Excitation and suppression of trapped-energetic-ion driven resistive interchange modes in LHD plasmas with intense deuterium beam injection

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Content of my talk


- Excitation and suppression of the EIC in the deuterium heating campaign will be discussed by this talk. The effects of the EIC on energetic particle and bulk plasma was presented by Mr. T. Bando (P-34: Effects of Trapped Energetic-Ion-Driven Resistive Interchange Modes on Deuterium Beam Ions and Background Plasmas of LHD)

1. Orbit in the helical devices and the excitation of the trapped energetic particle driven resistive interchange mode (EIC).
2. The characteristics of the EIC in deuterium experiment.
   1. Mode frequency dependence
   2. Stability of the EIC with D-beam
3. Strategy to suppress the EIC.
   1. EIC mitigation with ECH heating.
   2. EIC mitigation with RMP.
There are three types of orbit in Heliotron-type devices, such as LHD:

- The passing, the helically trapped, and the transitional particles.

The interaction between precession motion of the Eps and the MHD mode (resistive interchange mode at iota = 1 rational surface) is somewhat similar to Fishbone and off-axis Fishbone in Tokamaks.

D. Spong, APS 2014 tutorial talk.
EIC in the hydrogen / deuterium campaign (1)

EIC: Energetic particle driven resistive InterChange mode

- With the excitation of the EIC, the energetic particles are lost rapidly. The effect on the plasma is quite large, e.g., formation of the negative potential. ($\phi > 10kV$)

- EIC behavior when deuterium perpendicular injected NBIs are used is reported. It is noted that neutron emission rate is a good measure of the amount of the trapped particles since the beam-plasma reaction is the dominant in LHD.

Hydrogen experiments

Potential formation / lost EP
• Bursts of MHD activities less frequently activated are observed in deuteron campaign.

• Impact of each EIC burst is larger than that observed in hydrogen campaign. Therefore, trial for controlling the EIC is performed by using RMP application and ECH injection.
Bursting MHD activities together with the m/n = 1/1 chirping-down MHD mode is observed.

From ECE measurement, oscillations are localized near the iota = 1 rational surface.

The precursors-like oscillations before the onset of the EIC is quite complicated. (several patterns)
Onset of the EIC and chirping down mode

- First, a large deformation with $n = 1$ occurs, and the structure rotating into the direction the precession motion.
- The perturbation is localized on the $\iota = 1$ rational surface (\(-\rightarrow\) interchange mode).
- The rotation frequency is similar to the frequency of the precession frequency of the Eps (\(-\rightarrow\) EP driven mode).

![Graph showing Temporal Bp (integrated, f>100Hz) [a.u.] and Toroidal probe array, with a circular representation of Delta B vs Time [s]].
The observed frequency of EICs is proportional to the precession frequency of helically trapped EPs

- Precession frequency is proportional to the energy of EPs and does not depend on kinds of particles.

- EICs by PERP NBIs with 66 keV has the larger frequency than that with 60 keV and 45 keV.

- Initial frequency dependence supports the relationship between EICs and precession frequency shown in [1].

Drop of neutron emission rate (fraction of the lost Eps dSn/Sn), Amplitude of the magnetic fluctuations (scale of the events dBθ/Bt), and Neutron emission rate before EIC burst (EP pressure before the events Sn)
Amplitude is 2-3 times larger with D beams

- EICs are observed relatively low density plasma.
- Larger scale collapse are observed in higher density regime where the pressure of the EP is higher.
- With the same density regime, scale of the EIC is larger in D campaign.

Decease of the neutron emission rate
EIC excitation – analogy to Fishbone

In order to fulfill the dispersion relation

\[ \delta I + \delta W_{\text{MHD}} + \delta W_{k} = 0, \]

\[ -\frac{\partial \beta_{h}}{\partial r} > C_{th} \]

From Energetic Particle

Energy Principal with Energetic particle

- The beam is deposited at the outer region. The pressure of the energetic particle is larger in only one valley of the magnetic field out of two valleys.
- That is the reason why the energetic particle can resonate with \( m=1 \) (\( n=1 \)) MHD modes.

