Current status of LHD–NBI and upgrade of positive–ion based NBI

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Present NBI system in LHD

- LHD-NBI system is operated with high reliability as a primary heating device to extend the LHD operational regime.
Status of negative-ion based NBI
Large Helical Device

**Negative-Ion-Based LHD-NBI**

**Three injectors with six negative ion sources**

- High power NB injection is reliably carried out in every 3 minutes.
- Total achieved injection power is 16MW against the designed 15MW.
- Ion source achievement is 190keV-37A exceeding the designed 180keV-30A.

**Design (Achievements) for 1 injector**

- Energy: 180keV (190keV)
- Power: 5MW (7MW)
- Pulse: 10s (1.6s at max. power)
- Hydrogen injection of 180keV - 5MW for 1 injector.
- Two negative ion sources are attached side-by-side.
- Effective neutralization length is 5m.
- Focal length of the ion source is 13m, and the pivot point of two sources is located 15.4m downstream.
- Injection port is about 3m long with the narrowest part of 52cm in diameter and 68cm in length.
Giant negative ion source with multi-slotted GG accelerator used in the LHD-NB injector

- Cs-seeded filament-arc discharge multi-cusp source with an external filter.
- Large arc chamber of 35cm(width) x 140cm(length) x (19-23)cm(depth), with a hexagonal cross section.
- Four-grids single-stage accelerator (grid area : 25x125 cm²) divided into 5 sections with multi-slotted grounded grid.
- High current H⁻ beam production of 37A (340A/m²) at 190keV.
High-power injection of 16MW is steadily achieved every year with the negative-NBI.

- Performance of the negative-NBI system has been still improved by continuing the R&D in parallel with the operation.
- Total injection power of 16MW has been achieved with three injectors, which exceeds the designed value of 15MW, and, presently, 16MW injection is reliably carried out every year.
- Every injector has achieved the nominal injection energy and power of 180keV-5MW.
Status of positive-ion based NBI
Installed to explore the high ion temperature helical plasmas as a tools of ion-heating and diagnostic.

NB#4 was in operation in 2005 with 2 ion-sources (one injector) and upgraded to 4 sources in 2006.

Another injector (NB#5) was installed in 2010.

**NB#4:**
- Number of ion sources: 4
- Injection energy: 40keV(H)/60keV(D)
- Beam power: 6MW(H)/9MW(9MW)

**NB#5:**
- Number of ion sources: 4
- Injection energy: 40keV(H)/80keV(D)
- Beam power: 6MW(H)/9MW(9MW)
Configuration of positive-NB (NB#4)
Configuration of positive-NB (NB#5)  
(Operation: 2010~ )

Large Vacuum vessel (x2 of NB#4) to install more Cryo-sorption pump (x1.33 NB#4) and have better conductance for evacuation. Shorter horizontal pivot length, and longer vertical pivot length.
Benefits of positive-ion based NBs to plasma experiments
The high ion–temperature of Helical plasmas are explored intensively with the installation of positive–ion based NBI.

Fig. 1 Ion temperature profiles of NBI heated plasmas with C pellet injection.
NBs with relay sequence of 4 ion–sources were successfully injected for 63[s] with reduced power.

<table>
<thead>
<tr>
<th>Energy</th>
<th>25keV</th>
</tr>
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<tbody>
<tr>
<td>Injection Power</td>
<td>500kW</td>
</tr>
<tr>
<td>Duty (PS) (IS)</td>
<td>50% 25%</td>
</tr>
</tbody>
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Density increase before the ion-source change terminates the discharge.

- Introduction of Hydrogen gas for the pre-arc discharge of a subsequent ion-source increases the plasma density.
Positive ion-source development
Positive ion current: 75A
- Two ion sources are operated with one acceleration power supply.
  - Acceleration P.S.: 40kV - 180A
  - Deceleration P.S.: 2.5kV - 30A

Large rectangular arc chamber:
- 33cm(W) x 74cm(L) x 25cm(D)
- World's largest arc chamber as a positive ion source
  - Tungsten filaments: 12 - 18 of 1.8mm in dia.
  - Arc P.S.: 100V - 1800A
    (output is divided into 6 circuits)
  - Filament P.S.: 15V - 2520A
    (output is divided into 6 circuits)

Accelerator: Single-stage acceleration with three grids segmented into two parts
- Beam area: 20cm x 55cm
- Transparency: 35%
- Active cooling with cooling channels between aperture rows

Beam focal length: 8.3m
- Aperture displacement in a grid segment tilted as aiming at a focal point

R&D were performed at NB test-facility.
Magnetic field line traces, distributions of magnetic field strength, and distributions of primary electrons were calculated for several magnetic cusp configurations of arc-chamber by using a cusp field tracing code and primary electron orbit following code, which were developed by Dr. Tsumori at NIFS.
Several cusp-filed configurations are considered for the IS.

