Target fabrication and injection activities toward laser fusion reactor with wet wall

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And
Member of Roadmap Committee (Chair, A. Tomabuchi)
Presented at
2nd US-Japan Workshop on IFE target Fabrication, Injection and Tracking
Roadmap committee of IFE Forum* is working to make proposal for laser fusion research and conceptual design of laser fusion reactor.

- Chair A. Tomabuchi (Cent. Res. Inst. for Electric Power Industry), Co-chair Y. Kozaki,
- Reactor system
  - Y. Ueda (Osaka Univ.), M. Nishikawa (Osaka Univ.), A. Koyama (Kyoto Univ.), K. Okano (Cent. Res. Inst. for Electric Power Industry), T. Konishi (JAERI), A. Sagara (NIFS), T. Muroga (NIFS)
- Laser
  - T. Jitsuno, N. Miyanaga, M. Yamanaka, H. Nakano (Kinki Univ.), K. Ueda (Univ. Electro Com.), Y. Owadano (Electro-technical Laboratory Tsukuba), H. Kan (Hamamatsu Photonics), H. Kubomura (NEC)
- Plasma
  - H. Azechi, K. Mima, K. Murakami, K. Tsubakimoto, Y. Nakao (Kyushu Univ.), Y. Ogawa (Univ. Tokyo),
- Fueling
  - T. Norimatsu, T. Endo (Nagoya Univ.), T. Tanaka (Univ. Tokyo)
Outline

- Roadmap toward laser fusion reactor
  - Required targets and the research plan

- Requirement for injection and tracking for wet wall reactor
  - Central ignition target
  - Fast ignition target

- Experimental activities in 2003
  - Target fabrication
  - Simulator for reactor environment
Roadmap toward laser fusion power plant by fast ignition

ILE, Osaka

- **FIREX-I**
  - 1kJ/1ps
  - 10kJ/10ps
  - 50kJ/10ps

- **Laser for compression**
  - 10kJ/2ns, 0.53μm
  - 50kJ/3ns, 0.35μm

- **Ignition experiment**

- **Burn experiment**

- **FIREX-HR (20 kJ/1Hz)**
  - Non-nuclear, Integrated reactor system

- **Injection and irradiation demo**

- **Development of DPSSL**

- **Fueling and injection**
  - Laser 200 kJ for compression
  - + 50 kJ for ignition
  - Eth 10 MJ (Gain ~100)

- **Tracking and stirring**

- **Demonstration of Commercial Reactor**
  - Laser 800 kJ for compression
  - + 50 kJ for ignition
  - Eth 200 MW (Gain ~200)

- **Key:**
  - High rep-rate laser
  - Injection
  - Mass production of cryogenic target
  - Tracking of injected target and beam stirring would be skipped in LFER.
FIREX-I is approved and the design started in 2003.

Design will finish by March, 2003
Construction will start April, 2003
Laser tests will start April, 2004
Research plan of target for FIREX-II

- Cryogenic foam target with gas feeder will be used to demonstrate ignition and burn in FIREX-II.
- Use of the gas feeder reduces the burden of handling high pressure DT gas.
- Foam will sustain the uniformity of fuel layer under non-isothermal condition due to the cone.

How is the influence of the feeder and foam to the implosion performance?
Estimation of Ignition Energy and Gain

Initial plasma configurations
 ⇒ Uniformly - compressed plasma sphere (high gain)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, ( r_0 )</td>
<td>300 g/cc</td>
</tr>
<tr>
<td>Temperature, ( T_0 )</td>
<td>0.2 keV</td>
</tr>
<tr>
<td>Isentrope a</td>
<td>2.0</td>
</tr>
<tr>
<td>Radius, ( R_0 )</td>
<td>90 mm</td>
</tr>
<tr>
<td>( r_0 R_0 )</td>
<td>2.7 g/cm²</td>
</tr>
<tr>
<td>Mass, ( M_f )</td>
<td>0.89 mg</td>
</tr>
</tbody>
</table>

External Heating

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration, ( t_h )</td>
<td>10 ps</td>
</tr>
<tr>
<td>Spot radius, ( R_h )</td>
<td>20 mm [fixed]</td>
</tr>
<tr>
<td>Optical Depth, ( r L_h )</td>
<td>1.0 g/cm² [fixed]</td>
</tr>
<tr>
<td>Intensity, ( I_h )</td>
<td>7 - 22E19 W/cm²</td>
</tr>
</tbody>
</table>

※ In the heating region, the external heating rate \( P_h \) per unit mass is uniform, i.e. \( P_h [W/kg] = I_h / r L_h \).
Effect of supporting 30 mg/cc foam (C_{18}D_{26}O_6)

High Gain core: \( \rho R = 2.7\, \text{g/cm}^2, \rho = 300\, \text{g/cc}, \alpha = 2, E_{\text{int}} = 25\, \text{kJ}, (E_{\text{de}} = 500\, \text{kJ with 5\% coupling for implosion}) \)

Uniform core heating: \( I_h = 7 - 22\times 10^6\, \text{W/cm}^2, (t_h = 10\, \text{ps}, r_b = 20\, \text{mm}) \quad E_h = 8.8 - 27.6\, \text{kJ} \)

\[ \Rightarrow E_{dh} = 29 - 92\, \text{kJ with 30\% coupling for core heating} \]

Ignition and high gain are possible but lower density foam is necessary to make FI more attractive.
For FIREX-HR, development of continuous fueling system is the key.

