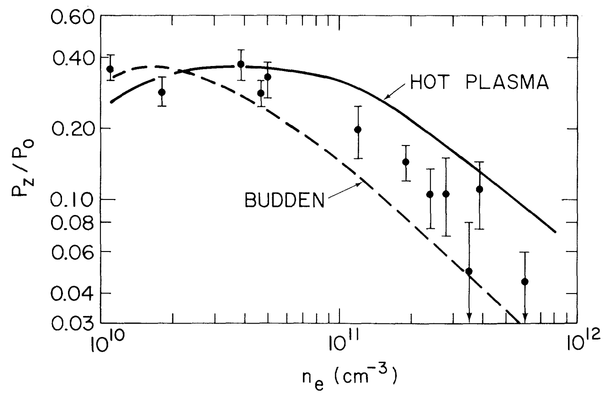

FIG. 4. Power received at 15 GHz vs plasma density for the same setup as in Fig. 3. Lines are predictions of the two models; P_0 described in text.

are in good agreement on the absolute value of P_z/P_0 at low densities and its relative insensitivity to density below about 5×10^{10} cm^{-3}. At higher densities we see the expected falloff, predicted by both models. The errors bars are large at low powers because we are measuring signals close to the minimum detectable signal level. Both models are in good qualitative agreement with the data, which falls between the two predictions; our other measurements also show this behavior.[5]

In conclusion, we have presented the first experimental evidence of tunneling parallel to an inhomogeneous magnetic field and have shown that this process is adequately described by the Budden formalism using either the Budden τ or the hot-plasma τ. Moreover, our results are the first quantitative confirmation of the Budden formula for propagation in any direction.

This work was supported by the U. S. Department of Energy and the National Science Foundation.

[1]K. G. Budden, *Radio Waves in the Ionosphere* (Cambridge Univ. Press, Cambridge, England, 1961); T. H. Stix, *The Theory of Plasma Waves* (McGraw-Hill, New York, 1962), Chap. 10; A. D. Piliya, Zh. Tekh. Fiz. 36, 2195 (1966) [Sov. Phys. Tech. Phys. 11, 609 (1966)]; R. B. White and F. F. Chen, Plasma Phys. 16, 565 (1974); T. M. Antonsen and W. M. Manheimer, Phys. Fluids 21, 2294 (1978).

[2]V. E. Golant and A. D. Piliya, Usp. Fiz. Nauk 14, 413 (1972) [Sov. Phys. Usp. 14, 413 (1972)], and references contained therein.

[3]H. Dreicer, in *Plasma Waves in Space and in the Laboratory*, edited by J. O. Thomas and B. J. Landmark (Edinburgh Univ. Press, Edinburgh, 1969), p. 157.

[4]D. B. Batchelor, Plasma Phys. 22, 41 (1980).

[5]R. F. Ellis, G. D. Tsakiris, and D. A. Boyd, Phys. Rev. Lett. 48, 93 (1982).

[6]M. A. Heald and C. B. Wharton, *Plasma Diagnostics with Microwaves* (Wiley, New York, 1965), Chap. 7.

[7]C. L. Olson, Phys. Fluids 15, 160 (1972).

Observation of the Growth and Saturation of Ion Waves Generated by Optical Mixing

C. J. Pawley, H. E. Huey, and N. C. Luhmann, Jr.
University of California, Los Angeles, California 90024

(Received 28 June 1982)

The first measurements of the growth and saturation of ion acoustic waves generated by optical mixing are presented. At lower power levels, the parameter dependence of the ion waves is shown to agree in detail with the predictions of optical mixing theory. However, at higher power levels a nonlinear saturation is observed and identified as increased Landau damping due to ion heating.

