Observation of the Density Threshold Behavior for the Onset of Stimulated Raman Scattering in High-Temperature Hohlraum Plasmas

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We show that the measured stimulated Raman scattering (SRS) in a large-scale high-temperature plasma scales strongly with the plasma density, increasing by an order of magnitude when the electron density is increased by 20%. This is consistent with linear theory, including pump depletion, in a uniform plasma and, as the density is typically constrained by other processes, this effect will set a limit on drive laser beam intensity for forthcoming ignition experiments at the National Ignition Facility. Control of SRS at laser intensities consistent with 285 eV ignition hohlraums is achieved by using polarization smoothing which increases the intensity threshold for the onset of SRS by 1.6 ± 0.2. These results were quantitatively predicted by full beam three-dimensional numerical laser-plasma interaction simulations.

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In the indirect drive approach to inertial confinement fusion, a high-Z radiation cavity (hohlraum) is used to convert laser energy into soft x rays to drive a fusion capsule implosion by ablation pressure [1]. In order to produce symmetric implosions, it is critical that laser beams are able to deposit their energy near the hohlraum wall after propagating through millimeters of under-dense plasma. In current ignition designs, beams are required to propagate through a relatively uniform high-density (1.5×10^{21} cm^{-3}) moderate-temperature ($T_e = 2.5$ keV) region created by the initial low-density gas fill compressed by the expanding hohlraum wall and blowoff material from the capsule [2]. Laser intensities are kept low (mid to low 10^{14} W cm^{-2}) to minimize laser-plasma instabilities and to efficiently heat the hohlraum.

In a uniform plasma, linear theory suggests that the stimulated Raman scattering (SRS) reflectivity scales with the linear gain exponent, $G_{\rm SRS} \propto (\frac{IL}{\nu_e/\omega_p})$, where $\nu_e/\omega_p = \sqrt{\pi/8}(k\lambda_d)^{-3}\exp[-(\sqrt{2}k\lambda_d)^{-2}]$ is the Landau damping and $k\lambda_d$ is the ratio of the Debye length over the wavelength of the plasma wave. Experimentally the gain can be scaled by changing the laser beam intensity or the plasma density. Previous SRS reflectivity measurements have not followed linear theory, observing little scaling of the SRS backscatter with small variations in electron density, but these studies focused primarily on higher laser-drive intensities well above instability thresholds and found that SRS backscatter results were dominated by filamentation [3,4], competition with stimulated Brillouin scattering (SBS) [5], density gradients [6], or nonlinear physics [7–10].

In this Letter, we report on the measurements of a density dependent intensity threshold for stimulated Raman scattering in hot-uniform hohlraum plasma at intensities below the filamentation threshold, providing a strong experimental basis for ignition experiments. We have measured the SRS sensitivity to small variations in the electron density and found it to be consistent with linear theory predictions; a 20% increase in plasma density results in an order of magnitude increase in the measured SRS, as the Landau damping decreases by a factor of 3.5, while SBS remains energetically insignificant ($R_{\rm SBS} < 1\%$).

Polarization smoothing is found to increase the SRS intensity threshold by a factor of 1.6 ± 0.2 where the threshold for backscatter is defined as the intensity ($I_{\rm th}$) at which 5% of the incident power is backscattered. These backscatter measurements are reproduced by PF3D simulations which models the laser beam propagation through the full 2-mm long plasma in three dimensions.

For this study, a novel high-density gas-filled hohlraum platform for studying laser-plasma interactions has been developed by introducing laser beams to blow down the 260 nm thick polyimide windows covering the laser entrance holes and uniformly distributing the heater beams on the hohlraum wall [Fig. 1(b)]. The bulk plasma conditions used in these simulations are calculated in two-dimensional axisymmetric geometry as a function of time using the hydrodynamic code HYDRA [11]. Previous Thomson scattering studies performed at low densities ($n_e/n_{cr} = 6\%$) demonstrated that the plasma conditions were insensitive to the heat conduction models [12], and for the studies in this Letter a flux limiter of 0.01 was used. Compared with previous high gas-filled hohlraum designs [Fig. 1(c)], this configuration created a more uniform plasma at high densities ($10\% < n_e/n_{cr} < 13\%$) reducing the thermally driven blast waves launched as the heater beams initially burn through the gas [Fig. 1(c)]. The density in the 1.6-mm diameter, 2-mm long hohlraum targets is varied by choosing the neopentane (C_5H_{12}) gas-fill pressure (<1.1 atm).

