Extension of Operational Regime in High-Temperature Plasmas and the Dynamic-Transport Characteristics in the LHD


E-mail: takahashi.hiromi@LHD.nifs.ac.jp

National Institute for Fusion Science, Toki 509-5292, Japan
\textsuperscript{1) Department of Nuclear Engineering, Kyoto University, Kyoto 606-8501, Japan}
\textsuperscript{2) Department of Nuclear Fusion and Plasma Science, University of Science and Technology (UST), Gajungro 217, Daejeon 305-350 Korea}
Outline

1. Extension of High-Temperature Regime in the LHD
   - Upgraded heating property and the new scenario
     with ICRF-wall conditioning

2. Characteristics of High-$T_i$ Plasmas with ion ITB
   - Centre-peaked $T_i$, reduction of $\chi_i$, energy-confinement improvement,
     and the negative $E_i$ formation

3. Dynamic Transport Analyses for High-$T_i$ Plasmas
   - Temporal change of the heat/momentum-transport state

4. Future Prospect
   - Toward the quasi steady state operation

5. Summary
Extension of High-Temperature Regime with Upgrade Heating Property
Achievement of $T_i = 7$ keV

- Installation of a new perp. NBI (6 MW/40 keV).
- New operation with ICRF wall conditioning.
  - $n_e$ profile: hollow $\rightarrow$ flat/parabolic,
  - Increase of $P_i/n_e$ in the core, $\rightarrow T_{i0}$ of 7 keV.
- High $T_i$ regime has been extended.

![Graphs and plots showing $n_e$ profiles and $T_i$, $T_e$ profiles with and without ICRF wall conditioning.](image-url)
Extension of high-$T_e$ regime

- Since 2007, Gyrotron x3 (Over 1 MW each/ 77 GHz).
- Increase of $P_{\text{ECH}}$ -> Extension of high $T_e$ regime.

(1) Achieved highest temperature -> $T_{e0} = 20$ keV ($n_{e\_fir} = 0.20 \times 10^{19}$ m$^{-3}$).

(2) High density condition,

$\rightarrow T_{e0} = 8.7$ keV ($n_{e\_fir} = 1.1 \times 10^{19}$ m$^{-3}$), $T_{e0} = 1.3$ keV ($n_{e\_fir} = 5.4 \times 10^{19}$ m$^{-3}$).

![Graph](image_url)
Characteristics of High-\(T_i\) Plasmas with Ion ITB
Typical time evolution in a carbon pellet discharge

In the C-pellet discharge,

- $T_i$ and $dT_i/dr_{\text{eff}}$ increased in the core -> ion-ITB
- $T_e$ was not improved -> $T_e/T_i$ dropped to 0.5.
- The energy confinement improved by a factor of 1.5.
- $\chi_i$ reduced in the entire region.
- The improved confinement was transient.
Relation between grad-$T_i$ and $V_\phi$ shear

- Centre-peaked profile of $V_\phi$ was formed.
- $V_\phi$ shear clearly increased with increase of $T_i$ gradient.
Radial electric field in ion ITB plasma

Neoclassical transport,

- Huge if $E_r = 0$.
- Significantly reduced due to $E_r$.

$E_r$ was measured using HIBP,

- Low $T_i$ -> $E_r \sim 0$
- Ion ITB -> Negative $E_r \leftrightarrow \text{grad } T_i$

![Graph showing the relationship between $Q_{\text{ion,NC}}$, $Q_{\text{e,NC}}$, $E_r$, and $T_i$ with $r_{\text{eff}}/a_{99} = 0.34$, $t = 4.74 \text{ s}$, and $V_s$ vs. $r_{\text{eff}}/a_{99}$ showing data points at $4.04 \text{ s}$, $4.34 \text{ s}$, $4.1 \text{ s}$, and $4.4 \text{ s}$].
Dynamic Transport Analyses for High-$T_i$ Plasmas
Temporal change of $\chi_i$ and $\mu_\phi$

