Mechanism of Low-Intermediate-High Confinement Transitions in HL-2A Tokamak

Southwestern Institute of Physics, Chengdu, China

In collaboration with
Institute for Fusion Theory and Simulation, ZJU, Hangzhou, China
National Institute for Fusion Science, Toki, Japan
University of Science and Technology of China, Hefei, China
WCI Center for Fusion Theory, Daejeon, Korea
Kyushu University, Kasuga, Japan
CEA, IRFM, Cadarache, France
Outline

1. Introduction
2. Experimental setup
3. Experimental results
4. Summary and discussion
1. Introduction

- Identification of the key plasma parameters, which control/determine the L-H transition and reveal its mechanism, has been a long term focus of investigation and a topic of interest.
- Understanding of transition physics is essential for assessing power threshold scaling and ensuring heating power requirements for future fusion reactors such as ITER.
- Study on dynamics of limit cycle oscillations (LCOs) with expansion of time scale provides an opportunity to investigate the subject quantitatively.
- The LCOs have been studied theoretically with predator-prey and bifurcation models, respectively.
- In experiment, spontaneous LCOs were observed on JET, JFT-2M, AUG, DIII-D, EAST, NSTX, H-1, and TJ-II.
- Mechanism, trigger and onset conditions of the L-I-H transitions are investigated on HL-2A tokamak.
2. Experimental setup

3D Langmuir probe arrays

- Sampling rate = 1 MHz
- Spatial resolution = 3 mm
- Diameter of tips is 1.5 mm.
- Height of tips is 3 mm.

Parameters measured simultaneously:
\[ T_e, n_e, \phi_f, \tilde{n}_e, E_r, P_e, E'_r, P_e' \]

etc. at a few radial and poloidal positions in two poloidal sections;

Complete data of edge turbulence in tokamak plasmas.
3. Experimental results

Shot I with L-I-H transitions
Bt=1.4 T, Ip=180 kA
\( P_{\text{NBI}}=1.0 \text{ MW} \)
\( \bar{n}_e = (2.8-3.2) \times 10^{19} m^{-3} \)

Shot II with L-I-L transitions
Bt=1.4 T, Ip=185 kA
\( P_{\text{NBI}}=1.0 \text{ MW} \)
\( \bar{n}_e = (2.5-3.0) \times 10^{19} m^{-3} \)

• Strong turbulent fluctuations of floating potentials and densities, and weak radial electric fields in the L-modes.
• Weak fluctuations of floating potentials and densities but strong radial electric fields in the I-phases.
• Rather weak fluctuations of floating potential and density but very strong radial electric field in the H-mode.

In the I-phases, all the fluctuations oscillate at same frequency of \( f_{\text{LCO}} \approx 2.6 \text{ kHz} \) which is identified to be close to the local Ion-ion collision frequency.
LCO in L-I-H & L-I-L transitions

Envelope of ne(a.u.)

envelope dE0|E0|<T_e>

LCO in L-I-H & L-I-L transitions

[Cheng & Dong et al., PRL 110, 265002 (2013)]

SWIP
Southwestern Institute of Physics
Brief numerical analysis of LCOs

\[ \frac{\partial \varepsilon}{\partial t} = N \varepsilon - a_1 \varepsilon^2 - a_2 V^2 \varepsilon - a_3 V_{zf} \varepsilon - a_d V \varepsilon, \]

\[ \frac{\partial V_{zf}}{\partial t} = \frac{b_1 \varepsilon V_{zf}}{1 + b_2 V^2} - b_3 V_{zf}, \]

\[ \frac{\partial N}{\partial t} = -c_1 \varepsilon N - c_2 N + Q, \]

\[ V = dN^2. \]

(a) \( \varepsilon, \ V_{zf} \) and \( N \) as functions of \( Q=0.01 \ t, \)

(b) the Lissajous diagram for \( \varepsilon \) vs. \( V_{zf} \) type-Y,

(c) the Lissajous diagram for \( \varepsilon \) vs. \( N \) type-J,

Kim, E.J.et al., 2003, PRL. 90185006.
Plausible loops for LCOs and I/L-H transition

Green for type-Y (CW) LCO,
Red for type-J (CCW) LCO,
yellow for I/L-H transition
• The temporal evolutions of (a) $D_\alpha$ emission, (b) inverse of the electron pressure gradient scale length $1/L_{pe}$, (c) the radial electric field $E_r$, and (d) the Reynolds stress $R_s$.

