PARTICLE ACCELERATION BY PLASMA WAVES

F. F. Chen, C. E. Clayton, C. Darrow, J. M. Dawson, C. Joshi
T. Katsouleas, W. Leemans, K. Marsh, W. Mori, J. Su,
D. Umstadter, and S. Wilks

PPG-1035 Jan. 1987

CENTER FOR
PLASMA PHYSICS
AND
FUSION ENGINEERING

UNIVERSITY OF CALIFORNIA
LOS ANGELES

Master

PARTICLE ACCELERATION BY PLASMA WAVES

F. F. Chen, C. E. Clayton, D. Darrow, J. M. Dawson, C. Joshi
T. Katsouleas, W. Leemans, K. Marsh, W. Mori, J. Su,
D. Umstadter, and S. Wilks

PPG-1035 Jan. 1987

Submitted to International Conference on Plasma Physics,
Kiev, USSR, April 1987

PARTICLE ACCELERATION BY PLASMA WAVES

F. F. Chen, C. E. Clayton, C. Darrow, J. M. Dawson, C. Joshi, T. Katsouleas
W. Leemans, K. Marsh, W. Mori, J. Su, D. Umstadter, and S. Wilks

1. INTRODUCTION

The work reported here examines theoretically, computationally, and experimentally the feasibility of a new generation of particle accelerators based on inverse Landau damping of large amplitude electron plasma waves. These waves have phase velocities v_ϕ close to c, so that particles trapped in them can be accelerated to large relativistic γ. If the pulses of particles and waves are kept short (< 1 cm), ions cannot move to prevent the plasma waves from reaching the wavebreaking amplitude of $e\phi \cong mc^2$. The corresponding electric field E(V/cm) is of order $[n(\text{cm}^{-3})]^{1/2}$ and, in principle, (at 10^{18} cm^{-3}) can lead to accelerators $>10^3$ times shorter than conventional ones. Laser fields can also reach GeV/m levels, but the plasma is needed a) to convert $E_\perp$ to $E_{||}$, b) to slow down the light waves, and c) to prevent the accidental production of plasmas by breakdown.

Three concepts are surveyed: 1) the Beat-Wave Accelerator[1], 2) the Surfatron[2], and 3) the Wakefield Accelerator[3]. Theory and computational work exists for all three, but experiments have explored so far only the physics of the BWA. In addition, there is a fourth idea[4], in which plasma waves are excited by sending a laser beam transversely across an ion wave. Here, we discuss only the physical processes, emphasizing recent results and ongoing experiments; further details can be found in the references. Several review articles exist[5–10] which include aspects of accelerator design.

2. THEORY AND SIMULATION

a) Beat-wave accelerator. Two laser beams E_j traveling in the same direction through a plasma will resonantly excite a plasma wave ϕ with $\omega_p = \Delta\omega$, $k_p = \Delta k = \omega_p/v_g$, growing at the rate $d\varepsilon/dt = \alpha_1\alpha_2\omega_p/4$, where $\varepsilon = e\phi/mc^2$ and $\alpha_j = eE_j/m\omega_j c$. Leptons injected above a trapping threshold will travel synchronously with the light pulse at a speed $v = v_g = \Delta\omega/\Delta k$ until they outrun the wave by gaining energy. This phase slippage limits the energy gain per stage to $\sim 2\varepsilon\gamma_\phi^2 mc^2$, where $\gamma_\phi = \omega_j/\omega_p$ is the γ corresponding to v_ϕ. The plasma wave itself suffers a phase slippage because ω_p falls below $\Delta\omega$ as the oscillating electrons become relativistically heavy. The Rosenbluth-Liu[11] saturation amplitude $\varepsilon_{max} = (16\alpha_1\alpha_2/3)^{1/3}$ due to this effect has been verified in one-dimensional computer simulations[1,7]. These also show the effects of finite pump risetime and of the decay in wave amplitude if the pump pulse is too long. By adjusting $\Delta\omega$ to match the shifted value of ω_p, it is possible to increase ε_{max}, but previous authors[12,13] disagreed on the direction of the shift. In a complete analytic treatment[14] of beat-wave excitation, we find that the *only* nonlinear frequency change of a plasma wave is a redshift due to relativistic mass increase; the blue shift sometimes obtained is a spurious Doppler shift seen in a frame in which the electrons are drifting.

