First Results of Deuterium Beam Operation on Neutral Beam Injectors in the Large Helical Device

K. Ikeda\textsuperscript{1)}, K. Tsumori\textsuperscript{1)2)}, M. Kisaki\textsuperscript{1)}, H. Nakano\textsuperscript{1)2)}, K. Nagaoka\textsuperscript{1)3)}, M. Osakabe\textsuperscript{1)2)}, S. Kamio\textsuperscript{1)}, Y. Fujiwara\textsuperscript{1)}, Y. Haba\textsuperscript{3)}, and Y. Takeiri\textsuperscript{1)2)}

\textsuperscript{1)} National Institute for Fusion Science, National Institutes of Natural Sciences
\textsuperscript{2)} SOKENDAI, (The Graduate University for Advanced Studies)
\textsuperscript{3)} Graduate School of Science, Nagoya University
Contents

• Introduction of Neutral beam injector (NBI) for the Large Helical Device (LHD), and schedule of first Deuterium experiments.
• Result of total beam injection power in 2017
• Deuterium operation on a positive ion based NBI (P-NBI)
• Deuterium operation on a negative ion based NBI (N-NBI)
• Summary
Neutral Beam Injectors for LHD

2 x **P-NBI** (Optimized for D)

- **Upgrade beam energy**
  - 40 keV → 60 keV (BL4)
  - 40 keV → 80 keV (BL5)

  6 MW/BL (H) → 9 MW/BL for D operation

3 x **N-NBI** (Optimized for H)

- **No energy increase**
  - 180 keV (BL1, BL2, BL3)

  5 MW/BL for H operation

(Expectation) ~3.5 MW/BL for D operation
NBI operation in 2017 LHD campaign

Start Deuterium experiment used high power deuterium beam

LHD Experiment

<table>
<thead>
<tr>
<th>Year</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Full H
- Mix D-H
- Full D-D
- D-H
- Full H

26 weeks

- ✓ Neutron budget
- ✓ Learning deuterium operation

P-NBI

29 weeks

H-beam operation

D-beam operation

H-beam operation

N-NBI

Both H and D beams are injected into LHD

Only changing operation gas
Result of NB Power in 2017

P-NBI  (Optimized for D)

• Upgrade beam energy
  40keV → **60 keV** (BL4)
  40keV → **80 keV** (BL5)

6MW/BL (H)→ **9MW/BL** for D operation

N-NBI  (Optimized for H)

• Without increase beam energy
  180keV (BL1, BL2, BL3)

5MW/BL for H operation

We provided totally **31MW beam power** into LHD plasma during mixed D-H phase
(D-beam from P-NBI and H-beam from N-NBI)
Deuterium operation on P-NBIs
Injection beam power by P-NBI

### Y2015 Hydrogen operation

<table>
<thead>
<tr>
<th>H</th>
<th>Gap distance</th>
<th>Energy</th>
<th>Injection power</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL4</td>
<td>5 mm</td>
<td>45 keV</td>
<td>6.5 MW</td>
</tr>
<tr>
<td>BL5</td>
<td>5 mm</td>
<td>44 keV</td>
<td>6.1 MW</td>
</tr>
</tbody>
</table>

### Y2017 Deuterium operation

<table>
<thead>
<tr>
<th>D</th>
<th>Gap distance</th>
<th>Energy</th>
<th>Injection power</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL4</td>
<td>8 mm</td>
<td>60 keV</td>
<td>9.4 MW</td>
</tr>
<tr>
<td>BL5</td>
<td>9 mm</td>
<td>75 keV</td>
<td>10.6 MW</td>
</tr>
</tbody>
</table>
Beam & source characteristics on D

- Small optimum perveance with same arc efficiency for beam current.
- Good beam divergence on D
  - Narrow beam width on D

- Good beam quality of high Deuteron ratio (83%) same as hydrogen discharge

*Concentration of heating power at plasma center*

*Mainly heated by full energy component*
Deuterium operation on N-NBI
First trial of D-operation in N-NBI

- Replacement of discharge gas from H to D by evacuating residual gas into a pipe and buffer tank.
  \[
  (I_{\text{ex}} - I_{\text{acc}}) \approx \text{electron current}
  \]
  \[
  I_{\text{acc}} \approx \text{negative ion current}
  \]

- Start 0.3 Pa D$_2$ source gas pressure.
- Low D$^-$ current and high electron current ratio at the beginning.
- That is recovered by Cs conditioning
  \[
  \text{D}^- \Rightarrow 40 \text{ A}
  \]
  \[
  \frac{I_e}{I_{\text{D}^-}} \Rightarrow 0.55
  \]
  Necessary optimization for D

- Increasing Cs signals
  \Rightarrow High sputtering
  \Rightarrow Change surface condition
  \Rightarrow High Cs consumption
Pressure dependence

