The Effects of Beam Intensity Structure on Two-Plasmon Decay in Direct-Drive Laser Fusion Targets

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Two-plasmon decay involves the conversion of an incident electromagnetic wave into two Langmuir waves at the quarter-critical density. Because of its comparatively low threshold and potential for hot-electron production, the theory of this instability has been extensively studied. Its linear behavior for idealized one-dimensional pump and plasma structures is well known. Two-plasmon decay is essentially a two-dimensional instability, however, since at least one of the product plasma waves must propagate at a finite angle to the pump. Thus, the short-scale-length azimuthal intensity variations produced by beam-smoothing techniques such as SSD can be expected to affect the growth and saturation of the instability. The size threshold for two-plasmon decay to be transversely localized as an absolute instability in a hot spot is calculated and compared with the intensity structures expected at quarter-critical density. This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC03-92SF19460.

Summary

Hot-spot effectiveness in driving two-plasmon decay is reduced relative to SBS and SRS because of the two-dimensional nature of the instability

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- SBS and SRS have maximum growth rates for backscatter; in two-plasmon decay the fastest-growing plasma waves have perpendicular components comparable to their parallel components.
- Hot spots in smoothed beams are aligned with the pump direction, so they should be less effective in driving TPD than SRS or SBS.
- TPD is near threshold for direct-drive conditions, but the threshold is exceeded in hot spots.
- The two-plasmon decay waves tend to propagate out of hot spots laterally, but absolute growth can still occur.
- Shorter amplification range may reduce hot-electron production by nonlinearly saturated waves.

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Outline

- Calculation of intensity distribution in spherically symmetric coronas
- Calculation of transverse absolute instability thresholds for two-plasmon decay (TPD)
- Comparison with hot-spot radii and intensities
- Summary and conclusions

The intensity pattern in a spherically symmetric plasma corona may be calculated using spherical harmonics

- **Neglecting polarization, the field amplitude satisfies the scalar wave equation:**

$$\nabla^2 \mathbf{E} + \frac{\omega^2}{c^2}\,\varepsilon(\mathbf{r})\mathbf{E} = 0$$

- **Absorption can be included by using a complex dielectric function:**

$$\varepsilon(\mathbf{r}) = 1 - \frac{\omega_{pe}^2(\mathbf{r})}{\omega\left[\omega + i\upsilon_{ei}(\mathbf{r})\right]}$$

- **$\mathbf{E}(\mathbf{r}, \theta, \phi)$ is expanded in spherical harmonics:**

$$\mathbf{E}(\mathbf{r},\theta,\phi) = \sum_{\ell,m} a_{\ell,m}\,\frac{1}{r}\,g_{\ell}(\mathbf{r})\,Y_{\ell,m}(\theta,\phi)$$

The solution to the radial wave equation can be represented by an asymptotic approximation

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- The radial wave functions satisfy

$$\frac{d^2g}{ds^2}+\left[\varepsilon(s)-\frac{\ell(\ell+1)}{s^2}\right]g=0,\ s=\frac{\omega_0}{c}r$$

