ADVANCED TARGET DESIGN FOR FAST IGNITION USING MULTI-SCALE SIMULATION


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Contents

• Fast Ignition and an advanced target
  • Fast Ignition Realization EXperiment (FIREX)
  • Advanced target
    • Improvement of cone-guided implosion
    • Double cone target

• Integrated Interconnecting Simulations
  • Effect of B-field at cone tip
    • w/ and w/o cone tip
    • realistic deformed cone-tip
Fast ignition and Central Hot Spot ignition

There is a new approach for inertial fusion energy, which is called the fast ignition scheme. In this scheme, there are two major key issues for the plasma physics:

1. Controlling radiation hydrodynamics to achieve a high density core plasma by **non-spherical implosion with cone-guided shell target**.

2. **Heating core plasma** efficiently by the short pulse high intense laser.

**Self ignition scheme**

**Fast ignition scheme**

**Ultra-intense Short-pulse laser**
Fast Ignition and FIREX (Fast Ignition Realization EXperiment)

Fast Ignition

Compression → Heating → Fusion Burn

Ultra-intense Short-pulse laser

Heating (LFEX) ; 10 kJ in $\omega$

Implosion (GXII) ; 2.5~6 kJ in $2\omega$
**FI$$^3$$ Project**

**Fast Ignition Integrated Interconnecting code**

- ALE radiation-hydro code
- Laser plasma interaction
- Relativistic Fokker-Planck code (hot electron transport) + rad. Hydro
- Cone-guided target

- $10^4 n_{cr}$ imploded core plasma
- $2000 n_{cr}$
- $\sim n_{cr}$
- Laser for implosion

[Diagram showing density profiles and different codes used in the project]
**FI³ Project**

*Fast Ignition Integrated Interconnecting code Project*

- **Radiation-Hydro code “PINOCO”**
  - Implosion Dynamics

- **Collective PIC code “FISCOF”**
  - Relativistic LPI

- **Fokker-Planck – Hydro code “FIBMET”**
  - Hot electron transport and Core heating

*Osaka Univ., NIFS, Kyushu Univ. Setsunan Univ.*

Data flow connected plan
Overview of the advanced target for FIREX-I

Simple target design

Latest advanced target design

gold cone target

CD shell

DT Cryogenic layer


CH coating (H. Nagatomo PoP, 2007)

CH foam (Sakagami, 2008)

DT Cryogenic layer

CDBr shell (S. Fujioka)
CH coating on the gold cone is effective to tamp the ablated gold plasma which is expanding inside the shell.


2D radiation hydrodynamics simulation

Areal density

Maximum density

Without coating

With coating
Double-cone target effectively focuses high energy electrons towards cone tip.

Double-cone target sustain sheath field at the outer surface to prevent them spreading away. Electron energy flux propagate through the tip is 93% of isolated cone case for double-cone, and 55% for single-cone targets. Assuming, $A=197$, $T_e=0.5\text{keV}$, $c_s \tau \sim 0.2\mu m$.

T. Nakamura et al., PoP 2007
Enhancing the Number of High-Energy Electrons Deposited to a Compressed Pellet via Double Cones in Fast Ignition

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sheath electric field (t=330 fs and 1500 fs)

quasistatic magnetic field (t=330 fs and 1500 fs)

Escaping electrons are reflected at vacuum gap because in early stage; sheath electric field after 1 ps; magnetic field
Overview of the advanced target for FIREX-I

- Gold cone target
- CH coating (H. Nagatomo PoP, 2007)
- CD shell (Sakagami, 2008)
- DT Cryogenic layer (S. Fujikawa)
- CH foam (Sakagami, 2008)

Design
Integrated Simulations

**FFI³** (Fast Ignition Integrated Interconnecting) Code System

H. Nagatomo, ILE Osaka Univ.

Radiation-Hydro “PINOCO”
(implosion)

A. Sunahara, ILT

Radiation-Hydro “Star”
with 3D ray-trace & detailed atomic data
(pre-foamed plasma)

Imploded core &
deformed cone profiles

FP-Hydro “FIBMET”
(core heating & fusion burning)

A constant electron beam profile is given

T. Johzaki, ILE Osaka Univ.

Fast electron &
ion profiles

H. Sakagami, NIFS, and H. Cai, IAPCM

PIC “FISCOF”
(relativistic laser-plasma interaction)
Simulations of heating core problem

