Critical issues of laser fusion reactor KOYO-F

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Outline

• Introduction
  – Conceptual design reactor KOYO-F
• Issues on liquid wall
• Tritium control
• Issues on neutron damage
Reactor Design Committee was organized to clarify the feasibility of Laser Fusion Plant based on Fast Ignition by IFE Forum and ILE, Osaka University

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- Co-chair; Y. Kozaki (IFE, Forum)
  T. Norimatsu (ILE, Osaka)

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- T. Kawashima (HP),
- S. Matsuoka (HP),
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- H. Furukawa (ILT)

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- Y. Soman (Mitsubishi Heavy Ind.),
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- Y. Furukawa (ILT),
- Y. Sakawa (Nagoya Univ.),
- A. Sagara (NIFS),
- T. Norimatsu (ILE)

**Purpose**
1) to make a reliable scenario for the fast ignition power plant basing on the latest knowledge of elemental technologies,
2) to identify the research goal of the elements
3) to make the critical path clear.
KOYO-F is a fast-ignition, laser-fusion power plant with 4 modular reactors powered by 1.2 MJ, 16Hz, cooled-, Yb:YAG ceramic laser.

- Electric output power 1018MW
- Laser (1.1MJ+150kJ)x16Hz (13%) (5.4%)
- Target gain 148
- Fusion yield 200MJx16Hz
- Blanket gain 1.2
- Thermal efficiency 41%
- Circulating power for laser, 193MW
## Compression and heating lasers based on identical amplifier architecture

<table>
<thead>
<tr>
<th></th>
<th>Compression laser</th>
<th>Heating laser</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main pulse</strong></td>
<td>1.1 MJ</td>
<td>TBD</td>
</tr>
<tr>
<td><strong>Foot pulse</strong></td>
<td>TBD</td>
<td>150 kJ</td>
</tr>
<tr>
<td><strong>Energy/pulse</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Wavelength</strong></td>
<td>UV (3(\omega)) 343 nm</td>
<td>Visible (2(\omega)) 515 nm</td>
</tr>
</tbody>
</table>
| **Band width**      | Narrow band       | Broad band 1.6 THz | Broad band (rectangular pulse) 
|                     |                   | ~3 nm         |
| **Efficiency**      | Efficient         | Sacrifice of efficiency |
|                     |                   | (Sacrifice of efficiency) |
| **Laser material**  | Cooled Yb:YAG ceramic |               |
| **Method for**      | Arrayed beam with different wavelength ~0.1 nm@1030 nm (0.08 THz@343 nm) | Broad-band OPA pumped by 3\(\omega\), Spectral angular dispersion | Broad-band OPCPA pumped by 2\(\omega\) |

**Remark**
- OPA: optical parametric amplifier
- OPCPA: optical parametric chirped pulse amplifier
Why Cooled Yb:YAG?

Because there are dramatic improvements in:

1. Wide Tuning Range of Emission Cross Section (Saturation Fluence)
   Realize an efficient energy extraction without optics damages

2. 4-Level Laser System
   Enough Laser gain even in diode-pump

3. Improved Thermal Characteristics
   High average power operation
Cooled Yb:YAG ceramic is promising as the laser driver material.
We experimentally confirmed performance of cooled Yb;YAG

**Diagram:**
- Flat Output Coupler
- AO Q-switch
- Thin Film Polarizer
- R=2000 High Reflector
- LN$_2$ Cryostat
- Fiber-coupled Laser Diode
- Focusing Lenses
- Pump Power 123W

**Graphs:**
- Thermal Conductivity (W/m K) vs. Temperature (K)
  - 1% single
  - 0.7% ceramics
- $g_0$ vs. Crystal Temperature (K)
  - $g_0 = 8$ cm$^{-1}$ at 1.3 kW/cm$^2$
  - Dope: 25 at.%
  - Thickness: 1 mm
  - Calculation using the observed $\sigma_{em}$ and $\sigma_{ab}$

**Intensity vs. Position (mm):**
- Horizontal profile
- Gaussian fit
Experimental results obtained by HALNA-20 showed DPSLL is a powerful candidate for the reactor driver.

