EXPERIMENTAL INVESTIGATION OF THE PHYSICAL PROCESSES IN A MAGNETOHYDRODYNAMIC LASER

by

SURENDRA PRASAD SHARMA

S.B., University of Gorakhpur (1962)

S.M., People's Friendship University (1968)

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF SCIENCE

at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September, 1978

(C) Massachusetts Institute of Technology 1978

Signature of Author

Department of Aeronautics and Astronautics

August 11, 1978

Certified by

Thesis Supervisor

Certified by

Thesis Supervisor

Certified by

Thesis Supervisor

Accepted by

Chairman, Departmental Graduate Committee

ARCHIVES

MASSACHUSETTS INSTITUTE

OF TECHNOLOGY

OCT 13:10:0
EXPERIMENTAL INVESTIGATION OF THE PHYSICAL PROCESSES
IN A MAGNETOHYDRODYNAMIC LASER

by

SURENDRA PRASAD SHARMA

Submitted to the Department of
Aeronautics and Astronautics on August 11, 1978,
in partial fulfillment of the requirements for
the degree of Doctor of Science.

ABSTRACT

With the aid of a CO₂ probe laser the small signal gain of plasmas
with compositions typical of MHD lasers has been measured. The experimental facility designed for the purpose simulates the flow-induced
electric field and is operated in pulsed mode. The advantage of the
pulsed technique is that the very complex kinetic processes which occur
in the MHD laser plasma as it flows downstream in an actual laser, are
displayed as a transient in the pulsed experiment, vastly simplifying
the diagnostic problem.

At an average static pressure of 50 torr laser gain on the order of
0.15% cm⁻¹ to 0.32% cm⁻¹ has been measured. The investigation was
carried out over a wide variety of plasma compositions, and it was found
that an MHD laser with ≈1% CO₂ mole fraction and .001% Cs mole fraction in
the plasma would provide the maximum (as recorded in this study) small
signal gain. An estimate of extractable laser power indicates, however, that the CO₂ mole fraction in an MHD laser power system should
be higher than 1% to limit the bottlenecking effect caused by low relaxation rate of the lower laser level.

By monitoring the laser gain in the afterglow of the pulsed dis-
charge, an estimate of the relaxation rate constant for the lower laser
level has been made, which is in agreement with the values reported by
the experimental investigators and analysts, who subscribe to the idea of
a loose coupling between the lowest bending mode CO₂ (0₁¹₀) and the lower
laser level CO₂ (1₀⁰₀).

The pulsed mode operation allowed the measurement of the rate of
CO₂ - Cs chemical interaction.
In conclusion, it is felt that an MHD laser might be able to provide higher specific power than either gasdynamic or electric discharge lasers, at thermal to optical conversion efficiencies in the range of 2 to 3 percent.

Thesis Supervisor: Jack L. Kerrebrock
Title: Richard Cockburn Maclaurin Professor of Aeronautics and Astronautics

Thesis Supervisor: Shaoul Ezekiel
Title: Professor of Aeronautics and Astronautics, and Electrical Engineering

Thesis Supervisor: Manuel Martinez-Sanchez
Title: Assistant Professor of Aeronautics and Astronautics
ACKNOWLEDGEMENTS

I wish to express my deepest appreciation to Professor Jack Kerrebrock for his continuous guidance, for his great patience during many slow and frustrating period of equipment design and most of all for his sharing of his superb technical expertise in the field of physics of fluids. I consider myself very fortunate to have worked with him.

I am indebted to Dr. Albert Solbes for introducing me to the finer points of experimental physics and plasma dynamics. The informal discussions with Professor Manuel Martinez-Sanchez were always an enlightening experience and enriched my outlook as a young scientist. Besides his hectic schedule, Professor Shaoul Ezekiel was never too busy to spare a moment or an hour to resolve my problems in laser physics.

My fellow graduate student, Robert Walter, and I have spent many hours discussing the CO₂ laser kinetics and other aspects of the project.

My special thanks should go to Mrs. Gayle Ivey and Miss Nancy Ivey for their fast and excellent typing of this manuscript.
<table>
<thead>
<tr>
<th>Chapter No.</th>
<th>Topic</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction</td>
<td>15</td>
</tr>
<tr>
<td>1.1</td>
<td>MHD Laser Concept</td>
<td>15</td>
</tr>
<tr>
<td>1.2</td>
<td>Review of Previous Work</td>
<td>16</td>
</tr>
<tr>
<td>1.3</td>
<td>Summary of Results and Discussion</td>
<td>22</td>
</tr>
<tr>
<td>2</td>
<td>Physics of CO₂ Lasers</td>
<td>26</td>
</tr>
<tr>
<td>2.1</td>
<td>CO₂ Laser Kinetics</td>
<td>26</td>
</tr>
<tr>
<td>2.2</td>
<td>Electron Excitation in an MHD Laser</td>
<td>28</td>
</tr>
<tr>
<td>2.3</td>
<td>Relaxation Processes</td>
<td>32</td>
</tr>
<tr>
<td>3</td>
<td>Experimental Apparatus</td>
<td>37</td>
</tr>
<tr>
<td>3.1</td>
<td>The Pulsed Simulation Technique</td>
<td>37</td>
</tr>
<tr>
<td>3.2</td>
<td>Pulsed Flow System</td>
<td>37</td>
</tr>
<tr>
<td>3.3</td>
<td>Plasma Diagnostics</td>
<td>40</td>
</tr>
<tr>
<td>3.4</td>
<td>CO₂ Probe Laser</td>
<td>43</td>
</tr>
<tr>
<td>4</td>
<td>Experimental Results and Analysis of the Data</td>
<td>44</td>
</tr>
<tr>
<td>4.1</td>
<td>Calibration and Preliminary Tests</td>
<td>45</td>
</tr>
<tr>
<td>4.2</td>
<td>Measurements Without Magnetic Field</td>
<td>47</td>
</tr>
<tr>
<td>4.3</td>
<td>Measurements With Magnetic Field</td>
<td>58</td>
</tr>
<tr>
<td>4.4</td>
<td>Relaxation Rates for the Lower Laser Level</td>
<td>60</td>
</tr>
<tr>
<td>4.5</td>
<td>Rate of Cs-CO₂ Chemical Interaction</td>
<td>64</td>
</tr>
<tr>
<td>5</td>
<td>Discussion of Results</td>
<td>66</td>
</tr>
</tbody>
</table>
# TABLE OF CONTENTS (cont'd)

<table>
<thead>
<tr>
<th>Chapter No.</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>70</td>
</tr>
<tr>
<td>6.1 Power Extraction</td>
<td>77</td>
</tr>
<tr>
<td>6.2 Suggestions for Future Work</td>
<td>79</td>
</tr>
</tbody>
</table>

**Figures**

<table>
<thead>
<tr>
<th>Figures</th>
<th>Page No.</th>
</tr>
</thead>
</table>

**Appendices**

<table>
<thead>
<tr>
<th>Appendix</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>123</td>
</tr>
<tr>
<td>B</td>
<td>127</td>
</tr>
<tr>
<td>C</td>
<td>133</td>
</tr>
</tbody>
</table>

**References**

<table>
<thead>
<tr>
<th>References</th>
<th>Page No.</th>
</tr>
</thead>
</table>
LIST OF SYMBOLS

a    optical depth
a_{1}, a_{2}   mirror absorption coefficient
A    geometric area
A*    nozzle throat area
A_{ji}    Einstein coefficient for transition from j level to i level.
\bar{B}    magnetic induction
B_{\nu}    Einstein coefficient for alkali \(_{p_{3/2}}\) - \(_{s_{1/2}}\) transition
\bar{c}    speed of light
\bar{c}_{ij}    relation collision velocity between species i and j, averaged over the distribution function.
\bar{E}    electric field in gas frame
E_{j}    Energy density of \(^{j}\)th vibrational level of CO\(_{2}\) molecule
f_{j}    mole fraction of 'j' species
g(\nu)    line shape function
h    Plank's constant
I    optical intensity
I_{0}    output intensity
I_{s}    saturation optical intensity
I_{\nu}    intensity per unit wave length
J    rotational quantum number
\bar{J}    electric current density
J_{x}, J_{y}   x, y components of current density vector
$k$\quad$\text{Boltzmann constant}$

$k_{i-j}$\quad$\text{kinetic rate constant}$

$k_{\text{Total}}$\quad$\text{thermalization rate constant of CO}_2\text{ molecules with other neutral species}$

$k_{\nu}$\quad$\text{absorption coefficient of frequency } \nu$

$k_{\text{Rotational}}$\quad$\text{rate constant for thermalization of rotational levels in a given vibrational state}$

$L$\quad$\text{optical cavity length}$

$m_e$\quad$\text{mass of electron}$

$m_H$\quad$\text{mass of 'H' heavy neutral particle}$

$\dot{m}$\quad$\text{mass flow rate}$

$M_j$\quad$\text{molecular weight of 'j' species}$

$n$\quad$\text{index of refraction}$

$n_{\text{CO}_2}$\quad$\text{CO}_2\text{ number density}$

$n_{\text{He}}$\quad$\text{He number density}$

$n_e$\quad$\text{electron number density}$

$N_{1,N_{100}}$\quad$\text{lower laser level population}$

$N_{2,N_{001}}$\quad$\text{upper laser level population}$

$p$\quad$\text{pressure}$

$p_0$\quad$\text{stagnation pressure}$

$P_0$\quad$\text{optical output power}$

$Q_1$\quad$\text{cross section}$

$r_{1,2}$\quad$\text{mirror reflectivities}$

$R_{1,2}$\quad$\text{pumping rate of lower, upper laser levels}$
s  ratio of effective to average conductivity

t₁, t₂  mirror transmission coefficients

T  gas static temperature

Tₑ  electron temperature

Tₑ  rotational temperature

v  gas velocity

x  axial coordinate

y  transverse coordinate in electric field and optical axis direction

z  transverse coordinate in magnetic field direction
GREEK SYMBOLS

\( \alpha \)  \quad \text{optical gain}

\( \alpha_0 \)  \quad \text{small signal gain}

\( \beta \)  \quad \text{Hall parameter}

\( \langle \beta \rangle \)  \quad \text{average Hall parameter}

\( \beta_{\text{app}} \)  \quad \text{apparent Hall parameter}

\( \beta_{\text{crit}} \)  \quad \text{critical Hall parameter}

\( \beta_{\text{eff}} \)  \quad \text{effective Hall parameter}

\( \delta \)  \quad \text{loss parameter}

\( \delta_{\text{CO}_2} \)  \quad \text{inelastic loss parameter for CO}_2

\( \lambda \)  \quad \text{wave length}

\( \nu \)  \quad \text{frequency}

\( \nu_0 \)  \quad \text{laser transition frequency at line center}

\( \nu_j \)  \quad \text{characteristic vibrational frequency of 'j' vibration level}

\( \nu_e \)  \quad \text{collision frequency}

\( \Delta \nu \)  \quad \text{broadened line width}

\( \nu_e \)  \quad \text{electron collision frequency}

\( \rho \)  \quad \text{gas density}

\( \sigma \)  \quad \text{electical conductivity}

\( \langle \sigma \rangle \)  \quad \text{average conductivity}

\( \sigma_{\text{app}} \)  \quad \text{apparent conductivity}

\( \sigma_{\text{eff}} \)  \quad \text{effective conductivity}

\( \sigma_j \)  \quad \text{collision cross section}
$\tau_{e,j}$ relaxation time due to 'j' species

$\tau_{rad}$

$\tau_{spont}$ spontaneous decay time
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>CO$_2$ Energy Level Diagram</td>
<td>85</td>
</tr>
<tr>
<td>2.2</td>
<td>Electron Cross Section for Vibrational Excitation of CO$_2$ Molecules from Ref. 7</td>
<td>86</td>
</tr>
<tr>
<td>3.1</td>
<td>Gas Flow System</td>
<td>87</td>
</tr>
<tr>
<td>3.2</td>
<td>Quartz Discharge Tube</td>
<td>88</td>
</tr>
<tr>
<td>3.3</td>
<td>End Flange</td>
<td>89</td>
</tr>
<tr>
<td>3.4</td>
<td>Discharge Current Pulse</td>
<td>90</td>
</tr>
<tr>
<td>3.5</td>
<td>Magnet Cross Section</td>
<td>91</td>
</tr>
<tr>
<td>3.6</td>
<td>Magnetic Field Distribution in Discharge Region</td>
<td>92</td>
</tr>
<tr>
<td>3.7</td>
<td>Magnetic Current Pulse</td>
<td>93</td>
</tr>
<tr>
<td>3.8</td>
<td>Cs Diagnostic System</td>
<td>94</td>
</tr>
<tr>
<td>3.9</td>
<td>Cs Absorption Diagnostics Calibration Experiment</td>
<td>95</td>
</tr>
<tr>
<td>3.10</td>
<td>Calibration Curve for Cs Absorption Diagnostics</td>
<td>96</td>
</tr>
<tr>
<td>3.11</td>
<td>Typical Scope Trace of Pressure Pulse (Top Solid Curve) and Cs Absorption Diagnostics (Chopped Curve)</td>
<td>97</td>
</tr>
<tr>
<td>3.12</td>
<td>Arrangement To Measure Optical Gain - (Schematic)</td>
<td>98</td>
</tr>
<tr>
<td>3.13</td>
<td>Gain Measurement</td>
<td>99</td>
</tr>
<tr>
<td>3.14</td>
<td>Sequence of Events During a Test</td>
<td>100</td>
</tr>
<tr>
<td>4.1</td>
<td>Measurement of Signal to Noise Ratio</td>
<td>101</td>
</tr>
<tr>
<td>4.2</td>
<td>Current Probe Calibration</td>
<td>102</td>
</tr>
<tr>
<td>4.3</td>
<td>Typical Scope Traces</td>
<td>103</td>
</tr>
<tr>
<td>4.4</td>
<td>Gain and Current Density Time History</td>
<td>104</td>
</tr>
<tr>
<td>4.5</td>
<td>Gain and Current Density (Exp. 4120)</td>
<td>105</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page No.</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>4.6</td>
<td>Transient Behavior of Gain</td>
<td>106</td>
</tr>
<tr>
<td>4.7</td>
<td>Laser Gain vs Seed Mole Fraction; $B = 0$</td>
<td>107</td>
</tr>
<tr>
<td>4.8</td>
<td>Gain vs $CO_2$ Concentration</td>
<td>108</td>
</tr>
<tr>
<td>4.9</td>
<td>Gain and Current Density (Exp. 4163)</td>
<td>109</td>
</tr>
<tr>
<td>4.10</td>
<td>Gain and Current Density (Exp. 3050)</td>
<td>110</td>
</tr>
<tr>
<td>4.11</td>
<td>Gain vs B Field</td>
<td>111</td>
</tr>
<tr>
<td>4.12</td>
<td>Laser Gain vs Cs Mole Fraction; $B \neq 0$</td>
<td>112</td>
</tr>
<tr>
<td>4.13</td>
<td>Gain vs Average Hall Parameter</td>
<td>113</td>
</tr>
<tr>
<td>4.14</td>
<td>Gain vs Current Density, $f_{CO_2} = 0.74%, f_{Cs} = 10^{-5}$, $p = 42.0$ Torr</td>
<td>114</td>
</tr>
<tr>
<td>4.15</td>
<td>Gain vs Current Density</td>
<td>115</td>
</tr>
<tr>
<td>4.16</td>
<td>Dependence of Gain on Electrical Conductivity</td>
<td>116</td>
</tr>
<tr>
<td>4.17</td>
<td>Gain vs $f_{CO_2}^2 / f_{Cs}$ Ratio</td>
<td>117</td>
</tr>
<tr>
<td>4.18</td>
<td>Lower Laser Level Deactivation</td>
<td>118</td>
</tr>
<tr>
<td>4.19</td>
<td>Gain Saturation Test</td>
<td>119</td>
</tr>
<tr>
<td>5.1</td>
<td>Increase in Electron Temperature During the Experiment</td>
<td>120</td>
</tr>
<tr>
<td>6.1</td>
<td>Laser Output and Saturation Intensity</td>
<td>121</td>
</tr>
<tr>
<td>6.2</td>
<td>Specific Power of Various Laser Systems</td>
<td>122</td>
</tr>
<tr>
<td>6.3</td>
<td>Schematic of MHD Laser Configuration</td>
<td>123</td>
</tr>
</tbody>
</table>
1. Relaxation Rate for Various Energy Transfer Processes ........................................ 81
2. Summary of Reported Values of $\text{CO}_2(10^00) - \text{CO}_2(01^10)$ .......................... 82
   Relaxation Rates
3. Summary of Reported Values of $\text{CO}_2(10^00) - \text{CO}_2(20^00)$ ......................... 33
   Relaxation Rates
4. Important Features of Other Investigations ......................................................... 84
CHAPTER I
INTRODUCTION

1.1 MHD Laser Concept

The MHD laser is a non-equilibrium MHD generator in which the electron gas, one of the constituents of its characteristic two temperature plasma, is used to produce a population inversion in a molecular additive, such as CO₂. The Joule dissipation, which maintains the electron temperature well above that of the carrier gas, is a measure of the pumping power of the laser, and can be as large as 500 watts/cm³, which suggests the possibility of very high lasing power densities.

The device has several appealing features. As the electric power generated by the MHD process is delivered locally to the molecular gas, entirely within the flow, there is no need to take high electrical power out of the source, and in turn put it back into a gas discharge. This eliminates many uncertainties stemming from power conditioning and from electrode phenomena inherent to electric discharge lasers. Further, the high speed flow which appears to be essential for the removal of waste heat in high power lasers is an intrinsic feature of the MHD laser. The process for inversion production being essentially local, there is a chance of achieving more uniform gain, hence better beam quality than in externally excited devices. Unlike gasdynamic laser, the inversion may be extended to a much larger length along the
flow providing more active volume for power extraction, and hence higher output power per unit of mass flow, \(( > 12 \text{ KJ/kg})\).

The overall efficiency of MHD lasers as a device capable of converting thermal energy into optical energy has been placed by many estimates (7.12) between 2-3%, much higher than that of even second generation gasdynamic lasers. This value is competitive even with the \(\sim 10\%\) efficiency of electrical to optical conversion of gas discharge lasers (high power > 50 KW), when the efficiency of the electrical power system (thermal to electrical conversion and power conditioning) is taken into account.

Due to the above mentioned attractive features of MHD lasers several feasible studies have been undertaken over a period of almost a decade, but with controversial results.

