Laser Fusion Experimental Reactor LIFT Based on Fast Ignition and the Issue

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IAEA-TM on Physics and technologies of IFE target and chambers
March 18, 2015
Outline

• Introduction
  – Laser Fusion Experimental Reactor, LIFT

• Critical issue in Phase I
  – Heating efficiency
  – Radiation safety
  – Target stability
  – Beam steering
Fast ignition has potential to achieve ignition and burn with smaller laser energy.

- Since fast ignition needs no hot central core, high gain can be achieved with smaller laser energy than that for central ignition.
- FI is robust to RT instabilities.

Key point is the heating efficiency.
Conceptual design committee for experimental reactor was organized on Feb. 2012 with support of IFE Forum.

- Chair Y. Kozaki, Co-chair T. Norimatsu, S. Fujioka

Advisory group
K. Ueda, A. Endo, Y. Ogawa, Y. Kato, H. Kan, M. Kikuchi, H. Tanigawa, K. Tobita, M. Nishikawa and K. Tomabechi

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Plant system group
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Y. Kajimura
Y. Kitagawa
T. Goto
M. Kondo
K. Tomabechi
T. Hayashi
T. Fukada
S. Fujioka
T. Norimatsu

The goal of this committee is to clarify scenario, specification and issue of experimental reactor.

Name, contributions from MCF
### Milestone of experimental reactor

The laser system will be commonly used for all phases.

<table>
<thead>
<tr>
<th></th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Purpose</strong></td>
<td>Repeated fusion burns</td>
<td>Send electric power to net</td>
<td>Tritium breeding Material test</td>
</tr>
<tr>
<td></td>
<td>Physics</td>
<td>&lt; 8MW</td>
<td></td>
</tr>
<tr>
<td><strong>Operation mode</strong></td>
<td>100 shots</td>
<td>1 week</td>
<td>0.5 year</td>
</tr>
<tr>
<td><strong>Fusion yield</strong></td>
<td>16MJ for phys. 40MJ for technol.</td>
<td>40MJ</td>
<td>40MJ</td>
</tr>
<tr>
<td><strong>Electric power</strong></td>
<td>No cooling system</td>
<td>~10MWe</td>
<td>40MWe</td>
</tr>
<tr>
<td><strong>Gain</strong></td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td><strong>Laser energy</strong></td>
<td>Comp. 500 + Heating 150, 2 omega, 30ps</td>
<td>Comp. 500 + Heating 150, 2 omega, 30ps</td>
<td>Comp. 500 + Heating 150, 2 omega, 30ps</td>
</tr>
<tr>
<td><strong>Chamber type</strong></td>
<td>Solid wall, SUS316</td>
<td>1st, Solid wall, Ferrite</td>
<td>Liquid wall</td>
</tr>
<tr>
<td></td>
<td>No W armor</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Blanket</strong></td>
<td>No blanket</td>
<td>①Solid breeder, water cooling</td>
<td>①LiPb self cooling</td>
</tr>
<tr>
<td></td>
<td>Average temperature increase by 200 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Chamber radius</strong></td>
<td>3.5m</td>
<td>3.5m</td>
<td>1.5m</td>
</tr>
</tbody>
</table>
LD pumped, cooled Yb:YAG ceramic laser will be used in all phases

<table>
<thead>
<tr>
<th></th>
<th>Implosion laser</th>
<th>Heating laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (kJ)</td>
<td>600kJ</td>
<td>200kJ</td>
</tr>
<tr>
<td>Pulse width</td>
<td>TBD</td>
<td>30ps, 1ps rise time</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>4Hz</td>
<td>4Hz</td>
</tr>
<tr>
<td>Wave length</td>
<td>$3\omega$</td>
<td>$2\omega$</td>
</tr>
<tr>
<td>Focusing spot size</td>
<td>TBD</td>
<td>66 $\mu$m</td>
</tr>
<tr>
<td>Energy of fundamental wave</td>
<td>860kJ</td>
<td>500kJ</td>
</tr>
<tr>
<td>Number of 32kJ module</td>
<td>28</td>
<td>16</td>
</tr>
</tbody>
</table>

