ceedings of the International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Culham, England, 1965 (International Atomic Energy Agency, Vienna, Austria, 1966), Vol. 2, p. 483.
[4]I. Alexeff, R. V. Neidigh, and W. L. Peed, Phys. Rev. 136, A689 (1964).
[5]G. E. Guest and C. O. Beasley, Phys. Fluids 9, 1798 (1966).
[6]C. P. DeNeef, R. C. Pechacek, and A. W. Trivelpiece, Phys. Fluids 16, 509 (1973); W. A. Perkins and R. F. Post, Phys. Fluids 6, 1537 (1963); A. Bariaud, R. Gravier, M. Korman, H. Luc, C. Renaud, and J. Tachon, Phys. Fluids 7, 1541 (1964); A. J. Lichtenberg, S. Sensic, and A. W. Trivelpiece, Phys. Rev. Lett. 13, 387 (1964).
[7]J. P. Blewett, in *Handbook of Physics*, edited by E. U. Condon and H. Odishaw (McGraw-Hill, New York, 1958), Chap. 9, p. 155.

Brillouin Backscattering and Parametric Double Resonance in Laser-Produced Plasma

C. Yamanaka, T. Yamanaka, T. Sasaki, and J. Mizui
Institute of Laser Engineering, Osaka University, Suita, Osaka 565, Japan

and

H. B. Kang
Institute of Plasma Physics, Nagoya University, Nagoya 464, Japan
(Received 3 December 1973)

Brillouin backscattering from laser-produced plasmas of hydrogen and deuterium has shown an isotope effect in the red-side region of the generated second-harmonic light. This isotope shift is explained by the parametric instability at the cutoff region using the phase-matching condition of the waves. The decrease of the reflectivity appeared when the laser intensity increased up to 1 order of magnitude larger than the threshold of the parametric instability. A broad-band laser showed more effective heating of the plasma than a narrow-band laser.

The interaction of an intense laser beam with plasma is one of the most interesting phenomena in laser fusion research.[1-3] In particular, the nonlinear excitation of the collective processes of plasma is very important to laser heating.[4] Many theoretical works[5-8] have been done to clarify the anomalous absorption due to these effects. Near the cutoff region, the parametric instability (photon-plasmon-phonon interaction) plays an essential role in the absorption, which has been verified not only in laser plasma,[4-9] but also in the ionosphere[10] and in laboratory experiments on microwave heating.[11,12] Induced scattering processes[13-16] in the underdense region have been discussed as a counteraction to the absorption.

To investigate the more detailed process of heating we have performed a laser-bombardment experiment on solid hydrogen and deuterium targets using a YAlG (yttrium aluminum garnet)-oscillator, glass-amplifier laser system and a glass-oscillator, glass-amplifier laser system. An isotope effect of Brillouin scattering due to the hydrogen and deuterium plasmas has been observed. The decrease of the reflectivity has appeared at above a certain laser intensity. Effective heating which had been predicted by the double resonance[17] of the parametric excitation was experimentally studied.

The mode of the laser beam was TEM_{00} and the energy was 40 J in 2 nsec. The beam divergence was less than 1 mrad. The spectral widths of the YAlG and glass laser systems were 6 and 60 Å, respectively. The laser beam was focused on the solid target, the dimension of which was $2\times 2\times 10$ mm^3, by an aspherical lens of focal length 50 mm. The image of the target was magnified 10 times to check the focal condition. The accuracy of the focal adjustment was about 50 μm.

The reflected and backscattered spectra were investigated near the incident wavelength and its second harmonic using a Czerny-Turner grating spectrometer with a mean dispersion of 8 Å/mm in the first order. The spectrum of the reflected light was shifted to the red from the incident light by 10 Å and became broad.

The ratio of the incident to the reflected laser light was measured by using a single biplanar photodiode, HTV-R317, with a filter, IR-80. In the glass-laser case, shown in Fig. 1, the reflectivity increased up to 18% and began to decrease above an intensity of 1.5×10^{14} W/cm^2. In the YAlG-laser case, the reflectivity was always a little bit higher than that for the glass-laser case.