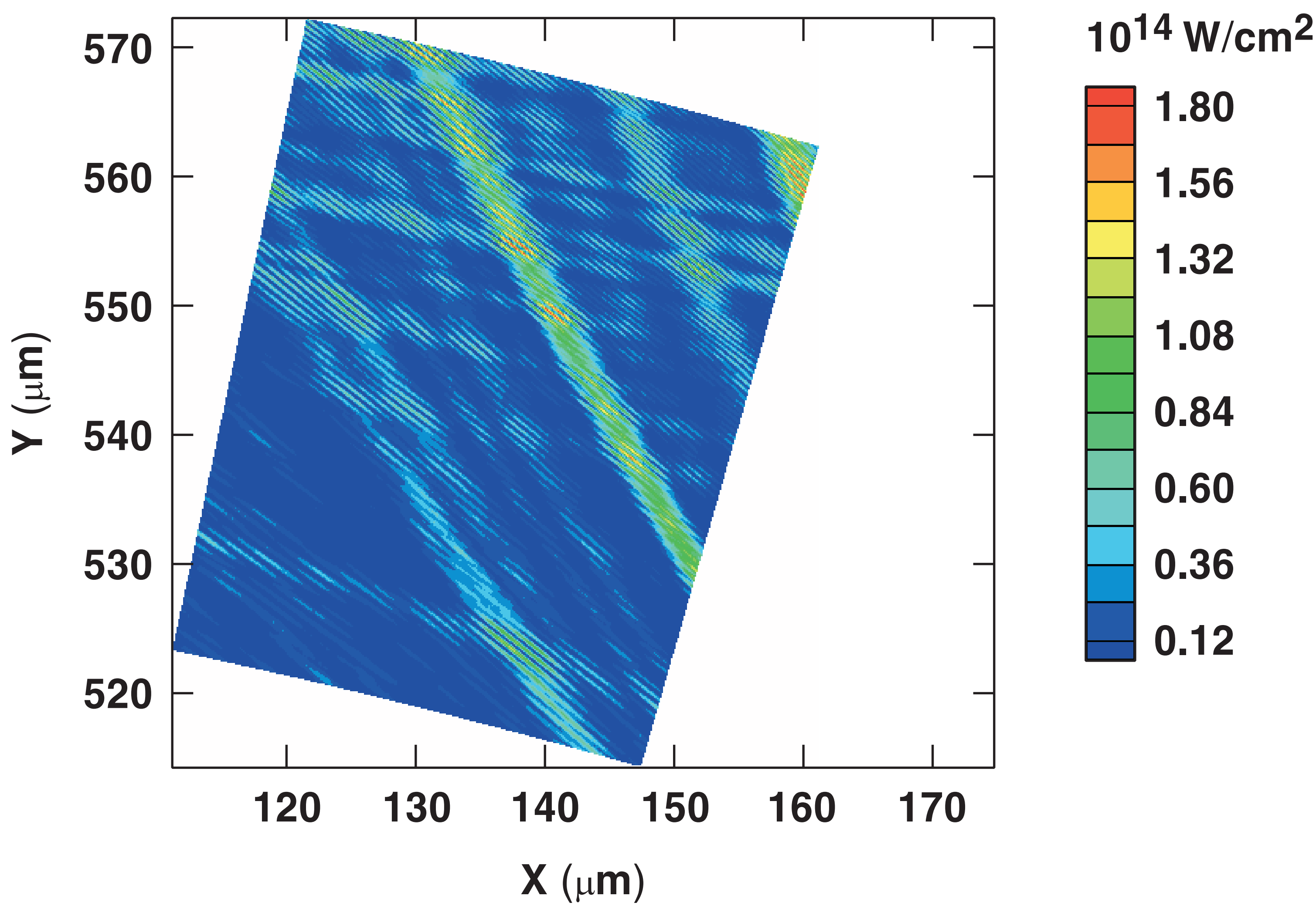
- The approximate solution can be written:

$$g_\ell(s)=2\sqrt{\pi}\left(\frac{3}{2}S_0\right)^{1/6}\left[Q(s)\right]^{-1/4}\mathrm{Ai}\left[\left(\frac{3}{2}S_0\right)^{2/3}\right],\ Q(s)=\varepsilon(s)-\frac{\ell(\ell+1)}{s^2},\ \text{and}$$

$$S_0=\int_{s_t}^{s}Q^{1/2}(s)ds$$

- This solution is valid for all radii (both over- and underdense plasma), and for scale lengths longer than a few microns is virtually identical to the exact numerical solution.

