Recent OSIRIS results on fast ignition simulations and new hybrid framework

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Outline

- Motivation
- Absorption of intense laser light at a sharp overdense boundary
- Isolated target simulations with more particles per cell
- Implementation of new hybrid algorithm for inhomogeneous plasmas
- Full-scale modeling of fast ignition
- Conclusions and perspectives
Fast ignition modeling is extremely demanding due to different scales.

**2D Simulation of a FI isolated target**

- Ignition laser
- $n_e \sim 10^5 n_c$

**Full-scale modeling is crucial**

- Ignition scale lasers are now coming online: predictive capability is required
- Existent modeling is not complete/self-consistent
- Several important questions need to be addressed:
  - What are the dominant laser absorption mechanisms?
  - How does laser absorption/e-spectrum changes during 15 ps?
  - What is the beam divergence?
  - What are the stopping mechanisms?
  - How important is the modeling of spherical isolated targets?

- 300 x 300 μm²
- Laser $\lambda_0 \sim 1 \mu m$
- Plasma $n_0 - 10^{22} - 2 \times 10^{26}$ cm$^{-3}$
- Time $\sim 15$ ps
- **Sim. time $\sim 2 \times 10^{11}$ cpu hours**
Laser absorption
Understanding absorption of intense lasers at sharp overdense boundaries

**Particles are accelerated in vacuum**

**Mechanism leads to energy dependent divergence**

* J. May et al., to be submitted (2010)
Self-similar shape when scaled to $2a_0$

Distribution functions are scaled to $2a_0$
Modeling realistic targets: the anomalous stopping of macroparticles
**OSIRIS simulation setup: isolated target**

**Physical Parameters**

**Laser**
- $\lambda_0 = 1 \mu m$
- $I_0 = 5 \times 10^{19} - 8 \times 10^{20} \text{ Wcm}^{-2}$
- $W_0 = 20 \mu m$
- plane polarized

**Plasma**
- $150 \mu m \times 130 \mu m$
- $n_{e0} = 100 \ n_c$
- $m_i/m_e = 3672 \ (\text{D}^+)$
- $T_{i0} = T_{e0} = 1 \text{ keV}$

**Core**
- drag force $\propto p$
- $\Delta p = -p \frac{A}{\gamma^2} \Delta t$
  (1 e-fold/10 $\mu m$ for 1 MeV $e^+$)

**Numerical Parameters**
- $\Delta x \perp k_p = 0.5$
- $\Delta z k_p = 0.5$
-Particles per cell = 4-25
- # particles = $10^9$
- # time steps = $10^5$
Anomalous stopping of macro-particles

Stopping depends on particle shape and size

Stopping vs. PPC for fixed density, cell size and particle shape

\[
\frac{d\gamma_b}{d\omega_p t} = -\frac{1}{4} \frac{\omega_p^2}{c^2} \frac{\Delta^2}{N} C(shape, size)
\]

n=10^{23}, quadratic shape, and 0.5c/\omega_p
Fast ignition at high intensity revisited

Preliminary result: Net heat flux is carried by higher yet low energy electrons
New hybrid framework for full-scale modeling of fast ignition
New hybrid algorithm*

\[ n_e \sim 10^5 n_c \]

\[ n_e < 10^2 n_c \]

proposed by B. Cohen, A. Kemp, and L. Divol (LLNL)

New hybrid algorithm


Full-PIC algorithm

- Full Maxwell’s equations
- Kinetic species
- $n_0 < 10^{23} \text{ cm}^{-3}$
- $\omega_p \Delta t < O(1)$
- $\Delta x \omega_p / c < O(1)$
- $c \Delta t / \Delta x < 1$
New hybrid algorithm*


**Hybrid-PIC algorithm**

- Maxwell’s equations + Ohm’s law (inertialess)
- Kinetic species
- \( n_0 > 10^{23} \) cm\(^{-3} \)
- \( \nu_{ei} \Delta t < O(1) \)
- \( c\Delta t/\Delta x < 1 \)
New hybrid algorithm*


Ignition laser

$n_e \sim 10^5 n_c$

$n_e < 10^2 n_c$

**Full-PIC code**

- Full Maxwell’s equations
- Kinetic species
- $n_0 < 10^{23}$ cm$^{-3}$
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**Hybrid-PIC code**

