{L} \ln \frac{P_{TRAN}}{P_{INC}} \quad (165)$$

The three curves have significantly different slopes and illustrate the effect of saturation. The HF intensity in the Raytheon experiment was 10^4 larger than in this study. The 000 - 101 transition is saturated at this higher intensity (see page 53). In the saturated case, a significant number of CO_2 molecules are pumped to the 101 level, reducing the total number of absorbers that the remainder of the HF

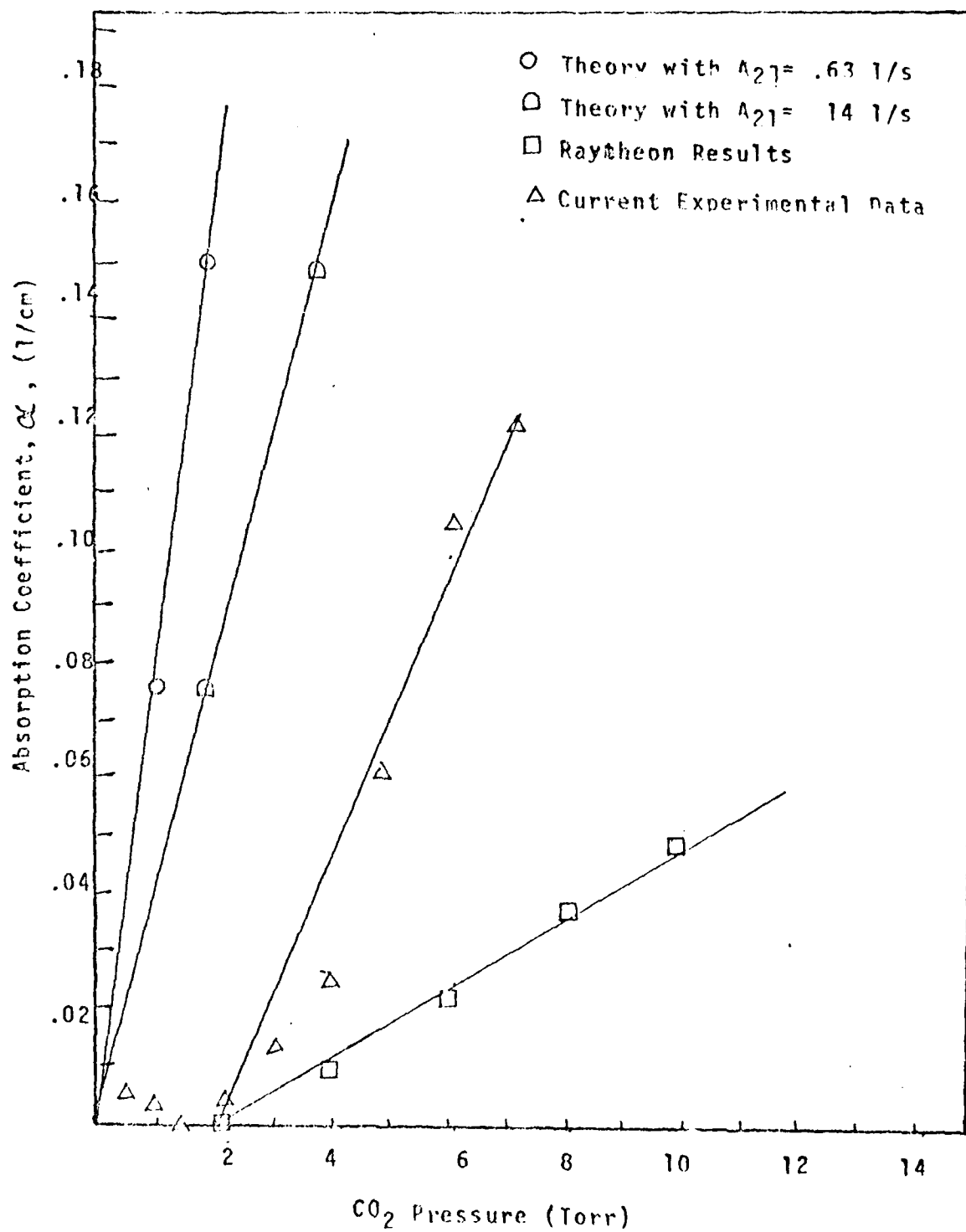


Figure 50.

pulse observes. This reduces the total absorption of the HF beam. Therefore, the Raytheon curve should lie below the results from this study.

The same reasoning explains why the theory curve is substantially above both of the experimental curves. The theory assumed no population of the upper level, $N_2 = 0$. That is, the result holds for a negligibly intense probe beam. Note that the slope of the theoretical curve is sensitive to the value of the Einstein coefficient for the 100 - 000 transition (eq. 112). The second value for $A_{21} = 14 \frac{1}{5}$ [29] is 22 times larger than the value given by reference [62] and used on page 38. There is a substantial uncertainty in the value of this coefficient.

Instability

Throughout this investigation, problems with power fluctuation were encountered. This was most pronounced in the CO₂ absorption of the HF beam. The instability was also observed in oscilloscope traces. An example trace is shown in figure 51.

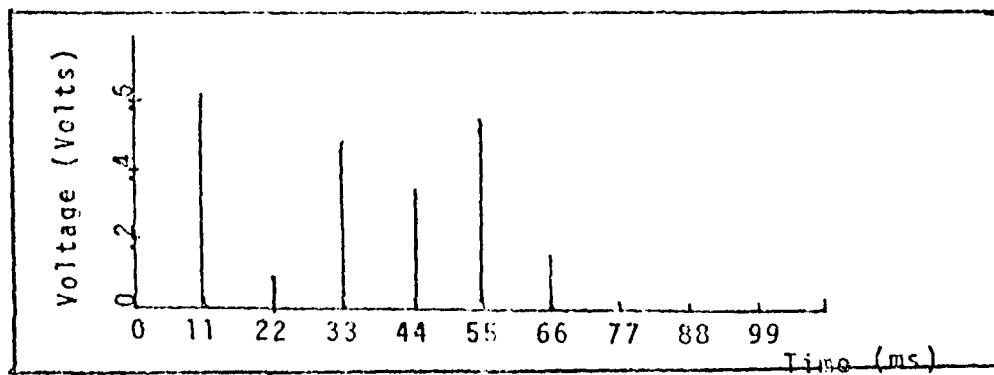


Figure 51.

HF Power Instability

The HF power varies on a pulse-to-pulse basis by as much as a factor of six. This variation is partially explained by a nonuniform SF_6/H_2 gas flow with contaminants and by varying electric discharge quality.

There exists an instability in HF frequency as well. This is most readily noted by observing the fluctuation in % absorption of the HF beam in the CO_2 cell with all variables held constant. The problems of power instability are removed by looking at the ratio of transmitted to incident power. This plot of transmitted to incident power as a function of time is shown in figure 52. A plot for a slow sweep of the PZ crystal voltage is also presented. The only explanation for the variations observed in these plots is a substantial frequency instability. Note that no correlation between frequency and PZ crystal voltage is observable, indicating that the frequency stability completely obscures the frequency changes caused by the PZ crystal.

The variation in the magnitude of the power instability as a function of repetition rate, discharge voltage, and pressure was studied and the results are presented in figures 53 -55. The best operating point is 20 pps, 14 kV, and 88 torr. Operating at 12 kV and 80 torr is nearly as good, but a 100pps repetition rate is a little high. Even at the optimum operating point, the signal to noise ratio is

