Elemental Researches on Liquid Wall of KOYO-F -Aerosols, Beam port, and Cascade flow -

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Presented at US/Japan workshop on Fusion Power Reactor Design and Related Advanced Technologies

UCSD, San Diego, CA, March 5-7, 2008
Outline

• Introduction of KOYO-F

• Stability of cascade flow

• Protection of beam ports by a magnetic field

• Experimental simulation of ablation process by alpha particles using punch-out dot target
KOYO-F is a commercial or very “close to” commercial power plant.

**System specification**
- **Thermal output**: 3664 MW
- **Electric power**: 1280 MW
- **System efficiency**: 33%

**Laser**
- Cooled Yb:YAG Ceramic
- 1.2MJ/16Hz
- (1.1MJ + 100kJ)
- **Efficiency**:
  - 13.1% for Main
  - 5.4% for heating
  - 11.8% in total

**Plasma**
- **Gain**: 160
- **Fusion Yield**: 200MJ

**Reactor**
- 4 modular reactors
- **First wall**: Liquid LiPb
- **Cascade flow**
KOYO-F with 32 beams for compression and one heating beam

Parameter of KOYO-F

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Number of beams</td>
<td>32 (compression)</td>
</tr>
<tr>
<td></td>
<td>1 (heating)</td>
</tr>
<tr>
<td>Inner size of chamber</td>
<td>3 m in radius</td>
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<tr>
<td></td>
<td>12 m in height</td>
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<tr>
<td>Thermal load on the first wall</td>
<td>1.8 MJ/m²</td>
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Tilted first panels to make no stagnation point of ablated vapor
After activity of Reactor Design Committee, elemental, collaborative researches are continued to increase the reliability of KOYO-F.

- Ablation and formation of aerosols
  - Ablation process of liquid flow from first wall and RT instabilities
    - Aerosols from planar source;
    - Simulation;
- Stability of cascade flow;
- Protection of beam port;
- Injection and tracking;
- Tritium recovery;
- Chamber Activation;
- Swelling;
Outline

• Introduction of KOYO-F

• Stability of cascade flow
  – (Collaborative work with Dr Kunugi of Kyoto University)

• Protection of beam ports by a magnetic field

• Experimental simulation of ablation process by alpha particles using punch-out dot target
Cascade flow of KOYO-F

1) The height of cascade is 30 cm that comes from free fall distance in 0.25 sec (4Hz).
2) There is a void at the top of each step to obtain a stable flow.
Design base of mockup

- Water was used instead of liquid LiPb for visibility.
- The mockup was designed to obtain the same Weber number.

**Reynolds number:** \( \text{Re} = \frac{u\delta}{v} \)

**Weber number:** \( \text{We} = \frac{\rho u^2 \delta}{\sigma} \)

\[
\frac{\text{We}_{\text{water}}}{\text{We}_{\text{LiPb}}} = \frac{\sigma_{\text{LiPb}}}{\sigma_{\text{water}}} \frac{\rho_{\text{water}}}{\rho_{\text{LiPb}}} \left( \frac{u_{\text{water}}}{u_{\text{LiPb}}} \right)^2 = 1
\]

\[
\therefore \frac{u_{\text{water}}}{u_{\text{LiPb}}} = 1.21
\]
The height of the front panel is the same as actual reactor but the width is $\frac{1}{4}$ of KOYO-F 15cm
Flow loop of mockup

Test Section

Flow Meter

Valve

Flow Meter

Valve

Valve

Valve

Tank

Pump

Pump

Tank

Drain

Drain

Electric Balance

8 l/min
A continuous flow was obtained if the thickness is > 3mm.

The flow rate was 1.5 times larger than KOYO-F.
Summary of this section

• A continuous stable flow was formed if the thickness of flow was > 3mm.

• Remaining issue: demonstration of free edge
• A slit would be the solution (Proposed by Kozaki)

No support on this edge
Outline

• Introduction of KOYO-F

• Stability of cascade flow

• Protection of beam ports by a magnetic field
  – (Collaborative work with Dr. Nakashima and Kajimura of Kyushu University)

• Experimental simulation of ablation process by alpha particles using punch-out dot target
After laser shot, the tip of beam port would be coated with a membrane of liquid LiPb due to condensation of evaporated LiPb but some protection scheme is necessary for long term operation.

Our primary goal is to reduce the load to 1/10 of original design.
Protection scenario

Magnetic field

First flow

Coil
Three dimensional hybrid code was used. Ions were treated as particles and electrons were treated as a fluid.

