Critical Issue in KOYO-F Design

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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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### 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.
# Basic specification of KOYO-F

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net electric output</td>
<td>1283 MWe (320 MWe x 4)</td>
</tr>
<tr>
<td>Electric output from one module</td>
<td>320 MWe</td>
</tr>
<tr>
<td>Target gain</td>
<td>167</td>
</tr>
<tr>
<td>Fusion Yield</td>
<td>200 MJ</td>
</tr>
<tr>
<td>Laser energy/Beam number</td>
<td>1.2 MJ (Compression=1.1MJ/32beams, Heating=100kJ/beam)</td>
</tr>
<tr>
<td>Laser material/Rep-rate</td>
<td>Cooled Yb:YAG ceramics at 150~220K/16 Hz</td>
</tr>
<tr>
<td>Chamber structure/Rep-rate at module</td>
<td>Cascade-type, free-fall liquid LiPb wall/4 Hz</td>
</tr>
<tr>
<td>Fusion power from a module</td>
<td>800 MWth</td>
</tr>
<tr>
<td>Blanket gain</td>
<td>1.2 (design goal)</td>
</tr>
<tr>
<td>Total thermal output from a module</td>
<td>916 MWth</td>
</tr>
<tr>
<td>Total thermal output from a plant</td>
<td>3664 MWth (916 MWth x 4)</td>
</tr>
<tr>
<td>Heat-electricity conversion efficiency</td>
<td>41.5% (LiPb Temperature 500℃)</td>
</tr>
<tr>
<td>Gross electric output</td>
<td>1519 MWe</td>
</tr>
<tr>
<td>Laser efficiencies</td>
<td>13.1% (compression), 5.4% (heating), Total 11.8% (including cooling power)</td>
</tr>
<tr>
<td>Recirculating power for laser</td>
<td>164 MWe (1.2 MJ x 16 Hz / 0.118)</td>
</tr>
<tr>
<td>Net electric output/efficiency</td>
<td>1283 MWe (1519 MWe - 164 MWe - 72 MWe Aux.) / 32.7%</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)
Conclusion of design committee

- 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) We concluded that such power plant can be constructed with improving current technologies and existing materials.

Our discussion based on limited data available now and left some important issue to be discussed.
What is the critical issue?

• Core plasma
  – High density compression of cone target.
  – Heating efficiency of 30% (absorbed energy in the core / ignition laser energy)
  – Adiabat a <2.5 (internal energy of compressed core / that of isothermally compressed core)

• Laser system
• Target Fabrication
• Chamber system
The detail physics of the Fast Ignition are investigated with computational simulations

**Simulation of non-spherical implosion for FIREX-I experiment (by PINOCO-2D)**

CH-DT shell target with gold cone is imploded by GXII laser. Even though, initial perturbation exists on the target surface, high density core plasma is formed.

- **w/O initial perturbation**
- **w/ initial perturbation**

**Generation of high energy electron (by FISCOF2D)**

Magnetic field in the cone geometry. The hot electrons are transported along cone surface guided by static magnetic and electric field.

Electron spectrum generated by the laser plasma interaction in the cone geometry

**Heating of core plasma by the high energy electrons is simulated (by FIBMET)**

In this simulation, initial condition of core plasma is determined by the implosion simulation, PINOCO-2D. Boundary condition of Input hot electron is determined by FISCOF2D. Temporal profiles of bulk-electron and ion temperatures averaged over the dense core region \((r > 10\text{g/cc})\) obtained for the three different REB conditions \((n_{e,\text{rear}} = 2, 10 \text{ and } 100 n_c)\)
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 ablated plasma
- implosion velocity
- shock hits the surface of the cone
- timing of maximum density
- hot spot

$\rho R = 2.4\text{g/cm}^2$
Actual energy and power of heating laser required for fast ignition after S. Atzeni, (Phy. Plasmas’99)

Assuming high energy electron range; $\rho d = 0.6 \text{ g/cm}^2$

- $E_h = 140\left\{\rho/(100\text{ g/cc})\right\}^{-1.85} \text{ kJ}$
- $P_b = 2.6\left\{\rho/(100\text{ g/cc})\right\}^{-1.0} \text{ PW}$
- $I_b = 2.4\times10^{19}\left\{\rho/(100\text{ g/cc})\right\}^{0.95} \text{ W/cm}^2$
- $r_b = 60\left\{\rho/(100\text{ g/cc})\right\}^{-0.975} \mu\text{m}$

We assumed 30% of laser energy is absorbed in 30-μm-radius, 100-μm-long core. In this case, required laser energy for high gain is $E_L = 60 - 100 \text{ kJ}$. 

