CHARACTERIZATION OF PLASMA AND LASER CONDITIONS FOR SINGLE HOT SPOT INTERACTION EXPERIMENTS

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Characterization of plasma and laser conditions for single hot spot interaction experiments


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The LANL TRIDENT laser system is being used for fundamental experiments which study the interaction of self-focusing, stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) in a single (diffraction limited) laser hot spot in order to better understand the coupling between these plasma instabilities. The diffraction limited beam mimics a single hot spot found in speckle distributions that are typical of random or kinoform phase plate (RPP or KPP) smoothing. A long scale length, hot plasma (1 mm, 0.5 keV) is created by a separate heater beam, and the single hot spot beam is used to drive parametric instabilities. The focal plane distribution and wavefront of the single hot spot beam are characterized, and the intensity of the single hot spot can be varied between $10^{14}$ - $10^{16}$ W/cm$^2$. The plasma density, temperature, and flow profiles are measured using gated imaging spectroscopy of collective Thomson scattering. Results of the laser and plasma characterization, and initial results of backscattered SRS, SBS, and beam steering in a flowing plasma are presented.

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1. Introduction

Parametric instabilities such as stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), and self-focusing are of importance to laser fusion research because they may significantly reduce the laser-plasma coupling efficiency in ignition scale targets, and may also cause capsule preheat due to fast electrons generated by these processes. For indirect drive (hohlraum) ignition target designs, these instabilities may also affect implosion symmetry by significantly altering the laser distribution at the hohlraum wall by mechanisms such as beam steering, beam spraying, and crossed-beam energy transfer.

Much progress in understanding the onset, saturation, and interplay between these instabilities has occurred in recent years. This may be attributed in part to the use of beam smoothing techniques such as random or kinoform phase plates (RPP or KPP), which smooth the large-scale spatial structure often found in high power lasers. The focal plane intensity distribution created by a RPP or KPP produces an ensemble of fine-scale hot spots which can be described by speckle statistics, and world-wide use of such techniques has now provided a common description for laser conditions. The characteristic size of each speckle (hot spot) is the diffraction limit of the focusing optic, and the speckle width and length are \( d_s \sim f \lambda_0 \) and \( \ell_s \sim 8 f^2 \lambda_0 \) respectively, where \( f \) is the focal length to diameter ratio, and \( \lambda_0 \) is the laser wavelength. Recent work has demonstrated the importance of laser hot spots in predicting the onset behavior for SBS and SRS (Rose & Dubois 1994, Fernández et al. 1995, Watt et al. 1996, Drake et al. 1996, Fernández et al. 1997).

In a speckle distribution with an ensemble of hot spots, the instabilities can be interdependent, and issues such as seeding and coupling of instabilities between hot spots arises, and complicates our understanding of these processes. Further, since there is a distribution of laser intensities, SRS, SBS, or self-focusing can all occur to some extent.
throughout the laser-plasma volume, depending on the local hot spot intensities. Most experiments measure spatially averaged SRS or SBS reflectivity, and the local reflectivity within hot spots can be much higher (Baldis et al. 1998). The smallest fundamental volume where the instabilities occur is within a single hot spot volume. Therefore, studying the coupling and saturation of instabilities in a single laser hot spot is a key first step to quantitative understanding of these processes in realistic (RPP or KPP smoothed) laser beams.

We report an initial set of experiments using a single hot spot (diffraction limited) laser to interact with a well-characterized, preformed plasma. The laser wavefront and focal plane intensity profile are measured, and are found to be nearly diffraction limited. The plasma density, temperature, and velocity profiles are measured using imaging Thomson scattering. Initial experimental results from the single hot spot interaction show evidence for beam steering due to transverse flow. SRS backscattering from these experiments show a very narrow spectrum (~ 4 nm) in certain low density regimes, whereas higher density experiments show a broader, more complex spectrum. Finally, evidence for SRS and SBS anti-correlation is given.

2. Laser Characterization

The experiments were carried out at the Los Alamos National Laboratory using the TRIDENT laser facility (Moncur et al. 1995). One of the three 527 nm laser beams was used to create and heat a large plasma, and will be discussed later in Sec. 3.1. The single hot spot (diffraction limited) laser was produced by configuring a second, lower energy laser to generate minimal wavefront distortion by using only rod amplifiers, by paying special attention to details such as mounting and alignment of certain optics, and by minimizing air turbulence throughout the beam path. The final beam diameter was kept at 36 mm in order to achieve good second harmonic conversion efficiency, and to utilize very high quality small optics. A lateral shearing interferometer was used to measure the relative
wavefront quality of the 527 nm beam. Fringe analysis shows that the root-mean-square wavefront distortion is $\sim 0.3 \lambda_0$ over 90% of the aperture, and the wavefront is fairly reproducible from shot to shot.