$$\frac{S}{N} = 2 \text{ OR } 3 \quad (166)$$

The frequency instability is a severe problem. With no

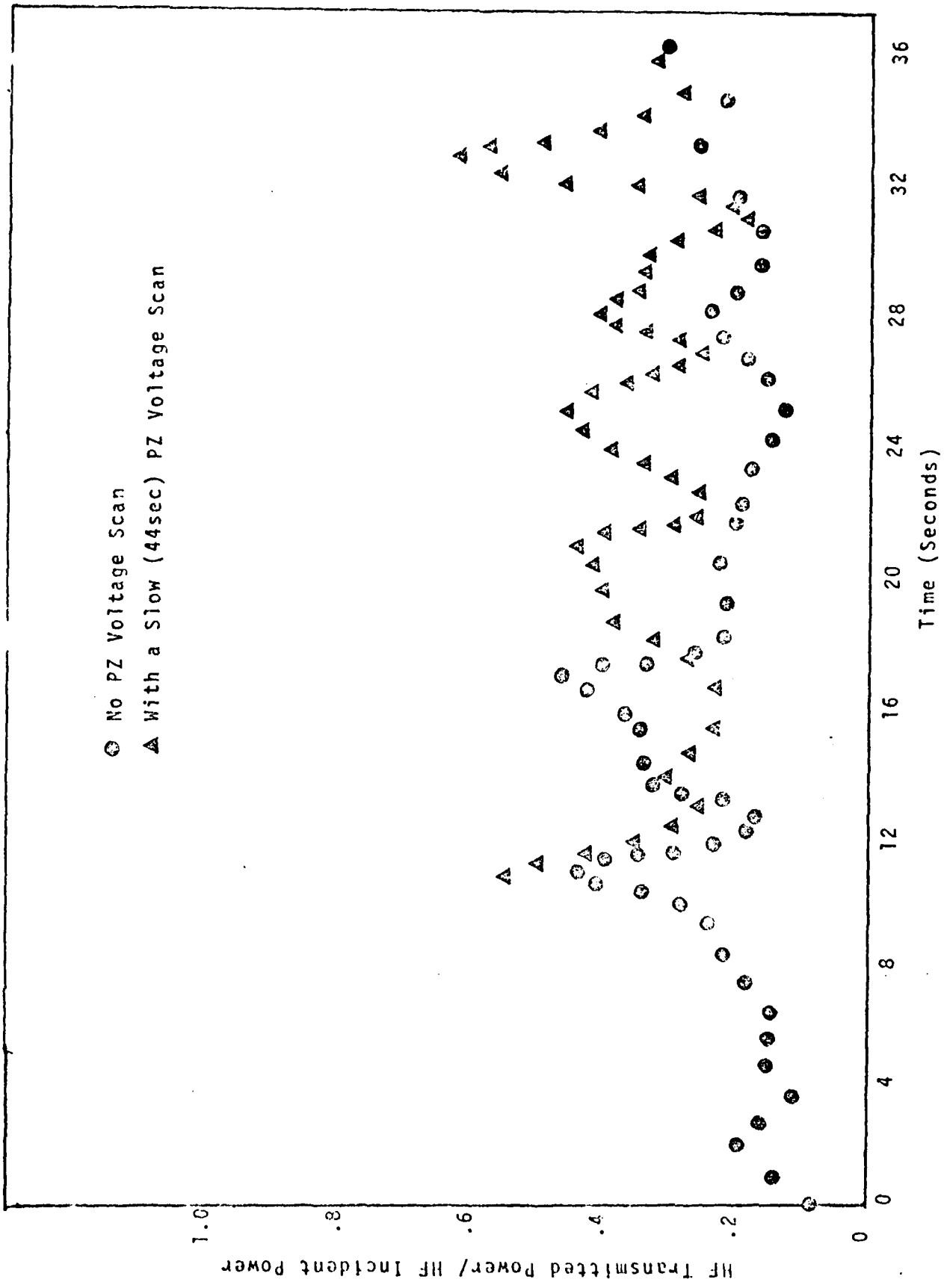


Figure 52
HF Frequency Stability

control over frequency, the actual frequency must be measured throughout time and correlated to the CO₂ power. Even more importantly, the HF frequency must be stable during the period of integration, otherwise only an average frequency power is observed. The frequency instability is worse than 1 ms, the period of integration in this study. No study of CO₂ output power with HF frequency was possible in this investigation. Recommendations concerning this problem are presented in the conclusions section.

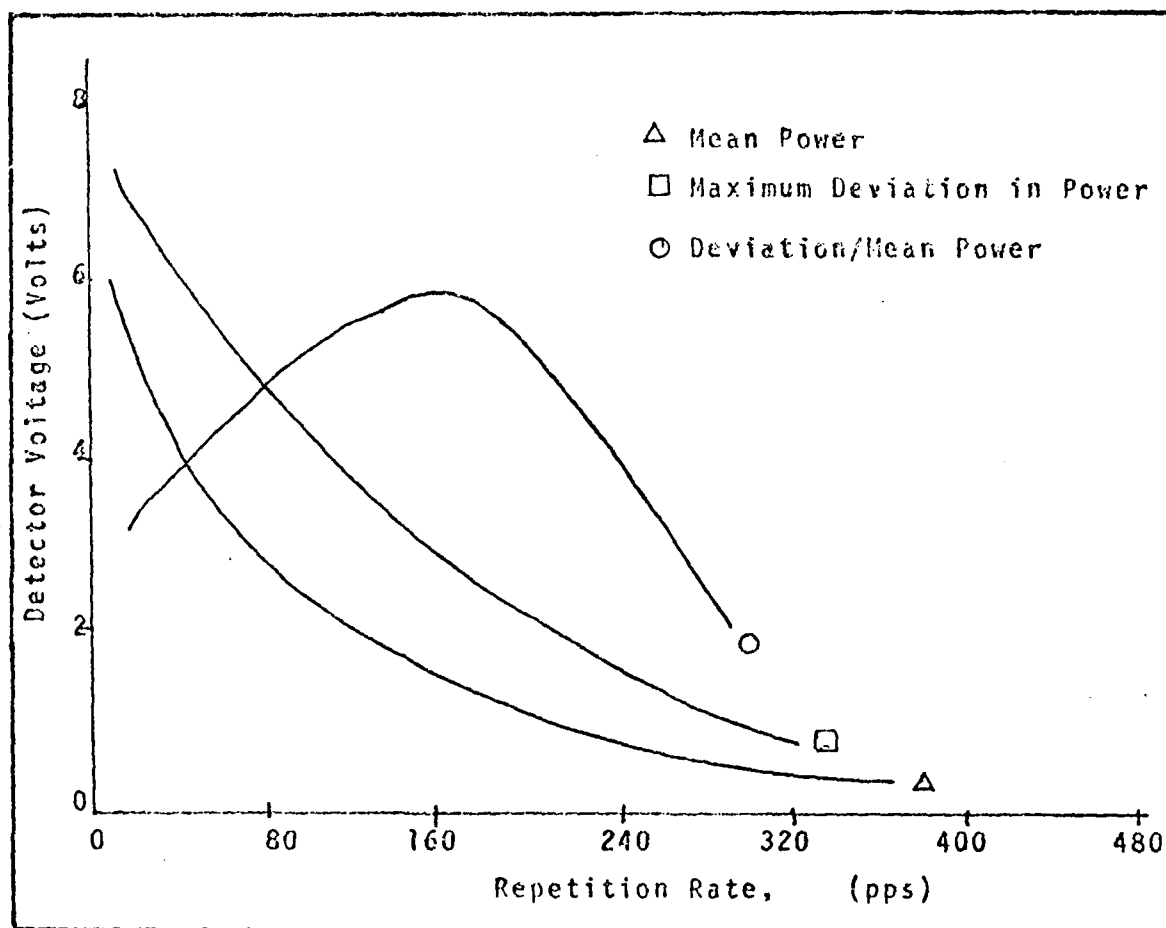


Figure 53

Power Instability versus Rep Rate

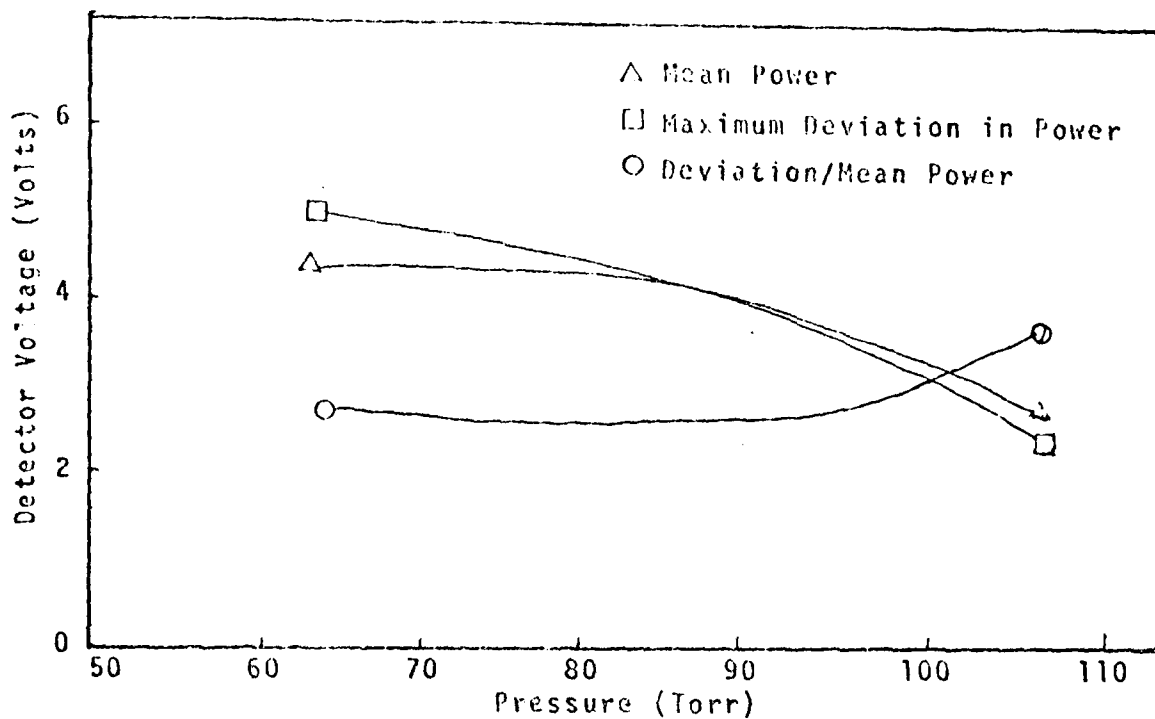


Figure 54
Power Instability vs Pressure

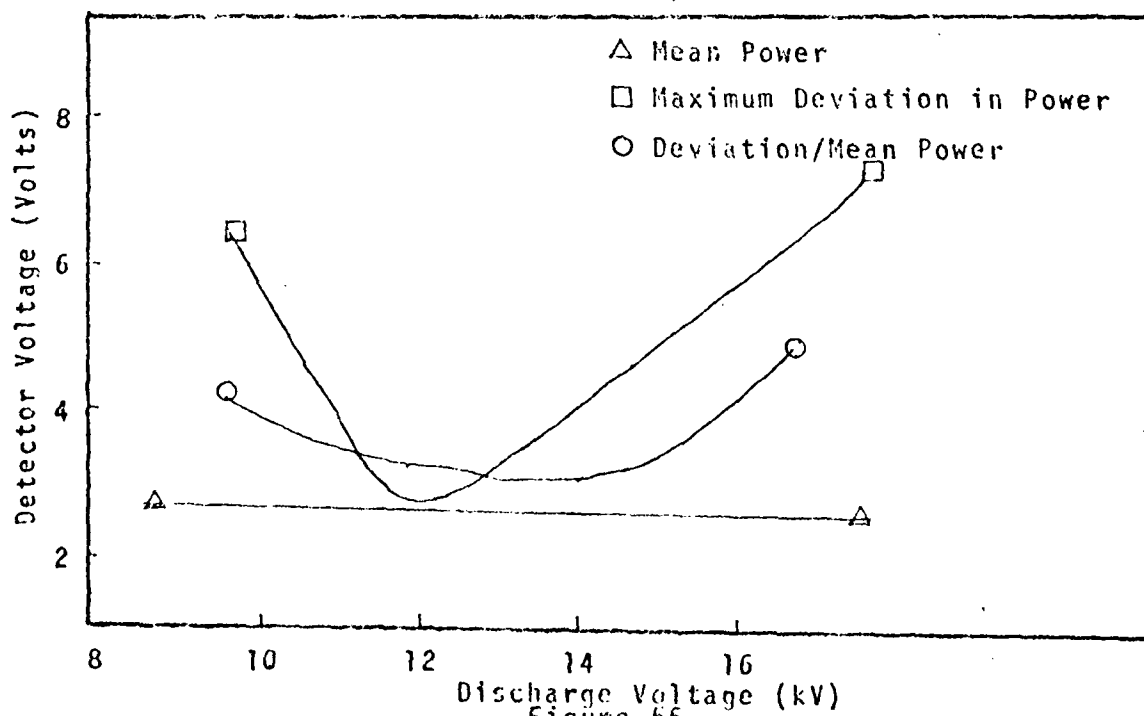


Figure 55
Power Instability vs Voltage

Conclusions and Recommendations

A complete study of the HF-pumped CO_2 laser developed by the Raytheon Corporation has been completed. Background theory for the design and performance of the laser system has been presented and applied. The HF laser's performance was experimentally characterized and output power maximized with respect to repetition rate, discharge voltage, pressure, gas mixture, and stability. Optical pumping of the 101 level of $^{12}\text{C}^{18}\text{O}_2$ by the HF $P_2(6)$ transition established lasing action to the 100 CO_2 level. The optical pumping was studied through an absorption experiment. No measurement of CO_2 output power as a function of HF frequency was made, due to a large HF frequency instability. Discrepancies between theory and experiment on this frequency dependence was explained however. Pulse shapes were observed and shown to agree with the kinetic model developed in this study.