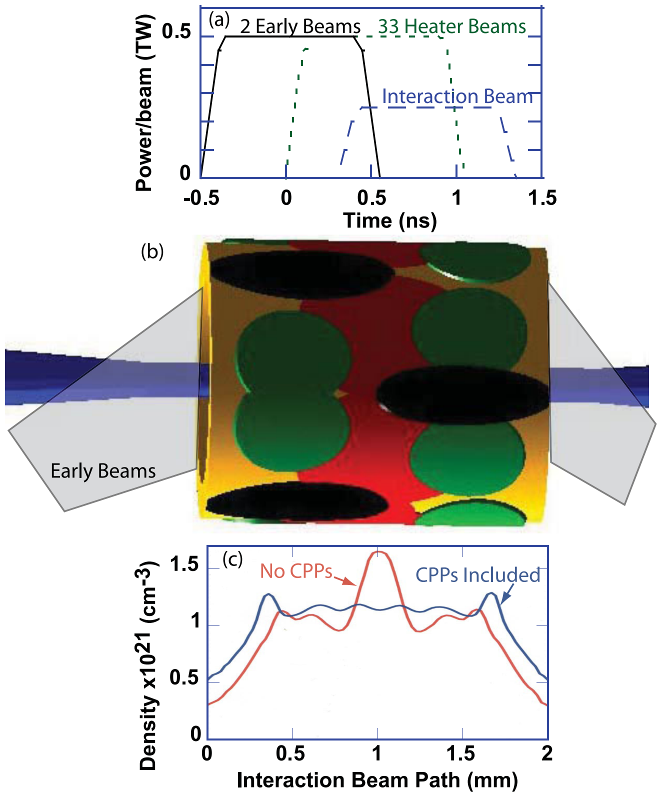

FIG. 1 (color online). (a) Beam timing; two laser beams blow down the windows on the laser entrance hole prior to the heater beams. (b) The heater beams are uniformly distributed over the hohlraum wall using new elliptical phase plates which produces a uniform plasma density along the hohlraum axis. (c) The simulated plasma density along the hohlraum axis is shown for conditions (blue curve) with heater beam phase plates and (red curve) without the heater beam phase plates.

The hohlraum is heated by 33, 1-ns long square pulsed, frequency tripled ($\lambda_o = 351$ nm) laser beams (15 kJ) at the OMEGA Laser Facility [13]. The heater beams are smoothed by elliptical phase plates that project a ~250 μm diameter intensity spot at the 1200 μm diameter laser entrance holes. The plasmas produced in these experiments are comparable to the conditions encountered by the laser beams propagating between the expanding hohlraum wall and the capsule blowoff in indirect drive ignition experiments on the National Ignition Facility [2].

An interaction beam was aligned along the axis of hohlraum (Fig. 1) providing a direct measurement of the laser beam propagation and transmission at ignition hohlraum conditions. The interaction beam is focused at the center of the hohlraum using an $f/6.7$ lens. A continuous phase plate (CPP) [14] was used to produce a 200 μm laser spot at best focus. The average on axis intensity at best vacuum focus for this beam is $I = 2.6 \times P$ (in GW) $\times 10^{12}$ W cm^{-2}, where P is the incident laser beam power ranging from 50 to 500 GW. On selected shots, a birefringent polarization smoothing (PS) crystal was installed in the interaction beam path to separate the speckles in the plasma and decorrelate the speckle patterns of each polarization while having minimal effect on the average intensity of the laser beam [15].

