Experiment and Simulation of plasma window

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UCANS2015
outline

- Introduction
- Plasma window test bench
- Simulation of plasma window
- conclusion
what is plasma window

cathode
Arc channel
anode

High pressure  Plasma  Vacuum
Traditional solid window

Disadvantage:
• Thermal damage
• Radiation damage
• Increase energy loss and energy spread
Windowless target

Windowless deuterium gas target

Expensive differential pump system
Complicated vacuum and mechanical system

Windowless hydrogen gas target for $^7$Be(p,$\gamma$) reaction measurement
Why plasma window

- needn’t worry about thermal problem.
- No radiation damage
- Very thin equivalent thickness (~nm)
- Effectively improve the performance of differential pump system
Non-vacuum electron beam welding

Electron beam current after exiting plasma window:
- Pure helium gas
- Aperture: 2.36mm
- Current: 45A

Plasma window

Air boring and non-vacuum electron beam welding with a plasma window, Ady hershcovitch, Physics of plasma, 12(2005)
Deuterium gas target using plasma window

- Plasma window
- Deflector plate
- Differentially pumped gas chamber
- Beam
- Roots blower
- Turbo molecular pump

50kW power supply

Operating gas pressure is 0.5 bar for argon
Diameter of plasma window: 5mm

High ion current beam need larger plasma window

- Small diameter Plasma window (2-5mm) is successfully used for electron beam welding and gas target.
- If larger diameter plasma window is possible, it has some potential use for high current ion beam.
Plasma window test bench

Vacuum gauge

Arc power supply

Plasma window

Two stage pump
Plasma window

Spectrum diagnostic
Pressure measurement
Water cooling

Cathode tip
Water outlet
Insulating pipe

Three aperture: 3mm, 6mm, 10mm

Cathode
anode
Copper plate
### Plasma window sealing effect

<table>
<thead>
<tr>
<th></th>
<th>Inlet pressure (kPa)</th>
<th>Outlet pressure (Pa)</th>
<th>Gas flow (SLM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>discharge</td>
<td>33.3</td>
<td>70</td>
<td>1.1</td>
</tr>
<tr>
<td>No discharge</td>
<td>12.7</td>
<td>220</td>
<td>12.3</td>
</tr>
</tbody>
</table>

Operating current is 40A operating voltage is 58V this prove the plasma window’s sealing effect!
Measurement with spectrometer

Schematic diagram of spectroscopy set up
Temperature of plasma

\[ \ln\left(\frac{I_{ji} \lambda_{ji}}{A_{ji} g_{ji}}\right) = -\frac{E_j}{kT_e} + \ln\left(\frac{\Omega V F_c}{4\pi} \frac{h c N}{Z(T_e)}\right) \]

Grating density: 300/mm
Arc current: 50A
Gas flow: 1.0 SLM
Inlet pressure: 26.1 KPa

\[ T \approx (15000 \pm 7\%) K \]

Temperature vs. Gas Flow (SLM)

- 30A
- 50A
- 70A
• Experiment show that the plasma window can work. But the sealing ability decreased quickly when plasma window’s aperture increase. It may consume much more energy
Simulation of plasma window

- Use magneto-hydrodynamic model
- Ansys fluent
- Basic assumptions
  - plasma is steady, continuous, axisymmetric and optically thin
  - Plasma is in LTE state
  - Swirling velocity is neglected
**Governing equation**

### Mass conservation equation
\[
\frac{\partial}{\partial z}(\rho \nu_z) + \frac{1}{r} \frac{\partial}{\partial r}(r \rho \nu_r) = 0
\]

### Momentum conservation equation
\[
\frac{\partial}{\partial z}(\rho \nu_z \nu_z) + \frac{1}{r} \frac{\partial}{\partial r}(r \rho \nu_z \nu_r) = -\frac{\partial P}{\partial z} + 2 \frac{\partial}{\partial z}(\mu \frac{\partial \nu_z}{\partial z}) + \frac{1}{r} \frac{\partial}{\partial r}[r \mu(\frac{\partial \nu_r}{\partial z} + \frac{\partial \nu_z}{\partial r})] + j_r B_\theta
\]

