Absolute Two-Plasmon Decay and Stimulated Raman Scattering in Direct-Drive Irradiation Geometries

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45th Annual Anomalous Absorption Conference
Ventura, CA
14–19 June 2015
Summary

In general, both stimulated Raman scattering (SRS) and two-plasmon decay (TPD) will play a role in direct-drive laser–plasma interactions

- Absolute TPD and SRS thresholds have different dependencies on laser and plasma parameters, but are comparable
- The modes with lowest thresholds tend to be either SRS or TPD; mixed polarization modes seem unimportant
- Larger scale lengths and temperatures favor SRS; larger incidence angles favor TPD
- The analysis presented here is linear; however there is evidence that the absolute SRS/TPD it describes persists well into the nonlinear regime
The origin in $k$ space corresponds to the plasma-wave turning point, allowing SRS and TPD to be absolute there

- In general, instabilities can only be convective in inhomogeneous plasmas*
- Near the turning point, however, there is a finite threshold for absolute instability**
- Enhanced multibeam convective gain near the origin in $k$ space suggests the potential for absolute instability there
- Convective SRS occurs for $n/n_c \leq 1/4$; for absolute SRS, the electromagnetic (EM) decay wave must have $k \approx 0$ and originate at $n/n_c \approx 1/4$

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Absolute SRS requires the component of $k$ perpendicular to the density gradient to vanish

- The $y$ components of the plasma-wave group velocity $v_g = 3v_T^2 k / \omega$ are equal and opposite, so TPD is absolute in the $y$ direction.

- For SRS, $v_{g1y} = 3v_T^2 k_{1y} / \omega$ and $v_{g2y} = c^2 k_{2y} / \omega$, so SRS will be convective in $y$ unless $k_{2y} \approx 0$. 
For a single beam, the absolute TPD threshold* is lower than the Rosenbluth convective threshold

- The Simon threshold (adjusted for s-polarized oblique incidence) is \( \eta \equiv \frac{I_{14} \kappa}{233 \, T_{keV} \cos \theta} > 1 \)

- The Rosenbluth convective gain is \( G_R = \frac{2 \pi^2 \gamma^2}{\kappa \, V_1 \, V_2} = \frac{I_{14} \kappa}{53.6 \, T_{keV} \cos \theta} \approx 4.35 \eta \)

- The nominal convective threshold is \( G_R > 2 \pi \) or \( \eta > \frac{2 \pi}{4.35} \approx 1.44 \)

- Therefore, the TPD absolute instability threshold lies below the convective instability threshold; this, in general, remains true for multiple beams

- The threshold for absolute SRS is comparable**

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Fourier analysis of the time-independent TPD equations results in a set of first-order linear differential equations

- Absolute TPD and SRS occur near quarter-critical, so the local density profile may be approximated by a linear gradient.
- Fourier transforming in space, the wave equations become first-order linear equations for the longitudinal and transverse components of the small-\( k \) decay wave.
- The larger-\( k \) decay wave may be taken to be longitudinal.
- For \( N \) beams there are therefore \( 3N + 1 \) linear differential equations that are integrated from \( k_x \rightarrow -\infty \) to \( k_x \rightarrow +\infty \) to obtain the spatial gain.
- Divergence of the gain indicates an onset of absolute instability; optimizing over \( \omega \) gives the threshold and frequency.
Fourier analysis of the time-independent TPD equations results in a set of first-order linear differential equations

- For a single beam, take the decay triangle in the \(x-y\) plane and normalize \( \hat{k} = c\hat{k}/\omega_0, \Delta = \omega/\omega_0 - 1/2, L = \omega_0 L/c \)