- Maxwell’s equations + Ohm’s law (inertialess)
- Kinetic species
- $n_0 > 10^{23}$ cm$^{-3}$
- $\nu_{ei} \Delta t < O(1)$
- $c \Delta t / \Delta x < 1$

If resistivity (Ohm’s law) matches collisional model transition is natural and self-consistent
New Features in v2.0

- High-order splines
- Binary Collision Module
- Tunnel (ADK) and Impact Ionization
- Dynamic Load Balancing
- PML absorbing BC
- Parallel I/O

osiris framework

- Massively Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium ⇒ UCLA + IST

Ricardo Fonseca: ricardo.fonseca@ist.utl.pt
Frank Tsung: tsung@physics.ucla.edu

http://cfp.ist.utl.pt/golp/epp/
http://exodus.physics.ucla.edu/
**Algorithm description and implementation: current deposition**

**Hybrid-PIC algorithm**

\[
\frac{d\mathbf{u}}{dt} = \frac{q}{m} \left( \mathbf{E} + \frac{1}{\gamma c} \mathbf{u} \times \mathbf{B} \right)
\]

Integration of equations of motion, moving particles

\[ \mathbf{F}_i \rightarrow \mathbf{u}_i \rightarrow \mathbf{x}_i \]

Integration of Field Equations on the grid

\[ \mathbf{J}_i \rightarrow (\mathbf{E}, \mathbf{B})_i \]

Weighting

\[ (\mathbf{E}, \mathbf{B})_i \rightarrow \mathbf{F}_i \]

\[ (\mathbf{x}, \mathbf{u})_i \rightarrow \mathbf{J}_{\text{fast}} \]

\[ (\mathbf{x}, \mathbf{u})_i \rightarrow \mathbf{J}_{i} \]

Weighting

\[ \Delta t \]

Weighting deposit currents

\[ (\mathbf{x}, \mathbf{u})_i \rightarrow \mathbf{J}_f \]

\[ (\mathbf{x}, \mathbf{u})_i \rightarrow \mathbf{J}_i \]

separate fast (f) and cold (e) electrons

\[ (v > \alpha v_{\text{th}}) \]

calculate \( \mathbf{J}_e \) from Ampère’s law

\[ \frac{\partial \mathbf{E}}{\partial t} = c \nabla \times \mathbf{B} - 4\pi (\mathbf{J}_f + \mathbf{J}_i + \mathbf{J}_e) \rightarrow \mathbf{J}_e \]

\[ 0 = \mathbf{E} + \nabla p_e - \eta (\mathbf{J}_e + \mathbf{J}_i) - \frac{\mathbf{J}_e \times \mathbf{B}}{en_e} + \left( \frac{d}{dt} \right)_{\text{coll},f-e} \frac{\mathbf{P}_{e,f}}{en_e} \]

\[ \frac{\partial \mathbf{B}}{\partial t} = -c \nabla \times \mathbf{E} \]

**Algorithm description and implementation: field solver**

**Hybrid-PIC algorithm**

\[
\frac{du}{dt} = \frac{q}{m} \left( E + \frac{1}{\gamma c} u \times B \right)
\]

Integration of equations of motion, moving particles

\( F_i \rightarrow u_i \rightarrow x_i \)

Integration of Field Equations on the grid

\( J_i \rightarrow (E, B)_i \)

Weighting

\((x, u)_i \rightarrow J_{\text{fast}} \)

\((x, u)_i \rightarrow J_i \rightarrow J_e \)

Integration of Field Equations on the grid

\[
0 = E + \frac{\nabla p_e}{en_e} - \eta(J_e + J_i) - \frac{J_e \times B}{en_e c} + \left( \frac{d}{dt} \right)_{\text{coll}, f-e} \frac{P_{e,f}}{en_e}
\]

where

\[
\eta = \frac{m_e \nu_{ei}}{n_e e^2}
\]

\[
\nu_{ei} = 0.51 \times 4 \sqrt{2 \pi e^4 Z_i^2 n_i / (3 \sqrt{(m_e) T_e^3/2})}
\]

\[

\nu_e = \int v f_e d^3v \\
\nu_e = \int v f_e d^3v \\
\nu_e = \int v f_e d^3v \\
\nu_e = \int v f_e d^3v
\]

\[
J_e = \frac{p_e}{n_e}
\]