The thickness of the all cusp magnets is 8mm.

- **Type2f**
- **Type2fa4** Additional Cusp Magnet of 4mm thickness
- **Type2fa6** Additional Cusp Magnet of 6mm thickness
- **Type2fa8** Additional Cusp Magnet of 8mm thickness

The thickness of all cusp magnets is 8mm.
Distributions of Magnetic Field Strength

Type2f  

Type2fa4  

Type2fa6  

Type2fa8
Type 2f and 2fa8 is the final candidate.

“Confinement” or “Population and Uniformity near the PG” of primary electrons??

Which is more important?

$\Rightarrow$ Need experimental verifications

**PG**: plasma grid, **BP**: back plate, **SW**: side wall
Primary electron distributions for type2f

- Less electrons near PG.
- Smaller field free regions
- Better confinement of primary electrons.
Primary electron distributions for type2fa8

- Larger field free region
- Better uniformity of primary electrons.
- More primary electrons near PG
- Poor confinement of primary electrons
Comaprrison of two different cuspsps with a same ion-source.

With one additional cusp line, the cusp configuration of LA ion–source can be changed to “type2fa8” from “type2f” without breaking the vacuum.

No significant difference are observed between the beam profiles of these two configurations.

Type2f has better arc–efficiency than type2fa8.

→ The “confinement” is more important than the “uniformity and populations near the PG”.

Note: The half of the PG was masked to reduce the beam current, so that it matches to the specification of acceleration power supply at TF.
The ion-source divergent angle and the focal length were evaluated at NB Test facility by using two carolie-meter arrays at test stand.
Using the same operational condition of beam injection to LHD, the ion-source performance of the NB#4 was tested at the beam-line.

- The Arc efficiency is 0.78[A/kW], which can be increased by decreasing the filament voltage setting.
- The maximum beam current is 103[A], which is 1.25 times larger than specification.
Upgarde of positive–NBI is planned to explore the further high–ion LHD–plasmas

- Both positive–ion based NBs are planned to be upgraded to increase their injection power of **9MW at 60keV**(NB#4) and **80keV**(NB#5).

- NB#4 a has critical problem at the beam dump.
Extrapolation of positive ion-source performance for the upgrade

- 80keV/9MW operation of NB-injection is necessary for Deuterium operation:
  - Requirement for single ion-source operation:
    - H:40keV/1.5MW (~75A) => D:80keV/2.25MW (~60A).

**Gap distance must be increased for 80keV deutron beam acceleration**

Optimum beam acceleration is governed by the Child-Langmuir law.

\[ J_{si} = \left( \frac{4}{9} \varepsilon_0 \sqrt{\frac{2Ze}{m_i}} \frac{V^{3/2}}{d_s^2} \right) \]

- Mass dependence
- Gap dependence
The mass dependence of the optimum pervenance, where the beam divergence shows minimum value, were surveyed by using several gas-species (H, He and Ar). The optimum pervenance roughly scales as $A^{-0.5}$.

The optimum beam current will reduce a factor of 0.71 for deuteron-beam.
The dependence of the optimum perveance on the GAP distance \(d\) between the plasma-grid and decel-grid was surveyed. From the dependence

\[ d_s = d + 6.7 \text{[mm]} \]

was found.

For the gap-distance of \(\sim 11\text{mm}\), it was found the optimum perveance of \(0.059\text{[A/kV}^{1.5}]\) \(=\frac{60\text{[A]}}{80\text{[kV]}^{1.5}}\times 2^{0.5/2}\) was achievable with LHD positive ion source.
Performance of the residual ion–dump limits the pulse duration of NB#4

The pulse duration of full power injection was limited to only 300ms for NB#4.

- Maximum of heat load of \(~18.1\,[\text{MW/m}^2]\) is expected with present configuration at 6[MW] H–injection.
- \(27.2\,[\text{MW/m}^2]\)@9[MW] with same neutralization efficiency(0.6).
An additional pair of coils and expansion of the dump area improve the uniformity of heat loads

- The bending magnet is moved to 20cm upstream from original location.
- The Maximum heat load is expected to be reduced to 14.2 \([\text{MW/m}^2]\) even for 9[\text{MW}] injection.
- Increase of neutralization efficiency(0.7) with 60keV(D) injection is accounted for the margin of design.
LHD–NBI has been operated since 1998 with negative-ion based NBI. LHD is a unique machine where the beam power is routinely supplied by negative-ion based NB.

Maximum injection power of 16MW was achieved by 3 negative-ion based NBIs.

Positive-ion based NB has been operated since 2005 and the 2\textsuperscript{nd} P–NB are installed in 2010. They are reliably operated and the total injection power reaches 12MW.

Major-upgrade of P–NBI is planned to increase the power to 9\text{MW/injector}. 

\section*{SUMMARY}