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Naval Research Laboratory
Washington, DC 20375-5000

NRL Memorandum Report 6369

Stimulated Raman Scattering of Intense Laser Radiation in a Nuclear-Disturbed Space Plasma

M. J. KESKINEN

Geophysical and Plasma Dynamics Branch
Plasma Physics Division

Y. C. LEE

Science Applications International Corp.
McLean, VA 22102

and

University of Maryland
College Park, Maryland

November 8, 1988

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3 DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S) NRL Memorandum Report 6369

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION Naval Research Laboratory

6b. OFFICE SYMBOL *(If applicable)* Code 4780

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS *(City, State, and ZIP Code)* Washington, DC 20375-5000

7b. ADDRESS *(City, State, and ZIP Code)*

8a. NAME OF FUNDING / SPONSORING ORGANIZATION SDIO

8b. OFFICE SYMBOL *(If applicable)* SDIO/T/IS

9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS *(City, State, and ZIP Code)* Washington, DC 20301

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO.
63220	s80000 srn01	Word Package #S813	

11. TITLE *(Include Security Classification)* Stimulated Raman Scattering of Intense Laser Radiation in a Nuclear Disturbed Space Plasma

12. PERSONAL AUTHOR(S) Keskinen, M.J. and Lee, Y.C.

13a. TYPE OF REPORT Interim

13b. TIME COVERED FROM ________ TO ______

14. DATE OF REPORT *(Year, Month, Day)* 1988 November 8

15 PAGE COUNT 19

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*

Beam propagation, High altitude nuclear explosion
Parametric instability
Stimulated raman scattering

19 ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Stimulated Raman scattering of intense laser radiation propagating in a nuclear-disturbed space plasma environment has been investigated. For parameters typical of a single high altitude nuclear explosion (HANE), we propagation due to Raman scattering, particularly for 10 μm radiation. 10 μm, respectively, and for beam power densities on the order of 10^5 W/cm^2. Here γ is the growth rate for simulated Raman scattering. For the multiple HANE case, approximate growth times $\gamma^{-1} \approx 10^{-3} - 10^{-2}$ sec can be achieved for laser wavelengths 1 μm 10 μm with beam power densities of 10^5 W/cm^2. As a result, a single burst HANE is not likely, due to stimulated Raman scattering, to effect the propagation of laser radiation with wavelengths of 10 μm and 1 μm and power densities on the order of 10^5 W/cm^2. However, the multiburst HANE environment may degrade laser propagation due to Raman scattering, particularly for 10 μm radiation.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS

21 ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL M.J. Keskinen

22b TELEPHONE *(Include Area Code)* (202) 767-3630

22c OFFICE SYMBOL Code 4780

DD Form 1473, JUN 86 *Previous editions are obsolete.* SECURITY CLASSIFICATION OF THIS PAGE

S/N 0102-LF-014-6603

CONTENTS

STIMULATED RAMAN SCATTERING OF INTENSE LASER RADIATION IN A NUCLEAR-DISTURBED SPACE PLASMA

I. INTRODUCTION

A key component of proposed Strategic Defense Initiative (SDI) systems is high power coherent radiation sources, either ground or space-based. The propagation characteristics of such radiation beams in the ambient and nuclear-disturbed environment is of the utmost importance for the successful implementation of SDI goals and objectives.

Much work has been devoted to the study of laser propagation in the ambient atmosphere[1,2]. For low beam power densities, well known effects such as turbulence broadening of the beam, distortion of beam spatial coherence, and random refraction and wander of the beam have been studied both experimentally and theoretically. At higher beam power densities, nonlinear effects, e.g., thermal blooming, stimulated scattering, and optical breakdown can play an important role in beam propagation by enhancing beam absorption and scattering.

For the nuclear-disturbed environment, while many studies have been made to assess the impact of the high altitude nuclear explosion (HANE) environment on the propagation of radiation in the radio frequency range,[3] very little work has been performed, particularly at high beam power densities, dealing with laser and optical propagation through the HANE environment.[4-6] In this study we focus on plasma parametric instabilities driven by the radiation beam. These instabilities are dependent on the beam power density and can affect beam propagation by scattering beam radiation energy. The fastest growing plasma parametric instabilities will involve high frequency electron dynamics.[5] From the results of our initial work[5] we focus on stimulated Raman scattering (SRS) since this instability can be quite rapid and can grow on fast ω_{pe}^{-1} time scales where ω_{pe} is the electron plasma frequency. The outline of this report is as follows. In

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Manuscript approved September 22, 1988.

Section II we outline the theory and attendant assumptions in stimulated Raman scattering in nuclear-disturbed plasmas. In Section III we present our results giving growth rates of stimulated Raman scattering (SRS) for a typical single HANE. In addition we also compute growth rates for SRS for the multi-burst case. Finally, in Section IV we summarize and discuss our results.

