IFE Roadmap and power plant concept based on fast ignition laser fusion

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Outline

- IFE Road map based on fast ignition concept
  - What is changed by fast ignition?
  - Small sized experimental reactor generating net electric power.
  - Critical issues and necessary technology development program

- Design study of fast ignition laser fusion power plant
  - Design windows of fast ignition laser fusion power plants
  - Chamber pulse conditions and free surface liquid wall concepts
# IFE road map committee by IFE Forum (2002~2003)

<table>
<thead>
<tr>
<th>Role</th>
<th>Name</th>
<th>Affiliation</th>
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<tbody>
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<td>ILE, Osaka University</td>
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Introduction

• The progress of implosion physics and DPSSL (Diode Pumped Solid-State Laser)

In 1997 IFE Forum organized "The Committee on Development Program of Laser Fusion Energy" (chair Y.Kozaki), members of universities, national laboratories and industries in Japan, and proposed IFE road map which had two major facilities, HGX(High Gain Experiment) and LFER (Laser Fusion Experiment Reactor) using a MJ class DPSSL.

• Fast ignition concept is attractive, as a high gain is achieved by small laser energy. The fast ignition experiment by PW laser at Osaka University demonstrated the heating efficiency of 20 % at the ignition equivalent laser intensity in 2002. FIREX-I (Fast Ignition Realization Experiment) project has started in 2003 for demonstrating the heating up to ignition temperature, and FIREX-II is considered for demonstrating ignition.

• The recent progress of fast ignition physics may bring a big change to an IFE road map, then IFE Forum organized a new committee "The Committee on Road Map for Laser Fusion Energy" (chair K.Tomabechi, co-chair Y.Kozaki) in 2002.
Purpose of The Committee on IFE Roadmap

• To investigate conditions of achieving laser fusion energy and assess the possibility of fast ignition reactor concepts,

• To identify milestones and necessary facilities,

• To identify critical paths and estimate cost and manpower,

• To propose a reasonable road map using fast ignition features and make a strategy of development including collaboration with industry.
1 keV heating was achieved in 2002.

Estimates of ignition burn on the FIREX project and prospects high gain

FIREX-I Heating to ignition temperature

FIREX-II Ignition and burn

High gain

Cone targets for a PW experiment and for a reactor of 90 MJ fusion yield.

Cone targets irradiated by heating laser through from the cone have big merits not only to eliminate the affection of ablated plasma but also to reduce the requirements for laser beam focusing and target injection technologies.
FIREX (Fast Ignition Realization Experiment)

Purpose: Establishment of fast ignition physics and ignition demonstration
Starting Conditions: high density compression (already achieved)
: heating by PW laser (1keV already achieved)

The overview of FIREX-II

- Heating laser 50 kJ
  - pulse width 10 ps
- Implosion laser 50 kJ/1ns
## Specification of laser fusion power plants

<table>
<thead>
<tr>
<th>Laser energy MJ</th>
<th>Fusion gain</th>
<th>Fusion pulse yield MJ</th>
<th>Rep rate, Hz reactor (laser)</th>
<th>Net electric power MWe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast ignition</td>
<td>~0.3</td>
<td>~80</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>150</td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>200</td>
<td>200 (KOYO-Fast)</td>
<td>240</td>
</tr>
<tr>
<td>Central ignition</td>
<td>2</td>
<td>100</td>
<td>200</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>100~150 (KOYO)</td>
<td>400~600 (KOYO)</td>
<td>~600</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Per reactor</th>
<th>Modular plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>100×6 600MWe</td>
<td>240×5 1200MWe</td>
</tr>
<tr>
<td>1200MWe</td>
<td>240×5 1200MWe</td>
</tr>
<tr>
<td>1200MWe</td>
<td>600×2 1200MWe</td>
</tr>
</tbody>
</table>
Milestones for Laser Fusion Power Plants

