Linear Growth and Nonlinear Saturation of Two-Plasmon Decay Driven by Multiple Laser Beams

\[ \frac{(I_s)_{\text{thr}}}{(I_s)_{\text{Simon}}} \]

\( \theta = 27^\circ, \ L_n = 150 \ \mu m, \ T_e = 2 \ \text{keV} \)

\( \theta = 0^\circ \)

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Summary

Two-plasmon decay (TPD) driven by multiple beams in inhomogeneous plasma is investigated using ZAK3D*

• Multibeam effects have been observed to be important in the TPD instability**

• Convective growth of shared plasma waves having $k \sim k_0$ have been predicted theoretically†

• Our simulations recover this result, but indicate that small-$k$ modes can share plasma waves and therefore give a lower absolute threshold for multiple beams

• ZAK3D models the nonlinear coupling to ion-density fluctuations

• In the nonlinear stage, Rosenbluth convective gain is not observed because of the existence of ion-acoustic fluctuations

• This might be able to explain why OMEGA experiments have shown hot-electron production for small convective gain

Collaborators

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The ZAK3D model is a time-enveloped fluid moment model that describes the coupling between Langmuir and ion-acoustic fluctuations.

Zakharov equation†

\[
\nabla \cdot \left[ 2i\omega_p(\partial_t + \nabla e\cdot) + 3\nu_e^2\nabla^2 - \omega_p^2 \left( \frac{\delta n + \delta N}{n_0} \right) \right] E
\]

\[
= \left( \frac{e}{4m_e} \right) \nabla \cdot \left[ \nabla \sum_{m=1}^{N} (E_{0,m} \cdot E^*) - \sum_{m=1}^{N} E_{0,m} \nabla \cdot E^* \right] e^{-i\Delta \omega t} + S_E
\]

Collisional plus Landau damping
Density gradient
Laser source
Noise source

\[
\left[ \partial_t^2 + 2\nu_j \cdot \partial_t - c_s^2 \nabla^2 \right] \delta n = \frac{1}{16\pi m_i} \left( \nabla^2 |E|^2 + \frac{1}{4} \nabla^2 \sum_{m=1}^{N} |E_{0,m}|^2 \right),
\]

Landau damping for ion
Ponderomotive force

where the laser field \( E_L = \sum_{m}^{N} E_{0,m} \exp(-i\omega_0 t) + c.c. \)

\( \Delta \omega = \omega_0 - 2\omega_{pe} \)

The Zakharov model makes some approximations

**Approximations**

\[ |\partial_t^2 E| \ll |\omega_p \partial_t E|; \]
\[ \frac{E^2}{4\pi n_0 T_e} \leq 1, \frac{\delta n_0}{n_{e0}} \leq 1, \text{ and } k\lambda_{De} \leq 1 \]

**Limitation**

1. lack of kinetic effects
2. dissipation is included only approximately
3. time envelope removes higher-order harmonics
The temporal growth rate agrees very well with Simon* predictions for a single-plane electromagnetic (EM) wave

Absolute growth rate of most-unstable mode for different laser intensities

Extrapolating the growth rate to zero gives the threshold of absolute instability.

$L_n = 150 \, \mu m$

$T_e = 2 \, \text{keV}$

Normal laser incidence.

Most unstable modes have $k_\perp \sim 0.1 \, k_0$

Two-plane EM waves with $p$-polarization show shared plasma waves in both the large- and small-$k$ regions.

Energy spectrum of Langmuir wave (LW) during linear growth phase (early time, arbitrary units).

Common wave at large $k^*$ (convectively saturated)

Common wave at small $k$ (corresponding to Simon’s absolutely unstable modes)

The absolute thresholds for different numbers of beams and beam configurations have been computed.

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- Four beams parallel (||)
- Four beams radial
- Four beams tangential

**Graph Details:**

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**Graph Axes:**

- Vertical axis: \( (I_s/\text{thr})/I_s \) Simon
- Horizontal axis: \( N \)
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The absolute threshold is lower than the convective threshold in most cases; the regime of linear convective growth is very restricted.
Comparison between ZAK3D and convective gain for four beams with parallel polarization shows consistency for large $k$.

The presence of absolute instability requires a treatment of nonlinear saturation.

*R. W. Short, this conference
In the nonlinear stage, a state of nonlinear Langmuir wave turbulence propagates to lower densities.

- TPD driven by two beams with in-plane polarization ($p$-polarized) is simulated in the nonlinear stage $I_{14} = 1.2$, $L_n = 330 \mu m$, and $\theta = 27^\circ$.

\[ \int |E(x, y, z, t)|^2 dydz / \int dydz \]

Lineout of energy spectrum at different times

Saturation of absolute mode

Convective saturation of common wave
Density perturbations generated by the strong Langmuir turbulence restore growth to the convectively saturated modes; these dominate at late times.

- Two beams, p-polarized, $I_{14} = 1.2$, $L_n = 330 \, \mu m$, and $\theta = 27^\circ$.
Summary/Conclusions

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- Convective growth of shared plasma waves having $k \sim k_0$ have been predicted theoretically†
- Our simulations recover this result, but indicate that small-$k$ modes can share plasma waves and therefore give a lower absolute threshold for multiple beams
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The Langmuir wave equation is formally equivalent to the fluid equations used by Liu\textsuperscript{†} and Simon\textsuperscript{‡}

Fourier transforming the Langmuir wave (LW) equation in time and space, after simple derivation it leads to these $N + 1$ equations

\[
\begin{align*}
\left[ 2\omega_{pe0} (\omega - \Delta \omega/2) - 3k^2 V_{te}^2 \right] u + \frac{i\omega_{pe0}^2}{L} \left( \frac{\partial u}{\partial k_x} - \frac{k_x}{k^2} u \right) &= \sum_{m=1}^{N} \frac{\omega_{pe0}}{4} \left( \frac{k^2}{k_{d,m}^2} - 1 \right) (\tilde{k} \cdot \mathbf{V}_{0,m}) u_{d,m}^* \\
\left[ 2\omega_{pe0} (\omega_d + \Delta \omega/2) + 3k_{d,m}^2 V_{te}^2 \right] u_{d,m}^* - \frac{i\omega_{pe0}^2}{L} \left( \frac{\partial u_{d,m}^*}{\partial k_x} - \frac{k_{xd,m}}{k_{d,m}^2} u_{d,m}^* \right) &= \frac{\omega_{pe0}}{4} \left( \frac{k_{d,m}^2}{k^2} - 1 \right) (\tilde{k} \cdot \mathbf{V}_{0,m}^*) u
\end{align*}
\]

where $\omega_{d,m} = \omega - \omega_{0,m}$, $k_{d,m} = k - k_{0,m}$, $u_{d,m} = u - u_{0,m}$, $V_0$ is the electron oscillation velocity in laser field

\textsuperscript{†}\textsuperscript{C. S. Liu and M. N. Rosenbluth, Phys. Fluids 19, 967 (1976).}
\textsuperscript{‡}A. Simon \textit{et al.}, Phys. of Fluids 26, 3107 (1983).