The Nonlinear Behavior of the Two-Plasmon–Decay Instability

Single-beam Zakharov simulations in the nonlinear regime

$\omega/2$ spectrum

$\log_{10}(I)$

Frequency (THz)

Time (ns)

$
\begin{align*}
\frac{\omega}{2} & \text{spectrum} \\
\log_{10}(I) & \\
\text{Frequency (THz)} & \\
\text{Time (ns)}
\end{align*}
$

$\log_{10}(E_{EPW}^{2})$

(arbitrary units)

$\approx \frac{1}{2}$ spectrum

$\nabla n_e$

$\frac{k_{\parallel}}{k_0}$

$\frac{k_{\perp}}{k_0}$

$t = 10$ ps

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Our understanding of multibeam two-plasmon decay (TPD) and its nonlinear behavior has significantly advanced over the past decade.

- Multibeam TPD has been firmly established.
- Zakharov models of the TPD instability agree with single and multibeam analytical thresholds and reduced-description particle-in-cell (RPIC) results in the nonlinear regime.
- Nonlinear coupling of primary TPD waves with ion waves leads to a broad Langmuir wave (LW) spectrum evident in $\omega/2$ and $3\omega/2$ spectra.
- Zakharov simulations including quasi-linear diffusion can predict energetic electron production and allow for the investigation of mitigation strategies.
- Half-harmonic ($\omega/2$) spectra have identified temperature islands on the target surface via localized $T_e$ measurements.
Collaborators


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The extended Zakharov model of TPD is used to analyze the threshold and nonlinear behavior of the TPD instability.

- **ZAK3D**\(^1\) is an excellent tool for studying the linear stability of multibeam-driven TPD.
- **ZAK3D** includes coupling to ion waves → LW turbulence.
- **QZAK**\(^2\) (2-D version of **ZAK3D**) evolves the distribution function → hot-electron production.
- **QZAK** simulations agree with kinetic RPIC\(^3\) in the nonlinear state in the regimes where they have been compared.
- **ZAK3D** includes multiple beams, extendable to incoherent and multicolor beams.

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\(^1\)J. Zhang et al., this conference, and to be submitted to Phys. Plasmas; D. F. DuBois and D. A. Russell earlier work.
The various TPD regimes are clearly visible in single-beam ZAK3D simulations

Absolute instability,\(^*\) \(k_p/k_0 \lesssim 0.1\)

\[
\eta \approx \frac{I_{14} L_\mu}{233 T_{\text{keV}}} > 1
\]

Zakharov simulation linear regime, \(t = 1\) ps

\\\[
\log_{10}\langle E_{\text{EPW}}^2 \rangle \quad (\text{arbitrary units})
\]

Rosenbluth convective gain,

\(k_p/k_0 < k_p,_{\text{max}}, \quad G_c = 2\pi\)

\[
\eta_{\text{conv}} \approx 1.25 \eta_{\text{abs}}
\]

Landau cutoff (LC):

\[
k_p \lambda_{\text{De}} = 0.25
\]

Above the absolute threshold, the TPD Langmuir waves rapidly fill $k$ space to the Landau cutoff limit.

For a single beam there is a very limited linear convective regime.

Single beam, $\eta = 1.3$, $L_n = 150 \mu m$, $T_e = 3$ keV, CH plasma

For a single beam there is a very limited linear convective regime.
Two beams, in-plane polarization
\[ \eta = 1 + \delta, \quad L_n = 330 \, \mu m, \quad T_e = 2 \, \text{keV} \] (OMEGA parameters)

Linear regime

Nonlinear regime

Common (shared) plasma-wave regime

E22206
Multibeam absolute TPD thresholds have been computed analytically and with ZAK3D

- Along the solid line the absolute TPD threshold condition is
  \[ \eta \approx \frac{I_{14} L \mu}{233 T_{keV}} \]

- The threshold depends on polarization and angle of incidence

\[ I_{14} = \sum I_{14, \text{single beam}} \]

R. W. Short’s absolute TPD threshold calculations\(^1\) in 2-D and 3-D agree with Zakharov simulations.\(^2\)

\(^1\)R. W. Short et al., this conference.
\(^2\)J. Zhang et al., this conference.
The TPD instability has several characteristic experimental signatures

