PIC and Fluid Simulations of Two-Plasmon-Decay Instabilities
Relevant to Direct Drive/Shock Ignition

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Shock Ignition Workshop

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Outline

• We have good understanding of the linear stage of TPD
  – Absolute mode growth rates from PIC agree with theory/fluid simulations
  – Convective modes seen in PIC and can be modeled with our fluid code
• Most hot e- are only produced in the nonlinear stage of TPD
  – No hot e- observed below TPD threshold
  – The appearance of >100 keV e- is correlated to new modes that are not seen in the linear stage
  – The new modes provide the first stage in a staged-acceleration mechanism
• Forward hot e- (>50 keV) flux from plane-wave, 2D PIC is >10X of experiment measurements
  – How to account 3D effects like speckles?
  – LPI and hydro are difficult to decouple
• Some good news for shock ignition?
We have performed PIC and fluid simulations with OMEGA parameters

- Boundary conditions for fields:
  - Periodic in the y direction
  - Open in the x direction
- Boundary conditions for particles:
  - Periodic in the y direction
  - Thermal reflecting in the x direction
- Fluid code (Yan et al., PoP 2010)
  - Solves the linear TPD equations in arbitrary density profiles
  - Can study TPD under ion density fluctuations

Typical parameters:
- Grid: 3600 x 6000, 100ppc
- I=4-20x10^{14} W/cm^2
- Te=1-3 kev, Ti=1-3 kev
- M/m=1- 2.5x 1846
- L=150 micron
The boundary diagnostic records the energy difference of the particles going out of and coming into the box.

It also records the energy distribution of the particles going out of the rear boundary.
There is general agreement for linear growth among theory, PIC, and fluid simulations.

- Both PIC and fluid simulations saw absolute and convective modes.
- The lower PIC growth rates in low $k_y$ were due to pump depletion.

$I=10^{15}$ W/cm$^2$, $L=150$ micron
$T_e=T_i=2$ keV, $M_i/m_e=3410$
(Yan et al., PRL’09)
‘Typical’ compression phase sees Raman and TPD absolute and convective modes

Parameters:

- $I = 6 \times 10^{14}$ W/cm$^2$
- $T_e = 3$ kev, $T_i = 1.5$ kev
- $L = 150$ micron
- $\eta = 1.2$
- $M/m = 3410$ (CH)

Convective modes (larger $k_y$) locate at lower density region
Most hot e- are produced in the nonlinear stage

- Steady state
- Saturation
- Linear

>50 keV electron distribution in px-py space
Net particle energy flux has reached a quasi-steady state
Most hot e- are generated in the nonlinear stage

The existence of >100 keV e- is consistent with hard X-ray diagnostic.
At steady state, 17% of laser energy is in the forward hot e- energy flux

Yakkobi et al. 2009 measured <0.3% hot e-
The appearance of hot e- (>100 keV) is correlated to new modes that are not seen in the linear stage.
Nonlinearly, the ponderomotive pressure of the plasma waves drives ion density fluctuations

- The ion density fluctuations calculated from the ion acoustic equation match the PIC results
- Ion acoustic wave (IAW) eq:

\[
(\partial_t - C_s^2 \nabla^2) \delta n = \nabla^2 |E|^2 / (16\pi m_i)
\]

Drop \(\nabla^2\), Since \(V_{||}^2 \ll V_{\perp}^2\)

Yan et al., APS 2010

Yan et al. PRL'09

TPD

\(\delta n\)

Raising TPD threshold

Yan et al., APS 2010
Ion density fluctuations can produce low-k, forward plasma waves
Plane-wave, 2D PIC simulations gave 10-100X more hot electrons than HXR measurements

<table>
<thead>
<tr>
<th>Max $I_{14}$</th>
<th>$T_e$(keV)</th>
<th>$T_i$(keV)</th>
<th>$L_\mu m$</th>
<th>$M_i/m_e$</th>
<th>Run time</th>
<th>Forward Hot e-(&gt;50kev)</th>
<th>Abs $\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>3</td>
<td>1.5</td>
<td>150</td>
<td>3410</td>
<td>5ps</td>
<td>~0 (100 ptc per cell)</td>
<td>~0</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>1.5</td>
<td>150</td>
<td>3410</td>
<td>10ps</td>
<td>17% (100 ptc per cell)</td>
<td>42%</td>
</tr>
</tbody>
</table>

B. Yaakobi et al., Phys. Plasmas 16, 102703 (2009): hot e- <0.3% of laser energy
Things to check about the validity of the PIC results

• Hot e- are due to TPD
  – All $\eta>1$ runs have significant absorption
  – Oblique incidence should increase effective $\eta$ (Afeyan)
• We believe we have reached steady state (<10 ps)
• Most hot e- go forward
• Are the hydro conditions used in the PIC simulations right?
  – LPI and hydro are coupled
• Is 2D, plane-wave model the right one?
  – What about the speckles?
TPD of speckles is intrinsically 3D

• Each beam is made up of many speckles (grass in a lawn model)

• Within each speckle, the polarization is not constant
Simulations with well-separated speckles did show reduced absorption

<table>
<thead>
<tr>
<th>Max I₁₄</th>
<th>Tₑ(keV)</th>
<th>Tᵢ(keV)</th>
<th>L₂µm</th>
<th>Mi/me</th>
<th>Run time</th>
<th>Forward Hot e-(&gt;50keV)</th>
<th>Abs</th>
<th>η</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>3</td>
<td>1.5</td>
<td>150</td>
<td>3410</td>
<td>5ps</td>
<td>~0 (100 ptc per cell)</td>
<td>~0</td>
<td>0.8</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>1.5</td>
<td>150</td>
<td>3410</td>
<td>10ps</td>
<td>17% (100 ptc per cell)</td>
<td>42%</td>
<td>1.2</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>1.5</td>
<td>150</td>
<td>3410</td>
<td>9ps</td>
<td>5% (100 ptc per cell, W=4micron)</td>
<td>22%</td>
<td>1.4</td>
</tr>
</tbody>
</table>
A simulation with higher laser intensity

- The profile comes from the hydro simulation e52490
  - Lilac simulation by K. Anderson

\[
I = 2 \times 10^{15} \text{W/cm}^2 \\
T_e = 1.6 \text{keV} \\
T_i = 550 \text{eV} \\
M/m = 3978 \\
L = 163.5 \text{micron (fit to exp function)}
\]
This run shows 52% absorption with only 6% in >100 keV e-.

Energy exchange through the right boundary
Summary

• We have good understanding of the linear stage of TPD

• Most hot e- are only produced in the nonlinear stage of TPD

• Forward hot e- (>50 keV) flux from plane-wave, 2D PIC is >10X of experiment measurements
  – How to account 3D effects like speckles?
  – LPI and hydro are difficult to decouple