Experimental studies of Raman scattering from foam targets using a 0.35 μm laser beam

H. Figueroa, C. Joshi, and C. E. Clayton
University of California, Los Angeles, California 90024

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Experimental studies of the forward scattered spectrum and stimulated Raman backscattering from foam targets are presented. An attempt has been made to isolate the effects of the presence of the quarter critical density on the Raman spectrum by creating plasmas with various peak plasma densities. The plasmas created had a length larger than 600 μm and a variable peak density between 0.11n_c and slightly higher than 0.25n_c. The total Raman reflectivity in the backward direction is of 0.3%, with 80% of its energy being scattered in a range of frequencies between 470 nm and 500 nm for all the targets used. The scattered intensity near the half-harmonic region shows a weak dependence on the presence of the n_c/4 density layer. The forward scattered spectrum obtained from targets with average densities between 0.11n_c and 0.22n_c shows a broadband of frequencies similar to the backscattered spectrum indicating that the forward spectrum is probably being seeded by the beating of the plasma wave from stimulated Raman backscattering (SRS-B) with the ion acoustic wave from stimulated Brillouin scattering (SBS).

I. INTRODUCTION

The current trend in laser fusion experiments is towards the use of shorter laser wavelengths and larger fusion pellets. These targets will create long scale length plasmas on the order of millimeters which will be heated mostly by inverse bremsstrahlung. However, parametric instabilities that scatter the laser light in the underdense region may be favored by the long scale lengths and efficient heating could be suppressed. One of these instabilities is the stimulated Raman scattering (SRS), characterized by the scattering of an incident electromagnetic (e.m.) wave from the high-frequency electron plasma waves. These plasma waves are excited by the ponderomotive force resulting from the beating of the incident and scattered e.m. waves at the Bohm–Gross frequency ω_{Bp}. Depending on the direction of the scattered light wave the scattering process is referred to as backscattering, SRS-B (scattering in the opposite direction of the incident e.m. wave) or strict forward scattering, SRS-F (scattering in the same direction of the incident e.m. wave). In the underdense plasma (ω_p/ω_B ≫ 1) the main difference between the two processes is that the plasma wave associated with SRS-B has k_p = 2k_0, whereas that associated with SRS-F has k_p = ω_p/c. Here ω_p is the plasma frequency and (ω_0,k_0) are the frequency and wavenumber of the pump e.m. wave. Since the growth rate is proportional to k, this difference between the back and forward scatter makes the forward scatter less competitive at intermediate densities.

Figure 1 shows, following Estabrook and Krueer, the thresholds for SRS versus the plasma scale length in the case of a linear density profile for a 0.35 μm laser and several densities for which kλ_p ≪ 1. The SRS-B threshold depends weakly on the plasma density. It can be seen that in order to overcome the threshold, very high laser intensities and/or very long plasma scale lengths are required. This condition is particularly severe for SRS-F and probably that is the reason why it has not yet been conclusively seen. Also, for density profiles decaying not faster than the exponential n = n_0 exp(-x/L), the inhomogeneous threshold for SRS-B decreases as the plasma density increases. Thus, we might expect SRS-B to be the strongest in regions close to the quarter critical density (n_c/4). However, contrary to expectations, several research groups working with 0.35, 0.53, and 1.06 μm lasers have reported a “gap” in the backscattered spectrum at densities near the quarter critical layer.

Figure 2 shows the time evolution of such a spectrum obtained by focusing a 0.35 μm, 1 nsec FWHM laser pulse on a solid flat Al target. The focal spot size was of approximately 70 μm giving an average laser intensity of 10^{15} W/
behavior of the Raman spectrum has been explained in terms of the enhanced Thomson scattering from the energetic electrons generated at \( n_e/4 \) that stream down the density gradient.\(^5\) Both explanations require the presence of the quarter critical density layer. Thus, a good way of isolating these two phenomena from those independent of the presence of the \( n_e/4 \) density layer would be to create plasmas of variable densities.

The principal motivation behind this work was then to create sufficiently long plasmas of densities less than and greater than \( n_e/4 \) and to examine the time dependent behavior of the scattered light in the back and forward directions.