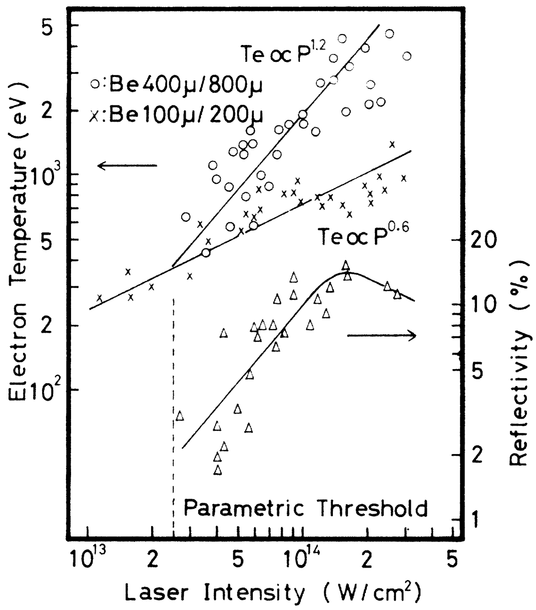

FIG. 1. Electron temperature and reflectivity versus laser intensity when glass laser system bombards a solid deuterium target. Threshold of parametric instability is indicated by vertical line.

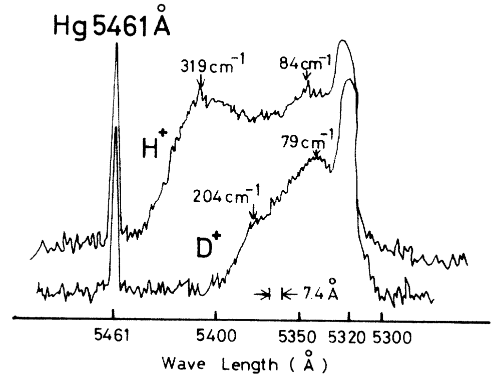

FIG. 2. Spectrum of backscattered light near the second harmonic when YAlG laser system bombards solid deuterium and hydrogen targets.

The decrease of the reflectivity, which begins at a laser intensity 1 order of magnitude larger than the threshold of the parametric instability, is explained as follows. At the threshold, the spatial region of the instability is so small that the reflectivity is still mainly determined by classical absorption. As the laser intensity increases, the anomalous absorption grows in to a larger region to reduce the reflectivity.

The backscattered light near the second harmonic[14] showed two side peaks at the red side of the second harmonic, which was especially clear when the YAlG laser was used, as shown in Fig. 2. These side peaks appeared at the central part of the laser focus, where the laser intensity reached the parametric threshold. As the laser intensity[18] increased, the intensity of the backscattered light grew and the spatial region of the backscatter source became wide. As for the growth rate of the side peaks with laser intensity, the glass laser system gave a larger growth than the YAlG system did. The frequency shifts of the first peak with the YAlG system of intensity 8×10^{13} W/cm^2 were 84 and 79 cm^{-1} from the center of the second harmonic for hydrogen and deuterium plasmas, respectively. The shifts of the second peaks were 319 and 204 cm^{-1}, respectively. These second peaks showed an isotope effect. In the case of the glass laser system, the incident spectrum was so broad that the fine structure of the scattered light was smeared.

The backscattered spectrum around the second harmonic is not due to scattering excited in the underdense region, because no side peaks were observed around the incident wavelength. These side peaks of the second harmonic are supposed to be created at the cutoff region and are closely related to the parametric decay instability, as this spectrum was only observed above the threshold of the parametric decay instability. The first side peak seems to be due to the scattered light produced by a modified instability of the electron plasma wave, because the frequency shift had no isotope effect. The second side peak is due to the Brillouin scattering having the following matching conditions:

$$\omega_0 + (\omega_e - \Omega_i) = \omega, \tag{1}$$

$$k_0 + (|k_e| - |k_i|) = k, \tag{2}$$

where ω_0 (k_0), ω (k), ω_e (k_e), and Ω_i (k_i) are the frequencies (wave numbers) of the pumping light, the scattered light, the electron plasma wave, and the ion-acoustic wave, respectively. At the cutoff region, k_0 and k are nearly equal to zero and $|k_e| = |k_i|$. The parametric condition is

$$\omega_0 = \omega_e + \Omega_i. \tag{3}$$

From Eqs. (1) and (3),

$$\omega = 2(\omega_0 - \Omega_i). \tag{4}$$

The ion-acoustic frequencies excited by the parametric decay instability are 3×10^{12} Hz and $\sqrt{2}\times3\times10^{12}$ Hz for deuterium and hydrogen plasmas, respectively, as shown in Ref. 4, Fig. 13. In Fig. 2 the shifts of the second side peaks of the deuterium and hydrogen plasmas are experimentally 6.11×10^{12} Hz (204 cm^{-1}) and 9.56×10^{12} Hz (319 cm^{-1}), respectively. These values are very close to the above estimated shift $2\Omega_i$ of Eq. (4). The ratio of these shifts is 1.56, which is theoretically expected to be $\sqrt{2}$, if the electron temperature is the same for both plasmas.