II. THEORETICAL MODEL

The basic geometry of our model consists of a monochromatic electromagnetic wave with frequency ω_0 and wavenumber $\underline{k}_0$ propagating in a plasma imbedded in a magnetic field as shown in Fig. 1. Since we are considering frequencies $\omega_0 >> \omega_{pe}$, Ω_e the effects of the ambient magnetic field on the electromagnetic wave will be small. Here ω_{pe} is the electron plasma frequency and Ω_e the electron gyrofrequency. In addition, since we will be investigating the scattering of high frequency modes with frequencies $|\omega| \gtrsim \omega_{pe} >> \Omega_e >> \omega_{pi} >> \Omega_i$, i.e., Langmuir waves, we take, as a first approximation, the electrons and ions to be unmagnetized. Here ω_{pi} is the ion plasma frequency and Ω_i the ion gyrofrequency. As a result, the general equilibrium implied by our model consists of electrons oscillating with high velocity $v_0 = eE_0/m_e\omega_0$ in a stationary ion background where e is the electron charge, E_0 the electric field associated with the incident electromagnetic wave, and m_e is the electron mass.

If one perturbs this equilibrium with a density and electric field perturbation of the form $\exp [i(\underline{k}_1 \cdot \underline{x} - \omega_1 t)]$ then beat oscillations will form with frequency $\omega_2 = \omega_1 \pm \omega_0$ and wave number $\underline{k}_2 = \underline{k}_1 \pm \underline{k}_0$. These sidebands will in turn beat with $(\omega_0, \underline{k}_0)$ and cause the growth or decay of the mode $(\omega_1, \underline{k}_1)$ provided the Manley-Rowe relations

$$\omega_0 = \omega_1 + \omega_2 \tag{1a}$$

$$\underline{k}_0 = \underline{k}_1 + \underline{k}_2 \tag{1b}$$

are satisfied. As a result, a Langmuir wave and a sideband electromagnetic wave can be parametrically driven to large amplitudes at the expense of the pump electromagnetic wave.

When $\omega_1 = \omega$ and $\underline{k}_1 = \underline{k}$ are Langmuir waves, the dispersion relation for stimulated Raman scattering can be found using the combined Vlasov-Maxwell equations and standard techniques to yield[7,8]

$$\frac{1}{\chi_e} + \frac{1}{\chi_i + 1} = \left(2k_o^2 v_o^2 \sin^2\alpha \cos^2\theta\right)/\omega_o(\omega - \Delta\omega + i\gamma_d) \tag{2}$$

where α is the angle between the beat wave $\underline{k} - \underline{k}_o$ and $\underline{v}_o$ (see Fig. 2), θ is the angle between $\underline{k}$ and $\underline{k}_o$, $\Delta\omega = (c^2/\omega_o)(\underline{k}\cdot\underline{k}_o - k^2/2)$, γ_d is the damping rate of the free electromagnetic wave with $\gamma_d = \nu_e\omega_{pe}^2/2\omega_o^2$, ν_e is the electron collision frequency, and $\chi_e(\chi_i)$ is the electron (ion) susceptibility given by

$$\chi_e(\omega,k) = 2\,(k\lambda_D)^{-2}\left[1 + \zeta_e Z(\zeta_e)\right]\left[1 + (i\nu_e/kv_e)Z(\zeta_e)\right]^{-1}$$

and

$$\chi_i(\omega,k) = 2(T_e/T_i)(k\lambda_D)^{-2}\left[1 + \zeta_i Z(\zeta_i)\right]$$

with $\zeta_e = (\omega + i\nu_e)/kv_e$, $\zeta_i = \omega/kv_i$, λ_D is the Debye length, $v_e(v_i)$ is the electron thermal velocity, Z is the plasma dispersion function and $T_e(T_i)$ is the electron (ion) temperature. We note that the Manley-Rowe relation requires $k = 2k_o\cos\theta$ in Eq. (2).

Eq. (2) has been solved for $\omega = \omega_r + i\gamma$ in several limits. For example, if $k\lambda_D = 2k_o\cos\theta\lambda_D << 1$, so that the plasma wave is not heavily damped, it is found[7,8] that $\omega_r \simeq (\omega_{pe}^2 + k^2v_e^2)^{1/2}$, the Bohm-Gross frequency, and

$$\gamma = -\frac{1}{2}(\gamma_p + \gamma_d) \pm \frac{1}{2}\left[(\gamma_p - \gamma_d)^2 + 4(v_o/c)^2\sin^2\alpha\cos^2\theta\,\omega_o\omega_{pe}\right]^{1/2} \quad (3)$$

where γ_p is the total damping (Landau and collisional) rate of the free plasma wave. The threshold beam power density is

$$\left(\frac{v_o}{c}\right)^2_{TH} = \sin^{-2}\alpha\cos^{-2}\theta(\gamma_p/\omega_{pe})(\gamma_d/\omega_o) \quad (4)$$

giving maximum growth rate for γ_{max} far above threshold ($\gamma_p << \gamma << \omega_{pe}$)

$$\gamma_{max} = (v_o/c)|\sin\alpha|\cos\theta(\omega_o\omega_{pe})^{1/2} \quad (5)$$