1.2 Review of Previous Work

Successful operation of a non-equilibrium MHD generator depends upon minimizing electronic energy losses to the working fluid, which has therefore usually been selected from the monatomic gases. When molecules are added to the fluid for laser operation, a significant fraction of electronic energy is lost to the internal storage modes of the former, for example the loss factor \(\delta\) for \(\text{CO}_2\) is about 5000.0 compared to the loss factor of 2.0 for \(\text{He}\). Thus the addition of molecular species could impair the non-equilibrium heating of electrons. Since a selective excitation of laser levels is imperative for creation of an inversion, which in turn in the case of MHD lasers depends upon
the properties of the electron gas, a question is raised whether the non-equilibrium generator can serve as an effective laser pumping source.

In 1969 effects of molecular additives (CO, N₂) on non-equilibrium generator performance were studied by Kerrebrock and Draper¹⁻² using the MIT experimental generator. Excitation of vibrational levels to near equilibrium with the electron gas was achieved. In an He + Cs + CO plasma, CO (δ=460) mole fractions up to 0.2% did not make any noticeable change in the collisional losses and at electron temperatures above 2200⁰K T_vib. to T_e was achieved. As the mole fraction of the molecular gas was increased, the inelastic losses became effective and, as expected, a drop in electron temperature was observed, however, the equilibration of T_vib. to T_e were achieved even at mole fraction of 1%, provided the electron temperatures were close to 3000⁰K. With proper estimates of achievable electron temperature, the molecular mole fraction which may be permitted to be injected into a non-equilibrium generator without degrading its performance may be extrapolated to values as large as a few percent.

In years to follow several theoretical and experimental investigations were conducted. First experimental studies were performed at the United Aircraft Research Laboratories.⁶⁻⁸ In a supersonic MHD channel (velocity ~ 3000 m/sec) small signal gains up to 0.15% cm⁻¹ were measured, but efforts to extract optical power from an oscillator were inconclusive. It was mentioned that due to probably the decomposition of insulating material at high temperatures, the inversion was poisoned by foreign
organic compounds, and laser oscillations of even He + Ne mixture were not realized. The analytical model produced by the group assumed a fully turbulent plasma with respect to ionization instabilities. Also, the model utilized the CO\textsubscript{2} relaxation data available in 1970. It predicted that approximately 20% of the Joule dissipation power could be converted into optical power, with an overall thermal to optical conversion efficiency of about 5%.

Zauderer et al at the General Electric Company measured a relatively high small signal gain exceeding $0.2\text{cm}^{-1}$ using a mixture composed of 78% He, 18% Ar, and 4% CO\textsubscript{2} with either 3-5% Xe or 0.1% Cs. In these experiments external voltage augmentation was required to maintain the discharge. The author claimed that for the laser to work the CO\textsubscript{2} mole fraction must be much larger than the Cs mole fraction, if most of the CO\textsubscript{2} population were to be kept unreacted with Cs. However, the ratio $f\text{CO}_{2}/f\text{Cs}$ was only 40 compared to $\sim 3\times10^3$ as value quoted by other investigators.\textsuperscript{5-12} A light scattering measurement showed that the Cs concentration dropped by a factor of 5 to 7 due to CO\textsubscript{2}-Cs chemical reaction. No efforts to extract laser power were made.

In 1977 Biberman et al. at the Institute of High Temperatures of the USSR Academy of Sciences reported the results of both experimental and theoretical investigations of MHD lasers. A short-circuited segmented MHD channel with constant cross section was used in the experimental study and was operated in pulsed-mode. In a 4.0 tesla magnetic field self-sustained discharge was maintained in a laser mixture of 1% CO\textsubscript{2} + 0.001% Cs
in He at a pressure of 15 torr. In the MHD induced discharge mode laser oscillations were established and a laser power density of 10 KJ/kg was recorded. With the estimate of losses in the salt Brewster windows (due to pollution by Cs – CO) placed at ~ 20%, the small signal gain was computed to be ~ 0.3% cm$^{-1}$. Laser oscillations were not recorded in every experiment due to deterioration of the windows, and to avoid this problem the investigators substituted Xe as the seed and ran the tests in a supersonic channel. The discharge in this case was not self-sustained and an external voltage was required. The small signal gain was measured to be 0.35% cm$^{-1}$ (3% Xe and 6% CO$_2$) with power density falling in the same range as before (10kW/kg/sec).

In theoretical work of Biberman et al. it was assumed that, due to the Fermi-resonance, a strong coupling between the symmetric stretch mode and the bending mode existed. Based on the model gain and intracavity laser intensity was calculated, from which, if extrapolated, value of the saturation intensity at 125 torr pressure (1.4% CO$_2$) is found to be 6kW/cm$^2$.

At MIT over a period from 1969 to 1978 various aspects of MHD lasers were studied by several investigators.$^{4,12,71}$ Lcwenstein$^4$ while constructing a theoretical model of MHD laser plasmas investigated the effect of quenching of excited Cs atoms by CO$_2$ molecules on the laser performance. Mnatsakanyan$^3$ studied this quenching phenomenon for an N$_2$, A$_2$ and Cs plasma. His results indicate that a molecular mole fraction of less than one percent can be responsible for severe depopulation of the
excited bound states and hence cause a sharp decrease in the electron number density. Extending the work of Mnatsakanyan and Shaw, Lowenstein made an effort to calculate the effects of collisions with $\text{CO}_2$ on the bound state populations of Cs. The inelastic losses due to $\text{CO}_2 - \text{Cs}$ encounters tend to disturb the bound electron equilibrium distribution and the magnitude of this perturbation can be obtained by comparing the rate of depopulation of the first excited states of Cs by $\text{CO}_2 - \text{Cs}$ collisions with the rate of excitation of the first state by electrons. The balance between the depopulation rate and the excitation rate determines the number density of electrons. The "quenching section" which is required to compute the rate of depopulation of the first state by encounter with $\text{CO}_2$ molecules has never been measured. In his calculation Lowenstein assumed a value of 70 Å$^2$ which is very close to the value for Cs - $\text{N}_2$ quenching. The analysis indicated upper limit of allowable $\text{CO}_2$ mole fraction in the MHD laser $n_{\text{CO}_2}/n_e \leq 100$. He predicted that at a Cs mole fraction of 0.001% the maximum small signal gain (0.02%cm$^{-1}$) would occur at a $\text{CO}_2$ mole fraction of 0.22%, and at the electron temperature of 3200°K 7% of Joule dissipation may be converted into laser radiation.

Another aspect which was investigated by Lowenstein concerns the evolution of ionization instabilities in an MHD laser plasma. The study concluded that the radiation field does not have any significant effect on the instability, however, the latter's influence on the radiation field may lead to a serious problem of non-uniformities in the direction
transverse to the optical axis. However, since he assumes a constant temperature and pressure along the flow, and therefore his solution corresponds to conditions which would prevail at a single station along an MHD channel, the conclusion about the evolution of non-uniformities along the flow direction does not make much sense.

The important features of these studies have been summarized in Table 4. The results from the three investigations\textsuperscript{4,7,10} which were available in 1974 when this experimental investigation was undertaken at MIT presented a very controversial picture:

1) Recommended Cs mole fraction for the successful operation of an MHD laser varied by 2 orders of magnitude, from $10^{-3}$ to $10^{-5}$. Both experimental studies\textsuperscript{7,10} indicated loss of atomic Cs due to its chemical interaction with CO$_2$, whose nature and resultant products is to date not very much researched. Lowenstein's conclusions regarding the quenching phenomenon called for another look at the physics of the laser. Finally, it was speculated that the discrepancy in the Cs mole fraction could be due to poor diagnostics.

2) Nighan\textsuperscript{7} et al. calculated that large values of gain ($\gtrsim 0.5$-1\% cm$^{-1}$) can be produced, however, during the experimental investigation it was measured to be only 0.05-0.15\% cm$^{-1}$. Zauderer\textsuperscript{9,10} measured a value of 0.2\% cm$^{-1}$.

3) CO$_2$ mole fractions allowed ranged from 1-4\%, which were in direct violation of the theory proposed by Lowenstein.
At this point it was felt that a better understanding of MHD laser physics was required and accordingly the present investigation was undertaken. This dissertation describes the results of the experimental investigation. The results of the analytical study conducted by Walter are described in Ref. 12, and will be mentioned frequently in forthcoming sections.

1.3 Summary of Results and Discussion

In the present study a different approach to the experimental investigations of MHD laser was taken. Since the physical phenomena in such a device might be exceedingly complex, as the kinetic and thermochemical complexity of molecules excitation is added to the already intricate behavior of the electrothermally unstable non-equilibrium plasma, a pulsed experiemnt simulating the kinetic situation of an MHD laser was designed, which allowed us to uncouple the fluid dynamics and bulk plasma phenomena. A further advantage of the pulsed technique is that the very complex kinetic processes which occur in the plasma as it flows downstream in the actual laser, are displayed as a transient in the pulsed experiment, vastly simplifying the diagnostic problem.

The experiment is designed to measure the small signal gain in MHD laser plasmas. By varying the applied electric field and changing the composition of the mixture (He+Cs+CO₂) a wide spectrum of kinetic conditions were achieved.

The small signal gain measured ranged from 0.06\%cm⁻¹ to 0.3\%cm⁻¹ arriving at the following optimum conditions for laser operation:
1) The optimum value for Cs mole fraction is determined to be $1.4 \times 10^{-5}$. It is concluded that operation at laser values would lead to very unstable inversion with the gain fluctuating by very large amount ($\pm 30\%$). However, at values higher than $10^{-5}$, the small signal gain is very insensitive to the variations in $f_{cs}$, a 10% increase would drop the gain only by $\sim 5\%$.

2) There is an optimum value for the current density for each particular gas mixture establishing a certain amount of Joule dissipation. In order to achieve favorable conditions the non-dimensional parameter $(T_e - T_g)/T_g$ should be kept around 9.0. The electron temperature determined by this parameter in conjunction with the Cs mole fraction would provide the required electron number density.

3) It has been observed that as the turbulence in the plasma grows higher values of gain are achieved, saturating at approximately at 0.32%cm$^{-1}$, the maximum gain value recorded during this study. In his numerical study Walter$^{12}$ discovered a behavior similar to this, wherein at low CO$_2$ mole fractions ($\sim 1-2\%$), very rapid growth of ionization instabilities was observed, the fluctuation parameter $\langle \eta^2 \rangle$ reached an asymptotic value of 0.5 from a modest value of 0.05 within a distance of 10cm as the mixture moved downstream with a velocity of 4300.0 m/sec. During this growth period very large values of intra-cavity laser flux were computed, however, when $\langle \eta^2 \rangle$ leveled off to the value 0.5 lasing stopped. The spread of the peak inversion was in the order of 2.0cm ($\tau = 2 \times 10^{-2}/4300 = 4.6 \mu$sec). Interestingly enough in the experimental
study the 0.32% cm$^{-1}$ gain did not last more than 4.0 μsec. It seems that in order to achieve longer lasting inversion, a more stable plasma would be a better choice, such achieved probably by increasing the CO$_2$ mole fraction.

4) Based on the measured values of small signal gain and approximate evaluation of saturation intensity using the results of Walter's analysis an estimate of extractable laser power has been made. The computed value for specific power at 3% CO$_2$ is 32 KJ/kg.

5) By monitoring the absorption of the laser signal in the afterglow the relaxation rate of the lower laser level by CO$_2$ molecules has been measured to be 3.3 × 10$^7$ atm$^{-1}$ sec$^{-1}$. This value matches the figure calculated by Seeber$^{58}$ and is in close agreement with the measurement performed by Bulthuis.$^{59, 60}$ Since the relaxation of the CO$_2$(01'0) made by He is much faster than by CO$_2$(000), there is no doubt that the measured rate is for the CO$_2$(100'0)–CO$_2$(01'0) process. The exact pathways of the relaxation mechanism are still a matter of serious discussion.

6) The pulsed technique has enabled us to measure the rate of Cs–CO$_2$ interaction, the cross section for which has been found to be in the range of 1.3 × 10$^{-24}$ m$^2$ to 4.6 × 10$^{-24}$ m$^2$ (400°K). A simple calculation shows that at a pressure of 0.1 atm in a mixture with 3% CO$_2$ the loss of metallic Cs due to this chemical reaction would be less than 1% (in a one meter long cavity).

Consistent gain measurements and preliminary power extraction calculations strongly suggest that construction of a high power MHD laser is
feasible. The measurement of relaxation rates of lower laser level and the fact that the rates are in agreement with the results from several other investigations certify the reliability of the data.
CHAPTER II
PHYSICS OF CO$_2$ LASERS

MHD lasers are characterized by relatively high electron number densities ($10^{19}$ - $10^{20}$ m$^{-3}$) and low average energies (0.2 - 0.4 eV), in contrast with the conditions in electric discharge lasers in which typical values of these parameters are in the ranges $10^{15}$ - $10^{16}$ m$^{-3}$ and 1-2 eV respectively. Low energy electrons of MHD lasers are most suitable for excitation of vibrational modes of a molecular species. CO$_2$ molecules have been a better choice as the laser medium for several reasons: (1) high quantum efficiency ($\sim$41%), (2) energy transfer to the upper laser level, CO$_2$(00'1), by electrons with energies $\sim$0.3 is several times larger than to the bending mode CO$_2$(01'0), and (3) He, the basic carrier gas acts as an effective coolant, selectively relaxing the lower laser level. In the following section we will review the properties of CO$_2$ molecules and the available data on excitation and relaxation rates of various vibrational modes of the molecule.

2.1 CO$_2$ Molecular Kinetics

CO$_2$ is a linear triatomic symmetric molecule with three normal modes of vibration, $\nu_1$ (symmetric stretch mode, fundamental frequency = 1337 cm$^{-1}$), $\nu_2$ (doubly degenerate bending mode, fundamental frequency = 667 cm$^{-1}$), $\nu_3$ (asymmetric stretch mode, fundamental frequency = 2349 cm$^{-1}$). The laser transitions involve the lowest vibrational levels, namely $\nu_3 - \nu_1$ and $\nu_3 - 2\nu_2$, therefore the modes may be modeled as harmonic oscillators (Fig. 2.1), as far as the laser kinetics is concerned. For every
vibrational level there exists a set of rotation levels, but with slightly different spacing for the different vibrational levels.

Two prominent laser transitions have been observed in CO$_2$ molecules:

$$\text{CO}_2(00^01) + \text{CO}_2(10^00) \text{ at } 10.6 \mu$$

and

$$\text{CO}_2(00^01) + \text{CO}_2(02^00) \text{ at } 9.6 \mu$$

where CO$_2$(00$^0$1), CO$_2$(10$^0$0) and CO$_2$(02$^0$0) are the first excited state of the asymmetric stretch mode, the first excited state of the symmetric mode and the second excited state of the bending mode, respectively.

Laser oscillation always starts on the 10.6 $\mu$ transitions, because the gain is slightly higher on these transitions than on 9.6 $\mu$ transitions, unless frequency selection devices are used in the cavity. Since both groups of transitions share the population of the same upper level (00$^0$1), the competition effect among the 9.6 $\mu$ and the 10.6 $\mu$ transitions precludes the operation of the 9.6 $\mu$ transitions. Probably for the same reason the laser kinetics of 10.6 $\mu$ transitions is extensively researched and studied. In the present study we will confine ourselves to this laser band as far as the experiments are concerned, for the sake of simplicity, and then discuss the 9.6 transitions.

Each transition band has two branches: P (transition from J rotational level to J+1) and R (transition from J to J-1). From the expression for gain

$$\alpha_{2, J+1, J \pm 1} = \left[ N_{2, J} - N_{1, J \pm 1} \frac{g_J}{g_{J+1}} \right] \frac{\lambda^2 g(v)}{4\pi n^2 \tau_{\text{spont} 2, J+1, J \pm 1}}$$

This matter will be further discussed in Chap. 5.
It can be seen that for the P branch the ratio of degeneracies \( g_J / g_{J+1} \) is less than 1.0, as \( g_J = 2J+1 \), the reverse is true for the R branch. This suggests that a P transition may oscillate even with partial \( N_2 < N_1 \) inversion (above some \( J_{\text{min}} \)).

The rotational population density \( N_{i,J} \) is

\[
N_{i,J} = \frac{N_i g_J \exp(-E_{i,J}/kT_{\text{rot}})}{\sum J g_J \exp(-E_{i,J}/kT_{\text{rot}})} \tag{2.2}
\]

so that \( N_i \) is the population density of \( i \)th vibrational state. The energy separation between two adjacent rotational levels increases as we go to higher rotational \( J \) values. However, even up to very high rotational levels the energy separation between the rotational levels is still smaller than or comparable to the thermal energy. Since the rotational relaxation rate is several orders of magnitude faster than the intermode vibrational transfer rate, even under excitation conditions, \( T_{\text{rot}} \), which represents the thermal energy of the vibrational state, may be assumed equal to temperature \( T \) describing the translational kinetic energy of the molecules.

Equation (2.2) suggests that in either case, whether inversion between the vibrational states exists or not, the relative population of one of the rotational levels would be higher than that of other levels (in the same vibrational state), thus when inversion is created, the laser oscillation starts on only one (at most only on a few) rotational transitions. It has been experienced that at room temperature P(20) is the line which starts to lase first and as long as the thermalization of rotational levels is rapid enough the lasing is maintained at P(20). Some other strong lasing lines are P(18) and P(22).
2.2 Electron Excitation in a MHD Laser

$N_2$ molecules are one of the main constituents in electric discharge and gasdynamic lasers because of their energy storage capability. They cannot decay to the ground state because of zero permanent dipole moment without any collisional relaxation. The first excited state of the molecule which is in resonance with the laser upper level, $CO_2(00^101)$, $(\Delta E \approx 18 \text{ cm}^{-1})$, can excite a ground level $CO_2$ molecule to $CO_2(00^01)$ at a rapid rate of $1.4 \times 10^7 \text{ atm}^{-1} \text{sec}^{-1}$. The equilibrium between $N_2 (v=1)$ and $CO_2(00^01)$ states, in effect, increases the effective lifetime of $CO_2(00^01)$, the upper laser level.

At an electron energy of $\approx 2.0 \text{ eV}$, which is typical of electric discharge lasers, the effective cross section for vibrational excitation of $N_2$ is about 6.0 times larger than that for $CO_2(00^01)$. However, for electron temperatures in the range 2500-4000°K, the rate for $N_2$ is one to two orders of magnitude less than that for $CO_2(00^01)$. Thus, in MHD lasers, $N_2$ would not be particularly useful, even if we risk the overloading of the nonequilibrium plasma by injecting another molecular species other than $CO_2$, into it.

