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LASER SCATTERING IN LARGE-SCALE-LENGTH PLASMAS RELEVANT TO NATIONAL IGNITION FACILITY HOHLRAUMS*

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Abstract

LASER SCATTERING IN LARGE-SCALE-LENGTH PLASMAS RELEVANT TO NATIONAL IGNITION FACILITY HOHLRAUMS

We have used homogeneous plasmas of high density (up to 1.3 10^{21} electrons per cm^3) and temperature (~ 3 keV) with large density scale lengths (~2 mm) to approximate conditions within National Ignition Facility (NIF) hohlraums. Within these plasmas we have studied the dependence of stimulated Raman (SRS) and Brillouin (SBS) scattering on beam smoothing and plasma conditions at the relevant laser intensity (3ω, 2 $10^{15}Wcm^{-2}$). Both SBS and SRS are reduced by the use of smoothing by spectral dispersion (SSD).

Current target designs for the NIF consist of gas-filled, gold hohlraums, 9 mm in length, heated with a 1.3 MJ laser (430 TW peak power) at 3ω (λ_0 = 0.351 μm wavelength)[1]. The laser energy is delivered to the hohlraum by 192 beams in shaped pulses about 15 ns long. The beams are focused with f/20 lenses arranged in clusters of 4 to produce effectively an f/8 beam. Beam smoothing, accomplished by the use of smoothing by spectral dispersion SSD[2], with kinoform random phase plates(RPP)[3,4], produces a flat top focal spot with an intensity that varies by a factor of two over the 3 to 5 mm laser path length within the hohlraum. At the time of maximum power the laser intensity peaks at 2 $10^{15}Wcm^{-2}$ at the best focus of the f/8 cluster, with other regions, along the beam path, at intensities between 10^{15} and 2 $10^{15}Wcm^{-2}$. Symmetric capsule implosions are accomplished by using two rings of beams, inner and outer, that reach the hohlraum wall at different distances from the laser entrance hole (LEH) and have different path lengths within the hohlraum plasma. Over most of their path length, the laser beams interact with a low-Z, fully-ionized, gas (a mix of He and H_2), but for the last 400 μm, with high-Z, high T_e gold plasma blown off from the hohlraum wall. The low-Z plasma between the hohlraum wall and the LEH has electron temperature (T_e) from 3 to 6 keV and electron density (n_e) from

$7\% n_{crit}$ to $12\% n_{crit}$, where n_c is expressed as a percentage of critical density ($n_{crit} = 9\ 10^{21}\ cm^{-3}$ for 3ω). There is concern that the conditions within the plasma, together with the intensity of the laser beam will lead to significant (>20%) scattering of laser light by stimulated Brillouin (SBS) and Raman backscattering (SRS)[6,7]. Calculations of the gain exponents, from linear theory, for SBS and SRS with plasma parameters taken from LASNEX[8] designs show both to be greater than 20[5,9]. For growth from thermal noise, gain exponents of 20 or larger result in significant reflectivities (>10%), in the absence of nonlinear effects other than pump depletion. In the gold plasma near the hohlraum wall, SBS is of particular concern because the acoustic wave is weakly damped.

