Observation of Stimulated Raman Scattering from 20-psec Laser-Produced Plasmas

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Raman scattering spectra obtained with 20-psec 1.064-μm laser pulses incident at 45° on nickel-foil targets show an intensity-dependent red shift relative to the subharmonic of the laser frequency. In conjunction with temperature data deduced from x-ray measurements, the results imply a change from the absolute to the convective instability with increasing intensity. The observation of Raman scattering is correlated with the appearance of a high-energy tail in the x-ray spectrum above 100 keV.

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Stimulated Raman scattering (SRS) in a laser-produced plasma involves the parametric decay of an incident photon into a scattered photon and a plasmon. In order that the scattered photon be launched below its own critical density, SRS may only occur at densities less than one quarter of the critical density for the incident photon. The two-plasmon ($2\omega_p$) decay (in which the incident photon decays into two plasmons) also occurs in this density region and may compete with SRS as the dominant instability. Both these instabilities, however, through the production of plasmons, can cause the efficient acceleration of electrons to high energies and this may cause significant preheat in laser fusion targets. Consequently there is considerable current interest in both phenomena.

SRS has been observed in several experiments. Elazar, Toner, and Wooding[1] observed the onset of SRS for 1–2-nsec duration, 1.06-μm laser pulses while Phillion and Banner[2] showed the Raman spectrum to have a peak centered around 1.8 μm when 1.06-μm laser pulses of between 100-psec and 2.2-nsec duration irradiated tantalum or layered disk targets. They also detected SRS using 0.53-μm light in pulses of 600-psec duration. Tanaka *et al.*[3] have measured the scattered spectrum as a function of laser intensity for 0.35-μm, 450-psec-duration pulses.

In this Letter we present the first observations of SRS in plasmas produced by short (20 psec duration) 1.06-μm neodymium laser pulses. Laser pulses with an energy of about 1 J and nominal duration of 20 psec were focused with an $F = 1$ aspheric doublet lens[4] onto 25-μm-thick nickel-foil targets angled at 45° to the incoming beam direction. The targets were so oriented to ensure that the scattered photons, which may undergo strong refraction towards the plasma density gradient, were collected by a rhodium-coated parabolic mirror placed around the target which allowed radiation to be collected over an angular range of 30° to 110° relative to the incoming beam direction. The nominally parallel output beam from the parabolic mirror was filtered to reject 1.06-μm radiation by use of dielectric and germanium filters and then focused onto the entrance slit of a 0.5-m grating monochromator. The light at the exit slit was detected with a room-temperature InAs detector. The on-target laser intensity was varied from 5×10^{14} to 5×10^{16} W/cm^2 by moving the target away from the position of best focus towards the focusing lens. To assist in interpretation of the scattered spectra, plasma temperatures were deduced from x-ray bremsstrahlung emission with eleven detector channels spanning the energy range 1–250 keV. The spectrum up to 55 keV was recorded with a seven-channel K-edge filter/p-i-n diode detector array and the 88–250 keV region covered by a K-edge/broadband filter set and NaI(Tl)/photomultiplier-tube detectors.

The spectrum of the scattered light between 1.8 and 2.5 μm was built up over a large number of laser shots for both p- and s-polarized incident light. For s-polarized light a sharp threshold for scattering similar to that reported by other workers[1-3] was observed at around 3×10^{15} W/cm^2. The scattered spectrum just above threshold is shown in Fig. 1(a) and exhibits a peak at 2.19 μm. At higher intensities [1.2×10^{16} W/cm^2, Fig. 1(b), and 5×10^{16} W/cm^2, Fig. 1(c)] similar spectra were observed with the peaks lying at 2.16 and 2.15 μm, respectively. Similar measurements were performed with p-polarized light; however, here scattering was only observed at the highest laser intensity where the signals were erratic over a broad spectral range with an indication of a peak lying to the blue of the subharmonic of the laser frequency [Fig. 1(d)].