Coupled 2D Fokker-Planck – Rad. Hydro simulations for

Spherical core & clean cone tip + $T_h = 1\text{MeV}$ fast electron beam

- Effects of B-fields

- Effects of cone tip on transport of fast electron & core heating

Imploded core & cone profiles + $T_h = 1\text{MeV}$ beam

- Effects of Implosion (non-spherical core & cone tip deformation)
  $\rightarrow$ 2D Integrated simulations (implosion + core heating)
Coupled Fokker-Planck Rad.-Hydro simulation model


**Fast Electron Transport**

Relativistic Fokker-Planck transport

\( f(r,z,p,\mu,\omega) \): Fast electron distribution function

- \((r,z)\) – CIP
- \((p)\) – Discontinuous Linear FEM
- \((\mu, \phi)\) – 2D Discrete Ordinate Sn method

\[ \rho, T \] → Energy deposition rate

**Radiation-Hydrodynamics with fusion**

Bulk Plasma; \( \rho, T_i, T_e, u, v(r,z) \)
- 1-fluid 2-temp. CIP code with thermal conduction
  + QEOS(Thomas-Fermi + Cowan’s EOS)

Radiation; \( \varepsilon(r,z,h\nu) \)
- Multi group flux-limited diffusion

**Resistive Fields**

- Ohm’s law for bulk electrons
  \[ \overrightarrow{E} - \overrightarrow{u}_b \times \overrightarrow{B} = \eta \overrightarrow{j}_b + \frac{1}{en_e} \overrightarrow{j}_b \times \overrightarrow{B} - \frac{1}{en_e} \nabla p_e \]

- Faraday’s law
  \[ \nabla \times \overrightarrow{E} = -\frac{\partial \overrightarrow{B}}{\partial t} \]

**2D Fokker-Planck + Hydro; “FIBMET”**
Core profile: CD core
\( \rho_0 = 200 \text{g/cm}^3 \), Gaussian with \( r_{\text{HWHM}} = 10 \mu\text{m} \),
\( \rho R_0 = 0.2 \text{g/cm}^2 \), \( m_{\text{fuel}} = 2 \mu\text{g} \)
\( T_i = T_e = 0.4 \text{keV} \) uniform

Fast electron beam
Injection; 65\( \mu\text{m} \) away from the core center.
Super Gaussian with \( r_{\text{HWHM}} = 15 \mu\text{m} \) in \( r \)-direction
\( T_{\text{fe}} = 1.0 \text{MeV} \) (slop temperature)
\( E_{\text{fe}} = 5 \text{kJ} \)
\( \tau_{\text{fe}} = 5 \text{ps} \)
\( P_h = E_{\text{fe}} / \tau_{\text{fe}} = 1 \text{ PW} \)
\( I_h = 1.4 \times 10^{20} \text{W/cm}^2 \) at the central axis
B-fields effects on core heating

Results 1/2

The Fast electron beam: $T_{fe} = 1.0$, $E_{fe} = 5$kJ, $\tau_{fe} = 5$ps

Initially, the core heating rate increases due to the beam pinching effect.

But, in the later phase, B-field due to $\nabla T_{e} \times \nabla n_{e}$ grows, which scatters the fast electrons. Thus the heating rate starts to decrease.

Beam pinching by B-field due to $\nabla x(\eta j_{f})$

Beam scattering by B-field due to $\nabla T_{e} \times \nabla n_{e}$
**B-fields effects on core heating**

**Results 2/2**

The Fast electron beam: $T_{fe} = 1.0, E_{fe} = 5\text{kJ}, \tau_{fe} = 5\text{ps}$

Temporal evolution of (a) core heating rates and (b) $<T_i>_{DD}$

- If only $\nabla x(\eta_{ij})$ is considered as the b-field source, Energy coupling from FE to Core $\eta_{fe\rightarrow core}$ is $\sim 1.8$ times higher than the case w/o fields.

- When B-field caused by $\nabla T_e \times \nabla n_e$ is included, $\eta_{fe\rightarrow core}$ becomes smaller by 20% compared with the case neglecting this field.

- (Even in this case, $\eta_{fe\rightarrow core}$ is 1.4 times larger than the case w/o fields).

