Integrated PICLS simulations
- NTF theory/simulation activity -

Yasuhiko Sentoku
A. Kemp, B. Chrisman, and T. Cowan
University of Nevada, Reno

08/28/2006@LLNL

Fusion Science Center Meeting
UNR/NTF activities 2006

• A graduate student (Brian Chrisman) is involved in our research. (support $40k by FSC, thanks!!)

• Theoretical study of the threshold density of kinetic and collisional regime & Collisional energy transfer mechanism in FI core.

• PICLS: model of large density scale plasma by the collisional reduced PIC technique. (Collision model is modified to treat degenerated plasmas)

• Pulse optimization of FI, 1D simulations.
Current plasma models either under-resolve physics or do not include ionization and collisions.

- hybrid simulation cannot resolve laser plasma physics
- PIC simulation cannot simulate extremely dense plasmas

develop an integrated plasma simulation code for large density scale plasmas including atomic physics models (collision, ionization, ...)

We have developed the capabilities to design and interpret experiments for Fast Ignition research.
Plasma Simulation of Large Density Scale Plasmas
- seamless switch from full to reduced PIC: **PICLS** -

In high density region $n > n_{\text{pic}}$, although the kinetic physics is not fully resolved, it is supposed to be suppressed by collision.
Transition density between kinetic and collisional regime
Collisional effects dominate laser-plasma interaction at high densities

Modeling plasma at high densities:
- Longitudinal beam-plasma instabilities are suppressed by collisions beyond near-solid density
- Allows smooth and efficient transition between kinetic- and Monte-Carlo modeling

\[ \Gamma_L = \frac{\sqrt{3}}{2^{4/3}} \omega_p (n_b/n_p) \]
Id-simulation of fast ignition

cold electron debye length physics is under resolved. $c/\omega_p$ scale (up to 1000$n_c$) is resolved.
corona plasma is heated by beam-plasma instability \((n_e < 100n_c)\)

electron phase plot \(x-p_x\) \(t=165\text{fs}\)

color indicates density (initial position)
corona plasma is heated by beam-plasma instability \((n_e < 100n_c)\)

electron phase plot \(x-p_x\) \(t=165\text{fs}\)

hot electrons and corona electrons are mixing behind cone target

color indicates density (initial position)
high density region \((n_e > \text{a few } 100n_c)\) is quiet
- no instability happens -

Plasma was heated by beam instability \((n < 100n_c)\)
Collisional Energy Transfer Mechanism
- illustrate four regimes of energy transfer in 1D -

Main contributions to heating cold electrons [Glinsky, 1995]:

\[
\frac{3}{2} n_c \frac{\partial T_c}{\partial t} = \frac{\partial}{\partial x} \left( \kappa(T_c) \frac{\partial T_c}{\partial x} \right) + \frac{j_h^2}{\sigma(T_c)} + \frac{3}{2} \frac{n_h T_h}{\tau_h} + \text{(kinetic)}
\]

- diffusion
- resistive
- drag

Graph showing the regimes of energy transfer:
- no diffusion
- diffusion/drag
- diffusion/resistive
- resistive/diffusion
- drag/diffusion
- drag/resistive

Temperature [eV] vs. Density [cm\(^{-3}\)]

- \( n_P \sim \alpha^{2/5} T_h^{1/2} L_T^{-3/5} \)
- \( 3 \times 10^{20} \text{ cm}^{-3}, 400 \text{ keV beam, } L_T = 10 \text{ um} \)
Collisional Energy Transfer Mechanism in Dense Plasma
- 1D PIC -

[Key, Sentoku, Sotnikov, Wilks(LLNL), submitted to PRL,
“Collisional Relaxation of Super Thermal Electrons Generated by Relativistic Laser Pulses in Dense Plasma”]
Collisional Energy Transfer Mechanism in Dense Plasma
- 1D PIC -

[Kemp, Sentoku, Sotnikov, Wilks (LLNL), submitted to PRL, “Collisional Relaxation of Super Thermal Electrons Generated by Relativistic Laser Pulses in Dense Plasma”]
Fl core is heated by the direct collision process

The restive heating quickly set in but saturates after the core temperature exceeds a few hundred eV.
Plasma Simulation of Large Density Scale Plasmas