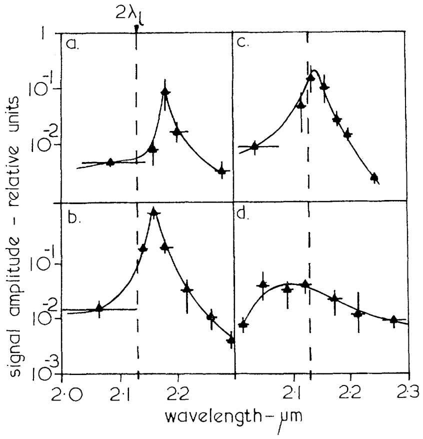

FIG. 1. SRS spectra for (a) s polarization, $I=3\times10^{15}$ W/cm^2; (b) s polarization, $I=1.2\times10^{16}$ W/cm^2; (c) s polarization, $I=5\times10^{16}$ W/cm^2; (d) p polarization, $I=5\times10^{16}$ W/cm^2.

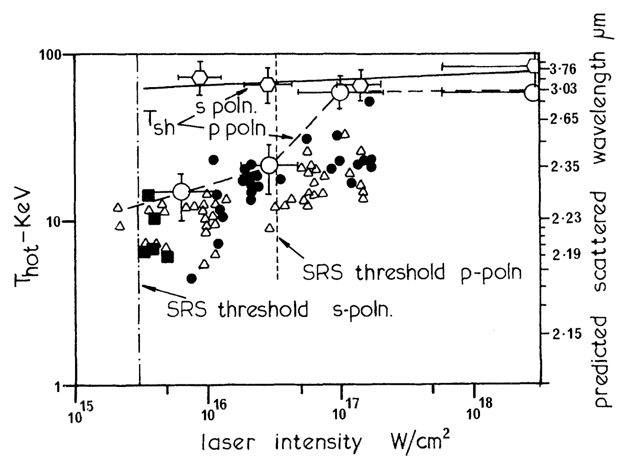

FIG. 2. Suprathermal temperature vs incident intensity as inferred from x-ray spectra. (Triangles, p polarization, 25-μm Ni foils; circles, s polarization, 25-μm Ni foils; squares, s polarization, 10-μm Al foils. The points with error bars are "superhot" temperatures.)

For s polarization the spectral peak always lay slightly to the red of the subharmonic. A red shift is expected when Raman backscattering occurs in a hot plasma, as a result of the thermal correction to the plasma dispersion relationship. This red shift can be shown to be given approximately by the expression[5]

$$\Delta\lambda/\lambda_1 = T_e/(113\text{ keV})$$

for backscattering at the maximum possible density and with λ_1 the laser wavelength.

In this expression the appropriate value for T_e is an "effective" temperature given by the average of the thermal and suprathermal temperatures weighted by the relative numbers of each population in the scattering region. Since in our conditions the underdense region would be expected to be flooded by suprathermal electrons generated by resonance absorption near the critical density surface[6] this average will be well approximated by the suprathermal temperature. To correlate the observed red shifts with temperatures the x-ray measurements in the 1–55-keV region were used to determine suprathermal temperatures as a function of laser intensity for both s and p polarizations. The results are shown in Fig. 2 as well as the value of the expected scattered wavelength calculated from the exact solution of the equations of energy and momentum conservation in a hot plasma. Clearly these values do not correspond to the experimental observations except at the SRS threshold where T_e is about 6 keV. The temperature deduced from the SRS data is the minimum able to produce scattering at the observed wavelength and so sets a minimum on the "effective" temperature in the scattering region. Thus the agreement between the SRS and x-ray–deduced temperatures at threshold indicates that the "effective" and suprathermal temperatures are equal to within the accuracy of these measurements.