The HF laser was modified to conduct these investigations. The gas flow rate was controlled to reduce SF_6 consumption. The optical cavity was modified to accommodate an aperture and piezoelectric crystal for control of the cavity length. The trigger and discharge circuitry were repaired and modified. Reliability of the laser was addressed in the main text, including discussions of the discharge circuit and gas recirculation and scrubbing.

In this modified form, the laser's performance was maximized for power at 79% SF_6 /21% H_2 , 88 torr total pressure, a 12 kV discharge voltage, and a 300 pps repetition rate. Stability in HF power was enhanced by reducing the repetition rate to 20 - 60 pulses/sec. Only 7 l/min flow rates were used. A

total multiline energy per pulse of 156 μ J was achieved with lasing on the $P_2(4)$, $P_2(5)$, and $P_2(6)$ transitions. An 88 μ J $P_2(6)$ single line energy was achieved and TEM 00 operation of the $P_2(6)$ transition achieved with an aperture of .221" diameter.

A beam divergence of 5-8 mrad multiline and 9mrad for the $P_2(6)$ transition was measured. Beam quality is rather poor, exhibiting the effects of aperturing, inhomogeneous gas flow and a nonuniform electric discharge.

A pulse-to pulse variation in power of a factor of six was the best power stability achieved. Frequency stability is worse than 200 MHz over a millisecond time interval.

Optical pumping of $^{12}C^{18}O_2$ by the HF $P_2(6)$ transition produced CO_2 lasing from the $(10^1)_I$ level to the $(10^0)_I$ level. Pumping was near threshold conditions, and as a result, CO_2 lasing was erratic, low intensity, and exhibited a shortened pulse width of 26 ns. No investigation of the effect of HF frequency on CO_2 power was possible, due to the large HF frequency instability.

The optical pumping was studied through an absorption experiment. The absorption coefficient was shown to vary linearly with pressure over the 0 -7 torr pressure range, as predicted by the presented theory. The magnitude of the absorption is less than predicted due to saturation.

HF and CO_2 pulse shapes were observed with FWHM of 106 ns and 26 ns, respectively. The HF pulse width agrees well with the kinetic model presented. This model was based on the HF cold reaction and electron attachment to

SF₆ to produce atomic fluorine.

Throughout this study, results were compared with the experimental data obtained by Raytheon, using the same HF laser and basic set-up. The issue of CO₂ power depending on HF frequency was addressed and the apparent contradiction between theory and prior experimental results explained.

Raytheon observed no significant variation in CO₂ power with changes in HF frequency over a 300 MHz range. A number of factors explain this observation. First, and foremost, the HF laser's frequency is unstable and the random fluctuation in frequency completely obscures the effect of a piezoelectric crystal. The frequency varies greatly during the period of observation and no meaningful power observations are possible without actively stabilizing the HF cavity. Secondly, under the conditions of the Raytheon study, the CO₂ transition is saturated as suggested by the authors of the Raytheon report. Calculations presented in the theory section support this claim of saturation. Finally, the CO₂ cell was not pumped uniformly in the Raytheon study, the beam was not Gaussian, and several axial modes were present in the HF pump beam.

Several recommendations may be made based on these results and conclusions.

The HF laser's performance could be enhanced by reducing contaminants in the SF₆/H₂ gas flow. A design modification to allow frequent cleaning of the chemical scrubbers would be a great advantage. Reducing the concentration of contaminants, particularly H₂S would enhance power and power

stability.

To investigate the dependence of CO_2 power on HF frequency, an active method of stabilizing the HF cavity is proposed. In this way the frequency instability problem could be overcome and the HF frequency easily controlled.

A direct investigation of the low signal gain of the optically pumped CO_2 system should be undertaken to validate the optical pumping theory presented on pages 43-47.

Studying the ratio of forward to backward CO_2 powers may also provide insight into the nature of the optical pumping.

Conclusion

An optically pumped molecular laser was operated and characterized. The HF pump laser's performance was documented and the kinetics of the electric discharge analyzed. The optical pumping scheme was studied by absorption measurements. The apparent contradiction between theory and experiment on the dependence of CO_2 power on HF frequency was resolved, but the frequency-power dependence was not experimentally established.

Bibliography

1. Grasyuk, A.Z., Letokhov, V.S., and Lobko, V.V., "Molecular Infrared Lasers Using Resonant Laser Pumping (review)," Soviet Journal of Quantum Electronics, 10(11), 1317 - 1338, (Nov 1980).
2. Jones, C.R., "Optically Pumped Mid-IR Lasers," Laser Focus, 58-74, (Aug 1978).
3. Rudko, R.I., Bua, D.P., Drozdowicz, Z., and Linhares, S.J., "Electric-Pulse-Initiated Chemical Laser," AFWAL-TP-81-1054 under contract F33615-77-C-1046, (1981).
4. Kompa, K.L., and Pimentel, G.C., "Hydrofluoric Acid Chemical Laser," Journal of Chemical Physics, 47, 857-858, (1967).
5. Spencer, D.J., Jacobs, T.A., Hirels, H., and Gross, V.F., "Continuous Wave Chemical Laser," International Journal of Chemical Kinetics, 1, 493-494, (1969).
6. Deutsch, T.F., "Molecular Laser Action in Hydrogen and Deuterium Halides," Applied Physics Letters, 10, 234-236, (Apr 1967).
7. Batowskii, O.M., Vasil'ev, G.K., Makarov, E.F., and Tal'roze, V.L., "Chemical Laser Operating on Branched Chain Reaction of Fluorine with Hydrogen", JETP Letters, 9, 200-201, (1969).
8. Jensen, R.J., "Electric Discharge Initiated $\text{SF}_6 + \text{H}_2$ and $\text{SF}_6 + \text{HBr}$ Chemical Lasers", Chemical Physics Letters, 7, 627-629, (1970).
9. Brandelik, J.E., and Paulson, R.F., "Operation of an HF ($\text{SF}_6 + \text{H}_2$) TE Laser at 10 kHz Pulse Repetition Rates", IEEE Journal of Quantum Electronics, QE-13, 933-934, (Dec 1977).
10. Buazek, C.J., Freiberg, R.J., Hitchen, J.J., Chenausky, P.P., and Wayne, P.J., "Premixed cw Chemical Laser", Applied Physics Letters, 17, 514-516, (Dec 1970).
11. Jacobson, T.V., Kimbell, G.H., and Snelling, D.P., "A High-Repetition Rate Chemical Laser", IEEE Journal of Quantum Electronics, QE-2, 496-497, (Apr 1973).
12. Voinov, A.M., Doubysh, L.E., Kazakevich, A.T., Mel'nikov, S.P., and Sinyankii, A.A., "High Pressure Radiation-Chemical Laser Initiated by a Fast Electron Beam From a Coaxial High-Voltage Diode", Soviet Journal of Quantum Electronics, 7, 234-235, (Feb 1977).

13. Spencer, D.J., Hirels, H., Jacobs, T.A., and Gross, R.W.E., "Preliminary Performance of a cw Chemical Laser", Applied Physics Letters, 16, 235-237, (Mar 1970).
14. Dashkin, A.S., Oboevskii, A.N., and Tomamshov, V.N., "Energy Characteristic of an Electron-Beam-Initiated HF Chemical Laser", Soviet Journal of Quantum Electronics, 7, 94-95, (Jan 1977).
15. Pummer, H., Breitfeld, W., Redler, H., Klema, G., and Kompa, K.L., "Parametric Study of a 10-J Hydrogen Fluoride Laser", Applied Physics Letters, 22, 319-320, (Apr 1973).
16. Pummer, H. and Kompa, K.L., "Investigation of a 1-J Pulse Discharge-Initiated HF Laser", Applied Physics Letters, 20, 356-357, (May 1972).
17. Wenzel, R.G., and Arnold, G.P., "A Double-Discharge-Initiated HF Laser", IEEE Journal of Quantum Electronics, QE-8, 26, (Jan 1972).
18. Chester, A.H., "Chemical Lasers, A status Report", Laser Focus, 28, 25, (1971).
19. Gross, R.W.E., and Bott, J.F., Handbook of Chemical Lasers, New York, John Wiley and Sons, 1976.
20. Hinchon, J.J., "Operation of a Small Single-Mode Stable cw Hydrogen Fluoride Laser", Journal of Applied Physics, 45, 1818, (Apr 1974).
21. Hann, D.E., Thrush, B.A., Lide, D.P., Ball, J.J., and Acquista, M., "Spectroscopy of Fluorine Flames. I. Hydrogen Fluorine Flow and the Vibrational-Rotational Emission Spectrum of HF", Journal of Chemical Physics, 34, 420-431, (Feb 1969).
22. Pressley, Handbook of Lasers with selected Data on Optical Technology, Cleveland: CRC Press, (1971), 317-318.
23. Buchwald, M.I., Jones, C.P., Fetterman, H.R., and Schlossberg, A.P., "Direct Optical Pumping of Multiwavelength CO₂ Laser", Applied Physics Letters, 29, 300-302, (Sep 1976).
24. Yariv, Amnon, Quantum Electronics, (Second Edition), New York: John Wiley and Sons, 1967.
25. Peterson, L.M., Arnold, C.B., and Lindquist, G.H., "Pulse HF Chemical Laser Linewidth Measurements using Time-Resolved Bleachable Absorption of HF Gas", Applied Physics Letters, 24, 615-617, (June 1974).
26. Siegman, A.E., An Introduction to Lasers and Masers, New York: McGraw-Hill, 1971, 120.

