Feasibility Study on the Fast-Ignition Laser Fusion Reactor With a Dry Wall FALCON-D*

*) Fast-ignition Advanced Laser reactor CONcept – Dry wall version -

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Fast Ignition vs Central Ignition

<table>
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<tr>
<th>Central ignition</th>
<th>Fast ignition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isobaric</td>
<td>Isochoric</td>
</tr>
</tbody>
</table>

A fuel volume in the fast ignition pellet is 1/5~1/10 times as small as that in the central one.

- A fusion yield in one shot is remarkably reduced in the fast ignition.
- A new reactor concept so as to make full use of this advantage.
Design specialized for fast ignition

- Fast ignition scheme enables the sufficient fusion gain with 1/10 times smaller energy than conventional central ignition scheme.

  - Low wall load
    - possibility of the dry wall chamber design
  
  - Relaxation in physics requirement on pellet implosion
    - flexibility in the core plasma design
  
  - Reduction in the number of beam lines
    - easiness in the maintenance

- The main purpose of this study is to clarify physics and engineering issues.
## Comparison with other designs

<table>
<thead>
<tr>
<th></th>
<th>FALCON-D</th>
<th>Osaka Univ. KOYO</th>
<th>Osaka Univ. KOYO-Fast</th>
<th>US HAPL</th>
</tr>
</thead>
<tbody>
<tr>
<td>chamber radius [m]</td>
<td>5.64</td>
<td>4</td>
<td>3</td>
<td>11</td>
</tr>
<tr>
<td>heating method</td>
<td>fast Ignition</td>
<td>central ignition</td>
<td>fast ignition</td>
<td>central ignition</td>
</tr>
<tr>
<td>chamber wall</td>
<td>Solid</td>
<td>liquid</td>
<td>liquid</td>
<td>solid*1</td>
</tr>
<tr>
<td>input energy $E_{in}$ [MJ]</td>
<td>0.4 (0.35/0.05)</td>
<td>3.4 (1.13/0.07)</td>
<td>1.2</td>
<td>2.36 *2</td>
</tr>
<tr>
<td>pellet gain $G$</td>
<td>100</td>
<td>176</td>
<td>167</td>
<td>148</td>
</tr>
<tr>
<td>target yield $E_{fus}$ [MJ]</td>
<td>40</td>
<td>600</td>
<td>200</td>
<td>350</td>
</tr>
<tr>
<td>pulse load (except neutron) [J/cm$^2$]</td>
<td>2.0</td>
<td>60</td>
<td>35</td>
<td>4.6</td>
</tr>
<tr>
<td>repetition rate $f_{rep}$ [Hz]</td>
<td>30</td>
<td>12(3 $\times$ 4)</td>
<td>16(4 $\times$ 4)</td>
<td>5</td>
</tr>
<tr>
<td>plant fusion power $P_{fus}$ [MW]</td>
<td>1200</td>
<td>7200</td>
<td>3200</td>
<td>1750</td>
</tr>
</tbody>
</table>

*1 considering magnetic intervention scheme
*2 assumed value from the pellet gain
Repetition Rate of Laser Pulse

- Repetition rate is limited by
  - **Laser engineering technology**
    - 16Hz laser system is considered in the KOYO-Fast reactor design
    - Technically >50Hz is achievable
  - **Chamber vacuum pumping**
    - Pumping capacity of ~50Pa·m³/s enables 30Hz repetition
    - Adequate design of pumping port can cover this requirement
  - **Pellet injection**
    - Multiple injector should be introduced
    - Pellet injection speed ~500m/s, and 50 Hz requires a chamber size < ~10m

- 30Hz repetition is acceptable and achievable
@ A low aspect ratio pellet is preferable, and a pellet gain of 80 ~ 100 has been demonstrated with a pellet aspect ratio of 2 ~ 4.

@ A pulse shape of an implosion laser is optimized for a low aspect ratio pellet. The slow implosion velocity is preferable.

@ The heating pulse laser should be injected around the maximum implosion phase within a time interval of a few tens picoseconds.
Difference in 1-D and 2-D heating calculations

1-D model

- No fuel loss from back surface of the heating region
- No energy loss due to pressure work
- The temperature of heating region is initially high (including hot spot)

2-D model
Fast heating calculation by 2-D code

- Heating the edge region of hemicircle region with the radial profiles of physical parameter obtained by 1-D code (assuming optimum heating depth $\rho L_h$).
Burning Simulation with 2-D code

- The threshold energy is reduced if the slow implosion is anticipated.
- $G=100$ can be achieved with 10kJ heating (50kJ laser heating with 20% coupling efficiency).
Results of Pellet Gain

- Coupling efficiency from implosion laser to the pellet $\eta_c : 0.03\sim0.05$
- Isentrope factor $\alpha : 1.8\sim2.5$
- Fuel compression ratio $\rho/\rho_0 : 600\sim1100$
- $\rho R$ value: 1.3 times larger than the value calculated from the averaged density due to the peaked density profile.

$\Rightarrow$ 0-D physics model can reproduce the 1-D/2-D simulation result if the density peaking effect is taken into account a correction coefficient of $\rho R$. 
Thermal response of the material to the heat load is calculated by 1-D thermal conduction equation with temperature-dependent material properties.

The energy deposition profile is calculated from photoabsorption coefficient and ion stopping of the material.

Assuming chamber radius of 5.64m and 30Hz repetition.

