Multibeam Absolute Stimulated Raman Scattering

R. K. Follett,[1] J. G. Shaw,[1] J. F. Myatt,[2] D. H. Froula,[1] and J. P. Palastro[1]

[1]Laboratory for Laser Energetics, University of Rochester
[2]Department of Electrical and Computer Engineering, University of Alberta

Direct-drive inertial confinement fusion (ICF) uses multiple overlapping laser beams to symmetrically implode a millimeter-scale cryogenic capsule of deuterium–tritium fuel. The on-target laser intensity is limited by laser–plasma instabilities that can scatter the incident laser light away from the target and produce high-energy electrons that preheat and degrade the implosion. The two primary instabilities that generate hot electrons in direct-drive ICF experiments are stimulated Raman scattering (SRS), which is the decay of an electromagnetic wave (EMW) into another EMW and an electron plasma wave (EPW), and two-plasmon decay (TPD), which is the decay of an EMW into two EPW's. Understanding the thresholds for these instabilities is critical for designing ICF implosions and developing mitigation strategies.

In most direct-drive ICF experiments, the intensity of a single laser beam is below the instability threshold for either SRS or TPD. For the case of TPD, numerous experimental and theoretical papers have shown that multiple laser beams can interact with shared EPW's, resulting in the instability being driven with single-beam laser intensities well below the instability threshold.[1–4] In particular, experiments on the OMEGA laser have demonstrated that using the overlapped laser intensity in the threshold formula for a monochromatic plane wave provides a reasonable approximation to the multibeam threshold. In contrast, relatively little work has been done on multibeam SRS because SRS is not typically observed in implosion experiments on the OMEGA laser.

This summary presents 3-D calculations of multibeam absolute SRS thresholds. The results provide an explanation for a number of experimental observations on OMEGA and the National Ignition Facility (NIF) that cannot be understood in terms of single-beam thresholds or shared daughter-wave theories. The multibeam coupling is shown to be weaker for SRS than for TPD, which results in thresholds that are consistent with both the NIF and OMEGA experiments. Additionally, the simulations show that it is generally not a good approximation to use the overlapped intensity in the single-beam threshold formulas to predict multibeam instability thresholds for SRS or TPD because the multibeam coupling is sensitive to the density scale length. Finally, in contrast to the single-beam SRS results, the shared EMW mode driven near the quarter-critical density is found to have a lower threshold than the absolute sidescatter mode that occurs at lower densities.

In inhomogeneous plasmas, TPD and SRS can have both convectively and absolutely unstable modes. Convectively unstable modes undergo finite spatial amplification when propagating across a resonant region.[5] Absolute instability corresponds to one of the daughter waves growing more rapidly than energy is convected out of the resonant region, resulting in temporal growth at a fixed point in space.[6,7] Here we will focus on the absolute form of the instabilities because, for conditions relevant to direct-drive ICF, SRS and TPD typically become absolutely unstable at laser intensities where the convective gains are still modest. There are two situations where energy advects slowly out of the resonant region and the absolute thresholds are minimized: (1) one of the daughter waves propagates nearly perpendicular to the density gradient, and (2) one of the daughter waves has a group velocity near zero, which occurs only near $n_\mathrm{c}/4$ for TPD and SRS.

The calculations presented here were performed using the laser-plasma simulation environment (*LPSE*) code.[8] *LPSE* solves the time-enveloped wave equations for the electrostatic and electromagnetic plasma response. The individual evolution equations in *LPSE* are linearized, but the coupling between the electrostatic and electromagnetic response leads to nonlinearity. Thresholds are determined by initially bounding the threshold and then iteratively running *LPSE* to narrow the threshold bounds until acceptable accuracy is achieved. The equations that were solved and the technique used to calculate thresholds are discussed in detail in Ref. 9. Unless otherwise specified, the simulations used a linear density gradient from $n_e/n_c = 0.22$ to 0.27, $T_e = 2$ keV, and $\lambda_0 = 2\pi c/\omega_0 = 0.351$ μm, and cubic grid cells with a side length of 0.074 μm. The grids were 10 μm wide in the transverse directions (perpendicular to the density gradient) with transverse periodic boundary conditions and absorbing longitudinal boundary conditions. All 3-D simulations used six beams with *f*/6.7 phase plates and polarization smoothing incident at 23° relative to and distributed uniformly about a common axis (similar to an OMEGA "hex"). Error bars correspond to the standard deviation from ensembles of calculations with random realizations of beam polarization, phase, and noise seed.

The primary result presented here is the 3-D multibeam absolute instability thresholds for TPD and SRS shown in Fig. 1. The thresholds are normalized to the single-beam thresholds ($I_{\text{thr,SB}}$) (Refs. 6 and 7). The fact that $I_{\text{thr}}/I_{\text{thr,SB}} \approx 1$ for OMEGA-like conditions ($L_n = 200$ μm, $T_e = 2$ keV) is consistent with the empirical observation that the TPD threshold can be predicted by using the overlapped intensity in the single-beam threshold formula. However, this is not true in general for TPD or SRS because the multibeam coupling becomes weaker with increasing scale length. Additionally, the multibeam coupling for SRS is weaker than for TPD, which explains why TPD is the predominant instability observed in OMEGA experiments despite the fact that $I_{\text{thr,TPD}} > I_{\text{thr,SRS}}$.

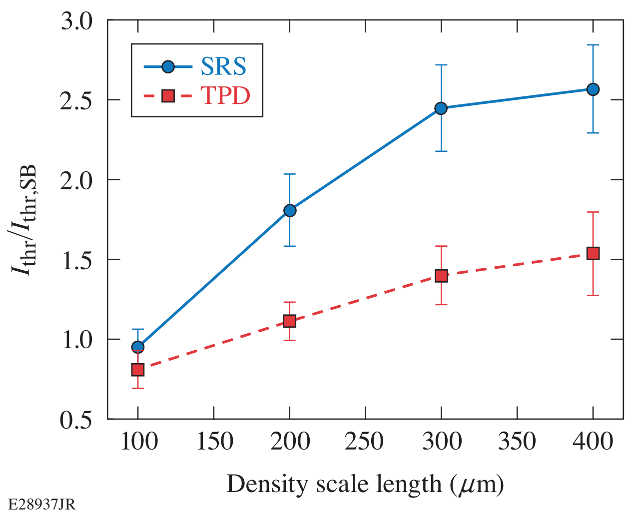

Figure 1
Absolute instability thresholds (normalized to the single-beam thresholds) for SRS (blue circles) and TPD (red squares) near $n_c/4$ as a function of density scale length using six beams with phase plates and polarization smoothing at $T_e = 2$ keV. The error bars were obtained from an ensemble of four calculations with random realizations of polarization and phase.

This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

1. C. Stoeckl *et al.*, Phys. Rev. Lett. **90**, 235002 (2003).
2. D. T. Michel *et al.*, Phys. Rev. Lett. **109**, 155007 (2012).
3. J. Zhang *et al.*, Phys. Rev. Lett. **113**, 105001 (2014).
4. R. K. Follett *et al.*, Phys. Rev. E **91**, 031104(R) (2015).
5. M. N. Rosenbluth, Phys. Rev. Lett. **29**, 565 (1972).

6. B. B. Afeyan and E. A. Williams, Phys. Fluids **28**, 3397 (1985).

7. A. Simon *et al*., Phys. Fluids **26**, 3107 (1983).

8. J. F. Myatt *et al*., J. Comp. Phys. **399**, 108916 (2019).

9. R. K. Follett *et al*., Phys. Plasmas **26**, 062111 (2019).