### II. EXPERIMENTAL CONDITIONS

The experiments described in this paper were carried out on the Glass Development Laser (GDL) system at the National Laser User's Facility at the University of Rochester.\(^6\) The experimental setup is shown in Fig. 3. The targets used were 600 ± 100 \( \mu \text{m} \) thick, 3 mm diam foam disks of various average densities. The average cell size was on the order of 10 \( \mu \text{m} \) in diameter for a target with a density of 6.92 \times 10^{-3} \text{g/cm}^3, or an electron density of 0.25\( n_e \). Preliminary experiments on Raman scattering and more recent experiments on Brillouin scattering from such targets have been reported in the literature.\(^7,8\) The average density of the foam targets used in these experiments was varied by altering the dextran (\( \text{C}_{68}\text{H}_{120}\text{O}_{78} \)) concentration in the aqueous solution during the foam making process.\(^9\) These targets were irradiated by a tightly focused 0.35 \( \mu \text{m} \), 850 psec (FWHM) laser pulse with an average intensity of 1.5 \times 10^{15} \text{W/cm}^2. Both back and forward scattered light were spectrally and temporally resolved by using a ½ m, 30 Å resolution optical spectrograph, and a Hamamatsu C979 streak camera with a resolution of 30 psec. A calibrated Gen-Tec ED200 calorimeter with filters to absorb radiation near 0.35 \( \mu \text{m} \) was used to measure the total Raman backscattered energy. The laser

![Diagram](https://via.placeholder.com/150)
FIG. 4. Backward spectrum from a 0.22\textit{n}_e foam target. The spectrum was attenuated 10\textsuperscript{6} times.

burnthrough, as predicted by simulations,\cite{7} was verified by time resolving the transmitted portion of the green line (0.53 \textmu m) contained in the main 0.35 \textmu m beam. This assured us that the entire thickness of the foam target had been ionized with a peak plasma density less than 0.44\textit{n}_c (which is the critical density for the 0.53 \textmu m probe beam), thereby creating plasma lengths larger than 600 \textmu m during the laser pulse.

That the foam target plasmas were hundreds of microns long was confirmed independently by imaging the Raman sidescattered light in the wavelength range 520–620 nm. For targets with an average density of less than \textit{n}_c/4, these images showed emission foam plasmas that were typically 300 \textmu m long. A second calorimeter was used to measure the reflected energy of the 0.35 \textmu m line.

III. RESULTS AND DISCUSSION

Both forward and backward spectra were obtained simultaneously from foam targets designed to produce plasmas with average densities between 0.11\textit{n}_c and 0.25\textit{n}_c. The optical path of the forward scattered spectrum was physically delayed by 1.2 nsec with respect to the backscattered spectrum so that the two were clearly resolved by the streak camera. Interestingly, irrespective of the target density the backscattered spectrum from all these targets had the strongest emission in a narrow band of wavelengths between 470 nm and 500 nm, corresponding to densities of 0.05\textit{n}_c and 0.07\textit{n}_c (assuming a plasma temperature of 1 keV) as shown in Fig. 4. The spectrum shown in this figure was attenuated by 10\textsuperscript{6} and only this band of wavelengths survived such strong attenuation. Up to 0.3\% (150 mJ) of the incident energy was Raman backscattered in the solid angle subtended by the focusing lens (i.e., 5 \times 10\textsuperscript{-3} sr). This rather large level of SRS-B rules out the possibility of the spectrum being caused by collective Thomson scattering of the incident laser beam from the enhanced noise fluctuations in the plasma.

In order to observe the behavior of the less intense regions of the spectrum, an arrangement of neutral density and cutoff filters was necessary to be able to reduce the scattered intensity around 500 nm (where the emission was the most intense) to levels comparable with those at other wavelengths. An example of one such spectrum from a target with an average density of 0.22\textit{n}_c is shown in Fig. 5(a). Here the short wavelength cutoff corresponds to the limiting case of scattering from zero density for a plasma temperature of 1 keV. The apparent gap in the spectrum between 520 nm and 585 nm is not real; it is caused by the filters (Kodak Wratten no. 25) used to suppress the very intense emission in this region. Unlike in Fig. 2, we can see now the emission extending right up to 700 nm or 0.25\textit{n}_c. In fact, these targets gave long wavelength cutoffs corresponding to densities between 0.22\textit{n}_c and 0.24\textit{n}_c. No detectable half-harmonic emission was observed with these targets, the detection threshold being > 10\textsuperscript{-6} J/A/sr. When a target with an average density of 0.25\textit{n}_c was used, we readily observed the half-harmonic emission for the first time.