### Source E_{fe}

- $E_{fe}$: 5kJ

### Energy coupling from FE to Core

- $E_{dep}$: 1.50kJ (30%)
- due to Collision: $E_{dep}/E_{fe}$
  - 1.38kJ (92%)
- due to Field: $E_{dep}/E_{fe}$
  - 0.12kJ (8%)

### Temporal Evolution

- $<T_e>_{DD}$: 5.87keV
- $<T_i>_{DD}$: 4.94keV
- $T_i$ local max: 7.24keV
- $Y_{n_{DD}}$: 7.95e10
Effects of Cone Tip

Fast electron transport: 2D Relativistic Fokker-Planck
- Short range binary collision & long range collective interactions are included.
- E-field is evaluated by generalized Ohm’s Law.
- Temporal evolution of B-field is calculated using Faraday’s Law.


Core Profiles
- CD core with Au cone tip

CD core:
ρ₀ = 200g/cm³, Gaussian with r_{HWHM} = 10μm,
Tᵢ = Tₑ = 0.4keV uniform
m_{fuel} = 0.002mg

Au cone:
ρ_{cone} = 19.32g/cm³, T_{cone} = 0.05keV

Fast electron beam
- Injection point is 50μm away from the core center.
- Super Gaussian with r_{HWHM} = 15μm in r-direction
- E_{fe} = 5kJ (50% coupling from LFEX laser to fast electron)
- T_{fe} = 1.0MeV (slop temperature)
- τ_{fe} = 5 ps
- P_h = E_{fe} / τ_{fe} = 1.0 (5ps) PW
- I_h = 1.4x10^{20}W/cm² at the central axis
Effects of Cone Tip
Results 1/2 Au –cone

Beam Intensity vs z (r < 20um) at 2ps

Angular spread source, out of tip (x < 20um) at 2ps

$E_{fe} < 0.5$ MeV

$0.5$ MeV < $E_{fe}$ < 2 MeV

2 MeV < $E_{fe}$

Injected region
out of tip

Injected region
out of tip

Injected region
out of tip

Beam intensity [PW]

z [μm]

θ [degree]

θ [degree]

θ [degree]

Case

$E_{dep\ core}$

$\langle T_e^{max}\rangle$

$\langle T_i^{max}\rangle$

w/o cone

w/o cone

Au cone

w/o cone

Au cone

Due to resistivity jump

Due to collisional and resistive drag

1.50 kJ

7.12 keV 5.62 keV

30.0% 49%↓

0.77 kJ

3.87 keV 3.38 keV

15.4% (49%↓)

(40%↓)
Effects of Cone Tip
Results 2/2 cone-tip material dependence

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho_{\text{solid}}$ [g/cm$^3$]</th>
<th>$&lt;Z&gt;$</th>
<th>$n_e$ /cm$^3$ (fully ionized case)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH</td>
<td>1.0</td>
<td>3.5</td>
<td>1.68e23</td>
</tr>
<tr>
<td>Al</td>
<td>2.70</td>
<td>13</td>
<td>7.78e23</td>
</tr>
<tr>
<td>Cu</td>
<td>8.96</td>
<td>29</td>
<td>2.45e24</td>
</tr>
<tr>
<td>Au</td>
<td>19.32</td>
<td>79</td>
<td>4.64e24</td>
</tr>
</tbody>
</table>

- **Small** Collisional effects (stopping, scattering, resistive fields)
- **Large**

Low-Z material is preferable for the cone tip material in perspective of generation and transport of fast electron because of the less collisional effects in cone tip.
## Effect of Cone Tip Deformation

(2D ALE-CIP Radiation-Hydro code, H. Nagatomo, ILE)

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

### Implosion Laser condition

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaussian pulse shaping</td>
<td></td>
</tr>
<tr>
<td>Wavelength</td>
<td>0.53 µm</td>
</tr>
<tr>
<td>Energy (on target)</td>
<td>2.5 kJ</td>
</tr>
</tbody>
</table>

### Shell Target
- CH 8 µm

### Gold cone
- 30° (Full angle)
- 250 µm

### Computational grids
- 280 (i-dir.) x 280 (j-dir.)
Effect of Cone Tip Deformation
Implosion dynamics of a cone-guiding CD shell target