In this case the growth rate assumes a linear dependence on E_o or v_o if $(v_o/c) > [\gamma_p|\sin\alpha|\cos\theta(\omega_{pe}\omega_o)^{1/2}]$. On the other hand, for short wavelengths $k\lambda_D = 2k_o\cos\theta >> 1$, is can be shown[7,8] that

$$\omega \approx \Delta\omega + 2(v_o/c)^2\sin^2\alpha\ \cos^2\theta\ \omega_o\left[\chi_e(\Delta\omega,2k_o\cos\theta)/(1 + \chi_e(\Delta\omega,2k_o\cos\theta))\right] - i\gamma_d \tag{6}$$

giving a growth rate

$$\gamma = 2(v_o/c)^2\sin^2\alpha\ \cos^2\theta\ \omega_o\mathrm{Im}\left[\chi_e(\Delta\omega,\ 2k_o\cos\theta)/(1 + \chi_e(\Delta\omega,\ 2k_o\cos\theta))\right] - \gamma_d \tag{7}$$

If collisional damping of the electrostatic wave is neglected, Eq. (6) and (7) give $\omega_r = kv_e$ and

$$\gamma = (\omega_o/2)(v_o/c)^2(\pi/2)^{1/2}\sin^2\alpha\ \exp(-\ 1/2)(k_o\lambda_d)^{-2} - \gamma_d \tag{8}$$

with threshold

$$(v_o/c)^2_{TH} = (8/\pi)^{1/2}(\gamma_d/\omega_o)\exp(1/2)(k_o\lambda_D)^2\sin^{-2}\alpha \tag{9}$$

and maximum growth rate

$$\gamma_{max} = (\omega_o/2)(v_o/c)^2(\pi/2)^{1/2}\sin^2\alpha\ \exp(-1/2)(k_o\lambda_D)^{-2} \tag{10}$$

For the nuclear environment the quantity $k_o\lambda_d$ can be of order unity with the result that Eq. (2) must be solved numerically.

III. RESULTS

We now proceed to solve Eq. (2) using parameters typical of HANE plasmas. For a CW laser with 10^8W peak power with a 5-10 m beam diameter, we find beam power densities I $\approx 10^2$ W/cm^2 and resulting quiver velocities $v_o = 25.6\ [I(W/cm^2)]^{1/2}\ \lambda_L(\mu m)$ cm/sec $\approx$ 2.5 x 10^3 cm/sec where λ_L is the laser wavelength. This gives nonrelativistic quiver velocities $v_o/c \approx 10^{-7}$. For the pulsed mode with 10^6J of energy with repetition rate of 5μ sec, we find $v_o/c \approx 10^{-5}$.

Fig 3(a)-(b) gives the growth rate γ for stimulated Raman scattering as a function of v_o/c for both the pulsed and CW modes using parameters typical of the later time ($t \gtrsim$ 30 min) evolution of a single high altitude nuclear burst. At late times, the HANE plasma can extend[9] several thousands (hundreds) of kilometers parallel (perpendicular) to the geomagnetic field and, as a result, provide a large plasma volume for scattering to occur. We take $n_e = 10^7$ cm^{-3}, $T_e = T_i = 0.2$ eV, and consider both 1 μm ($k_o\lambda_D = 6.2 \times 10^3$) and 10 μm ($k_o\lambda_D = 6.2 \times 10^2$) laser wavelengths. we find the shortest growth times $\gamma^{-1} \approx$ 1-10 sec for the 10 μm case in the pulsed mode.

Fig. 4(a)-(b) displays the growth rate for stimulated Raman scattering as a function of v_o/c again for both the pulsed and CW cases but using parameters typical of computer simulations [R. Dana, private communication] of a multiple high altitude nuclear burst scenario. Here we take $n_e = 2 \times 10^{11}$ cm^{-3}, $T_e = 2$ eV, and consider both the 10 μm ($k_o\lambda_D = 10$) and 1 μm ($k_o\lambda_D = 100$) cases. Here with find much larger growth rates with the fastest occurring on time scales $\gamma^{-1} \approx 10^{-3}$ -10^{-2} sec for the pulsed mode. The growth rates γ and corresponding growth times for the CW case are smaller due to the reduction in beam power density.

IV. SUMMARY AND DISCUSSION

We have computed the growth rates γ of stimulated Raman scattering of both 10 μm and 1 μm laser radiation using plasma parameters typical of a single and multiple high altitude nuclear explosion. We have considered both CW and pulsed modes of laser operation using parameters representative of proposed SDI systems.

For the single burst case, we find relatively long e-folding growth times $\gamma^{-1} \approx 1\text{-}10$ sec in the late time regimes for both the 10 μm and 1 μm cases in the pulsed mode. The decreased power densities in the CW case result in much smaller growth rates and longer growth times.

On the other hand, for the multiple burst scenario, where plasma densities are expected to be much higher than the single burst case, we find faster growth times $\gamma^{-1} \sim 10^{-3} - 10^{-2}$ sec. For the pulsed 10 μm case typical e-folding growth lengths $L_e = c\gamma^{-1}$ are on the order of 100 km. For nuclear plume dimensions on the order of several thousands of kilometers, one would expect many e-folding lengths over which stimulated Raman scattering can grow. Depending on the angle of arrival of the beam with respect to the HANE plasma, which is expected to extend several thousands of kilometers in altitude, Raman scattering of beam energy in the multiburst case is expected to be strong with subsequent deleterious beam attenuation, erosion, and degraded propagation.