- Temporal behaviour of $\chi_i$
  - Plasma Core -> Slow change, **great decrease**.
  - Peripheral -> Fast change, **small decrease**.
- Toroidal-momentum transport was also improved.
The slope in the flux-gradient relation $\rightarrow \chi_i, \chi_e$

- Improvement of the ion-heat transport $\rightarrow$ Back to low confinement branch.
- The electron-heat confinement was not improved.
The slope in the flux-gradient relation -> $\mu_\phi$

- (1) Decrease of $\mu_\phi$, (2) Increase of the intrinsic rotation.
- Back to low-confinement branch.
- $P_r = \mu_\phi/\chi_i$ kept unity.
Future Prospect and Summary
Toward quasi-steady-state operation

Strategy of high-$T_i$ operation in the LHD

- Verification how high $T_i$ is realized.
- Long pulse operations toward a reactor.

In the He-puffing discharge

- Steep $T_i$ gradient and reduction of $\chi_i$.
- $T_{i0} \sim 5$ keV/1 sec. was achieved.
- $T_i$ degradation was considerably smaller.

\begin{figure} 
\centering 
\includegraphics[width=\textwidth]{figure.png} 
\caption{} 
\end{figure} 

Summary

Progress of the extension of the high-temperature regime

- **High-temperature regime was successfully extended** due to the upgraded heating system and the optimization of discharge scenario.

High $T_i$ characteristics with ion ITB

- Centre-peaked $T_i$ and $V_\phi$, energy-confinement improvement, reduction of $\chi_i$ and $\mu_\phi$ and the negative $E_r$ were observed.

- Ion thermal transport and momentum transport moved to high confinement branch by the ITB formation.

Future works

- Investigation of the off-diagonal-terms effects.

- Performance integration of high-$T_i$, high $T_e$ and long-time sustainment.
ICRF-conditioning effect on the high-\(T_i\) discharge

Before the ICRF conditioning,

\(T_{i0}\) below 6 keV, hollow \(n_e\) profile.

After 30 discharges of ICRF conditioning,

- Residual pressure significantly decreased,
  - Decrease of neutral recycling,
  - Lower \(n_e\) with the parabolic profile,
  - \(P_i/n_e\) increased in the plasma core,
  - \(T_{i0}\) exceeding 6 keV.
Toward quasi-steady-state operation

Strategy of high-$T_i$ operation in the LHD

- Verification how high $T_i$ is realized in helical system.
- **Long pulse operations toward the fusion reactor.**

In the He-puffing discharge ($H/(H+He) \sim 0.75$),

- Steep $T_i$ gradient and decrease of $\chi_i$.
- $T_{i0} \sim 5$ keV/1 sec. was achieved.
- $T_i$ degradation was quite smaller.

![Graphs and figures related to plasma parameters and operations in the LHD.](image)
Newly installed NBI and gyrotrons

- Recent upgrade of heating system:
  - Since 2007, **Gyrotron x3** *(Over 1 MW each/ 77 GHz)*
  - 2010, **Perpendicular NBI** *(6 MW/ 40 keV)*
- Total PT power, **NBI: 28 MW, ECRH: 3.7 MW**

### History of total injection power to LHD

(a) $P_{\text{NBI_PT}}$
(b) $P_{\text{ECRH_PT}}$

- Installation of 1st positive NBI
- Installation of 1st 77 GHz gyrotron
- 2nd 77 GHz
- 3rd 77 GHz
- Installation of 1st 77 GHz gyrotron

### Power Levels

- **Positive, perp.**
  - 6 MW/ 40 keV
- **Negative, tang.**
  - 5 MW/ 180 keV
- **Positive, perp.**
  - 6 MW/ 40 keV
- **Negative, tang.**
  - 5 MW/ 180 keV
- **77 GHz gyrotron**
  - Over 1 MW
In the C-pellet discharge,