- **Fast Ignition Research Experiment (FIREX)**
  - **Purpose:** Establishing physics of fast ignition, and demonstration of ignition
  - **Starting Conditions:** high density compression (already achieved), heating by PW laser (1keV already achieved)

- **Laser Fusion Experimental Reactor (LFER)**
  - **Purpose:** Integration of technologies necessary for laser fusion power plants, and demonstration of net electric power generation
  - **Starting Conditions for engineering design**
    - Clarify physics by FIREX-I (Heating to ignition temperature)
    - Prospecting of key technologies (1kJ high rep-rate laser, target injection and tracking, chamber, blanket, tritium technologies, etc.)
  - **Starting Conditions for construction**
    - Ignition and burning by FIREX-II
    - Establishment of above technologies in elemental level

- **Demonstration Reactor (DEMO)**
  - **Purpose:** Demonstration of practical power generation including of economical, environmental, and safety prospection
  - **Starting Conditions:** Demonstration of net electric power and establishing technologies for practical power plants
A Road Map for Laser Fusion Energy

2005 2010 2015 2020 2025 2030 2035

- **FIREX-I**
  - Design
  - 10 kJ Heating Laser

- **FIREX-II**
  - Engineering Design
  - Repetition Test
  - Total 100 kJ Laser

- **DPSSL Development**
  - Laser Module
  - 100J 1kJ 10kJ

- **Advanced Laser**
  - Laser Module
  - 100J 1kJ 10kJ

- **Target Fabrication & Injection Technology**

- **Reactor Chamber & Liquid Wall Technology**

- **Reactor Technology Development** (Blanket, Liquid Metal, Final Optics, Tritium, Reactor Material, safety), ITER R&D

- **ITER R&D**
  - Design
  - Test I, II
  - Test III
  - 4 MWe

- **LFER**
  - Construction
  - 200 kJ Laser

- **DEMO**
  - Design
  - Practical Power Demonstration
  - 500 kJ ~1MJ Laser ~240 MWe

- **Ignition**

- **Power Generation Test**
## Major facilities and milestones for fusion power plants

<table>
<thead>
<tr>
<th>Facility</th>
<th>FIREX</th>
<th>LFER</th>
<th>DEMO</th>
<th>Commercial plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milestones</td>
<td>- Fast ignition physics establishment and ignition demonstration</td>
<td>- Demonstration of integrated reactor technologies and net electric power</td>
<td>- Demonstration of practical power generation</td>
<td>- Economically, environmentally attractive plants (Competitive COE) - Modular plants for scale up, flexible construction</td>
</tr>
<tr>
<td>Objectives</td>
<td>- Phase I (FIREX-I): Heating to ignition temperature (~10 keV) Phase II (FIREX-II): Ignition and burning</td>
<td>- Phase I: high rep-rate burning Phase II: Solid wall with test blanket, and liquid wall chamber Phase III: Net power generation, long time operation</td>
<td>- Demonstration of a reactor module for practical power plants - Credibility and economics demonstration</td>
<td>- Economically, environmentally attractive plants (Competitive COE) - Modular plants for scale up, flexible construction</td>
</tr>
<tr>
<td>Laser</td>
<td>~100 kJ implosion 50 + heating 50</td>
<td>200 kJ (~ 1 Hz)</td>
<td>0.5<del>1 MJ (</del> 3 Hz)</td>
<td>0.5<del>1 MJ (10</del>30 Hz)</td>
</tr>
<tr>
<td>Fusion pulse energy/power output</td>
<td>~1 MJ (1 shot / hour)</td>
<td>10 MJ 10 MWth/ 4 MWe Net output 2MWe</td>
<td>100 ~200 MJ 330 ~ 660 MWth 100 ~ 240 MWe</td>
<td>100 <del>200 MJ 3 Hz× (5</del>10) reactors 600 ~ 1200 MWe</td>
</tr>
<tr>
<td>Construction cost</td>
<td>300 ~ 400 M$</td>
<td>~ 1600 M$</td>
<td>~ 2300 M$</td>
<td>~ 2700 M$ / 1GWe</td>
</tr>
</tbody>
</table>
Reactor Chamber