20J x 10Hz Diode pumped solid state laser HALNA-20
How to access reactor driver?
Key: cooling

- Current Nd glass, flush lamp, air, room temperature
  - 3 shot/ day \((9 \times 10^{-5} \text{Hz})\)
- Flush lamp \(\rightarrow\) LD  Spectrum fits to pump Nd, by 100
  - 1 shot / 1000 sec \((9 \times 10^{-3} \text{Hz})\)
- Glass \(\rightarrow\) Ceramic  Thermal conductivity, by 30
  - 1 shot / 30 sec \((0.03 \text{ Hz})\)
- Nd \(\rightarrow\) Yb  Quantum efficiency, by 3
  - 1 shot / 10 sec \((0.1 \text{Hz})\)
- 300K \(\rightarrow\) 200K  Thermal conductivity, by 3
  - 1 shot / 3 sec \((0.3 \text{Hz})\)
- Air cooling \(\rightarrow\) Freon  Cooling rate, by 100
  - 30 shot / 1 sec  \((30 \text{Hz})\)
- High shoot rate is possible!!!
Beam arrays of implosion and hearting lasers

**Compression laser beam (343 nm)**
- Foot pulse beam (515nm)
- 8x8 incoherent arrays
  - 80cm × 80cm, 32 beams
  - $\Delta \lambda = 0.1 \text{ nm} \quad @\text{fundamental} \quad (\Delta \nu = 0.08 \text{ THz})$

**Heating laser beam (1030 nm)**
- 210cm × 210cm,
  - 21x21 coherent arrays or 9 bundles of 7x7 coherent arrays
  - (Grating DT = 3 J/cm²)

Lasers
Illustration of main amplifier using active mirror concept

ILE, Osaka

Lasers

- Fiber Oscillator
- Pre-Amplifier (~kJ, NIR)
- Main-Amplifier (~MJ, NIR)
  - 3rd Harmonics
  - compression Laser (1.1MJ, blue, ns)
  - 2nd Harmonics
  - OPCPA
  - Pulse Stretcher
  - Heating Laser (0.1MJ, NIR, ps)

8x11 tiles for compression beam

- ~180K Coolant lines
- Cold trap
- Ceramic Yb:YAG on 200K panel
- Beam expander
- 60 kJ, 80cm x 80 cm output beam

10 m

60kJ x 8 beams
Large diameter laser beams will be distributed to 4 modular reactors using rotating corner cubes.
Cooling system with 2MW at 200K can be constructed with existing technology.

Image of 600kW, two coolants refrigerator*

Electric input power 3600+1500kW  
Cooling water 1300m³/h (32-37°C)  
Cooling power 2MW at 200K (δT=5K)  
Efficiency >30%  
Coolant R507A(High) + R23(Low)

This image was produced by Maekawa MFG. Co. LTD.
# Overall Efficiency from Electricity to Laser

## ILE, Osaka

<table>
<thead>
<tr>
<th></th>
<th>Implosion Laser</th>
<th>Heating Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Laser Power</strong></td>
<td>17.6 MW(1.1MJ, 16 Hz)</td>
<td>1.6 MW(0.1MJ, 16Hz)</td>
</tr>
<tr>
<td>LD Electrical – LD Optical</td>
<td>60%</td>
<td></td>
</tr>
<tr>
<td>LD Optical – $1\omega$</td>
<td>42%</td>
<td></td>
</tr>
<tr>
<td>LD Electrical – $1\omega$</td>
<td></td>
<td>25.2% (= 0.6 x 0.42)</td>
</tr>
<tr>
<td>$1\omega$ – $3\omega$</td>
<td>70%</td>
<td>-</td>
</tr>
<tr>
<td>$1\omega$ – $2\omega$</td>
<td>-</td>
<td>80%</td>
</tr>
<tr>
<td>OPCPA Eff.</td>
<td>-</td>
<td>40%</td>
</tr>
<tr>
<td>Pulse Compression Eff.</td>
<td>-</td>
<td>80%</td>
</tr>
<tr>
<td>Transportation Eff.</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Harmonic Generation and Transportaion</td>
<td>63%</td>
<td>23%</td>
</tr>
<tr>
<td>Electric Input Power</td>
<td>111 MW</td>
<td>27.6 W</td>
</tr>
<tr>
<td>Crystal Heating Power</td>
<td>7 MW</td>
<td>0.7MW</td>
</tr>
<tr>
<td>Cooler Electric Power</td>
<td>23 MW</td>
<td>2.1 MW</td>
</tr>
<tr>
<td>Electric Power Demands</td>
<td>134 MW</td>
<td>30 MW</td>
</tr>
<tr>
<td>Total Electric Power</td>
<td></td>
<td>164 MW</td>
</tr>
<tr>
<td><strong>Overall Efficiency</strong></td>
<td></td>
<td>12% (13% + 5.4%)</td>
</tr>
</tbody>
</table>
After fast ignition, share of lasers in the construction cost becomes minor.