$1/L_{pe}$ and $|E_r|$ gradually increase; their oscillations are in phase.

$R_s$ is high/low and in/out of phase with $|E_r|$ in early/late LCO phase,
E×B and diamagnetic flows averaged over LCOs

Force balance equation of ions

\[ E_r = \frac{1}{n_i Z e} \nabla_r P_i(f) - v_{\theta i} B_\phi + v_{\phi i} B_\theta \]

- \( (V_E - V_{\text{dim}})/V_E > 60\% \) in L-mode & early I-phase but <10\% prior to I-H transition.
- Evolutions of \( \partial V_{\text{dim}}/\partial t \) and \( V_E \) or \( V_{\text{dim}} \) are strongly correlated.
- No evident correlations between \( \partial R_s/\partial r \) and \( V_E \) are observed.
The evolutions of (a) $I_s \sim n_e$, (b) $\Gamma$, (c) the phase relations between $\Gamma$ and $1/L_{pe}$ in LCO.

- The density increases/decreases at $\Delta r = -6 \text{ mm} / -3 \text{ mm}$
- The turbulent particle flux is negative/positive at $\Delta r = -6 \text{ mm} / -3 \text{ mm}$
- The $1/L_{pe}$ at $\Delta r = -6 \text{ mm}$ is in/out of phase with the particle flux $\Gamma$ at $\Delta r = -6 \text{ mm} / -3 \text{ mm}$
- The diffusion in this region is dominated by pressure gradient induced turbulence which leads to inward particle pinch in the process of particle ETB formation.
The temporal evolutions of (a) $D_\alpha$ emission, the flow energy production rates from (b) pressure gradient $P_{\text{dim}}$ and (c) Reynolds stress $P_{\text{RS}}$, (d) RMS of the density fluctuations $n_e^{\text{rms}}$, (e) the ratio of $P_{\text{RS}}/P_{\text{AT}}$,

- $P_{\text{dim}}$ fast increases twice prior to the L-I and I-H transitions while $P_{\text{RS}}$ does not.

- $P_{\text{RS}}$ is negative/positive in early/late I-phase.

- $n_e^{\text{rms}}$ increases/decreases in L-mode/I-phase.

- The ratio of $P_{\text{RS}}/P_{\text{AT}}$ has a peak prior to the I-H transition.
The time evolutions of (a) soft X-ray, (b) inverses of the scale lengths of electron temperature and density, and (c) pressure, (d) the ion-ion collision frequency and the growth rate of the diamagnetic drift flow, (e) the $E \times B$ flow shearing rate and the turbulence decorrelation rate.

The conditions for I-H transition

1. The I-phase has type-J LCOs,
2. The plasma pressure gradient scale length is less than a critical value (~1.7 cm)
3. The growth rate of the diamagnetic drift flow is equal to or slightly higher than the ion-ion collision frequency,
4. The $E \times B$ flow shearing rate is higher than a critical value (~$10^6$/s) and the turbulence decorrelation rate (4x$10^5$/s).
4. Summary

- Two types of LCOs were observed in L-I-H transitions.
- Three plausible loops of zonal flow vs. turbulence and turbulence vs. pressure gradient are proposed for the LCOs and I-H transition.
- The dominant roles played by the diamagnetic drift flow in I-phase and I-H transition are demonstrated.
- The formation process of density ETB reveals that inward particle pinch is responsible for the barrier formation.
- The rates of energy production from diamagnetic drift and turbulent Reynolds stress for $E \times B$ flow in L-I-H transitions are compared.
- The triggering mechanism and conditions for I-H transition are discussed.
- Much more theoretical and experimental investigations are in progress.
Thank you for your attention!