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THE PLASMA LASER: POPULATION INVERSION IN HYDROGEN PLASMAS.(U)
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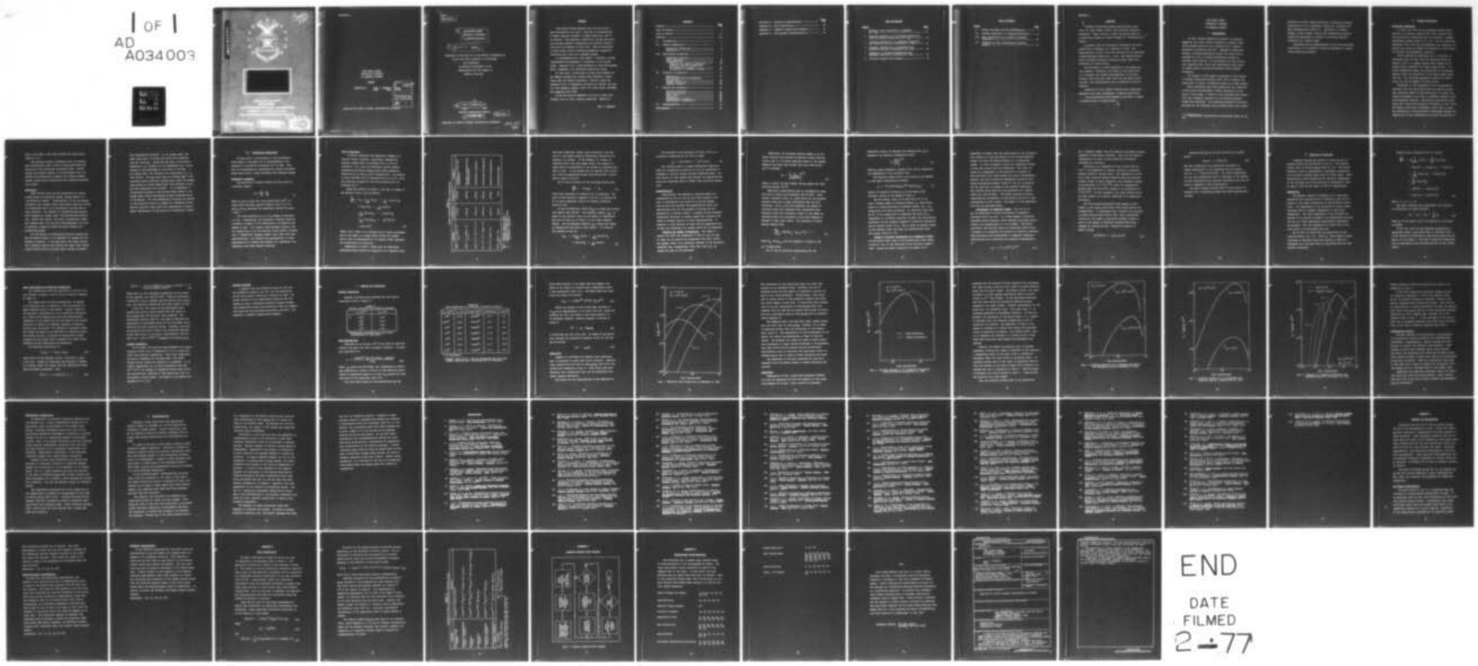

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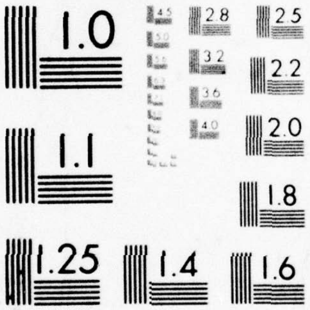

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THE PLASMA LASER: POPULATION INVERSION IN HYDROGEN PLASMAS

THESIS

GEP/PH/76-1

John J. Campbell
Capt USAF

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THE PLASMA LASER:
POPULATION INVERSION
IN HYDROGEN PLASMAS.

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Presented to the Faculty of the School of Engineering
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by

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Preface

This report differs greatly from the work which I had envisioned at the onset. The plan of accomplishing a rather complete analysis of plasma lasers soon had to be shelved. Unfortunately, questions of plasma generation and cooling, material optimization and possible applications are not answered in this work. What is determined is this: Under certain limiting assumptions, population inversions will occur in a hydrogen plasma.

In investigating for this report, I compiled a rather comprehensive bibliography of literature on the plasma laser. Appendix D is a cross-reference of this bibliography which, hopefully, will facilitate additional study.

At this time, I would like to thank those members of the Physics Faculty who, despite busy schedules, always found time for helpful discussion. Special thanks are extended to Dr. D. Shankland who helped me through the woes of a new computer program, and to Mr. Bruce Fiene, FTD/ETEO, who suggested this topic.

To my wife and two daughters, who had to learn that "Grumpy" was not just a cartoon character, "Thank you."

John J. Campbell

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Abstract

A rapidly recombining plasma preferentially populates the upper energy levels, thus producing population inversions. Laser devices in which the active medium is a recombining plasma are termed "plasma" or "recombination" lasers.

A computer code was developed to determine the level populations of hydrogen as a function of time. The instantaneous cooling of the free electrons in a completely ionized hydrogen plasma was assumed. The resulting population inversion produced estimates of gain which were sufficient for laser action.

The absorption of Lyman radiation in the plasma was also assumed. Generally, the effect of this absorption is to decrease the duration and magnitude of the gain. However, when the lower laser level and the ground level coincide, the resulting gain can be enhanced by this absorption.

Comparison of the computer results shows reasonable agreement with other researchers' computer predictions.

A cross-referenced bibliography is provided to assist in further study of plasma lasers.

THE PLASMA LASER:
POPULATION INVERSION
IN HYDROGEN PLASMAS

I. Introduction

In 1963, Russian physicists Gudzenko* and Shelepin suggested that under certain conditions a rapidly recombining plasma should act as a material with a negative absorption coefficient (Ref 40). Subsequent theoretical studies, conducted principally within the Soviet Union, expanded the uses of rapidly recombining plasmas as possible laser sources. An investigation of open literature suggested that little work dealing with this aspect of plasma physics was being performed outside Russian boundaries.

The purpose of this report, undertaken at the request of Foreign Technology Division, USAF, was to evaluate the feasibility of using a recombining plasma as a laser medium.

Time constraints which were placed upon the completion of this report necessitated a severe restriction of the scope of this study. A search of the available open literature and a computer analysis of a recombining hydrogen plasma were performed. The resulting population inversions and gain are the principal areas studied within this report.

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*Occasionally transliterated as Goodzenko (Refs 31, 32, 33).

Questions of actual plasma production, cooling and external coupling will not be addressed, except when inversion and gain considerations require it. Discussion of complex plasmas, plasma dynamic lasers, and recombination-chemical lasers will generally be limited to providing available references for further study.

Proceeding from an understanding of the above-mentioned limitations, it is possible to make an assessment of lasers using recombining plasmas.

II. General Background

Historical Background

In their 1963 work and in subsequent publications, Gudzenko and Shelepin proposed that under certain conditions population inversions could be achieved in rapidly recombining plasmas (Refs 40, 41, 51). The two physicists maintained that, once this configuration was attained, the plasma then should be capable of serving as a laser medium for incident electromagnetic radiation.

This recombination principle, as it is called, is predicated upon the fact that free electrons which are rapidly cooled in a highly ionized dense plasma can be preferentially captured into upper energy levels. In a dense recombining plasma, the probability of collisional capture favors the population of the upper energy levels (Ref 50). The resulting population inversion is short-lived, but may be useable for laser action.

Subsequent to the formulation of the recombination principle came the realization that the numerous population inversions might be used selectively to control the output wavelength of the laser in different regions of the electromagnetic spectrum. Theoretical calculations indicated that laser action should be attainable in the UV and VUV regions where more conventional lasers did not work. The possibility of attaining short wavelengths through the application of the recombination principle has spurred on much of the work in this area outside the Soviet Union (Refs 16, 71).

The available Russian literature does not indicate that recombination laser action is being preferentially developed in any particular wavelength range. Rather, Russian development appears to be concentrated upon extending the recombination systems into complex plasmas, dynamic lasers using recombination and chemical-recombination lasers.

