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Investigation of Stimulated Raman Scattering Using a Short-Pulse Diffraction Limited Laser Beam near the Instability Threshold

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Abstract:

Short pulse laser plasma interaction experiments using diffraction limited beams provide an excellent platform to investigate the fundamental physics of Stimulated Raman Scattering. Detailed understanding of these laser plasma instabilities impacts the current inertial confinement fusion ignition designs and could potentially impact fast ignition when higher energy lasers are used with longer pulse durations (> 1 kJ and > 1 ps). Using short laser pulses, experiments can be modeled over the entire interaction time of the laser using particle-in-cell codes to validate our understanding quantitatively. Experiments have been conducted at the Trident laser facility and the LULI (Laboratoire pour l'Utilisation des Lasers Intenses) to investigate stimulated Raman scattering near the threshold of the instability using 527 nm and 1059 nm laser light respectively with 1.5 – 3.0 ps pulses. In both experiments, the interaction beam was focused into a pre-ionized He gas-jet plasma. Measurements of the reflectivity as a function of intensity and $k\lambda_D$ were completed at the Trident laser facility. At LULI, a 300 fs Thomson scattering probe is used to directly measure the density fluctuations of the driven electron plasma and ion acoustic waves. Work is currently underway comparing the results of the experiments with simulations using the VPIC [K. J. Bowers, *et al.*, Phys. Plasmas, **15** 055703 (2008)] particle-in-cell code. Details of the experimental results are presented in this manuscript.

I Introduction

Understanding the fundamental physics of laser matter interactions in underdense plasmas remains a challenge. While much progress has been made, no single predictive tool exists that can cover any given set of plasma conditions. The lack of such a tool presents a challenge for designing laser based high energy density experiments. To improve current predictive tools, reduced models for laser plasma interactions in different regions of parameter space must be developed and validated. Since it is challenging to perform experiments in all parameter regimes, a good approach utilizes particle-in-cell or Vlasov simulations to construct the reduced models. However, these simulation codes require validation to ensure the accuracy of the models.

Recent progress in computational and experimental capabilities is encouraging, and good prospects are on the horizon to obtain the necessary physical understanding to formulate models that predict laser plasma instability behavior. Computers have now attained Petaflop speeds,[1] enabling large two and three dimensional simulations that should provide more realistic comparisons with experiments. Advances such as the deformable mirror provide a method for reproducibly generating diffraction limited laser focal spots,[2] the best configuration for comparison of experiments with simulations due to the high degree of experimental characterization. Compared with previous efforts to create a diffraction-limited Single-hot-spot,[3] which required the removal of the amplifier glass not used in the beam line to maintain a uniform laser phase front, deformable mirrors reduce setup time significantly and provide more control over changing experimental conditions. Short pulse technology such as Chirped Pulse Amplification[4] is now a common practice and mJ level short-pulse laser beam lines can be easily constructed to fit into different experimental configurations. Each of these technologies enables better experiments to be conducted under conditions closer to ideal for investigating and modeling laser plasma interactions.

One laser plasma instability of interest is Stimulated Raman Scattering (SRS), where the incident laser light resonantly couples with an electron plasma wave and a backscattered light wave. For SRS, one regime of great interest is the strongly damped regime, where $k\lambda_D > 0.3$. In this regime, the phase speed of the electron plasma wave (EPS) driven by the SRS becomes comparable to the electron thermal speed, and the plasma wave is expected to be strongly damped. In this case, however, the electron plasma wave traps electrons in its electrostatic potential wells leading to a reduction in damping and other nonlinear effects.[5,6,7] The interaction of the trapped particles with the electrostatic EPW is thought to lead to effects such as bending of the EPW wave fronts[8,9] and trapped particle self-focusing[10] that in turn affect the saturation of SRS. Accurate modeling of these phenomena are important for developing a predictive capability for SRS, and would be valuable for designing laser-based high energy density plasma experiments including inertial confinement fusion.[11]