PACS numbers: 52.35.Dm, 52.35.Mw

The nonlinear interaction of two electromagnetic waves ($\vec{E}_1$, $\vec{E}_2$) can produce a third (plasma) wave ($\vec{E}_p$) via the process of optical mixing.[1-3] The resultant density fluctuations can become appreciable when $\omega_1-\omega_2=\omega_p$ and $\vec{k}_1\pm\vec{k}_2=\vec{k}_p$ where ω_p, $\vec{k}_p$ satisfy the plasma dispersion relation $\epsilon(\omega_p,\vec{k}_p)=0$. This has, for example, been demonstrated for the case of mixing of two laser beams.[4] However, to date, there have been no detailed studies of the generation of ion acoustic waves via this process. Currently, such studies are of great importance because of the consequences of a significant level of stimulated Brillouin scattering (SBS) for laser fusion. The present work represents the first detailed study of optical-mixing–generated acoustic waves including their saturation via ion heating. Not only does this optical-mixing study provide insight into the saturation of SBS, it also models the actual laser interaction. Specifically, imperfect absorption of the laser light can lead to the Doppler-shifted light reflected from the moving critical layer beating with the incoming laser light. The SBS instability is thereby generated with an effectively enhanced initial noise level.[5,6]

In the present experiment [see Fig. 1(a)], two electromagnetic waves ($\omega_1/2\pi$, $\omega_2/2\pi \simeq 3.3$ GHz) with parallel polarization were propagated antiparallel to each other in a field-free plasma (0.75 m diam, 2 m long, $T_e \simeq 3$–4 eV, $T_e/T_i \simeq 15$, $n_e \simeq 0.1 n_{crit}$). The difference frequency between the two sources can be accurately set (and maintained) to within ± 100 Hz over the range from zero to many times the ion plasma frequency. In addition, the repetitively pulsed experiment ($\simeq 10$ Hz repetition rate) is triggered at constant phase with respect to the rf, permitting meaningful data scans over many pulses. With the exception of the addition of the second transmitting system and associated frequency-locking electronics, the experimental arrangement is identical to that described in our first reports of SBS in a microwave-plasma interaction.[7-9] However, here it should be noted that a given level of ion-wave fluctuations is observable in the optical-mixing case at approximately an order of magnitude less power (i.e., saturation at 50 kW instead of 500 kW). This eliminates obscuring effects such as density profile modifications and electron heating via inverse bremsstrahlung absorption, as well as permitting much increased microwave pulse durations. Interestingly, the ion-wave saturation levels are identical in the two studies, strongly supporting the identification of ion heating as the dominant saturation mechanism.

Before proceeding to a discussion of the experimental results, it will be helpful to review briefly

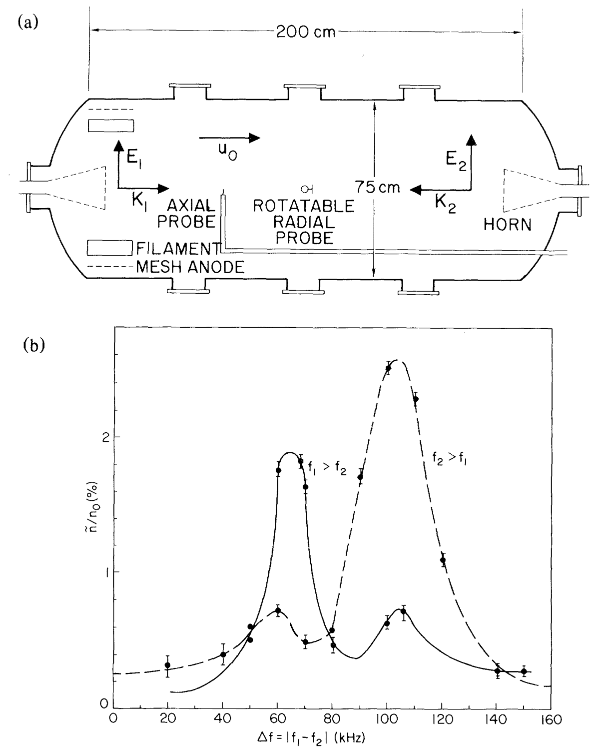

FIG. 1. (a) Experimental arrangement. (b) Amplitude of ion acoustic waves in a neon plasma as a function of the difference frequency ($\Delta f = f_1 - f_2$) between the two microwave sources ($\tau = 50\ \mu$s, $P_1 = 10$ kW, $P_2 = 20$ kW).

the predictions of optical mixing in the region below nonlinear saturation. Since the fields are well approximated by plane waves, the pondermotive force $F_{NL} = -(\omega_p^2/\omega^2)\nabla(\langle E^2\rangle/8\pi)$, where the relevant term in $\langle E^2\rangle$ is given by

$$\langle E^2\rangle = 2E_1E_2 \cos\{(k_1+k_2)x + (\omega_1-\omega_2)t\}. \quad (1)$$