Two-dimensional effects have been studied analytically[15] and in simulation[16,17]. For Gaussian pump beams, the plasma wave profile is non–gaussian[15], and radial electric fields can focus or defocus the fast particles, depending on their phase. This limits the injection phase angle range. In computations[16,17], one sees also the relativistic self-focusing of the light waves, which occurs for $P > (9/2)(\omega/\omega_p)^2$ GW. In addition, the accelerated beam is focused by its own magnetic field.

We have found a second saturation mechanism[18] limiting ε_{max}: harmonic generation. Though a plasma wave in a uniform plasma can grow to wavebreaking without distortion, spatial harmonics can develop by mode coupling if the density is rippled, say, by stimulated Brillouin scattering. Let the ripple have amplitude $q = n_1/n_0$ and wavelength $k_i >> k_p$. For a cold plasma, we find the modes at $k_p \pm nk_i$ interchanging energy and oscillating in amplitude with time, in a way expressible as a sum over

Bessel functions $J_n(q\omega_p t/2)$. The desired beat wave has a maximum amplitude $\varepsilon = \alpha_1\alpha_2 f(p)/q$, where f(p) is a thermal correction of order unity. Comparing this with Rosenbluth-Liu saturation, we see that harmonic generation dominates at low intensities $\alpha_1\alpha_2 \lesssim q^{3/2}$, as obtain in present experiments with $q \cong 0.4$ and $I_0(CO_2) < 4 \times 10^{13}$ W/cm^2. These results have been verified by computer simulation[19].

b) Surfatron[2]. The phase slippage due to the slight change in particle velocity during acceleration can be eliminated by applying a transverse dc magnetic field B_z. This field exerts just enough drag on the particles that they remain in phase with the maximum E_x field. Energy is gained without increase in x-velocity because a component v_y is added. This increases the width of the accelerator, but finite-angle optical mixing[9] minimizes this size increase. The beam itself is not broadened and in fact is greatly improved in energy spread. The surfatron effect has been verified in two-dimensional simulations. Pump depletion, however, limits the energy gain to $1/\varepsilon$ times that in the BWA. Methods for replenishing the pump have been suggested[9]. No experimental work with B_z fields has yet been done with lasers.

c) Wake-field accelerator. The plasma wave in this case is generated by a pulse of high-energy particles rather than by two laser beams. The inefficiency of lasers is obviated, and the fine tuning of the plasma density is also not necessary. The plasma acts as a transformer to convert the energy of a dense, "low" energy driving beam into the very high energy of a smaller number of particles. It is well known that the transformer ratio R cannot exceed 2 unless the driving bunch is shaped. P. Chen et al.[20] considered triangular pulses in which a pulse of electrons increases slowly in density over N plasma wavelengths c/ω_p and is then terminated abruptly. During the buildup of beam density, plasma electrons are removed to preserve quasineutrality. When the beam pulse ends, the plasma suddenly acquires a large positive charge, which excites an intense wake field. A particle injected and trapped in this field can gain πN times as much energy as in each driving electron. The energy is taken from the driving bunch by a retarding electric field within the pulse. This field can be made uniform by injecting a δ-function precursor pulse; in that case, R increases from πN to $2\pi N$. We have also shown[21,22] that the exact bunch shape is not critical, that the two-stream instability is not important unless γ is small, and that phase slip can be minimized by a weak gradient in plasma density. Two-dimensional simulations[21] confirm these results and show the importance of transverse motions at late times. If injection into the wake field is controlled so that the wake of the accelerated particles exactly cancels the wake field, very efficient conversion of energy can be achieved. Details on beam loading calculations are given in Refs. 22 and 23. The Wake-field Accelerator can potentially accelerate electrons to 1 TeV in 20 m, using a 10^{18} cm^{-3} plasma and shaped bunches of 5×10^{10} electrons 20 μm in radius and 3 mm long from a 50-GeV accelerator.

