Activities on Laser Inertial Fusion Test (LIFT) committee,
Tritium barriers in heat cycle,
and
Final optics for Ignition Beam of fast ignition

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Presented at US/Japan workshop on
Outline

• Recent Activities
  – Design Committee for Laser Fusion Test Reactor
• Tritium control
• Final optics
We organized Design Committee for Laser Fusion Test Reactor.

• Purpose
  – To update milestones (2002) and roadmap to KOYO-F (2005) focusing on by-product (physics, tritium breeding for the next step, material test)
  – To make conceptual design of the milestone using latest physics, existing materials and technologies that can be developed in near future

• Basic policy
  – to take account of total balance of system and avoid inconsistency in specifications of the elements.
Expected discussion points

• Core plasma
  – Point target designs for high rep. rate test (no electricity generation) and LIFT (with EG).

• Laser
  – Optimization of operating temperature of cooled Yb:YAG ceramic laser.

• Target
  – Injection system with coil gun

• Chamber
  – Tritium control
  – Maintenance
The committee consists of Integration WG, Core Plasma WG, Laser WG, Fueling WG and system WG.

- **Integration WG**
  - K. Ueda (UEC), A. Endo (Waseda U.), Y. Ogawa (Tokyo U.), H. Kan (HP), M. Kikuchi (JAEA), A. Sagara (NIFS), H. Tanigawa (JAEA), K. Tobita (JAEA), K. Tomabechi, M. Nishikawa, H. Shiraga (Osaka U), H. Fujita (Osaka U), T. Norimatsu (Osaka U), K. Okano (MAPI)

- **Core plasma WG**
  - H. Shiraga (Osaka U.)
  - T. Ozaki (NIFS)
  - H. Sakagami (NIFS)
  - K. Shigemori (Osaka U.)
  - T. Johzaki (ILT)
  - H. Sunahara (ILT)
  - T. Taguchi (Setsunan U)
  - M. Nakai (Osaka U)
  - H. Nagatomo (Osaka U)
  - H. Nishimura (Osaka U)
  - S. Fujioka (Osaka U)
  - K. Murakami (Osaka U)

- **Laser WG**
  - H. Fujita (Osaka U.)
  - T. Kawashima (HP)
  - J. Kawanaka (Osaka U)
  - R. Yasuhara (NIFS)
  - T. Yanagitani (Mikishma)

- **Fueling WG**
  - T. Norimatsu (Osaka U.)
  - A. Iwamoto (NIFS)
  - T. Endo (Hiroshima)
  - H. Yoshida (Gifu U)
  - R. Tsuji (Ibaragi U)
  - N. Sato (HP)

- **System WG**
  - K. Okano (CRIEPI)
  - Y. Ueda (Osaka U)
  - Y. Kitagawa (GPI)
  - T. Goto (NIFS)
  - M. Kondo (Tokai U)
  - Shimizu (Mitsubishi)
  - T. Hayashi (JAEA)
  - H. Fukada (Kyushu U)
  - S. Fujioka (Osaka U)
  - T. Norimatsu (Osaka U)

**Key date**
- **February, 27 2012** Kickoff meeting,
- **March 2013** Middle report on specifications for mile stone, scenario for the 1st MS.
- **March 2014** Final report
Plan toward laser fusion power plant
Outline

• Recent Activities
  – Design Committee for Laser Fusion Test Reactor
  – Latest experimental result on fast ignition

• Tritium control in heat exchanger

• Final optics
We assumed virtual gaps with zero thickness to discuss tritium permeation through a heat exchanger.

For simplification, we assumed Sieverts’ law for LiPb, stainless steel, and Henry’s law for pressurized water.

Chemical formula after permeation is very important to know the behavior of tritium.
- $T_2$, diffusion to the next loop
- $HTO$, accumulation in water

When the wall is wet, 99% of tritium forms $HTO$.