Substituting this into the ion fluid equations results in a predicted time-dependent ion-wave fluctuation given (neglecting nonlinear saturation mechanisms) by

$$\frac{\tilde{n}}{n_0} \simeq \frac{e^2E_1E_2}{m^2\omega_1\omega_2}\frac{m}{2M}k_s^2[k_sc_s(i\nu+\Delta\omega-k_sc_s-\vec{k}_s\cdot\vec{u}_0)]^{-1}\exp[-\nu(t-\tau)][1-e^{-\nu\tau}]\exp[-i(k_sc_s+\vec{k}_s\cdot\vec{u}_0)t], \quad (2)$$

where ν is the effective ion damping frequency (including both particle collisions and Landau damping), $\vec{u}_0$ is the ion drift velocity ($\simeq 0.1c_s$ for He, $\simeq 0.17c_s$ for Ne), τ is the duration of the rf pulse initiated at $t=0$ with $t>\tau$, $\Delta\omega = \omega_1 - \omega_2$, and ω_s ($\vec{k}_s$) is the frequency (wave number of the ion acoustic wave. Notice that Eq. (2) predicts that $|\tilde{n}/n_0| = O(1)$ for $eE_{1,2}/m\omega_{1,2}v_{te} = 0.2$ or for $P \simeq 50$ kW. We therefore expect to reach nonlinear saturation at extremely low power compared to the pure SBS case.[7-9]

The predictions of Eq. (2) have been quantitatively verified by experiment. To eliminate problems with rf modulation of the probe sheaths, the ion fluctuations are measured one-half an ion period after turn-off of the rf pulse. Figure 1(b) displays the magnitude of the observed density fluctuation level in a neon species plasma as a function of the difference frequency ($\Delta\omega/2\pi = f_1 - f_2$) between the two sources. The maximum is observed when $\Delta\omega = k_s c_s + \vec{k}_s \cdot \vec{u}_0$. The inferred ion drift velocity ($\simeq 0.17 c_s$) is in good agreement with the measured value. The smaller, secondary peaks were associated with optical mixing of the *reflected* electromagnetic waves ($r \simeq 15\%$) from each end of the chamber and the horns. Similar results were obtained with other ion species plasmas. Equation (2) also predicts that the density fluctuation level depends only on the product E_1E_2 and not on their individual values. As shown in Fig. 2(a), this is observed experimentally. Here E_1E_2 was held constant (equivalent power $P = 10$ kW) and the ratio E_1/E_2 was varied by over 2 orders of magnitude. As can be seen, the fluctuation level remained essentially constant.

