[6]E.g., TFR Group, in *Proceedings of the Seventh European Conference on Controlled Fusion and Plasma Physics, Lausanne, Switzerland, 1975* (European Physical Society, Geneva, 1975), Vol. 2, p. 1.
[7]M. Rosenbluth and C. S. Liu, Phys. Fluids 15, 180 (1972).

Reflection and Scattering from CO_2-Laser-Generated Plasmas

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The intensity of 10.6-μm radiation scattered from carbon plasmas has been measured as a function of incidence and collection angles (with angular resolution $\leq 1.3°$), and of laser mode structure. Over an incident intensity range 10^{11}–10^{13} W cm^{-2}, total reflectivity was typically $\lesssim 8\%$. At certain angles, reflectivity often showed 100% temporal modulation. The relevance of these results to critical-surface and stimulated-scattering phenomena is discussed.

The reflection and scattering of radiation from laser-produced plasmas is a topic of active experimental and theoretical interest. Extensive measurements on a wide variety of targets have been reported, for example, at wavelengths of $\lambda = 0.694$,[1] 1.06,[2-7] and 10.6 μm.[8-15] In most of these experiments the focusing arrangements were such that the target simultaneously encountered a wide range of angles of incidence (θ). This Letter describes measurements made with angular resolution higher than those in previous work,[5,12] and discusses the exceptionally strong time variation of reflectivity which has been observed with use of multimode lasers and the absence of detectable modulation when a laser is operated on a single transverse axial mode.

As shown in Fig. 1, a 75-J, 50-ns pulse from a plane-polarized multimode CO_2 laser of cross section 5 cm$\times$10 cm was focused by a 7.8-cm-diam ($f/4.4$), 22-cm-focal-length, KCl lens onto a solid-graphite target. Radiation backscattered into the focusing lens, and the incident radiation, were sampled by a 16% NaCl beam splitter and imaged onto photon-drag detectors PD2 and PD1. Radiation sidescattered into the remaining $\sim 2.0\pi$ ster was collected by a spherical copper mirror and focused into a photon-drag detector PD3 located behind the target. Variations of absorption with θ were investigated by placing annular apertures at the laser output window (thus restricting the uncertainty in $|\theta|$ to $0.65°$–$1.3°$) while the backscattered and sidescattered signals were measured into the collection angles of the lens and mirror, respectively. Similarly, the distribution of radiation scattered into angles $\varphi \pm \Delta\varphi$ was measured (with the full $f/4.4$ cone of radiation incident) by placing a series of annular apertures before the PD2 imaging lens, giving a resolution $\Delta\varphi = 0.4°$–$0.8°$.

Figure 2 shows the variation with θ of the total backscattered and total sidescattered radiation, when the target surface is in the focal plane. Similar results are obtained with the target displaced 1 mm from this plane (diffraction effects are then less important and θ is more meaningfully defined). It is noted that here the mean focal intensity increases with θ (3.3×10^{11}–3.6×10^{12}

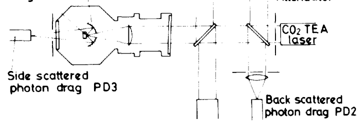

FIG. 1. Experimental layout.

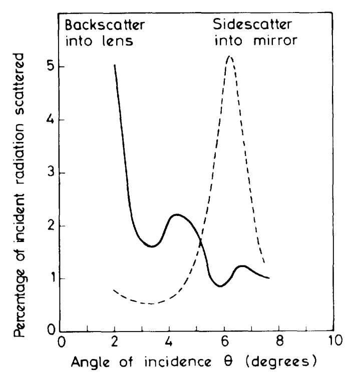

FIG. 2. Variation with θ, angle of incidence, of total backscattered radiation (into lens; solid curve) and sidescattered radiation (into mirror; dashed curve).

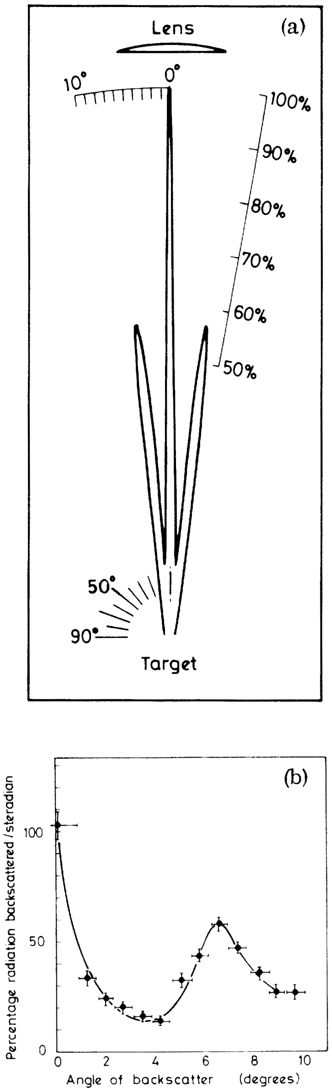

FIG. 3. (a) Polar diagram of scattered radiation per steradian (normalized to axial reflection); incident intensity 10^{13} W cm^{-2}, $\theta = 0 \pm 7°$. (b) Shot-to-shot error in backscatter data of (a).