Recent result indicates that tritium permeates as $T_2$ when the wall is dry and $T>500K$. (by Terai, presented at Nucl. Soc. Jpn (2011))
Technical data

ILE, Osaka

Heat Exchanger

T= 773K

Diameter 30 cm
Thickness 0.5 cm
Length 30 m

T= 710K

Turbine

T= 703K

T= 520K

Condenser

T= 513K

Radiator

T= 373K

Diameter 30 cm
Thickness 0.5 cm
Length 30 m

Diameter 50 cm
Thickness 1 cm
Length 50 m

LiPb 250 m³

Water 20 m³

Water 20 m³

Diameter 30 cm
Thickness 0.5 cm
Length 30 m
Steam generator, condenser and heat exchanger

(Data from Mitsubishi Heavy Industry Inc.)

Three columns are used for one modular reactor.

<table>
<thead>
<tr>
<th>Specification</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Vertical, helical coil</td>
</tr>
<tr>
<td><strong>Fluid in body</strong></td>
<td>LiPb</td>
</tr>
<tr>
<td><strong>Fluid in pipes</strong></td>
<td>Water, vapor</td>
</tr>
<tr>
<td><strong>Number</strong></td>
<td>3 columns/one modular reactor</td>
</tr>
<tr>
<td><strong>Heat flow</strong></td>
<td>305.4 MWt/column</td>
</tr>
<tr>
<td><strong>LiPb temp.</strong></td>
<td>Inlet 500C/Outlet 300C</td>
</tr>
<tr>
<td><strong>LiPb flow rate</strong></td>
<td>$2.94 \times 10^7$ kg/h/column</td>
</tr>
<tr>
<td><strong>Water temp.</strong></td>
<td>Inlet 240°C/Outlet 435°C</td>
</tr>
<tr>
<td><strong>Pipe size</strong></td>
<td>25.4mmφ × 200 pipes</td>
</tr>
<tr>
<td><strong>Body size</strong></td>
<td>Outer diameter 2.1m/High 15m</td>
</tr>
<tr>
<td><strong>Material</strong></td>
<td>SUS 316</td>
</tr>
<tr>
<td><strong>Total area of heat exchange</strong></td>
<td>$2 \times 10^3 m^2$</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
<td>2 mm</td>
</tr>
</tbody>
</table>
Solubility of hydrogen in coolants

We used solubility of hydrogen reported by Dr. Nishikawa and Fukada and Henry’s law for solubility of hydrogen in pressurized water.

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Henry constant Ln H(GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>323</td>
<td>2.04</td>
</tr>
<tr>
<td>373</td>
<td>1.92</td>
</tr>
<tr>
<td>423</td>
<td>1.71</td>
</tr>
<tr>
<td>473</td>
<td>1.35</td>
</tr>
<tr>
<td>523</td>
<td>0.838</td>
</tr>
<tr>
<td>573</td>
<td>0.198</td>
</tr>
<tr>
<td>623</td>
<td>0.093</td>
</tr>
</tbody>
</table>

Henry $P_{H_2} = H \cdot C_{H_2}$; Mole ratio

<table>
<thead>
<tr>
<th>Water in 2nd loop</th>
<th>20 m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>513K</td>
</tr>
<tr>
<td>$P_{\text{tritium}}$ in reactor</td>
<td>1 Pa</td>
</tr>
</tbody>
</table>

Tritium in LiPb | 13 g |

T$_2$ in 2nd loop | 2.7 mg |
Tritium diffusion through heat exchanger is critical issue for fusion plant.

If there is no tritium barrier, tritium spreads quickly over heat cycles. 1/5 of injected tritium goes to the second water loop in the worst case. Coating of Er2O3 enables tritium recovery as fuel, but insufficient in safety view point.
We are going to use double tubes. Thin lines in the wall are filled with carrier gas and oxygen to convert tritium to HTO.

This method is compatible with a coating barrier such as Er$_2$O$_3$ and ZrO$_2$. 
Tritium flux \(1.06 \times 10^{16}\) atoms/m\(^2\)·sec

Heat flux \(1.63 \times 10^5\) W/m\(^2\)

Partial pressure of tritium in the trapping tube is assumed to be zero.
With 30 lines, tritium permeation was reduced to $2/10^5$ of base line tube.
Tritium flow after reduction of $1/10^5$

- $7 \text{ mg/s in vacuum}$
- $1.2 \text{ mg/s in highly concentrated tritium water}$

Accumulation of tritium after 1 year full operation = 200MBq/cc

cf. tritium in Fugen (ATR) after 25 year operation 250MBq/cc

- $6 \text{ mg/s By target injection}$
- $12 \mu\text{g/s}$
- $10\text{g/year}$
- $0.1\text{g/year}$
• Double tube heat exchanger concept can reduce tritium permeation by $1/10^5$ with the surface increase factor of 1.6.