The conversion efficiency for electricity to laser is estimated to be 12% including the energy for cooling.
Radiation control for Phase III

ILE, Osaka

Flexible joint
Emergency valve
Anti vibration pads

Steering mirror
Neutron filter
2nd vacuum window
1st vacuum window

Laser
Neutron and tritium barriers for beam line
Outline

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  – Beam steering
### Point Design of Reactor scale Fast Ignition target for LIFT

**Request specifications to implosion**
- fuel $\rho$: 300 g/cc
- fuel $\rho R$: 2.4 g/cm$^2$
- Fuel radius: 80 $\mu$m
- isentrope parameter $\alpha$: 2.0
- implosion efficiency: 5%

Therefore:
- core energy: 19 kJ
- laser energy: 380 kJ

**Request specifications to heating**
- heating radius: 15 $\mu$m
- heating length: 33 $\mu$m
- heating time: 30 ps
- heating efficiency: 20%

Therefore:
- heating intensity: $1 \times 10^{20}$ W/g
- heating beam energy: 21 kJ
- heating laser energy: 107 kJ

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### Point Design of Reactor scale Fast Ignition target for KOYO-F

**Request specifications to implosion**
- fuel $\rho$: 300 g/cc
- fuel $\rho R$: 3.66 g/cm$^2$
- Fuel radius: 120 $\mu$m
- isentrope parameter $\alpha$: 2.0
- implosion efficiency: 5%

Therefore:
- core energy: 57 kJ
- laser energy: 1.14 MJ

**$\rho R$: 3.51 g/cm$^2$**

$\alpha$: 3

$\eta$: 8%

2.01 mg
Requirements for 50MJ output

Core density \( \rho \) [g/cm\(^3\)]
Core areal density \( R \) [g/cm\(^2\)]
Burn fraction \( B_T \)

\[
B_T = \frac{\rho R}{\rho R + 7} \min \left[ 1, \left( \frac{\rho R}{1.5} \right)^2 \right]
\]

Fusion output \( E_f \) [MJ]

\[
E_f = \frac{M_E}{5 m_p} B_T E_{DT}[MJ] = 14.13 \times 10^5 \frac{1}{\rho^2} \frac{(\rho R)^4}{\rho R + 7} \min \left[ 1, \left( \frac{\rho R}{1.5} \right)^2 \right]
\]

50MJ fusion output,

<table>
<thead>
<tr>
<th>( \rho ) [g/cm(^3)]</th>
<th>( \rho R ) [g/cm(^2)]</th>
<th>( R ) [micron]</th>
<th>( M_F ) [mg]</th>
<th>( B_T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 g/cm(^3)</td>
<td>1.90 g/cm(^2)</td>
<td>93 um</td>
<td>0.71 mg</td>
<td>0.21</td>
</tr>
<tr>
<td>300 g/cm(^3)</td>
<td>2.35 g/cm(^2)</td>
<td>77 um</td>
<td>0.60 mg</td>
<td>0.25</td>
</tr>
<tr>
<td>400 g/cm(^3)</td>
<td>2.75 g/cm(^2)</td>
<td>68 um</td>
<td>0.53 mg</td>
<td>0.28</td>
</tr>
</tbody>
</table>

30MJ fusion output,

<table>
<thead>
<tr>
<th>( \rho ) [g/cm(^3)]</th>
<th>( \rho R ) [g/cm(^2)]</th>
<th>( R ) [micron]</th>
<th>( M_F ) [mg]</th>
<th>( B_T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 g/cm(^3)</td>
<td>1.65 g/cm(^2)</td>
<td>83 um</td>
<td>0.47 mg</td>
<td>0.19</td>
</tr>
<tr>
<td>300 g/cm(^3)</td>
<td>2.04 g/cm(^2)</td>
<td>68 um</td>
<td>0.40 mg</td>
<td>0.23</td>
</tr>
<tr>
<td>400 g/cm(^3)</td>
<td>2.38 g/cm(^2)</td>
<td>60 um</td>
<td>0.35 mg</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Implosion of High gain target: Low-velocity implosion for LIFT is designed.