Implosion Laser 100 kJ

Target Injector

Heating Laser 100 kJ

Turbine Generator 4 MWe

Cone Target: Fuel DT Ice 0.1 mg  
: Cone PbLi 400 mg  
Fusion Yield: 10 MJ / 1 Hz  
Output Power: 10 MWth / 4 MWe

LFER (Laser Fusion Experimental Reactor)
Basic Concept of LFER

1) A small fusion experimental reactor using fast ignition cone targets and DPSSL laser systems. Reactor chamber sizes are determined primarily by pulse heat load on the first wall. We consider LFER chambers, having a radius and pulse thermal load of 2.5 m and 2.5 J/cm² for solid wall (phase-I, -II), and 1 m and 16 J/cm² for liquid wall (phase-III).

2) Two 100 kJ DPSSL (Diode Pumped Solid-State Laser) systems, for implosion and heating. For a heating laser, large final optics (10 m²) and a long beam line (30~50 m) are placed oppositely to a target injector.

3) Two chambers, a solid wall chamber used in Phase-I and II, and a liquid wall chamber used in Phase-III for net electric power demonstration. Around the chambers, there are about 60 final optics and beam lines of implosion lasers in spherically symmetric layouts.
In regard to the final optics of the heating laser and the shielding of laser beam-lines, there are still many remaining problems to be examined in detail.

4) Although in a small scale, we could foresee the basic configurations, layouts, and sizes of the fast ignition laser fusion plants.
Size comparison of major fusion facility

**FIREX**
- Gain ~10
- Laser 100 kJ

**LFER 10 MWth**
- Phase I: High rep pulse Test 10 MJ, 1 Hz
- Phase II: 10 MWth steady operation, net electric power ~2 MWe

**DEMO 200 MWe**
- Laser 3 Hz

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**Fusion pulse 1 MJ**
- Solid wall radius: 2.5 m
- Liquid wall radius: 1 m
- Pulse heat load: 2.5 J/cm²
- Average heat load: 2.5 W/cm²

**Fusion pulse 10 MJ, 1 Hz**
- Solid wall radius: 2.5 m
- Liquid wall radius: 1 m
- Pulse heat load: 16 J/cm²
- Average heat load: 16 W/cm²

**Fusion pulse 200 MJ, 3 Hz**
- Chamber inner radius: 3 m
- Pulse heat load: 35 J/cm²
- Average heat load: 106 W/cm²
- Neutron wall load: 4.2 MW/m²
Missions and Phase Operation of LFER
(Laser Fusion Experimental Reactor)

Phase-I: High gain targets and integrated high rep-rate technologies tested.

Phase-II: Reactor technologies tested comprehensively, such as testing blanket modules for tritium breeding and power generation, using solid wall chamber.

Phase-III: Using liquid chamber with full blanket, tested for net power generation. After achieving these missions, used as a material test reactor by long hour operation as a self-sustaining reactor.
Mass production of shells will be realized with currently exciting technologies.

Fuel loading would be the critical issue to reduce the inventory of tritium in the target factory.
Characteristics and issues of cone target

- size and mass

\[ r = 2 \text{ mm} \]
\[ M(\text{fuel}) = 2 \text{ mg} \]
\[ r(\text{cone}) = 3 \text{ mm, 8 mm h} \]
\[ M(\text{cone}) = 40 \text{ mg Pb} \]

240 MJ DT target without cone

240 MJ cone target

Issues: Estimation of energies and spectra of ions from cone targets, and consideration of optics protection from cone debris

Merit:
- Laser beam focusing by cone without interfering corona plasma
- Cone make guard for cryo targets from vapor and aerosol
- Cone mass give high injection accuracy
- To mitigate requirements for chamber conditions make high rep-rates possible.
New laser material for broadband