It was mentioned in Chapter 1 that a nonequilibrium generator is used as the electron source, and for laser operation $CO_2$ is added to the flowing gas. In order to maximize the Joule dissipation, which is required for effective electron heating, the generator is short circuited. A Faraday generator seems to be the logical choice for an MHD laser, as it is capable of high local efficiencies in the short-circuited mode.
It has been predicted° that high MHD interactions are possible when the electron number density is greater than \(5 \times 10^{18} \text{ m}^{-3}\), which has a positive effect on the pumping power of the device. However, an upper limit exists for the electron number density, beyond which the excitation of the bending and symmetric modes becomes significant. As the cross sections are electron temperature dependent, this limit would also be a function of \(T_e\), and, \(n_e\) in effect, will depend upon the Cs mole fraction. For \(f_{cs} = 10^{-5}\) Lowenstein\(^4\) places the limit at \(10^{19} \text{ m}^{-3}\).

As the power output from a laser cavity is almost proportional to the mixture static pressure, it would be advisable to operate an MHD laser at relatively higher pressure (say \(\approx 0.25\) atm).\(^12\) At this pressure the gain profile \(g(v)\) is homogeneously broadened:

\[
g(v) = \frac{\Delta v}{2\pi[(v_0 - v)^2 + \left(\frac{\Delta v}{2}\right)^2]}
\]  

(2.3)

where

\[
\Delta v = \Delta v_D + \sum \frac{1}{\pi \tau_i}
\]  

(2.4)

For this case the saturated gain is

\[
\alpha = \frac{\alpha_0}{1 + I/I_s}
\]  

(2.5)

where \(\alpha_0\) and \(I_s\) are the small signal gain and the saturation intensity respectively.
2.2.1 Nonequilibrium Generator with Molecular Additives

The process of electron heating due to Joule dissipation has been extensively studied.\textsuperscript{32,15} In essence the magnitude of electron energy is determined by the balance between the energy gain by mechanisms like acceleration in an electric field, recombination in a nozzle by a three body process, and the energy loss by mechanisms like elastic collisional losses, radiation losses and heat diffusion losses. Neglecting the radiation\textsuperscript{15} and the heat diffusion\textsuperscript{15} losses and considering the energy gain only by acceleration in an electric field we can write the energy equation for electrons:

\[
\frac{\partial}{\partial t} \left[ n_e \left( eV_1 + \frac{3}{2} kT_e \right) \right] + \nabla \cdot \left[ n_e \left( eV_1 + \frac{3}{2} kT_e \right) \vec{V}_e \right] \\
+ n_e kT_e \nabla \cdot \vec{V}_e = \frac{j^2}{\sigma} - \sum_s \Delta \varepsilon_s 
\]  

(2.6)

On the right hand side the first term is the Joule dissipation and the second term is the loss due to collisional processes. The term on the left hand side represents the temporal variations of the electron-gas energy (potential and thermal), their convective flux and the pressure work. At high magnetic fields, which would be required for successful operation of MHD lasers, the plasma becomes unsteady and non-uniform\textsuperscript{33,39} leading to an increased Joule dissipation and to a saturation of the "effective" conductivity. Solbes\textsuperscript{39} developed a quasilinear averaging technique to account for these "ionization instabilities". Growth of these instabilities occurs when the Hall parameter, $\beta$, defined as
\[ \beta = \frac{e B}{m_v e} \]  
\[ (2.7) \]

exceeds a limit, conveniently called the critical Hall parameter, $\beta_{\text{crit}}$. The parameter $\beta_{\text{crit}}$ is a unique property of the plasma and depends on the type of seed, plasma constituents, the degree of ionization, and the gas temperature.* For plasmas typical of MHD lasers, this value has been found to be \( \leq 1 \). The ratio of effective conductivity and spatial average conductivity, \( \sigma_{\text{eff}} / <\sigma> \) could drop to a value as low as 0.1. Oliver et al.² have shown that electrothermally induced eddy currents tend to develop together with a strong current density over the insulating wall.

When a molecular species is added to the nonequilibrium plasma,¹ ² damping of the ionization instabilities is observed. Draper points out that the time of electron temperature relaxation is increased:

\[ \frac{\tau}{\tau^*} = 1 + 2 \left( \frac{n_{\text{CO}_2}}{n_{\text{He}}} \right) \left( \frac{n_{\text{He}}}{n_e} \right) \left( \frac{kT_e}{eV_i} \right)^2 \]

\[ (2.8) \]

where $\tau$ and $\tau^*$ are the electron temperature relaxation times with and without molecules.

Molecular addition enhances the loss term, \( \sum_s \Delta \varepsilon_s \), in the energy equation (2.6), due to added inelastic losses. From the cross-section data for vibrational excitation of CO₂ by electrons we know that excitation of CO₂\(^0\)(001) and CO₂\(^1\)(010) levels are dominant; however due to the stimulated transition (10.6 μ), the molecules are continuously transferred to the CO₂\(^0\)(100) level. Further, it will be seen in the next section that the

---

* A detailed description and analytical expression for $\beta_{\text{crit}}$ can be found in Ref. 39.
relaxation processes tend to populate various levels of the bending mode. Thus a complete redistribution of the population amongst the vibrational levels takes place. Under these conditions the inelastic loss factor $\delta_{\text{CO}_2}$, which in "swarm" experiments has been measured to be $\approx 5000$, does not remain constant, in fact decreases. This indicates that the plasma in an MHD laser consists of several "gases", each describable by a temperature of its own.

2.3 Relaxation Processes

As the molecules are pumped to the desired excited state in order to create an inversion, they also lose energy by way of "relaxation processes". These processes may or may not be favorable to the creation of inversion depending upon whether they relax the lower or upper laser level. In gas lasers the relaxation may occur by three different mechanisms: (1) radiative decay, (2) collisional loss, and (3) diffusion out of the active area.

In CO$_2$ lasers the relaxation rates due to radiative decay and diffusion are very slow, at least by 3 orders of magnitude.$^{24,40,41,42}$ For this reason we will examine only the collisional relaxation in detail.

There are various units in which the relaxation rates are expressed. In this study we use the unit atm$^{-1}$ sec$^{-1}$. A relaxation time can be defined:

$$\frac{1}{\tau_e} = \frac{1}{kp}$$

(2.9)

where $k$ is the relaxation rate and $p$ the pressure of the relaxing agent.
2.3.1 *Relaxation Rates of the Upper Laser Level*

As is required for an efficient laser operation, the relaxation rates for $\text{CO}_2(00^01)$, the upper laser level, are very slow. For relaxation by $\text{CO}_2 - \text{CO}_2$ encounters:

$$\text{CO}_2(00^01) + \text{CO}_2(00^00) \rightarrow \text{CO}_2(03^00) + \text{CO}_2(00^00)$$  \hspace{1cm} (2.10)

The rate at a temperature of 400$^\circ$K is measured to be \(^47\)

$$k_{\text{CO}_2(00^01)-\text{CO}_2} = 2.8 \times 10^5 \text{ atm}^{-1} \text{ sec}^{-1}$$  \hspace{1cm} (2.11)

For the process:

$$\text{CO}_2(00^01) + \text{He} \rightarrow \text{CO}_2(03^00) + \text{He} + 416 \text{ cm}^{-1}$$  \hspace{1cm} (2.12)

The rate for $T = 300^\circ$K is:

$$k_{\text{CO}_2(00^01)-\text{He}} = 6.8 \times 10^6 \text{ atm}^{-1} \text{ sec}^{-1}$$  \hspace{1cm} (2.13)

It can be seen that although this process is slow, it populates the third level of the bending mode. Also, for a gas mixture typical of MHD lasers, 3\% $\text{CO}_2 + 0.001\%$ Cs + 97\% He, most of the relaxation will be performed by He, in contrast to electric discharge lasers.

2.3.2 *Relaxation Rate of the Lower Laser Level*

Although since 1966 at least ten experiments have been performed, as yet neither the basic mechanism of the process is known nor any universally acceptable data on the rates is available. Most confusion arises from the existence of Fermi resonance between $10^00$ level and doubly degenerate $02^00$ level of the bending mode.
For the relaxation process:

\[ \text{CO}_2(10^00) \rightarrow \text{CO}_2(01^00) \]

the rate constants reported range from \(7.6 \times 10^5\ \text{atm}^{-1}\ \text{sec}^{-1}\) to \(3.4 \times 10^8\ \text{atm}^{-1}\ \text{sec}^{-1}\). Collisions between \(\text{CO}_2(10^00)\) and \(\text{He}\) are believed to play almost no role in this process, \(^{49}\) at least they were not measurable.

There are several schools of thought on the mechanism of this relaxation process. Experimental measurements of rate of the Fermi resonance has been claimed by many investigators. Stark\(^{62}\) performed a series of experiments, using a 9.6\(\mu\) beam to disturb the equilibrium between the two levels and then monitor the absorption of a 10.6\(\mu\) beam. He reported a rate value as:

\[ k_{10^00 - 02^00} = 1.4 \times 10^5 [p_{\text{CO}_2} + 0.046p_{\text{N}_2} + 0.054p_{\text{He}}] \]  \(2.14\)

Rhodes et al.\(^{50}\) and Jacobs et al.\(^{61}\) reported this rate constant to be \(7.6 \times 10^8\ \text{atm}^{-1}\ \text{sec}^{-1}\) and \(2.3 \times 10^8\ \text{atm}^{-1}\ \text{sec}^{-1}\) respectively (see Table 3).

Rhodes et al. in their 1968 experiment observed two more absorption rates, the faster of these two were attributed to process like

\[ \text{CO}_2(02^00) + \text{CO}_2(00^00) \not\leftrightarrow \text{CO}_2(10^00) + \text{CO}_2(00^00) - 52.7 \ \text{cm}^{-1} \]  \(2.15\)

and

\[ \text{CO}_2(01^10) + \text{CO}_2(01^10) \not\leftrightarrow \text{CO}_2(10^00) + \text{CO}_2(00^00) + 50.1 \]  \(2.16\)

and based on this measurement a relaxation rate constant for \(\text{CO}_2(10^00)\) was reported as \(3.4 \times 10^8\ \text{atm}^{-1}\ \text{sec}^{-1}\). The third rate was ignored.
In 1974 Jacobs et al.\textsuperscript{61} repeated the experiment with smaller saturating pulse and faster electronics and came up with a rate constant of $2.5 \times 10^7 \text{ atm}^{-1} \text{ sec}^{-1}$ for $\text{CO}_2(10^00) \rightarrow \text{CO}_2(01')$ relaxation.

Bulthuis\textsuperscript{59,60} monitored the decay of laser power in the after-glow of the discharge and reported a bottleneck rate constant of $\sim 10^7 \text{ atm}^{-1} \text{ sec}^{-1}$. His experiment seems more realistic in predicting the relaxation rate $[\text{CO}_2(10^00), \text{CO}_2(02^00)] \rightarrow \text{CO}_2(01')$ since he used $\text{H}_2\text{O}$ to deplete the $01'$ population, before shorting the discharge.

Seeber\textsuperscript{58} based on his modified Schwartz-Slawsky-Herzfeld (SSH) theory calculates the value to be $3.3 \times 10^7 \text{ atm}^{-1} \text{ sec}^{-1}$. In Chapter IV we will see that this rate constant has been measured in this investigation and is $\sim 3.3 \times 10^7 \text{ atm}^{-1} \text{ sec}^{-1}$ (see Table 2).

Murray et al.\textsuperscript{54} measured gain at $10.6\mu$ and $9.6\mu$ transitions and found that they are almost equal, a strong coupling between $10^00$ and $02^00$ would not explain it. Theoretical calculations based on strong coupling predicted $40 - 50\%$ more gain at $10.6\mu$ band. By adjusting the figures such that a correlation between would be found they predicted a rate constant of $1.7 \times 10^6 \text{ atm}^{-1} \text{ sec}^{-1}$.

To sum up:

1) Most of the data suggest that the rate constant for $10^00 \rightarrow 01'$ relaxation would be somewhere in the range $1 - 3 \times 10^7 \text{ atm}^{-1} \text{ sec}^{-1}$.

2) If there is a strong coupling between $10^00$ and $02^00$, then the process

$$[10^00,02^00] + (00^00) \rightarrow 2(01') + 50.1 \text{ cm}^{-1} \quad (2.17)$$
is most likely to take place and both the 10.6\,\mu and 9.6\,\mu bands would be governed by this bottleneck rate in MHD lasers. Also the bending mode would not have a Boltzmann equilibrium.

3) If there is a weak link between $10^0_0$ and $02^0_0$ and depending upon the pathway one of the two bands would be more suitable for MHD laser operation. The reason being that $CO_2(01\,0)'$ is relaxed by He* much faster than by CO$_2$ and hence under MHD laser conditions (97\% He, 3\% CO$_2$) the bottleneck rate is not the relaxation of CO$_2(01\,0)'$, as it is in electric discharge lasers. For example, if

$$CO_2(02^0_0) \rightarrow CO_2(01\,0)' \tag{2.18}$$

is faster then 9.6\,\mu operation would more suitable.

\[ k_{CO_2(01\,0)' - CO_2} = 1.8 \times 10^5 \text{ atm}^{-1} \text{ sec}^{-1}; k_{CO_2(01\,0)' - He} = 2.7 \times 10^6 \text{ atm}^{-1} \text{ sec}^{-1} \text{ at } T = 400^\circ \text{ K.} \]
CHAPTER III
EXPERIMENTAL APPARATUS

3.1 The Pulsed Simulation Technique

The experimental facility utilized in the present investigation simulates the flow-induced electric field of an MHD laser by an applied field and thereby eliminates the complexities and expense of a high speed flow system. The experiments are conducted in a pulsed mode, the advantages of which will be pointed out in the sections to follow as each system is described individually. The sequence of events which occur during a test is schematically shown in Fig. 3.14. Helium is stored in a heated flask containing copper wool wet with liquid Cesium. By opening a fast-acting pneumatic valve the Cs + He mixture is allowed to flow through the test chamber into vacuum, giving the pressure transient sketched; simultaneously another valve is opened to allow CO₂ to flow through the tube. At a predetermined time the magnetic field is turned on and the shutter to the CO₂ probe laser is opened. A few milliseconds after, the electric field is pulsed to pass a prescribed current through the gas mixture.

3.2 Pulsed Flow System

The gas flow system is sketched in Fig. 3.1. The test chamber is fed by two separate gas lines carrying a Cs + He mixture pipe line and a CO₂ + He mixture. Both lines are simultaneously opened to the tube by activating two solenoid valves. The pipe lengths (from the valves to the discharge tube) are so matched that both the gas mixtures reach the tube at the same time, so no chemical reaction between Cs and CO₂ takes place before they reach the test chamber.
The stainless steel vessel containing copper wool (Fig. 3.1) is flushed by liquid Cs before conducting a series of tests, so as to thoroughly wet the Cu wool. The liquid Cs is then returned to the storage vessel. In order to keep the system at a uniform temperature, an oven was built around the pot with the Cu wool. Also, the pipe line from the pot to the discharge tube is heated by electrical tapes. During operation the pneumatic valve 10 is actuated allowing the He saturated with Cs to flow through the test chamber giving a pressure pulse of about 700 milliseconds. The temperature of the oven and the stainless steel tube is monitored and kept constant at a predetermined value. Under these conditions a reliable and repeatable seeding is provided. After the copper wool is wet the valve 5 is securely closed. The valves 1 and 9 are used to charge the Cs vessel with He to a desired pressure, and valve 9 is closed before firing the pressure pulse by suddenly opening the pneumatic valve. Valves 3 and 8 are normally closed, and are used to evacuate the Cs pots, when the liquid Cs is required to be transferred from or to one of the pots.

The CO$_2$+He mixture is passed to the test section through a 0.394 mm choked hole, which is situated near the inlet in the tube (see insert A in Fig. 3.1). This microhole prevents the flow of Cs+He into the CO$_2$ line and also determines the amount of CO$_2$ which is injected into the plasma.

3.2.1 Discharge Tube and Circuit

The discharge tube (the test section) is made from a quartz one inch square cross-section pipe. This dimension was chosen so as to ensure that wall effects (recombination and deexcitation are negligibl
small at the pressure level under investigation: ~50.0 - 70.0 torr). A conical quartz fitting is fused onto each end of the pipe to provide O-ring seals and flange mounting (Fig. 3.2), the overall length being approximately 40 cm. The end fitting butts up against an electrode block as shown in Fig. 3.3. Each block holds ten electrodes, each connected to a separate ballast resistor (~100 Ω) to encourage a uniform discharge. The tube is terminated at each end by brass bellows and adjustable flanges which serve as window and mirror mounts required for multipass small signal gain measurements. The bellows are supported by aluminum stands, insulated so as to prevent external shorting of the discharge, the middle point of the tube being grounded. The "tee" shape of the tube provides an easily accessible port for gas injection.

Eight tungsten electrodes are fused to the side walls of the tube, which, being in contact with the plasma, allow monitoring of the axial as well as transverse (Hall) voltages.

The discharge circuit is powered by a 66 µF capacitor-bank chargeable to 4000 volts. Two ignitrons are used as high power relays, one to initiate and one to terminate the discharge. They are triggered by current pulses from two thyratrons, which, in turn, are triggered by amplified signals from the oscilloscopes. The duration of the discharge, i.e. the time difference between the triggering of the two ignitrons, is usually 200-350 µsec, and is adjustable by means of a time delay circuit. A typical current pulse is shown in Fig. 3.4.
3.2.2 Magnet

An electromagnet surrounds the discharge tube, and consists of two rectangular Helmholtz coils, each with 8 turns of No. 10 insulated copper wire, resting on aluminum channels (Fig. 3.5). The magnetic field is nearly uniform (±0.3%) over most of the discharge region as shown in Fig. 3.6.

The magnet is powered by a 500 μF, 3000 V bank of capacitors interconnected with 55 μH inductors so as to form a transmission line. A resistor in series with the magnet allows to match the load impedance to the line impedance thus giving an approximately square pulse for a duration of 2-3 milliseconds (Fig. 3.7). The experiment is performed during the flat portion of the pulse. An ignitron-thyratron system is used as a switch, and a pick-up coil and integrating circuit allows monitoring of the magnet current during an experiment.