Hot spots are less intense where caustic meets quarter-critical density



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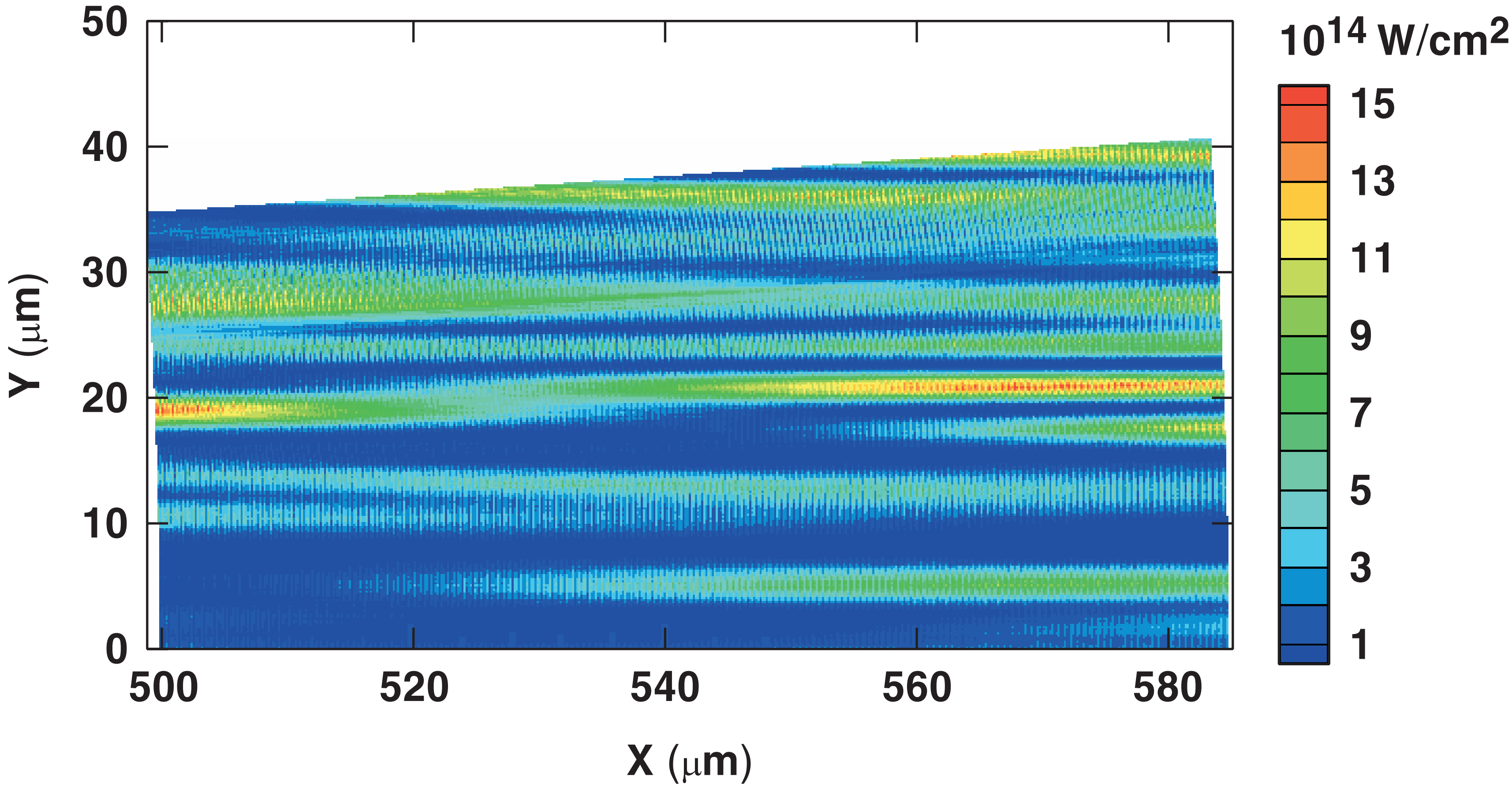
Quarter-critical hot spots reach ~15× nominal intensity



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Growth rates and instability thresholds for TPD are obtained from the dispersion relation

- The dispersion relation for TPD can be written $D(\omega, k) = 0$, where

$$D(\omega,\mathbf{k}) \equiv \left(\omega^2 - \omega_{e,k}^2\right)\left[\left(\omega - \omega_0\right)^2 - \omega_{e,k-k}^2\right] - \left\{\frac{\mathbf{k}\cdot\mathbf{v}_{osc}\omega_{pe}\left[\left(\mathbf{k}-\mathbf{k}_0\right)^2 - k^2\right]}{2k\left|\mathbf{k}-\mathbf{k}_0\right|}\right\}^2 .$$

