Physics-based Investigation of Negative Ion Behavior in a Negative-ion-rich Plasma using Integrated Diagnostics

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Outline

- Injection status of NIFS negative-NBI.
- NIFS R&D negative ion source.
  - Geometric and magnetic structures
  - Diagnostic system
- Previous diagnostic results.
- Mechanism to form negative-ion plasma.
- Flow of charged particles.
  - Positive ion and electron flows
  - H\(^{-}\) ion flow
- Filter and electron deflection magnetic fields.
- Summary
Total injection power of 16 MW has been achieved in $H^0$ injection with three negative-NBIs.

By optimizing caesium seeding and beam optics

$\rightarrow$ **Maximum injection power: ~16 MW**
(with three negative-NBIs).
NIFS R&D negative ion source and its magnetic structure

Cross-sectional view of R&D negative ion source (a half length of LHD source)

- Plasma Grid (PG)
- Extraction Grid (EG)
- Grounded Grid (GG)
- Caesium
- Driver region
- Extraction region

Magnetic field viewing from A side

- Cusp field
- Filter field
- Measured region (extraction region)

*EDM: electron deflection magnet
Several diagnostic devices are installed to measure plasmas in the extraction region:

1. **Directional Langmuir probe (Four-pin)**
   - Saturation currents, plasma potential (electric field), electron temperature.
   - Positive ion and electron flows.
2. **Directional photodetachment probe**
   - Local H⁻ density, H⁻ flow, H⁻ temperature
3. **Cavity ring-down**
   - Line-averaged H⁻ density
4. **Over-saturated cavity ring-down**
   - H⁻ temperature
5. **Hα CCD imaging**
   - Two-dimensional extracted H⁻ distribution
6. **Millimeter-wave interferometer**
   - Line-averaged electron density
7. **Surface wave probe**
   - Local electron density
8. **High resolution optical emission spectroscopy**
   - Temperature of hydrogen atom
9. **Hα laser absorption spectroscopy**
   - Line-averaged H atom density
10. **Caesium laser absorption spectroscopy**
    - Line-averaged Cs sensity
Our Previous Results (1)

Formation of hydrogen ionic plasmas

Changes in probe V-I curve

H₂ discharge

H⁺ density

Electron compensation due to H⁻ extraction

H⁺  H⁻  H⁻  H⁺  H⁻  H⁺  H⁻  H⁻  H⁺

Before beam extraction
(Cs seeded plasma)

During beam extraction

Before beam extraction
(Cs seeded plasma)
In the case of filament-arc discharge, $\text{H}^-$ ions are not extracted via direct reflection of $\text{H}^0/\text{H}^+$ on the PG surface but forms a background of “$\text{H}^-$ cloud” in front of extraction apertures.

Similar characteristic due to electron densities in both plasmas.
Our Previous Results (3)

H⁻ temperature is considerably low

\[ \nu_{th} = \frac{\nu_A + \nu_C}{2} \]
\[ \nu_{flow} = \frac{\nu_A - \nu_C}{2} \]

- Over-saturated CRD and directional photodetachment probe show very low H⁻ temperature of 1-1.5 eV.
- On the other hand, H⁰ and H⁺ temperatures are about 0.3 eV.
Charged Particles on the Surface

Change of negative and positive saturation currents near PG with beam extraction.

Larger increment of electron density is observed above the cusp line of deflection magnet.

Distribution of $\text{H}^-$ in front of plasma grid is almost flat, and decreases on the average through the parallel direction to $y$.

Electrons are considered moving from driver toward cusp lines on PG.

$\text{H}^-$ ion flow does not change and just decreases on the average.

Charged Particles on PG Surface

Electrons have smaller gyro radii.
- They are absorbed partially in the metal part of plasma grid.
- Electrons are filtered by the outer loops of electron deflection magnets.

Positive ions (H⁺, H₂⁺, H₃⁺) have larger gyro radii than electrons.
- They cannot penetrate inside plasma grid.
- Converted H⁻ ions have larger gyro radii then electrons, and possible form negative-ion plasma inside EDM loops.
3-dimensionally movable directional Langmuir probe is applied to obtain flow maps

**Directional Langmuir probe**
- Rotatable around stem axis
- Movable three dimensionally
- Four-probe tips

**Measured area of positive ion and electron flow**
- Extractoin region
- Plasma grid
- Extraction grid

**Measured area of H⁻ flow (using photodetachment)**
- Extractoin region
- Plasma grid
- Extraction grid
Electron and Positive Ion Flows

• Flow change appears in the $E \times B$ drift of electrons and positive ions due to applying extraction field to the source plasma.

• The change has a turning region around 20 mm apart from the plasma grid facing source plasma.

• The positive ions and electrons move together.

S. Geng et al., *to be presented at SOFT 2016*
Two-dimensional flows of charged particle were measured in the extraction region.

Before beam extraction H⁻ flow moves opposite direction to positive ions.

During extraction H⁻ ions, H⁻ flow comes from the metal part of the plasma grid, turn the direction at a “stagnation point” near 20 mm of z, and flows back to extraction aperture.
two-dimensional flow of H⁻ ions during beam extraction has been observed.

- The flows of positive ions (electron) and negative ions directed opposite direction toward the metal part of plasma grid.
- The ions change the direction at the similar region.

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Electron deflection magnetic field

- The magnetic field starting from electron deflection magnet (EDM) links to the nearest neighbor EDM at very near plasma grid.
- The structure repeats EDM by EDM like ridges.
The EDM field links to filter magnets (FM), and the structure covers the ridge field formed by EDMs.

The field structure is very thin comparing to the dipole field formed by the linkage between FMs.
Summary

- Total injection power of 16 MW has been achieved in H\(^0\) injection with three negative-NBIs.
- In order to increase the negative ion current, especially D\(^-\) current, physics-based diagnostic study has been continued.
- In previous experiments, (1) formation of ionic plasma, (2) electron compensation to extracted H\(^-\) ions, (3) widely spread distribution of extracted H\(^-\) ions, (4) response of electron and negative-ion plasmas to bias field, and (5) H\(^-\) temperature have been investigated.
- 2-dimensional flow of electron, positive ions and H\(^-\) ions have been obtained using directional Langmuir and photodetachment probes.
- The flow patterns are influence with superimposed magnetic structure of filter and electron deflection fields.
Considering the mechanism to form ion-ion plasma, more electron suppression is expected by increasing the magnetic field near PG.

→ Using Iron SG and rods on PG, magnetic strength increase on plasma side of PG.

→ Increased magnetic strength of electron deflection field is enable to reduce the filter strength to enhance D⁺ diffusion.