3.3 Plasma Diagnostics

The plasma diagnostics consists of: (1) electron temperature and number density measurement, (2) Cs concentration measurement, and (3) estimation of CO concentration in the plasma.

3.3.1 Electron Temperature and Number Density Measurements

During the discharge some electrons recombine with cesium ions giving to continuum radiation from the plasma. The intensity of the radiation at a given wavelength is related to the electron number density, the cesium ion number density, and the electron temperature by the following relation:
\[
I_0 \propto \frac{n_e^2}{T_e^{3/2}} \left[ \exp \left( \frac{hc}{kT_e} (\lambda_{6P}^{-1} - \lambda_{6P}^{-1}) \right) + 2.22 \exp \left( \frac{hc}{kT_e} (\lambda_{5D}^{-1} - \lambda_{5D}^{-1}) \right) \right]
\]

(3.1)

where \( I_0 \) is proportional to the continuum radiation from the plasma and \( \lambda_{6P,5D} \) are the wavelengths corresponding to the lower levels of the electron transitions from the continuum (Appendix A). From Eq. (3.1) it can be seen that is the radiation is monitored at two wavelengths, then the ratio of intensities may be used to calculate the electron temperature:

\[
\frac{I_{01}}{I_{02}} \propto \frac{\exp \left[ \frac{hc}{kT_e} (\lambda_{6P}^{-1} - \lambda_{6P}^{-1}) \right] + 2.22 \exp \left[ \frac{hc}{kT_e} (\lambda_{5D}^{-1} - \lambda_{5D}^{-1}) \right]}{\exp \left[ \frac{hc}{kT_e} (\lambda_{6P}^{-1} - \lambda_{6P}^{-1}) \right] + 2.22 \exp \left[ \frac{hc}{kT_e} (\lambda_{5D}^{-1} - \lambda_{5D}^{-1}) \right]}
\]

(3.2)

In the experiment the radiation was monitored at 4904 Å and 4285 Å. A spectral lamp GE 6.6A/T4Q/1CL - 200 W was used to calibrate the radiation recording system, the fiber optics and the photomultiplier tubes. The fiber optics bundle has a cross-section (optically sensitive) of 1 cm² and is capable of recording a radiation field from a 120° solid angle. The location the fibers are so chosen that the entire 1-inch width of the discharge tube is covered.

3.3.2 Cs Concentration Measurement

Determination of the actual concentration of metallic Cs in the discharge has been especially troublesome in MHD laser investigations. In the present study the measurement was done by resonance absorption at 4550 Å of light from a Cs spectral lamp. To minimize noise and record a
reference on each scope trace the light from the lamp was chopped at about 15 kHz, giving many periods during a gas flow pulse, as sketched in Fig. 3.13. During this pulse the lamp was powered by a D.C. power supply; during idle periods it was powered by a regular A.C. source designed for such lamps. The change in height of the pulse gives directly the absorption by the Cs population in the tube, and since the record spans the whole gas flow time, any fogging of the discharge tube can be detected.

In Fig. 3.8 the optical arrangement of the system is sketched. The housing of the lamp is heated to maintain the Cs vapor in the lamp at a particular temperature, which corresponds to the temperature at which the calibration of the Cs absorption measurement was done. For calibration two quarts test chambers sealed off with 60 torr and 120 torr of He were used. The set-up is sketched in Fig. 3.9 (see Appendix B). The calibration curve shown in Fig. 3.10 is used to estimate the Cs mole fraction from the absorption data recorded during the experimenta. A typical scope trace can be seen in Fig. 3.11.

3.3.3 Estimation of CO Concentration in the Plasma

In earlier experiments with MHD laser plasmas it was suspected that CO$_2$ dissociates to CO and O$_2$ during the discharge. To confirm this, radiation at the 5052 A triplet band of CO was monitored using a filter at 5050 A. To estimate the amount of CO present in the plasma, the diagnostics system was calibrated.

As mentioned before, the Hall and axial fields were measured by probes in contact with the plasma, which were fused into the discharge tube.
3.4 **CO$_2$ Probe Laser**

The probe laser is a CW electric discharge CO$_2$ laser. The optical cavity consists of a spherical gold-plated mirror (R=10 m) and a germanium semi-transparent (T=10%) mirror placed about 1.5 m apart. The discharge section is made of pyrex glass, water cooled, and has two, one at each end, flat germanium windows which are coated with antireflection coating (10.6 μ) on both sides. The flowing laser system is powered by a well filtered 50 kW-50 mA power supply. The gas mixture used comprises of 16% N$_2$, 14% CO$_2$, and 70% He. An adjustable orifice is placed in the laser cavity to operate the system in TEM$_{00}$ mode (Fig. 3.12).

The detection system consists of a liquid N$_2$ cooled HgCdTe infrared detector and a low noise-high gain (40 dB) small signal amplifier (Perry Model 603). The detector has a sensitive area of 1.0 mm$^2$. A typical scope trace showing a gain measurement can be seen in Fig. 3.13.

Three Tektronix 555 oscilloscopes with multi-trace plug-ins are used to record the data on Polaroid film. The sequence of events, as shown in Fig. 3.14, is initiated by throwing one switch. At first the two solenoid valves are activated, opening the Cs+He and CO$_2$+He flow systems to the discharge tube. At a time when the pressure in the tube reaches a preselected value (the delayed trigger mechanism of scopes is used to adjust the timing) trigger pulses are sent to activate the magnet and open the shutter to the CW CO$_2$ laser. After the magnet is stabilized the discharge is fired. Sometimes a preionizer pulse is required to start the discharge.
CHAPTER IV
EXPERIMENTAL RESULTS AND ANALYSIS OF THE DATA

After the experimental set-up was test-proven to be reliable and capable of reproducing the gasdynamic and electrical conditions in the test chamber consistently, several series of experiments were conducted during the period August 1976 to February 1978. This was carried out in three steps: Signal to noise ratio measurements, calibration and preliminary tests, and gain measurement experiments.

Before proceeding with the experimental investigation, it was necessary to measure the noise level and the magnitude of other errors, if any, in the diagnostic and data acquisition systems of the designed facility. A series of test runs was conducted to record the noise level in various electrical signals. Radio frequency noise transmitted from high current cables of magnet and discharge circuit was found to be the main source of the electrical noise. However, by use of proper insulation and grounding the signal to noise ratio was increased to an acceptable level.

a) Figure 4.1 shows absence of noise in the laser gain detection system. Here the discharge was fired through a Cs seeded He plasma, without CO$_2$ injection. The experiments were conducted in two sets; without and with magnetic field.

b) The calibration curve in Fig. 4.2 indicates a linear dependence between the discharge current and the probe current integrator output. Even when the magnetic field is on, the noise level, at the current values
of interest (0.2 amp/cm² to 1.0 amp/cm²) is negligible.

The data have been carefully read from Polaroid photographs to an accuracy of ± 0.1 mm in measured lengths. However, while presenting the recorded data in graphical form this uncertainty in the measured values has been accordingly plotted.

4.1 Calibration and Preliminary Tests

For data reduction, it was required to calibrate various diagnostic systems. The theory and technical approach for calibration of the Cs light absorption measurement are discussed in Appendix A. In Fig. A-1, the calibration curve, relating the measured absorption of Cs lamp light and the concentration of metallic Cs, has been shown. In absorption, as it is read from the photographs, can be measured with an accuracy of ± 2%, which, when reduced to Cs number density, does not exceed ± 10% mark. Electron number density and CO number density measurements were the other two systems which required calibration.

a) For the calibration of the electron number density, diagnostic system experiments named the 1000 series, were conducted. Several pre-selected values of current density in the range of 0.20 amp/cm² to 1.00 amp/cm² were passed through a Cs seeded He plasma and, along with other parameters, Cs bound-free continuum radiation was measured at 4904 ± 50°A and 4285 ± 50°A wavelengths. In order to minimize the calibration error other relevant parameters, such as axial electrical field, gas mixture pressure and Cs mole fraction, were kept constant for one set of experiments. Several such sets were conducted.
Using the basic equations governing an MHD plasma (see Appendix C), electron number density and electron temperature were analytically calculated from the recorded data (i.e. $E_x$, $J$, $f_{cs}$ and $p$).

A theoretical expression for the spectral emission of Cs free-bound radiation is given in Ref. 73 and has been discussed in Appendix A. Using this expression a relationship was found between the electron number density and the radiation emitted from a unit volume of the plasma in a unit solid angle in a unit frequency interval. Two fiber optic bundles, each with a field of view of 30° half angle, were calibrated with a standard light source, GE lamp 6.6A/T4Q/ICL-200 W.

Finally, the constants relating the electron number density (and the electron temperature) and the photo-multiplying tube output were found, and were henceforth used to reduce the data.

b) Gain in a medium with homogenous broadening saturates as:

$$\alpha(v) = \frac{\alpha_0(v)}{1 + \frac{I(v)}{I_s(v)}}$$ (4.1)

where the saturation intensity is given by

$$I_s(v) = \frac{4\pi\eta^2 \frac{h\nu}{(e^2 / t)^{\text{spont}}}}{\lambda^2 g(v)}$$ (4.2)

In order to measure the unsaturated gain, otherwise called the small signal gain, the intensity of the probe laser has to be far less than the saturation intensity. A series of experiments was conducted to ensure this, the probe laser intensity was varied between the values of 3.0 watts/cm$^2$ and 50.0 watts/cm$^2$ and gain was measured for a given plasma (Fig. 4.19).
Within the limits of errors due to the diagnostic system, gain was found to be constant (±10%). For actual gain measurements, the laser was operated at \( \approx 6.0 \text{ watts/cm}^2 \) intensity, a value low enough for safe operation of the Hg Cd Te detector.

Consistent laser gain measurements have been achieved over a wide range of conditions appropriate to MHD laser operation. The plasma conditions were controlled and systematically varied by maintaining the five basic parameters \((B, Jx, f_{Cs}, f_{CO_2}, p)\) to predetermined values. In order to investigate the effects of each individual parameter on the population inversion, all other parameters were kept constant, while varying the parameter in question. The temperature of the gas mixture was computed to be 400°K, a quantity constant in all the experimental runs.

All the experiments were carefully planned to illuminate the basic kinetics of inversion in CO\(_2\) under MHD conditions, the main task of this investigation. To facilitate this the experiments were divided into two categories; without, and with magnetic field, thereby isolating the effects of turbulence in the MHD plasma from other phenomena.

4.2 Measurements without Magnetic Field

The laser gain data without magnetic field provides a good record of collisional excitation and relaxation of CO\(_2\) molecules in a Cs seeded He plasma. Details of these processes will be discussed in chapter 5. Keeping the total static pressure in the test chamber between 33.30 torr and 70.00 torr, for various values of \(Jx, f_{Cs}\) and \(f_{CO_2}\), laser gain was measured as shown in Fig. 4.4 as a function of time. The principal features of this time history of the gain are:
a) The gain rises in a time of about 10 ms to a value of $0.1\text{cm}^{-1}$, is nearly constant for some 100 ms, then decreases, becoming strongly negative before the current is terminated at 330 ms.

b) The negative gain (absorption) then relaxes on about a 500 $\mu$s time scale.

During the course of our investigation, it was established that Fig. 4.4 describes the gain behavior only qualitatively. The time required for gain to peak and then convert into absorption were different for each run, and hence so were the excitation and deactivation frequencies of the laser levels.

Since the data obtained is a result of careful and systematic scanning through all the relevant parameters, a large number of possible combinations of laser pumping and relaxation rates have been achieved in this investigation. Thus almost all the information needed to predict the performance of an MHD laser plasma can be extracted from these results without detailed analysis of the individual processes favoring the inversion.

4.2.1 Small Signal Gain Measurements

Under some conditions small signal gain up to $0.3\text{cm}^{-1}$ has been measured. Maximum gain of $0.3\text{cm}^{-1}$ was recorded in experiment No. 4120. Current density of $0.382 \text{amp/cm}^2$ was applied to an He plasma composed of $0.93\% \text{CO}_2$ and $0.0015\% \text{Cs}$ (Fig. 4.5). The gain rises very rapidly, in 2 $\mu$s, stays constant at $0.3\text{cm}^{-1}$ for another 4 $\mu$s and then slowly falls, turning negative to a value of $-0.22\text{cm}^{-1}$. 
In a real MHD laser cavity, where the gas mixture may be flowing at a velocity of \( \approx 3000 \text{ m/sec} \) (\( \approx M = 3.0 \)), a channel length of 12 mm (\( 3 \times 10^6 \text{ mm/sec} \times 4 \times 10^{-6} \text{ sec} = 12 \text{ mm} \)) would be available for power extraction with a capability of generating zero power gain of 0.3\%cm\(^{-1}\) along the laser cavity. Depending upon the dimensions of the channel and on the electrical power dissipation, a 12 mm long optical cavity may or may not be adequate to extract the desired laser power efficiently.

In each case of MHD laser design, the dimensions of the laser cavity, output mirror transmission coefficient, and the nozzle dimensions have to be compromised to achieve the required results that power output. Here the matter has been pointed out only to demonstrate the usefulness of the information for MHD laser design.

For a clearer picture the entire spectrum of measured gain was plotted against the time during which the peak value remained constant and is shown in Fig. 4.5. It can be seen that for a gain value of 0.09\%cm\(^{-1}\) the transient behavior of the inversion literally disappears (\( \tau = 300 \mu \text{ sec} \)). The consequences of this result will be discussed in chapter 5 in more detail. It should be noted that the flowing MHD plasma (Mach = 3.0) will travel 0.9 m along the nozzle length and will provide enough room to extract huge laser power, while keeping the transmission coefficient of the output mirrors at a relatively lower value (which might be dictated by the lower zero power gain value of 0.09\%cm\(^{-1}\)).

Walter,\(^{12}\) in his analytical study of an MHD plasma, has arrived at an average small signal gain of 0.07\%cm\(^{-1}\), which yields laser power
densities of $\sim 1.8 \times 10^6$ W/m$^3$ and $\sim 60 \times 10^6$ W/m$^3$ using three temperature and two temperature models respectively. The deactivation rates:

$$k_{100 - \text{CO}_2} = 8.8 \times 10^5 \text{ atm}^{-1} \text{ sec}^{-1}$$

$$k_{100 - \text{He}} = 4.8 \times 10^4 \text{ atm}^{-1} \text{ sec}^{-1}$$

used in his three temperature model, as published by Murray, Mitchner and Kruger are much slower than measured in this work, (see section 4.

$$k_{100 - \text{CO}_2} = (3 \pm 0.3) \times 10^7 \text{ atm}^{-1} \text{ sec}^{-1}$$

$$k_{100 - \text{He}} = (7.5 \pm 0.5) \times 10^4 \text{ atm}^{-1} \text{ sec}^{-1}$$

This suggests that average extractable laser power can be close to a few tens of MW/m$^3$.

As has been said before the main parameters effecting the laser gain are: $J_x$, $f_{\text{Cs}}$, $f_{\text{CO}_2}$ (B = 0 in this section), their individual effects on inversion will be discussed in the following sections.

4.2.2 Effects of Cesium Concentration

It is believed that with CO$_2$ concentrations less than 1% in a Cs seeded He plasma the free electrons of the plasma remain, for all practical purposes, in saha balance with the bound electrons of metallic cesium. CO$_2$ molecules along with absorbing the translational energies of electrons, also quench the excited Cs atoms thus creating a source of additional energy drain. The degree of departure from Saha balance of the ionization process depends on the gas composition and the collisional activity of the various species. Quenching tends to decrease the number of electrons lowering the pumping capability of the laser plasma.
According to published cross sectional data electron-molecule vibrational excitation of the CO$_2$ asymmetric stretch mode dominates that of other models (bending and symmetric stretch) at electron temperatures higher than 0.3 ev. The population inversion thus created grows with increase in electron number density (and/or in electron temperature) only to an extent for several reasons. Even for a Maxwellian energy distribution, electron population having energies higher than $\sim$ 1.5 ev becomes significant enough to directly pump the lower laser level ($1^00$). Also due to the simultaneous growth at $01'^0$, which is coupled to $10^0$ stronger than to $00^01$, tends to get more crowded. Its poor deactivation by He and CO$_2$ intensifies this effect.

It is clear from the above that the inversion process can be optimized by properly selecting the average electron temperature and the electron number density, and this, in fact, prescribes the Cs seed number density. It need not be mentioned here that the optimum value for $f_{\text{Cs}}$ thus obtained will not be unique for the value of CO$_2$ concentration in the lower plasma.

Figure 4.7 provides a better understanding of this situation. The data are divided into sets such that each set represented experiments conducted at a particular and constant seed fraction. From all these sets each representing a different $f_{\text{Cs}}$ value, the peak gain values were selected and plotted against their respective seed fraction values. This technique allows us to find for each set that unique combination of other independent relevant parameters ($J_x, f_{\text{CO}_2}, p, B=0$), while $f_{\text{Cs}}$ is kept constant, which
produces maximum pumping power. This search, when carried out for each set in an identical manner, enables us to examine the physics and importance of proper seeding of MHD laser plasma.

As the Cs seed mole fraction is increased from \( \sim 8.0 \times 10^{-6} \) to \( 1.4 \times 10^{-5} \), a rapid rise in gain is seen, indicating strong positive dependence of 001° level excitation on electron number density. The optimum Cs seed mole fraction of \( 1.4 \times 10^{-5} \) at which the record gain of \( 0.32\text{cm}^{-1} \) was measured, seems to almost coincide with the value predicted by Lowenstein (\( \sim 10^{-5} \)). However, the small signal gain computed was \( 0.02\text{cm}^{-1} \), 15 times lower, with CO₂ concentration of 0.22% (in this work CO₂ = 0.93%).

Further increase in the seed fraction causes gain to decrease slower than the rise on the left side of the curve. As can be seen from the cross sectional data (Fig. ) for electronic excitation of 10°0 the pumping rate of the lower laser level will rise very slowly with increase in number of available electrons. Thus overcrowding of this level may be the sole cause of the drop in gain. In chapter 5 it will be demonstrated that quenching of excited Cs atoms can severely poison the laser plasma and a steep drop in gain may result. The degree of poisoning due to the quenching effect is set by the ratio \( n_{\text{CO}_2} / n_{e} \) and there exists a limit on its value beyond which the actual number of electrons present in the plasma is depressed far below the Saha value. Lowenstein estimates this value to

* It is needless to say that the absolute values of Ne will be misleading here, as the experiments were done at different pressures.
be ≈ 100, however, this study indicates a much higher value \((v_3 \times 10^3)\). Consequences of this result will be discussed in the sections to follow. At this stage we will simply deal with the engineering aspect of the laser.