Light scattered back into the original beam cone is collected by the full-aperture backscatter station (FABS) [16]. The light backscattered outside of the FABS reflects from a plate surrounding the interaction beam and is collected by the near-backscatter imager [17]. The FABS time resolves both the SBS ($-0.5 < \Delta\lambda_o < 1.5$ nm) and SRS ($450 < \lambda_{SRS} < 650$ nm) spectra using 1.5 and 0.25 m spectrometers, respectively, coupled to high-dynamic-range streak cameras. The total backscattered energy is measured in both spectra using absolutely calibrated calorimeters with an uncertainty of 5%.

Figure 2 shows that the SRS backscatter wavelength scales with the electron density inferred from the initial fill density. The peak SRS wavelength at 700 ps increases from 535 nm at an electron density of 10%n_{cr} to 580 nm at an electron density of 13%n_{cr}. Furthermore, the peak SRS wavelength increases in time consistent with the increased electron temperature observed in the simulations. The

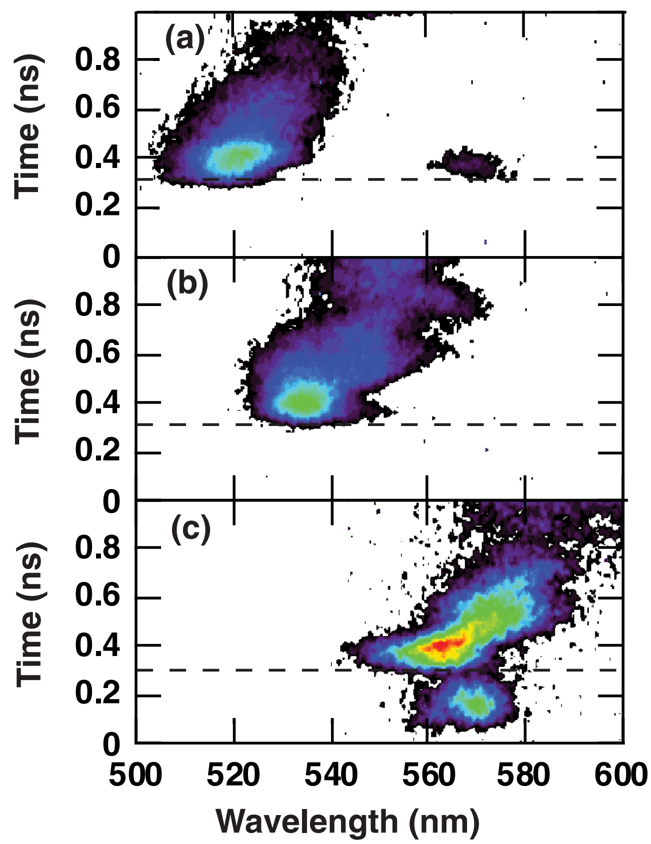

FIG. 2 (color online). The SRS spectra show that the peak wavelength increases with increasing plasma density (a) 10.1%n_{cr}, (b) 11.3%n_{cr}, (c) 13.0%n_{cr} and that the scattered wavelength increases in time as a result of the increasing electron temperature.

three spectra shown have an increasing intensity ($I_{10\%} = 12 \times 10^{14}\ \mathrm{W\,cm^{-2}}$, $I_{11\%} = 9.5 \times 10^{14}\ \mathrm{W\,cm^{-2}}$, $I_{13\%} = 4.2 \times 10^{14}\ \mathrm{W\,cm^{-2}}$) as the electron density decreases and maintain a nearly constant time integrated SRS reflectivity ($R \simeq 7\%$).

An instantaneous backscatter is determined at a time 700 ps after the rise of the heater beams once the plasma reaches high plasma temperatures where filamentation effects are negligible [18]. Furthermore, the SRS reflectivity peaks early in time when the plasma is cold and for the lower scattering conditions ($I \lesssim 8 \times 10^{14}\ \mathrm{W\,cm^{-2}}$, $n_e/n_{cr} \lesssim 12\%$) the signal is reduced below detection level ($< 0.01\%$) when the electron temperature reaches 2.7 keV (~ 800 ps). The instantaneous reflectivity is calculated by averaging over a 100 ps range and the error bars are given by the extreme reflectivities within this range.

