Three-Dimensional Effects in Laser Channeling in Fast-Ignition Targets

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A clean channel can be established by a high-intensity laser in the underdense plasma of fast-ignition targets.

- Channel advancing in 3-D PIC simulations is faster than in 2-D.
- The difference of channel advancing in 2-D and 3-D is due to the difference in laser self-focusing and ponderomotive force.
- Electrons are heated to relativistic temperatures, which reduces laser-plasma coupling in the channel.
- A low-density channel significantly improves the transmission of the ignition pulse for fast ignition.
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Simulations were carried out at NERSC through a DOE INCITE grant.
Laser channeling in millimeter-scale plasmas is a highly nonlinear and dynamic process

- Full-scale 2-D slab-simulation parameters*
  - box size: $1 \text{ mm} \times 0.25 \text{ mm}$
  - grids number: $10460 \times 2614$
  - particles number: $5.6 \times 10^7$
  - simulation time: $20 \text{ ps}$
  - $n = 0.1 \sim 1.0 \, n_{cr}$

- The simulations show many nonlinear phenomena
  - plasma piling up
  - laser hosing/refraction leads to channel bending
  - channel bifurcation/self-correction

- Important 3-D effects must be studied

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A low-density channel is established in 3-D PIC simulations

- 3-D PIC simulation parameters
  - box size: \(90 \times 90 \times 90\) \(\mu\text{m}\)
  - total particles number: \(3.0 \times 10^9\)
  - \(I = 10^{19} \text{W/cm}^2\), \(n = 0.5 \sim 0.6 \ n_{\text{cr}}\)
  - grids number: \(1728 \times 916 \times 916\)
  - simulation time: 2.8 ps

Phase space \(xyz\)

Time = 2.8 ps

\(E_z\) envelope isosurface
- 1.5
- 0.75

Density isosurface
- 0.1 \(n_{\text{cr}}\)
- 0.3 \(n_{\text{cr}}\)
- 1.0 \(n_{\text{cr}}\)
The pulse and the channel are nearly symmetric in the transverse directions

• The 3-D pulse is nearly symmetric in the transverse directions.

• The 3-D channel is nearly round.

• It is reasonable to assume cylindrical symmetry in 3-D.
A low-density channel is established faster in 3-D than in 2-D

- The channel in 3-D has a more regular shape.
- The average residual density in 3-D is smaller.
The stronger 3-D ponderomotive force allows the channel to form faster

- For the same laser ponderomotive force $F_p \sim a^2/w$, the channel is deeper in 3-D than in 2-D

$$\left( \frac{\partial^2}{\partial t^2} - c_s^2 \nabla^2 \right) \frac{\delta n_i}{n_{i0}} = c^2 \frac{Z_m e}{m_i} \nabla^2 (1 + a^2/2)^{1/2}$$

- $F_p$ is larger in 3-D than in 2-D due to self-focusing
  - 3-D: $w^2a^2 = \text{const}$
  - 2-D: $wa^2 = \text{const}$
  - $F_{p3-D}/F_{p2-D} = w_0/w_f > 1$ (if $w_{f2-D} = w_{f3-D}$)
Relativistic $T_e$ suppresses self-focusing and other nonlinear interactions

- PIC simulations show the residual electrons are quickly heated to relativistic $T_e$
- When $T_e$ is relativistic, the quiver velocity $v_z$ is reduced*
  
  \[ v_z = \frac{a/\gamma}{\left(1 + 5 \rho_{th}^2\right)^{1/2}} \]

- The ponderomotive force is decreased by $14 \times$ times for $\rho_{th} = 6$, leading to the laser-plasma decoupling
  - $w_f$ decreases by a factor of 2 in both 2-D and 3-D
- Decoupling at relativistic temperature increases the laser transmission

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Summary/Conclusions

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