3. EXPERIMENT

a) Excitation of fast plasma waves. In a previously reported[24-27] study, we have produced and detected plasma waves with $\omega/k \cong c$ by optical mixing of colinear CO_2 laser beams of 9.56 and 10.59 μm wavelength. A schematic of the apparatus is shown in Fig. 1. The CO_2 system produces a 2-nsec pulse containing a total of 16 J in the two lines, and an f/8 lens focuses the beams to 10^{13} W/cm^2 vacuum intensity. The plasma is preionized by an arc discharge in 1 T of H_2 and is fully ionized by the CO_2 pulse to a density in the 10^{17} cm^{-3} range. The density is accurately measured by the shift of the Raman backscattered light and is set to the resonant density. Forward and backward Raman and Brillouin scattering of each incident frequency can be monitored. The plasma wave is detected both by the forward scattered CO_2 light and by an elaborate ruby-laser Thomson scattering system using cylindrical optics[28], an optical multichannel analyzer (OMA), and a streak camera. Fig. 2 shows the fast plasma wave ($\lambda \cong 100\mu$m) detected by the ruby system at a scattering angle of only 0.4°. The magnitude of $\tilde{n}/n_0$ giving this signal is $\cong 3\%$, corresponding to a longitudinal field of $\cong 3$ GV/m. In Fig. 3, the spectrum of the forward scattered CO_2 light shows satellites of the incident (dashed) lines due to scattering from the plasma wave. The relative amplitudes are consistent with computer simulations. Efficient cascading to longer λ's is beneficial to energy transfer into the plasma wave.