- seamless switch from full to reduced PIC: \textit{PICLS} -

In high density region \( n > n_{\text{pic}} \), although the kinetic physics is not fully resolved, it is supposed to be suppressed by collision.
PICLS demonstrated collisional reduced PIC - numerical models for extremely dense plasmas -

Ultra intense laser foil interaction:
plasma density $160n_c$ (solid), $T_0=0$eV, laser $I=10^{18}$ W/cm$^2$, 500 fs

Quasi-static magnetic fields profiles

**full PIC ($\omega_p \Delta t < 2$) + collision ($n_{\text{pic}}=160n_c$)**

$t=130$ fs

$t=260$ fs

1000x2000 meshes
number of particles = $7.2e7$

CPU time: 20 nodes x 2 days

**reduced PIC ($\omega_p \Delta t > 2$) + collision ($n_{\text{pic}}=40n_c$)**

$t=130$ fs

$t=260$ fs

500x1000 meshes
number of particles = $1.8e7$

CPU time: 20 nodes x 4 hours
Ultra intense laser foil interaction:
plasma density 160n_c (solid), T_0=0eV, laser I=10^{18} W/cm^2, 500 fs

Quasi-static magnetic fields profiles

\[ \Delta t = \Delta x/c \]

full PIC (\(\omega_p \Delta t<2\))
(\(n_{pic}=160n_c\))

\[
\begin{array}{c}
t=130 \text{ fs} \\
1000\times2000 \text{ meshes} \\
\text{number of particles} = 7.2e7
\end{array}
\]

reduced PIC (\(\omega_p \Delta t>2\))
(\(n_{pic}=40n_c\))

\[
\begin{array}{c}
t=130 \text{ fs} \\
500\times1000 \text{ meshes} \\
\text{number of particles} = 1.8e7
\end{array}
\]
1d FI simulations
- find an optimum laser to heat core -

no numerical heating up to 10 ps (4th-order interpolation in PIC)
laser condition
- constant laser energy 30J (assuming 10 μm spot)-

intensity:
$I=5 \cdot 10^{18} \sim 4 \cdot 10^{20}$ W/cm$^2$

pulse length:
$t=5 \text{ps} \sim 50 \text{ fs}$
The highest intensity heats the core more efficiently.

I=5x10^{18}\text{W/cm}^2  
pulse length=6\text{ps}  
@t=10\text{ps}

I=5x10^{19}\text{W/cm}^2  
pulse length=600\text{fs}  
@t=5\text{ps}

I=2x10^{20}\text{W/cm}^2  
pulse length=150\text{fs}  
@t=5\text{ps}

The coupling efficiency $\sim 9\%$
hot electron in core region has two-temperature distribution

Temperature [MeV] vs. Intensity

- Bulk
- Tail

2d results
2d-PIC integrated fast ignition simulation

laser
$5 \times 10^{19} \text{ W/cm}^2$
pulse length 500fs

absorbing boundaries for particles/waves
simulation time $\sim 1$ ps

cold electron debye length physics is under resolved.
$c/\omega_p$ scale (up to $200n_c$) is resolved.
hot electron flows and magnetic fields

resistive field in cone

core is surrounded by MG-fields

3 MG

-3 MG

t=210fs

e-

strongly heated by the anomalous effects
lower energy hot electrons increased after laser-cone interface steepen

time evolution of \( n_c \) inside core region

hot electron spectrum in core region

Te\textasciitilde500keV

't=165fs'
't=330fs'
't=500fs'
hot electron in core region has two-temperature distribution

![Graph showing temperature vs. intensity with bulk and tail regions marked with '2d results'.]
Increasing pulse length (square pulse) of the highest intensity does not increase core coupling.

The pulse directly interacted with a solid plasma, and produced less energetic electrons and more fast ions. As a result, the corona was heated strongly, but not the core.
Hot electron energy spectrum

30 tau
5 times long pulse

intensity: $I=4\cdot10^{20}$ W/cm$^2$
pulse length: $t=50$ fs & 250 fs
summary of 1d simulations

• bulk of hot electrons contributes to the core heating. Higher intensity increases the core coupling.

• control of the hot e- bulk temperature is a key issue.

• direct interaction with a solid plasma after pre-plasma swept away makes the hot e- range too short, less coupling to the core.

• reducing the solid plasma density by coating plastic inside the gold cone might increase the coupling efficiency.

bulk hot e- temperature is empirically proportional to $1/n_e^{1/2}$. 
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