Mitigation of Inflationary Stimulated Raman Scattering with Laser Bandwidth



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Summary

Laser bandwidth in the form of frequency modulation can mitigate inflationary stimulated Raman scattering

- Stimulated Raman scattering (SRS) can inhibit the performance of ICF implosions by redirecting laser energy into unwanted directions and generating hot electrons that preheat the target fuel
- Inflationary SRS (ISRS) in inhomogeneous plasma occurs when electron trapping in the driven plasma wave creates a frequency shift that maintains phase matching over long distances, greatly enhancing the gain
- The instantaneous SRS reflectivity can be estimated based on local laser chirp and plasma wave amplitude
- Laser bandwidth enhances SRS when the scattered light follows the SRS resonance over a time long enough for electron trapping
- Laser bandwidth mitigates ISRS by shortening the interaction time

Broadband drivers in development at LLE (FLUX) have enough bandwidth to mitigate ISRS at ignition scale



In an inhomogeneous plasma, stimulated Raman scattering is resonant over a finite interaction length

A seed beam is amplified over a region where the frequency mismatch between the waves is close to zero ($\Delta \Omega(x) \equiv \omega_0 - \omega_1 - \omega_2(x) \approx 0$), leading to a fixed amplification*





Particle trapping modifies the local Langmuir wave frequency, which increases the interaction length and consequently the linear gain



* H. X. Vu, D. F. DuBois, and B. Bezzerides, Phys. Plasmas 9, 1745 (2002)



Kinetic inflation* occurs when particle trapping flattens the electron distribution





The transient gain is enhanced when the scattered light follows the SRS resonance



 $d\Delta\omega =$ of plasma and pump parameters:*

* H. Wen et al, Phys. Plasmas 28, 042109 (2021)



The enhanced transient gain can trigger kinetic inflation



9x larger amplification factor than that without kinetic inflation



The transient gain is reduced when the scattered light propagates in the opposite direction of the SRS resonance



A large bandwidth mitigates the transient gain enhancement of SRS



The frequency modulation affects convective gains in two ways: shifting the location of resonance and changing the effective wave vector mismatch

•
$$\left(1+\frac{V_1}{V_0}\right)\frac{\partial a_1}{\partial t}+\nu_1 a_1+V_1\frac{\partial a_1}{\partial x}+\frac{i}{2}\left[V_1\kappa(x)+\left(1+\frac{V_1}{V_0}\right)\delta\omega(t)-\left(1+\frac{V_1}{V_0}\right)\delta\omega(0)\right]a_1=\gamma_0 a_2$$

• $\left(1-\frac{V_2}{V_0}\right)\frac{\partial a_2}{\partial t}+\nu_2 a_1-V_2\frac{\partial a_2}{\partial x}+\frac{i}{2}\left[V_2\kappa(x)+\left(1-\frac{V_2}{V_0}\right)\delta\omega(t)-\left(1-\frac{V_2}{V_0}\right)\delta\omega(0)\right]a_2=\gamma_0 a_1$

effective mismatch

• Assuming $\kappa(x) = \kappa' x$ and $\delta \omega(t) = qt$ near the resonance location at t = 0, the convective gain* $G \approx \frac{G_R}{1-\eta}$, where $\eta = \frac{4q}{V_1 V_2 \kappa'}$

resonance location

- This result can be approximated using a simple model
 - Wave amplitudes grow with the growth rate $\gamma = \sqrt{\gamma_0^2 \frac{\delta\omega^2}{4}}$
 - The interaction ends when the frequency mismatch becomes larger than $\pi\gamma_0$



The normalized instantaneous gain is determined by the instantaneous chirp of the laser and the plasma waves that already exist in the interaction region





This model relies only on information localized in space and time. Therefore, it can be applied to arbitrary bandwidth forms



Without accounting for the electron plasma wave, the estimated gain is in reasonable agreement with simulation results in the $\eta \ll 1$ regime



* Estimation without EPW correction



The contribution of plasma waves become important when $\eta \approx 1$





The simple model is applicable for a wide range of temperatures





The simple model recovers the quantitative behaviors of the SRS gain at $\eta pprox 1$





The simple model approximates the simulation results for random frequency modulation





The inflationary SRS threshold reaches a minimum at the bandwidth when the SRS gain enhancement is most likely to occur



- Exponential density profile $L_{\rm n}=400\,\mu{
 m m}$
- 1D $I_0 = 1.31 \times 10^{15} \text{ W/cm}^2$, 2D $I_0 = 2.24 \times 10^{15} \text{ W/cm}^2$