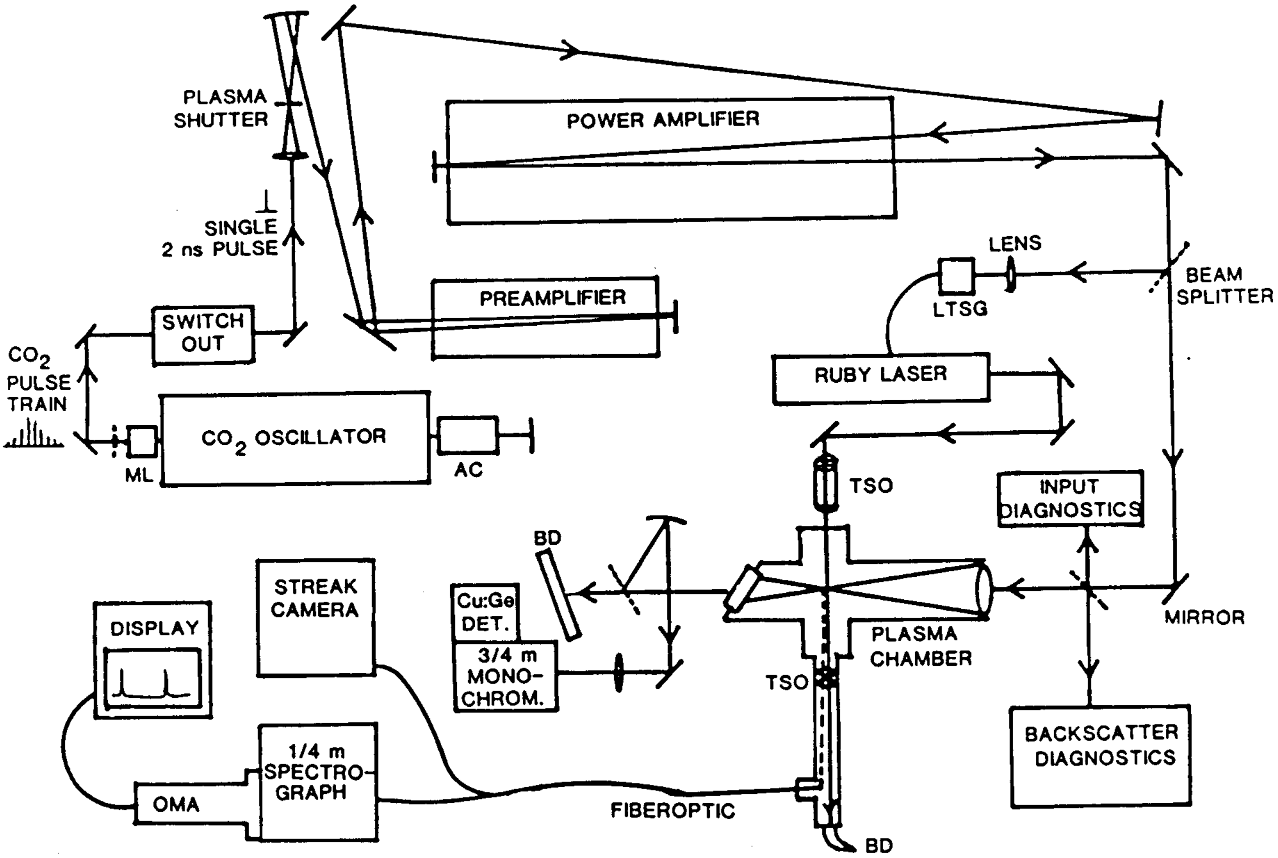

Fig. 1

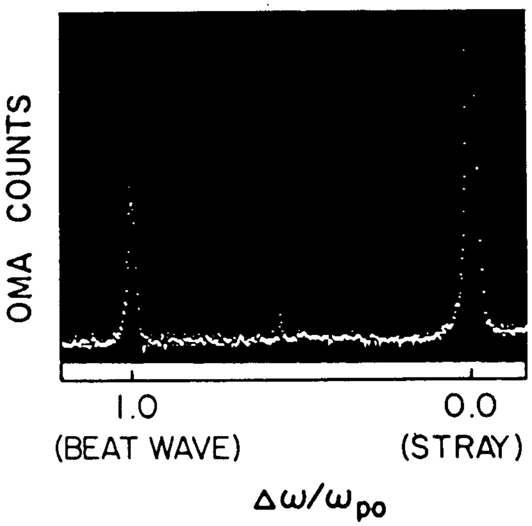

Fig. 2

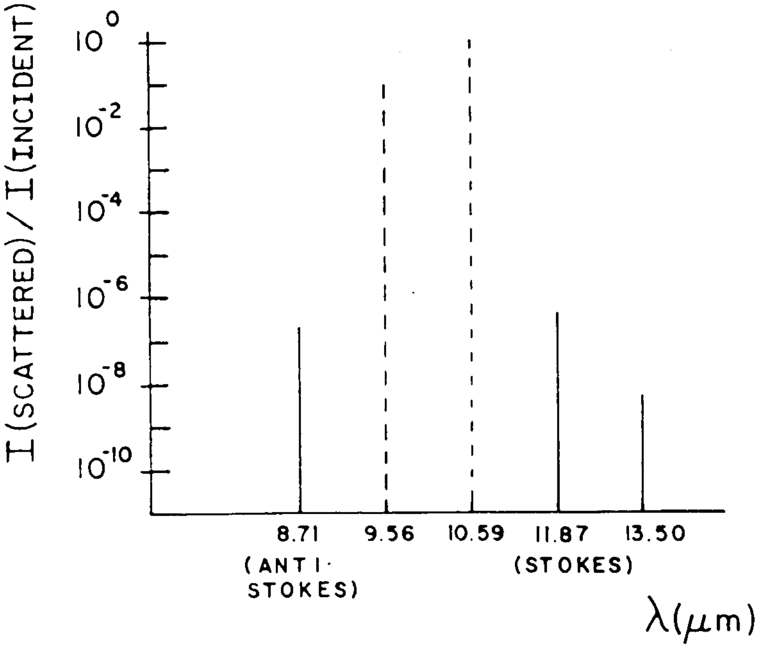

Fig. 3

b) Competing instabilities. Stimulated Brillouin (SBS) and Raman (SRS) backscatter of each incident frequency occurs at our intensities in addition to beat-wave coupling, giving rise to short wavelength ($k_i \equiv 2k_o \equiv 5\mu m$) plasma and acoustic waves, detected by ruby Thomson scattering at 7.5°. As shown by the streak camera, SBS occurs almost throughout the laser pulse and creates two nearly unshifted pump beams in the backward direction. Fig. 4 shows the ω and k harmonics of the slow waves observed so far. The modes at ω_p and $k = k_p \pm nk_i$ are due to quasiresonant mode coupling[18,19,20] of the small-k_p beat wave with the ion wave density ripple. These modes have approximately the right amplitudes to cause saturation in the present experiment, as predicted by theory[18]. This saturation mechanism if self-limiting because the slow waves (ω_p, nk_i) can heat the electrons and quench the mode coupling. In the future, use of shorter pulses will prevent the growth of SBS. The modes at $\omega = 2\omega_p$ in Fig. 4 are attributed to mode coupling with the second harmonic of the beat wave.