Definition

Laser devices which use the properties of a recombining plasma are generally termed "plasma lasers" or "recombination lasers." Unfortunately, in the non-Russian literature and, indeed, within the Russian works the choice of terminology tends to be inconsistent and may lead to some confusion. The practice of describing some gaseous laser systems as "plasma laser" has created some perplexity. Within this report, the terms "recombination laser" and "plasma laser" will be used interchangeably, but only to describe a system in which the active medium is a recombining plasma.

For the purpose of eliminating confusion between the gas and plasma lasers, it is expedient to compare the two systems in general. In the gas laser, the needed population inversion results from filling the upper laser levels almost directly from the ground state through collisions with superheated electrons. In the plasma laser, the upper laser level is filled from above with electrons from the continuum. Within the gas laser, the electron temperature (T_e) exceeds the ion temperature (T_i) corresponding to the percentage of ionization of the gas. In the plasma laser, the electrons are supercooled, $T_e < T_i$ (Ref 59:848). The gas laser uses the leading edge of the ionization pulse entering a rarefied gas, while the plasma laser works in a dense medium after the ionization source has been terminated (Ref 55:1218). It is impossible to continuously transition from the gas laser scheme to the plasma laser without destroying the gain characteristics of the medium. The time immediately following the removal of the ionization source is termed the "afterglow period" (Ref 30) and will enter later into discussions of experimental verification of the theory of recombination lasers.

III. Theoretical Background

At this point, a presentation of the theoretical basis which is necessary for an understanding of the existence of population inversions will be made. This will be accomplished by describing the relevent processes which occur within a dense optically-thin hydrogen plasma.

Population Inversion

The population inversion between the two levels is a positive number,

$$\Delta N = \frac{N_n}{g_n} - \frac{N_m}{g_m} \tag{1}$$

where N_n and N_m equal the total populations (cm^{-3}) of levels with principal quantum numbers n and m ($n > m$); and g_n and g_m represent the degeneracy factors of levels n amd m.

The total populations N_n and N_m change as functions of time. Consequently, the population inversion which is available to assist in the amplification of radiation may change in time. The complete time-dependent solution for the populations of all the discrete levels within a plasma, even a "simplified" hydrogen plasma, must often rely upon approximations. The validity and applicability of these approximations to obtain the solution of a particular configuration must merit careful scrutiny.

Level Population

To better understand the population changes of a discrete level, consider a stationary, homogeneous, hydrogen plasma which is optically-thin to its own radiation. Let n and m be principal quantum numbers designating arbitrary energy levels whose population densities are N_n and N_m (cm^{-3}) respectively. The density of free electrons will be represented by N_e (cm^{-3}), while the continuum occupied by the free electrons will be indicated by c*.

Using the notation of Table I, the rate of change of any discrete level n may be written

$$\begin{aligned}\frac{dN_n}{dt} = -N_n \{ & [\sum_{m>n} V(m,n) + \sum_{m<n} R(n,m)]\, N_e \\ & + B(n,c^*)N_e + \sum_{m<n} A(n,m)\} \\ & + \sum_{m>n} [R(m,n)N_e + A(m,n)]\, N_m \\ & + \sum_{m<n} V(m,n)N_e N_m + N_e{}^3\, B(c^*,n) \\ & + A(c^*,n)N_e{}^2 \qquad (2)\end{aligned}$$

where m and n take on an infinite set of values corresponding to the number of energy levels within the plasma. Eq (2) must be supplemented by an equation which expresses the conservation of electrons.

Examination of Table I shows that two additional mechanisms which affect the population of a discrete level

TABLE I
Atomic Processes and Rate Coefficients

Process	Coefficient	Dimensions	Comments
$H(n) + e^- \rightarrow H(m) + e^-$ $m>n$	† $V(n,m)$	cm^3/sec	Collision of First Kind (excitation)
$H(n) + e^- \rightarrow H(m) + e^-$ $n>m$	† $R(n,m)$	cm^3/sec	Collision of Second Kind (de-excitation)
$H(n) + e^- \rightarrow H^* + e^- + e^-$	† $B(n,c^*)$	cm^3/sec	Collisional Ionization
$H^* + e^- + e^- \rightarrow H(n) + e^-$	† $B(c^*,n)$	cm^6/sec	Collisional Recombination
$H^* + e^- \rightarrow H(n) + h\nu$	† $A(c^*,n)$	cm^3/sec	Radiation Recombination
$H(m) \rightarrow H(n) + h\nu$ $m>n$	$A(m,n)$	$1/sec$	Spontaneous Decay

$H(n)$ - hydrogen atom in level n
H^* - ionized hydrogen atom
ν - frequency of emitted photon
† - temperature dependent

have been neglected: namely, photo-ionization from the level n, and upward discrete transitions through the absorption of a photon. In the absense of a source of radiation other than the plasma itself, the neglect of these terms is justifiable if the plasma is optically-thin (Ref 11:155). If the plasma does not satisfy this criterion, then the appropriate terms (Refs 68:763-764; 72:450) must be added to Eq (2).

Eq (2) may be written in the following matrix form:

$$\frac{dN_n}{dt} = \Sigma K_{nm} N_m + D_n \tag{3}$$

which also represents an infinite set of equations. The ease of this notation, compared to Eq (2), is obvious and it is found frequently within the Russian literature (Refs 14, 89).

In this formulation, matrix $\{K_{nm}\}$ is termed the relaxation matrix (Ref 54:606). The diagonal element, K_{nn}, is equal to the absolute value of the number of transitions per unit of time out of level n to all other possible states. The non-diagonal element, K_{nm}, yields the number of transitions from state m into state n. In terms of the notation of Eq (2),

$$\begin{aligned} K_{nn} = -\{[\sum_{m>n} V(n,m) + \sum_{m<n} R(n,m)]\, N_e \\ + B(n,c^*)N_e + \sum_{m<n} A(n,m)\} \end{aligned} \tag{4}$$

The increase in the particles of level n from the continuum is described by the term D_n where

$$D_n = N_e^3 B(c^*,n) + N_e^2 A(c^*,n) \qquad (5)$$

The infinite sets of coupled differential equations which are represented by Eqs (2) or (3) are unyielding to attempts at solution without further simplifications. The next section of this report will discuss the approximations which are frequently used to render these equations manageable.

Approximations

Historically, the systems of equations which are represented by Eqs (2) and (3) have been studied in detail to characterize the decay of an ionized plasma. This section will present the approximations which are specifically used for the purpose of solving for the populations of various levels. A reading of the available background literature on plasma lasers will disclose that there is frequent mention of other approximations. In Appendix A, brief mention of these various approaches will be made and references for further study will be presented.

Limiting the Number of Equations.

The number of states over which the summations of Eqs (2) and (3) must be taken can be reduced by recognizing this fact: Within the plasma, there is an effective lowering of the ionization potential and, consequently, above some level n_2, the states are part of the continuum.

Physically, the principal quantum number n_2 is the value obtained from setting the maximum allowed electron radius equal to the Debye screening length in the plasma. Margenau and Lewis (Ref 76:595) and Griem (Ref 39:141) use for hydrogen

$$n_2 = \left[\frac{T_e}{4\pi N_T e^2 a_o^2}\right]^{1/4} \tag{6}$$

where a_o equals the Bohr radius, and N_T equals the total particle density (cm^{-3}).

Additional simplification may be introduced by using the work of Hinnov and Hirschberg (Ref 64:798). There exists a discrete level, n_1, above which all the discrete excited levels are in Saha equilibrium with the free electrons. Level n_1 has this property: The number of electrons which will recombine when transferred down through it from the continuum is equal to the number of electrons which will eventually ionize when passing up through it from lower levels. The principle of detail balance implies that

$$\frac{g_{n_1}}{g_{n_1-1}} \exp[-(E_{n_1} - E_{n_1-1})/T_e] = 1 \tag{7}$$

where E_{n_1} and E_{n_1-1} are the energies of levels n_1 and n_1-1 respectively.

Eq (7) may be solved by substituting for the degeneracy factors of hydrogen and assuming that $n_1 \gg 1$. Expansion and algebraic manipulation yield

$$n_1 \approx \left[\frac{R_y}{T_e}\right]^{1/2} \tag{8}$$

where R_y equals Rydberg's constant (eV), and T_e represents the temperature of the electrons (eV).

The discrete levels above n_1 but below n_2 are assumed to obey Saha's distribution function

$$N_n = n^2 N_e^2 (h^2/2\pi m_e T_e)^{3/2} \exp(|E_n|/T_e) \tag{9}$$

where h is Planck's constant, m_e is the mass of the electron, and E_n is the energy of level n.