A three-element, air-spaced achromatic lens (50 mm diameter, 250 mm focal length) was used to focus the interaction beam. The lens was mounted in the vacuum chamber, so a high quality debris shield was placed after the lens. The focal plane intensity distribution was measured in situ using a high quality 40X microscope objective and a CCD camera. Figure 1a shows an image of the hot spot laser at best focus, and an azimuthally averaged radial profile is also shown in Fig. 1b. The data shows a nearly classic Airy pattern for a circular aperture. Superposed is the theoretical radial profile for diffraction from a circular aperture at $f/7$, and is in excellent agreement with the measured results. The focal spot deviates somewhat from perfect diffraction limit in that there is more energy beyond the first Airy minima.

The single hot spot laser has a FWHM of $3.8 \pm 0.15 \mu m$, and produces a peak intensity of $1.0 \times 10^{16} W/cm^2$ for a nominal energy of 0.8 J (max), and a 200 psec gaussian pulse width. The laser power output is kept roughly constant to maintain beam quality, and the peak intensity can be adjusted between $\sim 10^{14} - 10^{16} W/cm^2$ using polished, calibrated neutral density filters.

3. Experimental Setup

3.1 Beam Configuration

The plasma is created using a 527 nm laser beam focused with a f/6 aspheric lens and a “stripline” RPP which produces a line focus that is $\sim 100 \times 1000 \mu m$ (Bauer et al. 1995). The laser energy is $160 \pm 10 J$ in a 1.3 nsec square pulse with 100 psec rising and falling edges. The laser power is constant within $\pm 10\%$ over the flat part of the pulse. The heater beam illuminates a 1 mm diameter target at normal incidence, and the line focus is in the horizontal plane. The single hot spot beam is incident $90^\circ$ to the heater beam, and is
offset parallel to the target surface between 100 - 400 μm to vary the plasma density. The 200 psec interaction beam is delayed by $1.8 \pm 0.05$ nsec with respect to the beginning of the heater beam, so that the heater laser will be off before the peak of the interaction pulse.

3.2 Diagnostic Configuration

A high quality dielectric beam splitter was placed in the interaction beam, and was used to sample the incident beam energy for each shot, and the reflected light from the plasma scattering processes. The reflected light from direct backscatter was collimated over the wavelength range of 527 - 1054 nm by the achromatic lens used to focus the laser in the plasma. The backscattered light was split further, and sent to two photodiodes filtered for SRS and SBS, and were recorded using fast transient digitizers. The photodiodes have a measured rise-time of ~ 200 psec, and were extensively calibrated. A 0.25-m spectrometer coupled to an optical streak camera was used to measure the time-resolved spectra from SRS, and the unresolved spectral line from SBS, and has a spectral and temporal resolution of 2 nm and 20 psec. Future experiments will use an additional high-resolution streaked spectrometer to measure the SBS spectra.

The transmitted beam angular distribution for the interaction laser was measured using a diffuser screen imaged onto a time-integrated CCD camera filtered for 527 ± 5 nm. The camera system was absolutely calibrated so that transmitted energy measurements can be obtained.

A 5 cm focal length f/6 achromatic was used to collect Thomson scattering signals at 90° from the heater beam. The target was imaged with 13X magnification onto the slit of a 0.5-m imaging spectrometer, and the image was oriented on the slit so as to image the plasma expansion normal to the surface of the target. The output of the spectrometer was coupled to a gated optical camera with ~ 120 psec framing, and the image was recorded using a CCD camera. The spectrometer was operated in either low or high dispersion to measure Thomson scattered signals from electron plasma waves (EPWs) or ion acoustic...
waves (IAWs) respectively. The original target position was recorded on the imaging spectrometer prior to each shot, and served as an absolute spatial reference. A schematic of the laser beam and diagnostic configuration is shown in Fig. 2.

3.3 Targets

The targets used were 1 mm diameter disks, and were either $6.5 \pm 0.1 \mu m$ thick CH, or $2.0 \pm 0.1 \mu m$ thick Al. The targets were supported on a glass stalk. Target alignment accuracy was $\pm 1^\circ$ in rotation, and $\pm 25 \mu m$ positioning along the direction of the heater beam.

