Design Windows and Roadmaps for Laser Fusion Reactors

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Outline

1. Design windows for attractive laser fusion reactor
2. Critical issues
3. Roadmaps
INTRODUCTION

- Based on the recent progress of implosion physics and diode pumped solid-state laser, **KOYO design study** has been carried out as a joint project of universities, industries, and international collaborations.

- Following the KOYO design study **Systems Analysis of laser fusion program** has been conducted by the **Committee on Laser Fusion Research Strategy** (chair Y. Kozaki) organized in the ICF Forum.

- **A network analysis technique PERT and GERT** (Graphical Evaluation and Review Technique), which was applied for **TOKAMAK program** by Sekiguchi committee organized by Institute for Future Technology in 1983 has been applied for evaluating the IFE research program in a similar way.

- We are now investigating the roadmaps of a laser fusion research program and new reactor concepts with considering the recent progress of the fast ignition physics, under the **Committee on Laser Fusion Roadmap** (chair K. Tomabechi, vicechair Y. Kozaki) organized in the IFE Forum.
Characteristics of laser fusion power plants

1. Separability of major system and high potential for modular plants
2. Pulse power and pulse repetition plants
3. Potential for small size plants, simple reactors

Laser fusion power plant KOYO
4 reactor modules (700 MWe x 4)

Liquid wall reactor modules
Conditions of economically attractive fusion plants

**IFE (Laser)**
- Fusion gain $G$ $\Rightarrow$ laser energy
- Power balance $\eta G \geq 10$
  $\Rightarrow$ laser cost
- Pulsed operation $\Rightarrow$ pulse rep-rate
- Geometry $\Rightarrow$ separability $\Rightarrow$ final optics

**MFE (DT)**
- Plasma $\beta$ $\Rightarrow$ magnet cost
- Neutron wall loading $\Rightarrow$ reactor size
- Geometry $\Rightarrow$ complex $\Rightarrow$ maintainability

[ Comparison of reactor size ]
Gain curves for central spark and fast ignition

- Target gain $G$ can be given by simple functions of $E_L^{1/3}$ in high gain region.

- Because maximum burning fusion power is proportional to radius of pellet, while fuel heating energy $E_L$ is proportional to volume of pellet.
- Multi reactor module plants can be optimized in rather low $r_c$ (reactor pulse rep-rate), 3~5Hz.
- While single reactor module plants are optimized in higher rep-rate, 10~20Hz.
(Gain curve: central spark conservative case, LD unit cost: 3.1Yen/W)
COE Sensitivity to Target Gain Curve

**Fig.1(1) COE of 1200 MWe Plants**

<table>
<thead>
<tr>
<th>Gain Curves</th>
<th>Central Spark</th>
<th>Fast Ignition</th>
</tr>
</thead>
<tbody>
<tr>
<td>upper line</td>
<td>$G = 100 \left( \frac{E_L \text{MJ}}{4} \right)^{1/3}$</td>
<td>upper line: $G = 150 \left( \frac{E_L \text{MJ}}{1} \right)^{1/3}$</td>
</tr>
<tr>
<td>lower line</td>
<td>$G = 150 \left( \frac{E_L \text{MJ}}{4} \right)^{1/3}$</td>
<td>lower line: $G = 300 \left( \frac{E_L \text{MJ}}{1} \right)^{1/3}$</td>
</tr>
</tbody>
</table>

**LD Cost**: 3.1 yens / W

**Fig.1(2) COE of 4 x 600 MWe Plants**
COE Sensitivity to Laser Cost

Fig.2(3) COE of 1200 MWe plants
LD Cost : 3.1~6.2 yens / W , Gain curves are conservative cases:
Central Spark G=100 (E_LMJ/4) \(^{1/3}\) ; Fast Ignition G=200 (E_LMJ/1) \(^{1/3}\)