The net result, then, is to solve Eqs (2) or (3) over a limited number of discrete states, n_1, above which there is a quasi-continuum of discrete states, $(n_2 - n_1)$, lying below the actual continuum. It should be noted that Eq (8) is not always used to establish the value of n_1. Frequently, an arbitrary selection is made, the calculations performed, and the answers compared to solutions corresponding to another choice of n_1. The n_1 which is finally chosen is the smallest value that does not significantly alter the results (Refs 59, 79).

Change in Electron Temperature as a Function of Time. As previously noted, many of the coefficients which appear in Eqs (2) and (3) are functions of the electron temperature. During the rapid cooling of the plasma, it is reasonable to expect that the time history of the electrons will reflect not only the effect of the cooling mechanism chosen, but also the heating effects of a recombining plasma. To date, attempts to allow for temperature change in time have fallen into two categories. The first considers the temperature of the electrons as constant at some arbitrary final value during the entire recombination process; the other allows for temperature variation from plasma processes by adding to Eqs (2) and (3) an equation for the time rate of change of the electron temperature when neutral heavy particles are introduced as a thermostatic gas (Ref 94:1062). The former approach obviously simplifies the mathematics of the problem and will be used subsequently in this report. The impact of this approximation will be discussed later.

Collisional or Radiative Plasma. Eqs (2) or (3) can be simplified if either collisional or radiative processes can be ignored. In a dense plasma, collisional processes should dominate; while radiative processes should control the recombination in a rare plasma. Zel'dovich and Raizer (Ref 102:408) derive an expression which allows a plasma to be classified as collision or radiation dominant. This derivation was accomplished by comparing classically derived rates for collisional and radiative recombination. If

$$N_e < 3.1 \times 10^{13} T_e^{3.75} \qquad (10)$$

for a hydrogen plasma, then the radiative processes dominate compared to three-body collisions. Thus, at low electron temperatures and high electron densities collisional processes are important.

According to an argument by Jones and Ali (Ref 71: 3-4), it is impossible to produce population inversions through radiative cascade alone. The probability of filling a level directly through radiation when the electron thermal energy is small compared to the ionization energy is proportional to $(n^{-1}T_e^{-1/2})$; while for temperatures greater than the ionization energy it is proportional to $(n^{-3}T_e^{-3/2})$. In both instances, the lower quantum levels are more likely to be filled, resulting in no population inversions.

The collisionally-dominated dense plasma is more likely to fill upper states then lower states during its recombination. To understand this, consider the principle of detail balance which states that, under equilibrium conditions, the number of particles leaving a state is equal to the number of particles entering that state through the inverse process. Using the notation of Table I yields

$$N_e^3\, B(c^*,n) = N_n N_e\, B(n,c^*) \tag{11}$$

Substituting from Eq (9) for the ratio of (N_n/N_e^2) yields

$$B(c^*,n) \propto n^2 B(n,c^*) \tag{12}$$

The rate coefficient for collisional ionization is itself proportional to n^2, producing this net result: $B(c^*,n) \propto n^4$ (Ref 68:760-763). The actual expressions for the rate coefficients will be discussed in the section on rate coefficients and effective probability and will be given in Appendix B, Rate Coefficients.

The above results indicate that if laser action is desired from a recombining plasma then dense systems must be used.

IV. Solution of Equations

A computer program was written to solve the set of equations which are represented by Eq (2). The approach follows that of Gordiets *et al* (Refs 36, 37). The second reference listed is essentially a translated condensation of the Russian language paper which is listed first. Since discrepancies exist between the two versions, comparisons of the two works will be facilitated by referring to them as Paper I (Ref 36) and Paper II (Ref 37) respectively.

Assumptions

The hydrogen plasma is considered to be stationary, homogeneous and optically thin to radiation, with the exception of the Lyman (transitions to ground state) series lines. The temperature of the electrons is cooled instantaneously from an original temperature to some final temperature. The final temperature of the electrons is assumed to be constant throughout the recombination process. The use of a fixed temperature significantly simplifies the problem. When the temperature is fixed, most of the rates need to be calculated only once.

Eq (2) will be solved for the populations of nine discrete levels, ($n_1 = 9$). Above n_1, there exists a quasi-continuum of discrete levels the totality of which is designated by g and which will be associated with the free electron processes.

Imposing these limitations, Eq (2) becomes

$$\frac{dN_n}{dt} = -\{[\sum_{m=n+1}^{9} V(n,m) + \sum_{m=1}^{n-1} R(n,m)]\, N_e$$

$$+ [B(n,c^*) + B(n,g)]\, N_e + A^*(n)\}\, N_n$$

$$+ \sum_{m=n+1}^{9} [R(m,n)N_e + A^*(m,n)]\, N_m$$

$$+ \sum_{m=1}^{n-1} V(m,n)N_eN_m$$

$$+ [B(c^*,n) + B(g,n)]\, N_e{}^3$$

$$+ [A(c^*,n) + A(g,n)]\, N_e{}^2 \qquad (13)$$

where n = 1, 2, ..., 9.

The above equations are supplemented by an equation of conservation of total electrons

$$N_T = N_e + N_g + \sum_{n=1}^{9} N_n \qquad (14)$$

where N_g is the density (cm^{-3}) of particles in the quasi-continuum.

In Eq (13), A*(n) is the effective probability of spontaneous decay to any state below n, whereas A*(m,n) is the effective probability of spontaneous decay from the state m to the state n. The idea of effective probability will be discussed in the following section on rate coefficients.

Rate Coefficients and Effective Probability

The coefficients which are necessary to solve Eq (13) are provided in Papers I and II and are listed in Appendix B, Table IV.

The plasma which is under consideration is assumed to be optically thin to radiation, with the exception of Lyman radiation which it may absorb. Holstein (Refs 66, 67) proposes a modification of the transition probability by a factor which depends only upon the characteristic dimensions of the plasma and the line shape of the emitted radiation to explain the apparent trapping of radiation emitted from the plasma. The trapping of radiation within the plasma is caused by the existence of selective absorption within the gas. A quantum of energy which finally escapes from the plasma does so usually only after having undergone several absorptions and emissions.

The effective probability is

$$A^*(m,n) = F(m,n)\,A(m,n) \tag{15}$$

where F(m,n) is the Holstein factor. This will be used in Eq (13). Assume an infinitely long cylinder of plasma, R in radius, where only Lyman lines are affected and where they are Doppler broadened. Then,

$$F(m,1) = 1 \text{ if } k(m,1)R \leq 2 \tag{16}$$

$$F(m,1) = \frac{1.6}{k(m,1)R\ \{\pi \ln[k(m,1)R]\}^{1/2}} \quad \text{if } k(m,1)R > 2 \tag{17}$$

where k(m,1) is the absorption coefficient at the center of the spectral line (Ref 67:1166). Since the absorption coefficient, k(m,1), depends upon the ground state population, the effective probability will also change in time.

In Eq (15), the values of the spontaneous decay probability, A(m,n), were obtained from the tables of Weise _et al_ (Ref 101:7,210-211) when possible. The appropriate formula, Table IV, was used to calculate the probability of spontaneous decay for the few upper levels which did not have tabulated values. Likewise, the total spontaneous decay from a level n was calculated directly, rather than by use of the large n approximation (Ref 12: 269) $A(n) = 1.66 \times 10^{10} n^{-4.5}$ suggested by Gordiets _et al_.

Initial Conditions

In all cases, the electrons were assumed to be instantaneously cooled from a temperature of 2 eV to some arbitrary lower electron temperature. This lower temperature was used to determine the various rates. The total density chosen entered the problem as a parameter. At an initial temperature of 2 eV and at densities less than 10^{16} (cm^{-3}), the plasma is completely ionized (Ref 96:12). The recombination commenced at time equals zero with all the discrete levels vacant. The radius of the plasma was assumed to be 0.3 cm.

Computer Program

A computer code was written to solve Eq (13) and the constraint equation, Eq (14), for the populations of the nine discrete levels as a function of time. The actual solution of the differential equations was performed by using a previously available program package. This Runga-Kutta routine was modified so that the integration step size was self-adjusting during execution. See Appendix C, Computer Program Block Diagram.

V. Results and Discussion

Initial Conditions

Computer solutions were generated for the initial conditions listed in Table II.