To investigate SRS in the high $k\lambda_D$ regime, experiments have been conducted at two different laser facilities, the Trident[12] and the LULI 100 TW laser facility. Both sets of experiments use picosecond laser pulses to drive laser-plasma instabilities. With short laser pulses, < 3 ps, experimental measurements can be directly compared with simulations over the same duration to validate the simulation code. Using multiple facilities for experiments provides a broader set of data with different laser wavelengths and measurements of different SRS properties: reflectivity of the interaction beam in one case, and density fluctuations of the electron plasma wave via time resolved Thomson scattering in the other. It is hoped that the broader, better-defined experimental approach taken here will lead to better models for SRS. This manuscript presents experimental results obtained at both the Trident and the LULI facilities.

II. Experimental setup

Details of the laser plasma interaction experimental setup for the Trident [12,13] and the LULI[14,15] laser facility have been described in previous work. However, a comparison of the basic differences between the two is warranted. Both sets of experiments are conducted using preformed helium gas-jet plasmas prior to firing the interaction beam. Experiments at the Trident laser facility use a frequency doubled ~2-3 ps, ~ 527-nm interaction laser pulse with 7 – 40 mJs of energy. During conversion, the KDP crystal operates in a saturated regime to maintain the pulse length of the 1ω beam which an autocorrelator measures on each shot. The LULI experiments use a 1059-nm interaction beam with a ~1.5 ps pulse length. A major difference between the two experiments is the diagnostics. At Trident, the experimental diagnostics measure the backscattered light energy and spectra to characterize the laser reflectivity. At LULI, a 300 fs 3ω (353 nm) Thomson scattering system measures the temporally resolved density fluctuations of the electron plasma wave.[14,15] The different experimental approaches increase the constraints for validating models of SRS by providing a larger data set with different interaction conditions and measurements of different SRS parameters.

III High $k\lambda_D$ measurements of SRS at LULI

Thomson scattering spectra from the SRS EPW density fluctuations are shown in figure 1 for different plasma densities. Varying the pressure of the gas-jet sets the peak density in the center of the plasma. The data for each measurement shows the wavelength dependence (horizontal axis) as a function of space (vertical axis). Two features stand out from the series of data. At higher plasma densities, the EPW spectra not only peak near the focal point, $z = 0$, but also extend towards shorter wavelengths and lower densities, consistent with a density profile in the pre-formed gas-jet plasma. From the spectra, one can see that the intensity of the peak in the data decreases with decreasing density or higher $k\lambda_D$. This is qualitatively expected as the EPW damping rate increases. To quantify the data, a region of 10 pixels by 10 pixels centered on the peak reflectivity is integrated to get the total signal, which is related to the integrated density fluctuations due to the EPW in the Thomson scattering volume. The region corresponds to ~50 microns along the spatial axis and 0.98 nm along the wavelength axis. Figure 2a, shows the density scaling of the time resolved Thomson scattered light signal near the peak of the interaction beam pulse ($t_o = -.7$ ps) as a function of density where decreasing density relates to increasing $k\lambda_D$. The data show that the EPW amplitude decreases with increasing $k\lambda_D$ with an interaction laser intensity of $I_o \sim 2.3\times10^{16}$ W/cm^2. The results are consistent with reflectivity measurements at Trident with comparable intensities,[13] although the 1ω light has a higher value $I\lambda^2$. In addition to the density scaling, an intensity scaling is also shown in figure 2b at a density of 0.016 n/n_c where n_c is for 1ω light. The data show little dependence on intensity in this high $k\lambda_D$ regime. This is consistent with the Trident experiments that show a saturation in reflectivity and a plateau with increasing intensity[13] and is consistent with VPIC simulations.[16,17] Future efforts will carefully compare all of these results to 2-D and 3-D PIC models of these experiments.

