Fast ignition Laser Fusion Reactor KOYO-F
- Summary from design committee of FI laser fusion reactor -

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IFE Forum

Presented at US-Japan workshop on Power Plant Studies and related Advanced Technologies with EU participation
After the Roadmap committee, we organized a conceptual design committee to make the issue clear. In total, 34 working group meetings were held from March 2004 to Sep. 2005.

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The committee is supported by IFE Forum and ILE, Osaka Univ.
Outline

• **Introduction**
  – Fast ignition
  – Gain estimation and the emission

• Chamber and plant system
• Laser system
• Fueling system
Fast ignition is attractive, because the gain is high with a small laser.

Processes for compression and ignition are separated.

Fast heating needs petawatt laser. Critical issue is relativistic dense electron dynamics.
FIREX-1 project has been started to demonstrate $Ti = 5$ keV.
600 times liquid density and 1keV heating have been demonstrated.
Two-D simulation checked by implosion experiments at Rochester Univ. indicated that high density compression of reactor-scale, cone target is possible.

One of key requirements to start FIREX-II is satisfied.
Although dynamics of cone-guided implosion is quite different from conventional spherical one, high $\rho R$ for ignition can be achieved.

- Existence of the cone causes non-symmetric slip boundary ablating plasma.
- Implosion velocity
- Shock hits the surface of the cone
- Timing of maximum density
- Hot spot
High gain will be achieved by increasing the laser energy at the same intensity.

FIREX-I  $Q \sim 0.1$

FIREX-II  $Q \sim 8$

Demo  $Q \sim 150$
By increasing the core size, high gain will be achieved.

ILE, Osaka
Fast Ignition Gain Performance

$\rho = 300\text{g/cc}, \alpha = 2 \text{ and } 3$

Energy coupling; $\eta_{\text{imp}} = 5\%$ for implosion & $\eta_{\text{heat}} = 30\%$ for core heating

In high gain region, target gain considerably decreases with increasing adiabat $\alpha$.
Outline

- Introduction
- Chamber and plant system
  - Chamber structure
  - Pumping
  - Protection of final optics
- Laser system
- Fueling system
KOYO-F with 32 beams for compression and one heating beam

- Vertically off-set irradiation
- Cascade surface flow with mixing channel
- SiC panels coated with wetable metal
- Tilted first panels to make no stagnation point of ablated vapor
- Compact rotary shutters with 3 synchronized disks
The surface flow is mixed with inner cold flow step by step to reduce the surface temperature.
Thermal flow of KOYO-F
(One module)

300 MWe

Water cycle

Turbin

SG

904MW

300 °C

F2+F3 (80cm)
12.84 ton/s
Average flow 7.8 cm/s

F1 (20cm)
8.56 ton/s
Average flow 24.3 cm/s

500 °C

Flow rate 21.4 ton/s

50MW

70MW

70MW

80MW

80MW

200MJ/shot x 4Hz

η_{ther-elec} = 30%

η_ther-elec = 30%
# Specification of KOYO-F

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net output</td>
<td>1200 MWe (300 MWe × 4)</td>
</tr>
<tr>
<td>Laser energy</td>
<td>1.1 MJ</td>
</tr>
<tr>
<td>Target gain</td>
<td>165</td>
</tr>
<tr>
<td>Fusion pulse output</td>
<td>200 MJ</td>
</tr>
<tr>
<td>Reactor pulse rep-rate</td>
<td>4 Hz</td>
</tr>
<tr>
<td>Blanket energy multiplication</td>
<td>1.2</td>
</tr>
<tr>
<td>Reactor thermal output</td>
<td>916 MWth</td>
</tr>
<tr>
<td>Total plant thermal output</td>
<td>3664 MWth (916 MWth × 4)</td>
</tr>
<tr>
<td>Thermal electric efficiency</td>
<td>41.5 % (LiPb Temperature ~500 C)</td>
</tr>
<tr>
<td>Total electric output</td>
<td>1519 MWe</td>
</tr>
<tr>
<td>Laser efficiency</td>
<td>11.4 % (implosion), 4.2 % (heating), total 8%</td>
</tr>
<tr>
<td>Laser pulse rep-rate</td>
<td>16 Hz</td>
</tr>
<tr>
<td>Laser recirculating power</td>
<td>240 MWe (1.2 MJ × 16 Hz / 0.08)</td>
</tr>
<tr>
<td></td>
<td>Yb-YAG laser operating 150K or 220K</td>
</tr>
<tr>
<td>Total plant efficiency</td>
<td>32.8 % (1200 MWe / 3664 MWth)</td>
</tr>
</tbody>
</table>
Estimation of Output Energy Structure
200MJ output (~1.2MJ driver; 1.14MJ imp + 71.5kJ heat) Case