TABLE II
Initial Conditions for Computer Solutions

N_e (cm^{-3})	T_e (eV)
** 10^{15}	0.05
10^{15}	0.20
10^{16}	0.05
10^{16}	0.10

**Calculation performed with and without consideration of absorption

Gain Calculations

Calculations of the gain (cm^{-1}) were made for selected lines at the point and time of maximum inversion. The gain was calculated from

$$\alpha = \frac{1.33 \times 10^{-12} \lambda^{4}_{mn} A^{*}(m,n)[N_m - N_n g_m/g_n]}{\Delta\lambda_{mn}} \qquad (18)$$

where λ_{mn} equals the wavelength (cm) originating in state m and terminating in state n; $A^{*}(m,n)$ is the effective probability of spontaneous decay $m \rightarrow n$; and $\Delta\lambda_{mn}$ equals the total line width of the transition (Ref 3:5).

The line width chosen for the calculations was the

TABLE III
Gain Coefficient (α) at Point of Maximum Inversion

N_e (cm^{-3})	T_e (eV)	$\Delta N'$max (cm^{-3})	Transition	α (cm^{-1})
10^{15}	0.05	2.2×10^{14}	3 → 2	7.5
**10^{15}	0.05	2.7×10^{14}	3 → 2	9.2
10^{15}	0.20	2.8×10^{12}	3 → 2	.09
10^{16}	0.05	3.5×10^{15}	3 → 2	25.7
10^{16}	0.10	2.9×10^{15}	3 → 2	21.3
10^{16}	0.10	3.5×10^{15}	2 → 1	15.8
†10^{16}	0.10	2.0×10^{15}	2 → 1	9.0

** No absorption

† Source: (Ref 74:15). Gain is calculated for full line width, assuming Stark broadening and no absorption.

Stark width because it is larger than the Doppler line width in the region of interest and, consequently, gives a more pessimistic value of α. The Stark width was calculated from (Refs 74:7;93:601)

$$\Delta\lambda_{mn} = 1.47\text{x}10^{-10}\ (m^2-n^2)\ \lambda_{mn}^2\ N_e^{2/3} \qquad (19)$$

Unlike the authors of Ref 74 who take one half of $\Delta\lambda_{mn}$ as an approximation to be used in Eq (18), Table III reflects the full line width in the cited values of α. On subsequent figures, inversion density is plotted in terms of

$$\Delta N' = N_m - N_n g_m/g_n \qquad (20)$$

to facilitate the use of Eq (18). In terms of the definition provided for population inversion in Eq (1), Eq (20) may be written

$$\Delta N' = g_m \Delta N \qquad (21)$$

Laser Gain

Figures 1-4 and Table III indicate that sufficient gain is available to make laser action probable. Additionally, results from the work of Jones et al (Ref 74:20) are plotted for comparison in Fig. 5. This latter work uses different rate coefficients and, for the particular case shown, ignores absorption.

The reason for the discrepancies in the magnitude of

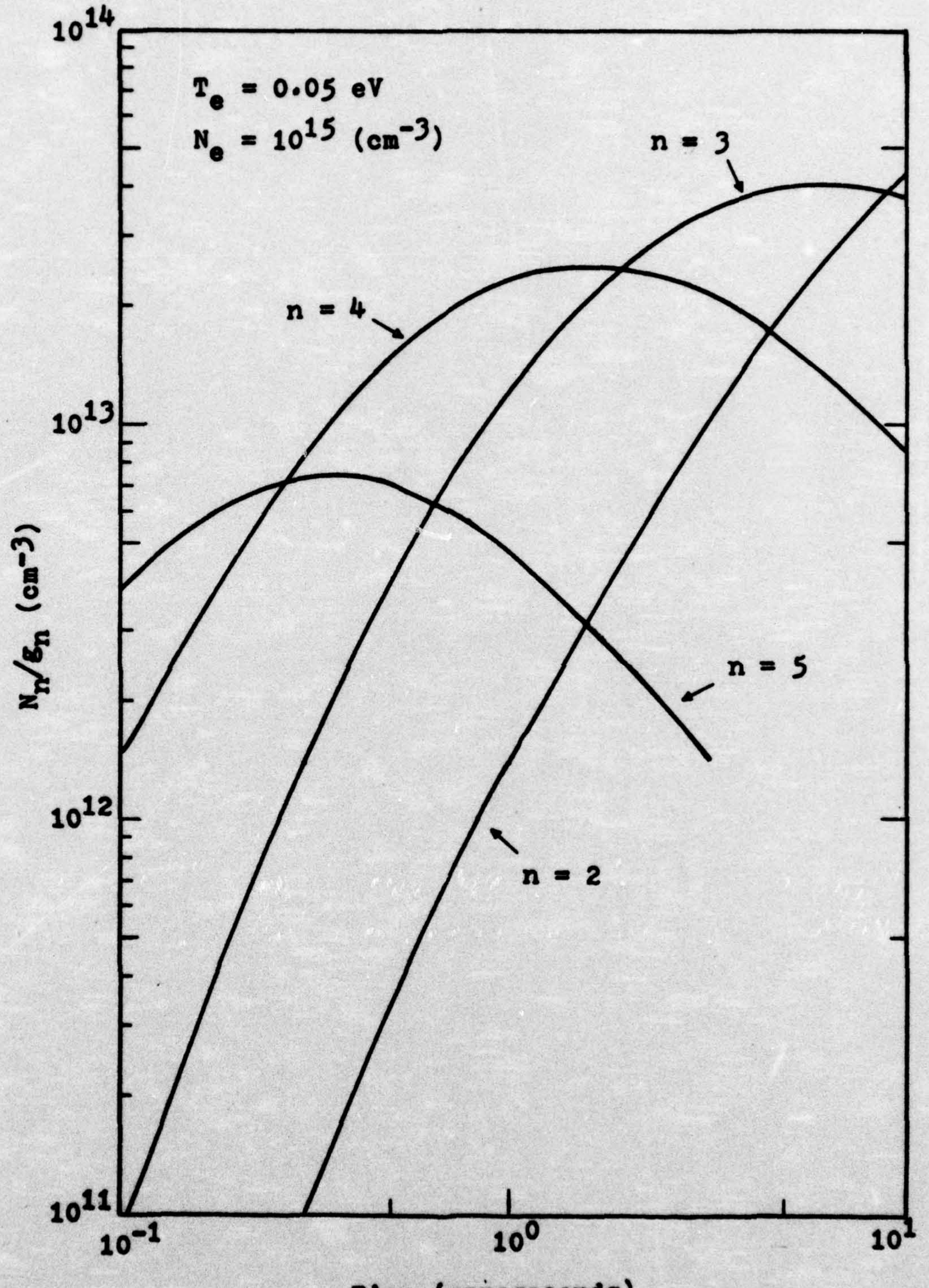

Fig. 1 Effective Level Population in Hydrogen vs. Time

the inversions for the transitions shown and their time history is not precisely known. Probably, the use of different rates and the neglect of absorption accounts for much of the noted difference. Unfortunately, this author did not become aware of this alternate computer code until the latter stages of this work. It would have been informative to use the coefficients of Jones et al within the computer code but time did not permit this course of action. The rate coefficients used by Jones et al will be presented within Appendix B.

The predicted gain, although very large, agrees reasonably well with that of Jones et al. However, it is orders of magnitude greater than the predictions of the Russian work, Paper II. The explanation for this discrepancy is not known, but certain inconsistencies in Paper II were detected. The Russians list gains for times at which population inversions no longer existed according to the graphical data (Ref 37:736-738 and tabular data Ref 36:798-799). Calculations could not reproduce the quoted gain values of Gordiets et al even at times at which inversions did exist.

The magnitudes of the gain estimated are very much dependent upon the methods chosen to handle absorption and cooling.