The x-ray spectra in the high-energy region above 88 keV showed the presence of a "superhot" tail in conditions when Raman scattering was observed. The superhot "temperature" was estimated from data in the 150–250-keV region and the values so obtained are also plotted in Fig. 2. The insensitivity of the temperature to intensity above the scattering threshold has been predicted in computer simulations.[7]

To assist in interpretation of these results we consider the effect of temperature on Raman side scattering for different plasma densities and scattering angles by solving the energy and momentum conservation conditions for SRS with the normal photon dispersion relations and the Bohm-Gross approximation to the plasmon dispersion relationship. The results for temperatures of 6 and 20 keV are given in Figs. 3(a) and 3(b), respectively. For $T_e = 6$ keV corresponding to the measured temperature near the SRS threshold, it is clear that a wavelength of 2.19 μm can only be produced by scattering very close to the maximum possible density, i.e., the absolute instability was being observed. For $T_e = 20$ keV corresponding to the measured temperature at the max-

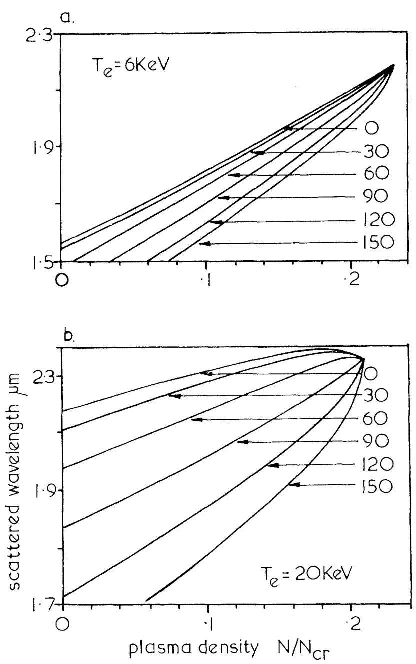

FIG. 3. Scattered wavelength vs density for a range of scattering angles and (a) $T=6$ keV, (b) $T=20$ keV.

imum intensity, the observed wavelength of 2.15 μm cannot be due to backscattering but must occur at angles greater than about 20°. To define the scattering angle more precisely a knowledge of the scattering density is required. If we assume that the density scale length seen by the scattered wave is independent of density and scattering angle (which is only applicable in rather limited conditions), SRS would be expected to occur at the highest possible plasma density (where the damping of the plasmon is lowest), implying that Raman forward scattering was being observed. This deduction is in agreement with the theoretical predictions where larger growth rates occur for forward than for backscatter in hot plasmas ($T \geqslant 10$ keV) because of the long wavelength of the plasmons produced.[7]

The observation of an additional superhot x-ray component in conditions where Raman scattering was occurring has been predicted in computer simulations[5,7] and is due to processes such as trapping of electrons in the large-amplitude plasmons produced by SRS. The energy of these electrons is a complex function of the scattering conditions through the phase velocity of the plasmons. Computer simulations indicate that the heated electron distribution produced in this way is roughly Maxwellian with a temperature equal to the wave-breaking energy of the plasmon. The superhot "temperatures" deduced from the hard-x-ray spectra of about 80 keV will then, according to this model, imply that sidescattering was being observed from densities of $\sim 0.1N_{cr}$ in the case of the highest laser intensity. Near the SRS threshold ($\simeq 3\times 10^{15}$ W/cm^2) where we have deduced that backscattering was being observed, the corresponding wave-breaking energy is ~80 keV, in reasonable agreement with the experiment.

The difference in scattering behavior between s and p polarizations of the laser beam can be explained as a result of the increased damping of the plasmons for p polarization. The relative level of Landau damping for the two cases can be determined from the relative population and temperature of the suprathermal electrons, which can be estimated from the x-ray bremsstrahlung data. The experimental data showed an increased level of resonance absorption for p polarization which was reflected in a larger number of suprathermal electrons for this polarization such that the plasmon was up to twice as heavily damped for p relative to s polarization. Such a difference may be sufficient to suppress SRS for p polarization at all but the highest laser intensities.

In conclusion, we have observed stimulated Raman scattering from plasmas produced by short, 20-psec-duration laser pulses on angled targets. The results indicate that a shift from backscatter to sidescatter occurs as the laser intensity and suprathermal plasma temperature increase, which is consistent with theoretical predictions. The onset of SRS has been correlated with the occurrence of a high-energy tail in the x-ray spectrum with an apparent temperature of around 80 keV. The SRS threshold is much higher for p-polarized incident light in comparison with s polarization, suggesting that the growth of the instability is inhibited by increased damping due to the increased numbers of suprathermal electrons generated by resonance absorption for p polarization.

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