In order to more fully assess the impact of plasma parametric instabilities on beam propagation, several remaining issues need to be addressed. We have made the assumption of a homogeneous plasma. In all probability, the HANE plasma will be highly structured or turbulent on scale sizes comparable to the beam radius and smaller. This density structure will affect the growth and evolution of Langmuir waves driven unstable by stimulated Raman scattering. In addition, we have not discussed nonlinear saturation mechanisms for stimulated Raman scattering in a nuclear environment. Resolution of these problems will give definitive information on beam propagation in the HANE environment.

Acknowledgments

We thank Dr. J.D. Huba and Dr. J.A. Fedder for discussions. This work was supported by SDIO/IST under contract to the Naval Research Laboratory.

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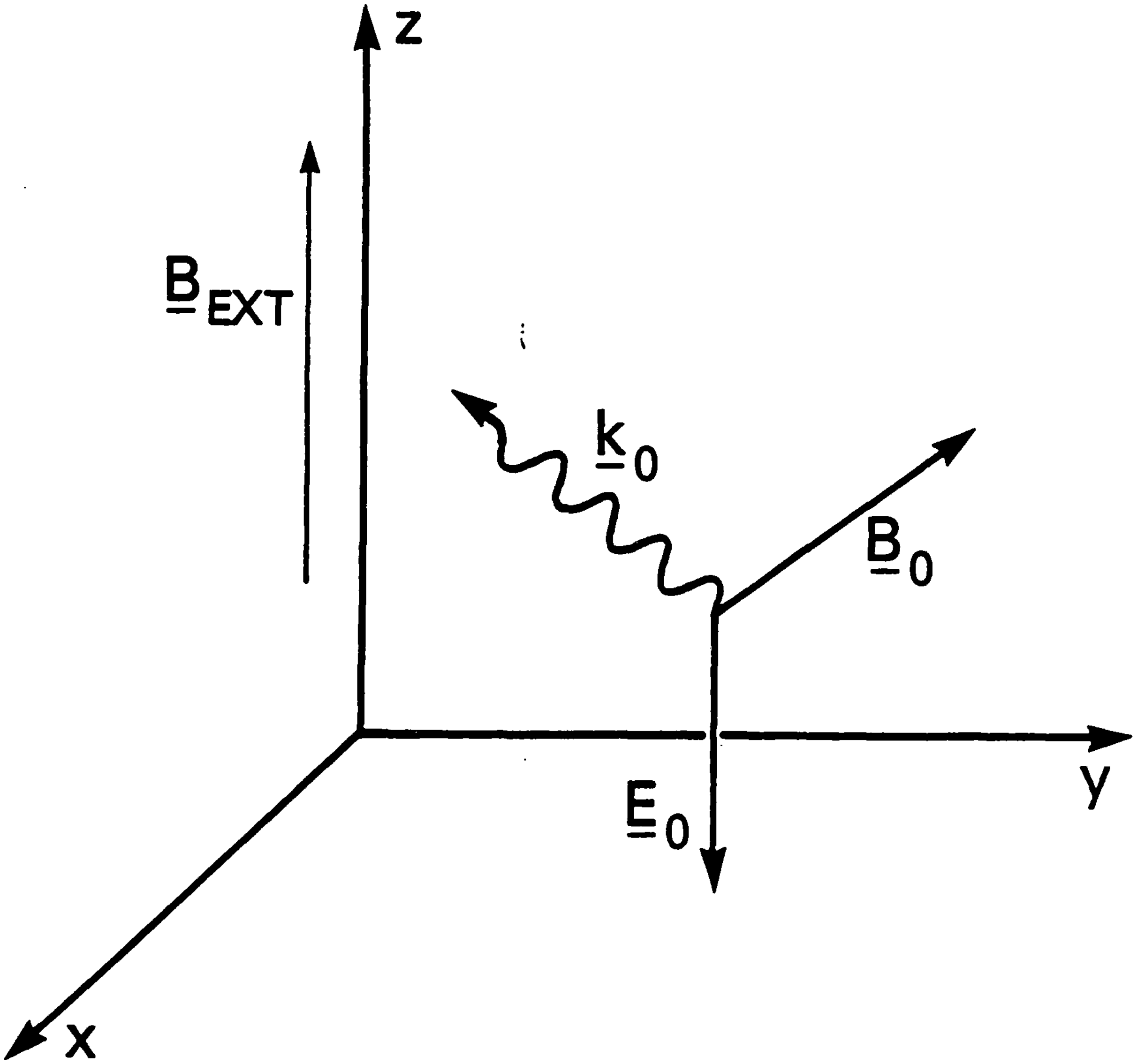

Fig. 1 Basic geometry of electromagnetic wave with wavenumber $\underline{k}_o$, wave electric field $\underline{E}_o$, and wave magnetic field $\underline{B}_o$, propagating in plasma embedded in magnetic field $\underline{B}_{EXT}$.