Absorption

Examination of Fig. 2 shows that absorption affects not only the magnitude but also the duration of the inversion between two levels. Such a result is certainly

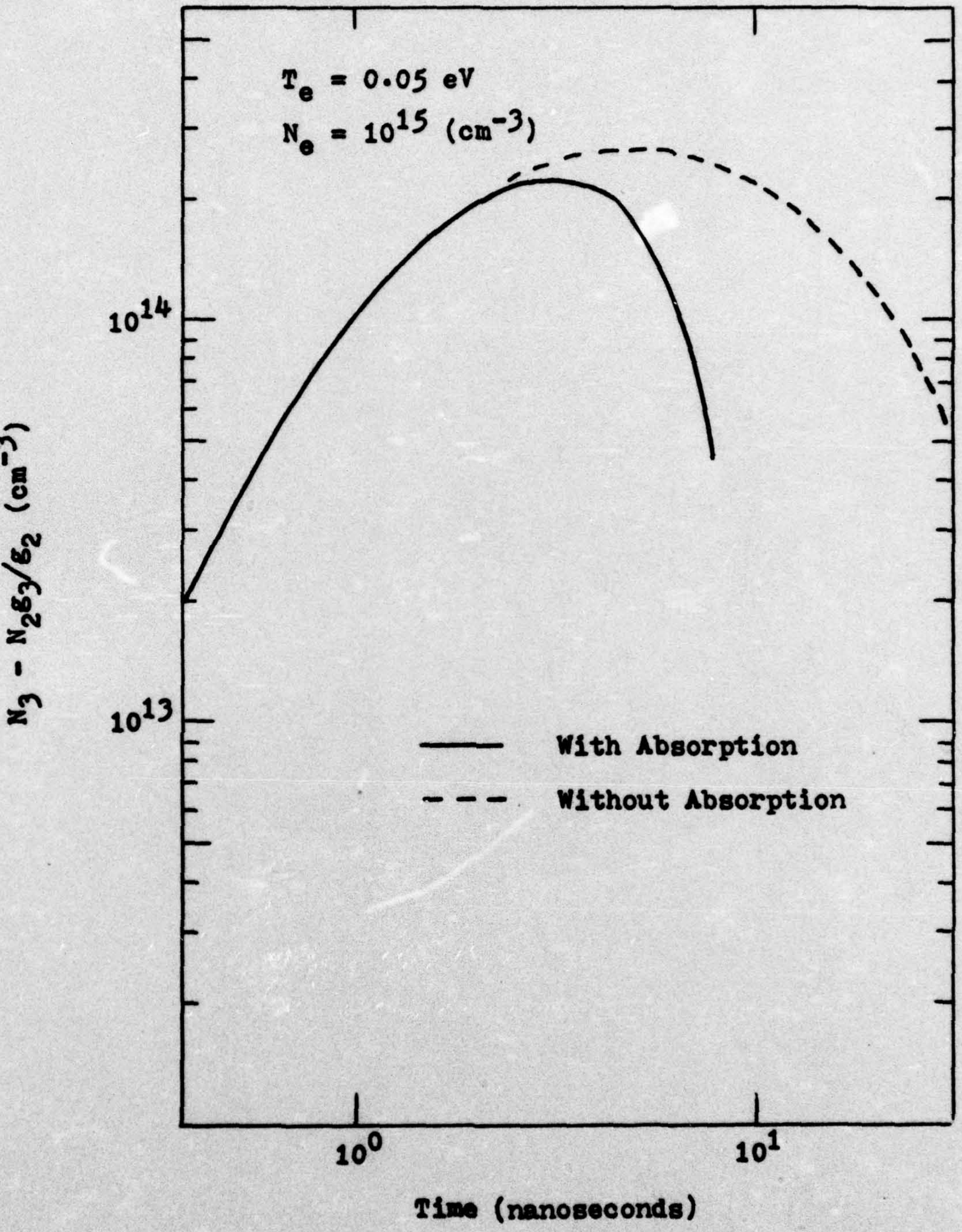

Fig. 2 Inversion Density of 3→2 Hydrogen Transition, With and Without Absorption, vs. Time

expected when the methods of level depletion are considered. The lower quantum levels are more likely to suffer radiative decay than the upper levels. According to Bethe, the total lifetime of a level against spontaneous decay is proportional to $n^{4.5}$ (Ref 12:269). It was previously mentioned that the lower levels are favored by radiative events compared to the upper levels. Consider specifically for the moment the 3 → 2 transition (H_α). The lower level, 2, is decreased primarily by spontaneous emission. As time progresses, the population of the ground state, n = 1, begins to increase until the effective probability of the 2 → 1 transition is affected. The population of level 2 then begins to increase at a faster rate because the principal avenue of depletion is reduced. The overall effect, then, is to terminate the inversion 3 → 2 sooner and at a lower value than would have been reached had absorption been ignored.

However, the effect of absorption may, in certain instances, increase the length of duration of the inversion. A lengthening occurs if the upper level is affected by absorption while the lower level is the ground state. If inversion exists prior to the onset of absorption effects, then the decrease in the rate of upper level evacuation increases the rate of population of level 2. Simultaneously, it decreases the rate of growth of level 1. Consequently, the inversion will last longer.

This may partially explain some of the discrepancy

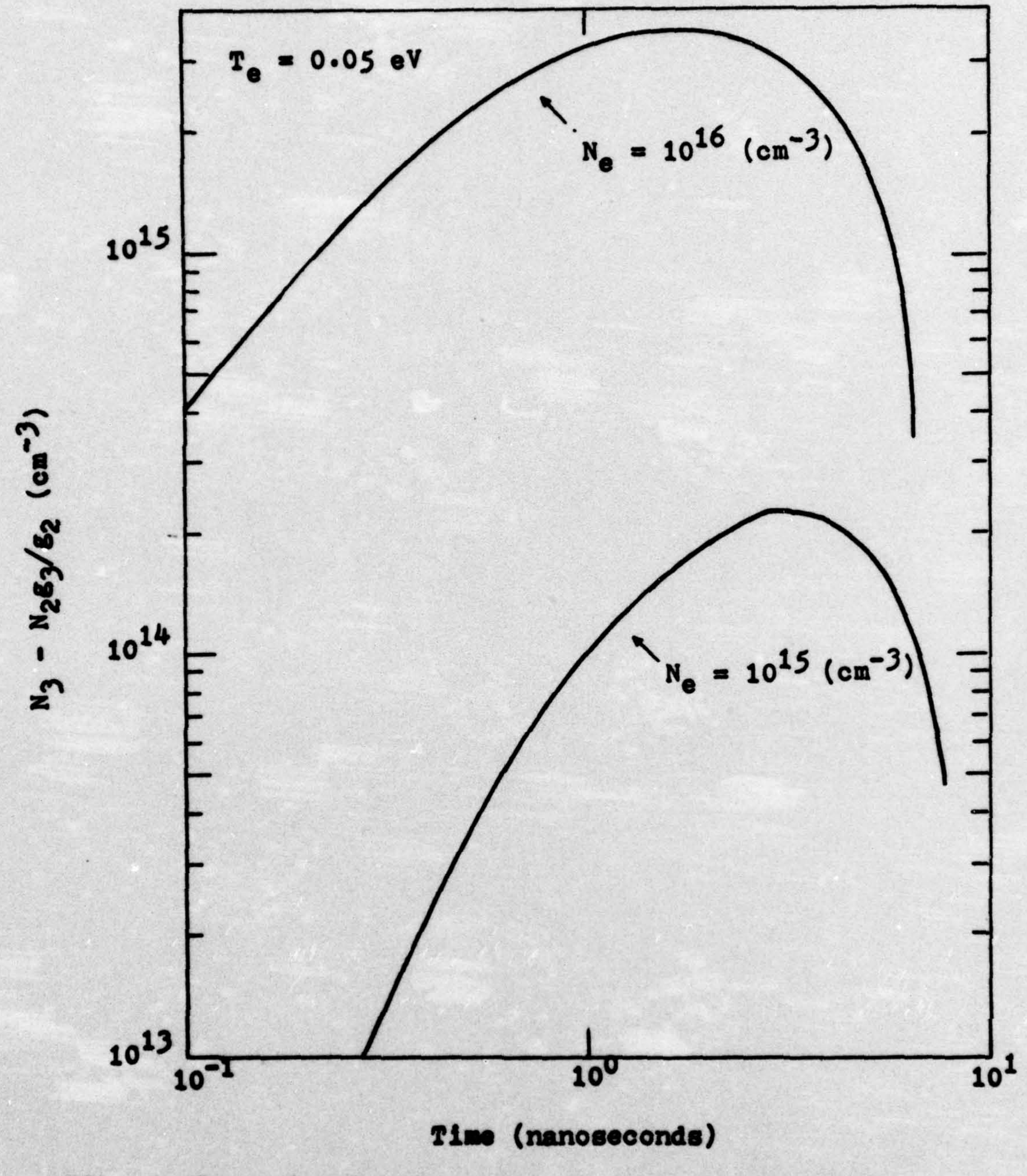

Fig. 3 Inversion Density of 3→2 Hydrogen Transition for Different Electron Densities vs. Time