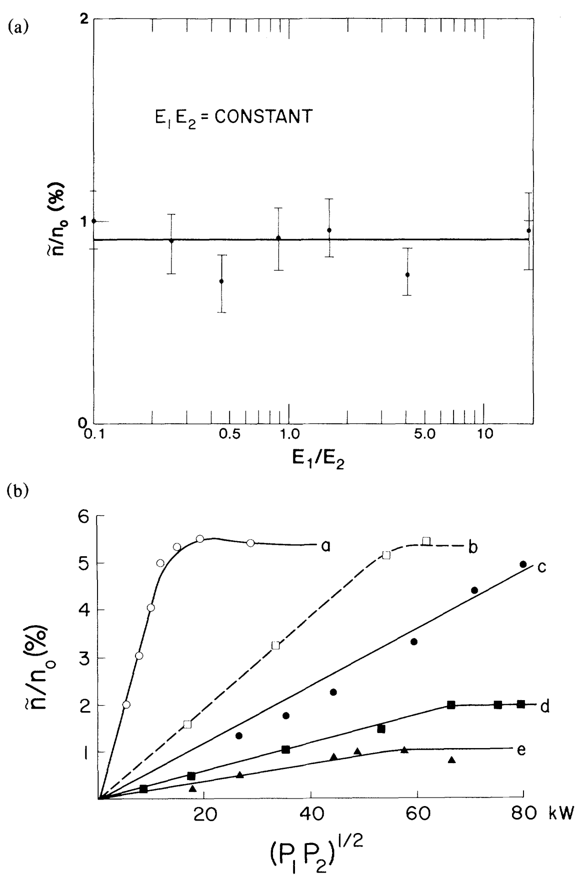

FIG. 2. (a) Amplitude of ion acoustic waves in a helium plasma as a function of E_1/E_2 with E_1E_2 held constant [$\tau = 10\ \mu$s, $(P_1P_2)^{1/2} = 10$ kW]. (b) Amplitude of ion acoustic waves as a function of $(P_1P_2)^{1/2}$ for pure and mixed helium- and neon-ion plasmas; a, pure helium, $\Delta f = 210$ kHz (resonant); b, pure neon, $\Delta f = 100$ kHz (resonant); c, pure neon; d, neon + 5% helium; e, neon + 10% helium. $\Delta f = 110$ kHz in all of the last three cases (d is near resonance).

The scaling of $\tilde{n}/n_0$ with the magnitude of E_1E_2 was studied. Figure 2(b) shows the maximum density fluctuation level as a function of $(P_1P_2)^{1/2} \propto E_1E_2$ for a pure helium plasma, a pure neon plasma, and two mixed-species neon-helium plasmas. For power levels $\lesssim 25$ kW the fluctuations are directly proportional to E_1E_2 as predicted by Eq. (2). In addition, the ratio of the fluctuations in the pure helium and neon plasmas is in good agreement with the predictions of Eq. (2). However, above this level an abrupt saturation of the fluctuations at $\simeq 5.5\%$ is observed in the helium plasma. Interestingly, this is exactly the saturation level observed in our microwave SBS experiments.[8,9] The neon plasma data exhibit an identical saturation for $(P_1P_2)^{1/2} \gtrsim 60$ kW. Note further the significant reductions in the ion-wave amplitude in the mixed-species plasmas due to the increased ion Landau damping.

The time history of the ion waves was also investigated. Figure 3(a) shows the measured temporal behavior for several power levels with the dashed curves being the simple predictions of Eq. (2). Once again we see strong indication of a nonlinear saturation mechanism at the higher power levels. The cause of this saturation was investigated in detail.

At the low power levels employed for these studies, both density-profile modifications and electron heating (inverse bremsstrahlung absorption) are negligible. In addition, even far into saturation the ion waves were found to be extremely pure with virtually no harmonic content. To investigate the possibility of saturation via ion heating, detailed measurements of the ion distribution function were performed with a retarding-grid energy analyzer. Figure 3(b) shows typical data indicating the formation of a hot-ion tail in the presence of the rf. As shown in the inset to Fig. 3(b), the enhanced tail is only found when the rf source difference frequency is tuned to the appropriate acoustic frequency. In addition, the fraction of hot ions was found to scale linearly with E_1E_2 up to $(P_1P_2)^{1/2} = 50$ kW.

The observed hot-ion tail production completely accounts for the saturation shown in Figs. 2(b) and 3(a). To demonstrate this, we performed self-consistent numerical calculations of the ion-wave amplitude taking into account the increased Landau damping due to the ion tail formation. This