A typical streak record of the details of the Raman emission for this kind of target in the vicinity of \textit{n}_c/4 is shown in Fig. 5(b). The half-harmonic radiation at 700 nm on the right-hand side is seen to appear first, indicating the presence of the quarter critical layer. The typical splitting of the half-harmonic radiation is not readily resolved in this picture because of overexposure of the film. Subquarter critical radiation follows about 250 psec later, but it does not extend continuously up to the half-harmonic region in contrast to Fig. 5(a). Instead, a very distinct gap between 620 nm and

FIG. 5. Time resolved spectrum from two types of targets. (a) Forward (above) and backward (below) spectrum from a 0.22\textit{n}_c target. The lack of radiation between 520 and 585 nm in the backward spectrum is the result of using a Kodak Wratten filter #25 to attenuate the radiation below 600 nm. (b) Backscatter spectrum from a 0.25\textit{n}_c target. The Raman gap can be observed between 630 and 700 nm.
700 nm is seen, lasting only while the strong half-harmonic emission is present. This gap, caused by reduction of the scattered signal by a factor of 10–20 compared to the signal obtained with a 0.22n$_c$ target, closes within 100 ps as soon as the strong half-harmonic radiation is over. It is conjectured that this strong emission is indicative of the bulk plasma being able to support the n$_c$/4 layer, whereas the weak part that follows is probably caused by localized residues of the quarter critical density.

Figure 6 shows the time integrated backscattered intensity versus the corresponding wavelength for the 0.22n$_c$ and the 0.25n$_c$ foam targets. The plot is a composition of several laser irradiations taken with different levels of attenuation, which sampled the scattered spectrum in a topographic manner. For both types of targets the overall behavior of the backscattered spectrum is very similar. It peaks around 500 nm and then drops off on both the long and short wavelength sides very rapidly. The difference between the two spectra becomes noticeable in the region near 600 nm. In this region, the spectrum from the 0.25n$_c$ target drops faster than the one from the 0.22n$_c$ target, reaching the detection threshold near 625 nm and rising above threshold again about 700 nm. There is a difference of only a factor of 10 in intensity between the two spectra at 600 nm, for instance (the 0.25n$_c$ spectrum being less intense). Since this reduction is concurrent with the appearance of the half-harmonic radiation, one is led to speculate that the process causing the half-harmonic is in some way responsible for further quenching the Raman instability below n$_c$/4, although even in the absence of the half-harmonic radiation the Raman emission peaks at 0.06n$_c$ and falls off rapidly at higher densities. In our experiments, however, if the half-harmonic is regarded as the signature for the 2$n_\omega$ instability, then it is clear that this instability cannot entirely account for the reduced Raman levels at densities close to n$_c$/4. Also, as Fig. 5(a) indicates, the Raman spectrum extends continuously up to 700 nm but the level of scattering between 600 nm to 700 nm is on the average 10$^4$ times weaker than that at the peak. The plasma is acting as a narrow band source. Such a strong suppression of Raman cannot be attributed to either the opacity or the influence of localized regions of n$_c$/4 which may be present. These results indicate that the quenching of the SRS-B instability in density regions near n$_c$/4 may be caused by other processes that are quite independent of the presence of the n$_c$/4 layer. Further studies are underway to resolve this issue.

When foam targets with average density of 0.5n$_c$ were used, the SRS-B reflectivity dramatically decreased to 10$^{-4}$ of the incident energy. As reported earlier, this is still a factor 10–30 greater than that obtained with foil targets. Since the average density is greater than n$_c$/4, Raman presumably cannot occur in the bulk of the plasma but occurs either locally or in the front blowoff plasma.

Figure 7 shows the reflectivity of the 0.35 $\mu$m line versus the average foam density used. The width of the band indicates variation in reflectivity over many laser irradiations. It has been shown recently that the backscattered light near the 0.35 $\mu$m line is caused by Brillouin scattering (SBS)\(^4\). The backscattered levels tend to increase as the target density increases, reaching a maximum level of 9% ± 2% for target densities of 0.20n$_c$. Such a high level of SBS can influence the Raman instability, since now SRS has to occur in a rippled density profile. These levels of reflected light near 0.35 $\mu$m were always present in our experiments.

