PIC simulations on resonance absorption and electron heating

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Background in resonance absorption and Raman/2$\omega_p$ instabilities

- When laser lights are obliquely incident on an inhomogeneous plasma and polarized in the plane of incidence, they can be resonantly absorbed near the critical surface.
  - A large plasma wave can be generated due to resonance absorption.
  - Energetic electrons are accelerated by plasma wave, which might preheat the target in ICF.
- Raman/2$\omega_p$ instability is another important energetic electron generation mechanism.
  - Part of the incident energy is scattered, part goes to the plasma wave, which heats plasmas as it damps.
  - They can generate very energetic electrons that can also preheat the target.
The Scheme of ICF

1. Irradiation
   - Laser or x-ray drive
   - DT fuel-filled pellet
   - Expanding blowoff
   - Imploding pellet

2. Compression
   - Compressed pellet

3. Thermonuclear ignition
   - Deuterium
   - Tritium
   - Helium 4
   - Neutron

Temperature vs. Mass density vs. Radius

Hot spot
Burn wave

Courtesy of D. Meyerhofer
An introduction to Particle-in-Cell (PIC) simulation

• Particle-in-Cell methods are widely used to simulate plasma physics especially when kinetic description is important.

Particles in cells

Computational cycle
(at each step in time)

Particle positions $z_i, v_i$

$d\vec{p}/dt = \vec{E} + \vec{v} \times \vec{B}/c$

$\rho_{n,m}, \vec{J}_{n,m}$

$\vec{E}_{n,m}, \vec{B}_{n,m}$

• Solve fields by Maxwell’s equations
• Update particle’s position and momentum by Lorentz force

Weight to grid

Push particles

Interpolate to particles

•
A linear density profile is used in all simulations

Density gradient scale length: \( k_0L = 100 \)
\( T_e \approx 600eV \)
Fixed ions or mobile ions with \( m_i = 1836m_e \)
\( T_i = T_e \)

1. \( v_{os} / c = 0.015 \) (\( I = 2.8 \times 10^{15} \text{ w/cm}^2 \) for \( 3\omega \))
2. \( v_{os} / c = 0.15 \) (\( I = 2.8 \times 10^{17} \text{ w/cm}^2 \) for \( 3\omega \))
At low intensity, there is only resonance absorption at the critical surface

Fixed ions

\( \nu_{os} / c = 0.015 \)

\( \theta = 8.8° \)

\( k_0 L = 100 \)

\( (k_0 L)^{2/3} \sin^2 \theta \approx 0.5 \)
A large electron plasma wave generates hot $e^-$ at the critical surface

$e^-$ distribution in phasespace $p1x1$
after resonance took place

Consider hot $e^-$ (>5kev) around critical surface (95-105 $c/\omega_p$)

$E_{\text{forward}} = 1.5E_L$ (input in a period) \hspace{1cm} \bar{E} = 6.2keV

$E_{\text{backward}} = 1.8E_L$ (input in a period) \hspace{1cm} \bar{E} = 6.3keV

And they are mostly trapped.
Hot $e^-$ near critical surface can be freed in mobile ions case

Phase space of energetic (>5kev) electrons

$E_{\text{forward}} \approx 13\% E_L$

$\bar{E} \sim 14\text{keV}$
Higher intensity laser causes additional Raman/\(2\omega_p\) scatterings near the \(\frac{1}{4}\) critical surface

\[ \nu_{os}/c = 0.15 \]

**Threshold for \(2\omega_{pe}\) instability:**

\[ \left( \frac{\nu_{os}}{\nu_e} \right)^2 > \frac{12}{k_0 L} = 0.12 \quad \text{(from Kruer's book)} \]

for \(\nu_{os}/c = 0.015, (\nu_{os}/\nu_e)^2 = 0.18\)

\(\nu_{os}/c = 0.15, (\nu_{os}/\nu_e)^2 = 18\)
Additional plasma wave and density perturbation at \( \frac{1}{4} \) critical surface

Fixed ions
\[ \frac{v_{os}}{c} = 0.15 \]
\[ \theta = 8.8^\circ \]
\[ k_0L = 100 \]
The instabilities at the $\frac{1}{4}$ critical surface have multiple modes
A pair of modes are found satisfying the frequency and wave number matching conditions

Matching conditions for $2\omega_p$ instability (from Kruer's book):

\[ \omega_0 = \omega_{ek1} + \omega_{ek2} \]
\[ \vec{k}_0 = \vec{k}_1 + \vec{k}_2 \]

in this case, \[ \vec{k}_0 = 0.9883\vec{e}_x - 0.1523\vec{e}_y \]
\[ \vec{k}_1 = 0.3592\vec{e}_x - 0.1523\vec{e}_y \]
\[ \vec{k}_2 = 0.6296\vec{e}_x \]
FFT in time shows the strongest mode has the frequency close to $\frac{1}{2}\omega_0$.
Hot $e^-$ near $\frac{1}{4}$ critical surface can move freely forward

$\nu_{as}/c = 0.15$ mobile ions
Hot $e^-$ near $\frac{1}{4}$ critical surface can move freely forward(2)

Hot (>50kev) electrons' distribution in x-px space

$v_{os}/c = 0.15$

mobile ions

Hot $e^-$ at $1/4$ critical surface can move forward. $E_{\text{forward}} \approx 3\%E_L$ \hspace{1cm} $\bar{E} = 138keV$

For fixed ion case, at critical surface, electrons seem trapped. $E_{\text{forward}} = 1.2E_L$ (input in a period) \hspace{1cm} $\bar{E} = 66keV$

$E_{\text{backward}} = 1.4E_L$ (input in a period) \hspace{1cm} $\bar{E} = 67keV$
Hot $e^-$ near $\frac{1}{4}$ critical surface can move freely forward(3)
## Energy distribution

<table>
<thead>
<tr>
<th>$v_{os}/c$</th>
<th>$I(w/cm^2)$</th>
<th>$k_0L$</th>
<th>$K.E.$ (forward) due to $2\omega$</th>
<th>$K.E.$ (forward) due to resonance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.015</td>
<td>$2.8 \times 10^{15}$</td>
<td>100</td>
<td>$(-50keV)$</td>
<td>$(&gt;5keV)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$13%E_L$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\bar{E} \approx 14keV$</td>
</tr>
<tr>
<td>0.15</td>
<td>$2.8 \times 10^{17}$</td>
<td>100</td>
<td>$(&gt;50keV)$</td>
<td>$(&gt;50keV)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$3%E_L$</td>
<td>$4%E_L$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\bar{E} \approx 138keV$</td>
<td>$\bar{E} \approx 90keV$</td>
</tr>
</tbody>
</table>
Summary

• Most of the hot electrons generated near the critical surface are trapped.
  – Response of ions can change the energetic electrons’ stream.

• Intense laser causes Raman/2ωp instability near the ¼ critical surface.
  – Hot electrons generated near the ¼ critical surface can freely move forward.
  – They have higher average kinetic energy than those generated near the critical surface.