27. Chester, A.N. and Hess, L.D., "Study of the HF Chemical Laser by Pulse-Delay Measurements", IEEE Journal of Quantum Electronics, CE-8, 1-13, (Jan 1972).
28. Sienko, R.D. and Plane, R.A., Chemistry, (Fifth Edition), New York: McGraw-Hill, 1976.
29. Omenetto, R., Analytical Laser Spectroscopy, New York: John Wiley and Sons, 1979, 128-129.
30. Davies J.T. and Vaughan, J.M., "A New Tabulation of the Voigt Profile", Astrophysical Journal, 137, 1302-1305, (1963).
31. Milonni, D.W., "Saturation of Anomalous Dispersion in cw HF Lasers", Applied Optics, 20, 1571-1578, (May 1981).
32. Herget, W.F., Deeds, W.E., Gails, H.M., Lovell, P.J., Nielson, A.H., "Infrared Spectrum of Hydrogen Fluoride: Line Positions and Line Shapes Part II. Treatment of Data and Results", Journal of the Optical Society of America, 52, 1113-1119, (Oct 1962).
33. Jaffe, B., Cook, W.R., Jaffe, H., Piezoelectric Ceramics, New York: Academic Press, 1971.
34. Pedrotti, L.S., Class Notes from PH 7.43, Spring 1981, AFIT, WPAFB, OH.
35. Warren, W.R., "Reacting Flow and Pressure Recovery Processes in HF/DF Chemical Lasers", Acta Astronautica, 1, 813-834(1973).
36. Miresl, H., Hofland, R., and King, M.S., "Simplified Model of cw Diffusion Type Chemical Laser", AIAA Journal, 11, 156-164, (Jan 1973).
37. Cotton, F.A. and Wilkinson, G., Advanced Inorganic Chemistry, New York: John Wiley and Sons, 1962, 534-539.
38. Weast, Handbook of Chemistry and Physics, (55th ED), Cleveland: CRC Press, 1974.
39. McDaniel, E.W., Collision Phenomenon in Ionized Gases, New York: John Wiley and Sons, 1964, 39.
40. Rohr, K., "Absolute Differential Cross Sections for e^- - SF_6 scattering in the alg and tla Resonance Region", Journal of Physics B, 12, L185-L188, (1979).
41. Lockett, A., Los Alamos Scientific Laboratory, cited as a private communication by [42].
42. Lyman, J.L., "Computer Model of the SF_6 - H_2 Electric Discharge Chemical Laser", Applied Optics, 12, 2736-2747, (1973).

43. Fehsenfeld, T.C., "Electron Attachment to SF_6 ", Journal of Chemical Physics, 55, 2000-2004, (Sep 1970).
44. Iatsurawa, H. and Suenomoto, S., "Long-lived Electron Beam Pre-Irradiation Effect in a Impact SF_6/H_2 Laser", Japanese Journal of Applied Physics, 19 L502-L512, (Sep 1980).
45. McGeehan, J.P., O'Neill, B.C., and Craigs, J.P., "Negative Ion/Molecule Reactions in Sulfur Hexafluoride", Journal of Physics D, 8, 153-160, (1975).
46. Ahearn, A.J. and Nannay, N.R., "The Formation of Negative Ions of Sulfur Hexafluoride", Journal of Chemical Physics, 21, 119-124, (Jan 1953).
47. Asundi, R.K., and Craigs, J.D., "Electron Capture and Ionization Phenomenon in SF_6 and C_7F_{14} ", Proceedings of the Royal Physical Society, 83, 611-618, (1964).
48. Curran, R.K., "Low energy Processes for F^+ Formation in SF_6 ", Journal of Chemical Physics, 34, 1959, (1961).
49. Fenimore, C.P., and Jones, G.W., "Decomposition of Sulfur Hexafluoride in Flows by Reaction with Hydrogen Gas", Combustion Flame, 8, 231, (1964).
50. Yariv, A., Introduction to Optical Electronics, (Second Ed), New York: Holt, Rinehart and Winston, 1976.
51. Golger, A.L. and Letolhev, V.S., "Population inversion Due to Saturation of Absorption in Molecular Rotational-Vibrational Transitions", Soviet Journal of Quantum Electronics, 3, 15-20, (1973).
52. Bushnell, A.H., Jones, C.P., Buchwald, M.I., Gundersen, M., "New HF Laser Pumped Molecular Lasers in the Middle Infrared", IEEE Journal of Quantum Electronics, QE-15, 208-209, (Apr 1979).
53. Osgood, R.H., "1 mJ Line Tunable Optically Pumped 16 Micron Laser", Applied Physics Letters, 28, 342-345, (May 1978).
54. Osgood, R.H., "Optically Pumped 16 micron Laser", Applied Physics Letters, 28, 342-345, (Mar 1976).
55. Chang, T.Y., and Wood, O.R., "Optically Pumped 33 atm CO_2 Laser", Applied Physics Letters, 23, 370-372, (Oct 1973).
56. Wang, J.H.S., Finzi, J., and Mstrun, F.N., "Cw Optically Resonance Pumped Transfer Laser in DF-CO_2 System", Applied Physics Letters, 31, 35-37, (July 1977).

57. Banwell, C.W., Fundamentals of Molecular Spectroscopy, (Second Edition), London: McGraw-Hill, 1972, 90.
58. Patel, "Gas Lasers", Lasers: A Series of Advances, Vol 3., edited by Levine, A.K., New York: Marcel Dekhewicz, (1970).
59. Subolev, M.N., and Sckovikov, V.V., "CO₂ Lasers", Soviet Physics Uspekhi, 10, 153-170, (1967).
60. Gordon, Howard and McCubbin, T.K., "The 2.8 μ m Bands of CO₂", Journal of Molecular Spectroscopy, 19, 137-154, (1966).
61. Oberly, R. and Rao K.H., "Near IR Absorption Spectrum of Oxygen-18 Enriched CO₂", Journal of Molecular Spectroscopy, 40, 356-366, (1971).
62. Statz, H., Tang, C.L., Koster, G.F., "Transition Probabilities between lower states in Carbon Dioxide", Journal of Applied Physics, 37, 4275-4280, (1966).
63. Javan, A., "Theory of a Three Level Maser", Physical Review, 107, 1579-1589, (Sep 1957).
64. Feld M.S., and Javan, A., "Lase Induced Line Narrowing Effects in Coupled Doppler-Broadened Transitions", Physical Review, 177, 540-562, (Jan 1969).
65. Panock, R.L. and Temkin, R.J., "Interaction of Two Laser Fields with a Three Level Molecular System", IEEE Journal Of Quantum Electronics, QE-15, 170-178, (Mar 1979).
66. Drozdowicz, Z., Temkin, R.J., Lax, B., "Laser Pumped Molecular Lasers- Part I: Theory" IEEE Journal of Quantum Electronics, QE-15, 170-178, (March 1979).
67. Drozdowicz, Z., Temkin, R.J., Lax, B., "Laser Pumped Molecular Lasers- Part II: Submillimeter Laser Experiments", IEEE Journal Of Quantum Electronics, QE-15, 865-869, (Sep 1979).
68. Dicke, R.H., "Coherence in Spontaneous Radiative Processes", Physical Review, 93, 99-110, (Jan 1954).
69. Skibanowitz, M., Herman, I.P., MacGillvary, J.C., and Feld, M.S., "Observation of Dicke Superradiance in Optically Pumped HF Gas", Physical Review Letters, 30, 309-312, (Feb 1973).
70. Friedberg, R. and Hartmann, S.R., "Superradiant lifetime, Its definitions and relation to Absorption Length", Physical Review A, 13, 495-496, Jan 1976.
71. Discussion with Capt Cook, Air Force Institute of Technology, AFIT/ENP, WPAFB, OH, 45433, (9 Sep 1981).

72. Dzakowicz, G.S. and Mutzke, S.A., "High-Pulse-Rate Glow-Discharge Stabilization by Gas Flow", Journal of Applied Physics, 44, 5061-5063, (Nov 1973).
73. Stull, D.D. and Prophet, H., JANAF Thermochemical Tables, (Second Edition), National Bureau of Standards, NSRDS-NBS 37, (June 1971).
74. Tritton, D.J., Physical Fluid Dynamics, New York: Von Nostrand Reinhold Co., 1977, 11.
75. Dolgov-Sovel'ev, G.G., Polyakov, V.A., and Chanik, G.M., "Laser Emission in the 2.8 μ m Range involving Vibrational-Rotational Transitions in the HF Molecule", Soviet Physics JETP, 31, 643-645, (Oct 1970).
76. Dorke, E.A., Professor, Air Force Institute of Technology, Class note from PH 6.61, Fall Quarter, 1980.
77. Compton, R.N., Christophorov, L.G., Hurst, G.S., and Reinhardt, P.W., "Nondissociative Electron Capture in Complex Molecules and Negative Ions Lifetimes", Journal of Chemical Physics, 45, 4635-4639, (Dec 1966).
78. Curran, R.K., "Low-energy Process for F- Formation in SF₆", Journal of Chemical Physics, 34, 1069, (1961).
79. Cirrigan, S.J.B., "Dissociation of Molecular Hydrogen by Electron Impact", Journal of Chemical Physics, 43, 4381-4386, (Dec 1965)..
80. Kondratiev, V.N., Rate Constants of Gas Phase Reactions, translated by Holtsling, National Bureau of Standards, 1972.
81. Igoshin, V.I., "Numerical Analysis of an HF-HCl Chemical Laser Utilizing the ClF + H₂ Chain Reaction", Kvantovaya Elektron, 6, 528-538, (Mar² 1979).
82. Fettis, G.C., Knox, J.N., Trotman-Dickerson A.F., "The transfer reactions of Halogen Atoms", Canadian Journal of Chemistry, 38, 1643-1647, (Oct 1960).
83. Suchard, S.H., Kerber, R.L., Emanuel, G., Whittier, I.S., "Effect of H₂ pressure on Pulsed H₂ + F₂ Laser. Experiment and Theory", Journal of Chemical Physics, 57, 5065-5075, (Dec 1972).
84. Mercer, P.D., and Protchard, H.O., "The Gas Phase Fluorination of Hydrogen-Methane Mixtures", Journal of Physical Chemistry, 63, 1468-1470, (Sep 1959).

