Magnetic Field in Integrated Simulation of Fast Ignition

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FIREX-I and GXII Compression Heating

Ultra-intense Short-pulse laser

Plasma Temperature (keV)

GEKKO IV
'88-89
High Density
GEKKO XII
'88-89
Cone target 2002
FI REX-I
Ignition condition
GEKKO II
'85-86
GEKKO MII
High gain

10^22
10^21
10^20
10^19
10^18
10^17
10^16
1.0
10
10^2
0.1
Plasma parameter (sec/m^2)

10^22
10^21
10^20
10^19
10^18
10^17
10^16
0.1
Plasma Temperature (keV)

FIREX-I
Implosion (GXII) ; 10 kJ (1 ns) in 0.53 um laser
Heating (LFEX) ; 10 kJ (10 ps) in 1.06 um laser
Contents

• Fast Ignition
  • Difference between experiments and simulations

• Magnetic field effect in implosion
  • Self-generated magnetic field in non-spherical implosion.

• Controlling e-beams using self-generating resistive magnetic fields.

• Controlling e-beams using external magnetic fields.
FIREX-I Integrated experiments

Compression Laser: GEKKO-XII

Fusion Fuel Target

Heating Laser: LFEX

<table>
<thead>
<tr>
<th>Beam#</th>
<th>9/12 beams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>280 J/beam (2.5 kJ total)</td>
</tr>
<tr>
<td>Duration</td>
<td>1.5 ns (Flat top)</td>
</tr>
<tr>
<td>Wavelength</td>
<td>527 nm</td>
</tr>
</tbody>
</table>

Shell
- Diameter: 500 μm
- Thickness: 7 μm
- Material: CD plastic
- Cone
  - Angle: 45 deg.
  - Material: Gold

Beam#
- 2 beam

Energy
- 400 ~ 2000 J

Duration
- 1.5 - 2 ps

Wavelength
- 1053 nm

Experiment
- Φ1: Aug. 16 – Dec. 24, 2010 (GXII + LFEX)
- Φ2: Jan. 5 – Jan. 25, 2011 (LFEX only)
2010 FIREX exp’t reproduced Yn @ 2002 exp’t

To achieve core temperature of 5keV with 10kJ heating, the energy coupling of heating laser to dense core $\eta_{L\rightarrow core}>10\%$ is required.
Integrated simulations showed smaller coupling (6.3 %) due to large beam divergence & collision in the Au tip.

LPI with PIC

\[ f(E) \propto E^\alpha \]
\[ \alpha = 1.228 \]
\[ T_h = 3.2 \text{MeV} \]

Implosion with Rad-hydro

\[ \rho \text{[g/cm}^3\text{]} \]

To enhance the heating efficiency, the beam guiding with small collisional loss in tip is indispensable.

Heating with FP

\[ \eta_{L \rightarrow \text{core}} = 6.3\% \]
Energy coupling in FIREX exp. was estimated by PIC+FP simulations.

Laser to forward electrons | Tip transmittance | Solid angle of the core | Deposition

w/o pre-plasma

50%

60%

60%

60%

Coupling = 0.5 × 0.6 × 0.6 × 0.4 = 7%

w/ pre-plasma

40%

60%

60%

Coupling = 0.4 × 0.6 × 0.6 × 0.1 = 1.4%

Pre-plasma significantly reduces energy coupling from laser to core.

A. Sunahara et al., IFSA’11 O.Tu_A.9
Is any numerical model missing in our integrated simulations?

In the non-spherical implosion magnetic field is generated and compressed by implosion.

\[
\frac{\partial B}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) + \frac{c}{e} \left[ \nabla \times \left( \frac{\nabla p_e}{n_e} \right) - \nabla \times \left( \frac{\nabla \times \mathbf{B} \times \mathbf{B}}{4\pi n_e} \right) - \nabla \times \left( \mathbf{R}_{\tau} + \mathbf{R}_{\eta} \right) \right]
\]

Magnetic field generation and transport in implosion are solved in post-process to estimate. \((T_e, n_e)\) in radiation hydro simulation \(\rightarrow\) magnetic transport equation.)
**Implosion simulation (Rad-Hydro)**

(2D ALE-CIP Radiation-Hydro code)

### 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
  - QEOS (Tomas-Fermi +Cowan)
  - SESAMI

### Implosion Laser condition
- Gaussian pulse shaping
- Wavelength: 0.53 μm
- Energy (on target): 2.5 kJ

### Shell Target
- CH 8 μm

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

### axial symmetry

### computational grids: 280 (i- dir.) x 280 (j – dir.)
The order of 10 MG magnetic field is generated, which can collimate the e-beams.