Figure 3 shows the measured instantaneous backscatter versus density at three intensities. It is evident that increasing the density by 20% reduces the intensity threshold by more than a factor of $I_{\mathrm{th}}(11\%)/I_{\mathrm{th}}(13\%) \simeq 2$; at the highest densities tested, the intensity must remain below $I_{\mathrm{th}}(13\%) = 4 \times 10^{14}\ \mathrm{W\,cm^{-2}}$ to maintain the backscatter reflectivity below 5% while at $11\% n_{cr}$ the threshold intensity increased to $I_{\mathrm{th}}(11\%) = 9 \times 10^{14}\ \mathrm{W\,cm^{-2}}$. Our experimental findings are consistent with theoretical predictions for a uniform plasma since Landau damping strongly decreases with electron density in this regime. The normalized damping rate increase from $\nu_e/\omega_p = 0.01$ at $n_e/n_{cr} = 13\%$ to $\nu_e/\omega_p = 0.035$ at $n_e/n_{cr} = 11\%$. Furthermore, for intensities below $9 \times 10^{14}\ \mathrm{W\,cm^{-2}}$, less than 10% of the backscattered energy is measured outside of the FABS, which is consistent with previous experiments and with being below the filamentation threshold [18].

The sensitivity of SRS to density shown in Fig. 3 indicates the importance of controlling the plasma density and the laser beam intensity in targets where SRS will adversely affect the experiment. For example, indirect drive ignition requires that the SRS remains low to prevent hot electron production [19] and to allow efficient laser beam propagation to the hohlraum wall. Current ignition designs for the National Ignition Facility [2] mitigate SRS by remaining in the strongly damped regime ($k\lambda_d > 0.4$) when the laser beam intensity is high and keeping the laser intensity below the backscatter threshold where the density is high and the temperature is low ($k\lambda_d < 0.4$).

Figure 4 shows that polarization smoothing reduces the SRS reflectivity at all times during the experiment and for all intensities. The SRS reflectivity peaks early in time as the interaction beam turns on and the plasma is still relatively cold ($T_e = 1.5$ keV). As the plasma temperature reaches its peak temperature ($T_e = 2.8$ keV), the SRS reflectivity drops below detection levels ($R < 0.01\%$).

Figure 4(b) shows that the intensity at which 5% of the incident power is backscattered for a CPP-smoothed laser beam is increased by a factor of 1.6 ± 0.2 when adding polarization smoothing. This observation shows that polarization smoothing is an effective mitigation technique for controlling stimulated Raman scattering in a high-temperature inertial confinement fusion plasma where filamentation effects are negligible.

Simulations of the interaction beam propagation and the instantaneous SRS reflectivity using the code PF3D [20] agree well with the measured backscatter for both cases—with and without polarization smoothing [Fig. 4(b)]. These

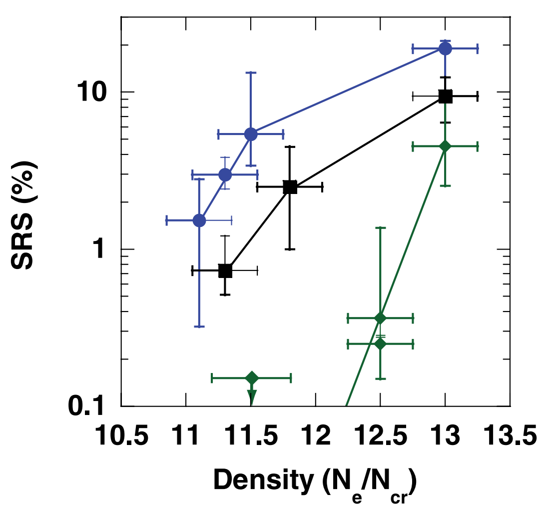

FIG. 3 (color online). The instantaneous SRS reflectivity, when full smoothing is applied (CPP and PS), is plotted as a function of the plasma density for various interaction beam intensities: (blue circles) $9 \times 10^{14}\ \mathrm{W\,cm^{-2}}$, (black squares) $5.2 \times 10^{14}\ \mathrm{W\,cm^{-2}}$, (green diamonds) $3.9 \times 10^{14}\ \mathrm{W\,cm^{-2}}$.