**Design conditions**

Target ::
Shell : DT gas 923 \( \mu \text{m} \) : DT solid 220 \( \mu \text{m} \):
CH ablator 27 \( \mu \text{m} \)
Fuel mass (DT) 0.62 mg

Laser :: 390 kJ (@ 0.35 \( \mu \text{m} \))

\[ \rho R: 2.32 \text{ g/cm}^2 \]
\[ \rho: 540 \text{ g/cm}^3 \]
\[ R: 40 \mu \text{m} \]

Requirement for \( \rho R \) (2.3 g/cc) will be realized with 390 kJ laser.
Deposition range dependence on heating laser condition

<table>
<thead>
<tr>
<th>(\rho) [g/cc]</th>
<th>(E_{\text{heating}}) [kJ]</th>
<th>Heating time [ps]</th>
<th>Spot size [(\mu)m]</th>
<th>Intensity [W/cm(^2)]</th>
<th>(E_{\text{heating laser}}) [kJ](coupling eff.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>39</td>
<td>30</td>
<td>30</td>
<td>(0.46 \times 10^{20})</td>
<td>195 (0.2) / 390 (0.1)</td>
</tr>
<tr>
<td>300</td>
<td>18</td>
<td>21</td>
<td>20</td>
<td>(0.69 \times 10^{20})</td>
<td>90 (0.2) / 180 (0.1)</td>
</tr>
<tr>
<td>400</td>
<td>11</td>
<td>17</td>
<td>15</td>
<td>(0.90 \times 10^{20})</td>
<td>55 (0.2) / 110 (0.1)</td>
</tr>
<tr>
<td>500</td>
<td>7</td>
<td>14</td>
<td>12</td>
<td>(1.10 \times 10^{20})</td>
<td>35 (0.2) / 70 (0.1)</td>
</tr>
</tbody>
</table>

For 300g/cm\(^3\) core, required laser intensity (under the optimal condition & laser spot = beam spot) is \(I_L = 3.5\times10^{20}\)W/cm\(^2\) (\(\eta_{L\rightarrow core}=20\%\)) ~ \(6.9\times10^{20}\)W/cm\(^2\) (\(\eta_{L\rightarrow core}=10\%\)).

- Hot electron temperature (Wilks’s model)
  \[
  T_h [\text{MeV}] = \left[ \frac{f_{\text{laser}}}{1.2 \times 10^{19} \text{W/cm}^2} \left( \frac{\lambda_{\text{\(\mu\)m}}}{1.06 \text{\(\mu\)m}} \right) \right]^{1/2}
  \]

- Deposition range
  \[
  R [\text{g/cm}^2] = 0.6 f_R T_h [\text{MeV}]
  \]

\(f_R\): range reduction/lengthening factor
\(
\rightarrow \text{depends on stopping power model.}
\)

To keep the deposition range < 1.2g/cm\(^2\),
\(I_L [\text{W/cm}^2] < 5\times10^{19} (1\omega), 2\times10^{20} (2\omega), 4\times10^{20} (3\omega)\)

The heating laser must be 2\omega.
Summary for heating laser

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>$0.53 \text{ m (2)}$</td>
</tr>
<tr>
<td>Energy $E_{iglaser}$</td>
<td>$\sim 200 \text{ kJ}$</td>
</tr>
<tr>
<td>Intensity $I_{iglaser}$</td>
<td>$\sim 2 \times 10^{20}$ $\text{ W/cm}^2$</td>
</tr>
<tr>
<td>Spot $r_{iglaser}$</td>
<td>$\sim 33 \mu\text{m}$</td>
</tr>
<tr>
<td>Duration $t_{iglaser}$</td>
<td>$\sim 30 \text{ ps}$</td>
</tr>
<tr>
<td>Coupling eff. $\eta_{iglaser}$</td>
<td>$20%$</td>
</tr>
<tr>
<td>Electron T $T_h$</td>
<td>$\sim 2 \text{ MeV}$</td>
</tr>
<tr>
<td>Radius of heating $r_b$</td>
<td>$33 \mu\text{m}$</td>
</tr>
<tr>
<td>Beam guide is important</td>
<td></td>
</tr>
</tbody>
</table>

Energy of heating laser can be reduced with higher $\rho$.