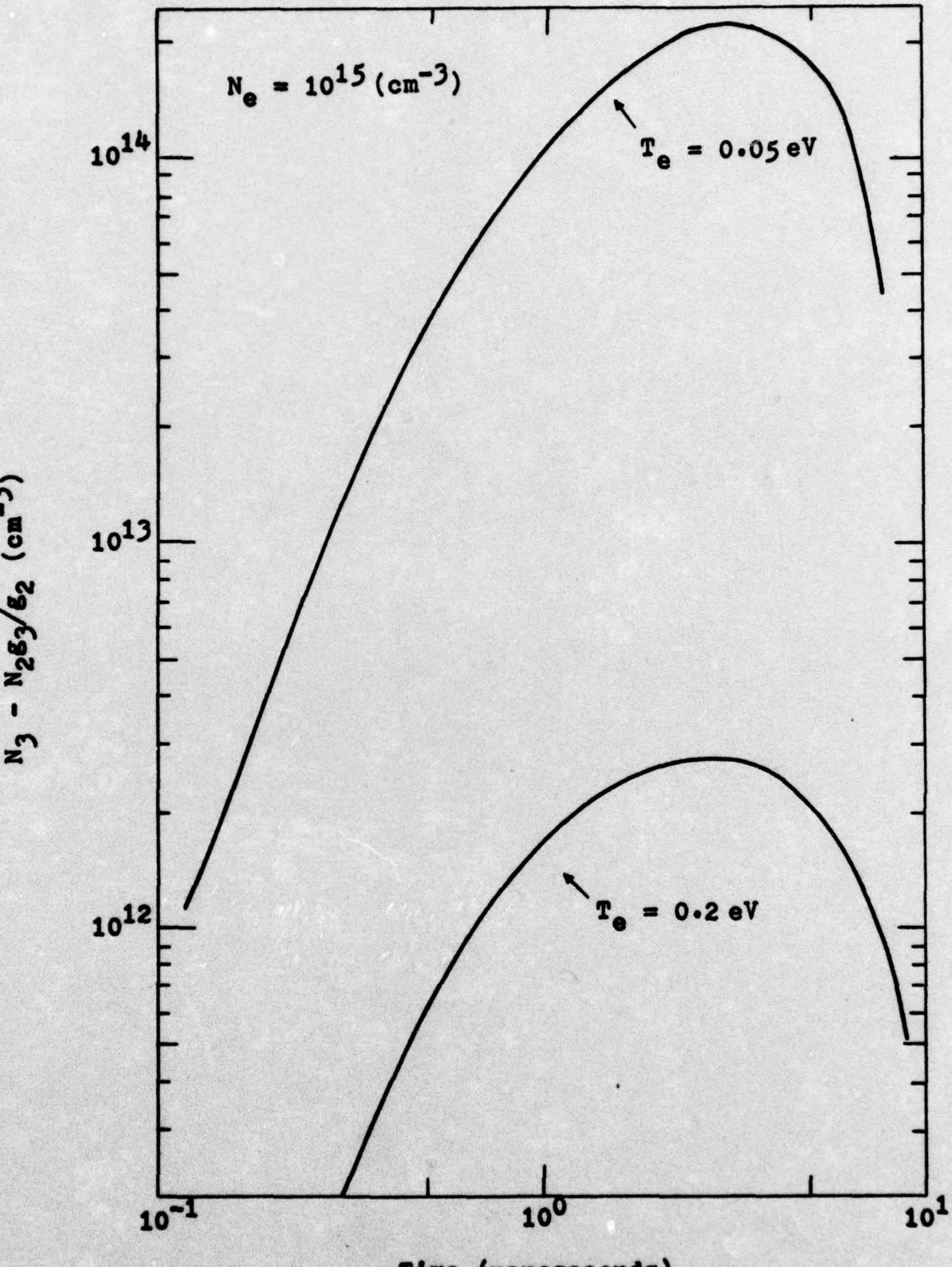

Fig. 4 Inversion Density of 3→2 Transition for Different Electron Temperatures vs. Time

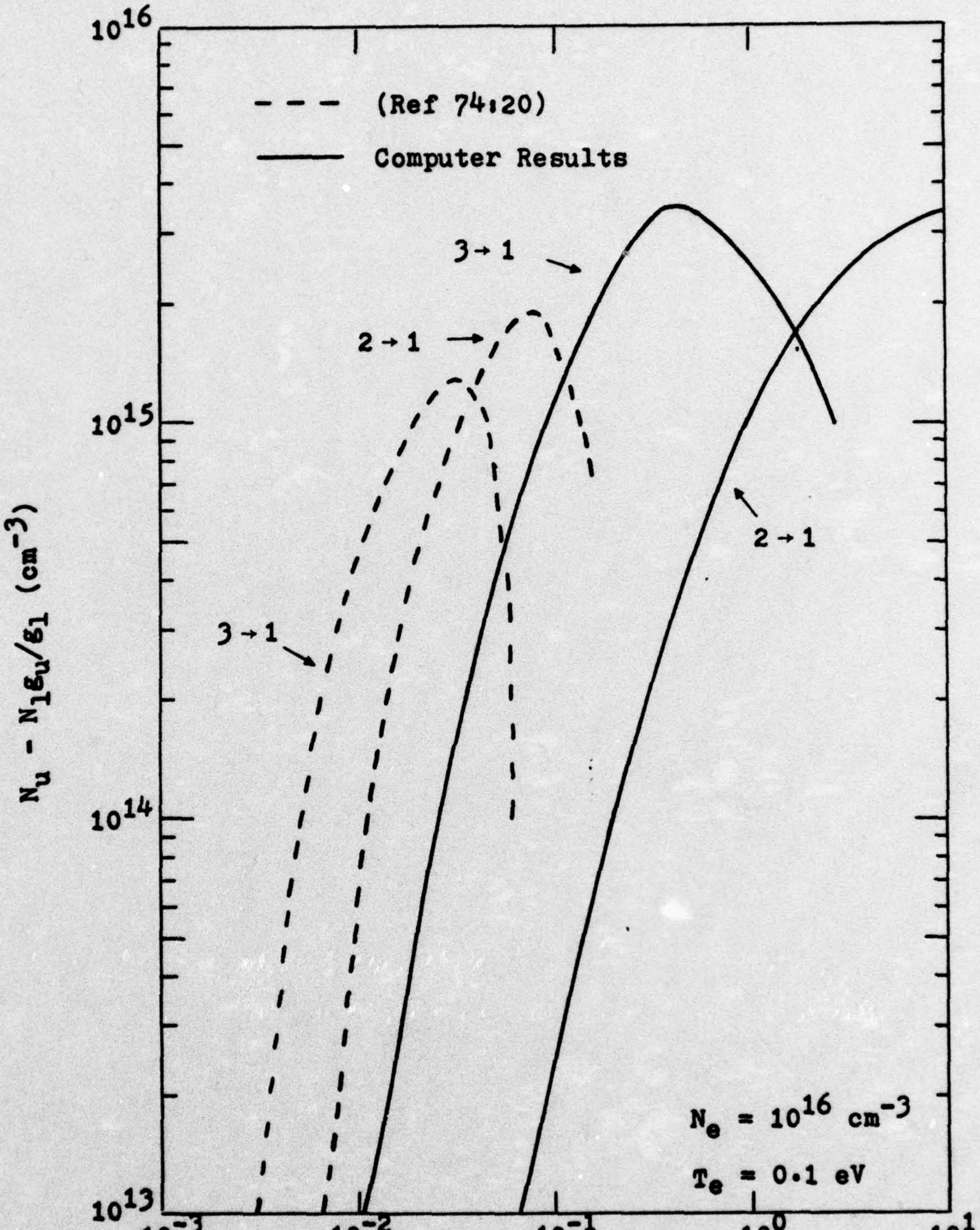

Fig. 5 Comparison of Computer Predictions for Hydrogen Population Inversions vs. Time

between results of this work and Ref 74 as noted in the comparison in Fig. 5.

It has been assumed that stimulated emission within the plasma was negligible. This is the approach taken within the Russian literature in general. However, some authors elsewhere have included this effect. Bohn (Ref 16: 16) makes mention of these calculations but does not publish them; while Jones et al (Ref 74) include stimulated emission explicitly in their computer code, although not in the instance cited in Fig. 5. To the knowledge of this author, there are no presently available data which allow for evaluation of the error involved in ignoring this effect.