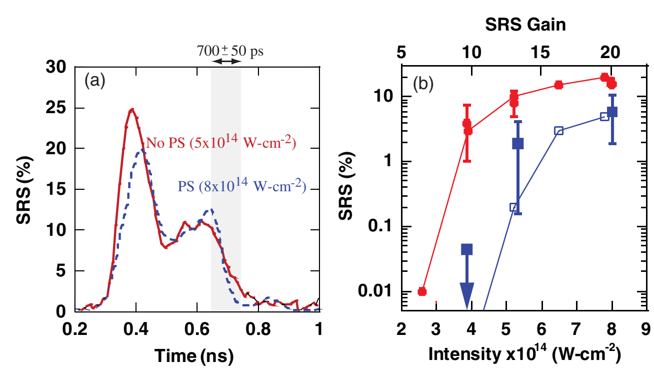

FIG. 4 (color online). (a) The measured SRS reflectivity with a CPP-smoothed beam (solid red curve) at an intensity of $5 \times 10^{14}\ \mathrm{W\,cm^{-2}}$ is equivalent at all times to the reflectivity measured at an intensity of $7.5 \times 10^{14}\ \mathrm{W\,cm^{-2}}$ when adding polarization smoothing (dashed blue curve). (b) The instantaneous SRS reflectivity at 700 ps is plotted as a function of the average interaction beam intensity; two laser-smoothing conditions are shown: CPP-only (red circles), CPP and PS (blue squares). The simulated reflectivities calculated by PF3D are shown (solid curves). All data shown are for a density of $n_e/n_{cr} = 11.5\%$.

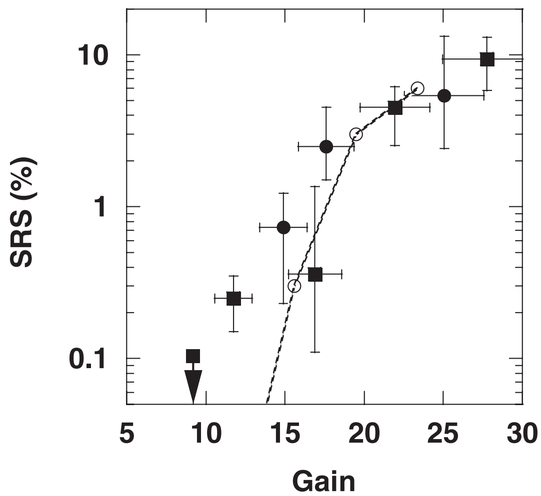

FIG. 5. The measured instantaneous SRS is plotted as a function of the linear gain exponent for intensities below $1 \times 10^{15}\ \mathrm{W\,cm^{-2}}$ (i.e., below filamentation) and a range of densities (solid circles are densities less than $12\% n_{cr}$ and solid square are densities above $12\% n_{cr}$). Polarization smoothing was used on these shots. The PF3D simulations (open circles) reproduce the measured scaling.

three-dimensional calculations use a paraxial approximation to model the whole laser beam propagating through the full 2-mm long hohlraum plasma. The code includes models for both SRS and SBS backscattering and shows that using a fluid-based modeling of SRS including linear kinetic corrections (i.e., Landau damping) coupled to accurate hydrodynamic profiles and a realistic description of the laser intensity pattern generated by various smoothing techniques leads to quantitative agreement between the measurement and calculated reflectivities [21].