(possibility of spatially/temporally smooth all quantities)

Advance B using Faraday's law

\[
\frac{\partial B}{\partial t} = -c \vec{\nabla} \times E
\]

**S.I. Braginskii, Rev. Plasm. Phys. 1, 205 (1965)**
OSIRIS simulation setup: laser-solid interactions

Physical Parameters

Laser
- $\lambda_0 = 1 \mu m$
- $I_0 = 5 \times 10^{19}$
- $W_0 = 5 \mu m$
- $\tau_0 = 350$ fs (1D); 200 fs (2D)

Plasma
- $L = 30 \times 5 \mu m^2$
- $n_{e0} = 1000 \, n_c$ (1D) - 500 $n_c$ (2D)
- $m_i/m_e = 1836$

Numerical Parameters

- 400 cells/$\mu m$ (full-PIC)
- 42 cells/$\mu m$ (hybrid-PIC)
- hybrid/full-PIC transition = 100 $n_c$
- Part. per cell = 200 (1D) - 9 (2D)
- cubic interpolation

Monte Carlo Coulomb collisions modeled in all simulations
New algorithm allows for smooth hybrid-PIC transition and accurate results.

1D simulations @ 0.85 ps
Very large speed-ups can be achieved while maintaining the accuracy of simulations.

<table>
<thead>
<tr>
<th>OSIRIS</th>
<th>h-OSIRIS</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Graph 1" /></td>
<td><img src="image2.png" alt="Graph 2" /></td>
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<tr>
<td><img src="image3.png" alt="Graph 3" /></td>
<td><img src="image4.png" alt="Graph 4" /></td>
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</tbody>
</table>

2D simulations @ 0.5 ps

*300X FASTER*
OSIRIS simulation setup: HiPER modeling*

**Numerical Parameters**
- 42 cells/μm
- hybrid/full-PIC transition = 100 n_c
- Particles per cell = 1000
- # time steps = $2.5 \times 10^5$
- cubic interpolation

**Physical Parameters**

**Laser**
- $\lambda_0 = 1 \mu$m
- $I_0 = 5 \times 10^{19} - 2 \times 10^{20} \text{ Wcm}^{-2}$
- $\tau_0 = 20 \text{ ps}$

**Plasma**
- $L = 800 \mu$m
- $n_e0 = 1 \text{ n}_c - 1.5 \times 10^5 \text{ n}_c$
- $m_i/m_e = 3672$

*HiPER profile from J. R. Davies and X. Ribeyre*
Higher intensities required in order to obtain ignition.

**Heat flux / Laser flux [\%]**

- **Line graph** showing heat flux and laser flux ratios for different intensities.
  - **I = 5 \times 10^{19} \text{Wcm}^{-2}**
    - 0.3x pond. scaling
    - 1.5x pond. scaling
  - **I = 2 \times 10^{20} \text{Wcm}^{-2}**
    - 0.25x pond. scaling

**Particle energy / laser energy [\%]**

- **Graph** comparing particle (ions, electrons) energy to laser energy for different intensities.
  - **I = 5 \times 10^{19} \text{Wcm}^{-2}**
    - 8% @ core
    - 17% total
  - **I = 2 \times 10^{20} \text{Wcm}^{-2}**
    - 10.5% @ core
    - 21% total

**Notes**

- J. Tonge | LLNL, August 4 | FSC 2010
OSIRIS simulation setup: isolated target

**Numerical Parameters**
- 42 cells/μm
- Hybrid/full-PIC transition = 100 n_c
- Particles per cell = 64
- # time steps = 10^5
- cubic interpolation

**Physical Parameters**

**Laser**
- λ₀ = 1 μm
- I₀ = 5x10^{19} - 2x10^{20} W cm^{-2}
- W₀ = 4 μm
- τ₀ = 5 ps

**Plasma**
- L = 150 x 120 μm^2
- n_e₀ = 10 n_c - 2x10^5 n_c
- m_i/m_e = 3672

*HiPER profile from J. R. Davies and X. Ribeyre*
Reduced divergence in spherical isolated targets