The linear gain calculations do not include the small scale structure in the laser beam, hotspots with a typical intensity of twice the average local intensity whose length, $\lambda_s = 8f^2\lambda_0$, and width, $\lambda_{perp} = f\lambda_0$, vary with f, the f-number of the lens. Simulations and calculations have shown that inclusion of hotspots lowers by about a factor of 2 the average intensity at which significant reflectivity occurs[10]. Filamentation, i. e., self-focusing of the hotspots, is expected to increase the danger of SRS and SBS because it increases the amount of laser energy at high intensity. Without filamentation, the hotspot intensities have a distribution that decreases as $\exp(-I/I_0)$ with ~4% of the laser energy in hotspots with intensity greater than 5 times the average. The power in a typical hotspot, $4.10^{-8} I_0 f^2 \lambda_0^2$ is above the self-focusing threshold power [11] equal to $17(n_{crit}/n_c)10^6 T_c(keV)$ (W), if $G = 5(I_0/2\ 10^{15}\ Wcm^{-2})(f^2\lambda_0^2/T_c(keV))(n_c/n_{crit}) > 1$, where λ_0 is measured in microns. For the portion of the NIF beam path at $2\ 10^{15} Wcm^{-2}$, filamentation is above threshold according to this simple criterion. However, the e-folding growth times for filamentation are slow enough (~10 ps) that temporal beam smoothing (e.g. SSD) with 0.8Å bandwidth (5 ps intensity autocorrelation time) is expected to restore stability by moving the hotspots faster than the plasma can respond. These estimates have been tested with F3D, a three dimensional laser propagation code that employs the paraxial approximation for the light wave, nonlinear hydrodynamics for the plasma response, and includes nonlocal heat transport[10]. The F3D results displayed in Fig. 1, show the reduction of filamentation with increase in SSD bandwidth in a low Z plasma. The value plotted is the fraction of the laser light energy at intensity above 5 times the average. In an experiment we would expect to see a reduction in SBS and SRS backscatter as SSD reduces the fraction of the beam at high intensity. The modification of the intensity distribution function does not persist over a great length. At greater distances into the plasma, the light diffracts to larger angles and the distribution of intensities returns to the initial one, namely, $\exp(-I/I_0)$, but with a decrease in the typical hotspot size and an increase in beam size characteristic of a smaller f-number (with a consequent decrease in I_0). Above the filamentation threshold and at sufficient depths into the plasma, the hotspot locations are not stationary but move about in a random manner. Intensity correlation times as short as 4 ps (equivalent to 1Å of SSD bandwidth) have been measured in simulations (for a mean intensity of 2×10^{15} Wcm^{-2}). Thus, if filamentation is required for the generation of large amounts of SBS and SRS, the process could limit SBS and SRS gain to regions where filaments first form.

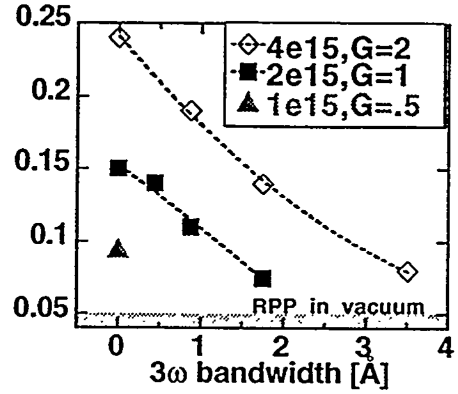

Fig. 1 Fraction of f/8 beam with intensity 5 times the spatial average (no time averaging). Filamentation in the plasma has increased this fraction above the 4-5% expected for a RPP beam in vacuum. (F3D simulation[10], CH_2 plasma, 10% n_{crit}, T_e = 3 keV. $I_0 = 10^{15}$, 2 10^{15} and 4 10^{15} Wcm^{-2}.)

The NIF laser 3ω bandwidth can be as large as 1.7Å but lower bandwidths are more desirable because the frequency conversion process is noticeably less efficient for bandwidths in excess of 0.8Å. SSD is not the only temporal smoothing scheme proposed for the NIF. A four colour scheme was also proposed in which each of the four f/20 beams in a cluster differed in wavelength by 3Å at 3ω. This scheme smoothes the laser hotspots faster in fact than SSD but, unlike SSD, it cannot smooth at all spatial scales. That is, the hotspots that are formed as a result of the interference of beamlets from each phase plate within a given f/20 quadrant are never smoothed. Over the time scale that filaments form, the rapid motion of the small scale structure produces no hydrodynamic response but the f/20 hotspots can still self-focus. F3D simulations of 4 colours confirmed their ineffectiveness, provided the simulation allowed the laser to propagate the longer distance a lower intensity hotspot takes to self focus.

Experiments were performed using the Nova laser at LLNL with targets developed to reproduce the plasma conditions and length scales of the NIF. The two plasma conditions that are important for the NIF are the inner beam plasma, which is a large scale length low-Z plasma with a high gain exponent for SRS and SBS, and the outer beam plasma which has shorter scale lengths and a higher gain exponent for SBS in the plasma near the gold wall[5]. The low-Z inner beam case was modeled with gasbag targets consisting of two membranes on either side of a thin washer which are inflated with an atmosphere of a heavy gas (typically C_5H_{12}) to produce an almost spherical volume of gas. Symmetric irradiation by nine "heater beams" leads to the production of a 6 -15%n_{crit} plasma with 1 - 2 mm scale lengths and T_e of 3 keV[12]. The NIF outer beam plasma was modeled with a cylindrical, "Scale-1" hohlraum, 1.6mm diameter by 2.7mm long, filled with methane gas. The gas retards the expansion of the gold wall and forms a shelf of gold similar in density and temperature to that seen by the NIF outer beam[5], with a similar calculated gain exponent for SBS. The experiments used the tenth Nova beam as an interaction beam configured at f/8 and with the capability of either; 4-colour operation[13] with 1.4Å separation (at 3ω) between its 4 separate quadrants; or 1-colour, with all the quadrants the same wavelength.