Lifetime = 650 µs

Nd:CNCG disordered poly-crystal
Roadmap of Reactor System Development

<table>
<thead>
<tr>
<th>Year</th>
<th>2003</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
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</table>

- **FIREX I**
  - Chamber and blanket integration
  - Chamber technology
    - Blanket technology
      - Pumping, fueling, and tritium safety
      - Final optics
      - R&D
      - Test
      - Elemental R&D for liquid LiPb wall
  - Chamber and blanket integration
  - R&D of liquid wall
  - Test of solid wall chamber
  - Test blanket development
  - IFMIF material test
  - ITER blanket R&D, high thermal load R&D
  - IFMIF construction

- **FIREX II**
  - Engineering design
  - Test of Integrated reactor technology
  - Demo of practical power generation

- **LFER construction**
  - T1 T2 T3

- **ED**
  - DEMO construction
  - OP

- **Single shot**
- **Power generation test**
Analysis of program schedule

• **Establishing physics of fast igniton** (Ignition and burn by FIREX)
  < FY2013

• 10kJ laser driver and integration test on high repetition technologies:
  < FY2015

• **Demonstration of integrated fusion technologies and power generation**
  (LFER)
  < FY2026

• **Demonstration of practical power generation** (DEMO plant)
  < FY2036
Estimation of program cost

- **FIREX** (100kJ single shot glass laser) **300~400M USD**
- Development of laser module for reactor, repetitive target irradiation technology
  (DPSSL 10 kJ for compression, 10 kJ for ignition)
  \(~360 \text{ M$} \) (Cost of LD is 180 M$ estimated from LD 600 MW, LD unit cost 30 cent/W assumption)
- **LFER** (200 kJ laser, Thermal~10 MW, Electricity~4 MW)
  \(~1600 \text{ M$} \) (Cost of LD is 600 M$ estimated from LD 6 GW, LD 10 cent/W)
- **DEMO** (1MJ laser, Thermal 200 MJ, 3 Hz, Net electric power 200 MW)
  \(~2300 \text{ M$} \) (Total laser driver cost is 1350M$ estimated from LD 6 cent/W)
- **Commercial plant** (600~1200 MWe with multi reactor modules)
  **2700 M$/GWe** (Total laser driver cost is 1000~1500M$)
Prospection of Laser Diode cost reduction

Prospection of LD cost reduction (Kozaki, data by W. F. Krupke, Izawa, 2002.11)

- 100 J module, 2005y
  : LD 3 MW, 3 M$ (1 $ / W)

- 1 kJ module, 2005~2008 y
  : LD 20 MW, 10 M$ (0.5 $ / W)

- HRX(high rep), 20 kJ, 2008~2011y
  : LD 600 MW, 180 M$ (0.3 $ / W)

- LFER 200 kJ, 2015~2020
  : LD 6 GW, ~600 M$ (0.1 $ / W)

- DEMO(200MWe) ~1 MJ, 2027~2030
  : LD ~20 GW, 1200 M$ (0.06 $ / W)

- Comercial plants (1 GWe) ~1 MJ,
  : LD ~20 GW, 1000 M$ (0.05 $ / W)
→ 10 GWe / year plants construction
→ LD 200 GW / year
→ 10 B$ / y LD market in the world

Prospection of LD cost reduction (Kozaki, data by W. F. Krupke, Izawa, 2002.11)
From KOYO to KOYO-Fast

- **KOYO design (Central hot spark ignition)**
  - Laser energy: 4 MJ
  - Fusion yield: 400~600 MJ
  - Reactor module: ~600 MWe
  - Laser cost: ~4000 M$ (assumption of LD unit cost 5 cent/W)
  - Large output modular plant: ~2400 MWe (for competitive COE)

- **KOYO-Fast design (Fast ignition)**
  - Laser energy: 500kJ~1 MJ
  - Fusion yield: 100~200 MJ
  - Reactor module: 100~300 MWe
  - Laser cost: 500~1000 M$ (LD unit cost 5 cent/W)
  - Small output modular plants: 600~1200 MWe
    (for a variety of future energy needs)
Summary

1. The inertial fusion energy development based on the fast ignition concept may offer a possibility to develop a practical small fusion power plant that may greatly enhance usefulness of fusion power to meet flexibly a variety of future energy needs.