85. Dodonov, A.F., Lavovskaya, G.K., Morozov, I. I., Blbright, R.I., Tal'roze, V.I., and Lyubimova, A.K., "Mass-spectrometric Measurements of the Rate Constant of Elementary Reactions of Hydrogen Atoms with Chlorine and Fluorine.", Kinetics and Catalysis, 1, 677-684.
86. Levy, J.B., and Copeland B.K.W., "The kinetics of the Hydrogen-Fluorine Reaction III. The Photochemical Reactions", Journal of Physical Chemistry, 72, 3168-3177, (Sep 1981).
87. Sarner, F.S., Propellant Chemistry, New York: Reinhold Publishing Corp, 1969, 119.
88. Guzov, I.P., Kormer, S.B., L'vov, L.V., Punin, V.T., Sinitsyn, H.V., Stankeev, E.A., and Urtin, V.D., "Measurements of the Recombination Constant of Atomic Fluorine", Soviet Journal of Quantum Electronics, 6, 1112-1119, (Sep 1976).
89. Modica, A.P., and Sillers, S.J., "Experimental and Theoretical Kinetics of High-Temperature Fluorocarbon Chemistry", Journal of Chemical Physics, 48, 3283-3289, (Apr 1968).
90. Bennet, J.E. and Blackmore D.R., "The measurement of the Rate of Recombination of Hydrogen Atoms at Room Temperature by Means of esr Spectroscopy", Proceedings of the Royal Physical Society A, 305, 553-574, (1968).
91. Jacobs, T.A., Giedt, R.R., and Cohen, N., "Kinetics of Decomposition of HF in Shock Waves", Journal of Chemical Physics, 43, 3688-3693, (Nov 1965).
92. Hancock, J.K., and Green W.H., "Vibrational Reactivation of HF in pure HF and in HF-Additive Mixtures", Journal of Chemical Physics, 57, 4525-4539, (Dec 1972).
93. Hinch J.J., "Vibrational Relaxation in Hydrogen and Deuterium Fluorides", Journal of Chemical Physics, 59, 233-240, (July 1973).
94. Quigly, G.P. and Wolga, G.J., "The deactivation of HF(1) and DF(1) by O, Cl, and F atoms", Journal of Chemical Physics, 63, 5263-5268, (Dec 1975).
95. Cohen, H., "A Review of Rate Coefficients for Reactions in the H₂-F₂ Laser System", TR-ol72(2279), 2 Sep 1973, The Aerospace Corporation, El Segundo, California.

Appendix A

Rate Constants for the $\text{SF}_6 + \text{H}_2$ /Electric Discharge Laser

Table V lists the reaction rate constants and characteristic times for the major reactions in the $\text{SF}_6 + \text{H}_2$, electric discharge laser of this investigation. The characteristic time for bimolecular reactions is given by

$$\tau = \frac{1}{k[M]} \quad (167)$$

and for three-body recombination as,

$$\tau = \frac{3.4}{k[M]^2} \quad (168)$$

These are the same characteristic times developed for the HF cold reaction (bimolecular) and the fluorine recombination (trimolecular) reaction in equations (59) and (55), respectively.

All rates and characteristic times will be evaluated at:

$$\begin{aligned} T &= 300^\circ\text{K} \\ T_e &= 25,500^\circ\text{K} \\ [\text{SF}_6] &= 4 \times 10^{-6} \text{ MOLES/CM}^3 & n_e &= 4 \times 10^{-11} \text{ MOLES/CM}^3 \\ [\text{H}_2] &= 1 \times 10^{-6} \text{ MOLES/CM}^3 \end{aligned}$$

All energies are in kcal/mole, temperature in $^\circ\text{K}$, concentrations in moles/cubic cm, and rate constants in units of cubic cm/mole sec, unless otherwise noted. The first rate coefficient listed for each reaction is the one used in the kinetic model and the calculation of HF power pulse shape, as given in Appendix B.

Table V
SF₆ + H₂ / Electric Discharge Rate Constants

Reaction	Rate Constant (K)	Time Constant (τ)	Reference
1. SF ₆ + e ⁻ → SF ₅ ⁻	$K = 2.32 \times 10^{16} \left(\frac{235.3}{T_e - 2287} \right)$		
	$= 2.4 \times 10^{14}$	$\tau = 1/K\eta_e = 95 \mu s$	[32]
	Calculated from experiment of [77]. P=100 torr; E/N=10 ¹⁷ V/cm ²		
	$K = 3.35 \times 10^{14}$		[33]
2. SF ₆ + e ⁻ → SF ₅ ⁻ + F	P=.1 - 1.5 torr; Helium Buffer; Electron Beam		
	$K = (5.081 - 7.093 \times 10^{-4} T_e + 3.253 \times 10^{-9} T_e^2 - 1.826 \times 10^{-14} T_e^3) \times 10^{14}$		
	$= 2.4 \times 10^{14}$	$\tau = 1/K\eta_e = 95 \mu s$	[32]
	Calculated from experiment of reference [78].		
3. SF ₆ + e ⁻ → SF ₅ ⁺ + F + e ⁻	$K = 2.2 \times 10^{12}$		[33]
	P=.1 - 1.5 torr; Helium Buffer; Electron Beam		
	$K = 5.55 \times 10^{16} e^{-236850/T_e}$		
	$= 5.1 \times 10^{12}$	$\tau = 1/K\eta_e = 4.5 ns$	[32]
4. SF ₆ + e ⁻ → SF ₅ ⁻ + F + e ⁻	$K = 1.12 \times 10^{15} e^{-56400/T_e}$		
	$= 1.2 \times 10^{14}$	$\tau = 1/K\eta_e = 189 \mu s$	[32]
	Calculated from experiment of [74]. P=10 ⁻⁶ torr.		

Table V
SF₆ + H₂ / Electric Discharge Rate Constants
(Continued)

Reaction	Rate Constant (k)	Time Constant (τ)	Reference
5. SF ₆ + e ⁻ → SF ₅ + F ⁻	$k = 2.32 \times 10^{13} \left(\frac{256.3}{T - 2287} \right)$ $= 2.4 \times 10^{12}$	τ = 1/k _{ne} = 9.5 ms	[22]
6. H ₂ + e ⁻ → H + H + e ⁻	$k = 10^{16} e^{-100,000/T_e}$	τ = 1/k _{ne} = 115 μs	[32]
7. H + e ⁻ → H ⁺ + e ⁻ + e ⁻	$k = 1.90 \times 10^{14}$ $k = 1.11 \times 10^{16} e^{-182,588/T_e}$	τ = 1/k _{ne} = 2.6 ms	[32]
8. H ₂ + e ⁻ → H ₂ ⁺ + e ⁻ + e ⁻	$k = 2.5 \times 10^{12}$ $k = 10^{16} e^{-195,000/T_e}$ $= 4.8 \times 10^{12}$	τ = 1/k _{ne} = 4.8 ms	[32]
9. SF ₆ + H → SF ₅ + HF(0)	$k = 2 \times 10^{15} e^{-30,187/T}$ $= 3.9 \times 10^{-7}$ $k = 2. \times 10^{16} e^{-30 \pm 5 / RT}$ $= 5.9 \times 10^{-7}$	τ = 1/k _H ≫ 1/s	[32] [37]
10. SF ₆ + M → SF ₅ + F + M	$k = P \left(8 \pi R T \left(\frac{1}{M} + \frac{1}{M_M} \right) \right)^{1/2} \times \sigma_{ab} e^{-E_a / RT}$ $\approx 1.05 \times 10^{-11}$ (E _a = 76 kcal/mole)	τ = 1/k _M ≫ 1/s	
11. SF ₅ + M → SF ₄ + F + M	$k = P \left(8 \pi R T \left(\frac{1}{M} + \frac{1}{M_M} \right) \right)^{1/2} \times \sigma_{ab} e^{-E_a / RT}$ $\approx 1.8 \times 10^{-34}$ (E _a = 66 kcal/mole)	τ = 1/k _M ≫ 1/s	

Table V
SF₆ + H₂ / Electric Discharge Rate Constants
(Continued)

Reaction	Rate Constant (K)	Time Constant (T)	Reference
12. H ₂ + M → H + H + M	$k = \frac{P}{8\pi RT} \left(\frac{1}{M_1} + \frac{1}{M_2} \right)^{1/2} \times \frac{1}{v_{0.0}} e^{-E_a/RT}$ $= 1.9 \times 10^{-12}$	T = 1/k M > 77°K	[27], [95]
13. F + H ₂ → HF(v) + H	$K(v=0) = 1.2 \times 10^{13} \times 10^{-360/T}$ $= 3.7 \times 10^{12}$ $K(v=1) = 2.4 \times 10^{13} \times 10^{-360/T}$ $= 7.5 \times 10^{12}$ $K(v=2) = 8.2 \times 10^{13} \times 10^{-360/T}$ $= 2.5 \times 10^{13}$ $K(v=3) = 4.1 \times 10^{13} \times 10^{-360/T}$ $= 1.3 \times 10^{13}$ $K = \sum_v K(v) = 1.2 \times 10^{14} e^{-(1.7 \pm 0.2)/RT}$ $= 6.93 \times 10^{12}$ $K = 1.42 \times 10^{11} e^{-1.6/RT}$ $= 1.11 \times 10^{13}$ $K = 10^{14} e^{-1.7/RT}$ $= 5.67 \times 10^{12}$ $K(0) : K(1) : K(2) : K(3) = 15:3:1:5$ $K(0) : K(1) : K(2) : K(3) = 15:26:1:5$ $K(v=1) = 3.7 \times 10^{13} e^{1.6/RT}$ $K(v=2) = 3.26 K(v=1)$ $K(v=3) = 1.63 K(v=1)$		
		T = 1/k H ₂ = 200 ns	[80]
			[31]
			[82]
			[12]
			[27]
			[83], [95]