Time [ns]

$R_{\text{Dn}}$ [#/cm$^2$]

$\rho_{\text{max}}$ [g/cm$^3$]

$T_{\text{max}}$ [keV]

$R_{\text{Dn}}$ 

$\rho_{\text{max}}$

$T_{\text{max}}$

1.85ns First bounce

1.90ns

1.97ns Just before cone-tip breaking $\rightarrow$ FP sim

2.02ns Maximum compression $\rho_{\text{max}} = 140\text{g/cm}^3$
Effect of Cone Tip Deformation
FP Transport + Rad. Hydro

Core plasma • • • Rad. Hydro
Implosion simulation results for a CD shell + Au cone target (1.97ns, 50ps before max. compression) 
\( \rho_{\text{min}} \) between cone and core = 1.5g/cm\(^3\)

Fast electron • • • FP Transport
Injection point is 75\( \mu \)m away from the \( \rho_{\text{max}} \) 
Super Gaussian, \( r_{\text{HWHM}} = 15 \mu \text{m} \) in r-direction 
\( E_{\text{fe}} = 5kJ \) (50% coupling of LFEX to fast electron) 
\( T_{\text{fe}} = 1.0\text{MeV} \) (slop temperature) 
\( \tau_{\text{fe}} = 5 \text{ps} \) 
\( P_{\text{fe}} = E_{\text{fe}} / \tau_{\text{fe}} = 1.0 \text{ (5ps) PW} \) 
\( l_{\text{fe}} = 1.4 \times 10^{20} \text{W/cm}^2 \) at the central axis

\( \int \rho dz \approx 0.14 \text{ [g/cm}^2\text{]} << \text{Range of MeV electrons} \)
Effect of Cone Tip Deformation

B-field around the “deformed” cone tip

$\nabla \eta \times j_f$ is large when the cone tip deformed!

Case 4 at 3ps; B-field [T]

Spherical core + clean cone tip

$\nabla \eta$ is large, but $\nabla \eta \times j_f$ is small.

• Huge B-field is generated at the contact surface between “deformed” cone tip and imploded CD plasma due to $\nabla \eta \times j_f$, which strongly scatters and traps the fast electrons.

• Due to the large beam divergence after propagation in the cone, self-guiding resistive field is not formed.

→ Reduction in core heating efficiency.
Effect of Cone Tip Deformation
Beam profile

Because of the scattering & trapping due to B-field at the contact surface between “deformed” cone tip and imploded CD plasma, the 30% of the beam power is lost and the angular spread becomes large.
Effect of Cone Tip Deformation
Fast electron heating rate [W/m³] (B-field effects)

w/o B-field case
• collisional process (scattering and drag) in the Au cone tip reduce core heating rate

W B-field case
• In addition to the collisional effects, the fast electrons are scattered and trapped in the cone by the B-field generated around the cone tip, and the core heating rate decreases further!

at t=3ps (w E-field  w/o B-field)
Using Integrated simulations, an advanced target for Fast Ignition is proposed and some ideas will be brought in next series experiment (Spring, 2010).

In hot electron transport simulations w/o cone tip case,

• Self-guiding B-field enhances the core heating efficiency.
• But the B-field generated by $\nabla T_{e x} \nabla n_{e}$ scatters the fast electrons from the core, reducing the heating efficiency in the spherical core with uniform temperature.

with cone tip case

• High-Z cone-tip reduces the core heating efficiency because of the collisional scattering and drag.
• If the tip shape is deformed, strong resistive B-field is generated at the cone-imploded plasma interface, which scatters and traps the fast electrons and then reduces the heating efficiency further.

• Thus, the low-Z material (e.g., CH or C) is preferable to the cone tip material.
At least for a cone tip material, low-Z material (e.g. CH or Diamond) is prefer.
Overview of Rad-Hydro code (PINOCO)

two-dimensional, two temperature hydrodynamics
  ALE-CIP
thermal transport (electron, ion)
  flux limited type Spitzer-Harm
  implicit method (9 points-ILUBCG)
Radiation transport
  multi-group diffusion approximation (16~64 groups)
  implicit method (9 points-ILUBCG)
Opacity, Emissivity
  local thermodynamic equilibrium (LTE)
  non-LTE, collisional radiative equilibrium (CRE)
Equation of state
  electron ; Tomas-Fermi model
  ion ; Cowan model
Laser ray-tracing
  1-D ray tracing
  inverse-Bremsstrahlung absorption
Fundamental Equations for Integrated Implosion Code (1)

- One fluid, two temperature fluid model.