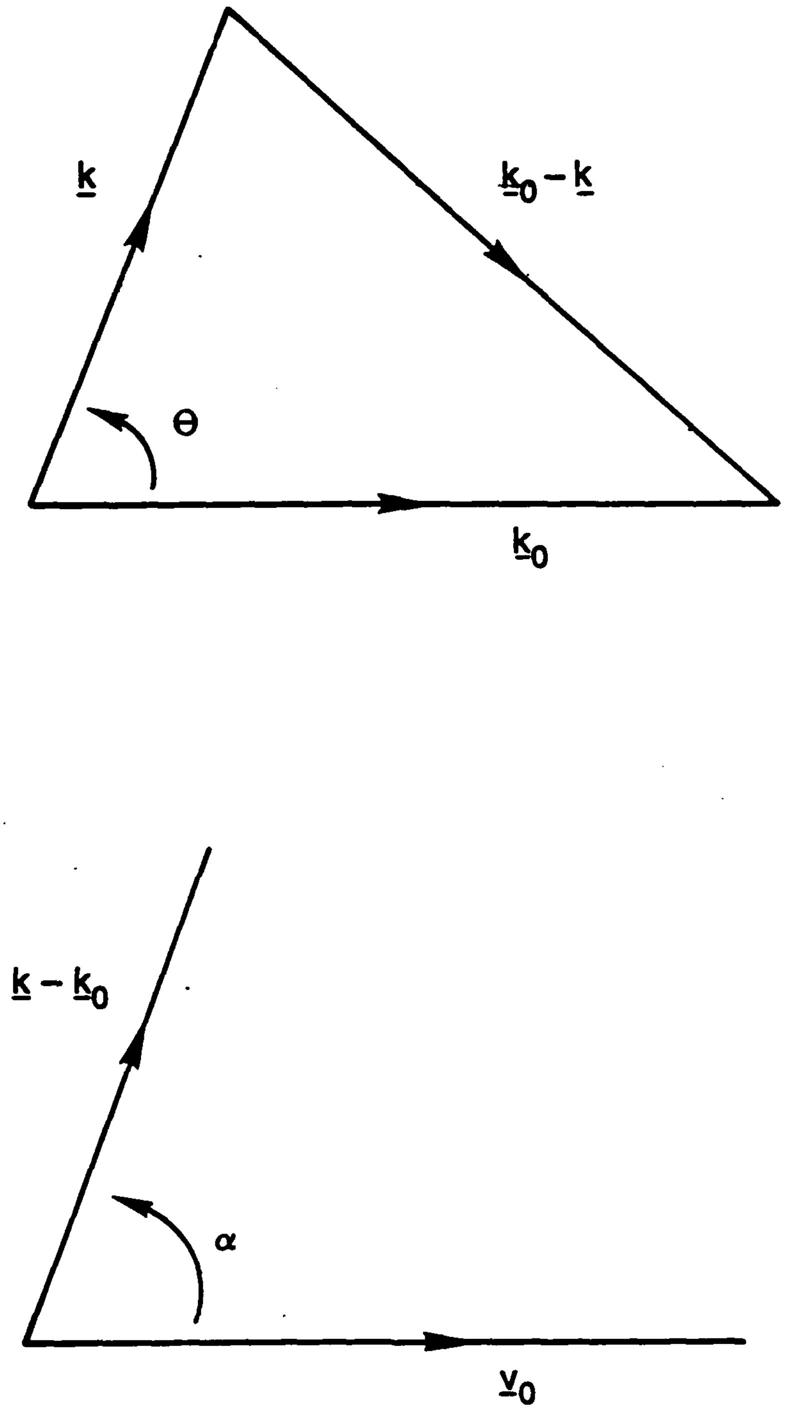

Fig. 2 Definition of angles α and Θ used in Eq. (2).