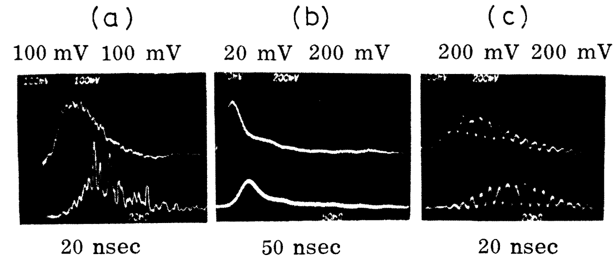

FIG. 4. Incident (top) and reflected (bottom) signals for (a) $\theta = 4.5 \pm 0.7°$, multimode, (b) $\theta = 0 \pm 7°$, single-mode, and (c) $\theta = 0 \pm 7°$, four-axial-mode pulses.

W cm^{-2}) so that the plasma has properties intermediate to those characterized in previous work[16,17] (60 eV $< kT_e <$ 1.3 keV). The reflectivity is qualitatively compatible with numerical predictions of strong optical resonance absorption plus inverse bremsstrahlung in inhomogeneous plasmas.[18] In common with other experiments using gain-switched transverse-excitation atmosphere lasers,[15] the absolute reflectivity was found to be insensitive to target material and incident radiation intensity (within the range $3\times10^{11}-10^{13}$ W cm^{-2}).

Two features of the subsequent observations are noteworthy: (i) Radiation is scattered into preferred angles (Fig. 3); (ii) its intensity is strongly modulated[2,6] [Fig. 4(a)]. Figure 3(a) shows the preferred scattering angles observed at 10^{13} W cm^{-2} incident intensity (with no aperture placed before the $f/4.4$ target lens, so that radiation is incident at a range of angles within the cone defined by the lens aperture shown on the polar diagram). These measurements are insensitive to target position (cf. results discussed for Fig. 2). The $0.4°-0.8°$ resolution of the backscattering data is indicated by the error bars in Fig. 3(b), which also show the shot-to-shot variation in the signal envelope (evaluated as a mean of 5–10 observations made under identical conditions). Angular discrimination for sidescattered radiation was obtained by placing apertures of various diameters in front of PD3, giving a resolution of $\pm 5°$.

A test was made to distinguish backscattering ($\varphi = \pi$) and specular reflection ($\varphi = \pi - 2\theta$) by stopping the same half of the incident and backscattered laser beams with two D-shaped masks, so that specular reflection was not detected. The addition of the stop did not reduce the percentage reflectivity, proving that radiation detected by PD2 was predominantly backscattered through π. (In a similar test, with use of rectangular masks to detect azimuthal asymmetry relative to the incident polarization plane, the backscattered radiation exhibited only a weak asymmetry.) At incident intensities of $10^{11}-10^{13}$ W cm^{-2} the amplitude of the time-resolved backscattered signal is modulated by 30–100%. Figure 4(a) illustrates the particularly strong modulation which occurs at $\theta = 4.5°$, and at wide backscattering angles. The influence of laser axial and transverse mode structure on these measurements was investigated by replacing the multimode laser (A) with a single-transverse mode 20 MW CO_2 laser (B) which had a similar risetime (50 ns full width at half-maximum) and lased on a single axial mode.[19] Spherical aberration in the focusing lens limited the incident intensity to $\sim 5\times 10^{11}$ W cm^{-2}. Two important differences were noted: (i) No modulation of the backscattered intensity was observed [cf. Fig. 4(b)] and, (ii) the backscattered reflectivity increased to $(30\pm 3)\%$. When the unstable optical cavities on laser B were readjusted to permit operation on approximately four axial modes (within a single transverse mode), strong modulation of the backscattered signal was observed at a peak intensity of 1.5×10^{12} W cm^{-2} [Fig. 4(c)], and the reflectivity was $\sim 22\%$. A strong correlation was noted between the periodicity of the observed modulation (using either multimode laser) and integral multiples of the oscillator-cavity transit time. This periodicity was investigated for Perspex, C, Al, Cu, Fe, and Ta targets, but no systematic variation with target plasma was noted, although two proposed modulation mechanisms[6,20] do predict an ion mass dependence.

The computed threshold[21] for stimulated Brillouin backscattering (SBS) is exceeded in the inhomogeneous plasma experiment of Fig. 3 by a factor $\gtrsim 30$, while the threshold for Raman sidescattering is exceeded marginally; therefore, although no spectral identification was made, it seems reasonable to infer from previous experiments on homogeneous plasmas[22] that the backscattered radiation peaking at $\theta=0$ and the beam periphery at $\sim 6.5°$ is indeed SBS from the underdense corona; however, in the present experiment, weak backscattering from regions very close to the critical surface, rather than noise, should stimulate the Brillouin scattering within the less dense outer regions. The significantly weaker backscattering signals observed at $\theta\sim 3°-5°$ are then consistent with strong resonant absorption at the critical surface, which is expected near these angles. (Since the critical surface may have significant curvatures induced by two-dimensional hydrodynamic expansion and by caviton formation,[23] θ has only an averaged spatial, rather than local, significance.)

