Transport Characteristics of Deuterium and Hydrogen Plasmas with Ion ITB in LHD

K. Nagaoka$^{1,2}$

H. Takahashi$^{1,3}$, M. Nakata$^{1,3}$, K. Tanaka$^{1,4}$, K. Mukai$^{1,3}$, M. Yokoyama$^{1,3}$, H. Nakano$^{1,3}$, S. Murakami$^5$, K. Ida$^{1,3}$, M. Yoshinuma$^{1,3}$, S. Ohdachi$^{1,3}$, T. Bando$^6$, M. Nunami$^{1,3}$, S. Satake$^{1,3}$, R. Seki$^{1,3}$, C. Suzuki$^{1,3}$, H. Yamaguchi$^1$, M. Osakabe$^{1,3}$, T. Morisaki$^{1,3}$ and the LHD Experiment Group

$^1$National Institute for Fusion Science, National Institutes of Natural Sciences
$^2$Nagoya University, Graduate School of Science
$^3$SOKENDAI, Department of Fusion Science
$^4$Kyushu University, Interdisciplinary Graduate School of Engineering Sciences
$^5$Kyoto University, Graduate School of Engineering
$^6$National Institutes for Quantum and Radiological Science and Technology
1. Introduction

2. Transport characteristics and improvement
   - $T_e/T_i$ dependence
   - $R/L_{Ti}$ dependence

3. Isotope effects
   - Lower $\chi_i$ in deuterium plasma
   - Nonlinear transport simulation (GKV)

4. Summary
• The $T_i$ is higher than the $T_e$ in the core of NBI heated plasma.
• The peaked $T_i$ profile with steep gradient (ion ITB) formed, and no ITB was observed in the $T_e$ and density profiles.
• Significant reduction of anomalous ion heat transport with $E_r<0$ (ion-root).
• Carbon impurity was expelled from the core (Impurity hole formation)
ITG is dominated in high-$T_i$ plasmas in LHD

Gyrokinetic Vlasov code (GKV)
- 5 dimensions in phase space
- local flux tube
- Inward shifted LHD plasmas

In high-$T_i$ regime ($R/L_{T_i} \sim 10$), **ITG mode** is the most unstable

- Growth rate increases with $R/L_{T_i}$ ($= -(R/T_i)(dT_i/dr)$)
- Growth rate increases with $T_e/T_i$ as well

Therefore, we focus on $R/L_{T_i}$ and $T_e/T_i$ dependence
Deuterium experiment in LHD
Specifications

- Helical mode numbers: $l/m=2/10$
- All superconducting coil system
- Plasma major radius: 3.42-4.1 m
- Plasma minor radius: 0.63 m
- Plasma volume: $30 \text{ m}^3$
- Toroidal field strength: 3 T
- 20 RMP coils

Deuterium experiment in LHD

Positive, perp.
6 MW/40 keV
-> 9 MW/80 keV

Negative, tang.
5 MW/180 keV

Negative, tang.
6 MW/180 keV

Positive, perp.
6 MW/40 keV
-> 9 MW/80 keV
Extension of high-\(T_i\) regime \((T_{i0}=10\text{keV})\)

- \(T_{i0}=10\text{keV} \pm 0.2\text{keV} \left(Z_{\text{eff}}=\sim2\right)\) was achieved
- C pellet + He gas puff
- D beams (p-NBI) + H beams (n-NBI)
- MHD bursts (EIC) degraded the neutron rate and \(T_{i0}\)

The ion heat transport with D is improved, although the D ion ratio is roughly 30% of ion density.
In order to evaluate the transport in more detail and discuss isotope effect, pure H plasmas and pure D plasmas are analyzed in this study.
1. Introduction

2. Transport characteristics and improvement
   - $T_e/T_i$ dependence
   - $R/L_{Ti}$ dependence

3. Isotope effects
   - Lower $\chi_i$ in deuterium plasma
   - Nonlinear transport simulation (GKV)

4. Summary
Pure Hydrogen and Pure Deuterium plasmas

Target plasmas analyzed in this study are High Purity of ion species

**H plasma:** \( \frac{n_H}{n_e} > 0.80 \) with H gas puff + H beams

**D plasma:** \( \frac{n_D}{n_e} > 0.80 \) with D gas puff + D beams
ITG like $T_e/T_i$ dependence

- Significant increase of heat transport depending on $T_e/T_i$ $\Rightarrow$ consistent with ITG turbulence
- No significant difference in $T_e/T_i$ dependence between H and D plasmas
Transport suppression with \((R/L_{Ti})\)

- Reduction of heat transport with \(R/L_{Ti}\), inconsistent with ITG nature
  \(\Rightarrow\) ion ITB formation
- Transport suppression in D plasmas
  \(\Rightarrow\) another mechanism of transport suppression depending on ion mass
Turbulent suppression depending on ion mass and $R/L_{Ti}$