Now we discuss the forward scattered spectrum. This spectrum was obtained from targets with average densities between 0.11n$_c$ and 0.22n$_c$. A typical example of such a spectrum is shown in Fig. 8 for a target with an average density of 0.22n$_c$. The vertical line at 530 nm is the trace green line contained in the 0.35 $\mu$m main laser pulse. It serves as a fiducial line for both spectral and temporal calibration. The forward spectrum typically extends over a wide range of wavelengths.

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**FIG. 6.** Time integrated backscatter spectrum from a 0.22n$_c$ and a 0.25n$_c$ target.

**FIG. 7.** SBS reflectivity versus target density. The width of the band corresponds to variation in the scattered intensity over many laser irradiations.
range of wavelengths from about 420 nm to 620 nm, it is polarized in the same direction as the incident beam, and it is about 10^5 times weaker than the backscattered spectrum. Typically, forward scatter was observed at the peak of the laser pulse and lasted for about 100–150 psec, whereas the backscatter occurred through the laser pulse. Also, a 20% decrease in laser energy quenched the forward scatter, indicating that this spectrum is probably the result of a nonlinear process excited near threshold.

One feature common to forward and backscatter was the wavelength range over which the two spectra occurred. The scattered spectrum from the SRS-F instability might be expected to be extended to lower densities or shorter wavelengths compared to the SRS-B spectrum, since the high density plasma waves characteristic of SRS-F have little Landau damping. However, as can be seen from Fig. 1, the threshold intensity for SRS-F at 0.1 \( n_e \) is already 3.5 \( \times 10^{16} \) W/cm\(^2\) and increases to 10\(^{17}\) W/cm\(^2\) at 0.05 \( n_e \) for a plasma scale length of 600 \( \mu m \). Of course, for plasma lengths of 600 \( \mu m \) and a linear profile, the local density scale lengths are shorter than 600 \( \mu m \), and therefore, the threshold intensities at a given density will be even higher than the ones estimated above. Since the average laser intensity in these experiments was on the order of 10\(^{15}\) W/cm\(^2\), the plasma had to have either a much longer scale length to exceed the threshold for SRS-F, or the instability was being generated locally in regions where the laser intensity was much higher (possible hot spots or filaments) or the forward scatter was not growing from noise. The coincidence of the spectral range for the forward and backward spectra suggest this last possibility, that the forward scatter is not growing from noise, but that it is possibly being seeded by SRS-B. There are two ways in which this coupling can take place. First, the plasma waves created at low densities by SRS-B can move up the density gradient until the plasma wave vector becomes short enough to support scattering in the forward direction. This possibility was first considered by Koch and Williams.\(^{10}\)

Assume that a plasma wave with frequency \( \omega_{epw} \) has been excited by SRS-B at a density \( n_b/n_e \) (the subscript \( b \) stands for backscatter) in the front side of the target. This wave will move to regions of higher densities until reaching a density where the \( \omega \) and \( k \) matching conditions for the excitation of SRS-F will be satisfied. At this point, the relations defining this instability will be

\[
\omega^2_{epw} = \omega_p^2 + 3k_p^2 v_e^2 ,
\]

where

\[
k_p = k_0 - k,
\]

is the \( k \) matching condition for 1-D SRS-F and

\[
k_0 = (\omega_0^2 - \omega_p^2)^{1/2}/c, \quad k_s = \left[ (\omega_0 - \omega_{epw})^2 - \omega_p^2 \right]^{1/2}/c .
\]

Substituting relations (3) and (2) into relation (1) one gets the following expression for the density \( n_f/n_e \), at which SRS-F is being excited as a function of the frequency \( \omega_{epw} \) of the plasma wave excited by SRS-B:

\[
6 \left( \frac{v_e}{c} \right)^2 \left[ \left( 1 - \frac{n_f}{n_e} \right) \left[ 1 - \frac{\omega_{epw}}{\omega_0} \right]^2 - \frac{n_f}{n_e} \right]^{1/2} + \left( \frac{\omega_{epw}}{\omega_0} \right)^2 \left[ 1 + \left( \frac{\omega_{epw}}{\omega_0} \right)^2 - 1 - 6 \left( \frac{v_e}{c} \right)^2 \frac{n_f}{n_e} \right] = 0 .
\]