IV. Spectral measurements of SRS backscatter at Trident

In addition to the SRS backscattered energy measurements made at Trident, the spectra of the backscattered light have also been measured. Figure 3 shows an example of three such spectra for the lowest laser intensities shot with the short pulse. Integrated plots of the spectra in figure 4 show two features of the spectra, a broadening and a shift in wavelength with increasing interaction beam intensity. The wavelength shift towards shorter wavelength is consistent with the simple picture of a nonlinear frequency shift due to electron trapping. That is to say, with higher intensities the amplitude of the EPW grows to larger values, leading to more trapped electrons and a larger frequency shift until the nonlinear effects of electron trapping saturate the growth of the SRS process. Unfortunately, an estimate of the expected frequency shift is difficult to establish. Simulations suggest that SRS occurs in short pulses, ~250 fs.[16] Thus, only a lower bound can be determined using the average reflectivity to estimate the EPW amplitude. In preliminary simulations, the frequency shifts are consistent with but smaller than the calculated values for simulation intensities near the onset. Independent measurements of the plasma density and temperature using the plasma formation beam as a Thomson scattering probe show that the gas-jet plasma conditions are consistent from shot-to-shot, although the resolution of the Thomson scattering probe is only slightly smaller than the spread in frequency shift. This suggests that a plasma mechanism such as electron trapping is responsible for the shift in wavelength not the plasma conditions. If these results can be confirmed, they would constitute one of the first direct measurements of a nonlinear frequency shift due to electron trapping.

The broadening of the spectra poses a more challenging problem. As with previous experimental measurements of SRS with Thomson scattering,[18,19] the temporal behavior of the SRS pulses is faster than the temporal resolution of the detection system. Thus, it could lead to artificial broadening of the measured reflected light as a result of the temporal integration. However, the previously measured spectra showed an asymmetric broadening towards lower electrostatic frequencies consistent with electron trapping.[18,19] In the present case, the broadening appears to be symmetric about the shifted frequency. Such broadening could be due to effects such as self-phase or cross-phase modulation of the backscattered light in the plasma. In which case, the broadening could represent a frequency shift due to electron trapping and a frequency broadening of the backscattered light via one of the suggested processes. At higher intensities, the backscattered light produces even greater broadening with periodic structure in the spectra. Examination of these spectra is underway to determine the mechanism responsible.

V. Conclusions

Data from experiments at both the Trident and the LULI laser facilities have been presented. The data from these experiments will be compared with the VPIC[1,9,8,17] particle-in-cell code for validation and subsequently for probing the behavior of SRS in the high $k\lambda_D$ regime. Data from both experiments appear to be consistent, but further analysis will attempt to quantify the results and determine if they are consistent with simulations and/or theory. Using both sets of data imposes more constraint on the simulations hopefully leading to a more robust validation and understanding of SRS. It should be noted that even though the work here focuses on SRS for high energy density laser plasmas, a similar approach for other laser plasma instabilities such as stimulated Brillouin scattering and two plasmon decay could impact other important areas of research such as fast ignition.[20] Current experiments to accelerate charged particles which could be used for fast ignition use sub-ps laser pulses. As the laser energy is increased to the kJ level required for fast ignition, the pulse lengths also increase changing from a regime in which the pulse length is too short for SBS to grow to one in which it can.[21]

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References

[1] Bowers, K. J. *et al.* submitted to Proc. 2008 ACM/IEEE Conf. Supercomputing (2008).

[2] Wattellier, B., *et al.*, Journal of the Optical Society of America B, **20** 1632 (2003).

[3] Montgomery, D.S., *et al.*, Laser and Particle Beams, **17** 349 (1999).

[4] Strickland, D. and Mourou, G., Optical Communication, **56** 219 (1985).

[5] Morales, G.J. and O'Neil, T.M., Phys. Rev. Lett. (USA), **28** 417 (1972).

[6] Manheimer, W.M. and Flynn, R.W., Physics of Fluids, **14** 2393 (1971).

[7] Dewar, R.L., Physics of Fluids, **15** 712 (1972).