2. The present assessment delineated a possibility to demonstrate electricity generation with a small power plant in a reasonably short time. It may be achieved by coordinated development efforts on relevant individual fusion technologies such as those of laser, reactor chamber, and fuel target, taking into account the characteristic advantages of the fast ignition concept.

3. It is important to advance both fast ignition physics research and reactor technology development in a coordinated manner, through the FIREX program and the reactor technology development program. Thus, it may become possible to move smoothly into the program to construct a laser fusion experimental reactor.
Design windows of power plants and an experimental reactor (summary 2)

1. We have examined the design windows and the issues of the fast ignition laser fusion power plants, and shown the possibility of small size, ~300 MWe fusion reactors, with ~200 MJ fusion pulse energy, ~4Hz rep-rates, by ~1 MJ laser. Using these reactor modules we can flexibly design large scale, ~1200 MWe modular plants driven by a ~16 Hz high rep-rate laser system. The small pulse energies mitigate technical constraints of the chamber as well as the final optics issues.

2. We have also shown the possibility of a very small fusion experimental reactor with fast ignition concept. We propose a small laser fusion experimental reactor (LFER), having fusion pulse energies of 10 MJ with 200 kJ laser, i.e., 100 kJ for implosion and 100 kJ for heating. LFER is aimed at integrating the technologies necessary to power plants and demonstrating net electric power generation in a small scale and short operation time, but scalable to a DEMO plant.

3. With LFER, we could consider a possibility to demonstrate electricity generation in a reasonably short time. It may be achieved by coordinated development efforts on relevant individual fusion technologies. It is important to advance both fast ignition physics research and reactor technology development in a coordinated manner.
From KOYO to KOYO-Fast

• KOYO design
  • 4 MJ laser → 600 MJ → 2400 MWe plant
    • laser cost → 400 Byen / 800 Byen (plant total)

• KOYO -Fast design
  • 1 MJ laser → 200 MJ → 1200 MWe plant
    • laser cost → 100 Byen / 300 Byen (plant total)

- Net output 1200 MWe (300 MWe x 4)
- Reactor module net output 300 MWe
- Laser energy 1.2MJ
- Target gain 167
- Fusion pulse output 200 MJ
- Reactor pulse rep-rate 4 Hz
- Reactor module fusion output 800 MWth
- Blanket energy multiplication 1.13
- Reactor thermal output 904 MWth
- Total plant thermal output 3616 MWth (904 MWth x 4)
- Thermal electric efficiency 42 % (LiPb Temperature ~500 C)
- Total electric output 1519 MWe
- Laser efficiency 8.5% (implosion), 5% (heating)
- Laser pulse rep-rate 16 Hz
- Laser recirculating power 240 MWe (1.2 MJ x 16 Hz / 0.08)
  (Comparative study on cooling power and laser performance; Yb-YAG laser operating 150K or 220K)
- Net plant output power 1200 MWe (1519 MWe - 240 MWe - 79 MWe Aux.)
- Total plant efficiency 33.2 %(1200 MWe / 3616 MWth)
Tasks of analysis for liquid wall chambers and solid wall chamber

Fast ignition cone target design → Fusion output energies, spectrum calculation (X-rays, ions, neutrons) → Ions energy absorption with ablated metal plasma → Energy deposition on liquid surface, phase change, and ablated vapor calculation → Metal vapor condensation, evacuation calculation → Estimation chamber gas conditions (10~50 mTorr) for fast ignition cone targets → Estimating rep-rates > 3 ~ 10 Hz

Fusion burning output estimation
ILESTA, MEDUSA

Ablation model considering the absorption with ablated metal vapor.