Deuterium

Hydrogen

EP Pressure estimated by MORH code

Iota(=1/q)

\( \rho \) [m]

\( Z \) [m]

\( R \) [m]

Ep pressure

(A)

(B)
Pressure gradient of the bulk plasma is not changed

- The pressure gradient which drive the pressure driven mode is not changed in H/D experiment.
- Why is EIC more stable in D beam heating?
In order to decouple the MHD and Eps, reduction of the mode width of the resistive interchange mode is effective. (higher temperature and/or smaller shear)

When the typical banana-width of the EPs is larger than the mode width, smaller effects from Eps (Comparison H/D).
Orbit width of the energetic particle

- EICs are excited with lower energetic particle pressure in D campaign.
- Banana width is proportional to the mass of the particle.
- Width of the deuterium is wider than that of hydrogen.
- Interaction to the interchange mode may be smaller in D beam.
- EICs are more stable with D beam
Resonance of the interchange mode and EPs

Typical displacement of the Interchange Mode

\[ \delta w \sim \left( \frac{q^2}{S^2} \right)^{1/3} \left( \frac{\beta \kappa_n}{L_p} \right)^{1/6} \]

S : Magnetic Reynolds Number \( \propto T_e^{3/2} n_e^{-1/2} \)
\( \wedge \)
S : Magnetic shear

- In order to decouple the MHD and Eps, reduction of the mode width of the resistive interchange mode is effective. (higher temperature and/or smaller shear)
- When the typical banana-width of the EPs is larger than the mode width, smaller effects from Eps (Comparison H/D).

R. Ueda, et.al, POP 21, 052502 (2014)
The control of the EIC using ECH was already reported in lower ion temperature regime. (X. D. Du et. al. Phys. Rev. Lett. 118 (2017), 125001)

Clear disappearance of the EICs are observed with EC heating at the center in the in deuterium campaign of high-Ti discharge condition.
• The electron temperature at \( \iota = 1.0 \) is slightly increased.

• Magnetic shear is decreased (becomes unstable) and location of \( \iota = 1 \) surface moved to outward (less energetic particle) with the increase in beta.

• Evaluation on the stability is not simple. Comparison of the radial mode width should be done.
EIC excitation and strategy for the stabilization of the mode:

1. Reduce the pressure gradient of the EPs. (not preferable for heating)
2. Stabilized the resistive interchange mode. (RMP application)
3. Decouple the MHD and EPs. (ECH heating)

In order to fulfill the dispersion relation:

\[ -\frac{\partial \beta_h}{\partial r} > C_{th} \]

Energy Principal with Energetic particle:

\[ \delta I + \delta W_{MHD} + \delta W_k = 0, \]

\[ \delta I = -\frac{\omega^2}{2} \int \rho_m |\xi|^2 d\mathbf{r}, \]

\[ \delta W_k = \frac{1}{2} \int \xi \cdot \nabla \cdot \mathbf{P}_h d\mathbf{r}, \]

To stabilized the mode,
RMP field by LID-coil and island formation

- RMP field resonant with iota = 1 rational surface can be applied.
Penetration of the RMP field and MHD instability

When the external field is applied, field is shielded with small field. External field penetrates the plasma and make magnetic island (m/n = 1/1).

- RMP application affects the resistive interchange mode.
- When the field penetrates and pressure gradient is reduced (island formation), resistive interchange modes disappear.
- Even the external field is partly shielded, MHD activities are suppressed to some extent.

Case A: magnetic island is formed.

• When the EICs are marginally unstable, RMP application control the EIC excitation. Penetration of the external field to the plasma is required.

• Total amount of the trapped EPs (estimated from FC) is not modified significantly since the Neutron Emission rate is not changed so much.

• Orbit of the EPs with RMP field will be investigated.
Scan of the RMP field with 2 density range

- EIC bursts disappear when the external field penetrates the plasma.
- In lower density regime, where EIC is more unstable, RMP does not affect the appearance of the EIC.

Total Neutron emission rate does not change significantly.
Summary

- From the resonance of the precession motion of the helically trapped particle and resistive interchange mode, so-called EIC mode appears in the Large Helical Device.
- The amplitude and the effects of an EIC events on plasma is enhanced in deuterium experimental campaign. It may be caused by that the EIC is more stable with D beams.

- Two methods to control EIC are performed.
  - ECH injection.
    - Disappearance of the bursting EIC is observed. Instead of EIC, complicated MHD activities appears. However, the energetic particles are well confined and not expelled by these activities.
  - RMP (m/n = 1/1) application.
    - When the external field penetrate the plasma, disappearance of the bursting EIC is observed without reducing the total amount of trapped EPs.
BACKUP SLIDES
Precursor-like oscillation

- Quite complex and not easy to understand.
- Stationary oscillation in toroidally and rotating poloidally.
- Sometimes it rotates toroidally.
- $n=10$, $m=1$???. (From the orbit,
The large negative electrostatic potential, \( \sim 25kV \), is formed with expels of EPs by EICs.

The formed potential is about two times larger than that of hydrogen experiments. The variation of potential occurs around \( \iota=1 \) surface.
EICs localize at $\iota=1$ surface

**Slowing down of the frequency**

133616 ECE

- Chirping down oscillation with $m/n=1/1$ structure which localizes around $\iota=1$ surface appears.

- The eigenfunction has tearing parity same as hydrogen case.