<table>
<thead>
<tr>
<th>$\rho$ [g/cm$^3$]</th>
<th>$E_{iglaser}$ [kJ]</th>
<th>$I_{iglaser}$ [W/cm$^2$]</th>
<th>$t_{iglaser}$ [ps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>161</td>
<td>$2.24 \times 10^{20}$</td>
<td>21</td>
</tr>
<tr>
<td>400</td>
<td>125</td>
<td>$2.15 \times 10^{20}$</td>
<td>17</td>
</tr>
<tr>
<td>500</td>
<td>114</td>
<td>$2.38 \times 10^{20}$</td>
<td>14</td>
</tr>
</tbody>
</table>
Heating process

Model for heating process

- Physical process consists of 3 major elements

\[ \eta = \eta_{\text{fast}} \cdot \eta_{\text{propa.}} \cdot \eta_{\text{core}} \]

- \( \eta_{\text{fast}} \)
  Energy of heating laser to that of hot electrons

- \( \eta_{\text{propa.}} \)
  Fraction of hot electrons that reach the core

- \( \eta_{\text{core}} \)
  Energy deposition efficiency

In FIREX-1

Experimental check required → To be improved
To improve the coupling efficiency, we successfully reduced the temperature of electron beam.

2013 before cool REB

\[
T_{\text{REB}1} = 1 \text{ MeV} \quad (4\%)
\]
\[
T_{\text{REB}2} = 3 \text{ MeV} \quad (7\%)
\]
\[
T_{\text{REB}3} = 15 \text{ MeV} \quad (89\%)
\]

2014 after cool REB

\[
T_{\text{REB}1} = 1.7 \text{ MeV} \quad (52\%)
\]
\[
T_{\text{REB}2} = 10 \text{ MeV} \quad (48\%)
\]

Peak/Foot $> 10^{11}$
Gradient of conductivity reflects electrons and generates magnetic field.

Magnetic field generated by fast electrons

\[ \frac{\partial \vec{B}}{\partial t} = -\nabla \times \left( \frac{\eta}{\mu_0} \nabla \times \vec{B} \right) + \left( \nabla \eta \right) \times \vec{j}_f + \eta \left( \nabla \times \vec{j}_f \right) \]
We can expect increase of heating efficiency by 10 times with a magnetic field.
Target design to improve the coupling efficiency

External magnetic coil

Inner High-Z coating

Heating
(4 of 4)

DLC cone

TONGARI-tip

Laser-driven capacitor

Compression
(9 of 12)

B-generation
(3 of 12)

*e. Fujioka et al., EPS-ICPP (2012).*
Fundamental equations of radiation hydrodynamics for laser plasma simulation with magnetic field transport

- mass equation
- momentum equation
  \[ \rho \frac{du}{dt} = -\nabla (P_{\text{th}} + \frac{B^2}{8\pi}) + \frac{1}{4\pi} \left( B \cdot \nabla \right) B \]
- ion energy equation
- electron energy
  \[ \rho \frac{d\varepsilon_e}{dt} = -P_e \nabla \cdot u - \nabla \cdot \left( \kappa \cdot \nabla T_e \right) - Q_{ei} + S_L + S_r \]
- radiation transport
- magnetic field transport

\[ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times \{ \mathbf{V} \times \mathbf{B} \} - \frac{c}{e} \left[ \nabla \times \left( \frac{m_e c}{4\pi e n_e \tau_e} \alpha_0 \mathbf{h} \left\{ (\nabla \times \mathbf{B}) \cdot \mathbf{h} \right\} \right] \]