The graph in Fig. 4.7 immediately suggest than an MHD laser operating with seed concentrations below \(1.4 \times 10^{-5}\) will not be a practical device, gain is too sensitive to the fluctuations in fcs in that zone. The data suggests that seed mole fraction should be in the vicinity of \(1.4 \times 10^{-5}\) to \(2 \times 10^{-5}\). It is important at this time to mention that in order to compensate per the loss of metallic Cs due to \(\text{CO}_2\) and Cs interaction one might have to seed the laser plasma in excess of the above recommended value, and an error, if any, is desirable in the positive direction. An estimate of the rate of \(\text{CO}_2\) - Cs interaction has been made in section 4.

4.2.3 Effects of \(\text{CO}_2\) Concentration

Using the data reduction method discussed in section 4.3.4 a plot of gain versus \(\text{CO}_2\) concentration has been obtained (Fig. 4.8). The laser gain coefficient for a pressure broadened profile which is applicable in this case of MHD laser, may be written in the form:

\[
\alpha(v) = \Delta N_{\text{CO}_2} \frac{\lambda^2}{8\pi n^2 \tau_{\text{spont}}} g(v) \quad (4.3)
\]

For simplicity considering the equation at the resonance \(v = v_0\):

\[
\alpha(v_0) = \Delta N_{\text{CO}_2} \frac{\lambda^2}{8\pi n^2 \tau_{\text{spont}}} \quad (4.4)
\]

As normalized line shape function \(g(v_0) = \frac{1}{\Delta v}\).
For pressure broadened profiles:

\[ \Delta \nu = \sum_{s} N_{s} \sigma_{s} \sqrt{\frac{8kT}{\pi \mu_s}} \]

Values for \( \sigma_{s} \) are:

\[ \sigma_{CO_2-CO_2} \approx 10^{-8} \text{ m}^2 \]

\[ \sigma_{CO_2-He} \approx 0.3 \times 10^{-8} \text{ m}^2 \]

Calculations show that for CO\textsubscript{2} concentrations of interest the broadening is dominated by the He, which is the dominant species. Hence we write:

\[ \Delta \nu \propto N_{He+CO_2} \]

or,

\[ \alpha(\nu_0) \propto \frac{\Delta N_{CO_2}}{N_{He+CO_2}} \quad (4.5) \]

or,

\[ \alpha(\nu_0) \propto \Delta f_{CO_2} \quad (4.6) \]

Thus we see that small signal gain is proportional to the population inversion normalized to the total number of neutral species, and hence the plot in Fig. 4.8.

Initially, as expected, gain rises linearly, with increase in molecular population. However, gain after reaching a maximum of 0.32%/cm\textsuperscript{-1} at 0.93% CO\textsubscript{2} concentration starts to drop at a much slower rate than the rise. The adverse effect on inversion may be attributed to already discussed following reasons: overcrowding of the laser lower level, increased inelastic losses of electron energy to CO\textsubscript{2} molecules, as the
relative number of the latter grows, and quenching of the excited Cs atoms. In spite of overloading of the nonequilibrium MHD interaction, inversion providing a gain of $0.09\text{cm}^{-1}$ is achieved, even at a $\text{CO}_2$ concentration of 3%.

It is important to note that for high laser output power, $\text{CO}_2$ population made available to the plasma should be as large as may be allowed without sinking the unsaturated gain to an unacceptable level. Also, recalling the graph in Fig. 4.6, it can be seen that laser operation at lower gain values ($\sim 0.1\text{cm}^{-1}$) provides a longer useful cavity. A laser design enthusiast can very well see that although the optimum value for $\text{CO}_2$ concentration is 0.93%, for efficient power extraction it will be much higher, the limit being the bottle-neck effect discussed in chapter 2. According to the theoretical study done by Walter the value is 3%, at which he predicts a gain value close to $0.1\text{cm}^{-1}$, a figure very much in agreement with the graph in Fig. 4.8.

4.2.4 Optimum Current Densities

As a variable during the investigation current density has been representative of the electrical properties of the plasma in question by simulating the $\mathbf{U} \times \mathbf{B}$ induced field of flowing systems. The qualitative effect of magnetic field on gain has been discussed in section 4.4, however the picture is not complete without consideration of the effect of its magnitude coupled with flow velocity $\mathbf{U}$, which is implicit in the magnitude of current density.

In a flowing system both $\mathbf{U}$ and $\mathbf{B}$, along with $f_c$, $f_{\text{CO}_2}$, and $p$,
have to be defined to create any desired plasma condition, however, in our case the current density serves as the closing link. The number density of electrons, their distribution function and average temperature are uniquely defined, consequently so are the excitation and deactivation rates of laser levels by the current density.

When, for fixed values of \( f_{\text{Cs}} \), \( f_{\text{CO}_2} \) and \( p \), the current density is varied, a value is reached where the gain is maximum. Results of such experiments for two different gas mixtures are plotted in Figs. 4.14 and 4.15. For the set of experiments of Fig. 4.14 the seed mole fraction was \( 10^{-5} \) with a \( \text{CO}_2 \) fraction of 0.74\%. At a constant pressure of 42.00 torr, maximum gain of \( 0.10\% \text{cm}^{-1} \) was recorded at a current density of 0.4 amp/cm\(^2\). The curve is almost cone symmetrical about the maximum, gain disappears at current densities below 0.22 amp/cm\(^2\) and above 0.50 amp/cm\(^2\).

On the other hand, in Fig. 4.15 the gain rises rapidly from seed to 0.125\%cm\(^{-1}\) when the current density is increased from 0.25 amp/cm\(^2\) to 0.3 amp/cm\(^2\), and with further increase in the latter, although it falls it tends to reach an asymptotic value of \( 0.05\% \text{cm}^{-1} \). The main difference in these data sets is in \( f_{\text{Cs}} \) and \( f_{\text{CO}_2} \), in this case (Fig. 4.15 being \( 6.0 \times 10^{-5} \) and 2.47\% respectively.

For a clearer view the corresponding conductivities have been plotted against gain in Fig. 4.16. At higher values of \( \text{CO}_2 \) mole fraction the plasma stabilizes, increase in conductivity does not effect the inversion severely and decay in gain is slower. As concluded before, laser operation at higher \( \text{CO}_2 \) concentrations (\( \sim 2\% \)) will be stable and predictable.
4.2.5 Effect of Quenching of Excited Cs Atoms

When the rate of relaxation of the excited state of Cs atoms by CO₂ molecules becomes comparable to the rate of its excitation by electrons, the electron number density is severely reduced. For a simple qualitative analysis we make following assumptions:

1. The excitation rate = $N_{Cs} N_e \tilde{C}_{e} Q_{e-Cs}$ \hspace{1cm} (4.7)

and

2. The Quenching rate = $N_{Cs}^{*} n_{CO₂} \tilde{C}_{Cs-CO₂} Q_{CO₂-Cs}$ \hspace{1cm} (4.8)

3. The vibrational levels of CO₂ molecules act in such a way that an average quenching cross section can be defined.

4. $N_{Cs}^{*} \approx N_e$

Then the effectiveness of the quenching process can be represented by the ratio $\frac{n_{CO₂}}{n_{Cs}} = \frac{f_{CO₂}}{f_{Cs}}$. In Fig. 4.17 the dependence of gain on this ratio can be seen. Gain increases linearly with $\log(f_{CO₂}/f_{Cs})$. Until the latter reaches a value of 700, a steep drop in gain follows that point. Shaw⁵ reports that the depression of electron number density below the Saha value is gradual, as the quenching rate increases, and at a critical value electron number density is severely reduced. The drop in gain in Fig. 4.17 is linear and it is concluded that, though quenching has become important, the critical point is not reached.

Taking 0.1%cm⁻¹ as the lower limit for desirable value of $f_{CO₂}/f_{Cs}$, we find 1800 to be the allowable value for $f_{CO₂}/f_{Cs}$. For $f_{Cs} = 2.0 \times 10^{-5}$, the CO₂ mole fraction is then 3.5%.
4.3 Experiments with Magnetic Field

The data taken without magnetic field provide a comprehensive knowledge about the excitation and relaxation processes of \( \text{CO}_2 \) molecules in a uniform MHD plasma. Gain measurements were made with magnetic field to observe the effects of non-uniformities. Two typical gain curves are presented in Fig. 4.9 and Fig. 4.10. During the first 10-15 \( \mu \) sec, a steep rise is seen, and then the inversion tends to follow an oscillatory pattern. It is believed that the Lorentz force, which in our configuration acts perpendicular to the laser beam, generates a pressure wave carrying the excitation out of the probe area. Taking the sound speed in the tube as 1000 m/sec we find a full wave period in the 2.54 cm tube of 25 \( \mu \) sec, which is close to the observed average period. The ratio \( J \times B/\rho \) ranges from 1.5 m\(^{-1}\) to 0.3 m\(^{-1}\).

It is concluded that the peak gain recorded in such experiments are the values which would be realizable in a flow system. The data so obtained has been reduced to find a relationship between gain and magnetic field strength and is presented in Fig. 4.11. The graphs have been plotted for three different values of \( \text{CO}_2 \) concentration. With increasing magnetic field, the effective dissipation in the plasma increases and hence the pumping, and consequently the gain. It will be seen from Fig. 4.11 that gain decreases with \( \text{CO}_2 \) population, which seems consistent with the result of section 4.2.3.

As an exercise in consistency of results a plot of gain versus Cs mole fraction (for \( B \neq 0 \)) is shown in Fig. 4.12. When compared with the graph
in Fig. 4.7 (for B = 0) it should be noted the optimum value for $f_{Cs}$, in both cases, is close to $10^{-5}$. The measured gain, in this section, is smaller than its value in Fig. 4.7 for a corresponding seed fraction, especially at higher values of $J \times B/p$, when the pressure wave becomes stronger. In a flow system designed for MHD interaction the Lorentz force vector acts opposite to the pressure gradient causing the motion and does not have any similar effect on gain. (In fact the inversion in a poorly designed nozzle system might not have a uniform profile, but due to other effects which will not be discussed here.) The gain measured in this section represents the lower limit for the particular case in question and higher values may be achievable in real practice. In this work however we will limit ourselves to the data in hand and simply remark that at state of the art fields of 4 to 5 tesla the gain would be of respectable value.

The measured apparent Hall parameter falls in the range of 0.45 to 0.67, close to the value reported by other experimental investigators (4, 7, 11). In the analytical calculation of Walter, $^{12}$ in which $\beta_{app}$ is computed by the model originated by Solbes $^{15}$ and Parma $^{29}$ and later modified by Cole, $^{16}$ a value of 0.1 has been reported ($f_{CO_2} = 3\% ; B=4.0$ tesla). Since this parameter is dependent on the electrode and insulator design and growth of electrothermal instabilities at higher magnetic fields realization of optimized Hall recovery may be difficult in an MHD laser (quantitatively the results of Parma's and Cole's models for high $<\beta> \geq 10$ may be questioned).
The non-uniformities in an MHD plasma profoundly influence electron temperature elevation and average joule dissipation of energy in the gas. In the limit when $<\beta> > \beta_{\text{crit}}^{33}$ a "turbulent state" is reached with an anomalous increase in resistivity. The value of $\sigma_{\text{eff}}/<\sigma>$, which is a measure of "turbulence", has been found to be on the order of $\sim 0.2$, with $\beta_{\text{eff}}$ closed to 0.5.

As the value of $<\beta>$ increases, gain rises and reaches the peak value of $0.32\text{ cm}^{-1}$, which interestingly enough coincides with the maximum value measured in absence of a magnetic field. The peak value with magnetic field was reached at a lower CO$_2$ mole fraction (0.74% vs 0.94%) and lasted only 4 µsec as compared to 10 µsec ($\beta = 0$).

It has been postulated that high turbulence somehow tends to create more favorable condition for pumping.

4.4 **Relaxation Rates for the Lower Laser Level (1^00)**

While the discharge is on, the vibrational levels of CO$_2$ are pumped and the population of any level can, in its simplest form, be computed by the rate equation:

$$\frac{d}{dt} N = W_p N_0 - \frac{N}{\tau_e}$$  \hspace{1cm} (4.9)

where $\frac{1}{\tau_e}$ represents the depletion of the population in question by collisional relaxation, excitation out of the level by electron impact, and radiative decay. When the discharge is short-circuitied, electronic pumping of the level ceases and the system in time approaches an equilibrium state. The transient behavior of the population can be described as:

$$N(t) = N_{\text{equ.}} \exp(-t/\tau_e)$$  \hspace{1cm} (4.10)
For our purpose the time constant $\tau_e$ hereafter will be referred as the collisional relaxation time constant, as the radiative decay of the lower and upper laser levels of $\text{CO}_2$ molecules is relatively very slow (chap. 2). The decay of population inversion in the afterglow of the discharge in simplified notation can be expressed as:

$$\Delta N = N_{20} \exp(-t/\tau_{e2}) - N_{10} \exp(-t/\tau_{e1})$$  \hspace{1cm} (4.11)

where 2 and 1 are subscripts for the upper and lower laser levels. The time constant $\tau_{e2}$ has very large values,\(^{47,48}\) for example, for a 97% He + 3% $\text{CO}_2$ gas mixture at a typical pressure of 50 torr, they are:

$$\tau_{e2}^{\text{He}} = 230 \ \mu\text{sec}$$

$$\tau_{e2}^{\text{CO}_2} = 1852 \ \mu\text{sec}$$

Thus, without introducing any appreciable error in the analysis (<5%) Eq. (4.12) can be rewritten as:

$$\Delta N = -N_{10} \exp(-t/\tau_{e1})$$  \hspace{1cm} (4.13)

A relaxation rate constant is defined as:

$$k = \frac{1}{\tau_p}$$  \hspace{1cm} (4.14)

and usually expressed in units of atm$^{-1}$ sec$^{-1}$. Since both the He and $\text{CO}_2$ participate in the deactivation process, the relaxation time constant $\tau_e$ can be split into two parts:

$$\frac{1}{\tau_e} = \frac{1}{\tau_{e,\text{He}}} + \frac{1}{\tau_{e,\text{CO}_2}}$$  \hspace{1cm} (4.15)
Using Eq. (4.9) and simple algebra, the following relationship can be obtained:

\[
\frac{1}{\tau_e^p} = k_{CO_2-He} + f_{CO_2} (k_{CO_2-CO_2} - k_{CO_2-He})
\]  

(4.16)

As the small signal gain measures the magnitude of the population difference \( \Delta N \), \( \tau_e \) is easily obtained from the data (Fig. 4.5; note the decay of laser beam absorption after the discharge is short-circuited). Values of \( \frac{1}{\tau_e^p} \) have been plotted against their respective CO\(_2\) concentrations in Fig. 4.18 and the following rate constants were determined:

\[
k_{CO_2-He} = (7.5 \pm 0.5) \times 10^4 \text{ atm}^{-1} \text{sec}^{-1}
\]

\[
k_{CO_2-CO_2} = (3.3 \pm 0.3) \times 10^7 \text{ atm}^{-1} \text{sec}^{-1}
\]

The mechanism of symmetric stretch mode relaxation by CO\(_2\) molecules is very complex (chap. 2) and this investigation cannot identify the individual pathways of deactivation. However, the following facts allow us to make some reasonable speculations:

1. The system measures the slowest rate and hence the "bottleneck" rates.

2. Deactivation of the CO\(_2\)(01'0) level by He is one order of magnitude faster than by CO\(_2\)\((k_{CO_2}(01'0)-He = 4.0 \times 10^6 \text{ atm}^{-1} \text{sec}^{-1}\) at T = 400°C) and the major role of CO\(_2\)-CO\(_2\) collisions is to bring the CO\(_2\)(10\(^0\)0) level to CO\(_2\)(01'0) either via CO\(_2\)(10\(^0\)0)→CO\(_2\)(02\(^0\)0) or CO\(_2\)(10\(^0\)0)+CO\(_2\)(01'0) transfers.

It is concluded that the rate measured for CO\(_2\)-CO\(_2\) relaxation is the bottleneck rate for the lower level deactivation:
\[ k_{\text{CO}_2(10^00) - \text{CO}_2(01')0} = (3.3 \pm 0.3) \times 10^7 \text{ atm}^{-1} \text{ sec}^{-1} \]
\[ = (4.3 \pm 0.4) \times 10^4 \text{ torr}^{-1} \text{ sec}^{-1} \]

This rate very closely coincides with the rate calculated by Seeber and is of the same order of magnitude as reported by Bulthuis and Ponsen. Table 2 compares the reported rates with the value measured in this experiment.

In Table 3 relaxation rates between \( \text{CO}_2(10^00) - \text{CO}_2(02^00) \) are listed. The investigators believe that all the levels in the bending mode do exist in Boltzmann equilibrium and bottleneck rate is determined by \( \text{CO}_2(02^00) \) population. A close examination of the rates tempts us to make following speculations:

1. If the explanation given by Stark is correct, then there must exist another process, slower than \( \text{CO}_2(10^00) - \text{CO}_2(02^00) \), which determines the bottleneck rate.

2. If the other rates are correct, then, definitely, the bottleneck exists at the \( \text{CO}_2(10^00) - \text{CO}_2(02^00) \) equilibrium.

