Target Design for Fast Ignition at ILE Osaka

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code development
FI3 Fast Ignition Integrated Interconnecting project
implosion code (PINOCO), relativistic Fokker-Planck-Hydro code (FIBMET), and collective PIC code (FISCOF)

results of the Fast Ignition integrated simulation
implosion
heating

target design for FIREX-I experiment and reactor scale
**FI³ (Fast Ignition Integrated Interconnecting code)**

- **Collective PIC code (Laser plasma interaction)**
- **ALE radiation-hydro code**
- **Relativistic Fokker-Planck Hydro code (hot electron transport)**
- **10⁴n_{cr}**
- **2000n_{cr}**
- **Laser for implosion**
- **PW Laser**
- **Petawatt laser**
- **X-ray, γ ray**
- **MeV electron**
- **MeV ion**
- **neutron, proton, ...**

(cf. in US; LSP→ Hybrid code)
The FI³ project involves the following components:

- **Radiation-hydro. Code PINOCO (implosion)**
- **Collective PIC code FISCOF1, or 2 (laser plasma interaction)**
- **Relativistic Fokker-Planck-hydro code FIBMET (hot electron transport)**

**Data flow in FI³ system.** (Black arrows are already executable data flows, and gray arrows are next plan to be considered.)

**Vector parallel machine**
- SX-5 (CMC Osaka), SX-6 (ILE), SX-7 (NIFS), SX-8 (ILE)

**Scalar parallel machine**
- Primepower (ITBL/JAERI Kansai), Itanium2, Xeon
Numerical simulation of cone-guided implosion using 2D radiation-hydro simulation code “PINOCO”

**PINOCO**

- 2 temperature plasma
  - Hydro ALE-CIP method
- Thermal transport
  - flux limited type Spiter-Harm
  - Implicit (9 point-ILUBCG)
- Radiation transport
  - multi-group diffusion approximation
  - Implicit (9 point-ILUBCG)
  - Opacity, Emissivity (LTE or CRE)
- Laser energy
  - 1-D ray-trace
- EOS
  - Tomas-Fermi
  - Cowan

**Laser condition**

- Wavelength: 0.53µm
- Energy: 2.5 kJ (Gaussian, on target, center focused)
- Ray-trace: 1 - D (radial direction)
In the spherical implosion, the CH shell target reach the maximum compression at 2.285 ns. In non-spherical implosion case, the shell continued to be compressed since a hot spot is not formed and an average $\rho R$ reached a higher value (0.15 g/cm$^2$).

H. Nagatomo et al., IAEA/FEC-IF/P7-29
1-D Collective PIC Simulations
by H. Sakagami (NIFS) and T. Nakamura (ILE)

Simulation time: 1000 [fs]
\[ \Delta t = 0.0056 \text{ [fs]} (0.0016 \omega_L), \sim 177,000 \text{ steps} \]
Spatial size: 308 [\mu m]
\[ \Delta z = 4.73e-3 \mu m, (0.0045 \lambda_L), \sim 65,000 \text{ meshes} \]
Total Number of Particle: \( \sim 3,574,000 \)
200 particles / mesh \((n > 2n_c)\)
\[ \Box \text{ Ions: immobile} \]

Initial plasma configuration

- Pre-plasma, scale length = 5 [\mu m]
- Peak density, \( n_{\text{e,peak}} = 100n_c \), width = 10 [\mu m]
- Rear Plasma, \( n_{\text{e,rear}} = 100n_c \) or \( 2n_c \), width = 50 [\mu m]
- Vacuum region: front 153 [\mu m], rear 60 [\mu m]

\[ \text{Fast electrons are observed at 5 [\mu m] behind of 100n_c region.} \]

Laser Pulse

Gaussian Pulse, \( \tau_{\text{FWHM}} = 150 \text{fs} \)
Wavelength, \( \lambda_L = 1.06 \mu m \)
Peak Intensity, \( I_{L,\text{max}} = 3 \times 10^{19} \) or \( 1 \times 10^{20} \) [W/cm²]
In the cone-guided implosion simulation by PINOCO-2D, there is low density (<=10Nc) spot between gold cone and imploded core plasma.

Implosion simulation (PINOCO-2D)
- Laser: 2.5kJ 2ω
- Target: CH (r=250μm, t=8μm)
- Cone: 30 degree, gold

Time history of electron number density distribution on the x-axis

2.40ns Density

\[ n_e/n_c \]

X [micron]

- t=2.0ns
- t=2.40ns
- t=2.30ns
Fast Electron Energy Distribution at a Top of Cone-This is used for Fokker Planck Simulation

Energy [MeV]

$E$ [a.u.]

$f(E)$

100nc

2nc
Fast Electron Profiles (PIC Code)

Fast electrons were injected at inner or outer surface of a gold cone.

