Magnetic Configuration Effects on TAE Induced Losses and Comparison with Orbit Following Model in LHD

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• Summary
Introduction

• It is crucial issue for fusion device to understand on AEs induced loss
  – Important to reduce the damage of PFC.

• Scintillator-based lost-fast ion probe is widely used to measure \( E/\chi \) of lost fast ions.
  – Fast ion lost due to GAE together with neutron drops in TFTR.

Study on TAE in High Beta LHD Plasmas

- TAEs are excited by NB ions in LHD.
- Very weak toroidal mode coupling on TAE
  \( B_t < 0.75 \text{ T} \) : \( \langle \beta \rangle = 1.0 \sim 2.0 \% \)
- Obvious fast-ion losses by TAEs are observed only at relatively low-\( B_t \) region
- Co-going fast-ion losses induced by TAE using bi-directional scintillator-based lost-fast ion probe being studied.
Configuration effect on orbit and safety factor on LHD

- Large deviation of orbit from the flux surface.
- High-energy of fast ions
- Low-$B_t$ experiment.
- Become large as $R_{ax\_vac}$ shifted.
- Safety factor profile becomes flat as $R_{ax\_vac}$ shift.
- Affect the profile of instability
- Charge exchange loss of fast ion ($\sim 180$ keV) is small.

- Impact of MHD instabilities on fast ion loss will strongly depend upon the magnetic configuration.
  - Contribute to the deep understanding of fast ion loss mechanisms.
Scintillator-based lost-fast ion probe (SLIP)

- **Double aperture structure** has a role in discriminating $E/\chi$ of detectable ions.
- **Scintillation point** gives the information of $E$ and $\chi$ of lost ions.
  - Scintillation points are measured with a CMOS camera and a 4x4 PMT array.
- The scintillator probe can collect wide region.
Whether fast ions reach the SLIP or not

- **Classification of reaching point from LCFS with vacuum field.**
  - Energetic ions were launched from LCFS.
  - $B_t=0.6$ T, $R_{ax}=3.60$ m
  - $E=180$ keV, $\chi \sim 40$ degrees
    - Typical pitch angle of TAE induced loss
  - **White**: detected by SLIP
  - **Black**: confined
  - **Blue**: loss w/o detected by SLIP

- **Although the SLIP is local diagnostic system, the information of loss can give whole image of loss.**
Magnetic Configuration Effect on TAE Induced Loss
Typical discharge with large Shafranov shift at $R_{\text{ax_vac}}=3.6 \text{ m}$

- Experimental condition.
  - $B_t=0.6 \text{ T (CCW)}$
  - $\langle n_e \rangle \sim 1.5 \times 10^{19} \text{ m}^{-3}$
  - $\langle \beta \rangle \sim 2.0 \%$
  - $R_{\text{mag}} \sim 3.86 \text{ m}$
  - $\langle \beta_{\text{fast}} \rangle \sim 1.0 \%$
  - $v_{\text{beam}}/\langle v_A \rangle \sim 1.6$

- Instabilities observed with pickup coil
  - TAE($m=1/n=1$)
    - Frequency $\sim 70 \text{ kHz}$
    - Amplitude of magnetic fluctuation: $\sim 0.5 \times 10^{-4} \text{ T}$
    - Peak of eigenfunction: $r/a \sim 0.6[1]$
  - Bulk plasma pressure excites instability
    - RIC (mainly: $m=1/n=1$)
    - Frequency: $\sim 2 \text{ kHz}$
    - Amplitude of magnetic fluctuation: $\sim 3.0 \times 10^{-4} \text{ T}$

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TAE: toroidal Alfvén eigenmode
RIC: resistive interchange mode
Energy and pitch angle of lost ion due to TAE/RIC

• Three domains are observed. (D₁ ~ D₃)

• D₁: $E=80 \sim 150$ keV, $\chi =25 \sim 35^\circ$ D₂: $E=50 \sim 190$ keV, $\chi =35 \sim 45^\circ$

• D₃: $E=50 \sim 190$ keV, $\chi =45 \sim 60^\circ$

• D₁: mainly RIC loss, D₂: mainly TAE loss, D₃: mainly collisional loss

RIC: resistive interchange mode
TAE induced loss dependence on magnetic fluctuation amplitude on MP position at \( R_{\text{ax_vac}} = 3.6 \text{ m} \) w/large shift

- \( b_{\text{TAE}} \) is magnetic fluctuation amplitude measured by pickup coil.
- \( \Delta \Gamma_{\text{SLIP}} \) is increment of loss induced by TAE.
  - \( \Delta \Gamma_{\text{SLIP}} \) is evaluated with removing RIC effects.
- Loss flux is proportionate to fast ion density \( \sim P_{\text{NBco}} \times \tau_{\text{se}} \)
  - Loss signal is normalized by fast ion density.
- Diffusive type of loss is observed.
TAE induced loss dependence on Mirnov fluctuation amplitude on various $R_{\text{mag}}$

- Number of loss grows as $R_{\text{mag}}$ shifted.
- The dependence becomes steeper as $R_{\text{mag}}$ shifted.
  - The convective loss process ($s=1$) changes to diffusive ($s=2$) as $R_{\text{mag}}$ shifted.
  - Finally to a stochastic transport of particle orbits in phase space.
- Eigenfunction of TAE becomes wider as $R_{\text{mag}}$ shifted.
- Fast ions stays away from loss cone can be lost due to TAE with wide eigenfunction.
- The effect of Shafranov shift at $R_{\text{ax,vac}}$ of 3.60 m on TAE induced loss is simulated.
Calculation of TAE induced loss using Orbit following model
Equilibrium is reconstructed using VMEC2000 [1]
Eigenfunction of TAE is calculated using AE3D [2]
Guiding center orbit in a plasma region is followed using DELTA5D [3]
  - It is the simple modeling at $\rho/a \sim 0.1$.
Lorentz orbit at the outside of the plasma is followed using magnetic field in vacuum.