Now, \( \omega_{epw} \) can be related to the density \( n_b/n_c \) where it was excited through the \( \omega \) and \( k \) matching conditions for SRS-B. Thus, Eq. (4) relates the original density \( n_b/n_c \) to the density \( n_f/n_e \) where this wave could seed forward scatter. This relationship is plotted in Fig. 9(a). Here we have assumed a temperature of 1 keV. If the plasma were a nondissipative medium the plasma wave would travel from \( n_b/n_c \) to \( n_f/n_e \) with a slight reduction in the amplitude of the density perturbation associated with it. This can easily be seen if one substitutes the dispersion relation of the plasma wave and

![FIG. 9. SRS-F excitation from SRS-B in an inhomogeneous plasma. (a) Relationship between the density \( n_b/n_c \) where the plasma wave was originally excited through SRS-B and the density \( n_f/n_e \) where the wave has to travel to excite SRS-F. The dashed bisector is shown for reference. (b) Number of \( e \)-foldings that the plasma wave decays through Landau damping in going from \( n_b/n_e \) to \( n_f/n_e \). The horizontal axis represents the density of origin \( n_b/n_e \).](image-url)
Poisson's equation into the relation for the conservation of the energy flux. However, because of the interaction of this wave with the plasma particles, the plasma waves generated at low densities will show a strong damping as they move to their corresponding \( n_f / n_c \). If we assume a plasma with a length \( L \) and a linear density profile of the form \( n = n_p x / L \) (\( n_p \) is the peak plasma density) we can estimate the number of e-foldings \( \alpha \) that the wave will decay in going from \( n_p / n_c \) to \( n_f / n_c \). In this case, \( \alpha \) will be given by \( \alpha = \frac{1}{\lambda} = \frac{e^{-x}}{\lambda} \) where \( \lambda \) is the spatial Landau damping given by \( \lambda = \frac{(1/2 \pi) \omega_p}{v_g \omega_L} \) is the temporal Landau damping, and \( v_g \) is the group velocity of the plasma wave. Figure 9(b) shows the number of e-foldings versus the original density \( n_p / n_c \). Only those plasma waves generated at densities higher than 0.07\( n_c \) will have a chance of reaching the necessary density layer to excite SRS-F. Waves generated below 0.05\( n_c \) will be heavily Landau damped. This means that the forward scattered spectrum will have a short wavelength cutoff around 490 nm. We see, however, that the forward spectrum extends to regions of shorter wavelength. This indicates that it is unlikely that this process is solely responsible for the presence of the forward scattered spectrum.

The other possibility for the observed forward scatter is through the coupling of SRS-B with SBS. This coupling occurs between the large \( k \) plasma wave of SRS-B and the ion acoustic wave of SBS with wave vector \( k_i \). The result of this coupling is the generation of plasma wave modes with wave vectors \( k_p \) and \( k_i \) and frequency \( \omega_p + n \omega_i \sim \omega_p + n \omega_i \). The small \( k \) mode with wave vector \( k_p - k_i \) will propagate in the opposite direction of the incident laser beam since \( k_i > k_p \). The effects of this coupling have been represented in Figs. 10(a) and 10(b). The solid curve in Fig. 10(a) represents the dispersion relation of a plasma wave in the absence of a ripple in terms of normalized dimensions. These normalized dimensions have been chosen in order to ease the comparison with the case when there is a ripple present. Here \( V \) is proportional to the electron thermal velocity \( V_T \), and \( k_i \) is the wave vector of a possible ripple. The dotted curves represent the dispersion relation of the spatial harmonics of the plasma wave that would exist in the presence of a stationary ripple with wave vector \( k_i \). These spatial harmonics would have the same frequency as the original plasma wave but their wavenumbers displaced by multiple integers of \( k_i \). One assumes that the density ripple is produced by the presence of SBS, then \( k_i = 2k_0 \) and the plasma wave from SRS-B will be located in the region limited by the points (1) and (2). The exact location of the plasma wave in this region will depend on the plasma density. The point (1) corresponds to zero density (\( k_p = 2k_0 \) or \( q = 2 \)), and the point (2) corresponds to the quarter critical density (\( k_p = k_0 \) or \( q = 1 \)). In the presence of a ripple, one should expect a strong interaction at the points where the dispersion relations of the various modes intercept each other. The interaction between these modes is plotted in Fig. 10(b). This plot is a numerical solution of the dispersion relation of a plasma wave in the presence of a stationary ripple given by Kaw et al. [see Eq. (17) in Ref. 11]. The chosen value for the parameter \( h^2 \) was 2. We see that now the original dispersion relation does not extend continuously from \( \alpha^2 = 0 \) to \( \alpha^2 = 5 \) as before, but instead, it breaks up at \( \alpha^2 = n^2 \), where \( n = 1, 2, \ldots \), creating forbidden bands of frequencies whose width depends on the value of the parameter \( h \). Waves with frequencies inside these bands will be damped. Outside these bands, the waves will be propagating modes.