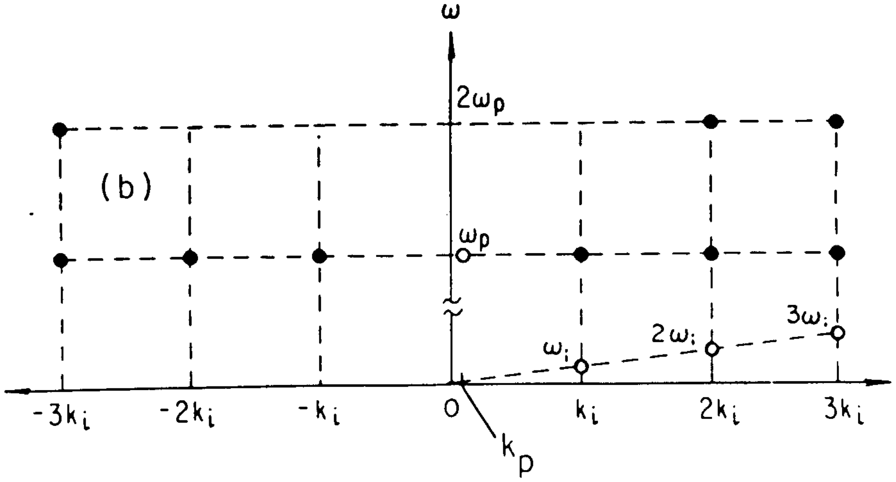

Fig. 4

c) Effects of a density ripple. Though the competing modes are well identified and have not interfered with beat-wave excitation, the experiments point out the importance of inhomogeneities in the form of a density ripple. In addition to the two-pump case treated above[19], we have also considered the effect of ripple on one-pump SRS[30–31], and the physical reason for the resulting plasma wave spectrum has been pointed out[30]. We have also applied the theory[31] to laser-fusion experiments[32].

4. FUTURE EXPERIMENTS

To proceed to the next stage in BWA experiments, we have installed a 3-atm. CO_2 laser system capable of producing two-frequency, 100 J pulses 100 psec long. These will be injected into the fully ionized plasma of a theta pinch. Injection of 2-MeV electrons from a linac into the beat-wave thus excited is expected to result in observable numbers of electrons accelerated to >10 MeV. In addition, a collaborative experiment with the University of Wisconsin and Argonne National Laboratory is being planned to test the feasibility of wake-field acceleration.

This work was supported by the U.S. National Science Foundation Grant No. ECS 83-10972, and by the U.S.D.O.E., Contract No. DE-AS03-83-ER40120.

