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Enhanced Scattering of Laser Light by Optical Mixing in a Plasma

B. L. Stansfield, R. Nodwell, and J. Meyer

The University of British Columbia, Vancouver 8, British Columbia

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The enhancement of the scattered signal due to the mixing of two optical beams in a plasma is observed. The two beams are produced in a dual-cavity organic-dye laser pumped by a Q-switched ruby laser. The presence of enhanced oscillations is demonstrated by a 50% increase in the intensity of the satellite in the scattered light spectrum of a third beam.

It has been proposed[1] that the mixing of two strong electromagnetic waves could be used as a plasma probe. The well-defined plasma waves that are generated[2] could be used to scatter a third beam, and, using the known frequency difference, accurately estimate the plasma density. This paper reports an observation of this type of enhanced scattering using three laser beams.

The conditions to be satisfied to generate measurable density waves are

$$\vec{k}_2 - \vec{k}_1 = \Delta\vec{k},$$

$$\omega_2 - \omega_1 = \Delta\omega \approx \omega_p,$$

where $\vec{k}_1, \vec{k}_2$ and ω_1, ω_2 are the wave vectors and frequencies, respectively, of the two incident beams, $\Delta\vec{k}$ and $\Delta\omega$ are the wave vector and frequency, respectively, of the driven oscillation, and ω_p is the plasma frequency.

In order that the resonance be well defined, we need $\Delta\omega > |\Delta\vec{k}| v_{\rm th}$, where $v_{\rm th}$ is the thermal velocity of the electrons.

If the incident electromagnetic waves are monochromatic with electric fields $\vec{E}_1$ and $\vec{E}_2$, then the density fluctuation at the plasma frequency and zero magnetic field is given by[3]

$$\frac{n^{(2)}}{n_0} = \frac{2}{c^2}\,\frac{e\vec{E}_1}{m\omega_1}\cdot\frac{e\vec{E}_2}{m\omega_2}\,\frac{\omega_1\omega_2}{\nu\omega_p}\sin^2\tfrac{1}{2}\beta,$$

where ν represents the damping frequency due to Landau or collisional damping. In our experiment Landau damping is dominant, and the correlation parameter $\alpha \approx 2.5$, giving an effective $\nu/\omega_p \approx 0.2$. The focused 2-MW beam gives a value for $|\vec{E}_1| \approx 10^3$ esu/cm and results in a fluctuation $n^{(2)}/n_0 \approx 2\times10^{-5}$. This fluctuation should produce scattering comparable to the normal satellite intensity (scattered power ≈10-14 times incident power), and hence ought to be observable.

Experiment.–The experimental setup is shown in Fig. 1. The dye laser uses cryptocyanine dissolved in glycerin as the active material, and is longitudinally pumped[4] by a Q-switched ruby laser. The two resonant cavities used with the common dye cell allow us to extract two separate beams, lasing near 7400 Å. The two beams can be independently tuned over about 80 Å by rotating the grating reflectors. The plane reflection gratings have 1200 lines/mm and are blazed

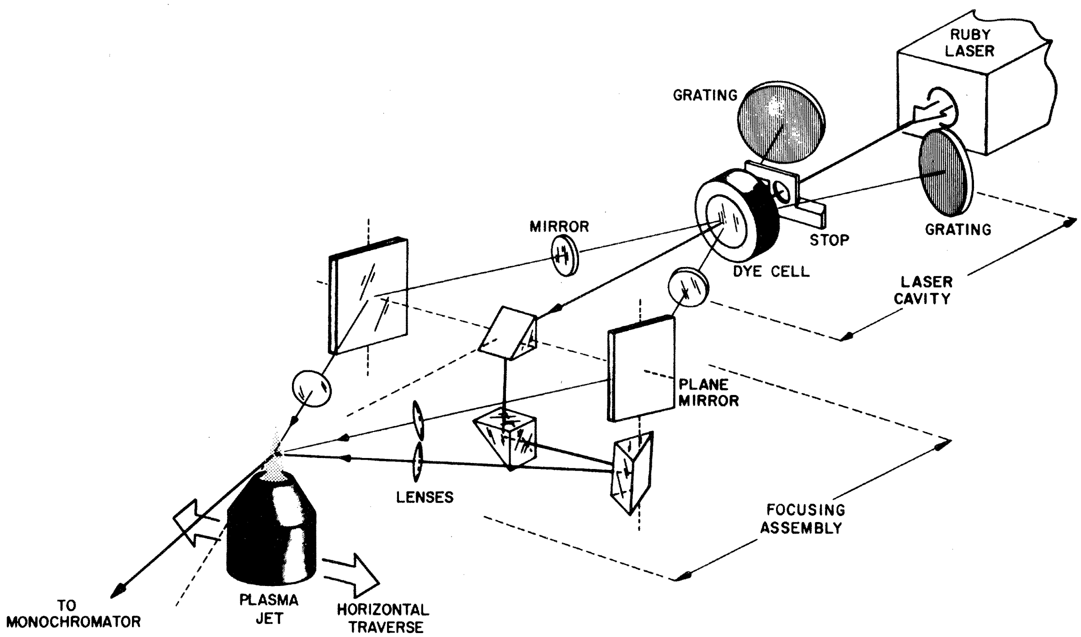

FIG. 1. Illustration of the experiment.

for 7500 Å. When pumped by a 75-MW ruby pulse, we can achieve an output power of 2 MW in each beam, and the linewidth is 2 Å. When the feedback in the cavities is small (i.e., lossy gratings) there is only a small interaction between the two output beams, but when the feedback in larger (well-blazed gratings in good condition) there is a strong coupling between them. To minimize this cross coupling, a pair of blades has been used (as shown in Fig. 1) to ensure that the two output dye beams use different regions of the dye cell, one through the upper half and the other through the lower half of the pumped volume.