A plasma wave with normalized wave vector \( q_0 \) excited by SRS-B will interact with the density ripple created by SBS to generate a large wave vector plasma wave \( q_1 \) and a small wave vector plasma wave \( q_2 \) which propagates in the opposite direction of the incident laser beam. If this small \( k \) vector is excited in the front half side of the plasma, as shown in Fig. 11, then it will propagate to lower densities until reaching a turning point. Notice from Fig. 10(b) that, for the spatial modes with small wave vectors \( q_2 \), their wave vector decreases as the mode moves to lower densities. This is in contrast to the usual case where the wave vector of a plasma wave increases as the density decreases.

Once the small \( k \) wave has been reflected to the forward direction, it will pass through the original density layer...
where it was generated, becoming a source of scatter in the forward direction. The result is that a particular density layer could scatter light at the same frequency in both the forward and the backward directions. The situation is in contrast to the case where SRS-F and SRS-B are excited independently. In this case, the scattering in the backward direction is red shifted with respect to the scattering in the forward direction because of the fact that the plasma wave from SRS-B has a larger wave vector than the plasma wave from SRS-F. Thus, in an inhomogeneous plasma, the presence of a rippled density will make possible the scattering in both the forward and backward direction in the same range of frequencies. This type of behavior was observed in these experiments as shown in Fig. 5(a). Thus, it is possible that the observed forward scattered spectrum is not being excited from noise but from the beating of the large $k$ plasma wave from SRS-B with the ion acoustic wave from SBS.

IV. CONCLUSIONS

In this paper we have presented time resolved studies of forward and backward scattered spectra from foam targets of various average densities. The main findings of our work are the following.

1. For targets with average density less than $0.25n_e$, up to 0.3% of the incident energy is backscattered within a solid angle of $5 \times 10^{-3}$ sr. These high reflectivities suggest that Raman scattering is operative in these long foam target plasmas rather than just enhanced Thomson scattering of the laser light.

2. When the foam density is increased to $0.5n_e$, the reflected Raman light drops to about $10^{-4}$ of the incident since the instability can no longer occur in the bulk of the plasma.

3. When targets with an average density less than $0.22n_e$ are used, no detectable half-harmonic emission is observed. In such targets, most of the Raman emission occurs in a range of frequencies between 470 nm and 500 nm.

4. When targets with average density slightly greater than $n_e/4$ are used, the half-harmonic radiation is detected for the first time. Concurrent to this, the Raman emission between 600 nm and 700 nm is further reduced by a factor of 10–20. When the half-harmonic emission ceases there is an abrupt increase of the scattered signal by the same factor in this range of frequencies near 700 nm. The peak emission still comes from around 500 nm.

5. Weak, broadband forward scatter is observed only when targets with average density less than $n_e/4$ are used. This emission occurs around the peak of the laser pulse and lasts for $< 150$ psec.

6. The forward scattered spectrum covers the same range of frequencies as the backscattered spectrum and disappears with a 20% reduction of the laser intensity. It is suggested that the possibility exists that the forward emission is being seeded by SRS-B. The most likely way in which this excitation can occur is through the coupling of the plasma wave from SRS-B with the ion acoustic wave from SBS.

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