(a) Output Power and Energy Spectrum of \( \alpha \)-particles leaking from each boundary (① ~ ④)
(b) Output Power of Radiation leaking from each boundary (① ~ ④)
(c) Output Power of Debris (thermal + Kinetic) leaking from each boundary (① ~ ④)
Summary of Burn Properties
Input and output energies [MJ] for ~ 200MJ output case

<table>
<thead>
<tr>
<th></th>
<th>Energy [MJ]</th>
<th>Heating side (①)</th>
<th>Opposite side (④)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver Energy※1</td>
<td>1.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Implosion</td>
<td>1.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating</td>
<td>0.0715</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fusion [MJ]</td>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carried out by</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutron※2</td>
<td>160 (80.0%)</td>
<td>12.7 MJ/str</td>
<td>12.7 MJ/str</td>
</tr>
<tr>
<td>Alpha※3</td>
<td>11.8 (5.9%)</td>
<td>1.31 MJ/str</td>
<td>0.67 MJ/str</td>
</tr>
<tr>
<td>Debris※4</td>
<td>19.4 (9.7%)</td>
<td>2.26 MJ/str</td>
<td>1.34 MJ/str</td>
</tr>
<tr>
<td>Radiation</td>
<td>1.85 (0.9%)</td>
<td>0.12 MJ/str</td>
<td>0.15 MJ/str</td>
</tr>
<tr>
<td>Error</td>
<td>6.9 (3.4%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gain</td>
<td>165</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

※1 The energy coupling efficiencies of 5% and 30% were assumed for implosion and core heating, respectively.
※2 Neutrons were assumed to be freely and isotropically escaped from the core.
※3 Alpha particle: Leakage/Source = 29.8% (70.2% is deposited inside the core.)
※4 Constitution (energy D:35.5%, T:49.9%, α:14.3% / Number D:43.6%, T:44.5%, α:11.5%)
The speed of ablated vapor 500 m/s at higher density region and 4000 m/s at the front.

(This work is on the way. Depends on the model for stopping range.)
Total mass of ablated materials was 6.2 kg/shot including oblique-incidence effect.
Lot of 0.1 \( \mu m \) radius clusters are formed after adiabatic expansion.

(Luk’yanchuk, Zeldovich-Raizer Model)
Future work: Hydrodynamic simulation including phase change is necessary to discuss the formation of aerosol.

Jet formation

Size of evaporated vapor in flight

RT instabilities would form larger particles. -->
Four Pb diffusion pumps will be used to keep the chamber less than 5 Pa.
A set of 3 rotary shutters and buffer gas will be used to protect the final optics from the bluster wave.

- 1st shutter: 32 rps
- 2nd shutter: 16 rps
- 3rd shutter: 4 rps

Potential effects:
- Miss fired target
- Target injection
- Blaster waves
- Charged particles from plasma: 1 - 2 μs
  - Alpha: 0.2 - 0.4 μs
  - X-rays: 10 ns
- Vapor
- Gas temperature (Local peak)
- Gas temperature (Local peak) @ 20,000K
- 1st bluster wave from the wall: v=3,000 m/s
- 2nd shot: v=150 m/s
- Temperature of inner surface (K)
- Wall surface
- Hole on 1st disk
- Hole on 2nd disk
- Hole on 3rd disk
- Gas temperature
- Temperature of inner surface
- Blaster waves
- Charged particles from plasma
- Alpha
- X-rays
- Vapor
Vapor coming into the beam duct can be stopped with 0.1Torr D$_2$ buffer gas.

