Study on TAE-induced Fast-Ion Loss Process in LHD

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Introduction

- TAE induced fast-ion loss process has been widely studied in tokamaks and heliotron/stellarator devices to find a method to reduce the \( \alpha \) particle loss in fusion device.
- In LHD, characteristics of transport and loss of fast ions due to TAE have been studied.
  - Little attention has been given to the change of dependence of fast-ion loss on TAE amplitude. It suggests the change of loss process.
- Previous work shows the loss process is changed from convective to diffusive with increase of TAE amplitude in axisymmetric plasma [1].
- This work is devoted for understanding of the loss character in 3D plasma.

Experimental setups
Effect of magnetic axis position on fast-ion orbits and TAE in LHD

- Small magnetic axis position at finite beta $R_{\text{mag}}$
  - Smaller deviation of fast-ion orbit from magnetic flux surface
  - Strong magnetic shear
    -> Narrow TAE gap -> Narrow radial extent of TAE mode

- Large $R_{\text{mag}}$
  - Larger deviation of fast-ion orbit from magnetic flux surface
  - Weak magnetic shear
    -> Wide TAE gap -> Wide radial extent of TAE mode

$R_{\text{mag}}=3.75$ m (Case A), 3.86 m (Case B), 4.00 m (Case C)
A set of apertures has a role in discriminating $E$ and $\chi$ of detectable fast ions.

Scintillation points give the information of $E$ and $\chi$ of lost-fast ions.

Photomultiplier (PMT) array: Each PMT views particular region of $E$ and $\chi$ on the screen. The time response is high enough to observe TAE-induced fast-ion loss.
Experimental results
Typical discharge with TAE

- **Experimental condition**
  - $B_t = 0.6$ T (CCW)
  - $\langle n_e \rangle \sim 1.2 \times 10^{19}$ m$^{-3}$
  - $\langle \beta \rangle \sim 1.5\%$
  - $\langle \beta_{\text{fast}} \rangle \sim 0.7\%$
  - $v_{\text{beam}}/v_A \sim 1.5$

- **Instabilities observed with Mirnov coil**
  - TAE ($m=1/n=1$)
    - Frequency $\sim 70$ kHz
    - Amplitude of magnetic fluctuation: $\sim 0.5 \times 10^{-4}$ T
    - Peak of eigenfunction: $r/a \sim 0.6$ [1]
  - Bulk plasma pressure excites instability
    - Resistive interchange mode (mainly: $m=1/n=1$)
    - Frequency $\sim 1$ kHz
    - Peak of eigenfunction: $r/a \sim 0.9$ [2]

Increase of fast-ion loss due to TAE

- Time traces of magnetic fluctuation on TAE frequency and $\Gamma_{\text{fast ion}}$.
  - Increase of fast-ion flux having $E$ of 50-180 keV and $\chi$ of 35-45° due to TAE is observed.
  - Fast-ion loss due to resistive interchange mode (RIM) is also observed on entire region of $E$ and $\chi$.
  - To focus on the TAE induced loss, effects of RIM on fast-ion loss are removed using numerical frequency band-stop filter.

Large (Small) TAE leads to (large) small increase of $\Gamma_{\text{fast ion}}$. 

Case B ($R_{\text{mag}}=3.86$ m)

#97435 $Bt=0.6$ T, $R_{\text{ax}}=3.60$ m
Dependence of fast-ion loss flux on TAE fluctuation amplitude

- Increment of lost-fast ion flux $\Delta \Gamma_{\text{fast ion}}$ as a function of magnetic fluctuation amplitude $b_{\theta \text{TAE}}$
  - $\Delta \Gamma_{\text{fast ion}}$ is normalized by fast-ion components created by co-NBs ($P_{\text{NBco}} \times \tau_s$).
- In case B, the dependence changes at $b_{\theta \text{TAE}}/Bt$ of $7 \times 10^{-5}$.
  - In lower $b_{\theta \text{TAE}}/Bt$ region: $\Delta \Gamma_{\text{fast ion}}/(P_{\text{NBco}} \times \tau_s) \propto b_{\theta \text{TAE}}/Bt$
  - In higher $b_{\theta \text{TAE}}/Bt$ region: $\Delta \Gamma_{\text{fast ion}}/(P_{\text{NBco}} \times \tau_s) \propto (b_{\theta \text{TAE}}/Bt)^2$
- Cases A and C, no clear change of dependence is observed.
  - The change of dependence may appear in unexplored $b_{\theta \text{TAE}}$ region.
Setups for orbit-following simulation including TAE fluctuation
Setups for orbit-following simulation

- **Inside the plasma**
  - Guiding center orbits of fast ions are followed by DELTA5D [2].
    - Including TAE fluctuation (detail is shown in next slide.)
    - Only applicable inside LCFS -> DELTA5D uses equilibrium reconstructed by VMEC2000 [3].