The value of \( k_{\text{CO}_2 - \text{He}} \) is very low for the relaxation rate of the lower laser level (except according to the value reported by Rosser, Hoag, and Gerry, and interestingly enough, coincides with the relaxation rate for the upper laser level. It would be wise to leave this rate with the comment that it represents a slow process of deactivation by the atoms, and \( \text{CO}_2 - \text{CO}_2 \) collisions establish the "bottleneck rate".
4.5 Rate of Cs–CO$_2$ Interaction

The exact nature of Cs + CO$_2$ chemical interaction is not known. Two possible reactions have been cited:

\[ \text{CO}_2 + \text{Cs} \rightleftharpoons [\text{CO}_2 \text{Cs}]_x \quad (4.17) \]

and

\[ \text{CO}_2 + 2\text{Cs} \rightleftharpoons \text{CO} + \text{Cs}_2\text{O} + \text{E} \quad (4.18) \]

Reaction (4.18) is believed to be weakly exothermic at room temperature. Without going into the details of the reaction mechanism, we will estimate the rate of interaction. Let $Q_{\text{Cs-CO}_2}$ be the cross-section for this interaction such that the frequency of chemical encounters

\[ \nu_{\text{Cs-CO}_2} = \frac{n_{\text{CO}_2} Q_{\text{Cs-CO}_2} \bar{c}_{\text{CO}_2}}{\sec^{-1}} \quad (4.19) \]

where $\bar{c}_{\text{CO}_2}$ is the mean velocity defined as

\[ \bar{c}_{\text{CO}_2} = \left( \frac{8kT}{\pi} \left( \frac{1}{M_{\text{CO}_2}} + \frac{1}{M_{\text{Cs}}} \right) \right)^{1/2} \]

Thus the fraction of Cs atoms lost due to the chemical reaction is:

\[ \frac{\Delta n_{\text{Cs}}}{n_{\text{Cs}}} = \nu_{\text{Cs-CO}_2} \sec^{-1} \quad (4.20) \]

and hence the cross-section

\[ Q_{\text{Cs-CO}_2} = \frac{\Delta n_{\text{Cs}}}{n_{\text{Cs}} n_{\text{CO}_2} \bar{c}_{\text{CO}_2}} \quad (4.21) \]

Several experiments were conducted in sets of two: one with, and one without CO$_2$, and from the Cs absorption diagnostics the $n_{\text{Cs}}$ was determined using the calibration curve 3.10. It should be remembered
that in the absence of CO₂ the Cs mole fraction remains constant throughout
the pressure pulse, which is confirmed by the absorption curve. From the
two curve we get the time history of total Cs atoms lost, i.e.

\[
(\Delta n_{\text{Cs}})_{\text{tot}} = \int_{0}^{t} n_{\text{Cs}} n_{\text{CO}_2} Q_{\text{Cs-CO}_2} \bar{C}_{\text{CO}_2} \, dt
\]  

(4.22)

A numerical differentiation of \((\Delta n_{\text{Cs}})_{\text{tot}}\) gives \(\Delta n_{\text{Cs}}\), from which the
cross-section can be calculated using the equation (4.21).

From several sets of data the cross-section was computed to be in the
range of \(1.3 \times 10^{-24}\) to \(4.6 \times 10^{-24}\) m².
CHAPTER V

DISCUSSION OF RESULTS

The measurements of axial electric field by two probes in contact with the plasma show that the conductivity does not remain constant throughout the experiment. Its value increases with time. It has been mentioned from time to time in previous chapters that due to redistribution of CO₂ molecules amongst their vibrational levels due to excitation and various relaxation processes, the value of the inelastic loss factor δ_{CO₂} goes down. Walter in his analytical three temperature study has observed that this reduction may be as large as 50%. While reviewing the relaxation processes we have seen that the levels in the bending mode relax much slower than would be required to attain a Boltzmann distribution within the mode. In that case it would be inaccurate to assign one temperature to all the levels of the bending mode. 02^0, 01^0 and 03^2 O should be described by three different temperatures, and one would require a "5 temperature" model. One would expect a drastic reduction in δ_{CO₂}, and hence increase in conductivity if this occurs. In the experiment, however, there is another phenomenon, which may cause the same effect. The electron energy equation if written for static conditions, i.e. if the fluid velocity is zero, will take the form:

\[
\left(\frac{3}{2} + \frac{r}{kT_e}\right) kT_e \frac{\partial n_e}{\partial t} = \frac{J^2}{\sigma} - \sum_s \varepsilon_s
\]  

(5.1)

where \(\varepsilon_s = \delta \frac{m_e}{m_s} \frac{3}{2} (T_e - T) n_e \nu_e\) is the loss term. Since J is maintained constant during the experiment, one would expect a gradual change in \(n_e\).
(and $T_e$ coupled with Saha equation). Further analysis shows that, in fact, a gradual evolution of the ionization process towards full ionization takes place, which results in an increase in the conductivity of the plasma.

Typical increase in electron temperature with time is shown in Fig. 5.1. We know that at higher electron number densities ($n_e/n_{He} > 10^{-5}$) pumping of the bending mode becomes significant, which has a negative effect on the inversion. This has been confirmed during the experiment, since in most cases where a positive gain in the beginning of the discharge was recorded, a gradual decrease in gain is observed, and toward the end of the discharge the gain turns into absorption.

The numerical model of Walter$^{12}$ predicts gains in the range of $0.1 - 0.15\%$ ($T_0 = 2090^\circ K$), however he points out that if the stagnation temperature is lowered to $1800^\circ K$ gain may reach a value of $0.21\%$, and it seems perfectly plausible that if $T_0$ is reduced further the calculated small signal gain may rise to the measured value of $0.3\%$ cm$^{-1}$. It is not clear, however, how low the static temperature has to be to achieve such an inversion. In the calculations using $T_0 = 2090^\circ K$, the static temperature falls to the range of $400^\circ K$ to $600^\circ K$, then, due to the Lorentz force, it rises as the fluid moves along the nozzle. This temperature range is slightly higher than that of the experiments.

Furthermore, Walter's calculations are based on a constant Mach number channel, which may not be an advantageous design for an MHD laser, probably a constant temperature or a compromise between the two may be better. At this point it is difficult to speculate, only after a series of numerical calculations would one be able to draw any conclusions.
The Russian group, by extrapolating from the losses in the cavity, came to the conclusion that a small signal gain of 0.3%/cm\(^{-1}\) was achieved in the experiments (T = 400°K), which equals the value measured in this investigation.

Walter concludes that the optimum CO\(_2\) mole fraction is 3%. In this study the maximum gain has been measured at 1% CO\(_2\) and, as will be shown in Chapter 6, maximum power extraction will not occur at 1% CO\(_2\). The output intensity is dependent on one more factor, namely, saturation intensity, whose value increases with increasing CO\(_2\) mole fraction. The gain is measured to decrease as \(f_{\text{CO}_2}\) is increased from 1%. Thus the optimum CO\(_2\) mole fraction definitely will be larger than 1% and may be equal to 3%. A power extraction experiment is needed to confirm this.

The fact that Walter did not account for Cs – CO\(_2\) chemical interaction does not effect the validity of his results, as the cross-section for the reaction is measured to be very small \(\sim 10^{-24} \text{ m}^2\). At pressures on the order of 0.25 atm only a few percent of Cs would be lost.

The electron temperatures measured range from 3300°K to 4500°K (1% CO\(_2\)), which is in close agreement with the prediction of the numerical study. The same is true for values at other CO\(_2\) mole fractions. The electron number density, when scaled down by a factor equal to the ratio of the pressures, is in good agreement with Walter's values. Under optimum conditions (1% CO\(_2\)) the value is \(6 \times 10^{18} \text{ m}^{-3}\) (p = 60 torr, \(f_{\text{Cs}} = 10^{-5}\)). Lowenstein, while studying the effect of quenching computed an upper limit for ratio \(n_{\text{CO}_2}/n_e \leq 100\) to be allowed into a laser cavity. In the present
study typical values have been on the order of $\approx 10^4$, and much higher
gain values have been recorded. This indicates that his estimate for
the quenching cross-section is unrealistically high. Furthermore, Walter
in his study showed that even if the cross-section is as high as assumed
by Lowenstein ($70 \text{Å}^2$), in an adequately preionized fluid, losses due to
quenching would be negligible.
CHAPTER VI

SUMMARY

With the aid of a 6 watts/cm² probe CO₂ laser (oscillating at 10.6μ infrared wavelength) the small signal gain of He + CO₂ + Cs plasmas with compositions typical of MHD lasers has been measured. Variables used to provide a wide spectrum of pumping and relaxation rates are:

1. Current density J varied from 0.2 amp/cm² to 0.75 amp/cm².
2. CO₂ mole fraction f CO₂ varied from 0.74% to 4.7%.
3. Cs mole fraction f Cs varied from 8.0 x 10⁻⁶ to 3.0 x 10⁻⁴.
4. Magnetic field B varied from 0.0 to 0.68 tesla.
5. Mixture static pressure P varied from 33.0 torr to 70.0 torr.

Under these conditions, the small signal gain was measured to be in the range of 0.06% cm⁻¹ to 0.3% cm⁻¹. During the ν300 μsec experimental time of each experiment, population inversion, in general, was found to be transient in behavior, which has been a very important feature of this investigation. Time scales for relaxation processes to attain equilibrium range from 1 μsec to 10³ μsec, in fact for most of the experiments it has been on the

*It is assumed that sufficient number of CO₂ molecules are available in the ground state.
order of 5.0 µsec (which has been computed based on the relaxation data measured during this study). Thus, gain (or absorption) lasting more than 5 µsec is a result of fully developed inversion kinetics and has been regarded as valid experimental data.

Due to redistribution of the CO₂ molecule population amongst its various vibrational levels, the average coefficient of inelastic losses changes, actually drops, sometimes enough to alter the electron number and electron temperature on the scale of 5-10 µsec. Under these conditions one single experiment is able to provide several valid experimental gain measurements.

The time history of the gain data tells another interesting story, that the higher the gain value, the shorter the time it lasts. A graph of gain versus its duration has been presented in Fig. 4.6. This phenomenon, apart from drop in δ CO₂ value may be due to another reason: severe reduction of ground state CO₂ molecules. In fact, a simple calculation based on rate equations has shown that at low CO₂ concentration (≈0.9% at p = 50.0 torr) more than 50% of the total molecular population participates in creation of a gain value of, say, 0.3% cm⁻¹, requiring a population inversion of \( \frac{N_{\text{CO}_2(0^01)} - N_{\text{CO}_2(1^00)}}{N_{\text{CO}_2}} \) = 1.7 x 10¹⁵ molecules/cm³. In experiment 4120, at 0.94% of CO₂ mole fraction, the measured gain reached a value of 0.32% cm⁻¹, but lasted only a few µsec, and then very rapidly dropped, turning into absorption. It is concluded that the pumping power of the

*It is assumed that sufficient number of CO₂ molecules are available in the ground state.
plasma, representing the number density and the temperature of electrons, was high enough to excite the required number of CO$_2$ molecules, but after a few micro-seconds the supply of ground level molecules had been depleted, and the inversion could not be maintained further. Thus, if the mixture static pressure is increased and the mole fraction of CO$_2$ is kept at $\sim$0.9%, both, high pumping power and adequate supply of CO$_2$ molecules may be maintained and the small signal gain on the order of 0.3% cm$^{-1}$ may be achieved. At this point it is important to note that CO$_2$ mole fraction is not the only nondimensional parameter which should be kept constant in order to duplicate the plasma conditions at any particular pressure, the others* will be discussed later in this section.

As the CO$_2$ mole fraction is increased, beyond 0.9%, gain drops, at 3% CO$_2$ the value is 0.1% cm$^{-1}$, and lasts for the entire duration of the discharge ($\sim$300 µsec). Three different phenomena affect the inversion kinetics as the CO$_2$ mole fraction is increased in the plasma: (1) more molecules become available in the ground state (for excitation); (2) the inelastic "load" on the non-equilibrium regime increases; (3) relaxation of the lower laser level by CO$_2$ molecules (to the 01'0 level) intensifies and finally reaches the "bottleneck", a saturation point.

In a flowing system (Mach number of 4) the plasma would move with a velocity of 0.4 cm/µsec and travel a distance of, say, half a

* $<\beta>$, $M$, $\sigma_{eff}$, $<\sigma>$, $\beta_{app}$, to name a few.
meter in \( \approx 125 \) \( \mu \)sec. Thus the plasma conditions creating an inversion lasting more than 100 \( \mu \)sec would provide enough active volume for power extraction.

The optimum Cs mole fraction has been found to be \( 1.4 \times 10^{-5} \). At lower values of \( f_{\text{Cs}} \) gain very sensitive to former's value, a 10% reduction in \( f_{\text{Cs}} \) causes a 30% drop in gain, whereas a similar increase \( (f_{\text{Cs, opt}} + 10\%) \) does not make any significant drop in the gain value \((-5\%)\). It is common knowledge that, in practice, even a moderate accuracy \((\pm 50\%)\) in seeding is hard to achieve, the error margin should be set only in the positive direction \(i.e. f_{\text{Cs}} + 50\%, \) for example, for reasons said before.

Although, it is known that Cs and \( \text{CO}_2 \) interact chemically, no concrete information about the nature of the resultant products or the rate of interaction is available, to date. During this investigation the cross-section for this interaction has been experimentally determined to be \( 1.3 \times 10^{-24} - 4.6 \times 10^{-24} \) \( \text{m}^2 \) at 400 K. Based on these data, at a pressure of 0.1 atm the characteristic time for the chemical reaction with 3% of \( \text{CO}_2 \) would be about 30 msec against the residence time of 0.17 msec of a 0.5 m cavity:

\[
\frac{t_{\text{res}}}{u} = \frac{L}{u} = \frac{0.5 \text{ m}}{3000 \text{ m sec}^{-1}} = 0.17 \text{ milli sec}
\]

which means that only \( 0.17/30 \approx 5.6 \times 10^{-3} \) fraction of the Cs number density would be lost and even with an accuracy of \( f_{\text{Cs}} + 10\% \) seeding, no noticeable change in \( n_{\text{Cs}} \) will occur.
The apparent Hall parameter has been found to be in the range of 0.45 to 0.67. The average Hall parameter is computed as ranging between 1.80 and 2.60 and definitely indicates signs of turbulence. With increasing $<\beta>$, the gain rises and achieved the recorded highest limit of 0.3% cm$^{-1}$ even at a low CO$_2$ concentration of 0.74%, though, for the reasons explained above, gain does last only for 10 µsec. This suggests that the pumping power is enhanced in a turbulent MHD plasma. At low values of $<\beta>$, the gain is close to 0.08% cm$^{-1}$, a value predicted by Walter. These results may tempt one to design a MHD laser to operate in the turbulent mode, however caution is warranted here, since a turbulent gain medium is likely to deteriorate the beam quality.

In order to duplicate the electrical conditions of this experimental study in real practice, an MHD laser should be designed to produce an induced field $u \times B$, at least, equal to the field $E$ externally applied in this study. An electric field of 20v/cm has been typical. Thus for a flow velocity of 3000 m/sec (Mach number 3) we estimate the required magnetic field $B$ to be 0.67 tesla, which is slightly higher than used in the experiments. At state-of-the-art fields of 4-5 tesla the induced field would be more than adequate.

Sometimes, the discharge character of a plasma is defined by the $E/p$ value. In the present work, on average, it is on the order of 0.5vcm$^{-1}$ torr$^{-1}$ (Table 4), which would be high enough to create a
self-sustained discharge \(^{11}\) (\(^{\sim\text{6.0 volts cm}^{-1}	ext{torr}^{-1}\})\) at higher magnetic fields, say, 4-5 tesla.

Joule dissipation is another important parameter. When written in non-dimensional form, its analytical expression is very useful in design considerations:

\[
\frac{T_e - T_g}{T_g} = \frac{\nu}{3\delta_t} M^2 <\beta>^2 \frac{\sigma_{\text{eff}}}{\langle\sigma\rangle} \frac{1 + \beta_{\text{app}}^2}{1 + \beta_{\text{eff}}^2}
\]

(6.1)

It should be noted that \(n_e\) does not directly affect the expression and Joule dissipation can be measured in terms of \(\frac{T_e - T_g}{T_g}\), which in our experiments has reached values up to 9.0. For this value, substitution of other numbers, results in Mach number of 4.4, which might be a value higher than easily achievable in practice. However, as it was said before by raising \(<\beta>\), the desired dissipation can be achieved. It is interesting to note that, according to the data, the effective Joule dissipation can be achieved even at 0.5 tesla magnetic field in a 4.4 Mach number flow system, and the induced field will be on the order of the required value. In order to "ignite" the discharge a preionizer might be needed, however,

From the gain data, recorded in the after-glow of the discharge, the relaxation rate constant for the lower level by \(\text{CO}_2\) molecules has been computed:

\[
K_{\text{CO}_2(0^00)\text{--CO}_2(01^0)} = (3.3 \pm 0.3) \times 10^7 \text{ atm}^{-1} \text{ sec}^{-1}
\]
This rate is equal to the value reported by Seeber, who, in his modified SSM theory model, assumes that $0^2 \,^0 \text{O}$ and $0^1 \,^1 \text{O}$ levels of the bending mode are not in thermal equilibrium. Bulthuis, based on his power decay measurements, reports a value very close to it ($\approx 10^7 \text{ atm}^{-1} \text{ sec}^{-1}$). Since this measurement did not identify any particular pathway for the $10^0 \,^0 \text{O} \rightarrow 01^1 \text{O}$ relaxation process, and the published rate constants for, even, the $10^0 \,^0 \text{O} \leftrightarrow 0^2 \,^0 \text{O}$ terms resonance are not in agreement, no speculation about the mechanism will be made. It will be sufficient to state this rate is the sum of the rates for all possible pathways:

(1) $\text{CO}_2(10^0 \,^0 \text{O}) \leftrightarrow \text{CO}_2(02^0 \,^0 \text{O}) \leftrightarrow \text{CO}_2(01^1 \,^0 \text{O})$

(2) $\text{CO}_2(10^0 \,^0 \text{O}) \leftrightarrow \text{CO}_2(01^1 \,^0 \text{O})$

(3) $\text{CO}_2(10^0 \,^0 \text{O}) \leftrightarrow \text{CO}_2(02^2 \,^0 \text{O}) \leftrightarrow \text{CO}_2(01^1 \,^0 \text{O})$

The time constant for this process, if computed for $p = 40 \text{ torr}$ and $f_{\text{CO}_2} = 0.03$, comes to be $20,000 \text{ sec}$, which is much larger than the time constant* for $\text{CO}_2(01^1 \,^0 \text{O}) \rightarrow \text{He}^5$ ($\approx 4 \text{ sec}$), suggesting that the former process establishes the "bottleneck rate".

The value for $K_{\text{CO}_2(10^0 \,^0 \text{O})} \rightarrow \text{He}$ relaxation process, found by extrapolation to $f_{\text{CO}_2} = 0$, is very low and falls within the error limit.