**Equation of motion of ions**

\[ m_i \frac{d\mathbf{v}_i}{dt} = Ze(\mathbf{E} + \mathbf{v}_i \times \mathbf{B}), \quad \frac{d\mathbf{x}_i}{dt} = \mathbf{v}_i \]

**Hydrodynamic equation of electrons**

\[ n_e m_e \frac{d\mathbf{v}_e}{dt} = -en_e(\mathbf{E} + \mathbf{v}_e \times \mathbf{B}) - \nabla P_e \]

**Faraday’s law**

\[ \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \]

**Ampere’s law**

\[ \nabla \times \mathbf{B}_p = \mu_0 (\mathbf{J}_e + \mathbf{J}_i) \]

\[ \mathbf{J}_e = -en_e \mathbf{v}_e, \mathbf{J}_i = en_i \mathbf{v}_i \]

• The electric field in plasma was calculated from motion of electrons and that in neutral region was calculated from Laplace equation.
Calculation model

Initial alpha particles

Beam port

Coil

$N_\alpha = 2.5 \times 10^{18} / \text{m}^3$

$V = 1.4 \times 10^6 \text{ m/s}$
Magnetic field is effective to reduce the alpha load on the tip of beam port.

- No influence on side wall of beam port
- Thermal load around the beam port was increased to 150% but this is acceptable.

Thermal load by alpha (%)

- 100% = 0.35 MJ/m²

Coil radius r = 13 cm
B = 0.9 T
Optimization of the coil radius

A magnetic field of >0.9 T is necessary to reduce the thermal load below 0.1 $I_0$. 

![Graph showing thermal load versus magnetic field at the center](image)
Thermal load around the beam port was increased to 150% but this is acceptable.

Thermal load on the inner wall of the beam port was increased to 0.15 $I_0$. 

コイル半径 $r = 13$ cm
コイル中心磁場強度 $B = 0.9$ T

Thermal load by alpha (%)

100% = 0.35 MJ/m²
To reduce the load on corner

Original design

With corner cut L = 6 cm

\[ r = 13 \text{ cm}, \quad B = 0.7 \text{ T} \]
Corner cut reduced the necessary magnetic field to 0.7 T.

The dependence of corner cut on the thermal load at $B=0.7$ T.

The magnetic field at the center was reduced to 0.7T with corner cut.
Summary of this section

• We successfully reduced the thermal load on the beam port to acceptable level using a 0.7 T magnetic field.

• Remaining issue;
  – Thermal load of 0.04 MJ/m²
    • SiC would be the solution
  – How to make the 0.7 T field
    • Pulse operation, 50kA, 100 μs, 4Hz
    • Cooling of coil, the conductor would be liquid LiPb
Outline

- Introduce Design of KOYO-F
- Stability of cascade flow
- Protection of beam ports by a magnetic field
- Experimental simulation of ablation process by alpha particles using punch-out dot target
Ablation depth and profiles of ablated plume obtained by simulation

Temporal profile:
- Intensity (W/cm²)
- Ablation Depth
- Time (ns)
- R = 3 m

Spatial profile:
- Number Density (cm⁻³)
- Velocity (m/s)
- Pressure: few kbars at Bragg peak

Bragg peak

Alpha

Liquid → Vacuum

Number Density

Velocity

Time = 1677 ns

Liquid

Vacuum
Laser irradiation simulates for $\alpha$-particles heating from backside of metal layer.

- Laser
- Glass plate: 7 ~ 10 $\mu$m
- Coated lead or tin: (Lithium was ignored because of light weight)

- Energy density:
  - This experiment: 5 MJ/m²
  - KOYO-F: 0.35 MJ/m²
- Pulse width:
  - This experiment: 15 ns
  - KOYO-F: 50 ns
Experimental setup. Laser-scattering measurement was used to observe flying situation of metal.
Dot target propelled toward without large divergence angle

Dot tin 9μm

Time resolution: 7.5 ns

Targets were propelled forward without large divergence angle

This result indicates the tilted-front-panel concept works well.
Velocities of mass center of tin particles were 1.0 ~ 1.5 km/s

\[ \frac{dP}{dt} = m \frac{dv}{dt} \]

\( p \sim 0.8 \text{ kbar} \)

@ 1km/s

(Similar to simulation)

1.0 ~ 1.5 km/s @ 10 \( \mu \) m thickness

250 ~400 m/s @ KOYO-F

5MJ/m²

0.35 MJ/m²
Spouted gas and small particles, and large particles were detected at 10-mm away from glass plate.

- Averaged density: $2 \times 10^{18}$ (cm$^{-3}$)
- Diameter: ~10 $\mu$m
Laser irradiation induces RT instability and break up solid thin surface, generates gas clusters and large particles.
Summary of this section

• When we discuss chamber clearance, we must consider hydrodynamic process of ablation.

• Large diameter (10 μm) particles would be formed.

• Remaining issue
• Discussion on the secondary particles are necessary.
Summary

• **Stability of cascade flow**
  • When the thickness of the flow is > 3 mm, a continuous stable flow was obtained on a hydrophobic panel.

• **Protection of beam port**
  • Thermal load of alpha particles was reduced to 1/10 of the original design. No ablation takes place.
    - Remaining issue: protection of inner wall
    - SiC would be the solution.

• **Aerosols (100 nm diameter) and particles (10 μm)**
  • Hydrodynamic process must be considered to discuss formation of aerosols and particles.
    - Remaining issue: Secondary particles