- LD unit cost of 3 yens / W is required to compete with conventional power plants in central spark modular plants, and even if LD cost of more than 6 yens / W can compete with the fossil fuel power plants with CO2 eliminated.
<table>
<thead>
<tr>
<th>Laser energy MJ</th>
<th>Target gain</th>
<th>Fusion pulse energy MJ</th>
<th>Pulse rep-rates reactor(laser)</th>
<th>Net output power MWe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 reactor</td>
</tr>
<tr>
<td>Fast ignition</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2 (ignitor 0.1)</td>
<td>100</td>
<td>20</td>
<td>3</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>80</td>
</tr>
<tr>
<td>0.4 (ignitor 0.1)</td>
<td>150</td>
<td>60</td>
<td>4 (24)</td>
<td>100</td>
</tr>
<tr>
<td>0.8 (ignitor 0.1)</td>
<td>250 KOYO Fast</td>
<td>200</td>
<td>3 (15)</td>
<td>240</td>
</tr>
<tr>
<td>Central spark</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>200</td>
<td>3 (15)</td>
<td>240</td>
</tr>
<tr>
<td>4</td>
<td>100 ~ 150 (KOYO)</td>
<td>400 ~ 600</td>
<td>~3 (6)</td>
<td>~ 600</td>
</tr>
<tr>
<td>Key design parameters</td>
<td>Design windows</td>
<td>Design constraints and issues</td>
<td></td>
<td></td>
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<tr>
<td>-----------------------</td>
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<td>-----------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Target gain G</strong></td>
<td>central spark concepts</td>
<td>-beam number ~90</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100<del>150 at 1</del>4 MJ</td>
<td>-irradiation nonuniformity ~0.3 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>fast ignition concepts</td>
<td>-required ignitor laser energy ~100 kJ</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100<del>300 at 0.2</del>1 MJ</td>
<td>-ignitor timing and focusing (~50 ps, ~50 µm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fusion pulse energy Ef = G E_L</strong></td>
<td>central spark concepts</td>
<td>-first wall protection</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100~600 MJ</td>
<td>-for liquid wall: ablation and evacuation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>fast ignition concepts</td>
<td>-for solid wall: charged particles intensities</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20~300 MJ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Reactor pulse rep-rate r_c</strong></td>
<td>liquid wall concepts</td>
<td>-evacuation time &lt;300 ms (conditions for laser</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3~10 Hz</td>
<td>beam propagation and pellet injection)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>dry wall concepts</td>
<td>-chamber radius R&lt; 5~10m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3~20 Hz</td>
<td>-beam propagation in high Z gas</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Reactor thermal power Pct = r_c Ef M</strong></td>
<td>100~4000 MWth</td>
<td>-adequate reactor power size</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-neutron wall loading, chamber radius</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-final optics damage and maintenance</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Laser energy E_L</strong></td>
<td>0.5~4 MJ</td>
<td>-laser cost (especially laser diode cost)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>laser efficiency η_d</strong></td>
<td>8~12 % (DPSSL)</td>
<td>-product of efficiency of many components</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>laser pulse rep-rate r_L</strong></td>
<td>3~30 Hz</td>
<td>-cooling medium, thermal effect compensation</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Reactor module number n</strong></td>
<td>1~10</td>
<td>-life time of key laser components</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-beam switching</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-layout of laser beam and final optics</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Corn target size and mass
- considering protection of chamber wall and optics -

\[ r = 2 \text{ mm} \]
\[ M(\text{fuel}) = 2 \text{ mg} \]

\[ r (\text{corn}) = 6 \text{ mm} \]
\[ M(\text{corn}) = 40 \text{ mg Pb} \]

240 MJ DT target without corn

240 MJ corn target

Corn Target Experiment
Requirements for IFE chambers (1)

What factors give the economically attractive laser fusion power plants?

- **Target gain and laser energy** (gain scaling)  
  >> Fusion pulse energy  
  >> Laser energy (cost)

- **Pulse repetition rate**  
  >> Fusion output power

- **Neutron loading on the first wall and the final optics**  
  >> The size of chamber and reactor building (Lifetime of material)

- **Intensity of X-rays and charged particles** on the first wall and the final optics  
  (Limiting factors of reactor size and rep-rate, or not?)
Results of economic analysis on laser fusion plants

- The sensitivity analysis on LD cost show that even if in the case of central spark concept (conservative target gain curve), the broad design windows of attractive power plants can be obtained in modular plants.

- When fast ignition can be achieved, the required laser energy is so small that very attractive fusion power plants can be achieved. But in the case of small laser energy and small fusion pulse energy, the design windows are strictly restricted by the rep-rates of laser pulse and/or reactor pulse.