[8] Yin, L., *et al.* Phys. Rev. Lett. **99**, 265004 (2007).

[9] Yin, L., *et al.* Physics of Plasmas, **15** 013109 (2008).

[10] Rose, H. A. and Yin, L., Physics of Plasmas, 15 042311 (2008).

[11] Lindl, J. Physics of Plasmas, **2** 3933 (1995).

[12] Moncur, N.K., *et al.*, Appl. Opt. (USA), **34** 4274 (1995).

[13] Kline, J. L., *et al.* Journal of Physics: Conference Series **112** 022042 (2008).

[14] Rousseax, C., *et al.*, Journal de Physique IV (Proceedings), **133** 259 (2006).

[15] Rousseaux, C., *et al.*, Physical Review Letters, **97** 015001 (2006).

[16] Yin, L. *et al.* Journal of Physics: Conference Series **112** 022033 (2008).

[17] Bowers, K.J., et al., Physics of Plasmas, 15 055703 (2008).

[18] Kline, J.L., *et al.*, Physical Review Letters, **94** 175003 (2005).

[19] Kline, J. L. and Montgomery, D. S., Laser and Particle Beams, **23** 27 (2005).

[20] Tabak, M., *et al.*, Physics of Plasmas, **1** 1626 (1994).

[21] Cobble, J. A., Johnson, R. P., and Mason, R. J., Physics of Plasmas, **4** 3006 (1997).