The electron temperature estimated by the foil absorption method for soft x rays from the plasma is shown in Fig. 1. In the case of the glass laser system the electron temperature had two components above the threshold of the parametric instability. The high-energy component increased as $I^{1.2}$, where I is the spatially averaged laser intensity. The low-energy component had a dependence of $I^{0.6}$. But, in the case of the YAlG laser system the separation of the high- and low-energy components was not clearly observed.[3] From these results we can say that the glass laser system induces more easily the instability of the plasma than the YAlG system does. Nishikawa and co-workers have presented a theoretical treatment of the double resonance[17] of the parametric excitation using two pumps, both being in resonance with the electron plasma oscillation and at the same time their beat frequency being in resonance with the ion-acoustic frequency. According to this theory, two features result: (1) When the beat frequency Δ is tuned to twice the ion-acoustic frequency, $2\Omega_i$, the total threshold power for excitation of the ion wave is

$$\Lambda_1^2\Lambda_2^2=(4\Gamma_i\gamma_e/\omega_e\Omega_i)^2, \quad \gamma_e>\Omega_i, \tag{5}$$

where $\Lambda_i=E_i^2/4\pi nkT_e$, with $E_i^2/4\pi$ the energy of the pumping field and nkT_e the electron thermal energy; Γ_i and γ_e are the damping rates of the ion acoustic-wave and the electron-plasma wave, respectively; and ω_e is the electron plasma frequency. The single-pump threshold is

$$\frac{16\sqrt{3}}{9}\frac{\gamma_e}{\Omega_i}\frac{\gamma_e\Gamma_i}{\omega_e\Omega_i}$$

for $\gamma_e\gg\Omega_i$ which is much higher than that for a double pump. If $\gamma_e<\Omega_i$, the theory for a single pump and a double pump yields the same threshold. (2) When the first-pump intensity is marginal for the decay instability, a very small second pump red shifted by Ω_i can produce the oscillating two-stream instability. The total threshold power for this case is

$$\Lambda_1^2\Lambda_2^2=8(\gamma_e^2\Gamma_i/\omega_e^2\Omega_i), \quad \gamma_e\gg\Omega_i. \tag{6}$$

Consider the experimental conditions for the results presented here. The glass laser had a spectral width of $\Delta\sim1.6\times10^{12}$ Hz (corresponding to $\Delta\lambda=60$ Å) whereas the width of the YAlG laser was only 1.2×10^{11} Hz ($\Delta\lambda=6$ Å). The information in Fig. 13 of Ref. 4 estimates Ω_i to be 3×10^{12} Hz for the case of $\gamma_e>\Omega_i$. Consequently one can expect the glass laser to approximate the conditions for a double resonance much closer than the YAlG laser. This line of reasoning also applies to the excitation of the oscillating two-stream instability which requires an even larger pump threshold than does the decay instability. Both types of instabilities can be induced more readily with the broadband glass laser. Although a clear demonstration of the double-resonance effect cannot be expected in the present experiments, experimental data on electron temperature, ion energy, reflectivity, and neutron yield[18] show that the broadband laser is much more effective in heating the plasma.

[1]N. G. Basov, P. G. Kriukov, S. D. Zakharov, Yu. V. Senatsky, and S. V. Tchekalin, IEEE J. Quant. Electron. 4, 864 (1968).

[2]F. Floux, D. Congard, L. D. Denoeud, G. Piar, D. Parist, J. M. Bobin, F. Delobeau, and C. Fauquigon, Phys. Rev. A 1, 821 (1970).

[3]*Laser Interaction with Matter*, edited by C. Yamanaka and H. J. Schwarz (Japan Society for Promotion of Science, 1973).

[4]C. Yamanaka, T. Yamanaka, T. Sasaki, K. Yoshida, M. Waki, and H. B. Kang, Phys. Rev. A 6, 2335 (1972).

[5]V. P. Sillin, Zh. Eksp. Teor. Fiz. 48, 1679 (1965) [Sov. Phys. JETP 21, 1127 (1965)].

[6]D. F. DuBois and M. V. Goldman, Phys. Rev. Lett. 14, 544 (1965).

[7]K. Nishikawa, J. Phys. Soc. Jap. 24, 916, 1152 (1968).

[8]A. A. Galeev and R. Z. Sagdeev, Nucl. Fusion 13, 603 (1973), and references therein.

[9]M. Waki, T. Yamanaka, H. B. Kang, K. Yoshida, and C. Yamanaka, Jap. J. Appl. Phys. 11, 420 (1972).