Between April 1994 and March 1996 three experimental campaigns measured backscatter from the f/8 beam focused on these new targets, at irradiances near 2 10^{15}Wcm^{-2}, the peak intensity along the NIF beam path. The results from the first two campaigns indicated that 4-colour beam smoothing had little advantage over 1-colour in reducing SBS and SRS in gasbag plasmas. The experiments showed that adding ~0.5Å of SSD beam smoothing did reduce SBS and SRS at 10%n_{crit}. [5]. The last f/8 interaction campaign, in March 1996, focused on a 1-colour laser configuration and investigated how much SSD bandwidth was required to reduce backscatter. This experiment also enlarged the parameter space in the gasbag measurements by studying plasmas whose density varied from 7% to 14% n_{crit}. The measurements also used the Scale-1 hohlraums to study the effect of beam smoothing on SBS on the outer NIF beam. During all of the measurements the f/8 interaction beam was smoothed with a random phase plate[3]. For the gasbags, the interaction beam was a 1 ns long constant power pulse with an intensity in the target plane of 2 10^{15}Wcm^{-2}. The Scale-1 hohlraums used a shaped pulse that increased its power in time, to a peak of 2.5 10^{15}Wcm^{-2}. SSD was added with a bandwidth of 0 to 1Å at 3ω.

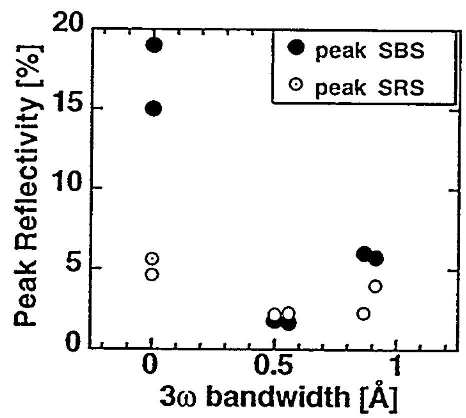

Fig 2 SBS and SRS backscatter data from Scale-1 methane-filled hohlraums with gold shelf plasmas similar to those encountered by the NIF outer beams. The reflectivity shown is the peak in time (averaged over the 50 ps diagnostic resolution) corresponding to the time of peak incident intensity. (2.5 10^{15}Wcm^{-2})

Fig. 2 shows SBS and SRS reflectivity as a function of SSD bandwidth for the scale-1 methane filled hohlraums. Both SBS and SRS are the peak value observed during the shaped pulse experiment, at the peak of the incident pulse. The quoted reflectivities include all backscatter from 0° out to 20° from the center of the beam. The SBS backscatter with no bandwidth is quite high (15-20%), addition of 0.5Å bandwidth reduces the SBS considerably (~2%). Two experiments were done at each bandwidth condition and the data seem reproducible. The experimental uncertainty is ±25%. of the quoted value of reflectivity.

Similar results were obtained from the gasbag plasmas at densities of 7 -

7.5% n_{crit} and 9.5 -10%n_{crit}. The gasbag is heated by a 1 ns pulse of ~22kJ of 3ω light. The f/8 interaction pulse turns on at 0.5 ns and is 1 ns in duration. The f/8 interaction beam irradiance was kept fixed at 2 10^{15}Wcm^{-2} while the SSD bandwidth was varied from zero to 1Å at 3ω. The backscatter data are shown in Fig. 3 where the peak SBS is plotted together with the SRS at peak T_e (averaged over the 50 ps diagnostic resolution). The SBS peaks at 0.8 - 0.9 ns while the SRS is plotted at 1 ns, when T_e is a maximum, just before the heaters turn off and the plasma cools[5]. The effect of SSD bandwidth is shown in Fig. 3(a) for the 10% n_{crit} targets. SSD reduces SRS slightly from 7% to 4% , the effect on SBS is similar, 6% to 3%. For the lower density, 7.5%n_{crit}, data in Fig. 3(b), SBS reduces from 10% to 6% while SRS drops from 4% to 1%. At 10% n_{crit} there is a slight benefit to increasing the bandwidth from 0.5 to 1Å, while for the lower density plasmas, and Scale-1 hohlraums, backscatter is minimized with 0.5Å bandwidth.