• We can set a fuel tritium barrier at the 1st heat exchanger but the tritium concentration in the second loop is still high, we need 3rd heat cycle as a bio-barrier.

• This technique is compatible with coating method such as Erbium oxide. By using both technique, tritium permeation can be reduced by $1/10^7 - 1/10^8$. (Final goal in ITER case, $1/10^8 - 1/10^9$)
Tritium

– We propose a tritium filtering system for a heat exchanger, which is compatible with coating technique.

– By using both techniques simultaneously, we can reduce the tritium accumulation in the second water loop to an acceptable level.
Outline

- Recent Activities
  - Design Committee for Laser Fusion Test Reactor
  - Latest experimental result on fast ignition
- Tritium control in heat exchanger
- Final optics
Final optics is the critical issue of a laser fusion reactor.

- Compression beam (L=30m)
  - 65kJ/10ns × 32 beams
    \( \Phi = 2.5 \times 10^{12} \text{ n/s cm}^2 \times (8 \times 10^{23} \text{ n/m}^2 \text{FPY}) \)
- Ignition beam (L=15 – 25 m)
  - 150kJ/30ps
    \( \Phi = 5 \times 10^{12} – 1.5 \times 10^{13} \text{ n/s cm}^2 \)

\[ \text{Fy} = 200 \text{MJx4Hz} \]

\[ 65 \text{kJx4 Hz} \]

\[ 2.5 \times 10^{12} \text{ n/s cm}^2 \]
\[ \sim 0.7 \text{ dpa/y} \]

\[ 1 \sim 3 \text{ dpa/y} \]

GIMM*1,2 or GILMM*3

This estimation is moderately supported by Snead’s experiment.

Energy of neutrons $\sim 0.1\text{MeV}$

0.1 dpa

We estimated that the life of reflective mirror is 2 month.

- Attenuation of SiO$_2$ optical fiber by DT neutrons $I_{in}/I_{out} = 1 \times 10^{-19}$ dB/cm/(n/cm$^2$)


- Thickness of multilayer coating $<10$ μm
- Total absorption of laser light $< 1$kW (water cooling from back side of mirror)

Life of mirror  2 - 4 months
Cost for mirrors is acceptable.

- Current cost for a 30cm-diameter mirror is 10k $.
- If we replace all mirrors for compression beams every 2 month in a short halt of laser operation.
- The cost for mirrors 1.4 M$/2 months
- Target cost 16 M$/2 months ( @ 20C/target)
- Sale 150 M$/2 months(@ 10 C/kWh)

- Running cost for mirrors is less than 1% of total sale, which is acceptable.
Final optics

Top view

Side view

- To chamber
- Air rock gates
- Mirror-pre-mounted cart
- Neutron shield gate
- 1st tritium barrier
- To maintenance yard
The critical issue of KOYO-F is the final optics for the heating 150kJ/30ps laser.

- The diameter of heating laser is about 3m. So, periodic replacement of expensive multi-coated mirror seems inappropriate.
- We look for a metal mirror but.....

Because of low damage threshold, metal mirror becomes big.

Level, Grazing Incident Liquid Metal Mirror* will be used for 150kJ/30ps heating laser.

- Conventional GIMM and GILMM*¹ are also critical due to bent of base frame.

There are many issue on this concept.

How is reflectivity?
How is the damage threshold of liquid Pb?
Is the surface stationary after laser shot?
How is the flatness of the surface?

We measured temperature dependence of damage threshold of mirrors.
The damage threshold of metal mirror increases with temperature.

**Dielectric mirror**

**Metal mirror**

- SiO2 Silica sub.
- SiO2 BK7 sub.