Fast Electron Transport

Relativistic Fokker-Planck transport
Electromagnetic Fields

Energy deposition rate

Radiation-Hydrodynamics

Bulk Plasma
• 1-fluid 2-temp. CIP code

Radiation
• Flux-limited diffusion

Imploded Core Profiles (ALE Rad-Hydro Code)
Implosion simulation of a canonical CD target
(2D ALE code “PINOCO” by Nagatomo)

RFP-Hydro simulations
REB was injected at inner surface of a gold cone.
Integrated Simulation Results
Core Heating rate & Temperature ($\rho > 50\text{g/cc}$)

$I_{L,\text{max}} = 1 \times 10^{20} \text{ [W/cm}^2\text{]}$

**Core Heating Rate**

*Early stage of core heating ($t < 2000\text{fs}$), $n_{er} = 2n_c$: Due to the lower beam intensity and higher averaged energy of electrons the core heating rate and the temperature rising rate are lower than those in the case of $n_{er} = 100n_c$.*

*After finishing laser irradiation,*

The relatively low-energy fast electrons confined in the cone tip due to the density gap continue to be released from the cone tip. The core heating period is long longer than $n_{er} = 100n_c$ case.

<table>
<thead>
<tr>
<th>$n_{er}$</th>
<th>Resultant core temp., $&lt;\text{Ti}&gt;$</th>
<th>Enhancement, $\Delta &lt;\text{Ti}&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$100n_c$</td>
<td>0.43keV</td>
<td>0.10keV</td>
</tr>
<tr>
<td>$2n_c$</td>
<td>0.50keV</td>
<td>0.17keV (~70%)</td>
</tr>
</tbody>
</table>

**Core Temperature**

Coupling efficiency in the case of $n_{er} = 2n_c$ from fast electrons to core is 25% from laser to core is 5.4%.
Laser Condition
Wavelength : 1 micron
Peak Intensity : $2.5 \times 10^{19}$ w/cm²
Spot size : 2.5 micron
Pulse duration : 100 fs

Plasma condition
30Nc cone target with rear side plasma, density of
a) 2Nc (1/15) ,  b) 10 Nc (1/3 ).
Electron spectrum depends on rear side plasma density. Sub-Mev electrons are confined inside the cone target for 2Nc case.

Strong electro-static field is induced inner and outer surface of the cone tip. The accelerated electrons are decelerated at the boundary.

Energy spectrum observed inside and outside the cone for 10Nc (upper) and 2Nc (lower).
The implosion and fast electron generation processes were considered.

Imploded core profiles  <-  ALE Rad.- Hydro. Code  PINOCO △
Fast electron profiles  <-  1-D Collective PIC & 2-D Collisional PIC
  △  Electron beam intensities were adjusted so that the total input energy corresponds to the PW experiments condition.

Results

Fast electron profiles:
- Energy coupling from Laser to Fast electrons : 1-D PIC (~20%) < 2-D PIC (27%)
- Averaged fast electron energy: : 1-D PIC (~1 MeV) ~ 2-D PIC (~1 MeV)
- Angular spread of the fast electrons : 1-D PIC (Beam) < 2-D PIC (60~90 deg.)

Core heating properties:
- Energy coupling from Fast electrons to Core : 1-D PIC (25~30%) > 2-D PIC (20%)
- Energy coupling from Laser to Core : 1-D PIC (~5%) ~ 2-D PIC (~5%)

The dense core is heated up to ~ 0.5 keV, which is still lower than the reported PW experiment results (~0.8 keV).
Target design working group;
(sub Working Group of IFE design WG organized by IFE Forum and ILE)

H. Azechi, K. Mima, H. Shiraga, R. Kodama, H. Sakagami, H. Nagatomo, T. Johzaki

is discussing about the following targets;

• FIREX-I
  10kJ (implosion), 10kJ (heating)

• Reactor scale
  1MJ (implosion), 100kJ (heating)
target design for FIREX-I

- FIREX-I experiment design condition
  - laser
    - 4.5kJ (10kJ, ideal) for implosion, 2
    - Gaussian (or another shape?)
    - 10kJ for heating
  - target
    - CH-DT
  - DT core plasma.
    - 300g/cc
    - \( \rho I = 0.2 \text{g/cm}^2 \) (desirable)
    - gain 0.1
Single Gaussian pulse implosion for FIREX-I
Single Gaussian pulse case (with radiation)
(density (upper), and elec. temp. (lower) [single Gaussian pulse shape]
90 g/cc of DT
Double Gaussian pulse implosion for FIREX-I

optimized double Gaussian pulse implosion
Double Gaussian pulse case (with radiation)
(density (upper), and elec. temp. (lower ) [double Gaussian pulse shape]
80g/cc of DT
target design for reactor

