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REFLECTION AND SCATTERING FROM CO2 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 ≤ 1.3°), and of laser mode structure. Over an incident intensity range of 10^{11} - 10^{13} watts cm^{-2}, total reflectivity was typically ≤ 8%. At certain angles reflectivity often showed 100% temporal modulation. The relevance of these results to critical-surface and stimulated-scatter phenomena is discussed.

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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 λ = 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 paper describes measurements made with higher angular resolution than heretofore[5,12], and discusses the exceptionally strong time-variation of reflectivity which has been observed using multi-mode 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 x 10 cm was focused by a 7.8 cm dia. 22 cm focal length KCl lens onto a solid graphite target. Radiation back-scattered 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 side-scattered into the remaining $\sim 2.0\pi$ steradians 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°) whilst the back and side-scattered 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°.

Fig. 2 shows the variation with θ of the total back and total side scattered 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} W cm^{-2}) so that the plasma has properties intermediate to those characterized in previous work[16,17] (60 eV < kTe < 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 TEA lasers[15], the absolute reflectivity was found to be insensitive to target material and incident radiation intensity (within the range $3 \times 10^{11} - 10^{13}$ 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)). Fig.3(a) shows the preferred scatter 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 back-scatter 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 side-scattered radiation was obtained by placing apertures of various diameters in front of PD3, giving a resolution of $\pm 5^{\circ}$.

A test was made to distinguish back-scattering ($\phi = \pi$) and specular reflection ($\phi = \pi - 2\theta$) by stopping the same half of the incident and back scattered 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, using rectangular masks to detect azimuthal asymmetry relative to the incident polarisation 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 back-scattered signal is modulated by 30 - 100%. Fig.4(a) illustrates the particularly strong modulation which occurs at $\theta = 4.5^{\circ}$, and at wide back-scatter 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 FWHM) 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)); (ii) the backscattered reflectivity increased to 30 ± 3%. When the unstable optical cavities on laser B were readjusted to permit operation on ~ 4 axial modes (within a single transverse mode), strong modulation of the back-scattered signal was observed at a peak intensity of 1.5×10^{12} W cm^{-2} (Fig.4(c)), and the reflectivity was ~ 22%. A strong correlation was noted between the periodicity of the observed modulation (using either multi-mode 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 back scatter (SBS) is exceeded in the inhomogeneous plasma experiment of Fig. 3 by a factor ⩾ 30, whilst the threshold for Raman sidescatter (SRS) is exceeded marginally. Although no spectral identification was made, it therefore seems reasonable to infer from previous experiments on homogeneous plasmas [22] that the back-scattered radiation peaking at $\theta = 0$ and the beam periphery at $\sim 6.5^{\circ}$ is indeed SBS from the under dense corona; in the present experiment, however, weak back-scatter from regions very close to the critical surface, rather than noise, should stimulate the Brillouin scatter within the less dense outer regions. The significantly weaker back-scatter signals observed at $\theta \sim 3\text{-}5^{\circ}$ 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 non-linear amplification. In all the experiments the laser bandwidth $\Delta\omega < (2\pi c/L)$, where L is the plasma inhomogeneity scale-length, and 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 back-scattering occurs over a finite spread of angles centred around the incident beam, and that scatter 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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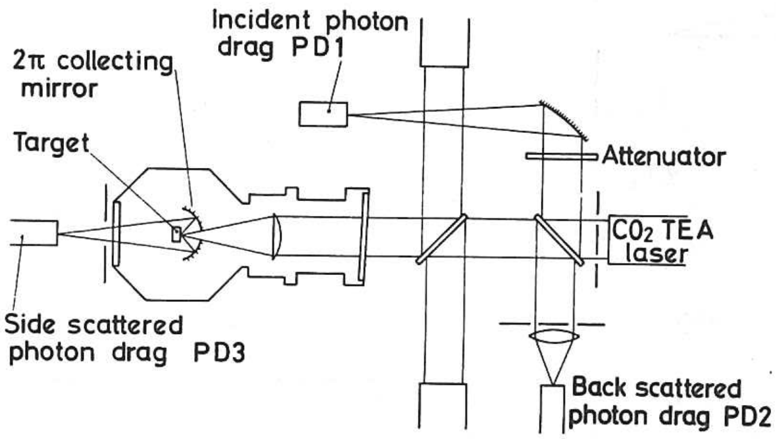


Fig. 1 Experimental layout.