REFERENCES

1. T. Tajima and J. M. Dawson, Phys. Rev. Letters, 1979, 43, 267.
2. T. Katsouleas and J. M. Dawson, Phys. Rev. Letters, 1983, 51, 392.
3. P. Chen, J. M. Dawson, R. W. Huff, and T. Katsouleas, Phys. Rev. Letters, 1985, 54, 693; 1985, 55, 1537.
4. T. Katsouleas, J. M. Dawson, D. Sultana, and Y. T. Yan, IEEE Trans. Nucl. Sci., 1985, NS-32, No. 5, 3554.
5. C. Joshi, W. B. Mori, T. Katsouleas, and J. M. Dawson, Nature, 1984, 311, 525.
6. F. F. Chen, Proceedings of the XII Yugoslav Symposium on Physics of Ionized Gases, Sibenik, Yugoslavia, 1984. (World Scientific Publishing Co., Philadelphia, 1985) pp. 937-982.
7. T. Katsouleas, C. Joshi, J. M. Dawson, F. F. Chen, C. E. Clayton, W. B. Mori, C. Darrow and D. Umstadter, in Laser Acceleration of Particles A.I.P. Conf. Proc., No. 130, ed. by C. Joshi and T. Katsouleas (American Institute of Physics, New York, 1985) pp. 63-98.
8. C. Joshi, IEEE Trans. Nucl. Sci., NS-32, 1985, 1576.
9. C. Joshi, "Plasma Accelerators," to be published in the Proc. of the XIIIth Int'l. Conf. on High Energy Accelerators, Novosibirsk, USSR, August 6-11, 1986.
10. C. Joshi, "Relativistic Plasma Waves and Particle Acceleration," Physics Today, January 1987.
11. M. N. Rosenbluth and C. S. Liu, Phys. Rev. Letters, 1972, 29, 701.
12. C. M. Tang, P. Sprangle, and R. Sudan, Phys. Fluids, 1985, 28, 1974.
13. R. Bingham, R. A. Cairns, and R. G. Evans, Report RAL-84-12, Rutherford Appleton Laboratory, 1984.
14. W. B. Mori, IEEE Transactions on Plasma Science, 1987, PS-15, 88.
15. R. Fedele, U. de Angeles, and T. Katsouleas, Phys. Rev., 1986, A33, 4412.
16. D. W. Forslund, J. M. Kindel, W. B. Mori, C. Joshi, and J. M. Dawson, Phys. Rev. Letters, 1985 54, 558.
17. W. B. Mori, C. Joshi, J. M. Dawson, D. W. Forslund, and J. M. Kindel, to be published in Laser Interaction and Related Plasma Phenomena, Vol. VII, ed. by H. Hora and G. Miley, 1987.
18. C. Darrow, D. Umstadter, T. Katsouleas, W. B. Mori, C. E. Clayton, and C. Joshi, Phys. Rev. Letters, 1986, 56, 2629.
19. C. Darrow, W. B. Mori, T. Katsouleas, C. Joshi, D. Umstadter, and C. E. Clayton, IEEE Transactions on Plasma Science, 1987, PS-15, 107.
20. P. Chen, J. J. Su, J. M. Dawson, K. L. F. Bane, and P. B. Wilson, Phys. Rev. Letters, 1986, 56, 1252.
21. J. J. Su, T. Katsouleas, J. M. Dawson, P. Chen, M. Jones, and R. Keinigs, IEEE Transactions on Plasma Science, 1987 PS-15, 192.
22. S. Wilks, T. Katsouleas, J. M. Dawson, P. Chen, and J. J. Su, IEEE Transactions on Plasma Science, 1987 PS-15, 210.
23. T. Katsouleas, S. Wilks, P. Chen, J. M. Dawson, and J. J. Su, Particle Accelerators, 1986, 17.
24. C. Joshi, C. E. Clayton, C. Darrow, and D. Umstadter, Proceedings of the Int'l Conf. on Lasers '84, ed. by K. M. Corcoran, D. M. Sullivan, and W. C. Stwalley, 1985, 467.
25. C. E. Clayton, C. Joshi, C. Darrow, and D. Umstadter, Phy. Rev. Letters, 1985, 54, 2343; 55, 1652.
26. C. Joshi, C. E. Clayton, C. Darrow, and D. Umstadter, in Laser Acceleration of Particles, A.I.P. Conf. Proc., No. 130, ed. by C. Joshi and T. Katsouleas (American Institute of Physics, New York, 1985) pp. 99-113.
27. C. E. Clayton, C. Joshi, C. Darrow, D. Umstadter, and F. F. Chen, IEEE Trans. on Nucl. Sci., 1985, NS-32, 3551.
28. C. E. Clayton, C. Darrow, and C. Joshi, Applied Optics, 1985, 24, 2823.
29. C. Darrow, D. Umstadter, C. Joshi, and C. E. Clayton, to be published in Laser Interaction and Related Plasma Phenomena, Vol. VII, ed. by H. Hora and G. Miley, 1987.
30. H. C. Barr and F. F. Chen, Phys. Fluids, 1987, 30, 1180.
31. H. Figueroa and C. Joshi, to be published in Laser Interaction and Related Plasma Phenomena, Vol. VII, ed. by H. Hora and G. Miley, 1987.
32. H. Figueroa and C. Joshi, submitted to Phys. Fluids, 1986.

b) Competing instabilities. Stimulated Brillouin (SBS) and Raman (SRS) backscatter of each incident frequency occurs at our intensities in addition to beat-wave coupling, giving rise to short wavelength ($k_i \cong 2k_o \cong 5\mu m$) plasma and acoustic waves, detected by ruby Thomson scattering at 7.5°. As shown by the streak camera, SBS occurs almost throughout the laser pulse and creates two nearly unshifted pump beams in the backward direction. Fig. 4 shows the ω and k harmonics of the slow waves observed so far. The modes at ω_p and $k = k_p \pm nk_i$ are due to quasiresonant mode coupling[18,19,20] of the small-k_p beat wave with the ion wave density ripple. These modes have approximately the right amplitudes to cause saturation in the present experiment, as predicted by theory[18]. This saturation mechanism if self-limiting because the slow waves (ω_p, nk_i) can heat the electrons and quench the mode coupling. In the future, use of shorter pulses will prevent the growth of SBS. The modes at $\omega = 2\omega_p$ in Fig. 4 are attributed to mode coupling with the second harmonic of the beat wave.