- Thermal cavitation technique is attractive to fill many shells simultaneously.

Demonstration of repetitive laser irradiation

- To persuade suspicious people, we are going to make a small integrated reactor system that demonstrate repetitive laser irradiation of injected targets. (2003-2006)

Scientific interest:
- Power distribution on target
- Reflectivity of phase conjugation mirror
- Influence of heat generation in the mirror
Collaborations

• We are going to collaborating with;
  – On target material
    • GA
    • Hirosaki Univ. (Photo-voltaic material)
    • Nihon Univ., Tokyo Inst. Technol. (Dopant, Monomer)
    • Ibaraki Univ. (Dopant)
  – On Cryogenic technology;
    • NIFS (D-³He)
    • LPI (Characterization)
  – Injection and tracking
    • GA
    • Nagoya Univ. (Pneumatic gun), Gifu Univ. (Tracking), ILT (Tracking and Stirring)
  – Reactor material
    • Tokyo Inst. Technol. (Irradiation with pulse power)
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Cascade reactor for fast ignition scheme

- New Koyo has a cascade flow of LiPb to prevent the ablation due to sputtering by energetic ions. The reactor has a hybrid structure to simplify the LiPb flow. The distance between the ceiling and the firing position is set to balance the ablation with condensation.

Thermal output 400 MJ
Rep-rate 3 Hz
Some protection scheme is necessary to use a cryogenic target in a wet wall reactor.

- Because of large latent heat of condensation, the thermal load in a wet wall reactor is 10 times as large as that in a dry wall reactor.

  Ref*1, D. Goodin to be published in Fusion Technology.
Design space for foam insulated central ignition targets

- When the density of foam layer is 50 mg/cc, the out-of-roundness is the critical issue because of large density jump. Melting occurs mainly by thermal radiation.

- Melting is the critical issue for 250 mg/cc foam shells because of poor insulation effect.
In the case of a fast ignition target, thermal load is concentrated on the leading side.

- When a target is injected into 650°C, 0.05 Torr Pb vapor at 300 m/s, the thermal load on the leading side exceeds Black body radiation.

- The cone works as a wake shield that reduces the thermal load due to the dynamic component.

- Because of large thermal conductivity of lead, the cryogenic layer would melt away.
Due to large heat capacity of the cone and lower initial temperature, foam-insulated cone target can survive in the wet wall reactor.

- Vapor pressure, 0.05 Torr, Chamber temperature 650°C
- The injection velocity, 200 m/s
- Foam density 250 mg/cc, Foam thickness, 100 um
Because of the large heat capacity of the cone, the temperature of the cone is representative of the target.

- Since there is no gas barrier inside, solid DT layer contacting with the cone will sublimate and be redistributed toward lower temperature zone.
- Influence of dry zone on the high density compression is future issue.
In wet-wall reactor, protection of final optics from neutralized particles seems most critical.

- Metal vapor on final optics makes plasma that damages the surface of optics.
- Neutrons can be ignored by locating the optics 30 m apart.
- Alpha particles and ions can be removed by a Magnetic field.
- Ablated metal from inner surface can be shielded by rotary shutters.
Protection scheme of final optics by rotary shutters
Timing chart for bluster wave and rotary shutters

ILE, Osaka

Temperature °C

- Vapor pressure
- Design pressure 0.05 Torr

Blaster waves
- 1st shutter 28 Hz
- 2nd shutter 14 Hz
- 3rd shutter 3 Hz

Charged particles from plasma 1~2 μs
Neutron, alpha, x-rays 10~20 ns

1st bluster wave from the wall
v=3,000 m/s @20,000 K
2nd?
3rd?

10 μs 100 μs 1 ms 10 ms 100 ms 1 s

Miss fired target
Target injection
2nd shot 3rd shot 4th shot
Rotary shutters impose severe accuracy for the injection velocity.

- Fire timing of the target and open time of the rotary shutters must be synchronized with accuracy of 0.2 ms.
- This requires the injection velocity of 200 +/-2 m/s.
A new design of FI target and the sabot

<table>
<thead>
<tr>
<th>Laser</th>
<th>Energy (including additional heating)</th>
<th>Fuel</th>
<th>DT(gas) (&lt;0.01mg/cc)</th>
<th>DT(Solid) (259mg/cc)</th>
<th>Gas barrier (CHO, 1.07g/cc)</th>
<th>CHフォーム (100mg/cc)</th>
<th>Outer diameter</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>507kJ</td>
<td></td>
<td>1,300 μm</td>
<td>200 μm</td>
<td>2 μm</td>
<td>230 μm</td>
<td>1,732 μm</td>
<td>1.88mg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cone</th>
<th>Material</th>
<th>Li17Pb83</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Length</td>
<td>8.5 mm</td>
</tr>
<tr>
<td></td>
<td>Diameter</td>
<td>5 mm</td>
</tr>
<tr>
<td></td>
<td>Mass</td>
<td>429 mg</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Sabot</th>
<th>Material</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass</td>
<td>200mg</td>
</tr>
</tbody>
</table>
Cut view of cryogenic cone target and the sabot
Ideally we can expect pointing accuracy of +/- 0.1 mm at 5m apart.