- $\omega/2$ and $3\omega/2$ emission spectra
  - TPD occurs from $n_c/4$ to the Landau cutoff ($\sim n_c/5$)
  - wavelength splitting and emitted power scale very nonlinearly with intensity

- Hard x-ray emission
  - the onset is generally observed after that of $\omega/2$ and $3\omega/2$ emission
  - result of energetic electrons generated by plasma waves turbulence
  - $E_x$ and $T_e$ scale nonlinearly with intensity

- The QZAK/ZAK3D simulations are consistent with some of the experimental observations
  - broad-angle hot-electron production
  - threshold scaling with overlapped intensity
  - broadband LW spectrum $\rightarrow$ LC
Multibeam TPD was established in 2003 in planar and implosion experiments using hard x-ray emission.

A scaling for the hot-electron fraction for many experimental configurations was obtained by D. T. Michel et al.* using a common-wave model.

Thomson scattering confirms the Landau cutoff limit*

Half-harmonic generation can be caused by inverse resonance absorption, Thomson scattering, or inverse parametric decay

- The absolute TPD instability \( (k_\perp/k_0 \leq 0.1) \) is close to the turning point of one of the TPD plasmons → ideal for plasmon-to-photon conversion via inverse resonance absorption
  - these photons have the smallest red shift from \( \omega_0/2 \) and are emitted along the density gradient

- Thomson scattering using any one of the incident or reflected beams
  - phase-matching conditions are difficult to satisfy for any of the primary TPD plasmons; scattered plasmons are more easily Thomson scattered

- The relative importance of the three processes is being investigated by D. A. Russel and D. F. DuBois
Evidence of nonlinear behavior of the TPD instability is best seen in $\omega/2$ spectra viewing the entire target sphere.

Broadband $\omega/2$ spectra are visible immediately at the start of the TPD instability and are consistent with broad LW spectra in ZAK simulations.

Possible signature of absolute TPD instability

Cryo shot $I_{14} = 9.3$

CH shot $I_{14} = 5.6$
The spectral signature of small-$k_{\perp}$ TPD instability can only be observed by viewing along the density gradient.

\[ I_{14} = 5.6 \]

\[ I_{14} = 5.76 \]

Small-$k_{\perp}$ TPD instability

Target surface

Imaged area \( \sim 50 \mu m \times 50 \mu m \)

Spectrum

Streak

\[ \log_{10}(I) \]

\[ \omega/2 \text{ spectrum} \]
Half-harmonic images of imploding targets provide insight to the localized nature of the TPD instability.

\[
\begin{align*}
I_{14} &= 8.6 \\
I_{14} &= 9.4 \\
I_{14} &= 10.6
\end{align*}
\]

**Entire \(\omega/2\) spectrum**

**Blue part of \(\omega/2\) spectrum**

**Standard tangential illumination**

**Nonuniform illumination**

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**SG4 phase plate**

**SG2 phase plate**
The spectral signature of the small-$k_{\perp}$ TPD instability near $n_c/4$ is a sharp red-shifted feature that can be used for $T_e$ measurements.

$$\Delta \lambda_{nm} = 4.4 \times 10^{-3} T_{e,\text{keV}}$$

small-$k_{\perp}$ plasmon-to-photon conversion assumed.

Intensity distribution at $n_c/5$ for incident angles $<30^\circ$ for shot 67675 with SG4 phase plates.
$T_e$ varies over the target surface and can exceed LILAC predictions by 10% to 20%.
Two-dimensional and 3-D nonlinear TPD simulations are being used to investigate TPD mitigation strategies

- Ion-wave damping
  - saturated LW intensity and hot-electron production depends on $\nu_{\text{IAW}}^*$

- Collisional damping
  - for NIF-scale lengths, the LW collisional damping can become important*

- Broadband and multicolor beam TPD
  - will use ZAK3D

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Future TPD simulations will center on quantitative prediction and mitigation options

- Quantitative predictions for fast-electron production \((QZAK\) extended to 3-D in the near future)\)
- Comparison of simulations with experimental fast-electron scaling laws
- TPD mitigation options
- TPD threshold behavior for beams with speckles
Summary/Conclusions

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