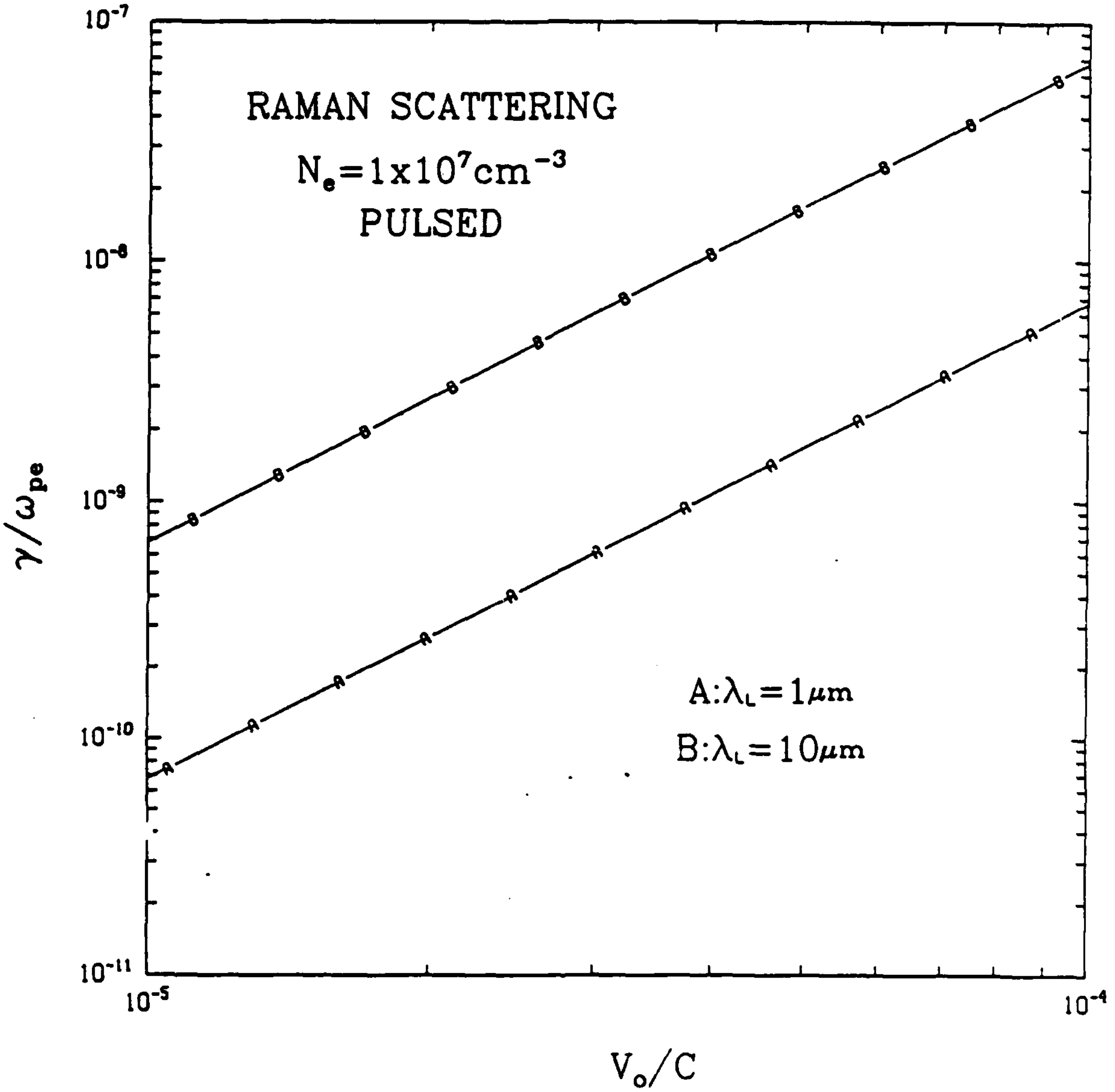

Fig. 3 Plot of growth rates γ/ω_{pe} vs. v_0/c for stimulated Raman scattering for $N_e = 10^7$ cm^{-3}, $T_e = 0.2$ eV, $\nu_e = 5 \times 10^3$ sec^{-1} with (a) $10^{-5} < v_0/c < 10^{-4}$ and (b) $10^{-7} < v_0/c < 10^{-6}$.