Required laser energy became \( \frac{1}{4} \) after fast ignition.

Number of LDs became \( \frac{1}{3} \) after use of Cooled Yb:YAG

Central ignition KOYO

Fast ignition KOYO-F
Issue of KOYO-F

- Following issues remained because of limited data
  - Stability of LiPb flow
  - Chamber clearance
  - Tracking and beam steering
  - Tritium barrier in heat exchanger
  - Swelling of structural wall
  - Life of final optics
  - Control of impurity in LiPb
Collaborators

- After the Reactor design committee of KOYO-F (2004-2006), elemental researches on the critical issue of KOYO-F have been continued through bilateral collaboration of NIFS in Japan.

Many thanks to:
1. R. Tsuji, Ibaraki Univ. on tracking,
2. Y. Kajimura, JAXA, on beam port protection,
3. H. Yoshida, Gifu Univ. on beam steering,
4. T. Kunugi, Kyoto Univ. on liquid wall,
5. H. Furukawa, ILT Osaka, on chamber clearance,
6. T. Endo, Hiroshima Univ. on Injection,
7. S. Fukada, Kyusyu Univ. on Tritium issue.

Outline

• Introduction

• Issues on liquid wall
  – Stability of LiPb (by T. Kunugi)
  – Chamber clearance (by H. Furukawa)

• Tritium control

• Issues on neutron damage
Ablation depth and profiles of ablated plume obtained by simulation

Temporal profile of particle loads

Spatial profile of deposited energy

Volumetric heating
Bragg’s peak
Non-symmetric chamber with cascade flow of liquid LiPb

- **Dimensions**
  - Inner diameter 3m
  - Inner height 10m+3m

Fusion Yield: 200MJ/shot

Blanket: Liquid LiPb

First wall: Liquid LiPb
  - 5mm thick cascade flow on side wall
  - Thin laminar flow on ceiling

- **Serrated inner wall to prevent the stagnation of ablated materials.**
Cascade flow of KOYO-F

1) The height of cascade is 30 cm that comes from free fall distance in 0.25 sec (4Hz).
2) There is a void at the top of each step to obtain a stable flow.
Design base of mockup

- Water was used instead of liquid LiPb for visibility.
- The mockup was designed to obtain the same Weber number.

Reynolds number: \( \text{Re} = \frac{u \delta}{\nu} \)

Weber number: \( \text{We} = \frac{\rho u^2 \delta}{\sigma} \)

\[
\frac{\text{We}_{\text{water}}}{\text{We}_{\text{LiPb}}} = \frac{\sigma_{\text{LiPb}}}{\sigma_{\text{water}}} \frac{\rho_{\text{water}}}{\rho_{\text{LiPb}}} \left( \frac{u_{\text{water}}}{u_{\text{LiPb}}} \right)^2 = 1
\]

\[
\therefore \frac{u_{\text{water}}}{u_{\text{LiPb}}} = 1.21
\]
The height of the front panel is the same as actual reactor but the width is ¼ of KOYO-F.
A continuous flow was obtained if the thickness is $> 3$ mm.

1st and 2nd steps

3rd step

Numerical simulation
Mixing of hot surface flow with cold inner flow was experimentally confirmed.
To simplify protection scheme of ceiling, KOYO-F has vertically unsymmetrical configuration.

- The thermal load on the ceiling is close to that of a dry wall chamber. But blistering due to alpha particles seems critical. → We need a protective layer on the ceiling.
POP experiment was conducted at KYOTO university.

- In order to confirm the behavior of the liquid film formed on the ceiling of the reactor chamber, proof-of-principle (POP) experiments and numerical simulations were conducted regarding the liquid-film flow on the ceiling wall.

- In order to obtain information of the liquid-film flow, measurements were taken of the liquid-film thickness formed on the inclined wall surface by using a confocal laser scanning microscopy.
Procedures of condensation experiments

- In the actual design, the ceiling of the reactor chamber has the cone-type structure inclined at an angle of 45 degrees.

- Condensation experiments were conducted by using an inclined plate which was sloped at an angle of 45 degrees.

