Observation of Stimulated Brillouin Backscattering from an Underdense Plasma

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(Received 12 May 1975)

Observations of stimulated Brillouin scattering from an underdense plasma in a magnetic field are reported. The shifts observed correspond with those expected from a plasma with the measured temperature. Scattering with twice the Brillouin shift $\delta\omega \simeq 2\delta\omega_A \simeq 4k_0c_s$ was observed when the fundamental Brillouin reflectivity approached 5%.

In this Letter we report observations of backscattered radiation from a laser-heated plasma column in a solenoidal magnetic field. The experiment was motivated by predictions[1] of backscattered radiation from underdense plasmas due to parametric instabilities and by experimental observations[2,3] of backscattered radiation from laser-irradiated solid targets.

The experimental setup and measurements of the plasma electron temperature and density are described by Rutkowski and co-workers.[4,5] A column of plasma was created and heated by axial CO_2-laser irradiation of neutral hydrogen gas in solenoidal fields up to 100 kG, using a mirror of 1-m focal length. Plasma columns 20 cm long with spectroscopically measured electron temperatures T_e as high as 130 ± 30 eV were produced.[4,5]

Observations of backscattered radiation were made by placing a 5% reflecting polyethylene beam splitter in the incident beam about 5 m from the plasma. Backscattered light reflected by it was focused onto the input slit of a 1.2-m Ebert infrared grating spectrometer with an instrumental width less than 25 Å full width at half-maximum. A small part of the incident beam was imaged at a different height on the input slit as a wavelength reference. Time-integrated spectra were taken using encapsulated liquid-crystal sheets and exposed Polaroid film. Time-resolved spectra were taken with a 10-nsec-response pyroelectric detector behind the exit slit of the spectrometer. From data taken for several magnetic fields and filling densities, only that for $B = 100$ kG and $p_0 = 28$ Torr will be discussed in detail here.

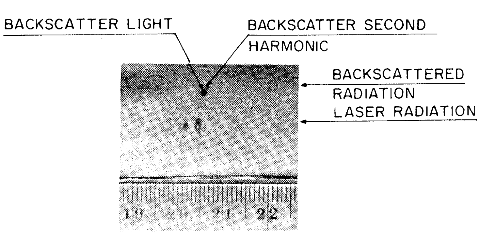

FIG. 1. Black-and-white reproduction of color slide taken of liquid-crystal display. The right spot of the laser radiation line is the P_{20} line; left spot is P_{18}. Laser energy 150 J.

The liquid-crystal sheet, placed at the focal plane of the spectrometer, changed color in response to radiation-induced local temperature changes. Color slides were taken of the sheet after each shot and the shifts were measured (Fig. 1). Because of thermal conductivity of the sheet, the images spread and fade quickly and the widths shown are artificially large. The backscattered radiation is shifted to the red about 80 Å from the P_{20} line in Fig. 1. Typical results of time-resolved observations are shown in Fig. 2. The backscattering signal begins 200–400 nsec after the laser spike, during the tail of the pulse, at which time the average intensity is still

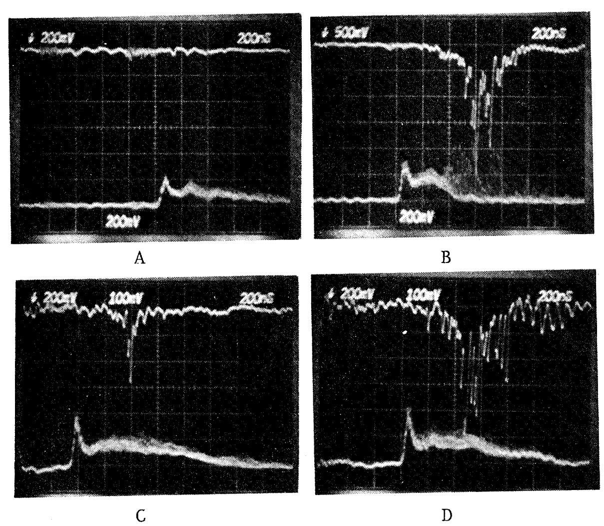

FIG. 2. Time-dependent backscattering traces; 200 nsec/div. Upper trace, pyroelectric-detector traces of backscattered radiation. Lower trace, incident laser radiation (photon-drag detector): (a) Vacuum shot. (b) Total backscattered radiation, 4000 Å to 15 μm; laser energy 182 J. (c), (d) 70-Å-wide band centered at $P_{20} + 70$ Å; laser energy 146 and 167 J, respectively.

$(2-8)\times 10^9$ W/cm^2 based on a measured vacuum focal-spot size of a few square millimeters. The spot size in the plasma may be different because of refraction, but this is difficult to measure. In addition, the incident laser intensity exhibited a curious spiked structure associated with backscattering, perhaps due to feedback from backscattered radiation entering the laser.