Radial electric field shear ($E\times B$ poloidal rotation)

$$\nabla_{E\times B} = |d\nu_{E\times B}/dr|(R/\nu_{ti})$$

Burrell PoP1997, Jolliet NF2012

$$\propto \rho^*(\partial_{\rho}((k-1)R/L_T - R/L_n)/\partial\rho + (a/R)\partial_{\rho}(U_{||}/\nu_{ti})$$

- stabilization mechanism for both ITG and TEM
- finite Larmor radius effects may appear in high-Ti plasmas

$$\rho_{D:10keV}^* = 1/90, \rho_{H:10keV}^* = 1/130$$

$\Rightarrow$ ion mass dependence

The $E\times B$ shear is a potential candidate of physics mechanism of turbulent suppression, although it should be confirmed by further experiments and global transport simulations in near future.
1. Introduction

2. Transport characteristics and improvement
   - $T_e/T_i$ dependence
   - $R/L_{Ti}$ dependence

3. Isotope effects
   - Lower $\chi_i$ in deuterium plasma
   - Nonlinear transport simulation (GKV)

4. Summary
Pure Hydrogen and Pure Deuterium plasmas

Target plasmas analyzed in this study are High Purity of ion species

H plasma: \( \frac{n_H}{n_e} > 0.80 \) with H gas puff + H beam

D plasma: \( \frac{n_D}{n_e} > 0.80 \) with D gas puff + D beam

Comparison with the same \( n_e \) and \( P_{i_{\text{tot}}} \)
Comparison between H plasma and D plasma

- Higher $T_i$ in D plasma
- Steeper density gradient in the edge of D plasma
- Larger electron heating power in H plasma with a factor of 1.5
  $\Rightarrow$ higher $T_e$ (20-30%)
Transport analysis

- Significant reduction of the ion heat transport in the core of both plasmas \( \Rightarrow \) Ion ITB formations
- Smaller heat transport in D plasma
- Density fluctuation (PCI) is smaller in D plasma \( \Rightarrow \) correlating with heat transport
Nonlinear gyrokinetic simulation (GKV) with plasma profiles obtained in experiment

- Destabilization of ITG mode and nonlinear saturation
- Transport level is reproduced with the accuracy of 20% in $T_i$ gradient
  $=>$ Global effects such as Er-shearing will improve the discrepancy
- Reproduce the reduction of ion heat transport in D plasma
Nonlinear gyrokinetic simulation (GKV) with plasma profiles obtained in experiment

- ZF energy partition is larger in D plasma with factor of 1.3
  => ZF enhancement may contribute the transport reduction in D plasmas
In D experiments in LHD, $T_{i0}=10\text{keV}$ was achieved, and transport analyses of Ion ITB plasmas and isotope effect were discussed.

On Ion ITB formation
- $T_e/T_i$ dependence is ITG-like
- Transport reduction with $R/L_{Ti}$
  - $\Rightarrow$ ion ITB
  - $\Rightarrow$ suggesting the improvement with ExB shear

On isotope effect
- Ion heat transport reduction in D plasma
- Nonlinear sim. (GKV) reproduced the reduction of $\chi_i$ in D plasma, and observed the increase of ZF

These mechanisms contribute to the achievement of $T_{i0}=10\text{ keV}$ in the helical plasma
Thank you for your attention!
Neoclassical transport

- Neoclassical transport calculation with FORTEC3D
- The solution with $\text{Er} > 0$ was obtained, and should be checked experimentally
- The NC transport is smaller than experimental evaluation
  => turbulent dominates the transport
- The difference of NC transport between H and D plasma is smaller and cannot explain the experimental observation
Strategy of evaluation of isotope effects in LHD

**Global confinement**

Scaling of confinement time

\[ \tau \sim A^{x_1} \cdot \rho_*^{x_2} \cdot \nu_*^{x_3} \cdot \beta^{x_4} \]

- wide parameter regime

**Local transport**

Dependence on local parameters, their gradients

\[ \chi \sim A^{x_1} \cdot \rho_*^{x_2} \cdot \nu_*^{x_3} \cdot \beta^{x_4} \cdot (T_e/T_i)^{x_5} \cdot (R/T_T)^{x_6} \cdot (R/T_n)^{x_7} \cdots \]

- underlying physics
- excellent profile measurement
Nonlinear gyrokinetic simulation (GKV) with plasma profiles obtained in experiment

- Destabilization of ITG mode and nonlinear saturation
- Reduction rate of heat transport reproduced the experiment
- ZF energy partition is larger in D plasma with factor of 1.3

Global effects such as Er-shear effect will improve the discrepancy in the heat transport