Table V
SF₆ + H₂ / Electric Discharge Rate Constants
(Continued)

Reaction	Rate Constant (K)	Time Constant (T)	Reference
14. H + F ₂ → HF(v) + H	$k = (2.5 \pm 1.5) \times 10^{10} e^{-(2.4 \pm 0.1)RT}$ $\times (4.02 \times 10^{13})$ $= 9.2 \times 10^{12}$ $k = 1.8 \times 10^{12}$, $E_a = 15 \text{ kcal/mol}$ $k = 1.58 \times 10^{12}$ $k = 10^{13.48} e^{-4.2/RT}$ $= 2.75 \times 10^{10}$ $k = 10^{12.72} T^{1/2} e^{-4/RT}$ $= 6.25 \times 10^{12}$ $k = (1.1 - 3.7) \times 10^{12}$	$\tau = 1/k F_2 > 109 \text{ ns}$	[85] [86] [80] [80] [80] [12:59]
15. H + F + M → HF + M	$k = 10^{15.69} e^{-3.05/RT}$ $= 2.9 \times 10^{13}$ $k = 10^{15.03} T^{1/2}$ $= 1.8 \times 10^{16}$ $k = 7.5 \times 10^{18} T^{-1}$ $= 2.5 \times 10^{16}$ $k = 10^{18} T^{-1}$ $= 3.3 \times 10^{15}$	$\tau = \frac{3.4}{k F M} > 20 \mu\text{s}$	[80] [80] [87] [81]

Table v

130

Table V
SF₆ + H₂ / Electric Discharge Rate Constants
(Continued)

Reaction	Rate Constant (K)	Time Constant (T)	Reference
b. M ₉ = HF	$K = 6.41 \times 10^{-7} \text{ s}^{-1} \text{ cm}^{-3} \text{ g}^{-1} \text{ at } T$ $= 4.23 \times 10^{-7}$		[83]
	$K = 7.6 \times 10^{-4} \text{ s}^{-1} \text{ cm}^{-3} \text{ g}^{-1}$ $= 7.6 \times 10^{-4}$		[12]
	$K = 5.98 \times 10^{-7}$		[92]
	$K = 5.96 \times 10^{-7}$		[93]
	$K = 1.13 \times 10^{-13} \text{ s}^{-1} \text{ cm}^{-3} \text{ g}^{-1}$ $= 1.13 \times 10^{-13}$		
	$K = 1.13 \times 10^{-13} \text{ s}^{-1} \text{ cm}^{-3} \text{ g}^{-1}$ $= 1.13 \times 10^{-13}$	$T = \frac{1}{K_{HF}} > 1 \mu\text{s}$	[32]
	$K = 5 \times 10^{-7} \text{ s}^{-1} \text{ cm}^{-3} \text{ g}^{-1} \text{ at } T^{1.5}$ $= 7.8 \times 10^{-11} \text{ (} T=1 \text{)}$		[83]
	$K = 1.5 \times 10^{-8}$		[93]
	$K = 1.16 \times 10^{-8}$		[92]
	$K = 1.31 \times 10^{-8}$		[94]
c. M ₉ = F	$K = 1.5 \times 10^{-10} \text{ s}^{-1} \text{ cm}^{-3} \text{ g}^{-1}$ $= 4.5 \times 10^{-12}$	$T \geq 200 \text{ ns}$	[83]
	$K = 1.5 \times 10^{-10} \text{ s}^{-1} \text{ cm}^{-3} \text{ g}^{-1}$ $= 2.4 \times 10^{-9}$		[32]

Table V
SF₆ + H₂ / Electric Discharge Rate Constants
(Continued)

Reaction	Rate Constant (K)	Time Constant (T)	Reference
19 d. $M = SF_6$ e. $M = H$	$K = v(5.45 \times 10^{-11}) T^{4.056}$ $= 6.1 \times 10^{-6} (v)$ $K = f(1.7 \times 10^{-11}) T^{13.9} T^{-0.08}$ $= 1.6 \times 10^{-13} (f(v) \sim 1)$ $f(3.0) = .95$ $f(2.0) = .73$ $f(3.1) = .73$ $f(2.1) = .51$ $f(3.2) = .62$ $f(4.0) = .53$ $K = 1.33 \times 10^{-18} T^{-1} e^{-0.35(4.5 - T)}$ $\sim 10^{-83}$	$T = \frac{1}{K SF_6} = 16.5 \text{ ms}$ $T = \frac{1}{K H} = 62 \text{ ns}$	[32]
20. $H + F + M \rightarrow H + F + M$		$T \gg \gg 1 \text{ s}$	[32]
21. $H + F(v) + H + F(v') \rightarrow$ $H + F(v-1) + H + F(v+1)$	$K = v(v+2) 5 \times 10^{-7} T^{1.5}$ $= 7.8 \times 10^{-11} (v=1)$ $K = 1.6 \times 10^{-15} v'(v+1) \frac{1}{T}$ $= 10^{-13}$	$T \approx \frac{1}{K H} > 1.3 \mu \text{ s}$	[32]
22. $H + F(v) + H_2(v') \rightarrow$ $H + F(v+1) + H_2(v'-1)$	$K = 10^6 T^{1.5}$ $= 5.2 \times 10^9$ $K = 10^8 T^{1.5}$ $= 5.2 \times 10^{11}$	$T = \frac{1}{K H_2} = 2 \mu \text{ s}$	[32]
			[83]

Table V
 $\text{SF}_6 + \text{H}_2$ / Electric Discharge Rate Constants
 (Continued)

Reaction	Rate Constant (K)	Time Constant (T)	Reference
23. $\text{A}^- + \text{B} \rightarrow \text{A} + \text{B}^-$ $\text{A}^+ + \text{B} \rightarrow \text{A} + \text{B}^+$	$K \sim 1.0 \times 10^{-14} \sqrt{T^{1/2}}$ $\sim 2.6 \times 10^{-16}$	$Z \approx 20 \text{ ns}$	[32]

Appendix B

Numerical Solution of the HF Laser Kinetic Model Equations

The set of differential equations modeling the $SF_6 + H_2$ in the electric discharge are as presented on page 26:

$$\frac{d[SF_6]}{dt} = -(K_1 + K_2 + K_3 + K_4 + K_5) n_e [SF_6] \quad (75)$$

$$\frac{d[H_2]}{dt} = -K_6 n_e [H_2] - \sum_U K_{10}(U) [F] [H_2] \quad (76)$$

$$\frac{d[H]}{dt} = 2K_6 [H_2] n_e - K_8 n_e [H] + \sum_U K_{10}(U) [F] [H_2] \quad (77)$$

$$\frac{d[F]}{dt} = +(K_2 + K_3 + K_4) n_e [SF_6] + \sum_M K_9(M) [F] [M] - \sum_U K_{10}(U) [F] [H_2] \quad (78)$$

$$\frac{d[F^*]}{dt} = +K_5 n_e [SF_6] - \sum_M K_9(M) [M] [F^*] \quad (79)$$

$$\begin{aligned} \frac{d[HF(U)]}{dt} = & +K_{10}(U) [F] [H_2] - K_{11}(U) [HF(U)] [F] \\ & + K_{11}(U+1) [HF(U+1)] [F] - \sum_{U' < U} K_{12}(U, U') [HF(U)] [H] + \sum_{U' > U} K_{12}(U, U') [H] [HF(U')] \end{aligned} \quad (80)$$

with the initial conditions

$$[H] = [F] = [F^*] = [HF] = 0 \quad [SF_6] = 4[H_2] = 4 \times 10^{-6} \frac{MOL}{CM^3} \quad (81)$$

The current forcing function is

$$n_e = \frac{1}{e} \int_{t_1}^{t_2} i(t) dt \quad (82)$$

Equation (82) is approximated by

$$n_e = \frac{1}{e} \left(\frac{i(t_1) + i(t_2)}{2} \right) \Delta t \quad \Delta t = 20 ns \quad (169)$$

The current, $i(t)$, is obtained from the pulse shape for current as observed by Raytheon and shown in figure 56.

The results of applying equation (169) to the pulse shape of figure 56 are presented in Table VI.

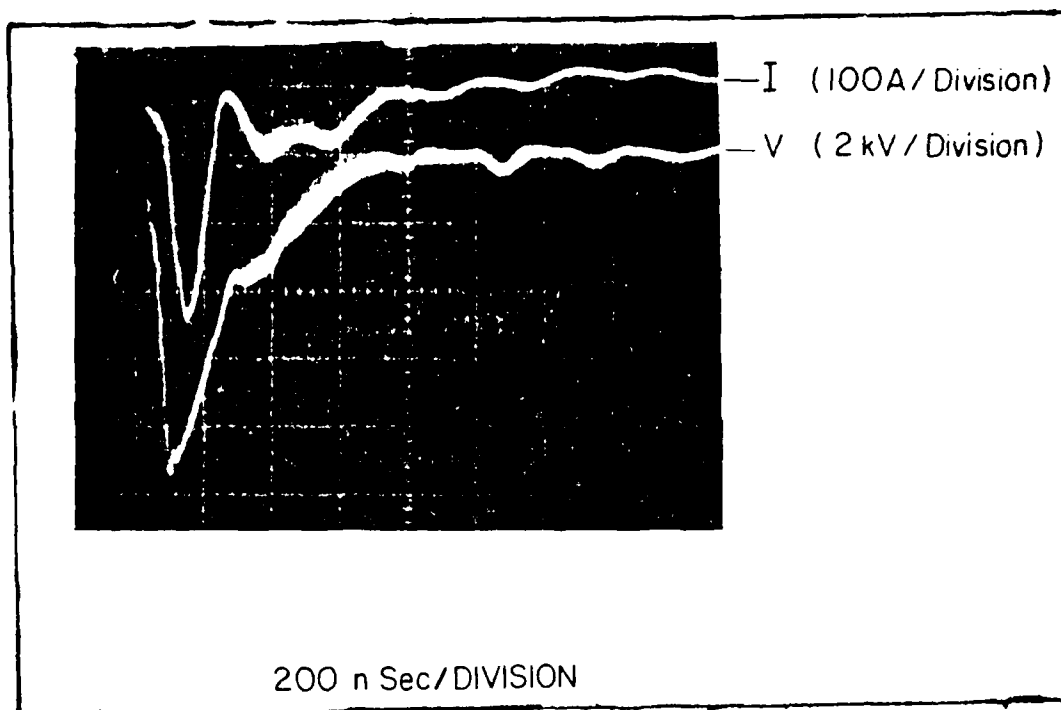


Figure 56.