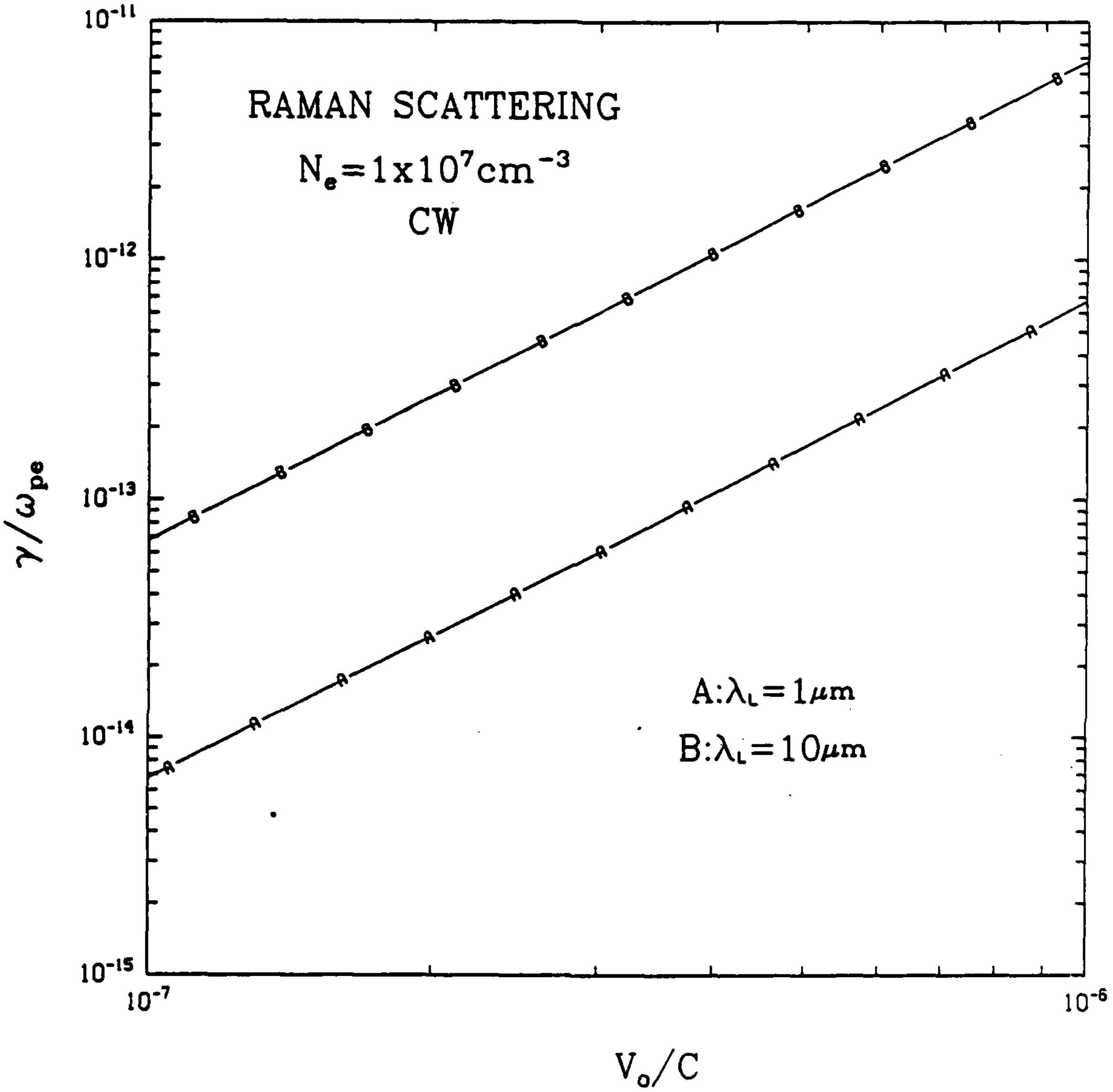

Fig. 3. (Continued) Plot of growth rates γ/ω_{pe} vs. v_o/c for stimulated Raman scattering for $N_e = 10^7$ cm^{-3}, $T_e = 0.2$ eV, $\nu_e = 5 \times 10^3$ sec^{-1} with (a) $10^{-5} < v_o/c < 10^{-4}$ and (b) $10^{-7} < v_o/c < 10^{-6}$.