- In modular power plants the requirement for reactor pulse rep-rates is mitigated, but laser rep-rate and beam sharing control may be critical issues for lower COE.
Issues and major subjects on liquid wall chamber

Fusion burning output estimation
ILESTA, MEDUS
X-rays ~ 30 keV
Charged particles 0.1keV ~ 1MeV
Ablation model with plasma absorption by abraded plasma

Required vacuum level
<10^{-2}\sim 10^{-4} \text{ Torr}

Nonlinear effect on laser beam
Impact on pellet injection

Estimating rep-rate >3 \sim 10 \text{ Hz}
Results of evacuation simulation with DSMC code and TSUNAMI code in different boundary conditions

The results of DSMC code and TSUNAMI code with different conditions.

The differences of results with different condensation ratio and viscosity are not so large as those with surface temperature.

DSMC 1
DSMC code with condensation ratio is 0.98

DSMC 2
DSMC code with condensation ratio is 0.92

TSUNAMI 1
TSUNAMI code without viscosity

TSUNAMI 2
TSUNAMI code with viscosity \((8.77 \times 10^{-5}\text{pa} \cdot \text{s})\)
using the value of Hg of 873 K and 1 atm
Ion spectra of fusion output (400 MJ target)

- X-ray spectrum is much harder than indirect target
- Particles and fast ions energy are 1-4 MeV
Pulse heat loads on chamber walls (400 MJ target case)

**Thermal pulse power on first wall**
*(400MJ targets) radius 2m, 4m, 8m*

<table>
<thead>
<tr>
<th></th>
<th>r=2m</th>
<th>r=4m</th>
<th>r=8m</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray peak</td>
<td>16</td>
<td>4.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$10^{10}$ W/cm$^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>alpha peak</td>
<td>2.4</td>
<td>0.3</td>
<td>0.037</td>
</tr>
<tr>
<td>$10^8$ W/cm$^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ions peak</td>
<td>19</td>
<td>2.4</td>
<td>0.3</td>
</tr>
<tr>
<td>$10^8$ W/cm$^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>alpha pulse width</td>
<td>0.3</td>
<td>0.6</td>
<td>1.2</td>
</tr>
<tr>
<td>μsec</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ions pulse width</td>
<td>0.4</td>
<td>0.8</td>
<td>1.6</td>
</tr>
<tr>
<td>μsec</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total pulse load</td>
<td>144</td>
<td>36</td>
<td>9</td>
</tr>
<tr>
<td>$J / cm^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average power</td>
<td>432</td>
<td>108</td>
<td>27</td>
</tr>
<tr>
<td>3Hz, W/cm$^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutron load</td>
<td>20</td>
<td>4.9</td>
<td>1.2</td>
</tr>
<tr>
<td>3Hz, MW/m$^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In the case of 2m chamber radius, the ablation depth is almost equal to the range of alpha particles, as the energy deposit with alpha particles is enough to ablate the mass of this depth.

When the radius is larger than 3m, the ablation depth increases softly with increasing fluence of charged particles, as the over 90 % of charged particles energy is absorbed with ablated liquid metal plasma.
Pulse heat loads on chamber walls (20 MJ, 100 MJ case)

Thermal pulse power on first wall (20 MJ targets) radius 2m, 4m, 8m

<table>
<thead>
<tr>
<th>Laser energy kJ</th>
<th>20 MJ r=4m</th>
<th>100 MJ r=4m</th>
<th>100 MJ r=8m</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray peak $10^{10}$ W/cm$^2$</td>
<td>0.2</td>
<td>1.0</td>
<td>0.25</td>
</tr>
<tr>
<td>X-ray peak $10^8$ W/cm$^2$</td>
<td>0.015</td>
<td>0.075</td>
<td>0.009</td>
</tr>
<tr>
<td>Total load J/cm$^2$</td>
<td>1.6</td>
<td>9.0</td>
<td>2.25</td>
</tr>
<tr>
<td>Average power 10Hz, W/cm$^2$</td>
<td>16</td>
<td>90</td>
<td>23</td>
</tr>
<tr>
<td>Neutron load 10Hz, MW/m$^2$</td>
<td>0.7</td>
<td>4.1</td>
<td>1.0</td>
</tr>
</tbody>
</table>
The peak surface temperature are about 2700K (r=4m, 20MJ case, at t=1.062 µsec), and 2500K (r=8m, 100MJ case, at t=2.087 µsec).