(mass)
\[
\frac{d\rho}{dt} = -\rho \nabla \cdot \mathbf{u}
\]

(momentum)
\[
\rho \frac{d\mathbf{u}}{dt} = -\nabla P
\]

(ion energy)
\[
\rho \frac{d\varepsilon_i}{dt} = -P_i \nabla \cdot \mathbf{u} - \nabla \cdot \mathbf{q}_i + Q_{ei}
\]

(electron energy)
\[
\rho \frac{d\varepsilon_e}{dt} = -P_e \nabla \cdot \mathbf{u} - \nabla \cdot \mathbf{q}_e - Q_{ei} + S_L + S_r
\]

(radiation transport)
\[
\frac{1}{c} \frac{dI^\nu}{dt} + \Omega \cdot \nabla I^\nu = 4\pi \eta^\nu - \chi^\nu I^\nu + S^\nu
\]

(laser absorption)
\[
\mathbf{v}_g \cdot \nabla I^k_L = -\mathbf{v}_{abs} I^k_L \quad S_L = \sum_k \mathbf{v}_{abs} I^k_L / \mathbf{v}_g^k
\]
multi-group diffusion-type equations for radiation transport

frequency: \( \nu \)  intensity: \( I^\nu \)  emissivity: \( \eta^\nu \)  opacity: \( \chi^\nu \)

Fundamental equation for radiation transport (6-D Boltzmann equation)

\[
\frac{1}{c} \frac{\partial I^\nu}{\partial t} + \Omega \cdot \nabla I^\nu = \eta^\nu - \chi^\nu I^\nu
\]

Legendre expansion 0-th order momentum equation is;

\[
\frac{\partial E^\nu}{\partial t} + \nabla \cdot F^\nu = 4\pi \eta^\nu - \chi^\nu c E^\nu
\]

1st order momentum equation is:

\[
\frac{1}{c} \frac{\partial F^\nu}{\partial t} + c \nabla \cdot P^\nu = -\chi^\nu F^\nu
\]

under isotropic assumption, and \( c >> 1 \), finally;

\[
\nabla \cdot \left( -\frac{c}{3\chi^\nu} \nabla E^\nu \right) = 4\pi \eta^\nu - \chi^\nu c E^\nu
\]

1D simulation + perturbation models; A standard target for GXII may be broken up before maximum compression

- ILESTA1D-FP
- + measured target surface roughness + Nakai-Azechi’s imprint model
Detail 2-D rad-hydrodynamics simulations for fast ignition are performed to evaluate the implosion performance.

CD shell target; multi-mode (l=2~40), initial target surface perturbation is given in PINOCO-2D simulation

- Target surface roughness measured + Nakai-Azechi initial imprint mode
- Uniform laser irradiation
- Computational grid (310x352)

[Graph showing initial amplitude]
overview of the implosions (cone-guided without initial perturbation on the shell target surface) $Y_n = 9.7 \times 10^7$
overview of the implosions (cone-guided with initial perturbation on the shell target surface) \( Y_n = 5.9 \times 10^7 \)
\( \rho R \) is reduced by the hydrodynamics instability

Angular dependence of \( \rho R \) (average, minimum, maximum) are compared (only quadrant spheres parts are evaluated)

\[ g/cm^2 \]
Cone tip is destroyed before the maximum compression time, if Rayleigh-Taylor instability is strongly grown.

During the imploding phase, due to the hydrodynamic instability which is occurred in acceleration phase, plasma expands into the shell, and the pressure inside the shell is increased. Thus, the imploding shell is decelerated, and maximum mass density is dropped. Also, the inner plasma collides with the tip of the cone, and it is destroyed before the maximum compression time.

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**With initial perturbation**
(t=1.97 ns, 100 ps before maximum compression, tip is broken.)

Y$_n$=5.9x$10^7$

**t=2.07 ns (perturbed target)**

**Without initial perturbation**
(clean cone-guided implosion)

Y$_n$=9.7x$10^7$

**t=2.08 ns (unperturbed target)**