Checking extracted current by operation gas pressure in low arc discharge power

Keeping low electron current ratio in wide range
Low gas pressure can be used in H
\[ \sim 0.3 \text{ Pa} \]

Deuterium

\[ \approx \frac{e}{D} \]

\[ \approx \frac{e}{H} \]

Hydrogen

\[ \approx H^- \]

\[ \approx e \]

\[ \approx e/H^- \]

\[ \approx H \]

\[ \approx e \]

\[ \approx \frac{(lex - lacc)}{lacc} \]

\[ \approx \frac{(lex - lacc)}{lacc} \]
Bias voltage dependence

Bias voltage plays a role of suppressing the entry of electrons into the beam.

Negative ion current is also suppressed by high bias.
Keeping low e/H− ≈ 0.2 in low bias.
3 V bias on PG

Large increase of electron in low bias in D.
High bias effectively decrease e/D−.

5.6 V bias on PG

Hydrogen

Deuterium

$$\approx e/D^-$$

$$\approx e$$

$$\approx H^-$$

$$\approx e/H^-$$

Current (A)

Bias (V)

$$\approx e/D^-$$

$$\approx e$$

$$\approx H^-$$

$$\approx e/H^-$$
Arc efficiency on N-NB source

Conservative beam operation have been done for safety reasons in this campaign.

Result of beam current for H and D during beam injection as the function of $P_{arc}$.

$P_{arc}$: Total arc discharge power used two source

- Beam current linearly increases by arc discharge power. (No saturation in D)
- Deuterium beam current is 66% of hydrogen beam current (averaged value), which reaches to 190A/m$^2$.
- Conservative beam operation have been done for safety reasons in this campaign.
Lower limit for electron current ratio

- Lower limit for co-extracted electron current ratio as the function of $P_{\text{arc}}$ clearly change in D operation.

\[
\frac{(I_{\text{ex}} - I_{\text{acc}})}{100\text{kW}} \approx \frac{e}{D} - \frac{I_{\text{acc}}}{100\text{kW}} \approx \frac{e}{H} - \frac{I_{\text{acc}}}{100\text{kW}}
\]

- $e/H^- < 0.3$ in high power operation in H.

- $e/D^-$ increased 0.38 at 370 kW arc discharge.

\[\Rightarrow \text{electron current limits beam power}\]

- Input discharge power strongly affects to electron current ratio in D operation. It may due to an increase of momentum flux.
**Injection beam power by N-NBI**

Negative ion source is **optimized for H operation**

### Y2017 hydrogen operation

<table>
<thead>
<tr>
<th></th>
<th>$I_e/I_{H^-}$</th>
<th>Energy (keV)</th>
<th>Inj. power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BL1</td>
<td>0.27</td>
<td>190</td>
<td><strong>5.6 MW</strong></td>
</tr>
<tr>
<td>BL2</td>
<td>0.30</td>
<td>178</td>
<td><strong>4.6 MW</strong></td>
</tr>
<tr>
<td>BL3</td>
<td>0.23</td>
<td>185</td>
<td><strong>4.8 MW</strong></td>
</tr>
</tbody>
</table>

### Y2017 Deuterium operation (only Gas change)

<table>
<thead>
<tr>
<th></th>
<th>$I_e/I_{D^-}$</th>
<th>Energy (keV)</th>
<th>Inj. power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BL1</td>
<td>0.49</td>
<td>190</td>
<td><strong>2.1 MW</strong></td>
</tr>
<tr>
<td>BL2</td>
<td>0.54</td>
<td>171</td>
<td><strong>1.9 MW</strong></td>
</tr>
<tr>
<td>BL3</td>
<td>0.39</td>
<td>178</td>
<td><strong>2.3 MW</strong></td>
</tr>
</tbody>
</table>

Conservative beam operation in D

Totally 15 MW (H)

Totally 6.3 MW (D)
Summary (1)

- First Deuterium beam injection have been done safely in five beam lines in LHD
- Total injection beam power up to 31 MW. \([\text{P-NBI}(D)/\text{N-NBI}(H)]\)
- 10.6 MW (75 keV) deuterium beam with shape width and 83% deuteron ratio has achieved on P-NBI by upgraded beam energy and optimizing electrode gap distance.
- Negative ion current for D is 66% of H, that is reached 190 A/m². Injection beam power is less than half with conservative beam operation.
Summary (2)

- In the D− beam, lower limit of the electron current ratio strongly depends on $P_{\text{arc}}$.
- This result suggests that deuterium momentum flux strongly influences to the surface condition and the production rate of deuterium negative ions.
- Improvement of deuterium negative ion and additional electron suppression method will be required for high power deuterium beam injection.

Thank you for your attention!