Kinetic Inflation of Convective Raman Scattering Driven by a Broadband, Frequency-Modulated Laser Pulse

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Stimulated Raman scattering (SRS), a process in which a light wave decays into a plasma wave and another light wave, can reduce laser absorption by scattering light away from the target. SRS can also generate hot electrons that preheat the fusion fuel in the direct-drive inertial confinement fusion (ICF) scheme, making fuel compression more difficult. Inflationary SRS (iSRS) occurs in the kinetic regime when the electron velocity distribution is flattened due to electron trapping. The flattening of the electron distribution not only reduces the Landau damping rate but also decreases the plasma wave frequency, leading to an SRS reflectivity much higher than what is predicted by the convective SRS gain model[1] for a Maxwellian velocity distribution. In this work, we study the convective gain and the kinetic inflation threshold for SRS driven by a broadband laser in an inhomogeneous plasma using the particle-in-cell (PIC) code *OSIRIS*. Based on the cancellation of the bandwidth effect and the spatial detuning effect, we derived a simple formula that can predict when the convective SRS gain is enhanced and when the iSRS threshold reaches a minimum. The analytic formula is consistent with the PIC simulation results over a broad range of parameter space.

The frequency of a pump with a sinusoidal phase modulation can be written as $\omega_0(x,t)=\bar{\omega}_0+\omega_\mathrm{m}\delta\sin\left(\omega_\mathrm{m}t-x\omega_\mathrm{m}/c\right)$, where $\bar{\omega}_0$ is the central frequency of the pump and $\omega_\mathrm{m}(\delta)$ is the phase modulation frequency (depth). The bandwidth of this broadband pump is defined as $\Delta\omega=2\omega_\mathrm{m}\delta/\pi$. If SRS is driven by a broadband laser in an inhomogeneous plasma, SRS resonance (the location where the frequency mismatch is close to zero) moves in time. When the SRS resonance follows the trajectory of the SRS scattered light, i.e.,

$$\xi\equiv\frac{\Delta\omega\omega_\mathrm{m}}{\bar{\omega}_0^2}=\frac{\omega_\mathrm{p}}{8\bar{\omega}_0k_0L_\mathrm{n}}, \tag{1}$$

where ω_p is the local plasma frequency, k_0 is the laser wave vector, and L_n is the density scale length, the SRS amplification is greatly enhanced.

Figure 1 shows that the condition for achieving the peak convective amplification depends on neither the temperature T_e nor the laser bandwidth $\Delta\omega$ (or the modulation frequency ω_m) alone. The convective gains in the fluid (open symbols) and kinetic (solid symbols) regimes for various bandwidths are normalized to the respective Rosenbluth gains,[1] 1.67 (fluid regime) and 1.14 (kinetic regime). As a reference, two runs with zero bandwidth (denoted as "$\Delta\omega=0$") were carried out and their convective gains are shown as stars in Fig. 1. The Rosenbluth theory is well recovered by the zero-bandwidth simulation in the fluid regime. In both the fluid (T_e = 0.1 keV) and kinetic (T_e = 2 keV) regimes and for all bandwidths, the convective gains increase as ξ increases, peaking near the value of ξ predicted by Eq. (1), and then decreasing back to the level at $\xi=0$.

Because iSRS depends on the plasma wave amplitude, one would expect the iSRS threshold to decrease when the maximum convective gain is enhanced. Accordingly, the iSRS threshold is expected to reach its minimum value when the maximum-gain condition [Eq. (1)] is satisfied. We carried out 1-D PIC simulations of self-seeded SRS in the kinetic regime to examine this hypothesis.

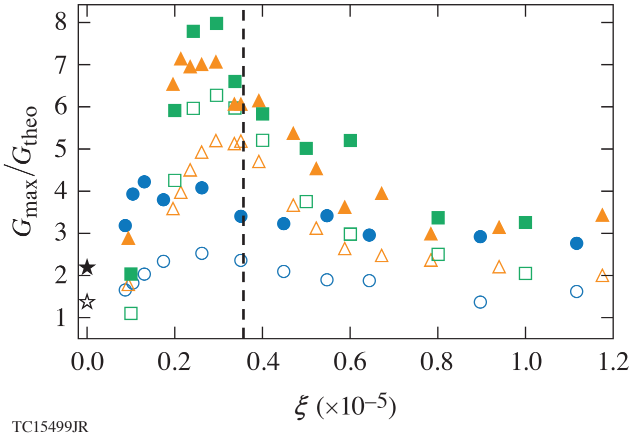

Figure 1
The maximum convective SRS gains in the fluid regime (open symbols) and kinetic regime (solid symbols) as functions of the normalized maximum chirp ξ. Four sets of simulations with bandwidth $\Delta\omega = 0$ (stars), 2 THz (circles), 6 THz (triangles), and 12 THz (squares) were performed in both the fluid and kinetic regimes. The vertical dashed line was obtained by evaluating Eq. (1).