- The speed of vapor is decelerated from 100 m/s to 30 m/s before the plume breaks due to RT instabilities.

- Mass of Pb vapor coming into the beam duct is 10mg/shot, that means 1 ton/year! Periodic cleaning is necessary.
Outline

• Introduction
  – Fast ignition
  – Core plasma
• Chamber and plant
• Laser system
  – Cooled, ceramic Yb:YAG
  – Beam distributor
• Fueling system
**Key technologies of laser for FI fusion plant**

**Foot pulse** to form pre-plasma  
- 32 beams  
- Controlled focus pattern  
- $2\omega$  
- wide band  
- coherent during amplification  
- in-coherent at focus point

**Main pulse for compression**  
- 32 beams  
- Controlled focus pattern  
- $3\omega$  
- wide band  
- coherent during amplification  
- low-coherent at focus point

**Common technologies for compression and heating lasers**  
- main amplifier  
  - laser material, LD  
  - Structure, optical shutter  
- beam switching  
  - Laser: 16Hz, reactor: 4Hz  
- Optics with multi-coating

**Heating pulse**  
- 1 beam  
- coherently bundled  
- $\omega$  
- wide band  
- OPCPA  
- Pulse compression  
  - Grating
<table>
<thead>
<tr>
<th></th>
<th>Compression laser</th>
<th>Heating laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave length</td>
<td>3ω</td>
<td>ω</td>
</tr>
<tr>
<td>Energy/pulse</td>
<td>1.1 MJ</td>
<td>100 kJ</td>
</tr>
<tr>
<td>Pulth width</td>
<td>TBD</td>
<td>30 ps</td>
</tr>
<tr>
<td>Pulse shape</td>
<td>Foot pulse + Main pulse</td>
<td>Flat top (2 ps reise time)</td>
</tr>
<tr>
<td>Beam number</td>
<td>32</td>
<td>1 bundle</td>
</tr>
<tr>
<td>F number</td>
<td>depends on plant design</td>
<td>F/10～20</td>
</tr>
<tr>
<td>Uniformity</td>
<td>1 % (foot pulse)</td>
<td>-----</td>
</tr>
<tr>
<td>Spot size</td>
<td>Controlled focusing pattern</td>
<td>≤ 50 µm</td>
</tr>
<tr>
<td>Rep-rate</td>
<td>16 Hz</td>
<td>16 Hz</td>
</tr>
</tbody>
</table>
Cooled Yb:YAG was chosen for the laser material.

<table>
<thead>
<tr>
<th></th>
<th>Compression laser</th>
<th>Heating laser</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main pulse</td>
<td>Foot pulse</td>
</tr>
<tr>
<td>Wavelength</td>
<td>UV (3ω) 343 nm</td>
<td>Visible (2ω) 515 nm</td>
</tr>
<tr>
<td>Bund width</td>
<td>Narrow band</td>
<td>Wide band 1.6 THz</td>
</tr>
<tr>
<td>Efficiency</td>
<td>8 - 10 %</td>
<td>Not so important</td>
</tr>
<tr>
<td>Laser material</td>
<td>Cooled Yb:YAG ceramic</td>
<td></td>
</tr>
<tr>
<td>Method for wide band</td>
<td>Arrayed beams with different wave length</td>
<td>One beam of arrayed beams</td>
</tr>
<tr>
<td></td>
<td>~0.1 nm@1030 nm (0.08 THz@343 nm)</td>
<td>Wide band OPA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pump light: 3w</td>
</tr>
<tr>
<td></td>
<td></td>
<td>band width=100nm</td>
</tr>
</tbody>
</table>