\[ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left\{ (\mathbf{V}_i + \mathbf{V}_e) \times \mathbf{B} \right\} + \frac{e}{c} \nabla T_e \times \nabla (\log n_e - \beta') - \nabla \times \left\{ \frac{1 + \alpha''}{4 \pi m_e} (\nabla \times \mathbf{B}) \times \mathbf{B} \right\} \]

\[-\nabla \times \left( \frac{m_e c}{4 \pi e} \frac{\alpha_0}{n_e \tau_e} \mathbf{h} \cdot (\nabla \times \mathbf{B}) \cdot \mathbf{h} \right) - \nabla \times \left( \frac{m_e c}{4 \pi e} \frac{1 - \alpha'}{n_e \tau_e} \mathbf{h} \times [\nabla \times \mathbf{B}] \mathbf{h} \right) \]

Electron heat conductivity is effected by magnetic field

\[ \kappa_e = \frac{\kappa_e}{1 + (\omega_{ce} / V_{ei})} \]

\[ \omega_{ce} = \frac{BT^{3/2}}{n_e} \]

This Braginskii coefficients must be solved with implosion dynamics simultaneously.

Next work
Integrated Simulations

$\mathcal{F}I^3$ (Fast Ignition Integrated Interconnecting) Code System

Radiation-Hydro “PINOCO” (implosion)

Nagatomo, ILE

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

Sunahara, ILT

Pre-formed plasma profile

Imploded core & deformed cone profiles

BFIELD

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

Johzaki, ILE

Fast electron & ion profiles

PIC “FISCOF” (relativistic laser-plasma interaction)

Sakagami, NIFS, Johzaki, ILE
Electron confinement by double-cone target

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.

Difficulty in fabrication
Tongari-Tip Guiding Concept

Extended & Tapered cone tip

Guiding of fast electron is expected.

Collisional effects in the tip becomes larger due to thicker tip.

Material selection is important.

\[
\frac{\partial \vec{B}}{\partial t} = \nabla \times (\eta \vec{j}_f) = \nabla \eta \times \vec{j}_f + \eta (\nabla \times \vec{j}_f)
\]

* A. Sunahara et al., Particles and Beams to be published
Cone-guided implosion with Tongari tip

**Laser condition**
- Wavelength: 0.53 µm
- Energy: 3.0 kJ (for $4\pi$)
- Gaussian (0.9 + 0.2 ns)

**Tip material**:
- CH ($\rho=1.0$ g/cc, $Z=3.5$), Al ($\rho=2.69$ g/cc, $Z=13$),
- DLC (Diamond-like-Carbon: $\rho=3.5$ g/cc, $Z=6$),
- Cu ($\rho=8.92$ g/cc, $Z=29$), and Au ($\rho=19.3$ g/cc, $Z=79$)
Any tip material cases, characteristics of the imploded core is almost the same

ρL on the axis

Al (2.69)

CH (1.06 g/cc)

DLC (3.5)
The tip-breakup-time is determined by the mass density of the pointed-tip.

DLC tip may guide the e-beam?
Core heating simulation with FP+Hydro code

Fast Electron Profiles from PIC sim.

\[ I_L = 3 \times 10^{19} \text{W/cm}^2 \text{ LPI with PIC} \]

Imploded core profiles from rad-hydro sim.

Density profile @2.7ns

\[ f(E) \propto E^\alpha \]
\[ \alpha = 1.228 \]
\[ T_h = 3.2 \text{MeV} \]

\[ f(E) \propto \exp(-E/T_h) \]

\[ \theta = 55^\circ \]

FP+Hydro simulation
Heating Performance

After 1ps injection

<table>
<thead>
<tr>
<th>Tip</th>
<th>$B_{\text{max}}$</th>
<th>$\Delta E_{\text{tip}}$</th>
<th>$\Delta E_{\text{core}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au Tongari</td>
<td>1510T</td>
<td>105%</td>
<td>-10%</td>
</tr>
<tr>
<td>Cu Tongari</td>
<td>1193T</td>
<td>98%</td>
<td>5%</td>
</tr>
<tr>
<td>Al Tongari</td>
<td>1204T</td>
<td>32%</td>
<td>35%</td>
</tr>
<tr>
<td>DLC Tongari</td>
<td>767T</td>
<td>47%</td>
<td>31%</td>
</tr>
</tbody>
</table>

*Relative to the Au flat tip case.*
Conclusion and Summary

B-fields may play an important role in Fast Ignition scheme.

Passive effect
- Non-spherical implosion generates B-field and it is compressed by implosion.

Active control
- “TONGARI” tip cone is proposed for fast electron guiding using self-generating resistive B-fields along the cone outer surface and evaluated it’s heating performance with Integrated simulations.
  - Implosion performance is almost the same as the normal tip case.
  - Tip breakup timing becomes later, and depends on the material density.
  - The resistive guiding is effective if low-Z material is used.
    - The energy coupling of fast electron to core is enhanced by 30% for DLC TONGARI tip case.
  - But using high-Z material, the energy loss in the long tip becomes larger, which results in lower energy coupling to core.
    - DLS or Al Tongari tip cone is expected to enhance the core heating efficiency.
- Compression of External B-field.