Figure 2(a) shows the time-averaged reflectivity as a function of pump intensity for three different bandwidths ($\Delta\omega = 0$, 4 and 15 THz). The sharp rise of the SRS reflectivity is a characteristic feature of kinetic inflation. The iSRS thresholds were obtained by fitting the reflectivity curve and then solving for the intensity corresponding to the steepest slope of the fitted function. The fitting function was $f(I) = \tanh[g(I - I_{\text{p}}) + a]\,(pI + q)$ for the free parameters g, I_{p}, a, p, and q. The iSRS threshold is defined as the pump intensity corresponding to the inflection point of the fitted curve.

Figure 2(b) shows that the iSRS threshold as a function of the normalized maximum chirp ξ reaches its minimum when the maximum-gain condition is satisfied somewhere in the simulation region (between the vertical black dashed lines) regardless of the electron temperature. The horizontal dashed blue (dashed–dotted orange) line corresponds to the iSRS threshold at zero bandwidth for the 2-keV (4-keV) simulations. The iSRS threshold initially decreases as the maximum convective SRS gain is enhanced ($\Delta\omega\omega_{\text{m}} \le \omega_{\text{p}}c/8L_{\text{n}}$) and then increases when the maximum local chirp rate of the pump exceeds the spatial detuning due to the density gradient $\left(\Delta\omega\omega_m \gg \omega_{\text{p}}c/8L_{\text{n}}\right)$. The thresholds for the two temperatures are quantitatively close to each other

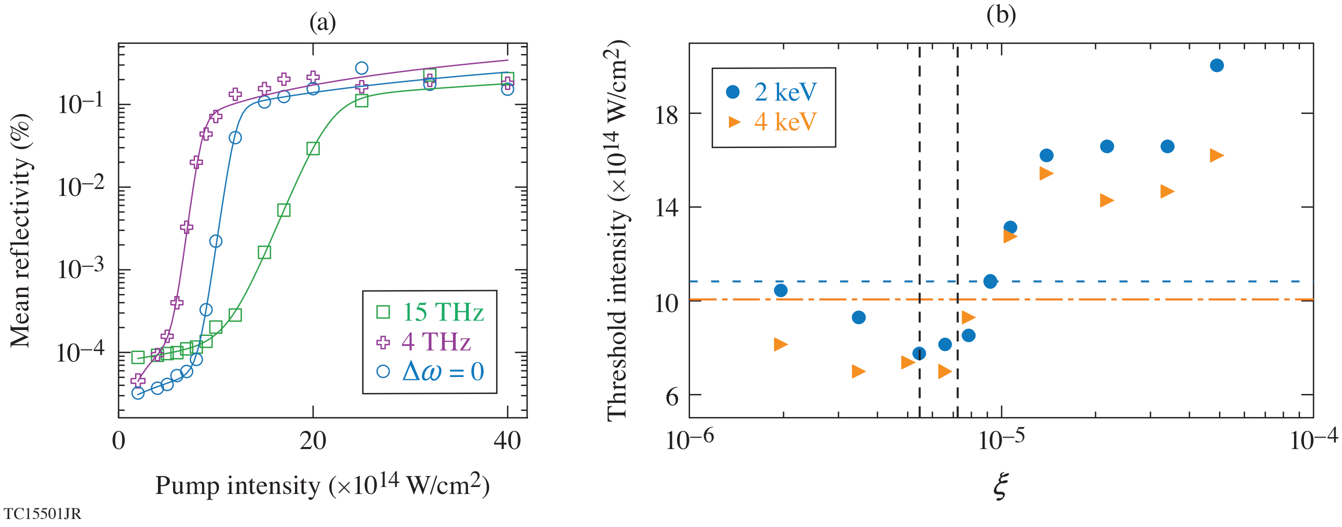

Figure 2
(a) The fractional reflectivity as a function of the laser pump intensity for laser bandwidth, overlaid with the fits of the reflectivity data. (b) The iSRS threshold in terms of pump intensity as a function of the normalized maximum chirp ξ for two sets of simulations with different electron temperatures. The dotted blue (dashed–dotted orange) line corresponds to the iSRS threshold at zero bandwidth for 2-keV (4-keV) electron temperature. The two dashed vertical lines correspond to the maximum-gain condition at the minimum and maximum plasma densities.

for all ξ values. The fact that the iSRS threshold depends only weakly on the laser bandwidth alone is encouraging for ICF target design: for a given finite bandwidth, one can mitigate iSRS by tuning the maximum chirp away from the maximum-gain condition.

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1. M. N. Rosenbluth, Phys. Rev. Lett. **29**, 565 (1972).