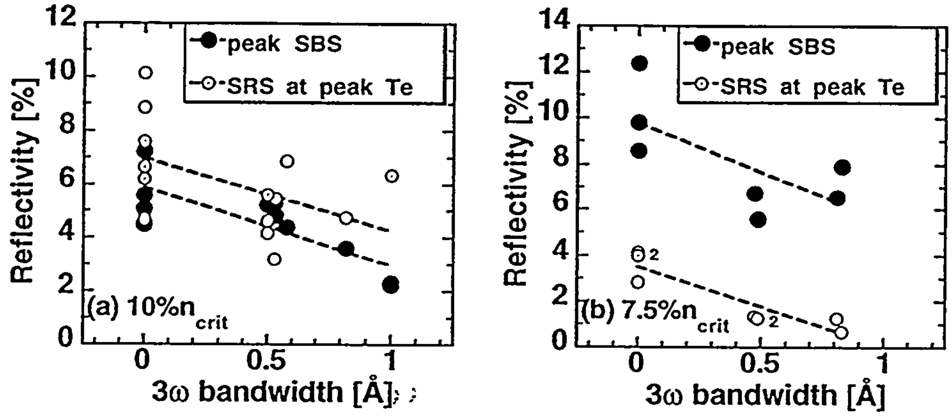

Fig 3 (a) Peak SBS reflectivity, together with SRS reflectivity at peak T_e (t = 1 nsec), from gasbag plasmas used to simulate the plasma encountered by the NIF inner beam at 10% n_{crit} at 2 10^{15}Wcm^{-2}, (b) similar data for 7.5%n_{crit} gasbags. Dashed lines are linear fits to the data, "2" indicates overlapping data points.

Apart from the reduction in SBS and SRS as SSD is applied, there is some additional evidence that the SSD is suppressing filamentation. Reference 5 describes SRS backscatter spectra from gasbags at 10%n_{crit} with and without SSD. SSD reduces the short wavelength SRS associated with lower density plasma. It is possible that this lower density SRS is coming from filaments where plasma has been moved out of the hotspot, reducing the density, while the higher intensity compensates for the lower SRS growth rate at low density. SSD, in reducing the fraction of energy at high intensity (Fig. 1) reduces the short wavelength SRS. In reference 5, and the newer experiments described here, the lower density SRS is reduced by either adding SSD or decreasing the laser intensity, both actions likely to reduce filamentation. The decrease in the total SRS at 10%n_{crit} is not large, as SSD is added, even though the SRS spectra indicate that filamentation has been reduced. It is possible that the gain exponent for SRS at the average intensity is high enough that filamentation is not necessary to drive large levels of SRS. The best that SSD (at these limited bandwidths) can do is reduce the intensity seen by SBS and SRS to that of the vacuum propagated RPP (i.e. the SSD will prevent the plasma response increasing hot spot intensities further). Since the SSD bandwidth cannot alter the intensity distribution on time scales comparable to the growth time for SBS and SRS (0.1 - 1 ps) we reach the point where once filamentation has been stabilized, the bandwidth can not do any more to reduce SBS and SRS.

A fuller discussion of this data and modeling will be published in a longer paper. However it is worth mentioning a trend in the data, shown in Fig 3, that is currently being studied. While the SRS is seen to increase with density, consistent with linear theory, the SBS decreases with increasing density, contrary to linear theory[14]. SBS decreases from 6% at 7.5%n_{crit} to 3% at 10%n_{crit} (Fig.3) to 0.3 - 0.4% between 11% and 14%n_{crit} (not shown). These trends are the subject of ongoing experiments that focus on the mechanisms that saturate SBS and SRS in large scale length, "NIF-like" plasmas[14,15]. However, the results of the studies shown here are that SBS and SRS in NIF-scale hohlraums should be at tolerable levels with moderate amounts of beam smoothing.

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