Linear theory predicts that the gain exponent for stimulated Raman scattering scales strongly with the background plasma density through the Landau damping and is linear with respect to laser intensity. Accordingly, the linear gain exponent determined by postprocessing the plasma properties from the hydrodynamic simulations using the code LIP [22] can be used to compare the measured backscatter between different experimental configurations. LIP calculates the steady-state convective spatial growth rate for SRS as a function of the scattered light frequency using a kinetic description of the plasma susceptibilities. At each time, the total gain (G_{SRS}) is determined by integrating the growth rate along light rays taking into account the spatially varying plasma conditions. The error in the calculated gains were determined by the uncertainty in heat transport models. The flux limiter was varied between $0.05 < f < 0.2$, which resulted in a 10% uncertainty in the gain.

Figure 5 shows that the measured SRS reflectivity scales with linear gain exponent over a wide range of densities ($10.8\% < n_e/n_{cr} < 13\%$) and intensities ($2.5 \times 10^{14} < I < 9 \times 10^{14}\ \mathrm{W\,cm^{-2}}$). This 20% increase in the electron density corresponds to a factor of 3 decrease in the Landau damping. Furthermore, Fig. 5 demonstrates that the resulting increase in scattering with density can be mitigated by reducing the laser beam intensity to maintain a constant linear gain exponent. Indeed, the density thresholds ($R_{\mathrm{SRS}} > 5\%$) measured in Fig. 3 correspond to nearly the same linear gain ($G_{13\%} = 22$, $G_{11\%} = 24$).

In summary, we have demonstrated that for a hot-uniform plasma at ignition relevant plasma conditions, SRS has a strong dependence on the plasma density; increasing the plasma density by 20% results in an order of magnitude increase in SRS. Our SRS measurements agree with linear damping rates over a wide range of laser intensities and plasma densities. Furthermore, we have experimentally demonstrated that the laser intensity can be increased by 60% when using polarization smoothing while maintaining similar backscatter losses. These results highlight the importance of controlling the plasma density and choosing the proper laser beam intensity in future ignition target designs.

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[1] J. D. Lindl *et al.*, Phys. Plasmas **11**, 339 (2004).
[2] D. A. Callahan *et al.*, Phys. Plasmas **13**, 056307 (2006).
[3] B. MacGowan *et al.*, Phys. Plasmas **3**, 2029 (1996).
[4] D. S. Montgomery *et al.*, Phys. Plasmas **3**, 1728 (1996).
[5] H. A. Baldis *et al.*, Phys. Rev. Lett. **62**, 2829 (1989).
[6] W. Seka *et al.*, Phys. Fluids **27**, 2181 (1984).
[7] J. C. Fernandez *et al.*, Phys. Plasmas **7**, 3743 (2000).
[8] S. H. Glenzer *et al.*, Phys. Rev. Lett. **86**, 2565 (2001).
[9] J. D. Moody *et al.*, Phys. Rev. Lett. **86**, 2810 (2001).
[10] D. S. Montgomery *et al.*, Phys. Plasmas **9**, 2311 (2002).
[11] M. M. Marinak *et al.*, Phys. Plasmas **8**, 2275 (2001).
[12] D. Froula *et al.*, Phys. Plasmas **13**, 052704 (2006).
[13] T. Boehly *et al.*, Opt. Commun. **133**, 495 (1997).
[14] S. Dixit *et al.*, Opt. Lett. **21**, 1715 (1996).
[15] D. H. Froula *et al.*, Phys. Rev. Lett. **101**, 115002 (2008).
[16] S. Regan *et al.*, Phys. Plasmas **6**, 2072 (1999).
[17] P. Neumayer *et al.*, Rev. Sci. Instrum. **79**, 10F548 (2008).
[18] D. H. Froula *et al.*, Phys. Rev. Lett. **98**, 085001 (2007).
[19] E. Dewald *et al.*, Phys. Plasmas **13**, 056315 (2006).
[20] R. L. Berger *et al.*, Phys. Plasmas **5**, 4337 (1998).
[21] L. Divol *et al.*, Phys. Rev. Lett. **100**, 255001 (2008).
[22] N. B. Meezan *et al.*, Phys. Plasmas **14**, 056304 (2007).