EXPERIMENTAL PROGRAM TO ELUCIDATE AND CONTROL STIMULATED BRILLOUIN AND RAMAN BACKSCATTERING IN LONG-SCALE PLASMAS*

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Laser-plasma instability is a serious concern for indirect-drive inertial confinement fusion (ICF), where laser beams illuminate the interior of a cavity (called a hohlraum) to produce X-rays to drive the implosion of a fusion capsule. Stimulated Raman and Brillouin backscattering (SRS and SBS) could result in unacceptably high laser reflectivities. Unfortunately, it is impossible at present to fully simulate these processes realistically. Our experimental program aims to understand these instabilities by pursuing a dual strategy. (1) We use a gas-filled hohlraum design, which best approaches ignition-hohlraum conditions, on the Nova laser to identify important non linear trends. (2) We are shifting towards more fundamental experiments with a nearly diffraction-limited interaction laser beam illuminating extremely well characterized plasmas on the Trident laser facility at Los Alamos to probe the relevant fundamental processes.

1. PLASMA CONDITIONS

Hohlraum designs planned for the National Ignition Facility (NIF) use plasma pressure from a He-H gas fill to tamp the gold-wall plasma[1]. The underdense He-H plasma allows laser propagation due to its low ionization state Z. High spatial-growth rates for stimulated Raman scattering[2] (SRS) and Brillouin scattering[3] (SBS) are predicted in the long-scale (size $\sim$ few mm) He-H plasma by linear convective theory[4], particularly backscattering. SRS and SBS are the growth of electrostatic waves, *i.e.*, electron-plasma waves (EPWs) and ion-acoustic waves (IAWs) respectively, which scatter laser light that in turn reinforces the electrostatic waves. Calculated linear gains are enormous and nonlinear saturation is expected.

We discuss two targets, designed using radiation-hydrodynamic simulations with the LAS-NEX code[5]. (1) A toroidally-shaped hohlraum filled with a low-Z gas and illuminated with the Nova laser (wavelength $\lambda = 351$ nm) best approaches NIF conditions and spatial scales[6,7]. Nine of the ten $f/4.3$ beams (heater beams) are on for 1.4 ns. An interaction beam (IB) is turned on once the plasma equilibrates at 0.4 ns and is kept at constant power for 1 ns. Various fills have been used at pressures up to 2.2 atm which fully ionize up to $n_e/n_c = 0.20$, where n_e is the electron density and n_c is the density above which 351 nm light becomes evanescent.
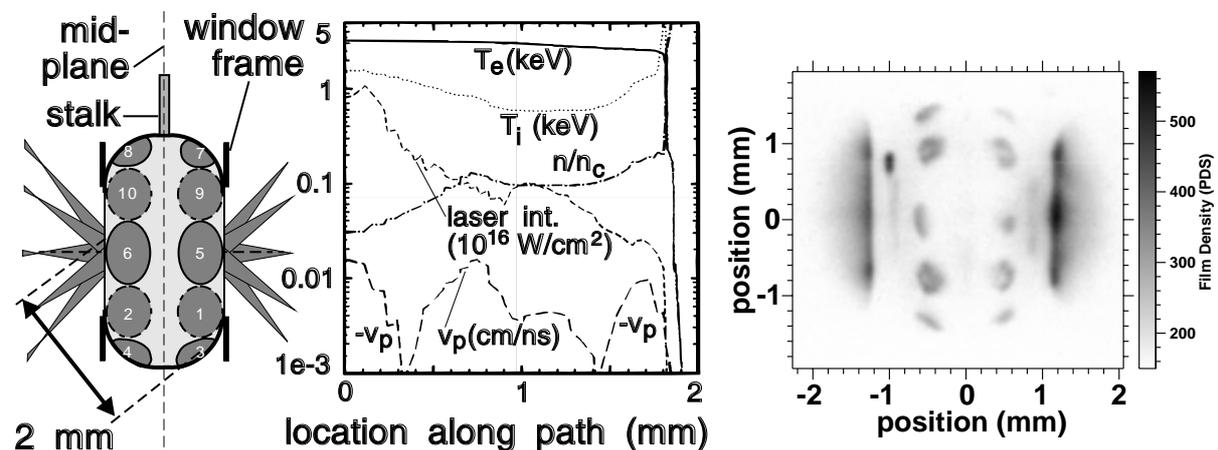
Figure 1: *Left: The gas-filled hohlraum and beam footprints are illustrated. Middle: LASNEX profiles within the hohlraum along a beam path at time 1 ns are plotted. Right: Hohlraum x-ray image (0.08 ns framing) taken at time 0.12 ns is shown. By using thin (2 μm) gold walls with no gas fill, sufficient L-shell photons reach our pinhole camera to record an image.*
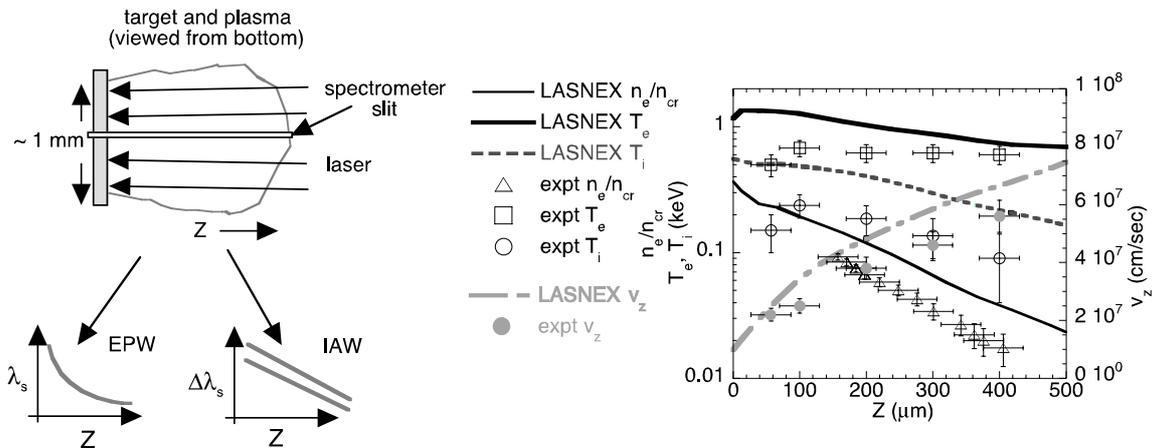
Figure 2: *Left: The geometry for the Thomson scattering measurement is illustrated. Scattering from EPWs yields the n_e profile, while scattering by IAWs yields the T_e, T_i and flow velocity v_z profiles. Right: Measured versus predicted spatial profiles normal to the target ($\hat{z}$) at 1.0 ns.*