4. Plasma Characterization

The plasma was characterized using collective Thomson scattering from the heater beam, and spatial profiles of the EPWs or IAWs were measured using gated imaging spectroscopy. A schematic of the Thomson scattering measurement is given in Fig. 3a, and shows the slit orientation with respect to the target image. The sampled scattering volume at the target plane was $\sim 10 \mu m$ wide (slit width), and $\sim 100 \mu m$ line-of-sight through the plasma. The spatial resolution of the imaging spectrometer was $\sim 25 \mu m$. Scattering from EPWs was examined to obtain measurements of the plasma density profile. Using the EPW and scattered light dispersion relations, the scattered light goes from long wavelength near the target surface to shorter wavelength farther away as the density goes from high to low, as indicated in Fig. 3a. A measurement of scattering from EPWs versus distance from target is shown in Fig. 3b near the end of the heater pulse ($t = 1.0 \pm 0.1 \ ns$) for a $6.5 \mu m$ thick CH target. Spectra at a given distance from the target surface show a cutoff at a maximum wavelength which corresponds to the peak density at that position. A density profile is obtained from the data by finding the edge of the maximum wavelength cutoff versus position, and assumes $T_e = 0.5 \pm 0.1 \ keV$ in the dispersion relations. A plot of
electron density $n_e/n_{cr}$ versus position from target surface is shown in Fig. 3c, where $n_{cr}$ is the critical density ($n_{cr} = 4 \times 10^{21}$ cm$^{-3}$ for 527 nm light).

Collective Thomson scattering from IAWs is used to measure profiles of electron temperature, ion temperature, and flow velocity. The scattering geometry determines the wavenumber of the IAWs being probed, and is given by $k_{IAW} = 2k_0 \sin(\theta/2)$, where $k_0 = 2\pi/\lambda_0$ is the laser wavenumber, and $\theta$ is the angle between the incident and scattered light.

The dispersion relations show that the separation between the upshifted and downshifted IAWs is a function of $T_e$, and the flow velocity produces a Doppler shift of the entire spectrum, as indicated in Fig. 3a. A measurement of scattering from IAWs versus distance is shown in Fig. 3d near the end of the heater pulse ($t = 1.0 \pm 0.1$ ns) for a 6.5 $\mu$m thick CH target. The separation between the upshifted and downshifted waves is clearly resolved, and the entire spectrum becomes more Doppler shifted further from the target surface. A spectral lineout taken at $z = 300 \pm 25$ $\mu$m is shown in Fig. 3e. The spectrum is asymmetric, and indicates a relative drift between electrons and ions, and is due either to transport effects, or to stimulated processes. The separation between peaks is mostly dependent on electron temperature $T_e$, and weakly dependent on ion temperature $T_i$. The width of each peak and the contrast between the center of the spectrum and the peak heights is dependent on $T_i$, and the overall Doppler shift from $\lambda_0$ depends on flow velocity. The entire spectrum is fitted using the Thomson scattering form factor for multi-ion species plasmas (Evans 1970), and is used to determine $T_e$, $T_i$ at that position. The flow velocity $v_z$ is determined assuming that the dominate flow component is mostly parallel to the laser beam. Figure 4 shows the experimentally measured profiles of $n_e/n_{cr}$, $T_e$, $T_i$, and $v_z$ at $t = 1.0 \pm 0.1$ nsec for a 6.5 $\mu$m thick CH target using the Thomson scatter data shown in Figs. 3b and 3d. Calculations of the plasma profiles using the 2-D hydrodynamics code LASNEX (Zimmerman & Krue 1975) are also shown as lines in Fig. 4, and are in rough
agreement with the measurements. These data can be used to further refine the simulations for the experiments.

5. Single Hot Spot Interaction

5.1 Theoretical Considerations

For a single laser hot spot, the peak intensity is well-defined, and allows the interaction to occur in regimes where the instabilities can operate alone, or in various combinations depending on laser intensity, electron density, and ion wave damping. Figures 5a and 5b show the intensity thresholds for SRS, SBS, and self-focusing as a function of \( n_e/n_{ce} \) for \( T_e = 1 \) keV, with weak IAW damping (5a) and strong IAW damping (5b). The thresholds for SRS and SBS are calculated assuming convective gain over a speckle length in a homogeneous plasma, and the threshold for self-focusing is set by the ponderomotive spatial gain rate times the speckle length being unity. Regimes where various combinations of these instabilities operate (in the absence of other nonlinearities) are indicated in the figures.