OPA: Optical Parametric Amplification
OPCPA: Optical Parametric Chirp Pulse Amplification
Characteristics of Nd:YAG and Yb:YAG as materials for high power laser

Advantage of Yb:YAG

- Close wavelength of oscillating light to pumping light
  \(\Rightarrow\) low heat generation
- Long fluorescent life time of upper level
  \(\Rightarrow\) easy to store energy
- Wide absorption spectrum
  \(\Rightarrow\) easy to pump with LD
- Wide fluorescent spectrum
  \(\Rightarrow\) short pulse amplification

Disadvantage

- Small cross section for stimulated emission
  \(\Rightarrow\) high saturation flounce
- Quasi three level system
  \(\Rightarrow\) energy loss due to re-absorption
Why cooled Yb:YAG?

Disadvantage

- Small cross section for stimulated emission
  ⇒ high saturation fluencies
- Quasi 3 level system
  ⇒ Gain loss due to reabsorption

Larger cross section for stimulated emission
 ⇒ Lower saturation fluence

Four level system
 ⇒ Higher efficiency with low pumping

Higher thermal conductivity
 ⇒ Smaller thermal strength

⇒ Appropriate characteristics for high intensity, average power laser
Cooled Yb:YAG ceramic is promising as the laser driver material.
Demonstration of high efficiency by cooling

**Opt-Opt conversion efficiency 74%**

- Output coupler (ROC 40mm)
- Pumped area: 230 µm, 1.4 kW cm²
- LD for pumping: 940nm 580mW
- Yb:YAG: 10 180K

**Diagram:**
- Quasi 3 level system
- 4 level system
- Optical–optical efficiency
- Threshold power vs. Temperature
- Room Temp. vs. <100K
We demonstrated high beam quality ($M^2 < 1.4$).

**Beam quality $M^2 < 1.4$**

- **M** = \[ \frac{\text{Experimental focusable spot size}}{\text{Ideal focusable spot size of Gaussian beam}} \]
Estimation of laser efficiency

Implosion laser:
Total efficiency: 11.4%
LD eff. = 60%, optical-optical eff. = 30%, (@160K)
THG eff. = 70%, transfer eff. = 90%

Heating laser:
Total efficiency: 4.2%
LD eff. = 60%, optical-optical eff. = 30%, (@160K)
SHG eff. = 80%, OPCPA eff. = 40%,
compressor eff. 80%, transfer eff. = 90%

Cooling of amplifier:
Thermal load of 5% of electric input power to LD
Cooling efficiency = 30% (safely assumed, 60%@160K)

Total efficiency of laser system includig refriierator= 8.7%
(9.2%)

- Supplementary power supply (air conditioner, etc.) is excluded
  in this estimation.
- Improvement of optical-optical eff. is needed.
Cooling efficiency of large, industrial refrigerator

Cooling efficiency of 10kW-class refrigerator

![Graph showing cooling efficiency vs temperature](chart.png)
Cooled Yb:YAG has potential to achieve 20% in electricity to laser efficiency.

More explore is necessary in:

- efficiency of refrigerator,
- coolant,
- cross section for stimulated emission,
- $\delta T/T$
- total cost of optics.
Candidates for amplifier architecture

Active mirror is practical for arrayed large-aperture amplifier.
Illustration of main amplifier using active mirror concept

8 beams
(1/4 of a plant)
Beam arrays of implosion and hearting lasers

Compression laser beam (343 nm)
- $\Delta \lambda = 0.1$ nm
- @ fundamental
- $\Delta \nu = 0.08$ THz
- 8x8 incoherent arrays
- 80cm $\times$ 80cm, 32 beams
- (DT = 10 J/cm²)

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

Foot pulse beam (515 nm)
- Absorber
Beam distributor

Laser beams will be distributed into 4 module reactors using either rotating corner cubes or plasma electorode optical switchs.
Outline

• Introduction
• Chamber and plant
• Laser system
• Fueling system
  – Target design
  – Status of fabrication
  – Batch process
### Target for KOYO-F