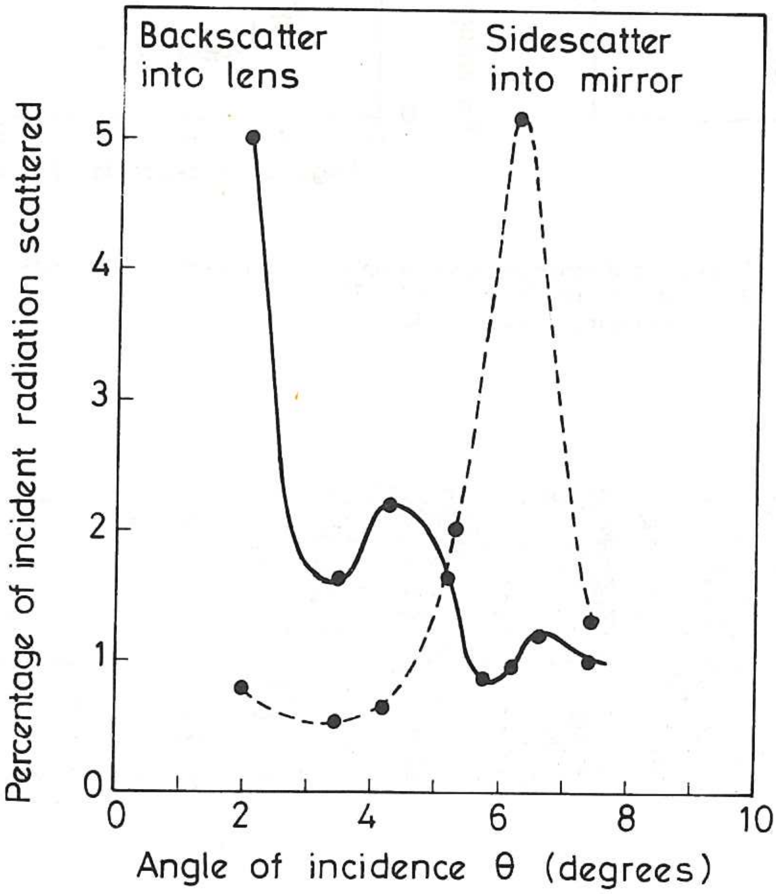
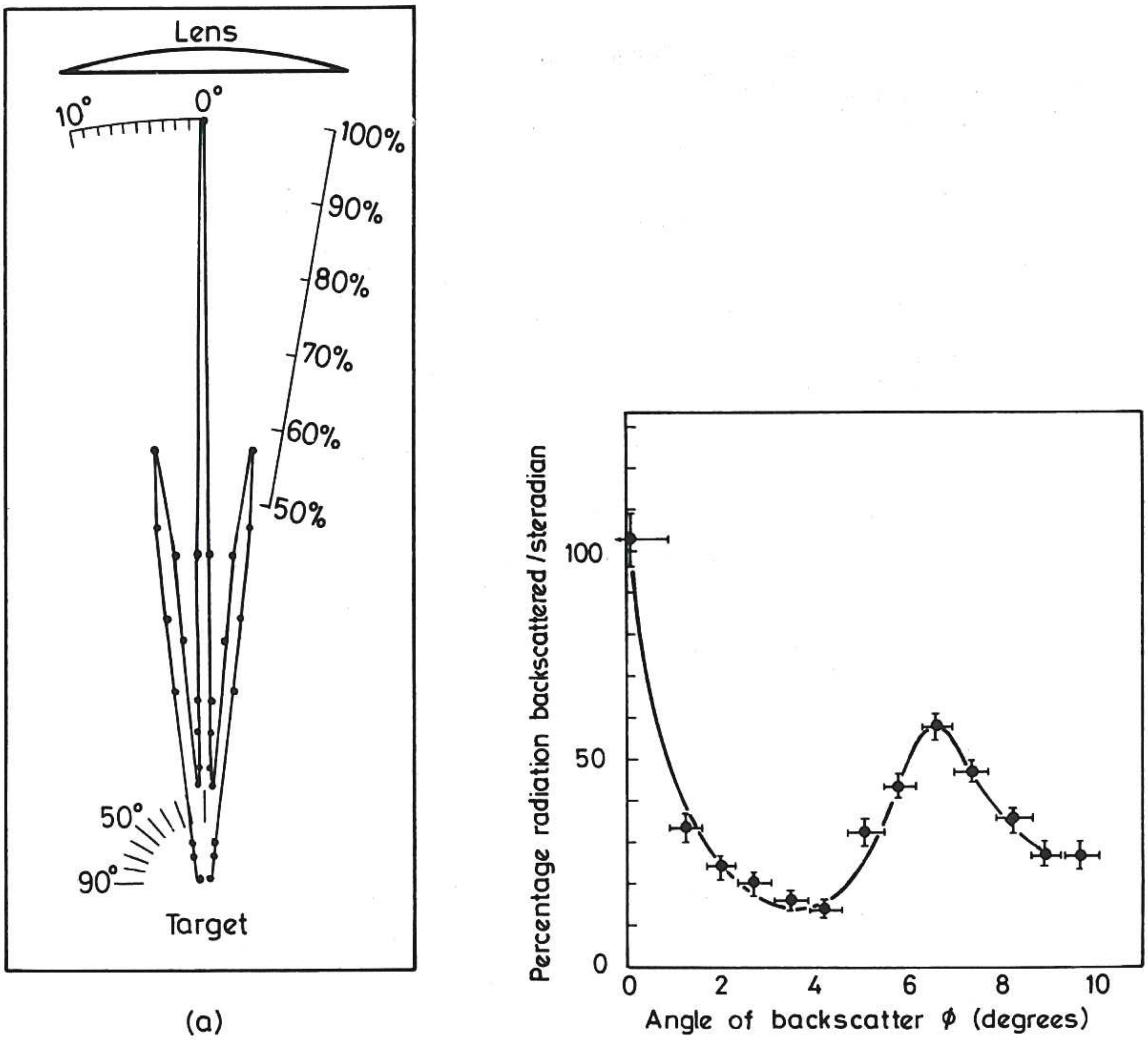
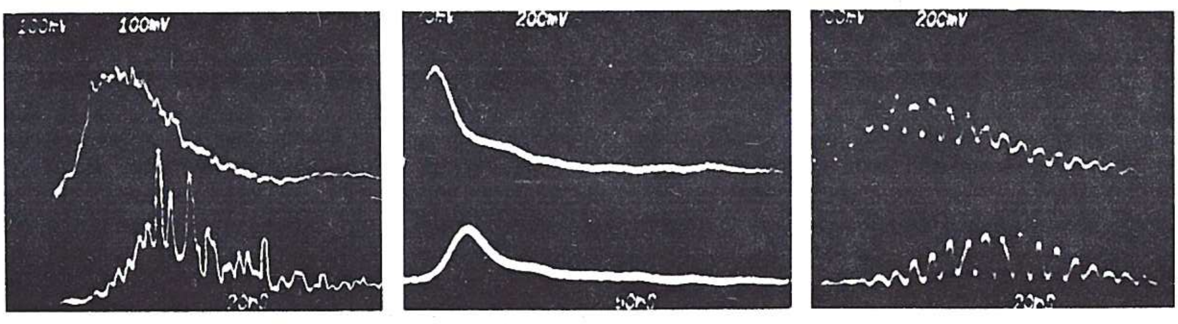


Fig. 2 Variation of total back, and side, scattered radiation with θ.



(a)

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



(a) (b) (c)

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.