- $T_i$ and $dT_i/dr_{\text{eff}}$ clearly increased in the core -> ion-ITB
- $T_e$ was not improved and $T_e/T_i$ dropped to 0.5.
- The energy confinement improved by a factor of 1.5.
- $n_e$ fluctuation significantly suppressed.
- $\chi_i$ reduced in the entire region.
- The improved confinement was transient.
Behavior of $E_r$ and turbulence in high-$T_i$ plasmas

- Negative $E_r$ was formed in the core and was gradually decreased with $T_i$ degradation.
- $n_e$ fluctuation started to increase from the peripheral region to the core.
- $T_i$ also decreased from the edge.
- The difference of the time constant of $T_i$ change is considered to form the steep $T_i$ gradient in the core.
Recovery of $T_i$ by an additional impurity pellet

Additional C pellet was injected in the $T_i$ degradation phase

- Increase of $V_\phi$ was not observed but the time constant of the degradation became longer.
- Clear recovery of $T_i$ and grad $T_i$.

Impurity effect is one of the candidate for the confinement improvement due to the suppression of turbulence.
2nd pellet reference #106452

LHD 106452  gas : Ar He  
18 Aug. 2011 (Thu.) 11:5
B=−2.750T, Rax= 3.600m, γ=1.254, Bq= 100%

[(4) High Te/Ti] High Ti with C-Pellet

Baking, TIG, Boronization 7/22  (B : CCW)
Quasi steady state #111366

LHD 111366  

\[ B = -2.850 \text{T}, R_{\text{ax}} = 3.600 \text{m}, \gamma = 1.254, B_q = 100.0^\circ \]  

\[ I_{\text{up}} : 0, 0, 0 \text{A} \]  

HeCDD, TiG, Boronization 7/22  

[(4) High Te/Ti] High Ti : ICH Wall Conditioning / ICH Optimization (B : CCW)

\[ T(eV) = 3.55 - 3.75 \text{keV} \]

\[ W_p \text{ max} = 1.502 \times 10^{19} \text{m}^{-3} \]

\[ t = 6.280 \text{s} \]

\[ I = 1.860 \text{m} \]

\[ r = 0.869 \text{m} \]  

\[ \text{gain} = 1.515 \text{ MW} \]

\[ t = 4.474 \text{s} \]

\[ R_{\text{ch1}} \text{, I}_1 \text{, visible brems.} \]

\[ \text{neutral pressure} \text{ [du] x 20} \]

\[ \text{frame 16} \]

[Graphs and data points related to plasma parameters and conditions are shown in the diagram.]

25/16
Temporal change of \( Z_{\text{eff}} \)

TASK3D for quasi-steady-state plasma

Prediction of achievable temperature

→ survey for “anomalous” modeling
→ Increased accuracy of prediction

- TASK3D simulation qualitatively reconstructed the experimental results.
Time-transient $P_{NB}$ was evaluated taking account of $E_C$ and $\tau_{se}$.

- Temporal change of the energy of the beam particle, which is produced every 0.1 ms, was calculated.
- Plasma is heated by the particles with $E > T_i \ (T_e)$.
- Heating contribution of the particles at $t = t_j$ was calculated and the temporal $P_{NB}$ was evaluated from the summation of $\Delta E = E_j - E_{j+1}$.

\[
E_{j+1} = \left( E_j^{3/2} \exp \left( -\frac{3\Delta t}{\tau_{se}} \right) \right. \\
- E_c^{3/2} \left( 1 - \exp \left( -\frac{3\Delta t}{\tau_{se}} \right) \right) \left. \right)^{2/3}
\]
High-power gyrotron has been successfully developed

- Output power of 1.8 MW was obtained for one second in a 77 GHz-gyrotron, which was developed in collaboration with University of Tsukuba.

Stationary operation for 1 sec

World’s highest output power (>1 sec) was achieved.

77 GHz-Gyrotron