By narrowing the slits and rotating the grating from shot to shot a time-resolved spectrum was obtained. A series of shots with a delay of 300 nsec between the laser spike and backscattering spike was selected and the peak backscattering intensity versus wavelength was plotted (Fig. 3). No backscattering was ever observed at the laser line with this detector. The red shift of 80 ± 15 Å is typical for the conditions reported on here.

To determine the amount of backscattered radiation, calorimetric measurements of both beams were made. The backscattered energy in the solid angle occupied by the $f/6.6$ focusing mirror varied from less than 100 mJ for laser energies below 70 J to 9 ± 0.5 J (instrumental error) for a laser energy of 150 J with fairly high shot-to-shot scatter (Fig. 4). Since the duration of the backscattering signal and the laser signal are comparable a maximum power reflectivity of about 5% may be deduced.

Red-shifted backscattered radiation from the plasma could conceivably arise from reflection from a receding critical surface, stimulated Raman scattering, or stimulated Brillouin scattering (SBS). These will be discussed in turn.

If the plasma were fully ionized at the filling density an electron density of 2×10^{18} cm^{-3}, which is $\frac{1}{5}$ the critical density for 10.6-μm radiation, would be produced. Single-ray Mach-Zehnder interferometry was used to measure the time-dependent average density across the plasma diameter (determined using streak photography and axial holographic interferometry) at several axial positions.[5] The maximum average density thus observed was $(3.5\pm 1.5)\times 10^{18}$ cm^{-3} at the front, still well below critical density. Toward the orifice, the average density dropped monotonically to $<5\times 10^{17}$ cm^{-3} as a result of plasma streaming out the orifice. However, the finite resolution of the instrument precluded detection of thin (< 1 mm) high-density structures which possibly could exist at the breakdown front if laser-driven detonation fronts[6,7] were produced. To test the possibility that reflection from a critical surface at the breakdown front could explain the observations, we measured the front velocity as a function of B and laser intensity with a streak camera (the same results were obtained with transverse interferometry), calculated the expected Doppler shift, and correlated it with the measured shift (see Fig. 5). The correlation was $r=-0.6$, eliminating this possibility. The fact that r is negative rather than zero implied that lower fields, which yield lower temperatures as a result of higher radial thermal conductivity,[5] also gave smaller shifts as expected from SBS, rather than larger shifts which would be expected from a Doppler shift from a faster-moving front.[4] It is quite unlikely that a critical surface

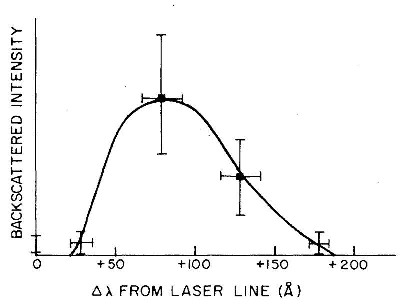

FIG. 3. Spectral scan for laser energy 140 ± 10 J.

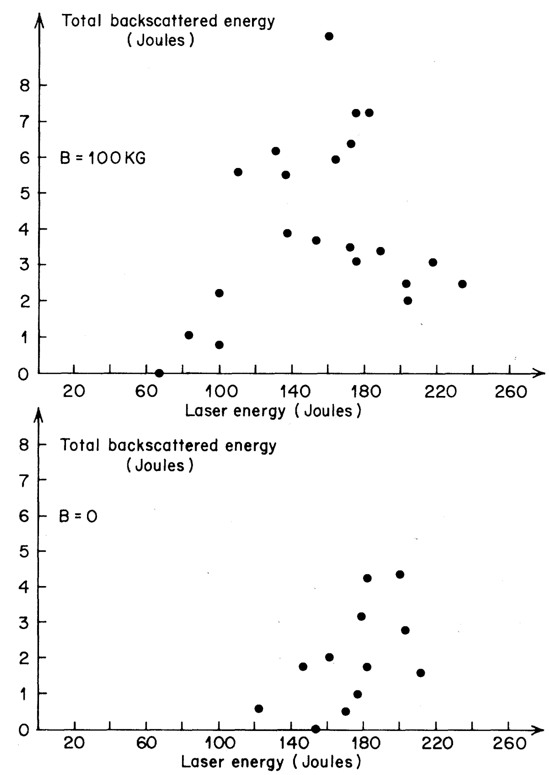

FIG. 4. Backscattered energy versus incident energy.

