Formation mechanism of toroidal rotation profile and characteristics of momentum transport in JT-60U

Japan Atomic Energy Agency


22nd IAEA Fusion Energy Conference,
13-18 October 2008,
Geneva, Switzerland
1. Motivation

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   i) Relation between the momentum diffusivity ($\chi_\phi$), the heat diffusivity ($\chi_i$) and the convection velocity ($V_{\text{conv}}$)
   ii) Intrinsic rotation by pressure gradient ($\text{grad}P_i$)
   iii) Role of electron cyclotron range of frequency wave (ECRF) on toroidal rotation

4. Summary
Motivation

Toroidal rotation velocity ($V_t$) profiles play one of the most critical roles for plasma transport and MHD stability. $V_t$ profiles are determined by various mechanisms.

External torque (NB)  Ripple loss of fast ions

Pressure profile  Toroidal rotation velocity ($V_t$) profile

intrinsic rotation

Momentum Transport

The formation mechanism of the $V_t$ profile has not been understood well, despite its urgency towards the future devices (ITER, DEMO).

This is due mainly to an experimental difficulty in evaluating the momentum diffusivity ($\chi_\phi$), the convection velocity ($V_{\text{conv}}$) and the intrinsic rotation separately.
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The formation mechanism of the \(V_t\) profile has not been understood well, despite its urgency towards the future devices (ITER, DEMO).

This is due mainly to an experimental difficulty in evaluating the momentum diffusivity \((\chi_\phi)\), the convection velocity \((V_{conv})\) and the intrinsic rotation separately.
Objectives

For understanding of the rotation mechanisms with integrating all of the terms, we separately investigate

(i) Relation between $\chi_\phi$, $V_{\text{conv}}$ and the heat diffusivity ($\chi_i$),

(ii) Intrinsic rotation by pressure gradient ($\text{grad}P_i$),

(iii) Role of ECRF on $V_t$ profile,

by using the original transient momentum transport analysis.
After separating diffusive and non-diffusive terms, relation between $\chi_\phi$ and $\chi_i$ is investigated

$\chi_\phi$ and $V_{\text{conv}}$ are evaluated by the transient momentum transport analysis with PERP-NBs.

$\mathbf{I_p\ scan\ in\ H-mode}$

$q_{95} = 3.9$, $P_{\text{ABS}} = 7.6-7.9$ MW

-20 -10 0 10 20
V_{\text{conv}} (m/s)

0 0.2 0.4 0.6 0.8 1
r/a

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I_p scan in H-mode
$q_{95} = 3.9$, $P_{\text{ABS}} = 7.6-7.9$ MW

from the radial profile
$r/a = 0.2-0.6$

$\chi_\phi$ increases with increasing $\chi_i$.
This tendency is observed over a wide range of radii for each discharge.
\( \chi_\phi / \chi_i \) depends on \( T_i \) strongly

The relations between \( \chi_\phi \) and \( \chi_i \) in H-mode plasmas is elucidated at constant \( I_p=1.2 \) MA, \( B_T\sim 2.5 \) T, \( \kappa_x\sim 1.36, \delta_x=0.34 \).

\[ P_{ABS}=5.6-9.1 \text{ MW}, \]
\[ n_e=2.0-3.0 \times 10^{19} \text{ m}^{-3} \]

\[ \chi_\phi / \chi_i \sim 0.7-3 \]

i) \( \chi_\phi / \chi_i \) varies from \(~0.7\) to \(3\) at the middle of plasma.

ii) \( \chi_\phi / \chi_i \) is larger at higher \( T_i \).

iii) Such a dependence of \( \chi_\phi / \chi_i \) on \( T_i \) has been found systematically.
Correlation between $V_{\text{conv}}$ and $\chi_\phi$ is found

H-mode plasmas at $I_p=1.2$ MA, $B_T=2.5-2.6T$, $\kappa_x=1.34-1.38$, $\delta_x=0.32-0.35$. $P_{\text{ABS}}=5.6-9.1$ MW, $n_e=2.0-3.0\times10^{19}$ m$^{-3}$

from the radial profile $(0.25<r/a<0.6)$

Inward convection velocity ($-V_{\text{conv}}$) increases with increasing $\chi_\phi$.

$-V_{\text{conv}}/\chi_\phi \sim 0.5-2$ (m$^{-1}$).

These findings of the correlation between $\chi_\phi$, $\chi_i$, $V_{\text{conv}}$ can contribute to the understanding of the anomalous momentum transport.
Intrinsic rotation by $\text{grad} P_i$

- External torque (NB)
- Ripple loss of fast ions

Pressure profile

Toroidal rotation velocity ($V_t$) profile

ECRF

Momentum Transport

\( \chi_\phi \leftrightarrow V_{\text{conv}} \)
Approach: How to investigate intrinsic rotation

**Externally driven rotation**

- External momentum source (NB)
- Momentum transport ($\chi_\phi$, $V_{\text{conv}}$)

**Intrinsic rotation ($\Delta V_t$):**
- Driven by the plasma itself

\[ V_t(r) = V_t^{\text{cal}} + V_t^{\text{intrinsic}} \]

- Measured by CXRS

**Steady $V_t$ profiles** with CO, BAL and CTR-NB can be reproduced by $\chi_\phi$ and $V_{\text{conv}}$.

\[ \text{grad} P_i = 2.4 \text{ MW, } \beta_N = 0.4 \]

\[ \text{P}_{\text{ABS}} = 2 \text{ MW, } \beta_N = 0.39 \]

\[ \text{P}_{\text{ABS}} = 1.7 \text{ MW, } \beta_N = 0.34 \]
Approach: How to investigate intrinsic rotation

V_t(r) = V_t^{\text{cal}} + V_t^{\text{intrinsic}}

Measured V_t deviates from the calculation in the CTR-direction with a large gradP_i.