At ending of charged particles pulse, the surface temperatures are about 1700K in both cases.
Chamber sizes of dry wall and liquid wall for same output

Dry wall chamber: for smaller pulse energy and higher rep-rates
Liquid wall chamber: for larger pulse energy and smaller radius chamber
What factors give plant sizes?

- **Fast ignition target design**: Target gain 250 with laser energy 800 kJ
  
  → Fusion pulse energy **200 MJ**
  
  → 60 MJ with laser energy 400 kJ

- **Optimum plant output power**
  
  → **Scale merits**: the 2/3 power law (such as fission plants)
    
    1200 ~ 1500 MWe (~ 2400 MWe in modular plants)

  → **Small size merits**: flexibility of construction and fitting in demand
    
    : assembling in factory and small indirect cost

- **Especially in laser fusion plants,**
  
  → **Decreasing neutron flux on final optics >> Small size of reactor buildings**

  → **Modular plants with multi small reactors and a high rep-rates laser**
    
    can give the design flexibility.
1200 MWe Reactor Plant and Building

300 MWe x 4 Reactors Plant and Buildings

(Beam layout is a critical issue)
Critical Issues and Major Tasks

Physics issues and major tasks (2002~2015)
- Fast ignition physics establishment and demonstration of ignition and burning (PW project, and FIREX)
- Hydro dynamic equivalent experiment of high gain target (EPOC: high uniformity ~50kJ laser facility)

Driver issues and major tasks (~2012)
- High repetition high power laser (100J and 1kJ DPSSL module, and excimer laser module development)
- LD cost down technologies
- Long-lifetime-laser-material development

Pellet technologies issues and major tasks (~2012)
- Cryo-target fabrication and corn target technologies
- Pellet injection, tracking, and shooting technologies

Reactor technologies issues and major tasks (~2012)
- Chamber wall protection technologies (for FIREX, and the high rep-rate burning experiment)
- Liquid wall chamber feasibility studies, simulation on liquid wall ablation, evacuation, and free liquid surface control
- Reactor structural material and final optics (pulse irradiation with charged particles and neutrons)
- Consistent reactor design (developing new power plant concepts and establishing a experiment reactor design)
### Table: Milestones and major facility specs on a laser fusion roadmap

<table>
<thead>
<tr>
<th>Milestones</th>
<th>Establishment of plasma physics</th>
<th>Steady burning experiment</th>
<th>Demonstration of power generation</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facility</td>
<td>FIREX</td>
<td>IFER</td>
<td>DEMO</td>
<td>Commercial plants</td>
</tr>
<tr>
<td>Purpose,</td>
<td>Demonstration of ignition and burning - 1st stage: Driven burning physics (Break even Q<del>1) Second stage: ignition and burning (α heating physics Q</del>10)</td>
<td>Integrated test of burning technologies - High gain, and high rep-rate fusion burning - High rep-rate laser - Reactor chamber test, tritium breeding blancket, material test, etc.</td>
<td>Integrated test of prototype power plant - Demonstrate of reliable power generation (facility performance, lifetime) - safety, and prospect for COE</td>
<td>Economically and environmentally attractive plants - COE (6~10 Yen/kWh) - Modular plants for using the characteristics of laser fusion - Flexibility of construction and operation</td>
</tr>
<tr>
<td>Conditions for starting and selection</td>
<td>- High density implosion (already demonstrated) - Short pulse laser heating physics (scaling for keV level heating) - Ultra high intensity laser technologies (already developed)</td>
<td>- Steady fusion output with fast ignition (Although evaluating the results of central spark concepts with US NIF, EPOC.) - Selection of driver based on module development - Selecting the chamber concepts (liquid wall and/or solid wall)</td>
<td>- Selecting the optimum target irradiation methods, and drivers - Lliquid metal cooling and/or gas cooling (considering multi chambers test) - Technologies scalable to commercial plants by multi module and scale up</td>
<td>Economically and environmentally attractive plants - COE (6~10 Yen/kWh) - Modular plants for using the characteristics of laser fusion - Flexibility of construction and operation</td>
</tr>
<tr>
<td>Laser energies</td>
<td>~ 80 kJ implosion 50+ heating ~30</td>
<td>200 kJ implosion 100+ heating 100</td>
<td>400 ~ 800 kJ</td>
<td>400 ~ 800 kJ</td>
</tr>
<tr>
<td>Target Gain</td>
<td>~ 10</td>
<td>100</td>
<td>150 ~ 250</td>
<td>150 ~ 250</td>
</tr>
<tr>
<td>Fusion pulse energies</td>
<td>~ 1 MJ</td>
<td>20 MJ</td>
<td>100 ~ 200 MJ</td>
<td>100 ~ 200 MJ</td>
</tr>
<tr>
<td>Pulse rep-rate</td>
<td>1 shot / hour</td>
<td>~ 1 Hz</td>
<td>~ 3 Hz</td>
<td>3 Hz × (5~10)</td>
</tr>
<tr>
<td>Fusion output power</td>
<td>-</td>
<td>20 MWth</td>
<td>120 ~ 240 MWe</td>
<td>1200 MWe</td>
</tr>
<tr>
<td>Laser efficiency</td>
<td>1 %</td>
<td>6 ~ 8 %</td>
<td>10 %</td>
<td>10 %</td>
</tr>
<tr>
<td>Construction cost</td>
<td>22 ~ 40 BYen</td>
<td>100 ~ 200 BYen</td>
<td>200 ~ 300 BYen</td>
<td>~ 360 BYen</td>
</tr>
</tbody>
</table>
Road maps for laser fusion reactors