(Private communication from air rifle association Japan)
Trajectory of fast ignition target with heavy cone.

In the case of a fast ignition target with cone, estimated variation is +/- 8 µm because of its large mass. Tracking in chamber could be skipped depending on the requirements.
In future wet-wall reactor, the speed of vapor flow is estimated to be 170 m/s at the periphery.

- When the fusion yields varies 10 % for shot to shot, the speed of vapor will also vary 10 % since the ablated mass is proportional to the fusion yield.
- The variation of the vapor was estimated to be 20 m/s.
- This estimation indicates that the shot to shot variation in the target position at the center due to cross wind is 5 m for the FI target with heavy cone.
# Necessity of tracking

<table>
<thead>
<tr>
<th></th>
<th>Tracking at muzzle</th>
<th>Tracking in chamber</th>
<th>Detection of firetiming</th>
<th>Beam stirring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central ignition target</td>
<td>Necessary</td>
<td>Necessary</td>
<td>Necessary</td>
<td>Necessary</td>
</tr>
<tr>
<td>FI target (without cone)</td>
<td>Necessary</td>
<td>Necessary</td>
<td>Necessary</td>
<td>Necessary</td>
</tr>
<tr>
<td>FI target (with right cone)</td>
<td>Depends on conditions</td>
<td>Depends on conditions</td>
<td>Necessary</td>
<td>Depends on conditions</td>
</tr>
<tr>
<td>FI target (with heavy cone)</td>
<td>Could be skipped depending on injector performance</td>
<td>Could be skipped</td>
<td>Necessary</td>
<td>Could be skipped depending on injector performance $\pm 100\mu$m</td>
</tr>
</tbody>
</table>
Key technologies related to target toward IFE

• Fabrication of low density foam shell with gas barrier and (insulator for wet wall reactor)
  – Density 10 mg/cc (Gain reduction)
  – Cell size 1 µm (To allow optical characterization)
  – Coating of gas barrier (Maybe interfacial polycondensation technique)
  – Coating of insulation layer (for mainly wet wall reactor)

• Direct fueling system
  – Thermal cavitation (controllability, cracks, tritium inventory)
  – Needle injection (Currently no demonstration)

• Injection
  – Speed control
  – Rifling
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Experimental activity of 2002 at ILE

- Target fabrication
  - Fast ignition targets
  - PS, Foam
  - Ion focusing
  - Beat wave acceleration
  - Polyimide shell

- Material development
  - Low density foam
  - Photo-voltaic polymer
  - Polymer with high Z

- Injection and tracking
  - Reactor simulator
We are going to use foam technique to make solid hydrogen layer in FI target with cone.
The first try was failure because of puncture of shell

- The foam layer becomes transparent, which revealed new issue, many micro-structures in the gas barrier coated with interfacial poly-condensation technique.
Simulation of liquid wall reactor started.
A lot of Pb particles, drops of dew, was observed on the surface of a quartz rod during a H$_2$ 10 Torr, 1400K, 1hr operation.

- To simulate diffusion of Pb vapor from wet-wall-reactor to the final optics, 25 g Pb was evaporated.
- No deposition of Pb at areas of T > 800K and T < 600K.
- A lot of Pb particles ranging < 300 μm at the area of 650K < T < 750K.
Many Pb particles ranging 0.1 to 30 μm were deposited on the bottom of furnace filled with 10 Torr H$_2$. 
Lead deposited on the 500K to 800K surface during a H$_2$ 0.1 Torr, 1400K, 1hr run. No dew on the bottom rod.

- To simulate diffusion of Pb vapor from wet-wall-reactor to the final optics, 14 g Pb was evaporated.
- No deposition of Pb at bottom area of T > 800K and T< 600K and at top area of T > 750K and T< 500K. Hydrogen gas flow from bottom to top carried the Pb vapor toward colder region.
No deposition of Pb was observed on witness plate in 0.1 Torr H$_2$.
Deposition of Pb was observed on the surface of a quartz rod during a $\text{H}_2$ 0.1 Torr, 780K, 1hr run.

- 9.5 g of Pb (1/3 of previous case) was evaporated during 1hr run.
- Deposition area moved inward.
- No drop of dew was observed.
- No deposition on bottom
- This result indicates that contamination of final optics can be avoided if the first bluster wave is blocked.
Summary

• A set of rotary shutters was proposed to protect the final optics from neutral Pb vapor. This scheme, however, imposes severe requirement on the injection velocity. (For example, 200+/- 1 m/s)

• FI target with heavy cone was proposed, which may allow no tracking and beam stirring.

• Wet-wall simulator in operation.
  – Preliminary result indicates no deposition on the surface T>800 C and T<500K.
  – Lot of aerosol in 10 Torr H₂ run, but no visible aerosol in 0.1Torr H₂ run.