The plasma jet is similar to the one used by Chan and Nodwell,[5,6] and was run at a constant current of 250 A, using helium as the working gas at a flow rate of 11.8 liter/min.

The generation of a plasma wave $\Delta\vec{k}$, and subsequent scattering from it, as shown in Fig. 2, require that the third beam $\vec{k}_L$ (which is the unabsorbed ruby-laser light which passes through the dye cell) and the scattered beam $\vec{k}_s$ form a closed triangle with $\Delta\vec{k}$. If $\vec{k}_L$ and $\vec{k}_s$ are in the same plane as $\vec{k}_1$ and $\vec{k}_2$, then $\vec{k}_L$ and $\vec{k}_s$ fall almost along $\vec{k}_1$ and $\vec{k}_2$, respectively. By using the third (or analyzing beam) $\vec{k}_L$ in a different place from the mixing beams $\vec{k}_1$ and $\vec{k}_2$, we are able to prevent $\vec{k}_2$ from firing directly at the detector. Combined with the fact that the mixing beams are far removed in wavelength from the scattering beam, this eliminates stray-light problems. The angle between the mixing beams is 45° in a horizontal plane, while the ruby beam is deflected down and across by mirrors, and enters the plasma at an angle ~13° below the horizontal. The detection system is designed to observe the scattered light in the inclined plane.

Normal scattering (i.e., without the dye laser) produces a scattering profile with a distinct satellite at 27.5 Å (= 57 cm^{-1}) on each side of the central wavelength (6943 Å). Their position indicates a density of 2.2×10^{16} cm^{-3} and a temperature of 17 000 K for the conditions used in this experiment.

To determine the effect of the dye laser on the intensity of the satellite, the wavelength setting of the monochromator was fixed at 6915 Å, which corresponds to the position of the normal satel-

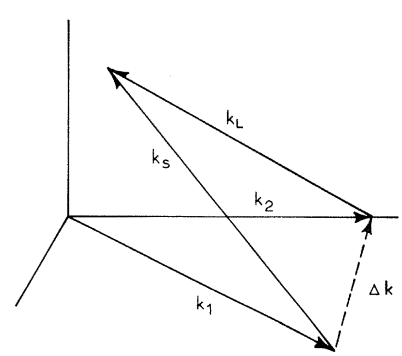

FIG. 2. Wave mixing and analysis.

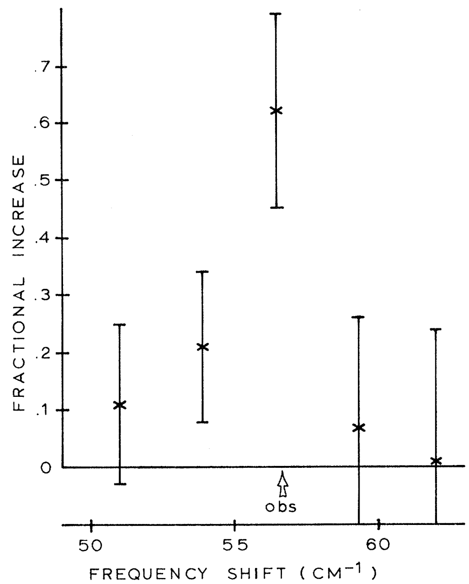

FIG. 3. The fractional increase of the satellite intensity as a function of the frequency difference between the dye lasers. The shift indicated by the arrow is that of the normally observed satellite.

lite, and the intensity of the satellite was measured with and without the dye-laser beams. By varying the wavelength of one of the dye lasers we were able to tune the frequency difference through the plasma resonance.

Results. – The results obtained are shown in Fig. 3, where we have plotted the increase in the satellite intensity as a function of the wave-number separation between the two dye beams. The error bars represent the standard deviation of the mean of at least 10 shots at each point (except for the 62-cm^{-1} shift where 5 shots were taken). It can easily be seen that there is an increase in the satellite intensity when the dye lasers are tuned to the resonance of the plasma. The slight increase on the low-frequency side may prove to be significant.

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Nonlinear Development of the Beam-Cyclotron Instability

M. Lampe, W. M. Manheimer, J. B. McBride, J. H. Orens, R. Shanny, and R. N. Sudan*
U. S. Naval Research Laboratory, Washington, D. C. 20390
(Received 29 March 1971)

A theory is presented for the nonlinear evolution of the beam-cyclotron instability, together with the results of a series of computer experiments confirming the main points of the theory. We conclude that at a turbulent level which is proportional to $(\Omega_{ce}/\omega_{pe})^2$, a transition is made to the nonmagnetic ion acoustic instability. For small T_i/T_e, the system then evolves until the fluctuating fields become strong enough to stabilize by ion trapping.

In this Letter we report on the nonlinear theory and on numerical simulations of the beam-cyclotron instability.[1-4] The instability passes through three distinct phases of evolution. At first, the beam-cyclotron instability develops quasilinearly. When the turbulence reaches a prescribed (relatively low) level, anomalous wave-particle interactions smear out the individual cyclotron resonances, and the instability becomes a nonmagnetic ion acoustic instability. This ion acoustic instability then evolves quasilinearly, if $T_i \ll T_e$, until the fluctuating electric fields become large enough to trap ions, stabilizing the system. The fields are then maintained at a nearly steady level and the plasma heating rate is very much reduced.

The beam-cyclotron instability arises in plasmas when ions drift with speed v_d relative to electrons, across a magnetic field. For $v_d^2 > c_s^2 \equiv T_e/M$, ion modes can couple to electron Bernstein modes to drive an instability.[1-4] If an electron's cross-field diffusion is included in its unperturbed orbit, the