As seen in Fig. 4, these plasmas have high Mach number transverse flows of \( M = v_z/c_s \sim 1 - 3 \) over the density range \( 0.1 \leq n_e/n_{ce} \leq 0.02 \), where \( c_s \) is the sound speed. The high transverse flow can affect the interaction in several ways due to the fact that density perturbations in the hot spot will be carried downstream by the flow. Beam steering is a result of the density perturbation from the laser ponderomotive pressure being carried down stream by the flowing plasma. Beam steering may also limit SRS or SBS growth, especially if there is also a transverse density gradient, such that the scalelength is shortened compared to the case with no flow. Also, nonlinear saturation mechanisms for SRS or SBS may be affected by transverse flow in that their perturbations may be swept out of the hot spot region. Future experiments will also explore plasmas with sub-sonic transverse flow to further examine the effects of flow on instability growth. Both flow regimes are relevant to ignition-scale hohlraums, where high transverse flow is expected
near the laser-entrance-holes (LEH), and sub-sonic flow is expected in the hohlraum interior. Initial experimental results from the single hot spot laser interaction are discussed next.

5.2 Transmitted beam measurements

Evidence for beam steering in a flowing plasma is obtained from measurements of the transmitted beam angular distribution. Figure 6a shows the time integrated transmitted beam distribution for a CH plasma at $n_e/n_{cr} \sim 0.05$, transverse flow $M \sim 2$, and peak intensity of $7 \times 10^{15}$ W/cm$^2$. The image is typical for cases with high intensity, and shows a large angular deflection in the direction of the flow. The image also shows interesting "bow-like" structures which are curved toward the direction of the flow. Superposed in Fig. 6a is a beam image with no plasma for calibration purposes. Measurements of the centroid of the deflected beam were obtained and are plotted versus peak intensity in Fig. 6b. A deflection of $\sim 6^\circ$ is measured for low intensities where only refraction is expected to occur, and the transmitted beam images show fairly little structure. Using the density gradient measurement shown in Fig. 4, and assuming a 0.9 - 1.0 mm length, an angle of $6.8 \pm 0.8^\circ$ is estimated for refraction alone, and is in good agreement with the lowest intensity data where nonlinear beam steering is not expected to occur.

5.3 SRS measurements

The density gradient scale length in the transverse direction (normal to target surface) is $\sim 100 \mu$m, which is much larger than the single hot spot diameter of $\sim 4 \mu$m, so the hot spot laser should see a fairly homogeneous density in the absence of nonlinear effects. Figure 7a shows a plot of the time-resolved SRS spectra from a CH plasma for $n_e/n_{cr} = 0.03$, transverse flow $M \sim 3$, and peak intensity of $7.7 \times 10^{15}$ W/cm$^2$. The SRS spectral width is $\sim 4$ nm, and is only slightly larger than the instrumental width of 2.5 nm. Figure 7b shows a plot of the time-integrated SRS reflectivity versus peak intensity for CH plasmas at $n_e/n_{cr} = 0.03$. The largest time-integrated SRS reflectivity observed is a few percent. No SBS was observed for this low density CH interaction over this range of
intensities. At higher densities, the SRS spectra from CH plasmas begin to show complex structure where it appears that SRS is coming in bursts over a broader density range. The time-integrated SRS reflectivity is similar to that shown in Fig. 7b. SBS is occasionally observed at the highest densities and intensities in the CH plasmas, and will be discussed next.

5.4 SRS and SBS anti-correlation

The ion acoustic wave damping can be varied by choice of target material. For these initial experiments, CH plasmas were used to produce strong IAW ($v_{ia} / \omega_{ia} \sim 0.1$), and Al plasmas were used for weak IAW damping ($v_{ia} / \omega_{ia} \sim 0.01$). In the strong damping regime, SBS was only observed at high density ($n/n_{cr} > 0.05$), and at the highest intensities. When both SRS and SBS were present, the data show a very interesting anti-correlation in time. Figure 8a shows a plot of the time histories of the SRS and SBS signals for a CH plasma, $n_e/n_{cr} \sim 0.075$ at a peak intensity of $8 \times 10^{15}$ W/cm$^2$. For each valley in the SRS signal, there is a corresponding peak in the SBS signal. This behavior is also seen for weak IAW damping. Figure 8b shows a plot of the time histories of SRS and SBS signals for a Al plasma, $n_e/n_{cr} \sim 0.055$, at a peak intensity of $7.8 \times 10^{15}$ W/cm$^2$. For this case the SBS signal starts first, and the SRS signals appear between the SBS bursts. For all cases where SRS and SBS were both present in these experiments, they showed a similar anti-correlation.