\( \alpha', \alpha'', \beta', \beta'' \): thermal transport coefficient*, which depend on Hall parameter \( \omega_{ce} \tau_{ei} \)

\( \mathbf{h} \): unit vector of magnetic field direction

*S. I. Braginskii, *Reviews of Plasma Physics* 1, 1965
Cone-guided implosion (“Rad-Hydro”+”B-field”)

(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)
- Magnetic field
- Laser energy
  - 1-D ray-trace
- EOS
  - QEOS (Tomas-Fermi+Cowan)

Implosion Laser condition
Gaussian pulse shaping (FWHM 1.2 ns)
- Wavelength : 0.53 $\mu$m
- Energy (on target) : 2.5 kJ
- Magnetic field : 300 T (3 MG)

Shell Target : CD 8 $\mu$m

Gold cone
30° (Full angle)

Gold cone
30° (Full angle)

computational grids : $300 (i\text{-dir.}) \times 300 (j\text{-dir.})$
The magnetic field is compressed. However, the hydrodynamic instability is seeded at early phase of the implosion by the anisotropic of thermal conductivity.

\( t = 1.34\, \text{ns} \)

Effect
1T B field was generated with laser-driven capacitor and coil.

Photo of capacitor-coil target

Current ~ several MA

kJ-ns laser beams

1mm

1 T B field was obtained.

\[ \lambda_L = 0.53 \, \mu m \]

\[ \lambda_L = 1.053 \, \mu m \]

Faraday rotation measurement

Pick-up probe measurement

Fire ring target would be the solution for the coupling efficiency.

Fin to generate ring current

Timing of B field and $\tau_B$ are the key of success.
Control of fast electrons by magnetic field seems the key point to improve the heating efficiency.

• Numerical simulation indicated that the heating efficiency can be increased with the external B by a factor of 8 and with self-generated B by a factor of 2.6.

• Next issue; How to create the external B field?

Fire ring target would be the solution.
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  – Beam steering
Operation scenario of Phase I

- Physical experiments 16MJ x 1Hz X 100s
- Reactor technology exp. 40MJ X 1Hz X 1s
- Chamber material SUS316, No blanket, No W armor
- 1 campaign /month, X 3 years.
- Conventional transmitting optics can be used.
- Tritium in vacuum line will be recovered and reused in the next campaign after isotope separation
- 1/3 of tritium will be remained in the chamber surface.

ILE, Osaka
Thermal load by a particles on the 1\textsuperscript{st} wall 4J/cm\textsuperscript{2}. We accept melting of the surface because of limited use.

Thermal load by x-ray (left) and particle (right). Fusion yield 200MJ, R=3m

Temperature at inner surface during 100 shots

Evaporation speed is $1.8 \times 10^{-10}$cm, which shows no influence on the chamber safety

Temperature along the cross section of wall at the last shot
Radiations in Phase I

- E x B acceleration of electrons by heating laser 1
  - ~ 40 MeV, at 10ns after laser shot
  - Hard x-rays by these electrons cause (g, n)reactions in chamber wall
- Nuclear reactions at chamber
  - (n, 2n), (n, p), (n, np), (n, d), (n, α)....
- Neutron captures ~ 9MeV, 70ns-80ns
- Decay radiations ~ 3MeV, μs ~ 10^6 year (93Zr)
## Nuclear reactions in SUS316

### Neutron captures radiate intense $\gamma$-rays

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Reaction</th>
<th>Energy (MeV)</th>
<th>Cross Section (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILE, Osaka</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Plasma diagnostics system must work and keep the data under $<9$MeV, 65kJ/m$^2$ $\gamma$-rays

### Total Gamma ray energy due to neutron capture is estimated to be 65kJ/m$^2$ in 10ns$\sim$0.1$\mu$s
Neutrons hit the chamber wall 70 ns after fusion burn and release γ rays (<9 MeV) in 10ns.