#### Basic specification
- **Compression laser**: 1.1 MJ
- **Heating laser**: 70kJ
- **Gain**: 165
- **Fusion yield**: 200MJ

#### Fuel shell
- DT(gas) (<0.01mg/cc): 1,500 µm
- DT(Solid) (250mg/cc+10mg/cc Foam): 300 µm
- Gas barrier (CHO, 1.07g/cc): 2 µm
- CH foam insulator (250mg/cc): 150 µm
- Outer diameter: 1,952 µm
- Mas of fuel: 2.57mg
- Total Mas of shell: 4.45mg

#### Cone
- **Material**: Li17Pb83
- **Length**: 11mm
- **Diameter**: 5.4 mm
- **Mas**: 520 mg

---

![Diagram of the target](image-url)
The cone works as a focusing device of the heating laser.

- Heating laser must be focused on a 30µm diameter spot.
- Heating laser
  - Beam size: 2 m x 2 m
  - Distance between target and focusing mirror ≈ 50 m
- Accuracy of target injection is not known.

→ **Assistant focusing mechanism is necessary.**

<table>
<thead>
<tr>
<th>On axis irradiation</th>
<th>30 µm shifted irradiation</th>
</tr>
</thead>
</table>

![Diagram](image)
Mass production of target is remaining issue but the elemental researches are promising.
Low density foam is the key of FI target.

- When the foam density is 10 mg/cc, the energy of heating laser is increased from 50 kJ to 55 kJ.
- Our final goal is to develop 10mg/cc foam shells. (Our achieved data, 43 mg/cc for shell and 5 mg for block)

Driver Energy for Core Heating,

(By Dr. Johzaki et al)
Fuel loading system by thermal cavitation method.

ILE, Osaka

n=20 x 80 (for 3 min at 2 Hz)

Air lock

Cooling zone
20 K He
100 torr

Loading zone
19 K DT
128 torr

Freezing zone
19 K DT
10 K DT
128 torr
1 torr

Liquid N2

Liquid He

Vacuum vessel

DT Pump

2nd Tritium barrier

Vacuum Pump

TRS

IS & Strage

Laser

To injector

Tritium inventory
100g

Not to scale
Step 1  Saturation of foam with liquid DT
Step 2  Evacuation by laser heating
Step 3 Finish
Hybrid injector for KOYO-F

Injection velocity 300+/-2 m/s
Rep rate 2 Hz
Pointing +/- 1 mm
Operation power including freezer 500 kW
Correlational detection by matched filter

Fourier conv. lens $f=5000$

Inv. Fourier conv. Lens $f=500$

He-Ne laser

Opt. Wedge

BE

3572

M

2mm

5.8mm

cone-target

Matched filter

CCD camera

1mm
Accuracy of detection was 140 µm at 5 m apart.

The accuracy will be improved with uniform irradiation, f-number, linearity of film to make filter.
Summary

1) We have examined the design windows and the issues of the fast ignition laser fusion power plants. ~1200 MWe modular power plants driven at ~16 Hz

2) For laser driver we have considered the DPSSL design using the Yb:YAG ceramic operating at low temperature (100~200K).

3) We have proposed the free fall cascade liquid chamber for cooling surface quickly enough to several Hz pulses operation by short flow path. The chamber ceiling and laser beam port are protected from the thermal load by keeping the surface colder to enhance condensation of LiPb vapor.

4) For exhausting DT gas mixed with LiPb vapor we have designed diffusion pumps using Pb (or LiPb) vapor with effective exhaust velocity about 8 m³/s DT gas.

5) For protecting final optics we have considered the combinations of rotary shutters for stopping neutral vapors and magnets for eliminating ions.
Future work

• Core plasma
  – Specification for lasers
  – Control of isentrope
• Laser
  – Frequency conversion
  – Phase control
• Reactor system
  – Stability of surface flow
  – Accuracy of injection
  – Tracking and beam steering
  – System integration
• Target
  – Low density foam
  – Accuracy ± 1 %