- Experimental conditions
  - Working fluid: Water
  - Material of the plate: Acrylic resin

- POP experiments regarding wettability

- Observation of the behavior when vapor was condensed on the surface of the inclined plate
Results of condensation experiments

Contact angle was **large** (=poor wettability)

1. Generation of many tiny droplets on the wall surface

   ![Image](image1)

   A few minutes

2. Grow and coalesce with surrounding droplets

   ![Image](image2)

   A few minutes

3. Flow down along the wall entraining surrounding droplets

   ![Image](image3)

   The liquid falling away from the wall surface was observed at third process

Contact angle was **small** (=good wettability)

1. Generation of many tiny droplets on the wall surface

   ![Image](image4)

   Several tens of seconds

2. Grow and coalesce into thin liquid film

   ![Image](image5)

   Several tens of seconds

3. Flow down along the wall surface

   ![Image](image6)

   The liquid never fell away from the wall surface at third process

> Once the liquid film is formed on the wall surface, the liquid will flow down along the ceiling wall and will not fall away from the wall surface as long as vapor will be supplied.
Procedures of measuring liquid-film thickness

- Contact angle was small (= good wettability)

- Measurements of the liquid-film thickness formed on the inclined wall surface were performed with a confocal laser scanning microscopy.

- Confocal laser scanning microscopy
  - Sampling frequency: 1000 Hz
  - Measurement accuracy: micro-meter order

- Distribution of liquid-film thickness obtained by traversing the microscopy in longitudinal and spanwise directions

Liquid film was transparent medium

Thickness of liquid-film could be obtained by measuring the distance between 2nd and 3rd peak of the light intensity
Results of measuring liquid-film thickness

接触角很小（= 良好的润湿性）

- 表面涂覆一次

平均厚度

<table>
<thead>
<tr>
<th>X(mm)</th>
<th>Y(mm)</th>
<th>0</th>
<th>30</th>
<th>60</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>152 μm</td>
<td>173 μm</td>
<td>154 μm</td>
<td>168 μm</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>150 μm</td>
<td>122 μm</td>
<td>128 μm</td>
<td>120 μm</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>135 μm</td>
<td>151 μm</td>
<td>141 μm</td>
<td>171 μm</td>
<td></td>
</tr>
</tbody>
</table>

- 总平均厚度：约150 μm

厚度为一层涂层约为50 μm，实际液体薄膜厚度约为100 μm

- 表面涂覆两次

平均厚度

<table>
<thead>
<tr>
<th>X(mm)</th>
<th>Y(mm)</th>
<th>0</th>
<th>30</th>
<th>60</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>210 μm</td>
<td>214 μm</td>
<td>213 μm</td>
<td>211 μm</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>202 μm</td>
<td>195 μm</td>
<td>194 μm</td>
<td>196 μm</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>199 μm</td>
<td>205 μm</td>
<td>200 μm</td>
<td>210 μm</td>
<td></td>
</tr>
</tbody>
</table>

- 总平均厚度：约200 μm

分布的平均厚度

- 大范围波动

- 小范围波动

ILE, Osaka

by T. Kunugi
Numerical simulations were performed with the STREAM, which was an unsteady 3D thermo-fluid numerical analysis code.

- Computational domain modeled on the test section inclined at an angle of 45 degrees
- Tiny droplets placed on the wall surface as an initial condition, in order to simulate the behavior of droplets and liquid film

**Numerical conditions**
- Analytical area: Hexahedron area of 1000 μm × 1500 μm × 500 μm
- Number of mesh: 50 × 75 × 25 = 93,750
- Size of mesh: 20 μm
- Temperature: 20°C
- Kind of fluids: Incompressible air and water
- Material of wall: Acrylic resin
- Flow field: Laminar flow in gravity field
- Interval time: $1.0 \times 10^{-5}$ sec
- Boundary conditions
  - Wall surface: No-slip condition
  - Both ends of X side: Free-slip condition (Symmetry plane)
  - Both ends of Y side and bottom of Z side: Outflow condition
Numerical results

➢ As an initial condition, tiny droplets were placed on the wall surface

Contact angle is large (45 degrees)

Tiny droplets coalesced into large droplet, and the large droplet flowed down along the wall surface

Contact angle is small (10 degrees)

Tiny droplets coalesced into thin liquid film, and the thin liquid film flowed down along the wall surface

The numerical simulations can retrieve the experimental results by T. Kunugi
Summary of POP experiment for protection of ceiling

- POP experiments and numerical simulations were conducted regarding the liquid-film flow on the ceiling wall.

- Once the liquid film is formed on the wall surface, the liquid will flow down along the ceiling wall and will not fall away from the wall surface as long as the vapor will be supplied.