- The intensity of g-rays at the chamber surface is estimated to be 6.5x10^9 W/cm^2
Radiation from the chamber after 100 shots in Phase I

From SUS 316 chamber

Energy of main g ray  1.3MeV
9Sv/h  at 1 hour after shots

Gamma ray power generated in SUS316 chamber wall after 16MJ, 100 shots of Phase I

From base concrete

Energy of main g ray 3MeV
0.4Sv/h  at 1 hour after 100 shots

Gamma ray power generated in the concrete base of the target chamber after 16MJ x 100 shots
Long-life -time RIs

<table>
<thead>
<tr>
<th>原子番号</th>
<th>核種</th>
<th>生成確率</th>
<th>崩壊形式</th>
<th>半減期</th>
<th>半減期(秒)</th>
<th>100ショット後 (Bq)</th>
<th>主なガンマ線MeV(相対頻度)</th>
<th>線量率 MeV/Bq/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z=1</td>
<td>3H</td>
<td>1.00E-06</td>
<td>β⁻</td>
<td>12.3y</td>
<td>3.9.E+08</td>
<td>0.0045(11%)</td>
<td>5.15E-04</td>
<td></td>
</tr>
<tr>
<td>Z=23</td>
<td>49V</td>
<td>8.79E-04</td>
<td>ε</td>
<td>330d</td>
<td>2.9.E+07</td>
<td>1.3.E+10</td>
<td>0.032(9.9%)</td>
<td></td>
</tr>
<tr>
<td>Z=24</td>
<td>51Cr</td>
<td>2.81E-02</td>
<td>ε</td>
<td>27.7d</td>
<td>2.4.E+06</td>
<td>4.8.E+12</td>
<td>0.0317</td>
<td></td>
</tr>
<tr>
<td>Z=25</td>
<td>53Mn</td>
<td>6.84E-03</td>
<td>ε</td>
<td>3.7e6y</td>
<td>1.2.E+14</td>
<td>2.4.E+04</td>
<td>0.08(100%)</td>
<td></td>
</tr>
<tr>
<td>Z=25</td>
<td>54Mn</td>
<td>9.68E-03</td>
<td>ε</td>
<td>3.12d</td>
<td>2.7.E+07</td>
<td>1.5.E+11</td>
<td>0.834(100%)</td>
<td></td>
</tr>
<tr>
<td>Z=26</td>
<td>59Fe</td>
<td>1.53E-04</td>
<td>β⁻</td>
<td>44.495d</td>
<td>3.8.E+06</td>
<td>1.6.E+10</td>
<td>1.099(57%). 1.291(47%) 0.621, 0.558</td>
<td></td>
</tr>
<tr>
<td>Z=27</td>
<td>57Co</td>
<td>2.30E-02</td>
<td>ε</td>
<td>2.71d</td>
<td>2.3.E+07</td>
<td>4.0.E+11</td>
<td>0.122(85%)</td>
<td></td>
</tr>
<tr>
<td>Z=27</td>
<td>60Co</td>
<td>3.35E-03</td>
<td>β⁻</td>
<td>1.925d</td>
<td>1.7.E+08</td>
<td>8.2.E+09</td>
<td>1.173(100%), 1.332(100%) 1.17, 1.33</td>
<td></td>
</tr>
<tr>
<td>Z=28</td>
<td>59Ni</td>
<td>2.40E-02</td>
<td>ε</td>
<td>7.8e4y</td>
<td>2.4.E+12</td>
<td>4.1.E+06</td>
<td>0.007(20%)</td>
<td></td>
</tr>
<tr>
<td>Z=28</td>
<td>63Ni</td>
<td>3.06E-03</td>
<td>β⁻</td>
<td>1.012y</td>
<td>3.2.E+09</td>
<td>3.9.E+08</td>
<td>0.00136</td>
<td></td>
</tr>
<tr>
<td>Z=40</td>
<td>93Zr</td>
<td>3.10E-05</td>
<td>β⁻</td>
<td>1.61e6y</td>
<td>5.1.E+13</td>
<td>2.5.E+02</td>
<td>0.016(4.7%)</td>
<td></td>
</tr>
<tr>
<td>Z=40</td>
<td>95Zr</td>
<td>5.00E-06</td>
<td>β⁻</td>
<td>6.40d</td>
<td>5.5.E+06</td>
<td>3.7.E+08</td>
<td>0.756(54%)</td>
<td></td>
</tr>
<tr>
<td>Z=41</td>
<td>95Nb</td>
<td>4.90E-05</td>
<td>β⁻</td>
<td>3.50d</td>
<td>3.0.E+06</td>
<td>6.6.E+09</td>
<td>0.765(99.8%)</td>
<td></td>
</tr>
</tbody>
</table>