*The rate constant for this process is well researched and studied, and known with reasonable ($\pm 10\%$) accuracy).
6.1 Power Extraction

The measured gains are quite large (by MHD laser standards) and in view of the other information made available by this investigation (the rate of relaxation of the lower laser level and the rate of chemical interaction between CO₂ and Cs), we will take a fresh look at the power delivering capabilities of MHD lasers. In its simplest form, the expression for the intensity extractable from a laser cavity may be written as:

\[ I_0 = \frac{P_0}{A} = 2I_s \left( \frac{\alpha_0 L}{L_i + T} - 1 \right) T \]  \hspace{1cm} (6.2)

The magnitude of \( I_s \), the saturation intensity, depends, exclusively, on the physical properties of the laser mixture, and on its composition and static pressure. \( I_s \) lets us estimate the magnitude of the maximum laser power which may be extracted from a particular laser medium. From the expression for

\[ I_s = \frac{4\pi n^2 \Delta \nu \nu}{(t_2^i/t_{\text{spont}})^2} \]  \hspace{1cm} (6.3)

it can be seen that its value increases directly proportional to \( p^2 \), since \( \Delta \nu \propto P \) and \( t_2^i \propto \frac{1}{p} \). Thus the output power from a low internal loss (Li) laser cavity goes up as \( \alpha_0 p^2 \).

The relaxation time \( t_2^i \), in CO₂ lasers, is basically the relaxation time of the upper laser level, however since a large number of levels are closely coupled with it in an inversion process Christensen et al.⁴² suggest that in in order to get any realistic
value one should use a $t_{\text{eff}}'$ instead of $t_2'$, the discrepancy may be
as actively involved in competing for population in a CO$_2$ laser.

Anderson$^{23}$ suggests another method for calculating the power
output from a gas laser, which calls for numerical solution of the
energy equations written for each vibration mode of the molecule.
Such an analysis for a MHD laser cavity has been performed by
Walter.$^{12}$ Walter's numerical model treats each mode individually
(assuming a vibrational temperature associated with each mode) and
uses the relaxation rate constants which are very close to the values
measured during this investigation. For rough estimates of the
laser power extractable from a MHD laser cavity, saturation intensi-
ties for various CO$_2$ mole fraction at a static pressure of 0.25 atm
have been evaluated by extrapolating the figures made available by
Walter's analysis. The results have been presented in Fig. 6.1.

For a given internal loss of the laser cavity (like absorption
of power in the mirrors), there exists an optimum coupling
parameter $T$.

$$(T)_{\text{opt}} = -L_1 + \sqrt{L_0 L L_1}$$  \hspace{1cm} (6.4)

Using the measured small signal gain data and the computed
saturation intensities, estimates of output laser intensities have
been made (Fig. 6.1). It can be seen laser intensities as large as
1 kW/cm$^2$ can be coupled-out from a MHD laser cavity, however it
would be erroneous to draw any conclusions about the total power

$^*$ Cavity width $L = 0.54m$
output, which depends upon the length along the nozzle within which the inversion can be maintained. Walter based on his numerical simulation of a MHD laser flow system points out that, although a high level of laser flux may be achieved at lower CO$_2$ mole fractions (say ~1% CO$_2$), after 5-10 cm of lasing length, the inversion is destroyed. Using these dimensions (height 2.3 cm) one gets a maximum laser output of 23.0 KW, and a power density of ~15.0 KJ/Kg.*

It should be noted that the actual power would be less than this value as it assumes that the entire wall acts as a coupling mirror.

Walter, further, mentions that at $f_{Cs} = 3\%$ this "usable length" extends to the entire length of the cavity (~45 cm) and computes a power density of 60 KJ/Kg, against 30.0 KJ/Kg estimated in this study.

In Fig. 6.2 specific power of various laser systems has been compared. It can be seen that the MHD laser may have a promising future as a high power laser.

6.2 Suggestions for Future Work

The investigation has established that small signal gains of up to 0.3% cm$^{-1}$ may be achieved in a MHD laser plasma. The measured relaxation rate of the laser lower level suggests that the capabilities of MHD lasers might have been overestimated by other investigators 6-8, the

*Walter used the dimensions of the MIT experimental nonequilibrium generator to calculate the gasdynamical parameters. In order to achieve a Mach number of 4 ($P_0 = 20$ atm; $T_0 = 2090^\circ$K) the mass flow required was $\dot{m} = 1.56$ Kg / sec.
bottom line predicted by this investigation is about 3-10 times less than previously computed. However, a close look at Fig. 6.1 would recommend the device as one of the promising competitors in the field of high power laser technology. In fact Biberman et al. measured 10KJ/Kg of specific power, which is very close to the bottom line predicted by Walter. 12

With the new understanding of non-equilibrium plasmas and their better numerical models 15, 16, 29 and the knowledge acquired by the numerical study of Walter and by this experimental investigation, a working model of the laser should be designed. On the design side, a better system for seeding of Cs and an appropriate location for CO₂ injection should be researched.

Further in the area of basic research the mechanism of lower laser level relation should be studied in more detail, the "bottleneck effect" which limits the magnitude of the laser power at 10.6μ, may not affect the emission at 9.6μ providing a possibility of high power laser operation at 9.6μ.

The measured relaxation rate for 10^0 + 01^0 process is very close to the values reported Bulthin's 59, 60 and Seeber 58 which suggests that the levels 01^10, 02^00, 02^0, 03^00 may not be in thermal equilibrium and in order to calculate the power output more accurately, an analytical model more vigorous than the three temperature model is warranted.
TABLE I

Relaxation Rates for Various Energy Transfer Processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Rate (atm$^{-1}$ sec$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_{Total}$</td>
<td>$\sim 10^{10}$</td>
</tr>
<tr>
<td>$k_{Rotation}$</td>
<td>$\sim 3.8 - 7.6 \times 10^{9}$</td>
</tr>
<tr>
<td>$k_{CO_2(00^01)}$</td>
<td>$\sim 3 \times 10^9$</td>
</tr>
</tbody>
</table>

(Summed overall neutral species)

(Thermalization of rotation levels in one vibrational level)
### TABLE II

**Summary of Report Values of CO$_2$(10$^0$0) -- CO$_2$(01'0) Relaxation Rates**

<table>
<thead>
<tr>
<th>Investigators</th>
<th>Methodology</th>
<th>Rate (atm$^{-1}$ sec$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhodes, Kelley, and Javan$^{50}$</td>
<td>Absorption at 10.6$\mu$m (1968)</td>
<td>$3.0 \times 10^8$</td>
</tr>
<tr>
<td>Seeber$^{58}$</td>
<td>Calculations (SSH theory) (1971)</td>
<td>$3.4 \times 10^7$</td>
</tr>
<tr>
<td>Bulthuis and Ponsen$^{59}$</td>
<td>Power decay in the afterglow (1972)</td>
<td>$9.9 \times 10^6$</td>
</tr>
<tr>
<td>Rosser, Hoag, and Gerry$^{49}$</td>
<td>Electric pulse, measured 4.3$\mu$m decay and gain at 10.6$\mu$m (1972)</td>
<td>$7.6 \times 10^5$</td>
</tr>
<tr>
<td>Bulthuis$^{60}$</td>
<td>Power decay (1973)</td>
<td>$7.7 \times 10^6$</td>
</tr>
<tr>
<td>This work</td>
<td>Measured gain at 10.6$\mu$m (1978)</td>
<td>$3.3 \times 10^7$</td>
</tr>
</tbody>
</table>
### TABLE III

**Summary of Reported Value of CO₂(10⁰O) - CO₂(02⁰O) Relaxation Rate**

<table>
<thead>
<tr>
<th>Investigators</th>
<th>Methodology</th>
<th>Rate (atm⁻¹ sec⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murray, Kruger, and Mitchner ⁶³</td>
<td>Experiments and Theoretical (1974)</td>
<td>0.9 - 1.5 x 10⁶</td>
</tr>
<tr>
<td>Jacobs, Pettipiece, and Thomas ⁶¹</td>
<td>Saturation at 10.6μ and measured gain 9.6μ</td>
<td>10⁷</td>
</tr>
<tr>
<td>Stark ⁶²</td>
<td>Monitored gain at 10.6μ and gain at 10.6μ after saturation</td>
<td>1.1 x 10⁸</td>
</tr>
</tbody>
</table>
## TABLE IV

### Important Features of Other Investigations \(^{(4,7,11,12)}\)

<table>
<thead>
<tr>
<th>Ref.</th>
<th>(E_{\text{volts/cm}})</th>
<th>(E/p) Volts cm(^{-1}) torr</th>
<th>Mach number</th>
<th>(\frac{T_e - T_g}{T_g})</th>
<th>(\langle \beta \rangle)</th>
<th>(\frac{\sigma_{\text{eff}}}{\sigma})</th>
<th>(n_e) (\text{cm}^{-3})</th>
<th>Gain (\text{cm}^{-3})</th>
<th>(f_{\text{CO}_2}) %</th>
<th>(f_{\text{Cs}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>90.0</td>
<td>1.18</td>
<td>4.7</td>
<td>9.0</td>
<td>10.0</td>
<td>0.1</td>
<td>(3-4 \times 10^{13})</td>
<td>0.05-0.15</td>
<td>2.0</td>
<td>(10^{-5})</td>
</tr>
<tr>
<td>2</td>
<td>57.3</td>
<td>8.30</td>
<td>5.0</td>
<td>9.6</td>
<td>39.0</td>
<td>0.05</td>
<td>(5.8 \times 10^{12})</td>
<td>0.2</td>
<td>4.0</td>
<td>(10^{-3})</td>
</tr>
<tr>
<td>3</td>
<td>120-240</td>
<td>6.0</td>
<td>3.0</td>
<td>13.0 (\beta_{\text{eff}}) (1-1.5)</td>
<td>(0.8)</td>
<td>(10^{13})</td>
<td>0.3</td>
<td>1.0</td>
<td>(10^{-5})</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>9.7</td>
<td>6.0</td>
<td>--</td>
<td>(10^{12})</td>
<td>0.02</td>
<td>0.2</td>
<td>(10^{-5})</td>
</tr>
<tr>
<td>5</td>
<td>174.0</td>
<td>1.0</td>
<td>4.0</td>
<td>9.8</td>
<td>0.3</td>
<td>0.4</td>
<td>(2 \times 10^{13})</td>
<td>0.8</td>
<td>3.0</td>
<td>(10^{-5})</td>
</tr>
<tr>
<td><strong>Present Work</strong></td>
<td>20.0</td>
<td>0.5</td>
<td>--</td>
<td>9.0</td>
<td>2.6</td>
<td>0.2</td>
<td>(6 \times 10^{12})</td>
<td>0.1-0.3</td>
<td>1-3</td>
<td>(10^{-5})</td>
</tr>
</tbody>
</table>

---

4. Lowenstein, A., et al\(^4\), Massachusetts Institute of Technology (Analytical Study)
5. Walter, R. F.\(^{12}\), Massachusetts Institute of Technology.
FIG. 2.1
CO₂ ENERGY LEVEL DIAGRAM
Fig. 2.2: Electron Cross Section for Vibrational Excitation of CO₂ Molecules from Ref. 7
Fig. 3.3: End Flange
FIG. 3.4: DISCHARGE CURRENT PULSE

Current Density $J_x$, amp/cm$^2$

Time, usec

0.0 to 1.0 amp/cm$^2$
**Fig. 3.6: Magnetic Field Distribution in Discharge Region**
Fig. 3.7: Magnet Current Pulse

Discharge takes place within this time

$B = 0 - 0.8 \text{ Tesla}$
Fig. 3.8: Cs Diagnostic System

- Photomultiplier Tube
- Lens
- Discharge Tube
- Lenses
- Cs Lamp
- Mechanical Chopper 15 kHz
- Pin Hole
Fig. 3.9: Cs Absorption Diagnostics Calibration Experiment

1. Lamp Holder
2. Heating Tape & Insulator
3. Cs Lamp
4. Pin Hole
5. Lenses
6. Oven
7. Test Chamber
8. Quartz Window
9. Lens
10. Photomultiplier Tube
11. Cs Pool
12. Oil Bath
13. Quartz Window
Fig. 3.10: Calibration curve for Cs absorption diagnostics

\( P_{\text{He}} = 60 \text{ torr} \)

\( T = 400^\circ \text{K} \)
Fig. 3.11: Typical Scope Trace of Pressure Pulse (top solid curve) and Cs Absorption Diagnostics (chopped curve)
Fig. 3.11: Typical Scope Trace of Pressure Pulse (top solid curve) and Cs Absorption Diagnostics (chopped curve)
Fig. 3.12: Arrangement To Measure Optical Gain—(Schematic)
Gain measurement without magnetic field

Gain measurement with magnetic field
From bottom: 1) Magnet Pulse, 2) Laser Pulse, 3) Pressure Pulse, 4) Cs Absorption Diagnostics

Fig. 3.13
Gain Measurement Without Magnetic Field

Gain Measurement With Magnetic Field

From Bottom: 1) Magnet Pulse, 2) Laser Pulse, 3) Pressure Pulse, 4) Cs Absorption Diagnostics

Fig. 3.13
Fig. 3.14: Sequence of Events During a Test
MEASUREMENT WITHOUT MAGNETIC FIELD

FROM BOTTOM: 1) DISCHARGE CURRENT, 2) LASER PULSE

MEASUREMENT WITH MAGNETIC FIELD

FROM BOTTOM: 1) MAGNET PULSE, 2) LASER PULSE

FIG. 4.1
Measurement Without Magnetic Field

From Bottom: 1) Discharge Current, 2) Laser Pulse

Measurement With Magnetic Field

From Bottom: 1) Magnet Pulse, 2) Laser Pulse

Fig. 4.1
Fig. 4.2: Current Probe Calibration
Fig. 4.3: Typical Scope Traces
Fig. 4.4: GAIN AND CURRENT DENSITY TIME HISTORY

\[ p = 42.0 \text{ torr}; f_{Cs} = 10^{-5}; f_{CO_2} = 0.74; J = 0.429/\text{cm}^2 \]
$p = 63.0$ Torr; $f_{cs} = 1.4 \times 10^{-5}$; $f_{CO_2} = 0.93\%$;

$J = 0.38 \text{ a/cm}^2$

**Fig. 4.5:** Gain and Current Density (Exp. 4120)
Fig. 4.6: Transient Behavior of Gain
Figure 4.7: Laser Gain vs Seed Mole Fraction; B = 0
Fig. 4.9: Gain and Current Density (Exp. 4163)

\[ B = 0.68 \text{T}; \quad J = 0.5 \text{ A/cm}^2; \]
\[ p = 21.0 \text{ torr}; \quad f_{\text{CO}_2} = 4.7\%; \quad f_{\text{Cs}} = 1.47 \times 10^{-4}. \]

Fig. 4.10: Gain and Current Density (Exp. 3050)

\[ B = 0.42 \text{T}; \quad J = 0.62 \text{ A/cm}^2; \]
\[ p = 46.0 \text{ torr}; \quad f_{\text{CO}_2} = 0.74\%; \quad f_{\text{Cs}} = 8 \times 10^{-6}. \]
Fig. 4.11: Gain vs B Field
Fig. 4.12: Laser Gain vs Cs Mole Fraction $B \neq 0$
Fig. 4.13: Gain vs Average Hall Parameter

Gain / cm⁻¹

3050
3049
4132
4164
Fig. 4.14: Gain vs Current Density, $\xi_{CO_2} = 0.74\%$, $\xi_{CS} = 10^{-5}, P = 42.0$ Torr
Fig. 4.16: Dependence of Gain on Electrical Conductivity

\[ P = 36.8 \text{ torr}; f_{\text{CO}_2} = 6 \times 10^{-5}; f_{\text{Cs}} = 2.47 \% \]

\[ P = 42.0 \text{ torr}; f_{\text{CO}_2} = 10^{-5}; f_{\text{Cs}} = 0.748 \% \]
$k_{\text{CO}_2(10^\circ\text{C})-\text{CO}_2} = 3.3 \pm 0.3 \times 10^7 \text{ atm}^{-1} \text{ sec}^{-1}$

**Fig. 4.18: LOWER LASER LEVEL DEACTIVATION**
Fig. 4.19: Gain Saturation Test

\[ p = 54.0 \text{ torr}; \quad f_{\text{Cs}} = 3 \times 10^{-5}; \quad f_{\text{CO}_2} = 1.67\%; \]
\[ J = 0.46 \text{ a/cm}^2; \quad B = 0.0 \text{ T} \]
Fig. 5.1: Increase in Electron Temperature During the Experiment
Fig. 6.1: Laser Output and Saturation Intensity
FIG. 6.2: SPECIFIC POWER OF VARIOUS LASER SYSTEMS AFTER REF. 23

A - THIS WORK

B - WALTER'S\textsuperscript{12} ANALYSIS

\(\eta\) - THERMAL TO OPTICAL ENERGY CONVERSION EFFICIENCY
APPENDIX A

MEASUREMENT OF Cs BOUND–FREE CONTINUUM

There are three possible mechanisms for emission of continuum radiation from a Cs seeded plasma: 2) Bremsstrahlung, 2) free-bound emission, 3) electron scattering by neutrals.

Free-free emission is due to an electron passing near a positive ion and being accelerated in the Coulomb field, known as Bremsstrahlung. The intensity of this type of radiation clearly depends on the product of electron and ion densities. For conditions typical of an MHD generator, Bremsstrahlung is at least 10 orders of magnitude below the free-bound emission.

Electron scattering by neutrals is a mechanism akin to Bremsstrahlung, except that the intensity depends on the product of electron and neutral densities. For a seed mole fraction of about $\sim 10^{-5}$, the electron scattering by neutrals would be more important than free-free emission by a factor of about $10^5 - 10^6$ at most. Thus, electron scattering emission is also well below the free-bound emission.

Free-bound emission is due to the capture of a free electron with a velocity, $v$, into a definite quantum level of the alkali metal, Cs. Any inert gas, He in this case, is considered as a buffer gas only and does not contribute to the continuum emission process. This type of radiation has been successfully used to measure electron temperature and number density. We will review the basic features of the physics involved in this process.
As a free electron of energy \(1/2 \, m_e \nu^2\) interacts with an ion to occupy a certain quantum state 'j' of the ion, a photon is emitted, such that

\[
h \nu = 1/2 \, m_e \nu^2 + h \nu_j \quad (A.1)
\]

where the ion kinetic energy has been neglected and \(\nu\) is the frequency of the photon emitted.