Liquid wall design and free surface fluid simulation

Impact on target injection trajectory and target gain by residual chamber gas

Non linear effects of laser beam propagation

Energy absorption with chamber gas and chamber gas dynamics calculation

Energy deposition on solid wall, thermal response, erosion calculation

Material lifetime analysis
Energies and spectra of ions from 400MJ target

TABLE  ENERGIES AND SPECTRA

<table>
<thead>
<tr>
<th></th>
<th>Average Energy</th>
<th>Range*</th>
<th>Energy MJ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-rays</td>
<td>35 keV</td>
<td></td>
<td>4 (1.0%)</td>
</tr>
<tr>
<td>α particles</td>
<td>3.5MeV</td>
<td>14</td>
<td>58 (14.5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>20</td>
<td></td>
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</tbody>
</table>

X-rays, alpha particles, debris ions and neutrons from a typical central spark target (KOYO 400 MJ)

* Ions range for Pb
Energy deposition and ablation depth from 400MJ target

- Alpha particles have long range, then deposit most their energies in ~10 μm layer.
- Debris ions (C and low energy H, D, T) deposit in short range, 0.5~2 μm layer.
- The ablation depths depend on the alpha particles beyond a certain intensity (2~4m chamber radius), but almost only depend on debris ions in the larger radius cases.
Pulse heat loads on chamber walls (20,100MJ target)

Pulse loads on the first wall from 20 MJ, and 100MJ targets, in radius 2m, 4m, and 8m cases.

<table>
<thead>
<tr>
<th>Laser energy (kJ)</th>
<th>20MJ (r=4m)</th>
<th>100MJ (r=4m)</th>
<th>100MJ (r=8m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>100</td>
<td>200</td>
<td>200</td>
</tr>
<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>(\alpha) peak (10^{8}) W/cm(^2)</td>
<td>0.015</td>
<td>0.075</td>
<td>0.009</td>
</tr>
<tr>
<td>Ions peak (10^{8}) W/cm(^2)</td>
<td>0.16</td>
<td>0.8</td>
<td>0.08</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 (10\text{Hz},W/cm^2)</td>
<td>16</td>
<td>90</td>
<td>23</td>
</tr>
<tr>
<td>Neutron load (10\text{Hz},\text{MW/m}^2)</td>
<td>0.7</td>
<td>4.1</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Fast ignition solid chamber concepts (240 MWe)

- Fusion output: 90 MJ/pulse, 600 MW
- Chamber inner radius: 8 m
- Pulse heat load: 2.2 J/cm²
- Pulse rep-rates: 6.7 Hz
- Average heat load: 15 W/cm²
- Neutron wall load: 0.6 MW/m²
- Chamber outer radius: 9.5 m
- Tritium breeding: Li₂O
- Heating Laser: 100 kJ
- Armor/coolant: W coated SiC/He
  - in: 700 °C
  - out: 900 °C
- Blanket coolant: He
- Implosion laser beam number: 32
- Heating laser beam number: 1
- Heating laser final optics: 30 m from center
- Surface area: 10 m²
Peak energy densities and Temperature profiles of the dry wall surface (20 MJ, 100 MJ targets)

- The energy deposition in a r=8m case by 100MJ targets are less than for melting, but in a r=4m case, the temperature of surface exceeds over melting temperature.

- The energy deposition in r=4m case by 20MJ targets are less than for melting
- The effect by instantaneous temperature rising should be considered.
Fast ignition liquid chamber concepts (240 MWe)

- Fusion output: 200 MJ/pulse, 600 MW
- Chamber inner radius: 3 m
- Pulse heat load: 35 J/cm²
- Pulse rep-rates: 3 Hz
- Average heat load: 106 W/cm²
- Neutron wall load: 4.2 MW/m²
- Chamber outer radius: 4.5 m
- Tritium breeding: LiPb

- Heating Laser: 100 kJ

- Liquid wall: LiPb
  - In: 350 °C
  - Out: 450 °C
- Blanket coolant: Water
  - In: 300 °C
  - Out: 400 °C
- Implosion laser beam number: 32
- Heating laser beam number: 1
- Heating laser final optics: 30 m from center
- Surface area: 10 m²
As the energy deposition of alpha particles in 2m radius case gets above the ablation threshold, the ablation depth is much larger than in large radius cases (about 2µm in r=3m, 4m cases), caused by alpha particles long range.