- This experimental result indicated that a layer wettable with liquid LiPb is necessary on the ceiling.

- Future work
  - Erosion of the wettable layer
  - Life time of continuous layer after condensation of blast vapor

If \( \tau > 250 \text{ ms} \), it can work as protector.
Irradiation Intensities of $\alpha$ particles and Debris Ions at the surface of Liquid Wall

- When heating laser is irradiated on target,
- I set time = 0.

- Characteristic time in an ablation of liquid wall of laser fusion is roughly sub nano second.

- The physics in an ablation of liquid wall of laser fusion is quite different from that of burning plasmas and magnetically confinement fusion.
The simulation code covers microscopic energy deposition and macroscopic expansion processes.

**Atomic Process Code**

- Ionization Degree, Population, Energy Level
  - Stopping Power Code
  - EOS Code
  - Emmissivity and Opacity Code

- Stopping Power
  - Ionization Degree
  - Pressure, Specific Heat

**ACONPL (Ablation and CONdensation of a PLume)**

- Read data of Ionization degree, Specific heat, Pressure, Stopping power, Emmissivity and Opacity from table.
- Interaction between X-ray, α particles, Ion debris From burning plasmas and liquid metal, gas, and plasmas.
- Phase Transitions from liquid to gas (plasma)

**Phase Transition from plasma to gas to liquid** (Condensation, Clusterization)

**Hydrodynamics of gas (plasma)**

**Radiation transport of self X-ray**
Large clusters are formed near the surface. The peak of number density is at 0.3m form the surface when the plume front reaches the center.
2D calculation indicated that the mass toward the center is 1/10 of ablated vapor.

Due to energy deposition process of alpha particles, ablated vapor is accelerated from inside. As the result, instabilities happen.

Time integrated angular distribution of Ablated materials.

To chamber center
We estimated that possibility of collisions of aerosols is $1/100$

Spatial distribution of ablated materials at the first bounce.

Gas component makes a hot, dense peak at the center but most of aerosols pass through the core without collision. As the result, the stagnation and precipitation of ablated material seems not so critical.
After laser shot, the tip of beam port would be coated with a membrane of liquid LiPb due to condensation of evaporated LiPb but some protection scheme is necessary for long term operation.
Three dimensional hybrid code was used.

ILE, Osaka

Ions were treated as particles and electrons were treated as a fluid.

Equation of motion of ions

\[ m_i \frac{dv_i}{dt} = Ze(\mathbf{E} + \mathbf{v}_i \times \mathbf{B}), \quad \frac{dx_i}{dt} = v_i \]

Hydrodynamic equation of electrons

\[ n_e m_e \frac{dv_e}{dt} = -en_e (\mathbf{E} + v_e \times \mathbf{B}) - \nabla P_e \]

Faraday’s law

\[ \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \]

Ampere’s law

\[ \nabla \times \mathbf{B}_p = \mu_0 (\mathbf{J}_e + \mathbf{J}_i) \]

\[ \mathbf{J}_e = -en_e \mathbf{v}_e, \quad \mathbf{J}_i = en_i \mathbf{v}_i \]

- The electric field in plasma was calculated from motion of electrons and that in neutral region was calculated from Laplace equation.
Calculation model

Initial alpha particles

Beam port

Coil

N\alpha = 2.5 \times 10^{18} / m^3

V = 1.4 \times 10^6 m/s
Magnetic field is effective to reduce the alpha load on the tip of beam port.

- No influence on side wall of beam port
- Thermal load around the beam port was increased to 150% but this is acceptable.

Coil radius $r = 13 \text{ cm}$

$B = 0.9 \text{ T}$
Outline

• Introduction
• Issues on liquid wall
• Tritium control
  – Tritium barrier in heat exchanger
• Issues on neutron damage
Tritium diffusion through heat exchanger is critical issue of 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$_2$. 
With 12 lines for tritium trapping

Partial pressure of tritium in the trapping tube is assumed to be zero.

Tritium flux $1.06 \times 10^{16}$ atoms/m$^2$·sec
Heat flux $1.63 \times 10^5$ W/m$^2$
With 30 lines, tritium permeation was reduced to $2/10^5$ of base line tube.
Tritium flow after reduction of $1/10^5$

1.2 mg/s in highly concentrated tritium water

7 mg/s in vacuum

6 mg/s By target injection

Accumulation of tritium after 1 year full operation = 200MBq/cc
cf. tritium in Fugen (ATR) after 25 year operation 250MBq/cc
Summary of tritium barrier

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

- Introduction
- Issues on liquid wall
- Tritium control
- Issues on neutron damage
  - Concept for first structural wall
  - Final optics
How to deal with neutrons damage of the first structure wall?