Amount of radio active waste after Phase I

<table>
<thead>
<tr>
<th>Weight (ton)</th>
<th>Main RI</th>
<th>Clearance level</th>
<th>After 50 years</th>
<th>After 100 years</th>
<th>After 150 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber</td>
<td>90</td>
<td>60Co</td>
<td>0.1 Bq/g</td>
<td>No</td>
<td>Disposal</td>
</tr>
<tr>
<td>Concrete base (upper 1m)</td>
<td>60</td>
<td>152Eu</td>
<td>-</td>
<td>120Bq/g</td>
<td>9.2Bq/g</td>
</tr>
<tr>
<td>Concrete of room wall</td>
<td>27000</td>
<td>152Eu</td>
<td>-</td>
<td>8.3Bq/g</td>
<td>0.63Bq/g</td>
</tr>
</tbody>
</table>

ILE, Osaka

Accumulation of long-life-time RIs in Phase I is acceptable.

Long-life-time RIs

BG radiation in Phase I 54Mn (3 × 10^{12} \text{Bq}) is the main element. The dose rate is estimated to be 10mSv/h.
Outline

• Introduction
  – Laser Fusion Experimental Reactor, LIFT

• Critical issue in Phase I
  – Heating efficiency
  – Radiation safety
  – Target stability
  – Beam steering
Scenario for fueling

Phase I

- Liquid N2
- Liquid He
- Vacuum vessel
- DT Pump
- Cooling zone: 20 K He 100 torr
- Loading zone: 19 K DT 128 torr
- Freezing zone: 19 K DT 128 torr, 10 K DT 1 torr
- Air lock
- 2nd Tritium barrier
- Laser
- Vacuum Pump
- TRS
- IS & Storage

Phase II and later

Osaka

n=20 x 80 (for 13 min at 2 Hz)

12 cm Air lock

TRS IS & Strage

Vacuum Pump

Vacuum vessel

To injector
Thermal cavitation technique enables batch filling

- Fill time by conventional diffusion is >24 h.
  Resulting large tritium inventory and accumulation of $^3\text{He}$
Loading of FI targets in sabots

Sabot loading section
(Similar system was proposed by E. Koresheva)
Large revolver allows sufficient time to cool
Injection system consists of gas gun followed by coil gun and tracking section.

Divergence of flight direction and tumbling of target must be experimentally checked.

- Injection velocity: 100 +/- 2 m/s
- Rep rate: 2 Hz
- Pointing: +/- 1 mrad
- Operation power including freezer: 500 kW
Real size injection system was constructed at ILE to check the stability of FI target after sabot release.
First campaign revealed “tumbling” is the issue.

V=88 m/s, P=10 Pa

<table>
<thead>
<tr>
<th></th>
<th>Velocity (m/s)</th>
<th>Pointing (mrad)</th>
<th>Tumbling (deg at Fire position)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final goal of gas gun</td>
<td>90+/-5</td>
<td>+/-1</td>
<td>+/- 2</td>
</tr>
<tr>
<td>Result</td>
<td>88+/-3</td>
<td>+/-0.6</td>
<td>5.4+/-6</td>
</tr>
</tbody>
</table>

ILE, Osaka

Piled contours of 10 shots at 1.7m from the muzzle
**Estimated angle at muzzle and release point**

In three cases, tumbling at muzzle was larger than observed.