- Fast Ignition experiment (FIREX)
- National Ignition Facility (NIF)

- Design
- Implosion laser 100 kJ, ~1Hz
- Fusion pulse 20 MJ, ~100 kJ
- 20 MW

- Integrated reactor technology test
- Steady burning experiment

- Advanced laser R&D

- Pellet fabrication, injection

- Reactor chamber technology

- Fusion reactor technology (Blanket technology, Tritium technology, reactor structural material, reactor design, safety etc.)

- DEMO Power generation

- Fusion pulse 200 MJ, 3 Hz
  Net output power ~200 MWe
FIREX II Target Chamber System

**Ignition Beam**
- $\lambda = 1053 \ (527) \ \text{nm}$
- 4 beams
- 10 kJ/20 ps
- F/5, 100 cm$^\phi$

**Implosion Beams**
- $\lambda = 351 \ \text{nm}$
- 92 beams
- 50 kJ/3 ns
- F/8, 15 cm$^\phi$
The basic design guidelines for KOYO - Fast

1) Target: Fast ignition target with corn
   - laser energy 800 kJ, fusion gain 250, fusion pulse energy 200 MJ
   - Reactor pulse rep-rate 3 Hz, 600 MWth
   - Blanket energy multiplication 1.1, reactor thermal output 660 MWth
   - Energy conversion efficiency 43%
   - Reactor electric output 284 MWe, and auxiliary electric power 6%
   - Laser recirculating power 24 MW (8.94%), laser efficiency 10% DPSSL case
   - Net electric power of one reactor module 240 MWe, and 5 reactors modular plant 1200 MWe

2) Laser: DPSSL implosion 700kJ, ignitor 100 kJ (option excimer laser)
   - efficiency 10%
   - rep-rates 15 Hz
   - laser gain medium HAP4, or Nd-YAG ceramics

3) Chamber: Liquid fast flow covering first wall with thin liquid layer
   - Pb
   - rep-rates ~3 Hz

4) Final optics: Fused silica optical wedge for implosion lasers (unsettled yet for ignitor)

[Options]
- Small DT fuel target (laser energy 400 kJ, fusion gain 150) for solid wall chambers
- Advanced-fuel-corn-target with magnetic wall protection and direct energy conversion
Summary

- Analysis of design windows shows that even with the conservative target gain scaling, the broad design spaces for attractive power plants can be obtained in modular plants, although costs and lifetimes of lasers are critical issues.
- Fast ignition offers opportunities for smaller size plants with smaller laser energy, then give high potential for competitive COE.
- We identified critical issues which should be achieved for fast ignition targets, high rep-rates lasers, pulse energy protection chambers, etc.
- Results of network analysis shows that laser fusion programs have much flexibility and could promote with small size facilities and a rather small cost. Especially in fast Ignition case, we could establish physics base of ignition and burning with small size facility, and achieve reactor technologies with a small size steady operation reactor.
- For achieving fusion energy goals we have various options which are based on common fusion reactor technologies. Laser fusion options offer some good candidates, which also could be achieved by strong supporting with fusion reactor technologies development.