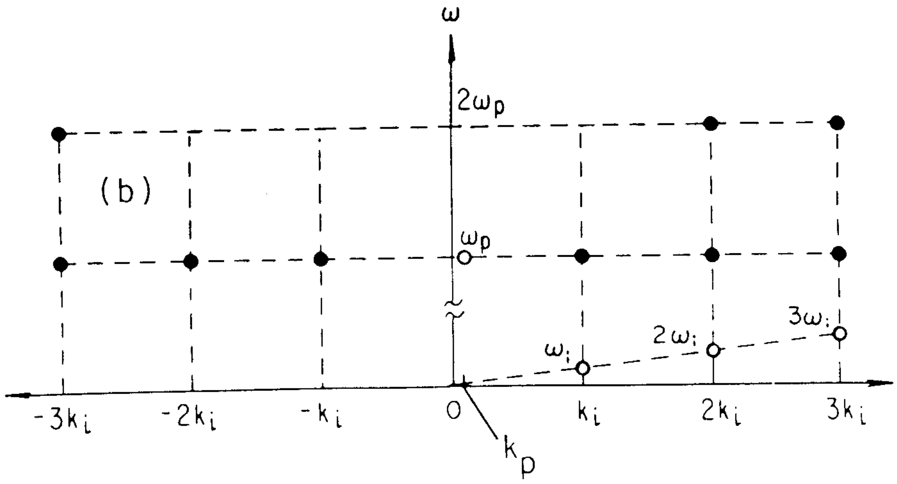

Fig. 4

c) Effects of a density ripple. Though the competing modes are well identified and have not interfered with beat-wave excitation, the experiments point out the importance of inhomogeneities in the form of a density ripple. In addition to the two-pump case treated above[19], we have also considered the effect of ripple on one-pump SRS[30–31], and the physical reason for the resulting plasma wave spectrum has been pointed out[30]. We have also applied the theory[31] to laser-fusion experiments[32].

4. FUTURE EXPERIMENTS

To proceed to the next stage in BWA experiments, we have installed a 3-atm. CO_2 laser system capable of producing two-frequency, 100 J pulses 100 psec long. These will be injected into the fully ionized plasma of a theta pinch. Injection of 2-MeV electrons from a linac into the beat-wave thus excited is expected to result in observable numbers of electrons accelerated to >10 MeV. In addition, a collaborative experiment with the University of Wisconsin and Argonne National Laboratory is being planned to test the feasibility of wake-field acceleration.

This work was supported by the U.S. National Science Foundation Grant No. ECS 83-10972, and by the U.S.D.O.E., Contract No. DE-AS03-83-ER40120.

from the plasma wave. The relative amplitudes are consistent with computer simulations. Efficient cascading to longer λ's is beneficial to energy transfer into the plasma wave.