The number of such recombinations is

\[- \frac{\partial n_e}{\partial t} = \int f_e(\nu) \, n_I \, \sigma_j \, \nu \, d\nu \quad (A.2)\]

where \(\sigma_j\) is the relevant cross-section and \(f_e(\nu)\) is the electron distribution function. Since the cross-section is expected to be isotropic and assuming that the free electrons have a Maxwellian distribution of energy, we obtain:

\[- \frac{\partial n_e}{\partial t} = \int n_e \, n_I \, \left[\frac{m_e}{2 \pi k T_e}\right] \exp \left(-\frac{m_e \nu^2}{k T_e}\right) c_j \, 4\pi \nu^2 \, d\nu \quad (A.3)\]

Using the Einstein's coefficients we can write the expression for a number of bound-free transitions at a given frequency as (neglecting the induced emissions)

\[N_j \, \frac{8\pi h \nu^3}{c^3} e^{-h \nu/k T_e} B_j \, d\nu = N_j \, \frac{8\pi \nu^2}{c^2} e^{-h \nu/k T_e} \alpha_{j \rightarrow \text{free}} \, d\nu \quad (A.4)\]

here \(\alpha_{j \rightarrow \text{free}}\) is the cross-section for photon emission and is given by

\[\alpha_{j \rightarrow \text{free}} = h \nu/c \, B_j.\]

*For a typical MHD laser plasma with only a few percent of molecules, this is a good assumption.*
The two processes described by (A.4) and (A.3) should balance exactly:

\[
\frac{m_e}{2\pi kT_e}^{3/2} \exp \left( -\frac{1}{2} \frac{m_e v^2}{kT_e} \right) \sigma_j 4\pi v^2 dv \\
= \frac{N_j}{\frac{8\pi v^2}{c^2}} e^{-h\nu/kT_e} \int_{\alpha_j \rightarrow \infty} d\nu \\
\]

Using the Saha equation and the relation

\[
\frac{d\nu}{dv} = \frac{m_e v}{\hbar} \\
\]

derived from (A.1) one gets the following relationship between \(\alpha_j \rightarrow \infty\) and \(\sigma_j\):

\[
\sigma_j = \frac{h^2 \nu^2}{m_e^2 c^2 v^2} \frac{g_j}{g_I} \alpha_j \rightarrow \infty \\
\]

\(g_j\) and \(g_I\) are the degeneracies of the state in question and the ion. Thus the radiation energy per unit volume per unit frequency into a unit solid angle \(J_{\nu j} = \frac{ch\nu}{4\pi} \frac{dn_e}{\partial t} \bigg|_{\nu} \)

The equation (A.8) is simplified by substitution of (A.7) and (A.3) and written in a convenient form:

\[
J_{\nu j} = \frac{1.5 \times 10^{-33}}{\lambda T_e^{3/2}} \frac{\Lambda_j n_e^2}{\lambda_j - \lambda^{-1}} \exp \left[ \frac{hc}{kT_e} (\lambda_j - \lambda^{-1}) \right] \\
\]
Here the coefficient $A_j$ is a quantum-mechanical property of the transition state in question. In Cs two prominent transitions, namely, from continuum to 6P and 5D lower levels of the electronic transitions.

Various values for these transitions are:

$A_j = 3.74 \times 10^{-6}$ for the 6P continuum

$= 8.30 \times 10^{-6}$ for the 5D continuum

and

$\lambda_j^{-1} = 19,700 \text{ cm}^{-1}$ for the 6P continuum

$= 16,900 \text{ cm}^{-1}$ for the 5D continuum

The radiation intensity is, then, proportional to $n_e^2$ at each transition. In order to determine the electron temperature one would be required to monitor the light output at two different wavelengths, and plot $\ln (J\lambda)$ against the wavelengths, the slope of the straight line would give the magnitude of $T_e$.

In the present study, the continuum radiation is monitored at 4904 Å and 4285 Å.
CALIBRATION OF Cs ABSORPTION DIAGNOSTICS

The method of absorption of resonant radiation is used to determine the Cs number density in the plasma. The light used for this purpose is generated by a low pressure Cesium spectral lamp. The image of a pinhole in the lamp housing is projected by two pyrex lenses through the test chamber, and the radiation that is transmitted falls on a photomultiplier tube provided by a filter to isolate the desired resonant line. The line selected is a doublehead in the blue region of visible light at wavelengths 4550 Å and 4555 Å. The output current of the P.M. tube is then proportional to the total incident energy, which can be expressed as

\[
I = \int_{-\infty}^{+\infty} I_{\nu_{\text{Lamp}}} (\nu - \nu_0) \exp \left[ - \int_{0}^{L} k_{\nu}(\nu - \nu_0) \, dx \right] \, d(\nu - \nu_0)
\]

(B.1)

where \( I_{\nu_{\text{Lamp}}} \) is the spectral intensity of the lamp, distributed about the central frequency \( \nu_0 \), \( k_{\nu} \) is the absorption coefficient of the plasma at frequency \( \nu \) and at station \( x \) along the beam and \( L \) is the total optical length inside the discharge tube ("1.0"). The total absorption coefficient \( \int k_{\nu}(\nu) \, d\nu \) is, for a given line, is proportional to the Cesium number density, the shape of the distribution \( k_{\nu}(\nu) \) depends on the broadening mechanisms that are present. Some of the important mechanism
will be discussed below:

1) **Natural Broadening**

   The half width for natural broadening, $\Delta \nu_n$, is given by

   $$
   \Delta \nu_n = \frac{e^2 v_0^2}{3 mc^3} f_{ji} = 9.4 \times 10^{-24} \frac{2}{v_0^2} f_{ji}
   $$

   (B.2)

   For the line at 4550 Å we have $f_{ji} \equiv$ oscillator strength $= 0.0174$ and

   $v_0 = 6.59 \times 10^{14}$ sec$^{-1}$, thus the natural bandwidth comes to be

   $$
   \Delta \nu_n = 7.10 \times 10^{4} \text{ Hz}
   $$

   The normalized shape of a naturally broadened line is

   $$
   g(\nu)^* = \frac{1}{\pi \left[ 1 + \frac{2(\nu - \nu_0)^2}{\Delta \nu} \right]^2}
   $$

   (B.3)

2) **Collisional Broadening**

   The half-width for collisional broadening is given by

   $$
   \Delta \nu_c = \sigma_c^2 n_g \left[ \frac{8kT_g}{\pi} \left( \frac{1}{M_r} + \frac{1}{M_g} \right) \right]^{1/2}
   $$

   (B.4)

   where $\sigma_c$ is the cross section for collisional broadening between radiating and neutral atoms. The line shape is similar to that of natural broadening.

*Otherwise known as Lorentzian line shape.*
3) **Inter-Atomic Stark Broadening**

The inter-atomic stark broadening occurs as the charged particles influence the radiating atoms. This type of broadening is as straightforward as it is for collisional or natural broadening. There are some numerical results for half-widths are available for some Cs lines.

4) Due to the similarity in the nature of broadening mechanism* of the three above, broadening can be combined as:

\[
\Delta \nu = \Delta \nu_n + \Delta \nu_c + \Delta \nu_s \quad (B.5)
\]

5) The half-width for Doppler broadening, \(\Delta \nu_d\), is given by

\[
\Delta \nu_d = 2\nu_0 \sqrt{\frac{2kTg}{M_r c^2 \log 2}} \quad (B.6)
\]

where \(M_r\) is the mass of the radiating atoms.

The line shape of a doppler broadened medium, in normalized form is described as

\[
g_D(\nu) = \frac{2(\log 2)}{\sqrt{\pi} \Delta \nu_D} \exp \left[ -\frac{4(\log 2)(\nu - \nu_0)^2}{\Delta \nu_D^2} \right] \quad (B.7)
\]

*The stark broadening is much more complex than the other two, the overall shape is inversely proportional to \((\nu - \nu_0)^{5/2}\), however the error in assuming a \((\nu - \nu_0)^{-2}\) dependence is very small.
Due to the exponential nature of the line shape, the Doppler influence on the other broadening mechanisms [Eq. (B-5)] is dominant at the line center, and in the wings of the line shape the Lorentzian shape dominates. For the present problems of determining the Cs number density ($f_{Cs} > 10^{-6}$ at $p = 50$ torr) a knowledge of the wing profile is sufficient.

When the term $K\nu L$, the optical depth, is greater than 3, the line center is completely absorbed and the ratio of incident and output intensities of the resonant radiation is proportionally to the number of radiating atoms and the number of the broadener gas atoms [see Eq. (B.4)], provided the same emitter (Lamp) is used. The line shape of lamp is again governed by the broadening mechanisms discussed before.

A precise determination of the spectral distribution of such a light source requires spectroscopic equipment with high resolving power ($\approx 0.01$ Å), and a calculation of $I _{\nu_{Lamp}}$, without the knowledge of the relevant parameters (of the lamp plasma) might lead to erroneous results. Therefore, instead of relying on an assumption as to the form of the function $I _{\nu_{Lamp}}$ [Eq. (B.1)], a calibration experiment was devised. A schematic of the apparatus is shown in Fig. 3.9. The light of the Cs lamp is collimated by means of glass lenses and is allowed to pass through the absorption cell. The beam is then focused on a photomultiplier tube.

The temperature of the lamp gradually increased, if only air convection as a cooling process is allowed. As the variation in temperature
might change the lamp line profile, it was decided to insulate the lamp housing, and to heat it to keep the temperature constant at a desired level. The absorption cell was kept in an oven and the Cs pool stem in an oil bath to promote even heating. Several thermo-couples, placed at different spots in the oven, monitored the temperatures (not shown in Fig. 3.9). To avoid condensations on the walls of the absorption cell, it was heated (in addition to the oven heating) by means of electrical tapes, and maintained the Cs pool as the coolest spot in the cell. By varying the oven temperature absorption of the Cs lamp light at various Cs mole fraction were made. The reading was corrected for the increase in He temperature by assuming a $1/\sqrt{T}$ dependence.

The experiment was conducted with two absorption cells, one filled with 60.0 torr of He, the other with 120 torr.

The results were reduced in form of a master calibration curve, showing the dependence of Cs mole fraction on the fraction of light transmitted through a 60 torr He cell.

The expression used to calculate the optical depth of the absorption cell was taken from Ref. 75 which reads:

$$a = \frac{2e^2 L n_{\text{Cs}}}{\Delta \nu} g_j f_j \exp \left[ - \frac{k \nu}{k T} \right] \left[ 1 + \frac{2(\nu - \nu_0)}{\Delta \nu} \right]^{-1}$$

(B.8)
where $g_j$, $f_{j1}$, $\nu_j$ are the degeneracy, the oscillator strength, and the frequency of 'j' level in Cs (i is the ground state).

For 4550 Cs line the values are:

$g_j = 4$

$g_i = 2$

$f_{j1} = 0.0174$

$\Delta \nu = 3 \times 10^9$ Hz

$\nu_j = 6.6 \times 10^{14}$ Hz
APPENDIX C
PLASMA EQUATIONS

In MHD laser regime the electrical behavior of the plasma is
overned primarily by the electron kinetics. The three equations des-
cribing the electrons in the plasma are the electron continuity equation,
the electron momentum equation (Ohm's law), and the electron energy
equation. In the Hall parameter range (typically larger than 3) charact-
eristic of nonequilibrium MHD generators, the plasma is subject to
ionization instabilities.\textsuperscript{32,33} These result in spatial and temporal
nonuniformities in $n_e$ and $T_e$ which reduce the values of $\beta$, the Hall
parameter and $\sigma$, the electrical conductivity. Solbes developed a quasi-
linear averaging technique to describe the bulk plasma by calculating
the effective values of $\sigma_{\text{eff}}$ and $\beta_{\text{eff}}$.

Neglecting the ion slip and electron pressure gradient, the local
Ohm's law can be written as:

$$\vec{J} + \vec{J} \times \vec{B} = [\vec{E} + \vec{u} \times \vec{B}]$$ \hspace{1cm} (C.1)

The Hall parameter and conductivity $\sigma$ are given by

$$\bar{\beta} = \frac{e\vec{B}}{m e v_e}$$ \hspace{1cm} (C.2)

$$\sigma = \frac{e^2 \bar{n}_e}{m e v_e}$$ \hspace{1cm} (C.3)

The electron collision frequency $v_e$ is computed as:
\[ \nu_e = \sum_i \nu_i \]  
\( \nu_i = c_i \sqrt{\frac{8kT_e}{\pi m_e}} n_i Q_i(T_e) \)  

where

The summation is taken over gas atoms, seen atoms, and ions. \( Q_i(T_e) \) is the Maxwell averaged momentum transfer cross section, while \( c_i \) depends on the force law and energy for the encounter. The appropriate values for the factors are available in plasma literature.  

For condition typical of plasmas under consideration the electron energy equation can be simplified to the form  
\[ (eV_i + \frac{3}{2} kT_e) \left( \frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \vec{u}) \right) = \frac{j^2}{\sigma} - \sum_s \Delta \varepsilon_s \]  

where \( \vec{u} \) is the flow velocity of the plasma, which in the present simulation experiment is zero. The loss term \( \Delta \varepsilon_s \) is

\[ \Delta \varepsilon_s = \frac{\Delta n_s}{\sigma} \frac{e}{m_s} \frac{3}{2} k(T_e - T) n_e \nu_e \]  

\( \delta_s \) for \( CO_2 \) in the range of electron temperatures of interest is approximately 5000. However as has been discussed in previous chapters its value is not constant, as the molecular gas undergoes significant vibrational excitation in the process of creating an inversion and redistributes its population amongst its various vibrational levels. As the electron number density and electron temperature are measured in the experiment separately, in the calculations, value of \( \delta \) is assumed.
constant, for simplicity.

Contribution of the first term is at a very small time scale\(^ {13} \)
(\(\simeq 0.1 \mu\text{sec}\)), the energy equation is simplified to a steady state
solution:

\[
\frac{J^2}{\sigma} = \sum_s \Delta \epsilon_s \tag{C.8}
\]

In the presence of ionization instabilities the equations are
written in an averaged form

\[
\langle J \rangle + \langle J \times \vec{b} \rangle = \langle (\vec{E} + \vec{u} \times \vec{B}) \rangle \tag{C.9}
\]

\[
\langle \frac{J^2}{\sigma} \rangle \approx \sum_s \frac{\Delta \epsilon_s}{s} \tag{C.10}
\]

or in terms of effective values of \(\sigma_{\text{eff}}\) and \(\beta_{\text{eff}}\) as:

\[
\langle J \rangle + \vec{J} \times \vec{b}_{\text{eff}} = \sigma_{\text{eff}} \, \left[ \langle \vec{E} \rangle + \vec{u} \times \vec{B} \right] \tag{C.11}
\]

assuming \(\vec{u}\) and \(\vec{B}\) are constant.

For the configuration of the experimental facility \((E_x - \text{induced}
field, E_y - \text{Hall field})\) we have,

\[
\langle J_x \rangle = \sigma_{\text{eff}} \langle E_x \rangle \frac{1 + \beta_{\text{eff}} \beta_{\text{app}}}{1 + \beta_{\text{eff}}^2} \tag{C.12}
\]

where \(\beta_{\text{app}} = \frac{\langle E_y \rangle}{\langle E_x \rangle}\) and is measured by two probes in contact with the
plasma.

The energy equation is simplified to
\[
\frac{\langle J \rangle^2}{\sigma_{\text{eff}}} = \sigma_{\text{eff}} \frac{E_x^2}{1 + \beta_{\text{app}}^2} \]

For a plane wave structure of the nonuniformities Solbes\textsuperscript{33}
gives the following relationship

\[
\frac{\sigma_{\text{eff}}}{\langle \sigma \rangle} = S \tag{C.14}
\]

and

\[
\beta_{\text{eff}} = \langle \beta \rangle S + t(S-1) \tag{C.15}
\]

where

\[
S = \left[ \frac{(1-r)^2 + \beta_{\text{crit}}}{(1-r)^2 + \langle \beta \rangle^2} \right]^{1/2} \tag{C.16}
\]

\[
t = \frac{1-r}{\langle \beta \rangle} + \left[ \frac{(1-t)^2}{\langle \beta \rangle^2} + 1 \right]^{1/2} \tag{C.17}
\]

\[
r = \frac{d \log v_e}{d \log n_e} \tag{C.18}
\]

\(\beta_{\text{crit}}\) is calculated by either of the two following relationships:

(A) Collision with Neutrals are Predominant

\[
\beta_{\text{crit}} = \frac{2-\alpha}{1-\alpha} \frac{1}{X_i} \left[ \frac{T_e}{T_e - T_g} + \frac{2(1-\alpha)}{1-\alpha} \frac{X_i}{X_i} \right]^{1/2} \left( 2m + \frac{T_e}{T_e - T_g} \right)^{1/2} \]

where

\[
X_i = \frac{3}{2} + \frac{e \nu_i}{k T_e}
\]
\[ \alpha = \text{degree of ionization} \]

\[ m = \frac{\partial \log \nu_{e-N}}{\partial \log T_e} \]

(B) Coulomb Collisions Dominate the Momentum But Not the Energy Equation.

\[ \beta_{\text{crit}} = \left[ \left( 1 + \frac{1}{2} \frac{(2-\alpha)(3T_g - T_e)}{(1-\alpha)(T_e - T_g)X_1} \right) \left( 1 + \frac{1}{2} \frac{(2-\alpha)(ST_e - T_g)}{(1-\alpha)(T_e - T_g)X_1} \right) \right]^{1/2} \]

The measured values of \( T_e \) and \( n_e \) are used to compute the appropriate quantities.
REFERENCES


45. Granek, H., "Cross-Relaxation in the Doppler Profiles of J-Levels and between J-Levels of the 00^1 and 10^0 Vibrational States in CO₂," Ph.D. Thesis, MIT Department of Electrical Engineering


Surendra Prasad Sharma was born on February 3, 1943 in Gorakhpur, India. He received the Sc.B. degree in physics from the University of Gorakhpur, India in 1962. In September 1963 he joined the Patrice Lumumba Peoples' Friendship University, where he received the Sc.M. degree in Power Machine Building in June 1968. His master's thesis dealt with the problems of aircooled turbine blade in a high temperature gas turbine power system.

The following fall the author, working for the Scientists' Pool of the Council of Scientific and Industrial Research, Government of India, joined Bharat Heavy Electronics Limited, Bhopal, India, and was involved in the development of a turbine blade profile, gasdynamical calculations and windtunnel testing. In July, 1970, the author joined the Indian Institute of Technology, Bombay, India, as a lecturer in the Department of Aeronautical Engineering, where he taught the design of aircraft engines.

In the fall of 1972 he joined the Massachusetts Institute of Technology. After working for a year on the stability analysis of MHD generators, he began work on MHD lasers in the Space Propulsion Laboratory, M.I.T., which lead to this dissertation.

He is a student member of the American Institute of Aeronautics and Astronautics. He is also a member of Sigma Xi.