Design point of KOYO-F
The damage threshold of metal mirror for a pico-second pulse can be explained by the heat capacity of metal in penetration depth of the electric field.

We estimate that the damage threshold of liquid Pb is 0.15 J/cm² for pico second pulse.
Level, Grazing Incident Liquid Metal Mirror* will be used for 150kJ/30ps heating laser.

We can theoretically expect reflectivity >98 % using liquid Pb.

Damage threshold of liquid Pb is estimated to be 0.15 J/cm²
Summary of final optics

• Compression beams
  – Replace every 2 – 4 month

• Ignition beam
  – Level, Grazing Incident Liquid Metal Mirror
    – Future issue
    – Reflectivity of liquid LiPb, influence of oxide layer
    – Flatness of the surface <1/10 λ
Thank you for your attention!

We invite you to attend CIFE 2012 in Yokohama April 25-27 2012.
Summary 2 and Roadmap to laser fusion power plant

i-LIFT can be fabricated using existing materials and improved technologies.

**POP experiment**

- NIF: Ignition and burn
- LMJ: Ignition and burn
- FIREX-I: Optimization of Ignition and burn
- FIREX-II: Hating to ignition temperature

**Laser Inertial Fusion Test**

- Laser engineering design
- Test of high rep operation
- Reactor design
- High average power laser

**Laser Inertial Fusion Energy DEMO**

- Driver development
- Target injection, tracking and beam steering
- Chamber, blanket

- Elemental development: 100J/1Hz
- Single: 10 min burst

- Continuous op. Life
- System integration for DEMO

- Cost: 2000～3000M$

- Repeated burn

- 10 MW Power to net

- 10kJ/1Hz
- 600kJ/1Hz solid/liquid wall test

- Cost: 3000～4000M$

**Reactor materials, ITER R&D results**
Fast ignition realization experiment (FIREX)

Preliminary; Demo of 600 times liquid density
Demo of heating of compressed plasma to 1keV with 1kJ / 1ps pulse (2002)

FIREX-I Demo of 5 keV with 10 kJ / 1ps pulse
FIREX-II Demo of ignition and burn
Members of FIREX project

H. Habara, R. Kodama, K. A. Tanaka
A. Sunahara, T. Johzaki
M. Isobe, A. Iwamoto, T. Mito, O. Motojima, T. Ozaki, H. Sakagami
K. Kondo
T. Kanabe
T. Taguchi
Y. Nakao
M. Key
P. Norreys
J. Pasley

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(NIFS)
(JAEA-KPSI)
(Fukui University)
(Setsunan University)
(Kyushu University)
(LLNL)
(Rutherford Appleton Lab)
(University of York)
Construction of pulse compressor continued and pop experiment started.

- **Nov, 2008**: Precision alignment of pulse compressor
- **Dec, 2008**: Target irradiation with high-power beam started
- **Feb, 2009**: Irradiation of Fast Ignition (FI) target started
- **June, 2009**: FI integrated experiment started (5 ps)
- **Sept, 2009**: FI integrated experiment (1 ps) / 1 beam
- **Aug, 2010**: FI integrated experiment (1 ps) / 2 beams
The 2nd beam has been activated.

- 1 kJ in 1 beam (2009)
  - $\rightarrow$ 2 kJ in 2 beams (2010)
- Beam profile improved

Contrast in LFEX pulse was substantially improved by introducing

- saturable absorber, and
- AOPF (amplified optical parametric fluorescence) quencher for a few ns range, and
- reduced spectral ripples for ps range.
Plasma diagnostic technologies are also improved to deal with hard x-rays and EMP.
New scintillator for neutrons was developed.

- Slow decay component was significantly reduced.
- Coupled with gated PMT, and used in FI integrated experiment.

scintillation:
BBQ (used for dye lasers)
4,4''''-Bis-(2-butylctyloxy)-p-quatarphenyl

host: p-Xylene

Quenching by oxigen

T. Nagai et al., to be published
Promising result on coupling efficiency was obtained.

Coupling efficiency of 20% ($\delta E_{\text{core plasma}} / E_{\text{heating laser}}$) is very promising toward laser fusion power plant by FI.