The Role of Pump Depletion in Stimulated Raman Scattering for NIF Parameters

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Motivation

- When laser light passes through a hohlraum during indirect drive, it can interact with a plasma and potentially produce Stimulated Raman Scattering (SRS)
  - Backscattering can be a direct loss of laser energy driving the implosion
  - Scattering can impact implosion symmetry and it can produce hot electrons which preheat the target
- Backscatter is limited by highly nonlinear physics which is incompletely understood
  - Several mechanisms have been proposed for the saturation of SRS
    - Nonlinear frequency shift* (Vu et al. PRL 2001)
    - Trapped particle instability** (Brunner and Valeo PRL 2004)
    - All rely on trapped particle effects and/or modification of the electron distribution function
- To focus these efforts, we have looked at how much incident laser energy makes it through the plasma

Simulation Parameters

- We have simulated a wide range of parameters in our study of SRS
  - Full-PIC code -- OSIRIS
  - Physical Length = 100 µm
  - 8192 cells
  - Mobile and fixed ions
  - 256-2048 particles/cell
  - 1D and 2D
    - Both plane wave and finite-width pulse for 2D

- In most cases, forward scatter and rescatter of the back-scatter dominates the long time behavior

- This poster is focused on:
  - 1D simulations, fixed ions
  - The initial onset of Raman backscatter
**Basic Picture**

\( T_e = 3 \text{ keV}, \frac{n}{n_c} = 0.129 \) \((k\lambda_D = 0.30), \text{ laser } v_{osc} = 0.01)\)

Plasma waves

Transverse light, split into **backward** and **forward** going
To compare the runs, backscattering is investigated through:
- backward light (backscattered light wave)
- and/or
depletion of forward light (incident light wave)
Depletion of forward light

- Black lines form the reference
  - Each black line is from the simulation with $v_{osc} = 0.006$
  - $v_{osc} = 0.006$ is just above the instability threshold for these plasma parameters

- Green lines are the amount of incident laser light that makes it through the simulation plasma

- The pump is consistently depleted to the threshold level
Electron temperature is held constant at 3 keV, but density varies between plots and driving laser intensities vary within a plot:

- Color maps correspond to laser $v_{osc}$
- Left to right has $n/n_{cr} = (0.161, 0.129, 0.105)$
- Corresponding to $k\lambda_D$ for Raman backscattering of $(0.25, 0.30, 0.35)$

Similar behavior with pump depletion is observed for the higher density case (lower $k\lambda_D$), but begins to deviate for lower density (higher $k\lambda_D$).
Nonlinear behavior at higher $k\lambda_D$

Parameters: $T_e = 3\text{keV}$, $n/n_{cr} = (0.161 \text{ left, } 0.105 \text{ right})$, $k\lambda_D = (0.25 \text{ left, } 0.35 \text{ right})$

Plots of frequency vs wavenumber for the longitudinal field (plasma waves)

- The driving intensities are above onset levels in both cases
  - And correspond to highest intensity levels of previous slide (“Pump depletion as density is varied”)
- Frequency is lower on the right due to density (plasma frequency is lower)
- However, there is also more nonlinear behavior, with a “frequency streak” and beam-like behavior (this has also been referenced as side-band behavior)

Note: backscatter at $\sim(0.4, 1.5)$ and forwards scatter at $\sim(0.3, 0.4)$
Looking at gain length

- The asterisks pinpoint the density and temperature of the previous simulations ($k\lambda_D$ in parentheses)

- Colors show gain length for the instability (in units of $c/\omega_0$)
  - Gain Length = ($\text{Damping Rate} \times \text{Light Group Velocity})/(\text{Growth Rate})^2$

- As $v_{osc} = 0.005 \rightarrow 0.010$ (top vs bottom plot)
  - The onset intensity for SRS found in simulations is crossed for the $[k\lambda_D = 0.30]$ case
  - The gain length for instability growth goes from longer than the simulated region to shorter for this case
    - Simulated Region = 1800 $c/\omega_0$

