Particle-in-Cell Modeling of Laser–Plasma Interactions in Three Dimensions

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Plasma-wave spectrum in 3-D simulation at $t = 7$ ps

Arbitrary units

56th Annual Meeting of the American Physical Society
Division of Plasma Physics
New Orleans, LA
27–31 October 2014
Summary

The hot-electron distribution near quarter-critical density has been studied by 3-D and 2-D particle-in-cell (PIC) simulations

- Two-plasmon decay (TPD), stimulated Raman scattering (SRS), and stimulated Brillouin scattering (SBS) are found to coexist in 3-D PIC simulations
- In PIC simulations with laser speckles, TPD generates more hot electrons in the forward direction than in the backward direction
- Laser beams with speckles can generate more hot electrons than a plane wave because of TPD
- Collisional effects can reduce fast-electron generation by a factor of 2
PIC simulations have been performed for parameters relevant to direct-drive inertial confinement fusion (ICF) experiments

- **Physical parameters (plane wave)**
  - scale length $L_n = 100 \ \mu m$
  - intensity $I = 9 \times 10^{14} \text{ W/cm}^2$
  - CH plasma, temperature $T_e = 2 \text{ keV}$, $T_i = 1 \text{ keV}$
  - laser propagates along the $x$ axis
  - linear density profile from 0.21 to 0.26 $n_c$
  - $\eta^* = 1.9$

- **Numerical parameters**
  - simulation box size: $400 \times 150 \times 120 \ c/\omega_0$ ($21 \times 8.4 \times 6.7 \ \mu m$) for the 3-D simulation
  - $400 \times 150 \ c/\omega_0$ ($21 \times 16 \ \mu m$) for the two 2-D simulations

2-D simulations are in the $x$–$y$ plane

2-D out-of-plane (SRS)

2-D in-plane (TPD)

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TPD, SRS, and SBS are observed in a plane wave 3-D PIC simulation

- TPD is localized in the $x$–$y$ plane
- SRS and SBS sidescattering are observed at $k_z \neq 0$
- Integrate the spectra $S(k_x, k_y, k_z, \omega)$ over $k_z$ and $\omega \sim (0.44, 0.56)$
The growth of different instabilities in 3-D simulations can be illustrated by the time history of field components.

- Steady state has been reached at the end of the simulation.
In the saturation stage, TPD spectra are broader in $k_x$ than SRS spectra

- Plasma waves with a larger $k$ vector can accelerate electrons with lower kinetic energy
Laser speckles and Coulomb collisions affect hot-electron generation

- Parameters (laser speckles)
  - \( L_n = 100 \, \mu m \)
  - Average \( I = 9 \times 10^{14} \, W/cm^2 \)
  - \( T_e = 3 \, \text{keV}, \, T_i = 1.5 \, \text{keV} \)
  - \( \eta = 1.3 \)

![Graph showing intensity cross section and net energy flux]

- Net energy flux

<table>
<thead>
<tr>
<th></th>
<th>No collisions</th>
<th>Collisional</th>
</tr>
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<tbody>
<tr>
<td>Backward</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forward</td>
<td></td>
<td></td>
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<tr>
<td>Speck 3-D</td>
<td>4.9%</td>
<td>4.5%</td>
</tr>
<tr>
<td>Speck 2-D</td>
<td>0.2%</td>
<td>0.0%</td>
</tr>
<tr>
<td>out-of-plane</td>
<td>0.7%</td>
<td>0.1%</td>
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<tr>
<td>Speck 2-D</td>
<td>1.8%</td>
<td>6.5%</td>
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<tr>
<td>in-plane</td>
<td>4.4%</td>
<td>10.2%</td>
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<tr>
<td>Plane wave 2-D</td>
<td>0.5%</td>
<td>0.0%</td>
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<tr>
<td>out-of-plane</td>
<td>0.9%</td>
<td>0.1%</td>
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<tr>
<td>Plane wave 2-D</td>
<td>1.3%</td>
<td>1.3%</td>
</tr>
<tr>
<td>in-plane</td>
<td>4.4%</td>
<td>5.2%</td>
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</tbody>
</table>
The distributions of hot electrons indicate that 2-D in-plane simulations may overestimate hot-electron generation.

- The distributions of hot electrons crossing the right boundary in laser speckle simulations.

<table>
<thead>
<tr>
<th></th>
<th>2-D in-plane (TPD)</th>
<th>2-D out-of-plane (SRS)</th>
<th>3-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature*</td>
<td>46 keV</td>
<td>21 keV</td>
<td>27 keV</td>
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<tr>
<td>Net energy flux</td>
<td>14.6%</td>
<td>0.8%</td>
<td>9.4%</td>
</tr>
</tbody>
</table>

*Fitting between 70 keV and 150 keV
TPD modes with larger $k$ vectors are found in 2-D in-plane speckle simulations

- Integrate the plasma-wave spectra $S(k_x, k_y, \omega)$ over $\omega$
Forward-going and backward-going plasma waves generate asymmetric hot electrons in 2-D in-plane simulations

- Integrate the spectra $S(k_x, k_y, \omega)$ over $k_y$
The hot-electron distribution near quarter-critical density has been studied by 3-D and 2-D particle-in-cell (PIC) simulations

Summary/Conclusions

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