- Laser energy
  - 1MJ for the implosion ($3\omega$)
  - 100kJ for the heating ($1\omega$)
- CH-DT shell with conical target
- DT core plasma
  - 300 g/cc
  - $\rho l = 3.5$ g/cm$^2$
- Fusion energy $> 200$MJ
  (gain $> 170$)
Burn Simulation Condition of a Reactor-Grade Target

Initial plasma configurations ($\eta_{imp} = 5\%$)

- Uniformly-compressed DT plasma sphere
  (Core heating experiment ~ high gain)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, $\rho_0$</td>
<td>300 g/cc</td>
</tr>
<tr>
<td>Temperature, $T_0$</td>
<td>0.2 keV</td>
</tr>
<tr>
<td>(Isentrope $\alpha$)</td>
<td>2.0</td>
</tr>
<tr>
<td>Radius, $R_0$</td>
<td>117</td>
</tr>
<tr>
<td>$\rho_0 R_0$</td>
<td>3.51 g/cm²</td>
</tr>
<tr>
<td>Mass, $M_f$</td>
<td>2.04 mg</td>
</tr>
</tbody>
</table>

External Heating ($\eta_c = 30\%$)

- Duration, $t_h$ 30 ps
  (Gauss 2.5psHWHM + flat 25ps + Gauss 2.5ps)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spot radius, $R_h$</td>
<td>15 µm</td>
</tr>
<tr>
<td>Optical Depth, $\rho L_h$</td>
<td>1.0 g/cm²</td>
</tr>
<tr>
<td>Intensity, $I_h$</td>
<td>$3.3 \times 10^{20}$ W/cm²</td>
</tr>
</tbody>
</table>
FIBMET
(Fusion Ignition and Burning code with Multiple Energy Transport)
2D cylindrical geom. (\( r - z \))

Eulerian Hydrodynamic code
1-fluid 2-temp. model
- Mass conservation
  \[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \]
- Momentum conservation
  \[ \rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p \]
- Energy conservation
  \[ \frac{\partial E_e}{\partial t} + (\mathbf{u} \cdot \nabla) E_e = -p(\nabla \cdot \mathbf{u}) - \nabla \cdot \mathbf{q}_e + S_e + S_{\alpha e} + S_{\epsilon E} \]
- Equation of State (Ideal gas)
  \[ p_i = n_i k T_i, \quad p_e = n_e k T_e \]
  \[ \varepsilon_i = \frac{3}{2} n_i k T_i, \quad \varepsilon_e = \frac{3}{2} n_e k T_e \]

Radiation
- Multi-group flux-limited diffusion
  \[ \frac{\partial E^{(i)}}{\partial t} - \nabla \cdot E^{(i)} = 4\pi \eta^{(i)} - c \chi^{(i)} E^{(i)} \]

Interaction
- Brems. & Inverse Brems.
- Thomson scattering

\( \square \) -particle \( \square \) Multi-group flux-limited diffusion
  (Levermore-Pomraning type)
  \[ \frac{1}{\nu} \frac{\partial \phi}{\partial t} - \nabla \cdot D_{LP} \nabla \phi + \sigma_a \phi = Q_{4\pi} \]
  with
  \[ D_{LP}(r,t) = \frac{\phi \lambda}{Q_{4\pi} (1 + 2 \delta)} = \lambda R \frac{\phi}{|\nabla \phi|} \]
  \[ \lambda(r,E,t) = R \coth R - 1, \quad R(r,E,t) = \frac{L}{1 + 2 \delta} \]

\[ Q_{4\pi}(r,E,t) = \int_{4\pi} \left\{ \frac{2}{\Delta E} (S \Psi(r,\Omega,E,t) + Q(r,\Omega,E,t)) \right\} d\Omega \]

Energy deposition rate [erg/cm\(^3\) s]
  \[ p_E(\vec{r},t) = \sum_{f=1}^{E_0} \int_{E_{f-1}}^{E_f} S_j(E) \phi(\vec{r},E,t) dE + \sum_{j=1}^{E_0} E_c S_j(E_c) \phi(\vec{r},E_c,t) \]

External core heating by electron particles

Uniform heating rate is assumed in a portion of the core
Time Evolution of Fusion Output and Core Energy

Driver info.

Implosion Laser : 1.17 [MJ]
Heating Laser : 71.5 [kJ]

Fusion output

Peak Power : $7.10 \times 10^{18}$ [W] at 101 [ps]
FWHM : 26 [ps]
Fusion Energy : 207 [MJ]
Target Gain : 171
Conclusion

- We have developed Fast Ignition Integrated interconnecting code, FI$^3$, which includes 2-D implosion, relativistic laser plasma interaction, hot electron transport, and burning process. And first integrated simulation have completed.

- FIREX-I target design.
  - redesigning for less laser energy (4.5kJ)

- Reactor scale design.
  - specification was decided by the design Working Group.