\[
\frac{\partial u_L}{\partial k_x} = iL \left( \frac{k_d}{k} - \frac{k}{k_d} \right) (k \cdot v_0) e^{ -4iL \left[ 2\Delta k_x - \frac{3}{2} \left( \frac{c^2 + k^2}{c^2} \right) k_x + \frac{3}{2} \left( \frac{c^2 + k^2}{c^2} \right) k_y \right] } u_d \\
\frac{\partial u_T}{\partial k_x} = iL \left( \frac{k_d}{k} \right) \left[ (k_x \dot{y} - k_y \dot{x}) \cdot v_0 \right] e^{ -4iL \left[ 2\Delta k_x - \frac{1}{2} \left( \frac{c^2 + k^2}{c^2} \right) k_x + \frac{1}{2} \left( \frac{c^2 + k^2}{c^2} \right) k_y \right] } u_d \\
\frac{\partial u_z}{\partial k_x} = iL k_d v_0 e^{ -4iL \left[ 2\Delta k_x - \frac{3}{2} \left( \frac{c^2 + k^2}{c^2} \right) k_x + \frac{3}{2} \left( \frac{c^2 + k^2}{c^2} \right) k_y \right] } u_d \\
\frac{\partial u_d}{\partial k_x} = iL \left( \frac{k_d}{k} - \frac{k}{k_d} \right) \left( \frac{c k \cdot v_0}{c} \right) (k \cdot v_0) e^{ 4iL \left[ 2\Delta k_x - \frac{3}{2} \left( \frac{c^2 + k^2}{c^2} \right) k_x + \frac{3}{2} \left( \frac{c^2 + k^2}{c^2} \right) k_y \right] } u_L \\
\quad + iL \frac{k_d}{k} \left[ (k_x \dot{y} - k_y \dot{x}) \cdot v_0 \right] e^{ 4iL \left[ 2\Delta k_x - \frac{1}{2} \left( \frac{c^2 + k^2}{c^2} \right) k_x + \frac{1}{2} \left( \frac{c^2 + k^2}{c^2} \right) k_y \right] } u_T \\
\quad + iL k_d v_0 e^{ 4iL \left[ 2\Delta k_x - \frac{3}{2} \left( \frac{c^2 + k^2}{c^2} \right) k_x + \frac{3}{2} \left( \frac{c^2 + k^2}{c^2} \right) k_y \right] } u_z
\]
For smaller $k_\perp$, TPD decay waves become more transverse

- The optimal SRS mode has $k \approx 0$ and is almost entirely electromagnetic
- The optimal TPD mode is almost entirely electrostatic (ES); for smaller $k_\perp$, the EM component and the threshold increase

<table>
<thead>
<tr>
<th>$k_\perp$</th>
<th>Threshold $I_{14}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06</td>
<td>1.54</td>
</tr>
<tr>
<td>0.02</td>
<td>1.85</td>
</tr>
</tbody>
</table>

$L(\mu) = 300$
$T_{\text{keV}} = 2.0$
The absolute threshold for TPD depends on angle of incidence and polarization.

\[ L(\mu) = 130 \]
\[ T_{\text{keV}} = 2 \]

![Graph showing the relationship between angle of incidence and threshold for TPD.](image)
For two $p$-polarized beams, an on-axis TPD mode ($k_y = 0$) has the lowest threshold at larger incidence angles.
At larger angles, the on-axis mode is closer to the hyperbolas than the off-axis modes.
Light from absolute SRS will be emitted along the density gradient

• The much-higher group velocity of the EM wave means the instability must be absolute in the direction perpendicular to the density gradient, i.e., $k_y \sim k_z \sim 0$ and the wave is purely transverse.

• Phase matching, and therefore threshold, will be insensitive to temperature.

• The spectrum of the emitted light will have the same dependence on temperature as for TPD.

• For s-polarization the threshold will be independent of pump incidence angle; for p-polarization the coupling is reduced for oblique incidence and the threshold increases with angle.

• Analysis of the $k$-space equations for a normally incident beam gives a threshold of $I_{14} > \frac{1995}{L^{4/3} \mu}$, close to the Liu, Rosenbluth, and White result.
For oblique incidence, TPD and SRS behave differently as a function of incidence angle

- Increasing temperatures and scale lengths favor SRS; increasing incidence angles favor TPD

![Graph showing the behavior of TPD and SRS](image)

\[
L(\mu) = 130 \\
T_{\text{keV}} = 2
\]

\[
L(\mu) = 300 \\
T_{\text{keV}} = 2
\]
The spectral signature of the absolute instability near $n_c/4$ is a sharp red-shifted feature that can be used for $T_e$ measurements.

Although the absolute instability is obtained from linear analysis, it can remain the most-intense TPD mode in the nonlinear regime, persisting throughout the pulse.
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