Discharge Current Pulse Shape

Equation (75) can be solved directly,

$$\frac{dSF_6}{dt} = -\left(\sum_i^5 K_i\right) \eta_e(t) dt \quad (75)$$

$$SF_6(t) = SF_6(0) \exp\left[-\sum_i^5 K_i \int_0^t \eta_e(t) dt\right] \quad (170)$$

$$\sum_i^5 K_i = 6.1 \times 10^{14} \frac{\text{CM}^3}{\text{MOLE-S}} \quad (171)$$

From Table VI, $\eta_e \sim 10^{-13} \frac{\text{MOL}}{\text{CM}^3}$ and $\Delta t = 20 \text{ nS}$, and the argument of the exponent is of the order 10^{-6} . Therefore,

$$SF_6(t) = SF_6(0) \quad (172)$$

is a very good approximation for the times of interest.

Equation (79) can now be solved directly, with the use of equation (172):

$$\frac{dF^-}{dt} + \sum_M K_9(M) MF^- = K_3 SF_6 \eta_e(t) \quad (173)$$

$$\sum_M K_9(M) M \approx K_9(M^*) \sum M = K_9' \quad (174)$$

$$\frac{dF^-}{dt} + K_9' F^- = K_3 S F_6 \eta_e(t) \quad (175)$$

Using an integrating factor of $S = e^{K_9' t}$ yields,

$$F^-(t) = e^{-K_9' t} \int K_3 S F_6(0) \eta_e(t) e^{K_9' t} dt \quad (176)$$

To evaluate this expression with a discrete summation approximation is difficult because the argument of the exponent is very large, $K_9' t \sim 10^4$. Therefore, the following technique is adopted. Let

$$\eta_e(t) = \sum_0^{\infty} a_i t^i \quad (177)$$

with the initial condition, $\eta_e(0) = 0$, gives

$$\eta_e(t) = \sum_1^{\infty} a_i t^i \quad (178)$$

Then,

$$\begin{aligned} F^-(t) &= K_3 S F_6(0) e^{-K_9' t} \sum_1^{\infty} a_i \int t^i e^{K_9' t} dt \\ &= K_3 S F_6(0) \sum_{i=1}^{\infty} \left[a_i \left(\sum_{r=0}^i (-1)^r \frac{i! t^{i-r}}{(i-r)! K_9'^{i-r+1}} \right) \right] \\ &= \frac{K_3}{K_9'} S F_6(0) \left[a_1 \left(1 - \frac{1}{K_9' t} \right) + a_2 \left(1 - \frac{2}{K_9' t} + \frac{2}{(K_9' t)^2} \right) t^2 + \dots \right] \\ &= \frac{K_3}{K_9'} S F_6(0) \left[\sum_1^{\infty} a_i t^i + O\left(\frac{1}{K_9' t}\right) \right] \end{aligned} \quad (179)$$

But, $\frac{1}{K_9' t} \leq 10^{-4}$, even at times of 20 nsec. Then,

$$F^-(t) \approx \frac{K_3}{K_9'} S F_6(0) \eta_e(t) \quad (180)$$

From Appendix A,

$$K_9' = 1.3 \times 10^{11} \text{ } 1/\text{s} \quad K_3 = 5.1 \times 10^{12} \frac{\text{CM}^3}{\text{MOLE} \cdot \text{s}} \quad S F_6(0) = 4 \times 10^{-6} \frac{\text{MOLE}}{\text{CM}^3} \quad (181)$$

And finally,

$$\bar{F}(t) = 3.9 \times 10^{-4} n_e(t) \quad (182)$$

Equations (76) - (78) do not depend on the solution of equation (80) and may be solved independantly. A step-by-step numerical integration will be used to evaluate these functions of time. With this numerical approximation, the system of equation (76) - (78) become

$$\Delta \bar{X}_1 = (\kappa_6 X_1 n_e(t) + \kappa'_{10} X_1 X_3) \Delta t \quad (183)$$

$$\Delta \bar{X}_2 = (2\kappa_6 X_1 n_e(t) - \kappa_8 X_2 n_e(t) + \kappa'_{10} X_1 X_3) \Delta t$$

$$\Delta \bar{X}_3 = (\kappa^2_{SF}(0) n_e(t) + \kappa'_9 (3.9 \times 10^{-4}) n_e(t) - \kappa'_{10} X_1 X_2) \Delta t \quad (184)$$

$$\quad \quad \quad (185)$$

Where

$$X_1 = [H_2] \quad X_2 = [H] \quad X_3 = [F]$$

$$\kappa'_{10} = \sum_{v=0}^3 \kappa_{10}(v) \quad \kappa^2 = \kappa_2 + \kappa_3 + \kappa_4$$

$$\Delta t = 20 \text{ ns} \quad X_1(0) = 10^{-6} \text{ MOLE/CM}^3$$

$$X_2(0) = X_3(0) = 0$$

This system was evaluated in a step by step fashion with the 20 ns time interval on a HP-25 programmable calculator. The results are presented in table VII.

The remaining equations to be solved are those for the population of HF vibrational energy levels from equation (80). For the $v=2$ to $v=1$ transition, it is not important to consider the $v=0$ level. Again, a step-by-step integration of the equations given by (80) yields the following system of equation. The system was solved, again using the HP-25 calculator with a step interval of 20 nsec. A table of the concentrations of HF(v) and of the population inversion

is presented in table VIII. These results are then used to calculate and plot the power pulse shape given in the main text in figure 3.

Table VI
Electron Number Density

Time (nsec)	Current (Amps)	$n_e(t)$ ($2.08 \times 10^{-13} \frac{\text{MOLE}}{\text{CM}^3}$)
0	0	1.25
20	20	3.13
40	30	4.38
60	40	6.25
80	60	13.75
100	160	28.75
120	300	39.00
140	325	40.00
160	315	36.56
180	270	29.38
200	200	18.75
220	100	10.00
240	60	4.38
260	10	0.63
280	0	1.25
300	20	3.75
320	40	6.88
340	70	9.38
360	80	10.63
380	90	10.94
400	85	10.31
440	75	9.06
480	65	7.81

Table VII
Hydrogen and Fluorine Concentrations

Time (nsec)	$[H_2] (10^{11} \frac{MOLE}{CM^3})$	$[H] (10^{11} \frac{MOLE}{CM^3})$	$[F] (10^{11} \frac{MOLE}{CM^3})$
20	10.0	.62	1.87
40	10.0	2.49	6.15
60	10.0	5.72	11.4
80	10.0	10.8	18.2
100	10.0	20.7	34.8
120	10.0	40.9	70.2
140	9.99	72.3	113.
160	9.99	112.0	148.
180	9.99	155.	170.
200	9.98	199.	177.
220	9.98	238.	166.
240	9.97	272.	145.
260	9.97	299.	120.
280	9.97	320.	94.
300	9.97	336.	75.
320	9.97	351.	64.
340	9.97	366.	61.
360	9.96	381.	61.

Table VIII

HF Concentration and Population Inversion

Time (nsec)	HF(1) 10^{12} MOL/CM ³	HF(2) 10^{12} MOL/CM ³	HF(3) 10^{12} MOL/CM ³	HF(2)-HF(1) 10^{12} MOL/CM ³
20	2.80	9.54	4.78	6.74
40	9.19	31.4	15.7	22.2
60	17.0	58.1	29.1	41.1
80	27.2	92.8	46.5	65.6
100	52.0	177.	88.8	125.
120	105.	358.	179.	253.
140	169.	567.	288.	398.
160	221.	754.	377.	533.
180	254.	865.	432.	611.
200	264.	899.	449.	635.
220	248.	841.	419.	593.
240	216.	732.	364.	516.
260	179.	604.	299.	425.
280	140.	470.	232.	330.
300	111.	373.	182.	262.
320	94.8	316.	153.	221.
340	90.4	300.	145.	210.
360	90.2	299.	144.	209.

Appendix C

HF Laser Operating Instructions

This appendix lists the HF laser turn-on procedure used in this study. The procedure differs from that of reference [3:84-89], due to the modifications made to the laser. The starred entries note changes and/or additions to the operating procedure dictated by these modifications.

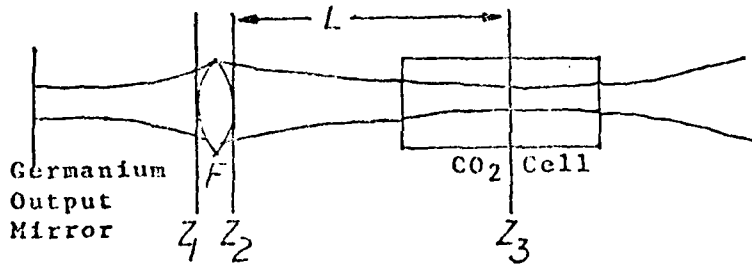
- * (1) Turn on the 400 cycle power generator
- * (2) Turn on the red warning light (outside lab door) on
- * (3) Turn room exhaust fan on
- * (4) Turn roof fan for vacuum pump and the vacuum pump on
- (5) Turn the chilled water supply on
- * (6) Turn the two pulse generators and their power amp on
- * (7) Turn on Boxcar Integrator #3 and establish triggering.
- (8) Turn on Voltage Doubler Fan and Fluid Cooling Pump
- * (9) Ground the TM 30 wire wound resistor, momentarily
- (10) Turn reservoir heater on, 75%. WAIT 5 MINUTES.
- * (11) Turn TM 30 unit on
- * (12) Turn gas detector on
- * (13) Check the gas pressure in the HF laser, (Approx 1 torr).
- * (14) Turn the HV DC 220 Voltage-Single Phase circuit breaker on
- (15) Open the SF₆ and H₂ gas bottles and main gas line valves
- (16) Let SF₆, and then H₂ gas, into the cavity; select mixture
- * (17) Adjust the By-Pass valve for the desired pressure
- (18) At 60 torr or better, turn on the gas recirculating fans
- * (19) Set reservoir setting at 85 - 90 %
- (20) Turn the HV DC supply on and raise voltage to desired level.
- * (21) Check for discharge, power pulse.

