Implosion and Heating Experiments of Fast Ignition Targets for FIREX-1 Project


Institute of Laser Engineering, Osaka University  
*National Institute for Fusion Science

22nd IAEA Fusion Energy Conference  
13 – 18 October 2008, Geneva, Switzerland
Contents of the talk

1. FIREX program
2. Fast Ignition Experiment on Gekko-XII
3. Ultrafast x-ray imaging: 2D-SIXS
   Core movement
4. Ultradast x-ray imaging: 1D+McMIXS
   Core and jet structure
5. Heating time measurement
6. LFEX laser
7. Summary
1. FIREX program

Fast Ignition Realization EXp’t, FIREX

- Implosion
- Fast Heating
- Ignition/Burn

- preliminary: Demo of 600 times liquid density
  Demo of 1 keV temp. by 1kJ/1ps.

- FIREX-I: Demo of 5-10 keV temperature by 10kJ/10ps.

- FIREX-II: Demo of ignition and burn by FI
Foam cryogenic D$_2$ (DT) with cone and gas fill tube is the target for FIREX

Issues:
- Hydrodynamics of foam/Liq-D$_2$
- Nonuniform core structure
- Heating performance

Foam cryogenic D$_2$ target with cone+fill tube

Implosion with Gekko-XII ($\lambda=0.53 \, \mu$m)

Gold cone

Gas feeder

Gas barrier ~ 3-5 μm

Foam material ~ 20 μm

500μm in diameter

Cryo target has been developed in cooperation with NIFS.

Heating Laser PW
FIREX / LFEX ($\lambda=1.05 \, \mu$m)
**FIREX-1: Integrated experiment of Fast Ignition**

*Development of*

- Foam shell target with a cone guide and fueling tube*
- Cryogenic target system for liquid D$_2$ fueling*
- *Advanced diagnostics for implosion and heating measurement*

*and demonstration of*

- Implosion by Gekko-XII and heating by PW/LFEX lasers

*Interactive Coordinated Research Program with the National Institute for Fusion Science (NIFS)*
2. Fast Ignition Experiment on Gekko-XII

Gekko-XII and PW laser system

Both lasers were used for experiment

Drive laser: Gekko-XII

\[ \lambda = 0.53 \ \mu m \]

\[ E = 2 - 4.5 \ kJ \]

\[ \tau = 1.2 \text{ ns (Gaussian / FlatTop)} \]

9 beams for implosion

3 beams for backlighting

Heating laser: PW

\[ \lambda = 1.05 \ \mu m \]

\[ E = 420 \ J \text{ max. (on target)} \]

\[ \tau = 0.47-0.8 \ \text{ps} \]

Spot size = 30 \ \mu m

Shut down in 2006
CD shell target with a gold cone for Fast Ignition experiment

- Shell diameter: 500 μm
- Thickness: 7 μm

<table>
<thead>
<tr>
<th>( d ) (μm)</th>
<th>( \theta = 30^\circ )</th>
<th>( \theta = 15^\circ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>75</td>
<td>○</td>
<td></td>
</tr>
</tbody>
</table>

\( \theta \): opening angle of cone
\( d \): distance of tip from the center
Advanced plasma diagnostics for implosion & heating

**X-ray diagnostics**
- Ultra-fast X-Ray Spectroscopic Imaging ✤ ✤
- Absolutely Calibrated X-Ray Spectroscopy ✤ ✤
- Synchronization measurement of heating beam ✤

**Fusion Particle Diagnostics**
- Fast/Multi-Channel Neutron Spectrometer ✤ ✤
- Neutron Babble Detector (Gamma-Ray Insensitive) ○ ✤
- Secondary Fusion Reactions/Fermi Degeneracy ✤ ○
- Burn Time (Diamond Detector) * ○ ○

*Interactive Coordinated Research Program with the National Institute for Fusion Science (NIFS)
X-ray imaging diagnostics for implosion & heating dynamics

X-Ray Pinhole Camera
(Δr=20 μm, Δt : integrated)
→ Overall implosion dynamics

X-Ray Framing Camera
(Δr=20 μm, Δt =80 ps)
→ Overall implosion dynamics

Gekko XII, 9 beams
0.53 mm, 5 kJ / 1.5 ns

X-Ray Streak Camera (2D-SIXS)
(Δr=20 μm, Δt =20 ps)
→ Core dynamics

X-Ray Streak Camera (1D+MIXS)
(Δr=15 μm, Δt =20 ps)
→ 1D:Shell implosion trajectory
   2D:Core dynamics
**3. Ultrafast x-ray imaging: 2D-SIXS, Core movement**

*Image sampling* is essential for 2D imaging on a streak camera.

---

**Conventional 1D**
- Continuous (resolved)
- Discrete (selected)

**MIXS**
- Continuous (resolved)
- Discrete (sampled)
  (like raster scan on TV)

**2D-SIXS**
- Discrete (sampled)
  (like CCD pixels)

1-D selected image  
1-D image sampling  
2-D image sampling

Many types of efforts have been made to demonstrate 2D imaging on a streak camera.
--- How to avoid overlapping of the data when streaked?
**Principle of 2D-SIXS: 2D Sampled-Image X-ray Streak camera**

- **Sampling pinhole-array mask** is set right in front of a **photo cathode**.
- Sampling pinholes are arranged as cyclically shifted so that vertically streaked signals do not overlap with each other.
- Two-dimensionally sampled signals are streaked with a **streak tube** to obtain temporally resolved data.

By reconstructing streaked sampling signals, we can obtain temporally resolved 2D images.