<table>
<thead>
<tr>
<th></th>
<th>Observed at 1.72m</th>
<th>Estimated at muzzle</th>
</tr>
</thead>
<tbody>
<tr>
<td>130312-#1</td>
<td>+5.1 88.2 m/s</td>
<td>+2.8</td>
</tr>
<tr>
<td>130312-#2</td>
<td>+8.0 82.3 m/s</td>
<td>+5.3</td>
</tr>
<tr>
<td>130312-#3</td>
<td>+1.6 86.6 m/s</td>
<td>+4.1</td>
</tr>
<tr>
<td>130312-#4</td>
<td>+9.7 77.0 m/s</td>
<td>+6.9</td>
</tr>
<tr>
<td>130312-#5</td>
<td>+5.6 79.6 m/s</td>
<td>+3.3</td>
</tr>
<tr>
<td>130312-#6</td>
<td>+14 79.6 m/s</td>
<td>+16</td>
</tr>
<tr>
<td>130312-#7</td>
<td>+8.9 85.2 m/s</td>
<td>+8.9</td>
</tr>
<tr>
<td>130312-#8</td>
<td>+8.9 75.9 m/s</td>
<td>+6.6</td>
</tr>
<tr>
<td>130312-#9</td>
<td>-2.3 70.3 m/s</td>
<td>-5.4</td>
</tr>
<tr>
<td>130313-#1</td>
<td>-2.3 80.1 m/s</td>
<td>-0.1</td>
</tr>
</tbody>
</table>

88.2 m/s 82.3 m/s 87.4 m/s 77.0 m/s 79.6 m/s 79.6 m/s 85.2 m/s 75.9 m/s 70.3 m/s 80.1 m/s
To check the influence of B-field, plastic targets were injected.

**Experiment 1:** aluminum target → plastic target

Fig.5 Aluminum dummy target

Fig.6 Plastic dummy target

**Experiment 2:** stabilization by spin

Fig.7 Without B-field

Fig.8 With rotating B-field
Plastic dummy targets showed better repeatability in tumbling.
The absolute tumbling angle should be reduced.
(Final goal is +/- 2 degree)
Issue to be checked

- Is deceleration by eddy current unstable for FI target?
- In our calculation, 50 µm off-center between target and B field results in 108 deg tumbling at 10m from the muzzle.
- Next plan
  - Q pole layout where Bz=0 at the center
  - Helical layout to induce target spin
Summary

• To reduce the gap between single-shot, fusion burn and commercial reactor, Laser fusion experimental reactor LIFT with 3 phases was proposed.
  – Phase I, repeated fusion burns,( 1Hz 100 shots )
  – Phase II, power generation ( < 1 week)
  – Phase III long time operation (0.5 year)

• Critical issues in Phase I are the heating efficiency, tumbling of injected target, and dumping of steered mirror.

• Thank you for your attention!
Steering mirror will be driven with an array of PZT actuators. Response was confirmed with a small module.

Large Sized Steering Mirror

- Size: ~1m
- Mass: ~100 kg
- Moment: ~10 kgm²

Control signal $+V_y$

- $-V_x$
- $+V_x$

HV amp & driver

- Compensator

PZT-actuator array

He-Ne Laser

Al Mirror

940g

300mm

<table>
<thead>
<tr>
<th>Stroke/Distance</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I</td>
<td>±5mm/20m</td>
</tr>
<tr>
<td>Phase II</td>
<td>±5mm/20m</td>
</tr>
<tr>
<td>Phase III</td>
<td>±5mm/30m</td>
</tr>
</tbody>
</table>
The rise time met the requirement but the dumping was far from the goal.

- Over-shoot must be reduced to 1/100
- Improve support structure
- Mode analysis
Concept of beam steering by control of wave-front

LCOS-SLM by Hamamatsu Pho.

Present status: 16mm x 12mm

Demonstration using 100mm x 100mm device with high resolution is necessary.

For a compression beam, 8 x 8 = 64 modules are necessary.