Laser plasma interactions in the relativistic transparent regime

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Talk overview

• What is the relativistic transparent regime?
• Why is it might be relevant to fast ignition?
• Experiment
• Simulations
• Propagation model
• Summary
Relativistic Transparency Regime

The critical plasma density, $n_c$, is when the laser frequency, $\omega_L$, equals the plasma frequency, $\omega_p$:

$$\omega_p = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}} = \omega_L$$

$$\rightarrow n_c = \frac{m_e \epsilon_0 \omega_L^2}{e^2}$$

Above this density the laser is unable to propagate. However, for $a_0 > 1$, the electrons have relativistic motion so $m_e \rightarrow \langle \gamma \rangle m_e$ where $\langle \gamma \rangle = (1 + a_0^2/2)^{1/2}$ for linear polarisation.

Therefore there is a modification to the critical density:

$$n_c' = \frac{\langle \gamma \rangle m_e \epsilon_0 \omega_L^2}{e^2} = \langle \gamma \rangle n_c$$

Consequence → the laser can propagate to higher densities.
Relevance of relativistic transparency to fast ignition

Distance from critical surface to dense core for different wavelengths

<table>
<thead>
<tr>
<th>$\lambda_L$ (nm)</th>
<th>$n_c$ (cm$^{-3}$)</th>
<th>$\rho_c$ (gcm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1053</td>
<td>$1.01 \times 10^{21}$</td>
<td>$\sim 0.004$</td>
</tr>
<tr>
<td>527</td>
<td>$4.03 \times 10^{21}$</td>
<td>$\sim 0.02$</td>
</tr>
<tr>
<td>351</td>
<td>$9.08 \times 10^{21}$</td>
<td>$\sim 0.04$</td>
</tr>
</tbody>
</table>

(5) About the time of ignition

Distance that fast electrons have to travel from the critical surface is quite far considering the large divergence observed in electron beams.

Maybe can use relativistic transparency in hole boring scheme to get closer to core?
Near critical density experiment
Foam targets

Images taken by C Spindloe

- Wigen Nazarov produced these CHO foam targets
- Assuming full ionisation, electron plasma densities of $0.9n_c$ to $30n_c$ were shot
Relativistic laser pulse
The Vulcan Petawatt laser system

1 Petawatt = 500 J / 500 fs
1.054 µm → $n_c = 1.0 \times 10^{21}$ cm$^{-3}$

For our experiment:
Energy = 255 ± 70 J
Pulse length = 550 ± 150 fs
Focal spot = 5.0 ± 0.5 µm
Peak intensity = $(7.7 \pm 3.4) \times 10^{20}$ Wcm$^{-2}$
Peak $a_0 \approx 35$
$n_{cy} = 25 \ n_c$

Contrast ratio ~ $10^{-7}$
Near critical density experiment
Experimental set up

**Foam targets**
- on axis electron spectrometer
- burn paper screen
- Copper activation stack
- foam
- laser

**10μm mylar comparison targets**
- on axis electron spectrometer
- Copper activation stack
- mylar target at 45°
- laser
Near critical density experiment
Electron spectra

Initial results measuring the electron spectra along the laser axis showed high energy electron spectra.

No electrons above the spectrometer threshold were measured from the comparison shot onto the 10 µm mylar target.
Near critical density experiment
Proton acceleration

Copper activation stacks were used to measure the whole proton beam spectra.

Proton spectra have higher maximum energy and greater number for both the 10 µm mylar and 3 mg/cm³ (0.9n_c) foam.
Near critical density experiment
Proton acceleration

\[ n_e (n_c) \]

\[ \rho_{\text{foam}} \text{ (mg/cm}^3\text{)} \]

\[ \varepsilon_{p,\text{max}} \text{ (MeV)} \]

10\(\mu\)m mylar
Near critical density experiment
Proton beam divergence

<table>
<thead>
<tr>
<th>Proton Energy</th>
<th>Sample Density</th>
<th>Proton Energy</th>
<th>Sample Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;7 MeV</td>
<td>3 mg/cm³ (249 J)</td>
<td>&gt;12.5 MeV</td>
<td>20 mg/cm³ (214 J)</td>
</tr>
<tr>
<td></td>
<td>45 mg/cm³ (202 J)</td>
<td></td>
<td>100 mg/cm³ (169 J)</td>
</tr>
<tr>
<td></td>
<td>10 μm mylar (182 J)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FWHM

42° 18° 26° 32° 46°
Near critical density simulations
Simulation set up

OSIRIS
- 3D3V particle-in-cell code (Run as 2D3V)
- Run on a computer cluster using up to 32 nodes

1. Stationary box
- allows the observation of plasma evolution after the laser has passed

2. Moving box
- simulation box travels at the speed of light so that large propagation lengths can be investigated

\[ a_0 = 15, \tau_L = 500 \text{ fs} \]
\[ n_e = 0.9 - 30 n_c \]
Proton plasma

Simulations performed using OSIRIS. We gratefully acknowledge the OSIRIS consortium UCLA/USC/IST for the use of the code.
Near critical density simulations
Laser propagation

Moving box simulations

The retardation of the laser pulse can be seen as the density increases - still the laser is propagating beyond $n_c$, the non-relativistic plasma density

Laser beam filamentation can be seen to affect the electron beam acceleration
Near critical density simulations
Laser propagation direction

Stationary box

0.9\textsubscript{\textit{n}_c} \\
t = 1.3\text{ps}

1.5\textsubscript{\textit{n}_c} \\
t = 1.3\text{ps}
Near critical density simulations
Laser propagation

As the density increases the laser propagation is reduced.

Stationary box

Late time proton density
Near critical density simulations

Similar general trends in maximum proton energy
The larger the distance from the end of the channel to the rear surface, the larger the area the electrons emerge from, reducing the electric field strength
Near critical density simulations
Propagation depth

Ponderomotive hole boring (Wilks, PRL, 1992):

\[ v_{hb} = 0.7c a_0 \sqrt{\frac{m_e n_c}{m_i n_e}} \]

For \( a_0 = 15 \), \( \tau_L = 500 \text{ fs} \)
\[ \rightarrow d_{hb} = v_{hb} \tau_L \]

Model:
Laser energy
\[ \epsilon_L = \tau_L A \frac{c \epsilon_0}{2} \left( \frac{a_0 m_e c \omega_L}{e} \right)^2 \]

Complete absorption into e⁻:
\[ (\gamma - 1)m_e c^2 = \frac{1}{2} a_0^2 m_e c^2 \]

Plasma energy
\[ \epsilon_{plasma} = \frac{1}{2} a_0^2 m_e c^2 n_e A d_{prop} \]

Equating \( \epsilon_L \) to \( \epsilon_p \):
\[ d_{prop} = \frac{c \epsilon_0}{e^2} \frac{\tau_L \omega_L^2}{n_e} \]
\[ d_{model} (\mu m) = \frac{151}{n_e} \] (with \( n_e \) in units of \( n_c \))
Near critical density simulations
Shock acceleration of protons

Evidence for shock acceleration of the protons is seen in some of the simulations, particularly in the $n_e = 3n_c - 15n_c$.

The shock ion acceleration does not reach such high energies that are observed from the rear side TNSA.

Silva, PRL (2004)
Summary
Relativistic transparency regime investigation

Experiments:
• Foam targets produced near critical density plasma
• Proton acceleration diagnosed interaction

Simulations:
• Observed large changes in propagation direction
• Investigate laser propagation depth
• Trends observed agree with experiment