Temporal resolution depends directly on performance of the streak tube, and 1-3 ps can be achieved with commercially available streak cameras.
Example of 2D-SIXS sampling mask (with 1560 sampling pinholes)

40x39 SIXS mask (3 cycle)

23.400 (40 pinholes/line)

23.800

0.600

0.600

1.800

0.200

0.200

22.800 (3 x 13 = 39 lines)

1.800

23.800

23.400 (40 pinholes/line)

pinhole 50 mm φ

Hamamatsu: C7700-31
24 mm cathode

40 pinholes/line x 39 lines = 1560 pinholes

Ta 25 mmt
Streaked sampling image signals of a symmetrically imploded core plasma

**GEKKO XII** (12 beams)
- Gaussian pulse
- Total energy: 5.04 [kJ]
- Pulse length: 1.5 [ns]
- Wavelength: 530 [nm]

**CD shell Target**
- Diameter: 500 μm
- Thickness: 7 μm

**Image reconstruction**
- Frame interval ~ 24[ps]
- Temporal resolution ~ 24[ps]
- Spatial resolution ~ 20[μm]

No heating in this experiment
X-ray emission from the imploded core was found to be moving towards the cone.

Movie for about 400 ps

CD shell without cone

CD shell with a cone

($d = 50 \mu m$, $\theta = 30$ deg)
Position of the peak x-ray emission moves towards and stays at the cone tip.

Stagnation near the tip

The core is interacting with the cone tip.

Shiraga, et al., RSI (2008)
Another new 2D-SIXS application: Monochromatic Sampling-Image X-ray Streak camera (M-SIXS) has been developed

### Principle of M-SIXS

- Photocathode of x-ray streak camera
- Magnified image
- SIXS
- Toroidally bent crystal
- Direct x-ray shield
- Sampling pinhole array
- Plasma

### Goals of M-SIXS

<table>
<thead>
<tr>
<th>Goal</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temporal resolution</td>
<td>$\Delta t &lt; 10$ ps</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>$\Delta x \sim 10$ µm</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>$E/\Delta E \sim 200$</td>
</tr>
</tbody>
</table>

### Improved points

- Comparing to M-XFC, there is no interval of image recording
  ➔ Seamless images with a time resolution better than 10 ps
- The number of crystals is limited only one for each spectral line
  ➔ Simplified and speedy crystal alignment
Two x-ray photon energies were chosen to derive electron temperature profile of the core plasma.

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Silicon (220)</th>
<th>Quartz(11.2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuning energy (keV)</td>
<td>3.27 (Cl-Heβ)</td>
<td>3.51 (Cl-Lyβ)</td>
</tr>
<tr>
<td>Energy band (eV)</td>
<td>11.7</td>
<td>20.6</td>
</tr>
<tr>
<td>Image magnification</td>
<td>25.8</td>
<td>26.2</td>
</tr>
<tr>
<td>Bending radius (mm)</td>
<td>200/195.3</td>
<td>200/189.5</td>
</tr>
<tr>
<td>Size of crystal (mm)</td>
<td>6 × 6</td>
<td>6 × 6</td>
</tr>
</tbody>
</table>

**Setup in this experiment**

- **Temporal resolution**: 20 ps
- **Spatial resolution**: 31 µm
- **Energy resolution**: $E/\Delta E \sim 200$
4. Ultradast x-ray imaging: 1D+MIXS, core and jet structure

1D sampling: MIXS
Principle of multi-imaging x-ray streak camera (MIXS) to obtain time-resolved 2-D x-ray images


\( \text{10}^{11} \text{ fps achieved} \)
1D+McMIXS for implosion hydrodynamics measurement

McMIXS: Multi-channel Multi-Imaging X-ray Streak Camera

Ch. A: Broad band (Ti filter: 2-5 keV)
Ch. B: Lower energy (Pd filter: 2-3 keV)

CD shell with a gold cone
No heating in this experiment
Temperature can be derived from the signal intensity ratio between two spectral channels.

Spectral responses
Bremsstrahlung @ \( Te = 1 \text{keV} \)

Ch. A: 2 - 5 keV
Ch. B: 2 - 3 keV

Signal intensity ratio (B/A) vs temperature
(Bremsstrahlung assumed)
MIXS images of shell targets with cone

Target (500φCD shell + Au cone) (θ = 30 deg, d = 75 µm)

Core is created at the center, then moves toward the cone tip. (t = 138-184 ps)
- Hot jet-like plasma is ejected from the core towards the cone tip. (276-322 ps)
- Plasma flow stagnates at the cone tip. (414-506 ps)

Central part of the core plasma is cool.
Head (right hand) of the jet is hot, while the following part of the jet is cold and dense.

Possible to directly observe the heating dynamics when heating laser injected.
5. Heating time measurement

Heating must be synchronized to the implosion

Heating time measurement with an X-ray Framing Camera

Images of Imploding shell

Framing interval= 80ps

Hard x-ray signal due to heating beam injection (not imaged)

Synchronization of heating beam injection to implosion can be accurately monitored.

Koga, et al., RSI (2008)
6. LFEX laser

LFEX : New short-pulse high-power laser for FI heating

3.6 kJ/1 beam (full 4 beam equivalent =14.4 kJ) achieved, June 2006
1 beam became operational, March 2007.
4 beams will be completed, February 2009.
Now under conditioning for use in FI heating experiment
Hydrodynamics of the imploded core plasma of FI targets were investigated with ultrafast x-ray spectroscopic imaging techniques.

- Core is created at the center, then moves toward the cone tip.
- Hot jet-like structure is formed from the core towards the cone tip.
- Plasma flow stagnates at the cone tip.

Experimental results are consistent with two-dimensional hydrodynamic simulations.

Target design taking into account of these phenomena is quite important because such core movement and jet formation can affect the condition of the cone at the time of the heating beam injection.

Heating experiment by using LFEX laser will be started soon.
Thank you!