Design of the solid first wall

- X-rays and charged particles
- F82H (3mm)
- W (1mm)
- Coolant (supercritical water, 623K)
- Adiabatic boundary
- Convection cooling
- Analyzed region (4mm)
Particle spectra are calculated by 1-D hydrodynamic simulation. α-particle spectrum is obtained from the flux-limited multi-group diffusion approximation method.

X-ray spectrum is calculated from the time-integral of the radiation from the pellet surface.
Surface (~10μm) temperature increases with very short time scale (μsec) at the arrival of debris ions.

The saturated maximum surface temperature is substantially below tungsten melting point (3680K) and threshold temperature for roughening (2500K).
Thermomechanical analysis model

- Calculations were held by ANSYS® code.
- A simple bilinear approximation was used to describe stress-strain behavior in a plastic deformation. No dynamic effect was considered. Temperature dependence of yield stress were included.

The surface strain is correlated with the temperature. The plastic strain at the maximum temperature reaches 0.01 (compression).

The surface stress during plastic deformation coincides to the yield stress determined by the temperature at the time.

The region close to the surface undergoes plastic deformation not only in heating phase but also in cooling phase.

The deeper region (>20μm) only undergoes elastic deformation.
The effect of fast deformation

- In IFE condition strain rate is very large ($\dot{\varepsilon} \sim 10^4 \text{ s}^{-1}$) due to very short pulse length. (Hall-Petch’s relation: $\sigma_y = \sigma_0 + k_s \sqrt{d}$)
The research in Tohoku University provided ultra fine-grained material that has grain size of several tens nanometers by molding a metal powder with a small amount of additives through mechanical alloying (MA) process (normally grain size is 1-10 μm).

In case of molybdenum, the thermomechanical properties in high temperature region or after irradiation are substantially improved.

In case of tungsten, ultra fine-grained tungsten (UFG-W) has been developed by MA with TiC powder under the atmosphere of hydrogen or argon.*

First wall design with UFG-W

- UFG-W shows several improvement in its themomechanical properties by the reduction of intergranular embrittlement accompanied with the interference of grain boundary movement due to the existence of TiC.
  - Temperature increase: thermal conductivity is slightly (a few %) decreases but it causes little problem.
    Structural change does not occur due to its high recrystallization temperature (>2000K)
  - Thermal stress: shows ~3GPa yield stress under high strain-rate*
    ⇒ possibility of avoiding plastic deformation
  - Sputtering: not a concern as normal tungsten
  - Blistering: 3MeV-He with $10^{23}$/m$^2$ fluence (10 times of that in HAPL) causes little surface morphological change**.
- The design of the dry wall for a commercial reactor with UFG-W might be attractive.

Maintenance schematic diagram

Reactors room (Neutron shield)

Cask

Vacuum vessel (Tritium boundary)

Target injector

Final optics

Guide rail

Chamber outer radius \( R_{\text{out}} = 6.6 \text{m} \)
(blanket thickness 1 m)
Laser beam lines more than 100 might be required in the central ignition case so as to improve the irradiation uniformity for the target compression.

In the fast ignition case, this requirement can be mitigated, and the number of the laser beam lines could be reduced.

32 beam lines are employed.

Moreover a few of beam lines might be removable. Since the upper pole beam line is an obstacle for the maintenance, this beam line is removed.

In addition, another beam line is replaced with the heating laser.

Eventually, 30 beam lines for compression laser
• The location of final optical devices can be divided into 6 groups (red, blue, green).
• To access the final optical device, 6 access corridors are placed on the reactor room wall.
• All final optical devices for compression beam lines can be replaced through those corridors.
Preliminary concept of final optics system

Schematic view

- Concrete wall (3.7m)
- Final optics module
- Beam duct
- Final optics system
- Reflection Mirror
- Shielding block
- Gate valve
- Area of maintenance corridor
- Reactor room
- Shielding module

- Build-in style in the wall of the reactor room
- Final optics module and shielding modules
- Several bending points of beam duct for reducing neutron shreming
1. Rationale

In a fast-ignition scenario a fusion yield in one shot is remarkably reduced; typically 1/5 ~ 1/10 as low as that of the central ignition. This might make it possible to introduce a new attractive reactor concept for a laser fusion reactor. Here we have designed FALCON-D with a dry wall concept, so as to make full use of this advantage in the fast ignition scenario.

In FALCON-D reactor, the pellet gain G~100 is feasible with laser energies of 350kJ for implosion, 50kJ for heating, resulting in the fusion yield of 40 MJ in one shot. By increasing the repetition rate up to 30 Hz, the fusion power of 1.2 GWth is available, and the net electric power of about 0.4 GWe is achievable.

2. Core plasma analysis

A relatively low aspect ratio pellet with A = 2 ~ 4 is adopted, and the achievement of the pellet gain of 80 ~ 100 has been confirmed with a 1-D ILESTA code. A pulse shape of an implosion laser is optimized for a low aspect ratio pellet. The slow implosion velocity is preferable.
3. **Dry wall chamber design**

   A dry wall of a ferritic steel with a tungsten armour is employed, and the feasibility of this dry wall concept is studied from various engineering aspects such as surface melting, physical and chemical sputtering, blistering and exfoliation due to helium retention, and thermo-mechanical fatigue. The UFG-W seems to be attractive for the armour material.

4. **Maintenance scenario**

   As for the maintenance scheme the first wall and blanket system is divided into 20 sectors and a large maintenance port is introduced for replacing the blanket sector. The final optics is built in the wall region of the reactor room.