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IN A MICROWAVE PLASMA INTERACTION EXPERIMENT

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PPG 422

July, 1979

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28

OBSERVATION OF STIMULATED BRILLOUIN SCATTERING
IN A MICROWAVE PLASMA INTERACTION EMPIRIMENT

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Stimulated Brillouin scattering of microwave radiation is investigated in an underdense laboratory plasma. The energy and momentum selection rules are seen to be satisfied for a variety of incident wavelengths ($\lambda_0 = 3 \sim 10$ cm) and ion species (He, Ne, Ar and Kr). The threshold power, growth rate and scattered power appear to be consistent with the finite interaction length theory. Saturation of the backscatter is observed and compared with existing theories.

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Stimulated Brillouin scattering (SBS) is a serious obstacle preventing the efficient absorption of the incident laser light in laser pellet interaction experiments¹⁻⁵. We report here the first observation of SBS in a microwave-plasma interaction which may help to elucidate some of the physics relevant to the laser-plasma case. Specifically, the threshold power, growth rate, and saturation level have been determined for SBS in a $0.1 n_{cr}$ plasma.

The experiments were performed in an unmagnetized plasma of 75 cm diameter and 2 m length produced by a multi-filament discharge with surface multipole magnetic confinement. Typical operating parameters are gas filling pressure $1 - 3 \times 10^{-4}$ Torr, electron density $n_o = 10^{10} \sim 10^{11} \text{ cm}^{-3}$, electron temperature $T_e \approx 2 \text{ eV}$, and electron-ion temperature ratio $T_e/T_i \approx 10 \sim 12$. The microwave pump of frequency $\omega_o/2\pi = 3.4 \sim 16 \text{ GHz}$, power $P \leq 1 \text{ MW}$ and pulse width $\tau_p = 0.1 \sim 10 \text{ } \mu\text{sec}$ is introduced along the chamber axis by means of a high gain ($\approx 20 \text{ dB}$) gridded horn. For the experiments described herein, n_o was maintained at $0.1 n_{cr}$, where n_{cr} is the critical electron density corresponding to each microwave frequency. For purposes of scaling, the above mentioned pulse widths roughly correspond to 50 psec duration Nd glass laser experiment. The incident and backscattered electromagnetic waves are separated for detection using either a circulator or directional coupler, and then fed either into a square law detector for power measurements or into a spectrum analyzer for frequency shift measurements. The ion waves associated with SBS are detected using movable Langmuir probes. RF pick-up is not found to be a problem since the waves are measured long after the disappearance of the microwave pump. However, it should be noted that the ion frequency during the rf pulse may be considerably different than that measured afterwards since we are in the strong pump limit³.

Convincing evidence for the existence of SBS in these microwave experiments is obtained by verifying that the energy and momentum selection rules, $\omega_o = \omega + \omega_s$ and $k_o = k + k_s$ are satisfied where (ω_o, k_o) , (ω, k) , and (ω_s, k_s) are the frequency and wavenumber vector of the incident wave, ion wave, and scattered wave, respectively. In Fig. 1, the momentum selection rule is shown to be well satisfied for a variety of incident wavenumbers ($k_o = 0.71, 1.15, 1.80$ and 1.97 cm^{-1}) and ion species (He, Ne, Ar and Kr). The experimental value of k is determined from the wave phase velocity and frequency measured by an axially movable Langmuir probe. The solid line in Fig. 1 shows the relation $k = 2k'_o$, where k'_o is the wavenumber of the incident wave in the plasma ($k'_o \approx 0.95 k_o$ for $n_o \approx 0.1 n_{cr}$).

The verification of the SBS energy selection rule in microwave-plasma interactions is more difficult. Since τ_p is chosen to be small in order to avoid additional ionization of the background gas, the frequency shift between the incident and scattered waves is partially masked by the spectral broadening of the input microwave pulse itself. To measure the frequency shift of the reflected electromagnetic wave, we operated with the maximum ion wave frequency to provide the maximum frequency shift (390 kHz). The incident and reflected pulse spectra were obtained over many experimental pulses using a storage spectrum analyzer yielding a frequency shift of 210 kHz, with the shift in the red direction for the reflected wave. Considering that the reflected wave is a combination of the incident wave ($\tau_p \approx 4 \mu s$), unshifted reflected wave due to waveguide mismatches and chamber reflections, as well as the scattered wave, the agreement rule is close enough for us to feel that the energy selection rule is also satisfied in our experiment.