Driver Energy for Core Heating,
Fast Ignition Gain Performance

\[ \rho = 300 \text{g/cc}, \]

Energy coupling: \( \eta_{\text{imp}} = 5\% \) for implosion & \( \eta_{\text{heat}} = 30\% \) for core heating

Pulse width of >10 ps would be accepted for the heating laser. This result relaxes requirements for heating laser. We can use transmitting optics.
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) 1,500µm
DT(Solid) (250mg/cc+10mg/cc Foam) 300µm
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
Issues toward high gain

- Can we achieve low adiabat $\alpha$?
  - Current experiments $\alpha > 2.4$
  - Pulse control is necessary.

- Can we deposit 20-30% heating laser energy in a 60 $\mu$m diameter x 100 $\mu$m area?
  - Current theory 15-20%
What is the critical issue?

- Core plasma
- Laser system
  - Construction of laser itself seems possible with existing technology.
  - Beam steering of ignition beam may be critical.
- Target Fabrication
- Chamber system
## 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></td>
<td>Main pulse</td>
<td>Foot pulse</td>
</tr>
<tr>
<td>Energy/pulse</td>
<td>1.1 MJ</td>
<td>TBD</td>
</tr>
<tr>
<td>Wavelength</td>
<td>UV (3ω) 343 nm</td>
<td>Visible (2ω) 515 nm</td>
</tr>
<tr>
<td>Band width</td>
<td>Narrow band</td>
<td>Broad band 1.6 THz</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Efficient</td>
<td>Sacrifice of efficiency</td>
</tr>
<tr>
<td>Laser material</td>
<td>Cooled Yb:YAG ceramic</td>
<td></td>
</tr>
<tr>
<td>Method for broad band</td>
<td>Arrayed beam with different wavelength ~0.1 nm@1030 nm (0.08 THz@343 nm)</td>
<td>Broad-band OPA pumped by 3ω, Spectral angular dispersion</td>
</tr>
</tbody>
</table>

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
Overall Efficiency
from Electricity to Laser

<table>
<thead>
<tr>
<th></th>
<th>Implosion Laser</th>
<th>Heating Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Power</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></td>
<td></td>
</tr>
<tr>
<td>LD Optical – $1\omega$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LD Electrical – $1\omega$</td>
<td></td>
<td>25.2% ($= 0.6 \times 0.42$)</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 Transportation</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>Overall Efficiency</td>
<td></td>
<td>12% (13% + 5.4%)</td>
</tr>
</tbody>
</table>
Beam arrays of implosion and hearting lasers

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

**Heating laser beam (1030 nm)**
- 210cm x 210cm
- 21x21 coherent arrays or 9 bundles of 7x7 coherent arrays
- (Grating DT = 3 J/cm²)
- Foot pulse beam (515 nm)

- (DT = 10 J/cm²)
Illustration of main amplifier using active mirror concept

Lasers

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

8x11 tiles for compression beam
~180K Coolant lines
Ceramic Yb:YAG on 200K panel
Cold trap
Beam expander
Faraday Rotator
60 kJ, 80cm x 80 cm output beam

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.

Electric input power  
3600+1500kW

Cooling water  
1300m$^3$/h (32-37°C)

Cooling power  
2MW at 200K  
($\delta T=5K$)

Efficiency  
>30%

Coolant  
R507A (High) + R23 (Low)

Image of 600kW, two coolants refrigerator*

This image was produced by Maekawa MFG Co. LTD.
Issue in Laser System

- Steering system of Heating Laser
  - Mirror radius 1.5m
  - Time response <10ms
  - Steering angle 1mrad

These requirement will be achieved using a honeycomb mirror driven with PZTs. However…..
Stability?
Influence of neutrons on PZT?
What is the critical issue?

- Core plasma
- Laser system
- Target Fabrication
  - Low density foam, cone with LiPb
  - Accuracy for the initial $\rho R/I_{laser}$
- Chamber system
ターゲットの大量生産、フォームの低密度化については今後の課題。
Fuel will be loaded by dipping shells in liquid DT and heat them to evacuate the central voids.

- This technique enables fuel just in the foam layer without feedback control.

- Necessary condition
  Diameter of foam shell $> >$ diameter of vent port $> >$ diameter of feeder port $> >$ diameter of foam cell.

\[
\frac{2\gamma}{R_h} = \rho gh
\]
Step 1  Saturation of foam with liquid DT
Step 2  Evacuation by laser heating
インジェクター1基あたりのトリチウム必要量は約100g。
Hybrid injector for KOYO-F

Injection velocity: 300+/-2 m/s
Rep rate: 2 Hz
Pointing: +/- 1 mm
Operation power including freezer: 500 kW
Critical issue in target fabrication
Can we make low density foam?