- For the $[k\lambda_D = 0.35, 0.25]$ cases, it is also evident that the onset intensity thresholds of ($\sim 0.011, 0.002$ respectively) match with whether the simulation domain is longer/shorter than the gain length
For $T=3\text{keV}$, $k\lambda_D=0.30$: Shortening the box

- To see how the length of the interaction region (box length) affects possible SRS activity, we shortened the simulated region
  - From $1800 \, \text{c}/\omega_0$ to $500 \, \text{c}/\omega_0$
- Looking purely at the plasma wave activity, it appears fairly similar, albeit more regular
  - successive bursts of SRS grow after previous bursts convect out of the box/region-of-activity

Both are longitudinal E-field
For $T=3\text{keV}$, $k\lambda_D=0.30$ : Shortening the box II

- The forward and backward light exiting the box show large differences between the two
  - Black for long (original box), green for shorter
- Backscattered light for the longer box is much more dramatically bursty
  - Scattering does not necessarily just turn on and off
  - Even if plasma waves look saturated and are convecting through the box, there can be recurring scattering events going on throughout the plasma
- Pump depletion of the forward light for the longer box is more significant
  - If the pump depletes to the onset intensity matching roughly with $[\text{BoxLength} = \text{GainLength}]$, then we would expect a shorter box to have a higher threshold value
  - Less length for interaction means less energy is drawn out of the laser
Scattering off convecting plasma-packets

• Even for the shorter box length, one can see that scattering may recur off the convecting plasma waves

• Backscattered light matches with a convecting, nonlinear plasma “packet”
\( k\lambda_D = 0.30 \) (I)

- In the next slides, we keep \( k\lambda_D \) of the SRS plasma wave fixed (\( k\lambda_D = 0.30 \))
- There are two temperatures, 1 and 3 keV
- The instability growth rate is the same between the two cases
  - By varying the driving laser intensity
  - Both are kept significantly above their respective thresholds
- The maximum E-field of the plasma waves is still lower for the lower-temperature case
  - Saturation does not appear to be correlated with growth rate

Te = 1keV  
Note: scale half that of 3kev for ease of viewing
The group and phase velocities of the SRS plasma wave are evident in the instability’s behavior. The appearance of plasma wave energy moving at the phase velocity is evidence that trapped particles can stream across from an already saturated point and disrupt the SRS in neighboring regions of the plasma.

Note: Similar structures/velocities are also evident in the 3keV plot on the previous slide.
\[ k \lambda_D = 0.30 \text{ (III)} \]

The phase velocity, while different in the two cases, still has qualitatively similar “beam” formation. When the SRS plasma wave is modulated so that trapped particles begin streaming between vortices, there are beam modes that are evidenced in \( \omega \) and \( k \) space. These beam-like particles result from the degenerating wave-structure.
\[ k \lambda_D = 0.30 \quad (IV) \]

- Lineouts of the forward light exiting the box show much more depletion for the 3keV case
- The horizontal lines represent a theoretical onset intensity level based on setting the gain length equal to the plasma length
- It appears that nonlinearities more strongly affect the lower temperature/lower density case
  - One idea might be that although frequency shifts are similar in both cases, the frequency shift is proportionally larger in the 1keV case, thereby affecting the instability before it pump depletes to the onset intensity level
Conclusions

- Density, temperature, and driving laser intensity were varied, while keeping $k\lambda_D$ and gain length fixed.

- The length of the available region for instability affects the magnitude of the growth:
  - For example, when $T_e = 3\text{keV}$ and $k\lambda_D = 0.30$, the incident laser is depleted until it reaches the onset intensity level.

- The instability may saturate before it fully depletes the pump if nonlinearities are strong enough.

- Even though the plasma wave may have saturated in magnitude, light still Raman-scatters off convecting plasma packets.

- Future work includes exploring at which time the kinetic nonlinearities can significantly impact the depletion of laser energy.