(2) Plasmas that are quasi homogeneous along the direction of beam propagation ($\hat{k}_0$) are pre-formed by line-focusing a beam of the Trident laser[8] ($\lambda = 526.6$ nm) for 1.2 ns onto a CH disk 6.7 μm in thickness and 1 mm in diameter[9]. A second Trident beam for SRS and SBS inter-actions, either a regular beam or a well characterized $f/6.9$ nearly diffraction-limited beam[10], travels parallel to the disk and along the line focus plane. The plasma expansion is mostly normal to $\hat{k}_0$, so the IB beam samples a $\approx$ 1 mm-long plasma with constant n_e, depending on the chosen IB-disk separation. Trident and Nova plasmas are similar in important areas such as the onset and saturation of SBS[9,11]. Moreover, Trident plasmas have been characterized with unprecedented detail with a diagnostic that images light from collective Thomson scatter-ing along the direction of plasma expansion with a framing time of 0.12 ns[10]. The diagnostic geometry and the plasma profiles, predicted and measured, are shown in Fig. 2. The profile measurements are necessary for truly detailed comparisons between theory and experiment.

2. EXPERIMENTAL RESULTS AND FUTURE DIRECTIONS

High-energy glass-laser beams used for ICF are not spatially uniform. Mitigation tech-niques include passive optics for beam smoothing. For Nova and some Trident experiments we have used a binary random-phase plate (RPP)[12,13]. RPPs produce a "smooth" focal spot envelope with a superimposed fine-scale speckle (or "hot spot") pattern. A significant fraction of the beam energy is in hot spots. RPP hot-spot statistics affect the character of SBS and SRS onsets profoundly, as seen in models and simulations [14,15]. The result of integrating the SBS gain over the hot-spot distribution, including beam diffraction and pump depletion, is a non lin-ear system which exhibits critical behavior[14]. In the long-scale regime the instability-dephasing length is much longer than the typical hot-spot length ($l_{hs} \sim 7f^2\lambda$). There, as the average beam intensity I is increased the reflectivity R sharply increases from R_{seed} once I exceeds a critical intensity value I_c. $I = I_c$ when the linear gain $R/R_{seed} = \exp[G(I_c, l_{hs})] \approx e^1$, in contrast with the customary threshold $G = 2\pi$. Once $I >> I_c$ hot-spots undergo pump-depletion or non linear saturation and R levels off. Sharp onsets are also evident on 3-Dim. SBS simulations [15]. High-T_e and long density scales also allow SRS study where the same theory applies.