Instantaneous Cooling

Although expedient for calculations, the assumption of instantaneous electron cooling is not experimentally justifiable. Experimentally, numerous schemes have been proposed to achieve the cooling of the electrons. These include collision with container walls, heavy particle collisions, and expansions into vacuum and through nozzles. These schemes attempt to ensure that cooling is accomplished as quickly as possible. Since the cooling must take place in less time than it takes to produce the inversions, cooling schemes may be a limiting factor in the plasma laser.

Appendix D lists specific references within the literature which deal with the cooling problem. These indicate that even with finite-time-cooling, inversion and subsequent gain are attainable.

Experimental Verification

An examination of available literature indicates that the Russians have a rather comprehensive program for the theoretical study and development of the plasma laser. However, published information from within the U.S.S.R. concerning experimental development of population inversion through the use of a recombining plasma is surprisingly limited. Much of the Russian theoretical work has indicated rather specific experimental techniques (Ref 7:931-937), but there appears to be no subsequent experimental work published. Experimental confirmation of this principle originates largely from outside Russian boundaries.

Hoffman and Bohn (Ref 65:878-880) have verified the existence of population inversion in expanding hydrogen plasmas for the Paschen (4→3) and Brackett (5→4) transitions. The 4→3 laser transition has also been detected in the work of Bockastein _et al_ (Ref 15:1260) working with pulse discharges into a medium in which hydrogen was present as an impurity. The line was detected during the afterglow period.

The experimental demonstration of the feasibility of the plasma laser is perhaps best accomplished in the works of Collins _et al_ (Refs 18;19). Working with dense Helium plasmas, they have successfully detected stimulated emissions during the afterglow stage. These scientists maintain that a laser would have been realized had a longer gain path been available.

VI. Recommendations

Presently, enough theoretical and experimental evidence exists to recommend the further study and development of plasma lasers. Present limitations, such as the absense of rates for specific processes, will be erased only through experimental and developmental programs.

In terms of the work of this report, several logical extensions suggest themselves. Questions of plasma production, electron cooling and material optimization which were side-tracked because of time constraints certainly need to be investigated. Answers to these questions will help remove or modify some of the assumptions made in this study, such as the instantaneous cooling of electrons to a final arbitrary temperature.

In the following pages, recommendations are given which allow for extension of the scope of this report. The tasks outlined are neither necessarily of equal complexity nor are they of equal impact upon final results. Rather, they represent what might have been attempted had more time been available.

The computer code calculates the necessary rate coefficients of Eq (2) within the main program. Modifying the code so that each rate calculation is performed within individual subroutines would greatly facilitate the comparison of results when different rate formulas are employed. Perhaps one of the first attempts should be a comparison of the results obtained when using the rate coefficients of Jones et al (Ref 74) versus the rates of the present study. By changing only the rate coefficients, the impact of this change upon population inversion may be determined.

Previously, it was mentioned that the assumption of instantaneous cooling of the electrons to some final arbitrary temperature could not be defended on physical grounds. Possible schemes of electron cooling should be investigated. Expansion of the plasma or introduction of heavy particles are possible methods of cooling the electrons. In using a specific method, not only is the assumption of instantaneous cooling removed, but also a concurrent time history of the electron temperature is provided. In terms of the mechanics of the computer program, the calculation of the various rates must be iterated throughout the total computation rather than being calculated just once as they are when the final electron temperature is constant. Presently, the final temperature of the electron is arbitrarily chosen. The use of a "physically realizable" system should remove some of the arbitrariness of the electron temperature and allow for laser operation predictions in terms of more realistic parameters.

The question of using constituents other than hydrogen is certainly not trivial. As noted on several different occasions, even "well-known" hydrogen has rates that are not understood exactly. Attempts to scale hydrogen results to hydrogen-like systems are frequently encountered within the literature (Refs 10, 11, 16). However, the conclusions drawn from these attempts are, at best, likely to be only as good as the hydrogen results and may be much poorer. By the same token, calculations for non-hydrogen-like systems are beset with major difficulties in determining the appropriate rate coefficients for the various processes. Current literature shows that the trend in plasma laser development is definitely towards these systems, but that an analytic approach is much more tedious. Despite these hindrances, it is probably in the area of non-hydrogen-like systems where the plasma laser will finally be constructed.

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Appendix A

Methods of Approximation

Frequently, Eqs (2) and (3) must be solved through the use of one approximation or more. Within this report, specific techniques of approximation have been applied to these equations. These techniques represent only some of those which are cited in the literature on the plasma laser. Other methods which are not used specifically within this work but which are often employed are these: one-photon approximation, quasi-stationary approximation, and diffusion approximation. These frequently used approaches will be discussed briefly and references for further study will be provided. No attempt will be made to justify a particular method.

The works of Biberman *et al* (Ref 14) and Gudzenko *et al* (Ref 59) provide summaries of useful approximations. Both works list extensive bibliographies for additional information.

One-Photon Approximation

The form of Eqs (2) and (3) is simplified when the one-photon or single-quantum approximation is used. It is predicated upon the fact that transitions are most probable between adjacent states. Consequently, many terms involving a given level and another level which is not immediately adjacent to it may be ignored. Application of the single-photon approximation is especially useful when radiative processes can be ignored. Then this approximation is used, only the main diagonal elements and the immediately adjacent diagonal elements in the relaxation matrix are non-zero. This allows the system to be solved in terms of the populations of the ground state and free electrons.

References: [13, 14, 59, 68, 98]

Quasi-stationary Approximation

By using the quasi-stationary approximation, the system of rate equations can also be algebraically solved in terms of the ground state population and the free electron density. The basis for this approach is the fact that under most conditions the time for relaxation of the ground state and the free electrons is significantly longer than the relaxation time of the excited levels (Ref 10:300). Consequently, all derivatives appearing on the left hand side of Eqs (2) and (3) may be set equal to zero, with the exception of the ground level rate which is assumed not to equal zero. This particular approach is employed very frequently and is referred to within the literature under these names: BKM (Bates, Kingston, and McWhirter) method, constant sink, stationary sink, and constant runoff approximation.

References: [10, 11, 44, 59, 64, 78]

Diffusion Approximation

In the diffusion approximation, the upper levels are characterized by quantum numbers and energies which are assumed to be continuous functions. This approach is based upon the fact that at high values of n the spacing between levels gets smaller and smaller. The rate equations can then be solved by equations of the Fokker-Planck type. Closely related to this approach is the modified diffusion approximation (MDA) which attempts to combine the continuous-like properties of the highly excited states with the obviously discrete nature of the lower energy states where the spacing between levels is significant. In effect, it unites the diffusion and single quantum approximations.

References: [13, 14, 59, 61, 86]

Appendix B

Rate Coefficients

The rate coefficients of Refs 36 and 37 were used to characterize the processes shown in Table I. The appropriate formulas are listed in this appendix in Table IV. The authors of the above-mentioned references attribute these rates to semi-empirical information and the assumption of a Maxwellian velocity distribution of the free electrons (Ref 37:735). Unfortunately, there is no definitive information within the available literature to suggest that these rates are more or less correct than other possible formulations. Even for the case of hydrogen, the appropriate cross-sections from which the collisional rates are derived are subject to question.

Jones and Ali (Ref 74) use rates attributable to Drawin (Ref 27:484-486) for three-body recombination and ionization. Their three-body ionization coefficient is in the notation of this report

$$B(n,c^*) \approx 1.18\text{x}10^{-8}\, n^3 R_y T_e^{-\frac{1}{2}}\, \psi(1,X_n) \qquad (22)$$

where

$$X_n = R_y/n^2 T_e \qquad (23)$$

and

$$\psi(1,X_n) = \int_{X_n}^{\infty} (1-X_n/u)\exp(-u)\ \ln\,(1.25u/X_n)\ du \qquad (24)$$

The rate for the reverse process is obtained through application of the principle of detail balance. The coefficients of excitation and de-excitation by electron impact used by Jones and Ali are attributable to Seaton. Changing to the notation of this report yields

$$V(n,m) \approx 8.2\text{x}10^{-7}\, n^{-5} m^{-3} (n^{-2} - m^{-2})^{-4}\, T_e^{-\frac{1}{2}} \exp(-|X_n - X_m|) \quad (25)$$

while R(m,n) comes from detail balance considerations.