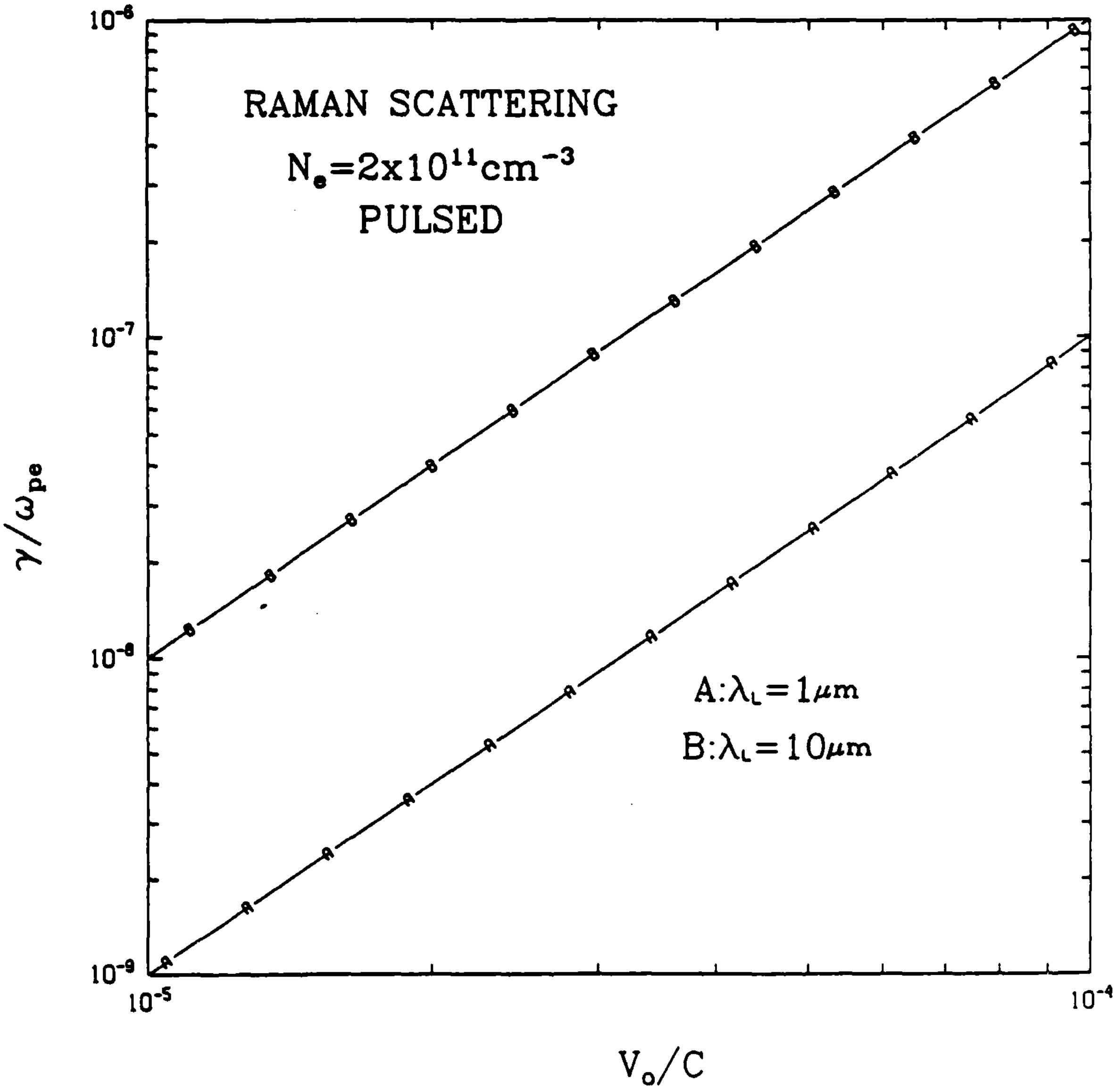

Fig. 4 Plot of growth rates γ/ω_{pe} vs. v_o/c for Raman scattering for N_e = 2×10^{11} cm^{-3}, T_e = 2 eV, ν_e = 10^6 sec^{-1} with (a) $10^{-5} < v_o/c < 10^{-4}$ and (b) $10^{-7} < v_o/c < 10^{-6}$.

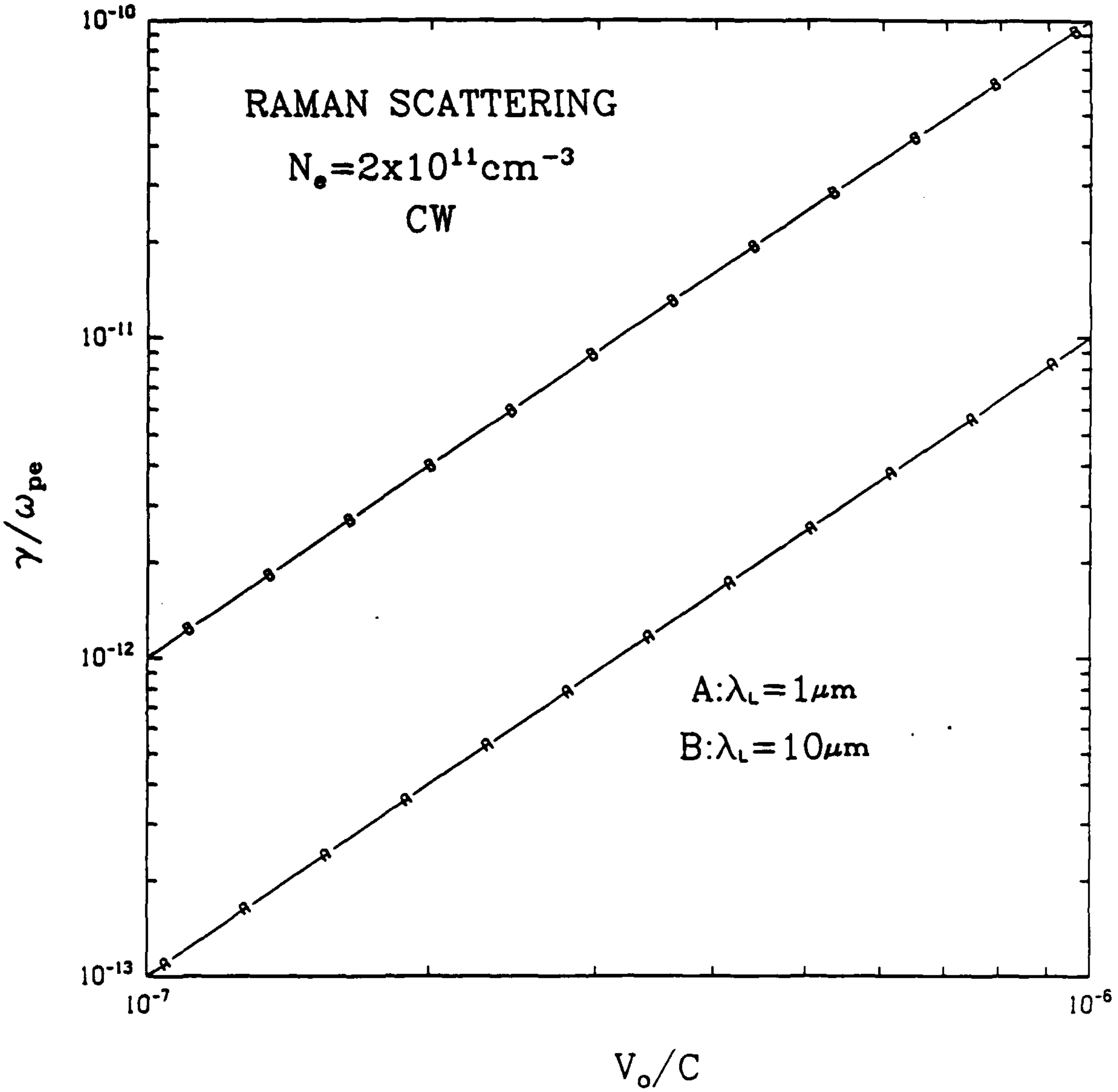

Fig. 4. (Continued) Plot of growth rates γ/ω_{pe} vs. v_o/c for Raman scattering for N_e = 2×10^{11} cm^{-3}, T_e = 2 eV, ν_e = 10^6 sec^{-1} with (a) $10^{-5} < v_o/c < 10^{-4}$ and (b) $10^{-7} < v_o/c < 10^{-6}$.