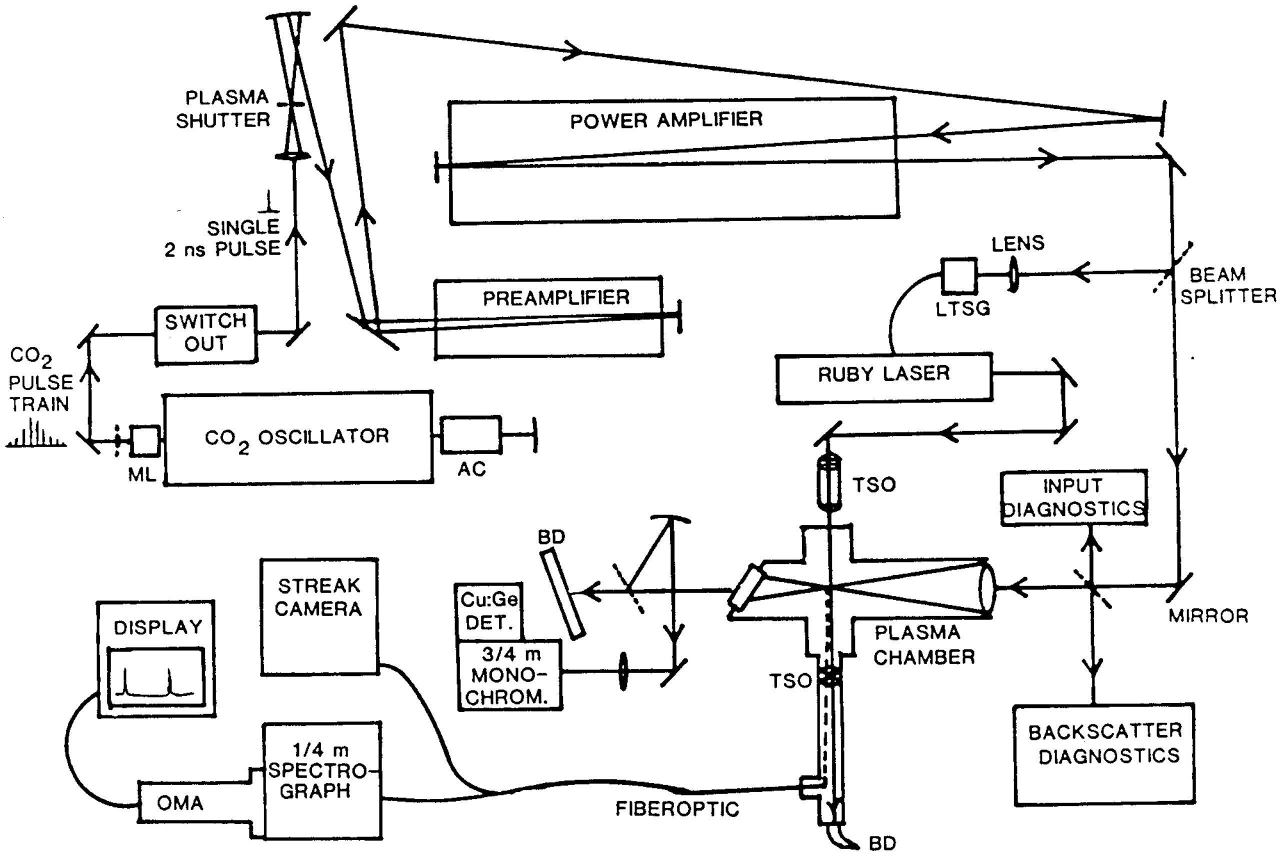

Fig. 1

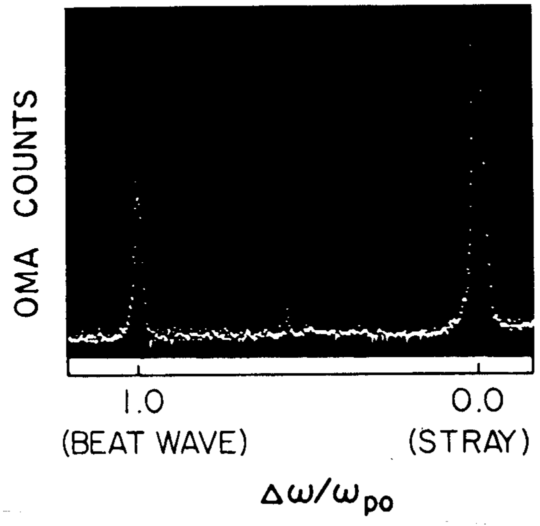

Fig. 2

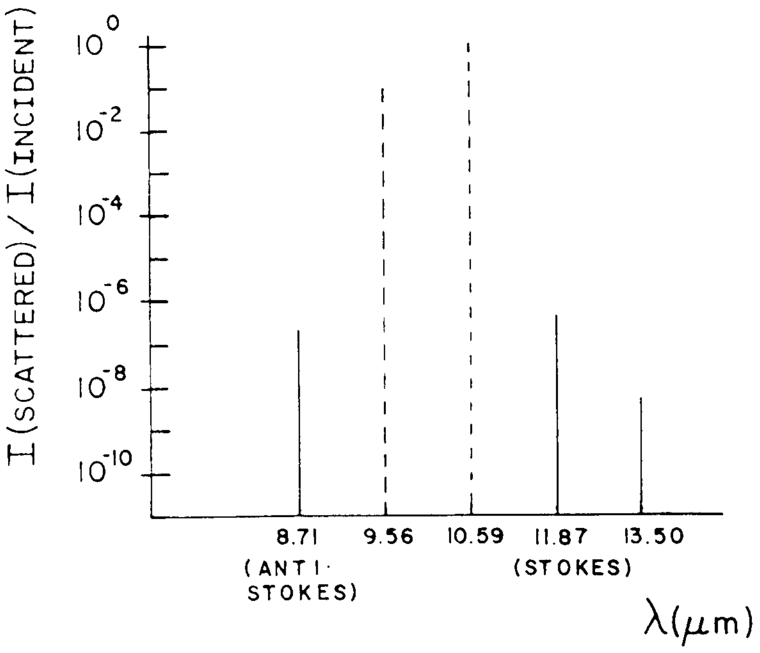

Fig. 3