### Energy conservation equation
\[
\frac{\partial}{\partial z}(\rho \nu_z C_p T) + \frac{1}{r} \frac{\partial}{\partial r}(r \rho \nu_r C_p T) = \frac{\partial}{\partial z}(k \frac{\partial T}{\partial z}) + \frac{1}{r} \frac{\partial}{\partial r}(r k \frac{\partial T}{\partial r}) + \frac{j_r^2 + j_z^2}{\sigma} q_r + \frac{5}{2e} k_b (j_z \frac{\partial T}{\partial z} + j_r \frac{\partial T}{\partial r}) + B_\theta (j_r \nu_z - j_z \nu_r)
\]

\[
\frac{\partial}{\partial z} (\sigma \partial \phi/\partial z) + \frac{\partial}{r \partial r} (r \sigma \partial \phi/\partial r) = 0
\]

\[
-(\frac{\partial}{\partial z} \frac{\partial A_z}{\partial z} + \frac{1}{r} \frac{\partial}{\partial r} \frac{\partial A_z}{\partial r}) = \mu_0 j_z
\]

\[
-(\frac{\partial}{\partial z} \frac{\partial A_r}{\partial z} + \frac{1}{r} \frac{\partial}{\partial r} \frac{\partial A_r}{\partial r}) = \mu_0 j_r
\]
## Boundary condition

<table>
<thead>
<tr>
<th></th>
<th>P</th>
<th>$\nu$</th>
<th>T</th>
<th>$\phi$</th>
<th>$\nabla \phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AB: Inlet</strong></td>
<td>$P = 52.5KPa$</td>
<td>/</td>
<td>$T = 300$</td>
<td>$\partial \phi / \partial n = 0$</td>
<td>$A_i = 0$</td>
</tr>
<tr>
<td><strong>HI: Outlet</strong></td>
<td>$P = 60$</td>
<td>/</td>
<td>$\partial T / \partial n = 0$</td>
<td>$\partial \phi / \partial n = 0$</td>
<td>$\partial A_i / \partial n = 0$</td>
</tr>
<tr>
<td><strong>AI: Axis</strong></td>
<td>$\partial P / \partial n = 0$, $\partial \nu / \partial n = 0$</td>
<td>$\partial T / \partial n = 0$</td>
<td>$\partial \phi / \partial n = 0$</td>
<td>$\partial A_i / \partial n = 0$</td>
<td></td>
</tr>
<tr>
<td><strong>CD: Cathode</strong></td>
<td>$\partial P / \partial n = 0$</td>
<td>0</td>
<td>$-k \partial T / \partial n = h_w(T - 400)$</td>
<td>$\phi = -140$</td>
<td>$\partial A_i / \partial n = 0$</td>
</tr>
<tr>
<td><strong>EF: Anode</strong></td>
<td>$\partial P / \partial n = 0$</td>
<td>0</td>
<td>$-k \partial T / \partial n = h_w(T - 400)$</td>
<td>$\phi = 0$</td>
<td>$\partial A_i / \partial n = 0$</td>
</tr>
<tr>
<td><strong>DE&amp;FG: Wall</strong></td>
<td>$\partial P / \partial n = 0$</td>
<td>0</td>
<td>$T = 400$</td>
<td>$\partial \phi / \partial n = 0$</td>
<td>$\partial A_i / \partial n = 0$</td>
</tr>
<tr>
<td><strong>BC&amp;GH: Wall</strong></td>
<td>$\partial P / \partial n = 0$</td>
<td>0</td>
<td>$T = 300$</td>
<td>$\partial \phi / \partial n = 0$</td>
<td>$\partial A_i / \partial n = 0$</td>
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Temperature Distribution
Pressure Distribution

Pressure and velocity distribution along axis
Comparison of Experiment and Simulation results

Inlet pressure: 51kPa
Aperture: 3mm
Length: 51mm

How to increase the aperture?

- Power is proportional to $r^2$, 10 times of 3mm plasma window

Aperture: 10mm
Fixed Current: 50A
Two stage construction

![Diagram of two stage construction with graphs showing power and pressure relationships.](image)
Conclusion

- A test bench of plasma window is built. Small aperture plasma window experiment is done.
- A simulation model is set up, the simulation result is agree with experiment result. It can be used for evaluating the performance of larger aperture plasma window.
- Large aperture will need very high power, So we design a new structure of two stage plasma windows with 10mm aperture, experiments have been done and the feasibility is proven.
Future

- Do plasma window experiments with deuterium gas
- Improve the structure of plasma window
- Use the simulation method to optimized the property of large diameter plasma window
- Build two stage plasma window with large diameter if possible
Thank you for your attention!