The energy rates of direct loss alpha particles from the fast ignition targets increase over three times larger than central ignition cases, the estimation of ablation depth by alpha particles is much important for chamber design.
Fig. 2  The chamber gas pressure distributions simulated by TSUNAMI code, (a) after 20 msec, (b) after 40 msec, and (c) KOYO reaction chamber geometry.
The pressure distributions simulated by DSMC code

The chamber gas pressure goes down fast to the saturated vapor pressure with radial flow and axial flow.
The velocity distributions simulated by DSMC code

ILE OSAKA
Case1: The temperature of liquid surface is same as coolant temperature 550 °C
Case2: Cooling only by thermal conduction (2mm thick liquid film cooled by coolant)
Case3: The surface temperature of side walls are same as case2, while those of the upper and bottom walls are cooled to coolant temperature 550 °C.
(Simulation initial conditions: 0.01 Torr Pb gas pressure uniformly in chamber)

The gas flow around the pressure $10^{-3}$~$10^{-4}$ Torr is very sensitive to the liquid surface temperature. The average chamber pressures of case 2, and case 3 go down slowly, as the surface temperature of liquid film goes down very slowly only by thermal conduction.
As the gas exhausting speed depends on the liquid surface temperature, it is necessary to cool liquid surface not only by thermal conduction but also by surface flow.

- Liquid wall design guideline:
  - Designing the free surface wall which can be cooled fast.
  - Designing the surface flow for making renewal surface (Estimating the possibility to get ~4 Hz repetition).
  - Considering free surface such as,
    - Free liquid fall with short pass (cascade structure of ~20cm pitch for renewal in 200 msec)
    - Divergent flow from bulk flow to surface flow thorough by holes or slits.
Design philosophy and basic concept for PbLi chamber

1) **No pressurized pipe or vessel in the chamber** vessel for avoiding high pressure in chamber in accidents, and for achieving simple maintenance and long life use.

2) **Fast cooled free surface wall** using divergent flow thorough from bulk flow (small holes or slit structure)

3) Feritic steal for cylindrical vessel and upper dome cover vessel

4) **Sic/Sic septate wall** without pressure bulkhead

5) Adjusting holes or slits on the septate to control divergent flow for stabilizing and fast cooling free surface

6) Two layers LiPb blankets (~20 cm for free surface first wall and ~80 cm for blanket necessary to tritium breeding) and ~45cm grafite neutron reflector.
graphite 45 cm

SiC/SiC septate with holes

SiC/SiC Chamber septate with holes controlling free fall flow

LiPb flow

F1  F2  F3
Chamber heat deposit and power flow for generation

free surface flow
Critical Issues and Major Tasks

• Physics issues and major tasks (2002~2015)
  - Fast ignition physics establishment and demonstration of ignition and burning (FIREX with high density implosion cone target)

• Driver issues and major tasks (~2012)
  - High repetition high power laser (100J and 1kJ DPSSL module, and excimer laser module development)
  - LD cost down (not only mass production but also technical breakthrough)
  - Long-lifetime and wide spectrum laser-material development (coupled with LD development)

• Target technologies issues and major tasks (~2012)
  - Cryo-target fabrication and cone target technologies
  - Target 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)
  - Final optics development for heating laser (life time evaluation or searching new alternative concepts such as impact ignition)
  - Self consistent reactor design (for guiding key technology R&D and preparing LFER design)
Target concept and gain curve of impact ignition (by Murakami)
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 ]