Temporal modulation of the scattered signal would then arise from the phase relationship between modes in the incident and reflected beams. Weaker modes reflected from the critical surface are not sufficiently intense to stimulate significant scattering from the (more weakly pumped) gain medium. The scattered signal thus carries the integral round-trip transit-time periodicity arising from the incident axial-mode structure, but modified by the nonlinear amplification. In all the experiments the laser bandwidth $\Delta\omega < 2\pi c/L$, where L is the plasma inhomogeneity scale length, so the SBS instability threshold should be insensitive to $\Delta\omega$; the lower reflectivity observed in the multimode laser experiments may perhaps be explained by postulating that a *restricted* number of laser modes grow to a limit determined by saturation.

In conclusion, it is noted that absorption in the plane target is typically 92%, that weak backscattering occurs over a finite spread of angles centered around the incident beam, and that scattering experiments having high azimuthal and angular resolution offer a convenient technique to help elucidate fine-scale structure of the critical surface.

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[1]E. Jannitti and G. Tondello, Opt. Commun. 10, 186 (1974).

[2]M. Waki, T. Yamanaka, H. Kang, K. Yoshida, and C. Yamanaka, Jpn. J. Appl. Phys. 11, 420 (1972).

[3]L. M. Goldman, J. Soures, and M. J. Lubin, Phys. Rev. Lett. 31, 1184 (1973).

[4]C. Yamanaka, T. Yamanaka, T. Sasaki, J. Mizui, and H. B. Kang, Phys. Rev. Lett. 32, 1038 (1974).

[5]B. H. Ripin, J. M. McMahon, E. A. McLean, W. M. Manheimer, and J. A. Stamper, Phys. Rev. Lett. 33, 634 (1974).

[6]N. G. Basov, O. N. Krokhin, V. V. Pustovalov, A. A. Rupansov, V. P. Silin, G. V. Sklizkov, V. T. Tikhonchuk, and A. S. Shikanov, Zh. Eksp. Teor. Fiz. 67, 118 (1974) [Sov. Phys. JETP 40, 61 (1975).

[7]K. Eidmann and R. Sigel, Phys. Rev. Lett. 34, 799 (1975).

[8]C. Yamabe, E. Setoyama, M. Yokoyama, and C. Yamanaka, Phys. Lett. 50A, 349 (1974).

[9]K. Dick and H. Pepin, Opt. Commun. 13, 289 (1975).

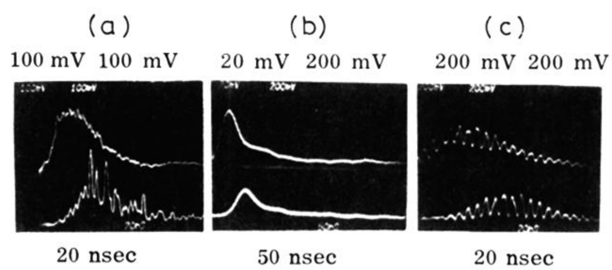
[10]H. A. Baldis and C. R. Neufeld, Opt. Commun. 15, 95 (1975).

[11]K. B. Mitchell, T. F. Stratton, and P. B. Weiss, Appl. Phys. Lett. 27, 11 (1975).

[12]J. Martineau, P. Paranthoën, M. Rabeau, and C. Patou, Opt. Commun. 15, 404 (1975).

[13]E. Fabre, C. Popovics, and C. Stenz, in *Proceedings of the Seventh European Conference on Controlled Fusion and Plasma Physics, Lausanne, Switzerland,*

1975 (European Physical Society, Geneva, 1977), Vol. 1, p. 80.
[14]T. A. Hall and Y. Z. Negm, Opt. Commun. 16, 275 (1976).
[15]P. E. Dyer, S. A. Ramsden, J. A. Sayers, and M. A. Skipper, J. Phys. D 9, 373 (1976).
[16]G. E. Bromage, T. P. Donaldson, B. C. Fawcett, and I. J. Spalding, J. Phys. D 9, 133, (1976).
[17]T. P. Donaldson, J. W. Van Dijk, A. C. Eklerbout, and I. J. Spalding, Ref. 13, paper 82.
[18]M. M. Muelier, Phys. Rev. Lett. 30, 582 (1973).
[19]T. Stamatakis and A. C. Selden, to be published.
[20]W. L. Kruer, E. J. Valeo, and K. G. Estabrook, Phys. Rev. Lett. 35, 1076 (1975).
[21]C. S. Liu, M. N. Rosenbluth, and R. B. White, Phys. Fluids 17, 1211 (1974).
[22]A. A. Offenberger, M. R. Cervenan, A. M. Yan, and A. W. Pasternak, J. Appl. Phys. 47, 1451 (1976).
[23]T. P. Donaldson and I. J. Spalding, Phys. Rev. Lett. 36, 467 (1976).



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