Thresholds of Absolute Instabilities Driven by a Broadband Laser

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In direct-drive inertial confinement fusion (ICF), a millimeter-scale spherical capsule is uniformly illuminated by symmetrically oriented laser beams.[1] The lasers ablate the outer layer of the capsule, which generates pressure to implode the fuel. The primary mechanism by which laser energy is converted into thermal energy in the ablator is through electron–ion collisional absorption, but a number of parametric instabilities can also occur when the lasers interact with the plasma corona of the imploding capsule, many of which can adversely affect the quality of the implosion.

Of particular importance are the stimulated Raman scattering (SRS) and two-plasmon–decay (TPD) instabilities, which correspond to the decay of an incident electromagnetic wave into an electromagnetic wave and an electron plasma wave (EPW) or into two EPW's, respectively.[2] The resulting high-phase-velocity EPW's can accelerate electrons to high energies. These energetic electrons can deposit their energy in the cold fuel, reducing the compressibility of the capsule.

It has long been known that introducing bandwidth into the drive lasers reduces the homogeneous growth rate for these instabilities,[3] and it has been shown analytically that bandwidth can increase the thresholds for absolute SRS and TPD.[4] There are no existing lasers, however, with sufficient energy and bandwidth to demonstrate instability suppression in ICF experiments. Optical parametric amplification of a broadband seed beam using a high-energy monochromatic pump beam provides a potential path toward high-energy broadband lasers. As an alternative, recent experiments have successfully demonstrated that stimulated rotational Raman scattering can increase the bandwidth of high-energy lasers.[5]

This summary presents a numerical study of absolute instability thresholds for SRS and TPD using a broadband pump beam. The calculations suggest that the absolute thresholds can be increased significantly with ~1% bandwidth at ICF-relevant conditions. Several different field spectra are considered, and it is found that the coherence time of the laser is the predominant factor in determining the effectiveness of a given pump spectrum.

Figure 1 shows absolute instability thresholds for SRS and TPD as a function of the laser period over the laser coherence time for Gaussian, Lorentzian, flat, and Kubo–Anderson process (KAP) power spectra (KAP bandwidth corresponds to a laser field that has a constant intensity but undergoes random Poisson-distributed phase jumps). The thresholds were calculated using the laser–plasma simulation environment (*LPSE*). The coherence time was defined as $\tau_c = \int_{-\infty}^{\infty} |g(\tau)|^2 d\tau$, where $g(\tau) \equiv \left\langle E_0^*(t) E_0(t+\tau) \right\rangle / \left\langle |E_0(t)|^2 \right\rangle$ and E_0 is the electric field of the pump beam. The thresholds are normalized to the analytic thresholds for a monochromatic pump[6,7]

$$I_{\mathrm{thr,SRS}}\left(10^{14}\ \mathrm{W/cm^2}\right) = \frac{858}{\left[L_\mathrm{n}(\mu\mathrm{m})\right]^{4/3}\left[\lambda_0(\mu\mathrm{m})\right]^{2/3}}, \tag{1}$$

where L_n is the density scale length and λ_0 is the pump central wavelength.

As a function of coherence time, the thresholds for the various power spectra shown in Fig. 1 exhibit a universal scaling. This demonstrates that the pump coherence time is the predominant factor in determining how effective a laser with a given power spectrum will be for instability suppression. Despite being the only field spectrum that does not have amplitude modulation in the time domain, KAP bandwidth results in nearly the same thresholds as the other spectra, which indicates that amplitude modulation does not significantly impact the absolute threshold.

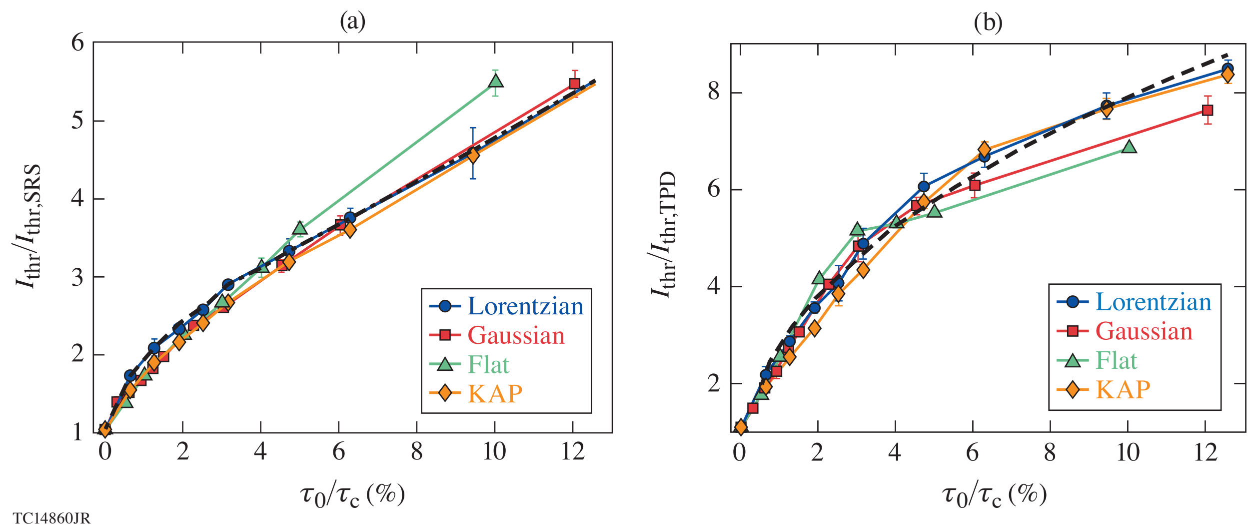

Figure 1
Absolute (a) SRS and (b) TPD thresholds from *LPSE* simulations plotted in terms of the laser period over the coherence time for an L_n = 208-μm scale length plasma with an electron temperature of T_e = 2 keV. The various field spectra are represented by blue circles (Lorentzian), red squares (Gaussian), green triangles (flat), and yellow diamonds (KAP). The error bars correspond to the standard deviation from four-run ensembles varying the random-number–generator seed for the pump spectra. τ_0 is the laser period.

Approximate scaling laws for the absolute instability thresholds were obtained by systematically varying the laser bandwidth, density scale length, central wavelength, and electron temperature:

$$I^{\tau}_{\text{thr,SRS}}\left(10^{14}\ \text{W/cm}^2\right) \approx \frac{798}{L_n(\mu\text{m})\,\lambda_0(\mu\text{m})}\left(\frac{\tau_0}{\tau_c}\right)^{1/3}, \tag{2}$$

$$I^{\tau}_{\text{thr,TPD}}\left(10^{14}\ \text{W/cm}^2\right) \approx \frac{232\left[T_e(\text{keV})\right]^{3/4}}{\left[L_n(\mu\text{m})\right]^{2/3}\left[\lambda_0(\mu\text{m})\right]^{4/3}}\left(\frac{\tau_0}{\tau_c}\right)^{1/2}, \tag{3}$$

where T_e is the electron temperature. In addition to the bandwidth dependence in Eqs. (2) and (3), the threshold scalings with L_n, λ_0, and T_e have changed relative to the monochromatic result. Equations (2) and (3) predict that a laser with $\tau_0/\tau_c \approx 1.5\%$ would allow a doubling of the drive intensity in direct-drive implosions.

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.

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