Figure 2 displays the scattered power P_s and the normalized density fluctuation level $(\tilde{n}/n_0)^2$ for experiments performed in an argon plasma using a 5.5 GHz microwave source. Since the microwave absorber material placed in the chamber to prevent reflections is not totally absorbing the residual reflected power without the plasma ($\approx 2\%$) is subtracted from the total reflected power P_r to obtain P_s . Referring to Fig. 2, we observe that both P_s and $(\tilde{n}/n_0)^2$ initially increase exponentially and then begin to saturate with further increase of P_0 . This saturation occurs when $\eta_0 = E_0^2 / 8\pi n_0 K T_e \approx 6$ and $v_0/v_e \approx 0.9$, where $v_0 = eE_0/m_e \omega_0$ is the quiver velocity of an electron in the field of the pump wave and $v_e = (K T_e / m_e)^{1/2}$. The corresponding values for 8.6 GHz are $\eta_0 = 1.5$ and $v_0/v_e \approx 0.45$. It should be noted that the density fluctuations displayed in Fig. 2(a) were measured quite far from the horn (≈ 60 cm) and are a factor of 2-3 lower than the peak fluctuations (see Fig. 3). We note that an almost linear relation between P_s and $(\tilde{n}/n_0)^2$ is obtained in the nonsaturated region.

In Fig. 3, $\tilde{n}$ is shown as a function of axial distance from the horn. These data yield an interaction length ℓ for SBS, of about 94 cm ($\ell \approx 130$ cm at 8.6 GHz). In this experiment, the interaction length appears to be limited in size by the divergence of the microwave beam; the measured density and temperature scale lengths are two and twenty times as large, respectively, as ℓ . We therefore restrict ourselves to a discussion of SBS from a finite length homogeneous plasma.

For our parameters, the absolute instability threshold exceeds the convective threshold by nearly an order of magnitude^{1,3,6}. Therefore, finite interaction theory¹ yields the following convective threshold condition for SBS:

$$\int_0^{L_c} \left[\gamma_o^2(z) / c \gamma_s \right] dz = \frac{\gamma_o^2(o) \ell_t}{c \gamma_s} = 1, \quad (1)$$

where

$$\gamma_o(z) = \frac{\sqrt{3}}{2} \left(k_o^2 v_o^2(z) \omega_{pi}^2 / \omega_o \right)^{1/3} \quad (2)$$

is the spatially dependent strong coupling growth rate, γ_s is the damping rate of the ion wave, ω_{pi} is the ion plasma frequency and L_c is the chamber length.

The interaction length ℓ_t is calculated for several pumps in Table I. Here, P_{oth} is the threshold power obtained experimentally, A is the beam area, γ_o is calculated from Eq. 2 with (P_{oth}/A) , and γ_s is obtained experimentally from the time history of the ion waves. We consistently find that $\ell \approx \ell_t$ at the threshold value of pump power. In addition, we attempted to observe SBS for a pump wave of $\omega_o/2\pi = 16$ GHz and a power $P_o = 150$ kW. However, we did not observe the appropriate ion waves. For the above power level, the calculated value of $\ell_t = 170$ cm $> \ell$. Thus, it also seems consistent that we could not find SBS as $\ell < \ell_t$ for this case.