SBS I_c magnitudes and dependencies on ν_i and on f number measured in the Nova toroidal hohlraums[7,16] and in the Trident line plasmas[9] are predicted theoretically reasonably well[14].
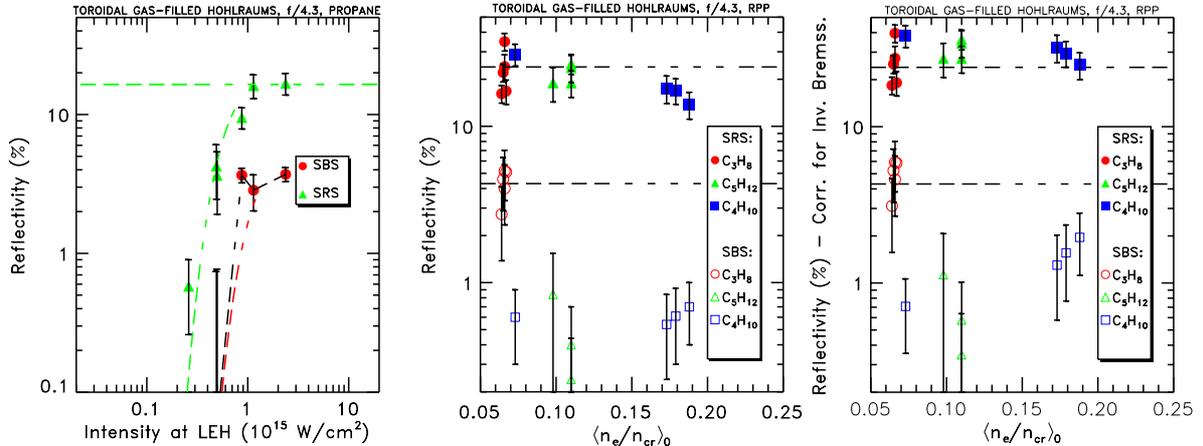
Figure 3: *Left: Time-averaged R_{SRS} and R_{SBS} are plotted versus I. Center: R_{SRS} & R_{SBS} are plotted versus initial n_e/n_c. Right: R_{SRS} & R_{SBS} are corrected for inverse-Bremsstrahlung absorption of the scattered light.*

SRS onsets in toroidal hohlraums have been measured also. For C_5H_{12} ($n_e/n_c = 0.11$) the observed $I_c \sim 10^{14}$ W/cm²[16] is consistent with theory within our ability to ascertain the value of the Landau-damping frequency of EPWs (ν_e) within hot spots[17]. Fig. 3-Left shows R_{SRS} and R_{SBS} versus I of the RPP-smoothed IB from 1 atm C_3H_8 fills ($n_e/n_c = 0.07$). All the reflected light near and within the beam cone is measured[18] and included in the values shown. The observed $I_c \sim 3 \times 10^{14}$ W/cm² for SRS is significantly higher than with $n_e/n_c = 0.11$ because of the higher ν_e from Landau damping at lower n_e. In contrast, the observed SBS I_c are similar for both n_e values because the Landau-damping rates for IAWs (ν_i) do not change. Fig. 3-Left includes fits to R_{SRS} and R_{SBS} from the model in Ref. ([14]).

We have studied SBS and SRS saturation extensively. In a fixed-length homogeneous plasma the convective gain exponents are $G_{SBS} \propto (n_e I)/\nu_i$ and $G_{SRS} \propto I/\nu_e$. SRS and SBS are not simply gain-limited when $I \gg I_c$ since R levels off with increasing I[9,7,16], as in Fig. 3-Left. Only time-integrated hohlraum R_{SRS} and R_{SBS} are discussed, as the plasma is approximately in steady state while the IB is on. R_{SRS} and R_{SBS} vary in time due to hydrodynamic-evolution details[19], but this is outside the scope of this paper. R_{SRS} is remarkably constant over a wide range of n_e, as shown in Fig. 3-Center and Right. According to LASNEX, changing n_e changes T_e and T_i little, allowing fairly clean comparisons. R_{SBS} would increase exponentially with n_e if linear convective theory applied. Fig. 3-Right shows a vastly different result. In plasmas with multiple ion species, ν_i/ω_i depends on the relative ion masses[20,21]. We exploit this by using the hohlraum gas fill to vary ν_i/ω_i while keeping T_i/T_e fixed. The measured R_{SRS} from toroidal hohlraums depends approximately linearly on ν_i/ω_i[22,16], even though SRS does not involve IAWs. This is attributed to the coupling of SRS to the Langmuir Decay Instability (LDI), where the SRS EPW further decays into another EPW and an IAW[23]. We have imaged the SRS light at the target plane with 25 μm resolution and 0.15 ns framing[24]. We deduce from these images that significant SRS occurs throughout the beam path, contrary to expectations from convective theory, *i.e.*, highest scattering at the end of the SRS gain region. Ubiquitous SRS is more consistent with saturation mediated by LDI, *i.e.*, SRS clamped by secondary decay throughout the plasma except for a short growth region. In spite of modeling successes in SRS-LDI coupling[25,26], much more work will be required to explain our data thoroughly[27]. R_{SBS} from toroidal hohlraums is influenced also by ν_i/ω_i[16]. Since SBS is not simply gain-limited, any ν_i dependence is difficult to explain. Competition between SRS and SBS might be involved, but it is strange that the SBS reflectivity is constant for a wide range of ν_i/ω_i while the SRS reflectivity is changing significantly. SBS saturation is apparently sensitive to boundary conditions. In Trident line plasmas when $I \gg I_c$, we have raised the intensity-saturated R_{SBS}
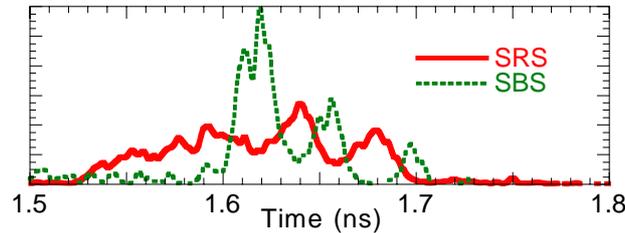
Figure 4: *The instantaneous R_{SBS} and R_{SRS} reflectivity of the Trident diffraction-limited beam from a CH line plasma is plotted versus time.*