The laser turn off procedure is the reverse of the above listed procedure.

Appendix D

HF Beam Propagation

The theory of gaussian beam propagation will be used to calculate the beam spot size as a function of axial distance for two different focusing lenses. The following model is used:



At Z_1 , $W=W_1$ and $R=R_1$. From the results of the beam divergence experiments, $W_1 = 6\text{mm}$, $R_1 = 95.3\text{cm}$. The focusing lens is $F_1=25\text{cm}$ or $F_2=50\text{cm}$.

For a thin lens,

$$\frac{1}{Q_2} = \frac{1}{Q_1} + \frac{1}{F} \quad (186)$$

where

$$\frac{1}{Q(Z)} = \frac{1}{R(Z)} - \frac{i\lambda}{\pi W^2(Z)} \quad (187)$$

Then

$$\frac{1}{R_2} - \frac{i\lambda}{\pi W_2^2} = \left(\frac{1}{R_1} - \frac{1}{F} \right) - \frac{i\lambda}{\pi W_1^2} \quad (188)$$

and equating the real and imaginary parts of equation (188)

$$\frac{1}{R_2} = \frac{1}{R_1} - \frac{1}{F} \quad \text{and} \quad W_2 = W_1 \quad (189)$$

Translating the beam through the distance L to Z_3 :

$$Q_3 = Q_2 + L \quad (190)$$

But,

$$Q_2 = \frac{1}{\left(\frac{1}{R_1} - \frac{1}{F}\right) - \frac{i\lambda}{\pi\omega_1^2}} = \frac{R_1 F \pi \omega_1^2}{\pi \omega_1^2 (F - R_1) - i\lambda R_1 F} \quad (191)$$

And thus,

$$Q_3 = Q_2 + L = \frac{R_1 F \pi \omega_1^2 + L (F - R_1) \pi \omega_1^2 - i\lambda R_1 F L}{\pi \omega_1^2 (F - R_1) - i\lambda R_1 F} \quad (192)$$

or,

$$\frac{1}{Q_3} = \frac{\pi \omega_1^2 (F - R_1) - i\lambda}{\pi \omega_1^2 (R_1 F + L F - R_1 L) - i\lambda R_1 F L} \quad (193)$$

Equation (193) can be rewritten as

$$\frac{1}{Q_3} = \frac{(F - R_1) R_1 F + L (F - R_1) + \lambda \frac{R_1 F L}{\pi \omega_1^2}}{(R_1 F + L F - R_1 L)^2 + \left(\lambda \frac{R_1 F L}{\pi \omega_1^2}\right)^2} + i \frac{\left(\lambda \frac{R_1 F}{\pi \omega_1^2} - \right) R_1 F}{(R_1 F + L F - R_1 L)^2 + \left(\lambda \frac{R_1 F L}{\pi \omega_1^2}\right)^2} \quad (194)$$

From equation (186)

$$\frac{1}{Q_3} = \frac{1}{R_3} - i \frac{\lambda}{\pi \omega_3^2} \quad (195)$$

Define the position, L , by Z specifying the beam waist.

Then,

$$\frac{1}{R_3} \rightarrow 0 \quad \omega_3 \rightarrow \omega_0 \quad (196)$$

Equating the real parts of equation (194) and (195) yields

$$L = -(F - R_1) R_1 F \left[\left(\lambda \frac{R_1 F}{\pi \omega_1^2} \right)^2 + (F - R_1)^2 \right] \quad (197)$$

Equating the imaginary parts of equations (194) and (195)

yields

$$\frac{i\lambda}{\pi \omega_0^2} = i \frac{\left(\lambda \frac{R_1 F}{\pi \omega_1^2} \right) R_1 F}{(R_1 F + L F - R_1 L)^2 + \left(\lambda \frac{R_1 F L}{\pi \omega_1^2} \right)^2} \quad (198)$$

Or, simplifying equation (198),

$$\omega_0 = \omega_1 \left[\frac{(R_1 F + L F - R_1 L)^2 + \left(\lambda \frac{R_1 F L}{\pi \omega_1^2} \right)^2}{(R_1 F)^2} \right]^{1/2} \quad (199)$$

Now, substitute equation (197) into equation (199).

After simplification,

$$\omega_0 = \omega_1 \left[\frac{(\lambda \frac{R_1 F}{\pi \omega_1^2})^2}{[(\lambda \frac{R_1 F}{\pi \omega_1^2})^2 + (R_1 - F)^2]^{\frac{1}{2}}} \right] \quad (200)$$

For the initial values of R_1 and ω_1 quoted in the first paragraph,

$$\left(\lambda \frac{R_1 F}{\pi \omega_1^2} \right)^2 = .58 \text{ AND } 1.16 \quad (201)$$

for $F=25 \text{ CM}$ and $F=50 \text{ CM}$, respectively.

Since,

$$\lambda \frac{R_1 F}{\pi \omega_1^2} \ll R_1 - F \quad (202)$$

$$\omega_0 \approx \omega_1 \left(\frac{\lambda \frac{R_1 F}{\pi \omega_1^2}}{R_1 - F} \right) = \frac{\lambda}{\pi \omega_1} \frac{R_1 F}{R_1 - F} \quad (203)$$

and

$$\omega_0 = 7.4 \times 10^{-5} \text{ CM AND } 3.4 \times 10^{-4} \text{ CM} \quad (204)$$

for $F=25 \text{ CM}$ and 50 CM , respectively.

From equation (197), the value of L is 339 CM or 105.2 CM for $F=25 \text{ CM}$ and $F=50 \text{ CM}$ focal lengths.

Equation (199) can be used to obtain the spot size at

$Z = L \pm 20 \text{ CM}$,

$$\omega_3 \approx \omega_1 \left(\frac{R_1 F + \lambda F - R_1 \lambda}{R_1 F} \right) = \omega_1 \left(1 + L \left(\frac{1}{R_1} - \frac{1}{F} \right) \right) \quad (205)$$

For $F=25 \text{ CM}$, $\omega_3 = 3.5 \text{ mm}$ and for $F=50 \text{ CM}$, $\omega_3 = 1.1 \text{ mm}$, at the ends of the CO_2 cell, if the cell is centered at the beam waist, $Z=339 \text{ CM}$ and 105.2 CM , respectively.

The location, $L=105.2\text{CM}$, is rather large for the laboratory and the beam size of 0.35mm at the ends of the CO_2 should be satisfactory. Thus, the $F=23\text{CM}$ focal length lens will be used to focus the HF beam into the CO_2 cavity.

VITA

Glen Paul Perram was born on 6 May 1958 in Phoenix, Arizona. He graduated from Westland High School in Columbus, Ohio in 1976 and attended the School of Engineering, Cornell University, from which he received the degree of Bachelor of Science, with distinction, in May 1980. Upon graduation, he received a commission in the USAF as a distinguished graduate of the AFROTC program and entered the School of Engineering, Air Force Institute of Technology in June 1981.

Permanent Address: 331 King Edward West
Columbus, Ohio 43228

REPORT DOCUMENTATION PAGE		HEADLINE INFORMATION FOR THE CONTINUING FORM	
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. REPORT TYPE AND PERIODICITY	4. REPORT NUMBER
AD-A111 140		HS Thesis	
5. AUTHOR	6. CONTRACT OR GRANT NUMBER	7. PERFORMING ORGANIZATION NAME AND ADDRESS	8. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
Glen P. Perram 2Lt USAF		Air Force Institute of Technology Wright-Patterson AFB, OH 45433 AFIT/ENG	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. DISTRIBUTION STATEMENT (of this Report)	11. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)	12. DATE
	Approved for public release; distribution unlimited.		December 1981
13. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Agency)	14. NUMBER OF PAGES	15. PRICE (including GST, if applicable)	16. SECURITY CLASSIFICATION
	100		Unclassified
17. SUPPLEMENTARY NOTES	18. ABSTRACT (Continue on reverse side if necessary and identify by block number)		
Prepared in cooperation with the Avionics Laboratory, AFVAL, WPAFB, OH 45433 (Dr. W Schuebel and J. Brandelik/AADO/AFVAL).	Optical pumping of the $000 - (10^0)_H$ transition in $^{12}C^{18}O_2$ by the $P_2(6)$ transition of an $SF_6:H_2$ electric discharge HF chemical laser was used to establish a population inversion between the $(10^0)_H$ and $(10^0)_L$ levels of $^{12}C^{18}O_2$ and lasing at 4.3 microns. The HF pump laser was characterized and maximum power		

achieved at 795 SF₆/210 H₂, 82 torr total pressure, a 12 kV discharge voltage, and 500 pulses/sec. lasing on the P₂(4), P₂(1), and P₂(0) transitions was observed with a beam divergence of 0.6 rad. A pulse-to-pulse variation in output power of a factor of 10 and a frequency instability greater than 200 MHz/msec. was observed. A 106 micro-coul, 100 msec pulse was observed outline.

The P₂(1) 11.0 CO HF beam at 37.5 micro-J was coupled into a .5 inch diameter pyrex cell with 7 torr ¹²C¹⁸O₂ with a 25 cm focal length CaF₂ lens. A 26 msec CO₂ pulse was observed in the forward propagating direction. CO₂ lasing was erratic, due to near threshold pumping conditions.

A theoretical model of the kinetics of the SF₆ + H₂/electric discharge was established. Pulse widths predicted by this theory and those observed experimentally agree well. The predicted power amplitude is larger than observed, due to losses not included in the model.

The dependence of CO₂ output power on HF frequency was not observed experimentally. The contradiction between established theory and previous experimental results was explained, however.

END

DATE
FILMED

3-82

DTIC