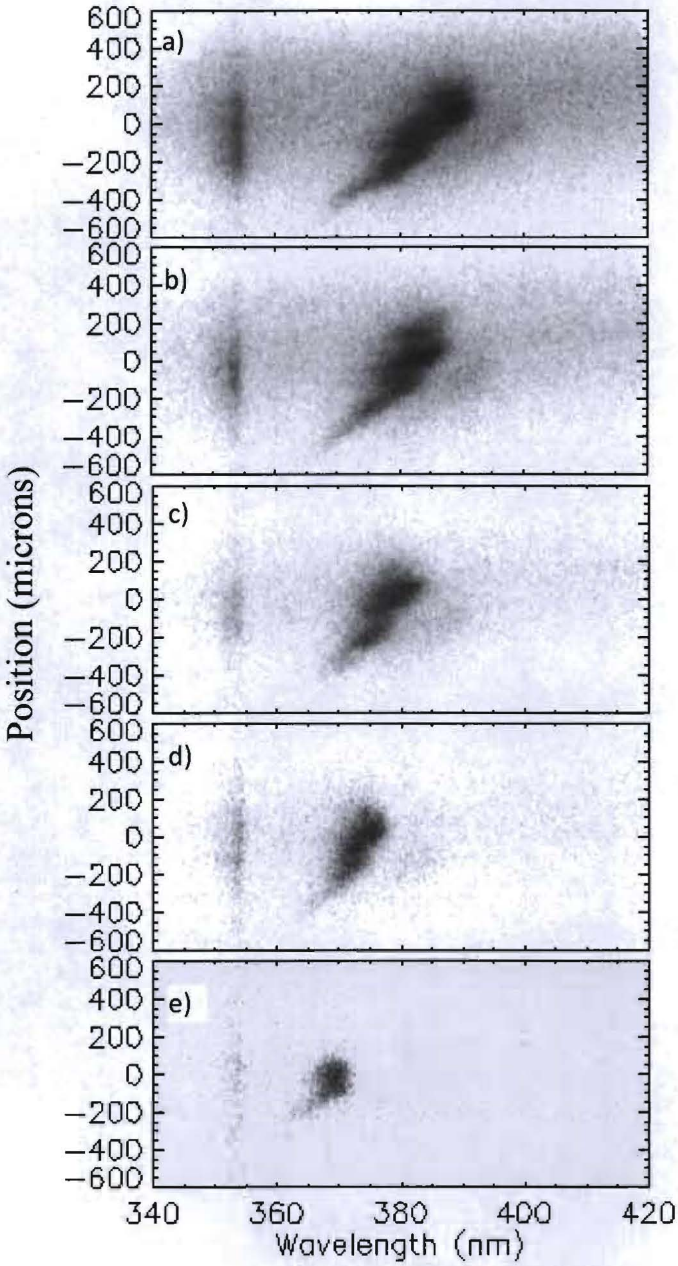
Figure Captions

Figure 1: Thomson scattering spectra for six different gas-jet pressures with peak densities n/n_c of a) 0.070, b) 0.053, c) 0.040, d) 0.026, and e) 0.012, assuming an electron temperature of 300 eV.

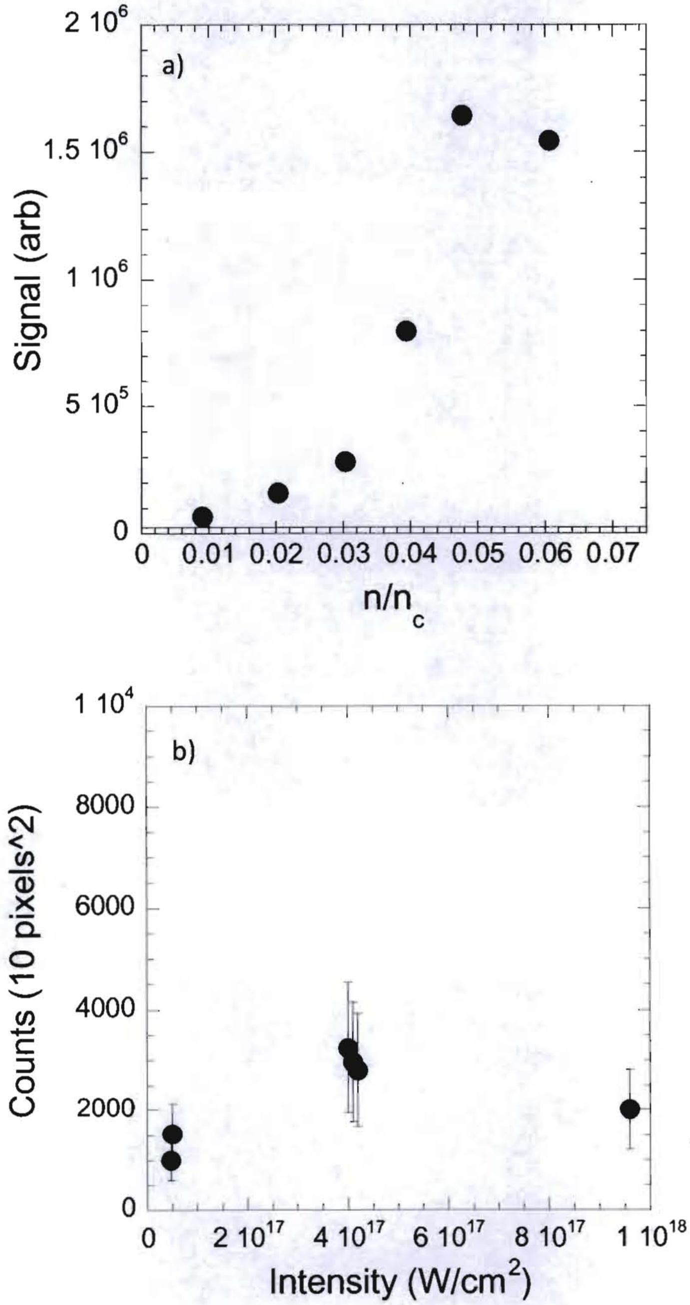
Figure 2: Thomson scattering signal from SRS EPW integrated over space, ~50 microns, and wavelength, 0.9 nm, as a function of a) peak density for fixed intensity (~ 2.3×10^{16} W/cm^2) and b) interaction beam intensity at fixed density ($n/n_c \sim 0.012$, high $k\lambda_D$).