by seeding SBS with an external light source[11].

Much work remains to understand SRS and SBS saturation. Underlying observed trends in complicated NIF-relevant plasmas, there are undoubtedly coupled physical processes which we hope to uncover by detailed comparisons of theory to the single-hot-spot experiments. For example, Fig. 4 shows the evolution of R_{SRS} and R_{SBS} of the diffraction-limited Trident beam. R_{SRS} and R_{SBS} are anticorrelated and oscillate in time with a period similar to acoustic transit times across the IB. Promising modeling efforts for these experiments are underway.

References

[1] HAAN, S. W. et al., *Phys. Plasmas*, **2** (1995) 2480.

[2] GOLDMAN, M. V. et al., *Phys. Fluids*, **8** (1965) 1404.

[3] GORBUNOV, L. M., *Soviet Physics JETP*, **28** (1969) 1220.

[4] ROSENBLUTH, M. N., *Phys. Rev. Lett.*, **29** (1972) 565.

[5] ZIMMERMAN, G. et al., *Comments Plasma Phys. Controlled Fusion*, **2** (1975) 51.

[6] WILDE, B. H. et al., in *Proc. 12th International Conf. on Laser Interaction and Related Plasma Phenomena, Osaka, 1995*, G. H. MILEY Ed., page 255, AIP Press, NY, 1996, Conf. Proc. No. 369, Part 1.

[7] FERNÁNDEZ, J. C. et al., *Phys. Rev. E*, **53** (1996) 2747.

[8] MONCUR, N. K. et al., *Appl. Optics*, **34** (1995) 4274.

[9] WATT, R. G. et al., *Phys. Plasmas*, **3** (1996) 1091.

[10] MONTGOMERY, D. S. et al., accepted to Lasers and Particle Beams, 1998.

[11] FERNANDEZ, J. C. et al., *Phys. Rev. Lett.*, **81** (1998) 2252.

[12] KATO, Y. et al., *Phys. Rev. Lett.*, **53** (1984) 1057.

[13] DIXIT, S. M. et al., *Appl. Optics*, **32** (1993) 2543.

[14] ROSE, H. A. et al., *Phys. Rev. Lett.*, **72** (1994) 2883.

[15] BERGER, R. L. et al., *Phys. Rev. Lett.*, **75** (1995) 1078.

[16] FERNÁNDEZ, J. C. et al., *Phys. Plasmas*, **4** (1997) 1849.

[17] AFEYAN, B. B. et al., New regimes of parametric instabilities in plasmas with flat-topped and depleted tail velocity distribution functions, submitted to Phys. Rev. Lett., 1997.

[18] KIRKWOOD, R. K. et al., *Rev. Sci. Instrum.*, **68** (1997) 636.

[19] MONTGOMERY, D. S. et al., *Phys. Plasmas*, **5** (1998) 1973.

[20] VU, H. X. et al., *Phys. Plasmas*, **1** (1994) 3542.

[21] WILLIAMS, E. A. et al., *Phys. Plasmas*, **2** (1995) 129.

[22] FERNÁNDEZ, J. C. et al., *Phys. Rev. Lett.*, **77** (1996) 2702.

[23] DUBOIS, D. F. et al., *Phys. Rev. Lett.*, **14** (1965) 544.

[24] WILKE, M. D. et al., *Rev. Sci. Instrum.*, **68** (1997) 672.

[25] DRAKE, R. P. et al., *Phys. Fluids B*, **3** (1991) 2936.

[26] BEZZERIDES, B. et al., *Phys. Rev. Lett.*, **70** (1993) 2569.

[27] RUSSELL, D. A. et al., submitted to Phys. of Plasmas, 1998.