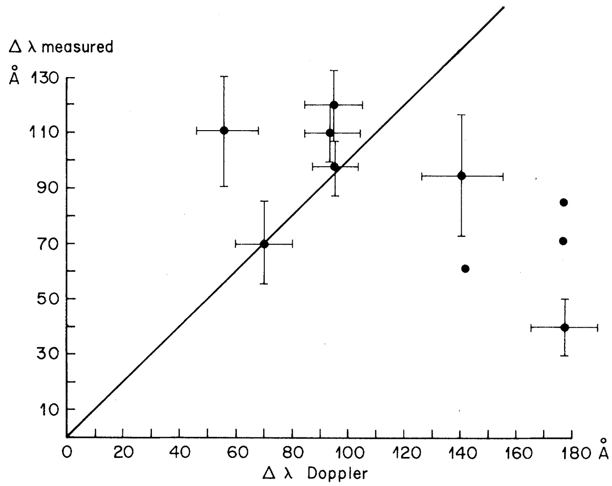

FIG. 5. Measured shift versus Doppler shift.

exists behind the breakdown front since it would prevent radiation from reaching the front, leaving nothing to drive it.

Stimulated Raman scattering[1] would cause shifts $\sim\omega_p$, which is 100 times the shift observed, ruling out this explanation.

There are two models in the literature describing laser-breakdown propagation and the resulting plasmas. Afanas'ev *et al.*[6] and later Rehm[7] described a computer model which predicted formation of a detonation front coincident with the breakdown front with a compression of 2 over the filling density at the time of the backscattering. These models predict significant fluid motion ($u_f \lesssim c_s$). Steinhauer[8] predicts a "bleaching wave" with $u_f \ll c_s$ and no compression. Regardless of which theory is correct, SBS with the observed shift would be expected. SBS theories predict a shift $\delta\omega = 2k_0(c_s + u_f)$, where k_0 is the laser wave number in the plasma and $c_s = [k_B(T_e + T_i)/m_i]^{1/2}$ is the ion acoustic wave speed. Sufficient gain to explain 5% reflectivity should not occur in the very-low-density parts of the plasma,[1] so that temperature and density profiles in the dense parts of the plasma need be considered. In Steinhauer's theory $u_f \ll c_s$ and the predicted shift is 100 ± 20 Å for the 130 ± 30 eV temperature measured. In the detonation-front theory T_e reaches 130 eV at a point well behind the front where $u_f = 0$; toward the front T_e goes down while u_f goes up. As a result the sum $u_f + c_s$ varies by only 12% in 2 cm and a shift of 100 ± 30 Å is predicted. At other points, either the density is too low or the gradient of $u_f + c_s$ is too high for significant SBS. For the estimates a value of $T_e/T_i = 2$ was used based on a model[9] similar to that of Burnett and Offenberger[10] for our conditions. Both these shifts are within the spectrum of Fig. 3 and thus SBS is the likeliest candidate to explain the observations regardless of which gas-dynamic theory is correct.

In addition, on shots with reflectivities $\sim 5\%$, a small amount of backscattered radiation at twice the Brillouin shift $\delta\omega \simeq 2\delta\omega_A \simeq 4k_0c_s$ at a very slightly different angle was observed (Fig. 1). A calculation of the ion-wave amplitude required to produce 5% reflectivity yields $\delta n/n_0 \sim (k\lambda_D)^2$, where λ_D is the Debye wavelength. This is the level at which Dawson, Kruer, and Rosen[11] predict second-harmonic generation of the excited acoustic waves, and scattering from these waves could explain the scattered radiation at twice the fundamental shift.

The authors would like to thank D. Scudder and H. Rutkowski for their help in taking the data, and Professor G. C. Vlases and Professor A. Hertzberg for many helpful discussions and comments. This work was supported by the U. S. Energy Research and Development Administration and NASA.

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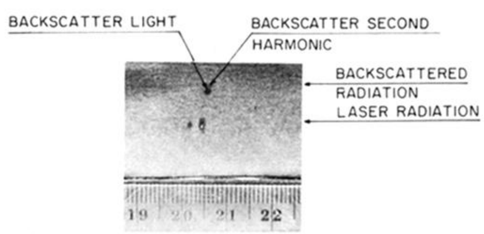

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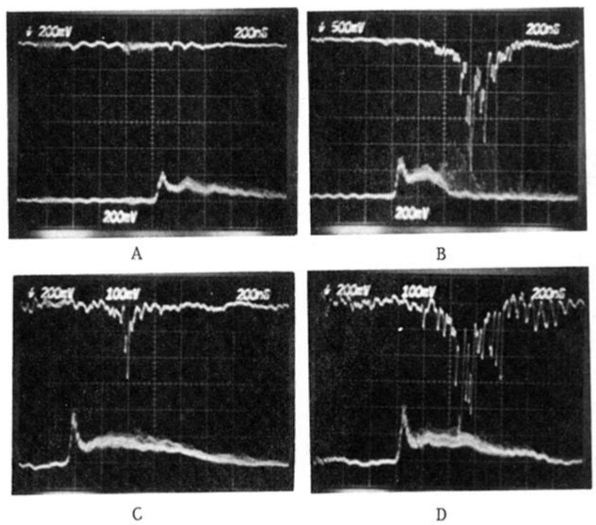

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