[10]W. F. Utlaut and R. Cohen, Science 174, 245 (1971).

[11]K. Kato, M. Yoseli, S. Kiyama, and S. Watanabe, J. Phys. Soc. Jap. 20, 2097 (1965).

[12]R. A. Stern and N. Tzoar, Phys. Rev. Lett. 17, 903 (1966).

[13]D. W. Forslund, J. M. Kindel, and E. L. Lindman, Phys. Rev. Lett. 30, 739 (1973).

[14]K. Eidman and R. Sigel, Max-Plank-Institut für Plasmaphysik, Garching, Report No. IPP IV/46, 1972 (unpublished).

[15]F. F. Chen, University of California, Los Angeles, Report No. PPG-159, 1973 (unpublished).

[16]J. L. Bobin, M. Decroisette, B. Meyer, and Y. Vitel, Phys. Rev. Lett. 30, 594 (1973).

[17]D. Arnush, B. Fried, C. Kennel, K. Nishikawa, and A. Y. Wong, University of California, Los Angeles, Report No. PPG 139, 1972 (unpublished).

[18]C. Yamanaka, T. Yamanaka, and T. Sasaki, in "Laser Interaction and Related Phenomena," edited by H. J. Schwarz (Plenum, New York, to be published).

Convective Velocity Field in the Rayleigh-Bénard Instability: Experimental Results

P. Berge and M. Dubois
Service de Physique du Solide et de Résonance Magnétique, Centre d'Etudes Nucléaires de Saclay, 91190 Gif-sur-Yvette, France
(Received 27 November 1973)

We used the frequency analysis of the light scattered from a fluid to study the convective velocities in the Rayleigh-Bénard instability. The spatial dependence of the velocity is in agreement with theory. The behavior of the convective flow with the temperature seems to reach the predicted theoretical one only for $R > 1.5R_c$.

When a horizontal shallow layer of a quiescent fluid is submitted to a constant thermal gradient which is directed parallel to the body force (i.e., "heated from below"), the quiescent state breaks down and thermal convection sets in, provided this gradient exceeds a critical value. When the fluid is confined above and below by rigid surfaces, the convection cell patterns are rolls whose forms are dependent on the geometry of lateral walls. We have in mind standard fluids that can be described in the range of temperature under experimental considerations by the Boussinesq approximation.

Many studies, both theoretical and experimental,[1] have been devoted to this subject, usually referred to as the Bénard problem, but very little has been done about velocity measurements. The aim of this Letter is to report preliminary measurements of convective velocity near the critical instability gradient.

The local velocity of the fluid is measured with a laser velometer using a system of real fringes.[2] Two incident laser beams on the same vertical plane are sent through the fluid; they intersect at the midheight of the cell. At this crossing point they interfere, producing plane fringes parallel to the bisecting plane of the two beams, hence parallel to a horizontal plane. An elementary computation gives the separation of the fringes; in our experimental arrangement it has the value

$$i = \tfrac{1}{2}\lambda_0/(n^2 - \cos^2\alpha)^{1/2}.$$

Here λ_0 is the wavelength of the incident beam in air, n is the mean value of the refractive index of the fluid, and α is half the angle of the two beams in air.

If a particle passes through the fringes with a velocity $\vec{V}$ making an angle θ with the vertical direction, the light scattered from this particle will be modulated with period $t = i/V\cos\theta$. In the case of a single velocity $\vec{V}$, the spectral analysis of the scattered intensity gives a single frequency peak at $f = t^{-1} = V\cos(\theta)/i$, or $f = V_z/i$. Notice that it is not possible to know the direction of the velocity with the "arrangement" described above; one can only measure the absolute value of its vertical component V_z. Therefore, we always made our measurements in the middle horizontal plane of the cell, where the direction of the convective velocity is supposed to be less distorted from the vertical.

In order to know if the measured vertical component V_z corresponds to an upward or to a downward motion, we can insert in the path of one of the laser beams a continuous phase shift; hence there is continuous vertical displacement of the fringes, the direction of which with respect to the body force is known. The corresponding shift of the measured frequency peak gives directly the orientation of the velocity.

The cell containing the fluid [in this case silicone oil, the viscosity η of which is equal to 1 S (stokes) at 25 C] is a rectangular box of 4.5 mm height, 100 mm length, and 60 mm width (see Fig. 1). The temperature of the upper and lower glass plates confining the oil is fixed to a desired value by two continuous water flows coming from two separate thermostats. In practice the upper plate was maintained at ~25 C. The vertical walls of the cell are made of glass, a much better conductor than the oil.