Numerical evaluation of the coefficients of Gordiets _et al_ compared to those employed by Jones indicate that the former values are generally smaller by a factor of 10^2 in the region of interest. This discrepancy is apparently significant; but in terms of the usage in this report, it indicates that the very existence of an inversion is not very dependent upon the rates used. However, the impact on gain and duration of inversion may be significant for different rates (Ref 73). Obviously, experimental verification of the appropriate rates in dense plasmas is needed.

The rates of Gordiets _et al_ were used for two reasons: First, there appeared to be no priori evidence contradicting their use for estimate purposes; and, second, possible confirmation of a numerical solution might be obtained by standardization of rates.

TABLE IV
Formulas For Rate Coefficients (Gordiets *et al*)

Process	Equation
Spontaneous Decay A(m,n)	$1.57\times10^{10}\ n^{-3}m^{-5}(n^{-2}-m^{-2})^{-1}$
Radiative Recombination A(g,n) + A(c*,n)	$-5.2\times10^{-14}\ n^{-3}(R_y/T_e)^{1.5}\ \exp(X_n)\ E_1(-\lvert X_{10}-X_n\rvert)$
Excitation V(n,m)	$1.73\times10^{-7}\ n^{-5}m^{-3}(R_y/T_e)^{4.5}(X_n-X_m)^{-4}\ \exp(-\lvert X_n-X_m\rvert)\ U(\lvert X_n-X_m\rvert)$
De-excitation R(m,n)	$V(n,m)\ n^2m^{-2}\ \exp(\lvert X_n-X_m\rvert)$
Collisional Ionization B(n,g) + B(n,c*)	$8.65\times10^{-8}\ n^{-5}(R_y/T_e)^{3.5}\ \Phi(X_n-X_{10})$
Collisional Recombination B(g,n) + B(c*,n)	$5.5\times10^{-31}\ n^{-3}\ (R_y/T_e)^5\ \exp(X_n)\ \Phi(X_n-X_{10})$

$X_n = R_y/n^2T_e$

$U(z) = 1 + zE_1(-z)\exp(z)$

$\Phi(\mu) = \int_\mu^\infty z^{-4}U(z)\exp(-z)dz$

E_1 = Exponential Integral

Sources: (Ref 36:792-794) and (Ref 37:734-735).
Note: Last two rates are incorrect in Ref 37.

Appendix C

Computer Program Block Diagram

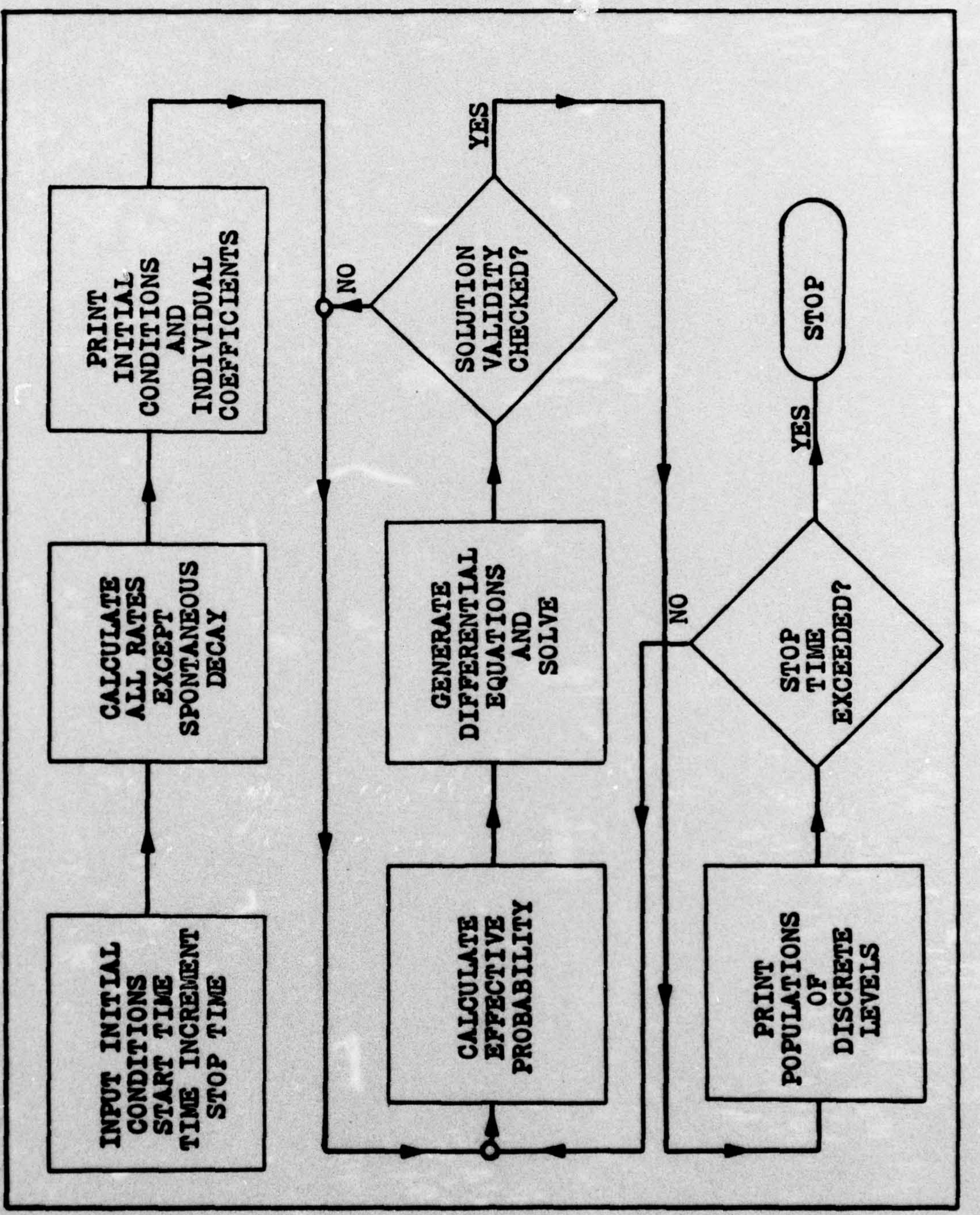

Fig. 6 Computer Program Block Diagram

Appendix D

Bibliography Cross-Reference

The following list of plasma laser interest areas is cross-referenced to the bibliography by number. The topic under which a given reference is listed is the emphasis area of the paper. In some cases, the same reference may be listed under more than one subject. Many of the references listed under "Rate Coefficients" do not deal directly with plasma laser systems, but they do provide needed background.

Alkali Plasmas for Lasers:	1, 6, 23, 34, 38, 57, 75, 79.
Approximations:	34, 59, 61, 86, 98.
Chemical Plasma Systems:	33.
Cooling of Plasmas:	35, 50, 54, 75, 84, 94.
Experimental Work:	7, 15, 17, 18, 19, 20, 21, 52, 65, 80, 87, 90.
Gain Projections:	9, 16, 22, 36, 37, 38, 40, 41, 42, 51, 72, 74, 91, 95.
Laser Devices:	18, 19, 49, 55, 83, 84, 85, 91.
Non-Atomic Recombination Principle:	31, 33, 37, 44, 45, 46, 47, 48, 55, 56, 60, 89.

Plasma Generation:	7, 55, 95.
Rate Coefficients:	1, 5, 13, 14, 17, 23, 25, 27, 28, 29, 36, 64, 68, 69, 70, 72, 73, 78, 81, 82, 88, 89, 92, 95, 97, 99, 100.
Review Articles:	8, 14, 59, 68, 76, 77.
X-Ray - VUV Lasers:	16, 32, 43, 53, 58, 71, 72.

VITA

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Population Inversion
Recombination Laser

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A rapidly recombining plasma preferentially populates the upper energy levels, thus producing population inversions. Laser devices in which the active medium is a recombining plasma are termed "plasma" or "recombination" lasers.

A computer code was developed to determine the level populations of hydrogen as a function of time. The instantaneous cooling of the free electrons in a completely ionized hydrogen plasma was assumed. The resulting population inversion produced estimates of gain which were sufficient for laser action.

The absorption of Lyman radiation in the plasma was also assumed. Generally, the effect of this absorption is to decrease the duration and magnitude of the gain. However, when the lower laser level and the ground level coincide, the resulting gain can be enhanced by this absorption.

Comparison of the computer results shows reasonable agreement with other researchers' computer predictions.

A cross-referenced bibliography is provided to assist in further study of plasma lasers.