Each V_t profile is calculated using $\chi_{\phi}$, $V_{\text{conv}}$ evaluated by modulation experiment for every discharge. (NO scaling is used.)
Local gradP_i causes intrinsic rotation mainly

**L-mode plasmas** (I_p=1.5 MA, B_T=3.8 T)

- P_ABS=2.4 MW
- =6.0 MW
- =6.4 MW
- =11 MW

**H-mode plasmas** (q_95=3.9, P_ABS~7.8 MW)

- I_p=1.2 MA
- I_p=1.5 MA
- I_p=1.8 MA

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i) The intrinsic rotation (∆V_t) grows with increasing gradP_i.

ii) Almost the same tendency is observed in L-, H-mode, CO-, CTR-rotating plasmas, over a wide range of \( \chi_\phi \).

iii) Even for the different in I_p, the similar dependence is observed.

The proper evaluation of the momentum coefficients (\( \chi_\phi, V_{conv} \)) has enabled us to evaluate the intrinsic rotation.
Intrinsic rotation by ECRF

- External torque (NB)
- Ripple loss of fast ions
- Pressure profile
- Toroidal rotation velocity ($V_t$) profile
- ECRF
- Momentum Transport

Intrinsic rotation

$\chi \leftrightarrow V_{\text{conv}}$
Change in $V_t$: CO-direction inside EC deposition : CTR-direction outside EC deposition

Change in $V_t$ is caused by the change in (i) the momentum transport, (ii) the intrinsic rotation by $\nabla P_i$, (iii) the intrinsic rotation by ECRF.

$\rho_p=1.0$ MA, $B_T=3.8$ T, $P_{NB}=7.6$ MW
ECRF changes $\chi_\phi$ and $V_{\text{conv}}$. However, Change in $\chi_\phi$ and $V_{\text{conv}}$ does not affect $V_t$ (BAL-NB)

The change in $V_t$ by changing the momentum transport is estimated in a similar experimental condition.

The momentum transport degrades with ECRF. However the $V_t$ determined by the transport hardly changes in the region $0.4<r/a<0.7$ because of the BAL-NB injection (= low torque)
ECRF drives: CO-intrinsic rotation inside the EC, CTR-intrinsic rotation outside the EC

The change in the intrinsic rotation by $\text{gradP}_i$ is also estimated from the relation between the intrinsic rotation and $\text{gradP}_i$.

$\text{gradP}_i$ degrades with ECRF.

Grad$P_i$ degrades with ECRF.

The degradation of grad$P_i$ increases the CO-rotation inside $r/a \sim 0.4$. Even the changes in the momentum transport and $\text{gradP}_i$ are taken into account, ECRF driven rotation is still remarkable.
Rotation inversion radius depends on EC deposition radius

To clarify the relation between EC deposition radius and the rotation inversion radius,

EC deposition scan is demonstrated: $r/a \approx 0.3, 0.45$ and 0.6.
($I_p=1.0$ MA, $B_T=3.8$ T, $P_{NB}=7.5$ MW, $P_{ECH}=2.1-2.7$ MW)

The rotation inversion radius accompanies the EC deposition radius.
CTR-\( V_t \) starts around the EC deposition radius and propagates to the edge region.

Starting time of the change in \( V_t \) is investigated in the case of \( r/a \sim 0.3 \).
\( (I_p=1.0 \text{ MA}, B_T=3.8 \text{ T}, P_{NB}=7.5 \text{ MW}, P_{ECH}=2.1-2.7 \text{ MW}) \)

Local EC driven intrinsic rotation propagates in the radial direction.
Summary

We investigate the characteristics of the momentum transport in H-mode plasmas.

\( \chi_\phi \) increases with increasing \( \chi_i \), \( \chi_\phi / \chi_i \approx 0.7-3 \) at the middle of plasma,

\( \chi_\phi / \chi_i \) increases with \( T_i \).

\(-V_{\text{conv}}\) increases with increasing \( \chi_\phi \), \(-V_{\text{conv}}/\chi_\phi \approx 0.5-2 \) (m\(^{-1}\)).

The characteristics of the intrinsic rotation by pressure gradient is found by separating the effects of momentum transport.

The CTR-intrinsic rotation (\( \Delta V_t \)) grows with increasing \( \text{gradP}_i \).

This tendency is almost the same in L-, H-mode, CO-, CTR-rotating plasmas, even in the different \( I_p \), over a wide range of \( \chi_\phi \).

The role of ECRF on \( V_t \) profile is also found.

ECRF degrades both the momentum and thermal confinements.

ECRF drives the CO-intrinsic rotation inside the EC deposition and drives the CTR-intrinsic rotation outside the EC deposition.