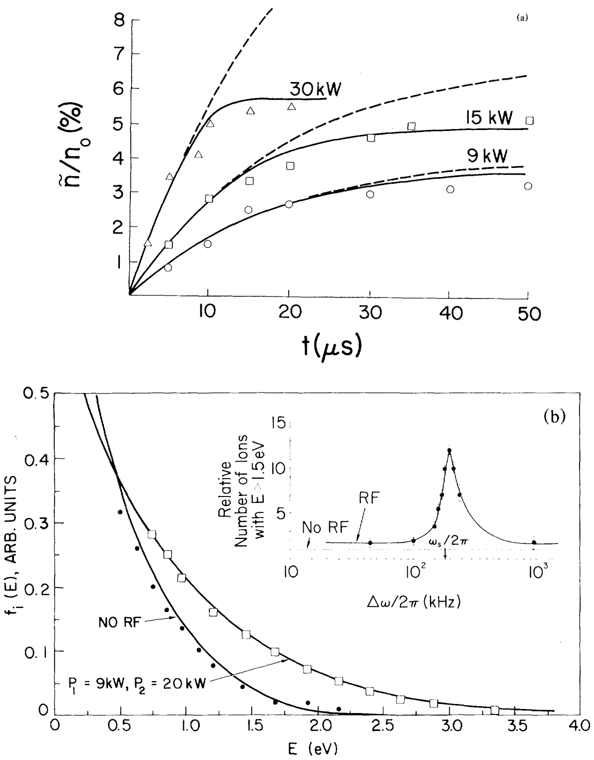

FIG. 3. (a) Time evolution of the amplitude of the ion acoustic waves for several power levels. The dashed lines represent the predictions of Eq. (2) while the solid lines are obtained by a self-consistent treatment of the ion tail formation. (b) The tail of the ion distribution function for the cases of no rf and rf with the appropriate difference frequency between sources (helium plasma, $\tau = 50\ \mu$s). Inset: Relative fraction of hot ions with $E > 1.5$ eV as a function of source difference frequency, with and without rf ($P_1 = 10$ kW, $P_2 = 20$ kW).

is done at each time step by calculating both the energy input and the wave energy with the difference assumed partitioned to the ions through collisions as well as Landau damping which creates a hot-ion tail. This tail greatly increases the damping by raising the effective temperature in the vicinity of the wave phase velocity. Similarly to Kruer and Estabrook,[10] we assume the hot-ion tail temperature θ_h to be $\simeq \frac{1}{2}Mc_s^2$ which is in good agreement with experiment. The increased Landau damping together with the pondermotive force further heats and enlarges the tail providing the sharp-cutoff saturation level observed in the experiment. The results of these numerical calculations are plotted as solid curves in Figs. 2(b) and 3(a). The agreement is seen to be excellent. In addition, the measured saturation level is identical to that in our microwave SBS studies[7-9] which is also predicted by this model. This provides the first conclusive verification of the predicted saturation of SBS ion waves via ion-tail heating.[10-12]

In conclusion, we have studied in detail the growth and saturation of ion acoustic waves driven by optical mixing of two microwave beams.

This work was supported by the Lawrence Livermore National Laboratory Laser Fusion Program, U. S. Department of Energy Contract No. DE-AS08-81 DP40143, and U. S. Air Force Office of Scientific Research Contract No. F49620-76-C-0012.

[1]N. Kroll, A. Ron, and N. Rostoker, Phys. Rev. Lett. 13, 83 (1964).
[2]B. I. Cohen, M. A. Mostrom, D. R. Nicholson, A. N. Kaufman, and A. B. Langdon, Phys. Fluids 18, 470 (1975).
[3]G. Schmidt, Phys. Fluids 16, 1676 (1973).
[4]B. L. Stansfield, R. Nodwell, and J. Meyer, Phys. Rev. Lett. 26, 1219 (1971).
[5]I. M. Begg and R. A. Cairns, J. Phys. D 9, 2341 (1976).
[6]C. J. Randall, J. R. Albritton, and J. J. Thomson, Phys. Fluids 24, 1474 (1981).
[7]H. E. Huey, A. Mase, N. C. Luhmann, Jr., W. F. DiVergilio, and J. J. Thomson, Phys. Rev. Lett. 45, 795 (1980).
[8]A. Mase, N. C. Luhmann, Jr., J. Holt, H. Huey, M. Rhodes, W. F. DiVergilio, J. J. Thomson, and C. J. Randall, in *Proceedings of the Eighth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Brussels, 1980* (International Atomic Energy Agency, Vienna, 1981), Vol. II, p. 745.
[9]H. Huey, A. Mase, C. Pawley, J. Holt, and N. C. Luhmann, Jr., Bull. Am. Phys. Soc. 26, 933 (1981).
[10]W. L. Kruer and K. G. Estabrook, in *Laser Interaction and Related Plasma Phenomena*, edited by H. J. Schwarz, H. Hora, M. J. Lubin, and B. Yaakobi (Plenum, New York, 1981), Vol. 5, p. 783.
[11]W. L. Kruer, Phys. Fluids 23, 1273 (1980).
[12]K. Estabrook, J. Harte, E. M. Campbell, F. Ze, D. W. Phillion, M. D. Rosen, and J. T. Larsen, Phys. Rev. Lett. 46, 724 (1981).