- The neutron load on the first structure wall of KOYO-F is 40-70 dpa/y. So, swelling of the blanket wall is unavoidable.

To allow expansion, we keep gaps between cells and the cell is mounted on the frame at one fixed point and two sliding points. -> we expect 2 year continuous operation.
How to protect the final optics

- α particles, ions
- Neutral vapor
- Neutrons

Magnetic field
Synchronized rotating shutter and inert gas in beam duct
Distance
Neutron load on final optics of KOYO-F

- Compression beam (L=30m)
  \[2.5 \times 10^{12} \text{ n/s cm}^2 \cdot (8 \times 10^{23} \text{ n/m}^2\text{FPY})\]
- Ignition beam (L=15 – 25 m)
  \[5 \times 10^{12} - 1.5 \times 10^{13} \text{ n/s cm}^2\]

Fy=200MJx4Hz

65kJx4 Hz

2.5 \times 10^{12} \text{ n/s cm}^2

\sim0.7 \text{ dpa/y}

1\sim3 \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
  \[ \frac{I_{\text{in}}}{I_{\text{out}}} = 1 \times 10^{-19} \text{dB/cm/(n/cm}^2) \]

- Thickness of multilayer coating <10 $\mu$m
- Total absorption of laser light < 1kW (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.
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 multicoated mirror seems inappropriate.
- Conventional GIMM and GILMM*¹ are also critical due to bent of base frame.

Because of low damage threshold, metal mirror becomes big.


## Neutron damages on glass lense and metal mirror

<table>
<thead>
<tr>
<th>Defects and size</th>
<th>Defect source</th>
<th>Effect on laser beam</th>
<th>When defects appear?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lenses</td>
<td>Collision</td>
<td>Increase of absorption</td>
<td>Life: 5 min for 3cm thick optics</td>
</tr>
<tr>
<td>Defect in grid (Color center)</td>
<td>Sputtering</td>
<td>No influence</td>
<td></td>
</tr>
<tr>
<td>$\lambda_{\text{defect}} &lt; \frac{1}{10} \lambda_{\text{laser}}$</td>
<td>Blistering by He</td>
<td>Scattering</td>
<td>$&gt;1 \text{ dpa, 1 year}$</td>
</tr>
<tr>
<td>Mirror</td>
<td>$\lambda_{\text{defect}} = \lambda_{\text{laser}}$</td>
<td>Swelling of structure by He</td>
<td>Defocusing</td>
</tr>
<tr>
<td>$\lambda_{\text{defect}} &gt; 10 \lambda_{\text{laser}}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Swelling of support frame would increaser the focusing size. Estimated life time of GIMM is 1 year.
Level, Grazing Incident Liquid Metal Mirror* will be used for 150kJ/30ps heating laser.

Shallow liquid metal pool

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

This concept can equalize deformation of frame.

Summary 1
Issue of KOYO-F and the current solution

• Stability of liquid flow
  – Cascade flow. OK
  – If wettable Ceiling, OK

• Tracking and beam steering
  – Tracking, OK
  – Damping of large mirror to be studied.

• Life of final optics
  – Implosion beam OK by replacing them every 4 M.

• Tritium barrier in heat exchanger
  – $\text{Er}_2\text{O}_3$ coating + double tube concept +TRS in the 2$^{\text{nd}}$ loop

• Swelling of structural wall
  – Scale scheme for blanket cell
  – Textile blanket wall

• Impurity control in LiPb
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** Ignition and burn
- **FIREX-II** Optimization of Ignition and burn
- Hating to ignition temperature

- **Repeated burn** 10 MW Power to net
- **10kJ/1Hz** Laser Inertial Fusion Test i-LIFT
- **600kJ/1Hz** solid/liquid wall test

**Elemental development** 100J/1Hz
- Driver development
- Single 10 min burst, Target injection, tracking and beam steering
- Continuous op. Life System integration for DEMO

**Cost:**
- Laser Inertial Fusion Energy DEMO
  - Cost: 3000~4000M$

**Cost:**
- Laser Inertial Fusion Test i-LIFT
  - Cost: 2000~3000M$

**Reactor materials, ITER R&D results**
Thank you for your attention!