6. Summary and Conclusions

The first series of these single hot spot laser-plasma interaction experiments have been performed. The interaction laser beam has nearly diffraction limited performance, and produces a spot with FWHM $\sim 4 \mu$m. The laser wavefront has also been measured with lateral shearing interferometry, and the details of the laser focal spot are consistent with the measured phase. The plasma has been extensively characterized using imaging Thomson
scattering, and spatial profiles of the electron density, electron temperature, ion
temperature, and flow velocity have been obtained.

Initial interaction experiments have been performed using the single hot spot beam. Evidence of beam steering in plasmas with high Mach number transverse flow has been observed. Additionally, the transmitted beam angular distribution shows “bow-like” structures which are curved in the direction of flow. In certain low density regimes, the SRS spectra are quite narrow, but are broader and show a complex, bursty behavior at higher densities. Finally, when both SRS and SBS are present, they appear to be anti-correlated in time.

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References

Figure Captions

Figure 1. (a) Far-field image of the single hot spot beam; (b) Azimuthally averaged radial profile of the far-field data, with diffraction from a theoretical f/7 beam superimposed.

Figure 2. Schematic of laser beams and diagnostic configuration

Figure 3. (a) Layout of imaging orientation with respect to the target for Thomson scattering measurements. Schematics are shown for EPW and IAW scattering in this setup. The EPW feature produces long wavelength scattering at high densities near the target surface, and shorter wavelengths at lower densities. The IAW feature produces Stokes and anti-Stokes waves, the separation of which indicates electron temperature. Doppler-shift increasing to shorter wavelengths indicates plasma flow; (b) Scattering from EPWs as a function of distance from target surface at \( t = 1.0 \pm 0.1 \) ns for CH plasma (shot # 9537); (c) electron density profile versus distance from target surface (Z) taken from data in Fig. 3b; (d) Scattering from IAWs as a function of distance from target surface at \( t = 1.0 \pm 0.1 \) ns for CH plasma (shot # 9519); (e) Spectral profile of IAW data shown in Fig. 3d at \( Z = 300 \pm 25 \) \( \mu \)m. Superimposed is the Thomson scattering form factor for a fully-ionized CH plasma, with fit parameters \( T_e = 0.62 \pm 0.1 \) keV, \( T_i = 0.136 \pm 0.05 \) keV, and \( v_z = 4.6 \pm 0.4 \times 10^7 \) cm/sec.

Figure 4. Plot of electron density, electron temperature, ion temperature, and flow velocity profiles at \( t = 1.0 \pm 0.1 \) ns measured by Thomson scattering from EPW and IAW data shown in Figs. 3b and 3d. Simulated plasma profiles from 2-D LASNEX are indicated with solid and dashed curves.

Figure 5. Plot of convective intensity thresholds for SBS, SRS, and self-focusing versus density for (a) weak ion wave damping, and (b) strong ion wave damping. Different
regimes can be accessed, for example, by changing $n_e/n_{cr}$, intensity, and ion wave damping, to obtain

A: SRS and SBS unstable, B: Only SBS unstable, C: SBS and self-focusing unstable; D: SRS unstable, and E: SRS and self-focusing unstable.

Figure 6. (a) Time-integrated transmitted beam angular distribution for a CH plasma, $\sim 7 \times 10^{15}$ W/cm$^2$, $n_e/n_{cr} \sim 0.05$, $M \sim 2$. Image shows "bow-like" structures bending toward the plasma flow. No plasma case (calibration) is superimposed to indicate a reference position. (b) Measured centroid of deflected transmitted beam verus peak laser intensity. Dashed lines indicate the expected $6 - 7.5^\circ$ from refraction alone.

Figure 7. (a) Time-resolved SRS spectra from a 0.03 ne/ncr CH plasma with peak intensity of $\sim 8 \times 10^{15}$ W/cm$^2$. Spectra are quite narrow ($\sim 4$ nm); (b) plot of time-integrated SRS reflectivity verus intensity for these plasma conditions.

Figure 8. plot of SRS and SBS reflected signals for (a) CH plasma, and for (b) Al plasma. The SRS and SBS reflected signals shown anti-correlation in time.
Figures 1 a - b
Figures 2 a-b
target and plasma (viewed from bottom)

(a) 

- spectrometer slit
- laser
- Position
- EPW
- IAW

(b) 

\[ \lambda_s (\text{nm}) \]

Position (\text{\mu m})

(c) 

\[ n_e/n_\text{cr} \]

Position (\text{\mu m})

(d) 

\[ \Delta \lambda (\text{\AA}) \]

Position (\text{\mu m})

(e) 

Relative Intensity

\[ \Delta \lambda (\text{\AA}) \]

Figures 3 a-e

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Figures 5a and 5b
Figures 6a and 6b
Figures 7 a-b

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Figures 8 a-b

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