When Eq. 1 is satisfied, the scattered power P_s arising from exponential growth out of the noise P_n is

$$P_s = P_n \exp(2\gamma_o^2 \ell / \gamma_s c), \quad (3)$$

where

$$P_n = \frac{P_o}{A} r_o^2 V_s^2 \tilde{n}_n^2 \Delta\Omega \quad (4)$$

and $r_o^2 = 8 \times 10^{-26}$ cm², $V_s = A\ell$ is the scattering volume, A is the horn aperture cross section, R_o is the distance from the scattering center to the horn, $\Delta\Omega = A/R_o^2$ and $\tilde{n}_n$ is the background ion fluctuation level in the vicinity of $2k_o$. Figure 2 implies an exponential growth of P_s . This dependence on P_o is the same as predicted theoretically. Knowing the values of P_o , A , V_s , $\tilde{n}_n$ and $\Delta\Omega$ we can evaluate the backscattered power from Eqs. 3 and 4. The value of P_s estimated from this relation is in agreement with the experimentally measured value for all pump frequencies investigated. The threshold was also investigated by introducing a light ion mass impurity into the plasma. An increase appropriate to the increased Landau damping was observed.

Finally, let us consider the saturation mechanism(s). Phillion et al.⁵ have suggested that ion heating could saturate SBS due to Landau damping of the ion waves. Following their expression, the ion heating rate can be estimated from the relation

$$\frac{d}{dt} (n_o K T_i) = \frac{P_o}{A \ell} r \frac{\omega}{\omega_o}, \quad (5)$$

where ω/ω_o is the fraction of the reflected wave energy given to the ion waves and r is the reflectivity. When the present experimental parameters are inserted, we require a pulse width of $\tau_p > 5 \times 10^{-5}$ sec to observe the appropriate ion heating. Energy analyzer measurements have verified the lack of ion main body heating for the present pulse durations.

Kruer⁷ has proposed that the backscatter can be limited by a saturation of the ion waves due to trapping. He predicts that $\bar{n}/n_o$ is given by

$$\frac{\bar{n}}{n_o} = \frac{1}{2} \left\{ \left[1 + \frac{T_i}{T_e} \right]^{\frac{1}{2}} - \left[3T_i/T_e \right]^{\frac{1}{2}} \right\}^2 \quad (6)$$

which yields $\frac{\bar{n}}{n_o} \approx 13\%$ for $T_e/T_i \approx 10-12$. This value $\bar{n}/n_o$ is approximately a factor of two to three times larger than our observed $(\bar{n}/n_o)_{\max} = 5\%$.

Finally, Ikezi et al.⁸ have observed nonlinear frequency or wavenumber shifts in ion acoustic waves which are attributed to trapped ions. This shift can limit SBS by moving the ion frequency out of the resonance region which is quite narrow ($\approx 8\%$) for our parameters. Using their Eq. (28) we estimate a limiting density fluctuation level $\bar{n}/n_o \approx 3.5\%$ which is in excellent agreement with our observed value. It should be noted that energy analyzer measurements indicate the presence of a population of accelerated ions travelling at $\sim 2 c_s$ produced by the rf pulse.

In conclusion, we have observed, for the first time, stimulated Brillouin scattering in a microwave-plasma interaction. The results obtained in our experiment are consistent with the theory for a finite homogeneous plasma. Saturation of the scattered wave is observed which is consistent with ion trapping.

We would like to thank Drs. J. J. Thomson, J. Kindel, W. Kruer, D. Forslund, K. Estabrook, J. Dawson and M. Herbst for helpful conversations concerning the saturation processes for SBS. This work was supported in part by the Office of Laser Fusion, U. S. Department of Energy, Contract No. DE-AS03-76-SF00034, PA DE-AT03-76DP40010, and U. S. Air Force Office of Scientific Research Contract No. F49620-76-C-0012.

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f_o (GHz)	$I(o)=P_{oth}/A$ (W/cm ²)	$\gamma_o(o)$ (sec ⁻¹)	γ_s (sec ⁻¹)	l_t (cm)
3.4	645	3.2×10^6	2.5×10^4	73
5.5	987	4.3×10^6	4.0×10^4	65
8.6	564	4.2×10^6	5.0×10^4	85

Table 1. Calculated value of threshold interaction length for several pump frequencies.

Fig. 1 Wavenumber of ion waves versus incident electromagnetic wavenumber.

Fig. 2(a) Ion wave amplitude ($z = 60$ cm) versus incident power.

Fig. 2(b) Scattered power versus incident power.