@ 0.6 ps

0.5x pond. scaling
pond. scaling

~20°
Modeling of realistic targets is crucial.
Towards full-scale modeling of fast ignition

<table>
<thead>
<tr>
<th>Laser</th>
<th>2D full-scale</th>
<th>3D scaled down</th>
<th>3D full-scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>ao</td>
<td>6-12</td>
<td>6-12</td>
<td>6-12</td>
</tr>
<tr>
<td>Spot [μm]</td>
<td>20-30</td>
<td>7-10</td>
<td>20-30</td>
</tr>
<tr>
<td>Duration [ps]</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Target</th>
<th>2D full-scale</th>
<th>3D scaled down</th>
<th>3D full-scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [n_c]</td>
<td>$10^2-2\times10^5$</td>
<td>$10^2-2\times10^5$</td>
<td>$10^2-2\times10^5$</td>
</tr>
<tr>
<td>Size [μm²(3)]</td>
<td>300x300</td>
<td>100x100x100</td>
<td>300x300x300</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Simulation time [CPU hours*]</th>
<th>2D full-scale</th>
<th>3D scaled down</th>
<th>3D full-scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIC</td>
<td>$2\times10^{11}$</td>
<td>$4\times10^{13}$</td>
<td>$1\times10^{15}$</td>
</tr>
<tr>
<td>Hybrid-PIC</td>
<td>$1\times10^6$</td>
<td>$7\times10^6$</td>
<td>$2\times10^8$</td>
</tr>
</tbody>
</table>

*CPU hours includes 2D PIC and Hybrid-PIC.
OSIRIS is highly optimized for modeling at very large scales.

**OSIRIS strong scaling up to ~300k CPUs**

- Spatial domain decomposition
- Local field solver
- Minimal communication
- Dynamic Load Balancing

**New hardware features**

- **SIMD units**
  - tailored code already in production

- **GPUs**
  - CUDA development (test PIC code)

- **PowerXCell**

**Speed up**

- 81% efficiency
- 294,912 CPUs

**Ideal**

- 100
- 10
- 1

**CPUs**

- 4,096
- $10^4$
- $10^5$

**Germany**

**JUGENE**

**J. T onge | LLNL, August 4 | FSC 2010**
GPU acceleration for PIC codes is under development: Rigorous particle sorting routine for any many core architecture

<table>
<thead>
<tr>
<th></th>
<th>Intel i7</th>
<th>GTX 280</th>
<th>Speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposit [ns]</td>
<td>8.2</td>
<td>0.21</td>
<td>40×</td>
</tr>
<tr>
<td>Push [ns]</td>
<td>19.9</td>
<td>0.43</td>
<td>46×</td>
</tr>
<tr>
<td>Sort [ns]</td>
<td>-</td>
<td>0.44</td>
<td>-</td>
</tr>
<tr>
<td>Total [ns]</td>
<td>30.0</td>
<td>1.08</td>
<td>28×</td>
</tr>
</tbody>
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- Overall speedup of about 28 on a 2D Electrostatic code in single precision (Decyk et al. ICAP 2009 proceedings and submitted).
- Extrapolating to EM codes (<3ns/particle/step is possible—>100 time speed up!!)
- Implementation of a EM algorithm using a different sorting routine and thread size. Speed ups of 87- 27 depending on the plasma temperature (X. Kong et al. submitted).
- A variety of approaches are being investigated: UCLA/IST/URochester
- UCLA is building a 200 Tflop GPU cluster with FI as one target application
Conclusions and perspectives

New algorithm allows for efficient full-scale of fast ignition

Physics behind transport and stopping can be understood in a self-consistent way

e\neg cooler than pond. Scaling allow for high efficiency at core with ultrahigh laser intensities

Modeling of spherical isolated targets crucial to infer ignition conditions

New approach can have significant impact in ignition modeling and guiding of future experiments

Next steps
- Modeling full-scale FI with isolated targets
- Compare cone guided FI with channeling
- Model shock ignition scenario
- Full-scale 3D modeling of ion acceleration in laser-solid interactions