- 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)
Critical issue in target fabrication
Shot to shot variation

- Implosion time 12 ns
- High $\rho R$ time 0.2 ns (1.7% of implosion time)
- This means shot to shot variation in the laser power and target mass must be less than 1%.

Can we control the fuel mass with the accuracy of +/- 1%?
What is the critical issue?

• Core plasma,
• In the laser system

• Target Fabrication
• Chamber system
  – Protection of beam port
  – Chamber clearance
  – Tritium confinement
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 panel to make no stagnation point of ablated vapor
- Compact rotary shutters with 3 synchronized disks
Thermal flow of KOYO-F

δt=0.5 °C/shot  δt=1.3 °C/shot
The surface flow is mixed with inner cold flow step by step to reduce the surface temperature.
To prevent stagnation of ablated LiPb, front panels were tilted by 30 degree.

Cone type ceiling

Tilted front panels

Position of mass center of ablated vapor
We estimated the ablation process using ACORE. Stopping power in ionized vapor was calculated.

Ziegler’s model

\[
\frac{dE}{dx} = \frac{4\pi e^4 Z^2 n_e}{m_e v^2} K_0 \left( \frac{\hbar}{n_e v^2} \sqrt{\frac{4\pi n_e e^2}{m_e}} \right)
\]

Present model

\[
-\frac{dE}{dx} = n_i \sum_\alpha \sum_{P_{nl}} \pi \left( \frac{Z_0 e^2}{I_{nl}} \right)^2 G \left( \frac{v}{v_{nl}} \right) G(V) = \frac{\alpha^{3/2}}{V^2} \left[ \alpha + 2 \left( 1 + \beta \right) \ln(2.7 + V) \right]
\]

**Graphs:**
- **Graph 1:** 3D plot showing ionization rate of Pb vs. temperature (eV) and number density (cm⁻³).
- **Graph 2:** Plot of stopping power vs. energy (MeV) with different models: Ziegler, Corrected Bethe, and present model.
Density, Temperature and velocity profile of ablated material.
Lot of 0.1 µm radius clusters are formed after adiabatic expansion.

(Luk’yanchuk, Zeldovich-Raizer Model)

20% of ablated vapor becomes aerosol.
Beam ports and ceiling will be made with porous metal and followed by condensation of vapor ablated by previous shot.

Condensation rates of the fast and slow component at the first bounce are about 60% and 100%, respectively.

These rates are sufficient to keep the vapor pressure < 5 Pa and to form a 2 μm-thick, protective layer before the next laser shot.

Aerosol mainly appears in slow component. Now secondary particles because the surface energy > kinetic energy
Critical issues in chamber 1

• Probability for direct exposure of the same place <1/10³ – 1/10⁴
  – If we assume maintenance period of 2 years and acceptable erosion of 3-mm-thick, the probability for direct exposure of the same place with \( \alpha \) particles must be less than 1/10⁴.
  – Improve flow control, material selection, chamber radius

• Protection of beam ports
  – Our first plan was to keep the surface temperature less than surrounding area to enhance the condensation. But this would not work because of the small temperature dependence of condensation.
  – Porous metal saturated with liquid LiPb
  – Magnetic field
Critical issues in chamber 2

- Although tilted front panels will reduce the stagnation to $1/10^3$, few gram of LiPb vapor will stagnate at the center.
  - Off set irradiation,
  - Large (~10 µm) particles due to RT instabilities and related secondary particles
Tritium necessary for one fuel loading system is about 100g

Tritium inventory
76 g as liquid

0.82 g as vapor

1.2 g/13 min

5mg/s

4g in 1600 targets

Tritium necessary for one fuel loading system is about 100g
Tritium in gas phase and LiPb leach their ultimate concentrations in 30 sec 6 hr, respectively.

2.8〜28 g in LiPb
0.1 ppm〜1ppm

Tritium can be recovered as fuel but diffusion through the heat cycle seems most critical.

Tritium barrier
Gap for tritium recovery

3 mg/s
30% burning rate
TBR=1.3

Tritium of 1 kg is necessary as the initial inventory for 1200MW plant.
Summary

• Core plasma,
  – High density compression of cone target
  – Heating efficiency of 30%
  – Adiabat a <2.5

• In the laser system
  – Construction of laser itself seems possible with existing technology.
  – Beam steering of ignition beam may be critical.

• Target Fabrication
  – Low density foam, cone with LiPb
  – Accuracy for the initial $\rho R/I_{laser}$

• Chamber system
  – Protection of beam port
  – Chamber clearance
  – Tritium confinement

These are important but not critical.

Target fabrication is technically challenging and quite critical.

Diffusion through heat cycle seems critical