- **Outside the plasma**
  - Lorentz orbit of fast ion is followed.
    - The SLIP measures the $E$ and $\chi$ of fast ions according to Larmor motion.

TAE fluctuation included in orbit-following simulation

- Fluctuation of the TAE is mostly perpendicular to the magnetic field line.
  - TAE is classified into shear Alfvén type.

- Fluctuation is modeled as
  \[ \delta B = \nabla \times (\alpha B) \]
  \[
  \alpha \propto \frac{m}{\omega_{TAE}} \phi(\psi) \sin \left( n\zeta - m\theta - \omega_{TAE} t \right)
  \]

- Eigenfunction \( \phi \) is calculated with AE3D [1].
  - The profile of TAE agrees with that obtained in experiment [2].

- Frequency chirping down rate is 20 kHz/ms.

Results of orbit-following simulation
Dependence of fast-ion loss flux on TAE fluctuation amplitude

- The $E$ of lost-fast ion: 120-180 keV
  - cf. EXP: 50-180 keV

- The $\chi$ of lost-fast ion: 30-40$^\circ$
  - cf. EXP: 35-45$^\circ$

**In case B**
- The change of dependence is reproduced.
- The critical $b_\theta TAE/Bt$ is $3 \times 10^{-5}$.
- Same order as experiment: $7 \times 10^{-5}$

**In case A**
- The dependence is similar to the experimentally observed dependence in low $b_\theta TAE/Bt$ regime.
- The critical value of $b_\theta TAE/Bt$ is predicted in unexplored regions of experiments.
Orbits of fast ions with TAE fluctuation

- **Small TAE**: A fast ion near the confinement/loss boundary is lost immediately due to radial excursion by TAE (convective process).
- **Large TAE**: Orbit of a fast ion confined in the interior region is gradually expanded due to TAE -> Reaches LCFS (diffusive process).

![Orbits of fast ions](image)

- **Small amplitude** ($b_{\text{TAE}}/Bt=7\times10^{-6}$)
- **Large amplitude** ($b_{\text{TAE}}/Bt=5\times10^{-5}$)

- $Bt = 0.6 \text{ T}$
- $E = 180 \text{ keV}$, $\chi = 30 \text{ degrees}$
Possible explanation of the phenomenon

- Small TAE: barely confined fast ions are lost -> convective process is dominant.
- $b_{\theta \text{TAE}}$ increases -> orbits of fast ions existing interior region is expanded, then finally, lost from the plasma.
- Diffusive loss increases with $b_{\theta \text{TAE}}$ -> Exceed convective type loss.
- Plateau region of fast-ion loss flux in case A might be due to the change of the transport of barely confined fast ions.

Convective type loss
$\Delta \Gamma_{\text{fast ion}}/(P_{\text{NBco}} \times \tau_s) \propto b_{\theta \text{TAE}}/Bt$ [1]

Diffusive type loss
$\Delta \Gamma_{\text{fast ion}}/(P_{\text{NBco}} \times \tau_s) \propto (b_{\theta \text{TAE}}/Bt)^2$ [1]

Summary

• Characteristics of TAE-induced fast-ion loss process are studied in the wide parameter ranges of LHD using SLIP.

• Dependence of $\Delta \Gamma_{\text{fast ion}}$ on $b_{\theta\text{TAE}}$ changed at certain $b_{\theta\text{TAE}}$ in case B ($R_{\text{mag}} = 3.86$ m).
  – Low $b_{\theta\text{TAE}}$ region: $\Delta \Gamma_{\text{fast ion}}/(P_{NB\text{co}} \times \tau_s) \propto b_{\theta\text{TAE}}/Bt$
  – High $b_{\theta\text{TAE}}$ region: $\Delta \Gamma_{\text{fast ion}}/(P_{NB\text{co}} \times \tau_s) \propto (b_{\theta\text{TAE}}/Bt)^2$

• To study the observed phenomenon in detail, simulation based on orbit-following models that incorporated magnetic TAE fluctuation is performed.
  – The simulation reproduces the change of fast-ion loss dependence on TAE fluctuation amplitude.
  – It suggests the change of loss process from convective to diffusive character as predicted in axisymmetric model.

• The observed change of fast-ion loss dependence on TAE fluctuation amplitude can be explained by the change of the dominant loss process.