- If $k_{\perp max}$ is the perpendicular wave number giving the maximum growth rate, the propagation velocity of the fastest-growing amplitude is

$$V = \left.\frac{\partial\omega_r}{\partial k_\perp}\right|_{k_{\perp max}} = \left.\frac{\partial D(\mathbf{k},\omega)/\partial k_\perp}{\partial D(\mathbf{k},\omega)/\partial\omega}\right|_{k_{\perp max}}$$

Fastest growth rates occur for comparable perpendicular and parallel wave vectors

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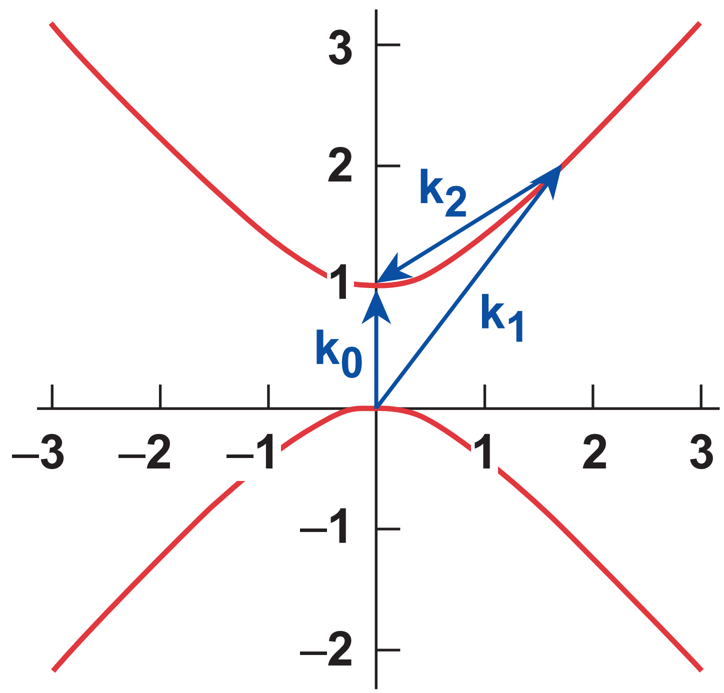

- Growth rates are limited by inhomogeneity for small wave vectors and by Landau damping for large wave vectors.
- For NIF, lowest threshold ~10^{14} W/cm^2; marginal, but exceeded in hot spots.

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The threshold for transverse absolute instability can be obtained from the homogeneous dispersion relation

- Assuming the density is uniform perpendicular to the pump, the condition for absolute instability is found by imposing boundary conditions of zero incoming waves at y = 0, L.
- The result is

$$\frac{(k-k_0)^2-k^2}{k|k-k_0|}\,\frac{\nu_0}{\sqrt{\nu_{\perp 1}\nu_{\perp 2}}}\,kL > \pi$$

- This can be approximated by $I_{14}^{1/2} > 0.68\,\frac{T_{keV}}{L_{\perp\mu}}$
- Easily satisfied in hot spots.

Bandwidth increases threshold for absolute TPD and/or reduces time available for growth

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- Hot spots are caused by interference between different parts of the laser beam; bandwidth causes spots to move or flicker.
- Maximum velocity due to bandwidth is $\frac{V}{c} \sim F\frac{\Delta\lambda}{\lambda} \sim 1.2 \times 10^{-3} F\Delta\nu(\mathrm{THz})$.
- At this relative velocity, the instability is no longer absolute at typical hot-spot intensities; but most hot spots won't move this fast.
- Some hot spots don't move at all; some may vary in intensity without moving.
- Effect of bandwidth on TPD requires convolution of hot-spot temporal and spatial variation with absolute TPD threshold conditions.

Summary/Conclusions

Hot-spot effectiveness in driving two-plasmon decay is reduced relative to SBS and SRS because of the two-dimensional nature of the instability

- SBS and SRS have maximum growth rates for backscatter; in two-plasmon decay the fastest-growing plasma waves have perpendicular components comparable to their parallel components.
- Small-radius hot spots in smoothed beams are aligned along the pump, so they would be expected to be less effective in driving TPD.
- TPD is near threshold for direct-drive conditions, but the threshold is exceeded in hot spots.
- The two-plasmon decay waves tend to propagate out of hot spots laterally, but absolute growth can still occur.
- Shorter amplification range may reduce hot-electron production by nonlinearly saturated waves.