Figure 3: SRS backscattered light spectra from the Trident experiments for three different interaction beam intensities a) 2.6×10^{16} W/cm^2, b) 2.4×10^{16} W/cm^2, and c) 1.6×10^{16} W/cm^2.

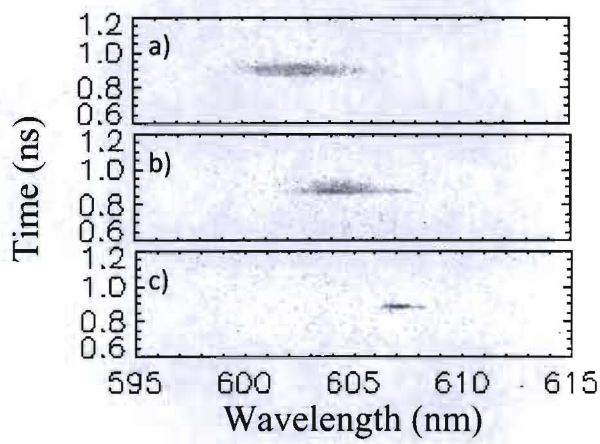
Figure 4: Plots of the integrated backscattered spectra as a function of wavelength.



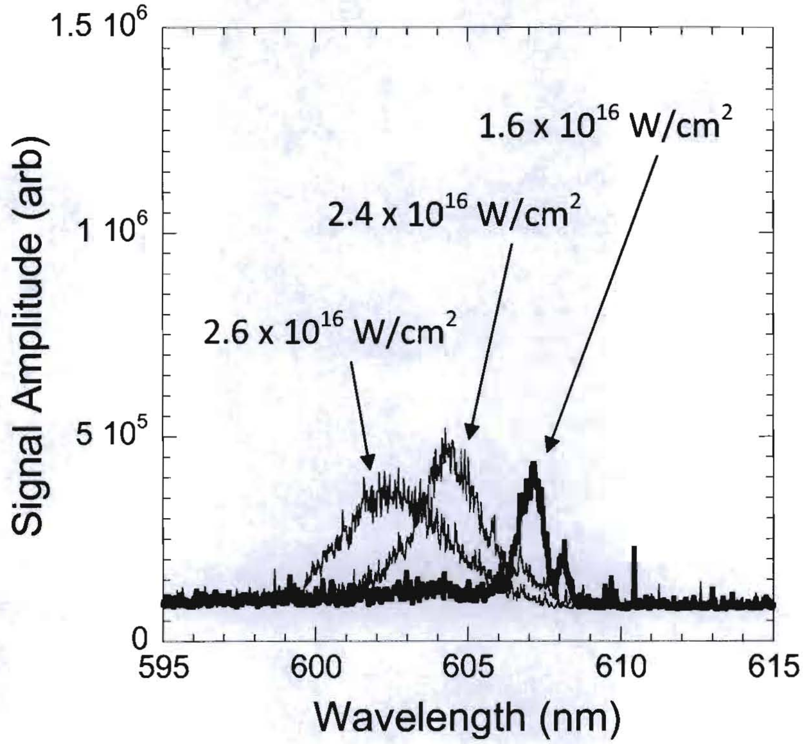
a)
b)
c)
d)
e)
Position (microns)
Wavelength (nm)
600
400
200
0
−200
−400
−600
340
360
380
400
420



a)
Signal (arb)
n/n_c
b)
Counts (10 pixels^2)
Intensity (W/cm^2)



Time (ns)
a)
b)
c)
1.2
1.0
0.8
0.6
595
600
605
610
615
Wavelength (nm)



1.5 10^6
1 10^6
5 10^5
0
595
600
605
610
615
Wavelength (nm)
Signal Amplitude (arb)
1.6 x 10^16 W/cm^2
2.4 x 10^16 W/cm^2
2.6 x 10^16 W/cm^2