Birth profiles and pitch angle of fast ions

- Fast ion created by NB#1 and NB#3 are considered in this calculation.
  - NB#2 is injected on the CW direction producing Ctr.-going ion.
  - SLIP installed at outboard side cannot detect Ctr.-going ions.

- Pitch angle of fast ions are less than ~30 degrees
  - All of them are co-going ions.

Birth positions of the beam ions

Initial pitch angle distribution of beam ions

Birth profile of fast ion

\[ \langle n_e \rangle \sim 1.5 \times 10^{19} \text{m}^{-3} \]
\[ T_e(0) \sim 0.8 \text{ keV} \]
\[ B_t = 0.60 \text{ T} \]
Model of the fluctuation

- Fluctuation of the TAE is mostly perpendicular to the magnetic field line.
- Fluctuation is modeled as[1]
  \[ \delta B = \nabla \times (\alpha B) \]
  \[ \alpha(\psi, \theta, \zeta) = \sum_l \alpha_s(\psi) \sin(n_l \zeta - m_l \theta - \omega_{\text{real}} t) \]
  \[ \alpha_s(\psi) = \nabla_{//}\phi = \alpha_k \left( \frac{n_l}{m_l} - t \right) e^{-(\psi - \psi_{\text{peak}})^2 / \Delta^2} \]
  - \( \phi \) is calculated with AE3D
  - Effect of electric field due to fluctuation is neglected
- Additional term due to TAE is...
  \[ \frac{d\theta}{dt} = \ldots + e v_{//} B \frac{\partial \alpha}{\partial \psi} \frac{\partial \psi}{\partial \psi} \frac{\partial P_\theta}{\partial \psi} \]
  \[ \frac{d\psi}{dt} = \ldots + e v_{//} B \frac{\partial \alpha}{\partial \psi} \frac{\partial \psi}{\partial \psi} \frac{\partial P_\psi}{\partial \psi} \]
  \[ \frac{d\rho_{//}}{dt} = \frac{\bar{I} - (\rho_{//} + \alpha) g'}{D} \frac{\dot{P}_\theta}{D} + \frac{\bar{I} - (\rho_{//} + \alpha) I'}{D} \frac{\dot{P}_\zeta}{D} + \frac{d\alpha}{dt} \]

In DELTA5D, we input birth position/energy of the fast ions. -> fast ions in the plasma have slowing-down profile.

We include the TAE fluctuation at several milliseconds later after starting the calculation, and sum all of the particles.

1024 particles are considered in each run.
Connecting procedure between DELTA5D and Lorentz orbit

- Lorentz orbit is solved from the SLIP position to the plasma backwardly.
- We judge loss is detected, if following conditions are fulfilled.
  - Distance = Larmor radius ± 20%
  - Energy difference < 5 keV.
  - Pitch angle difference < 5 degrees.
- If we set the half threshold -> not changed dramatically.
- Equivalent to the calculation of the Lorentz orbit launched from LCFS with random gyro phases.
Fast ion transported to the LCFS by TAE
The points that fast ions transported to LCFS

- The points locate relatively weak magnetic field region.
- The region is not changed if the amplitude of the mode is changed.
  - Number of fast ions increase as increasing the mode amplitude.
Number of fast ion reaching the LCFS dependence on TAE amplitude at $R_{\text{ax}_{\text{vac}}}=3.60$ m with large shift

- Number of particle transported to the LCFS increase with increasing the amplitude of the mode
  - $b_0$ indicates the amplitude of the mode at TAE centre.
  - Number of ions w/o TAE mode is 773/10000.
  - No increment of fast ions are observed at $b_0/B < 3.0 \times 10^{-4}$
- Number of fast ions quadratically grows with increasing of $b_0$
  - It shows diffusive type.
Fast ions reaching LCFS due to TAE in $R_{ax\_vac} = 3.60$ m

Number of fast ion reach the LCFS due to TAE.

- Number of particle reaching the LCFS grows with increasing $b_0$.
- Shafranov shift induce...
  - Growing number of loss
  - Steeper dependence
    - Linearly to quadratically.

![Graph showing relationship between $b_0/B$ and total loss](image)
Fast ion lost due to TAE measured by the SLIP
Compare the region covered by SLIP and reaching points

- Comparison between reaching points on LCFS and the LCFS region which fast ions having pitch angle of ~ 40 degrees goes to the SLIP.
- The SLIP can catch most of ions transported to the LCFS due to TAE.
Pitch angle distribution of TAE induced loss detected by SLIP

Pitch angle distribution of lost ions
Detected by the SLIP in calculation

- Pitch angle distribution of lost ion reach the SLIP at $R_{\text{mag}}$ of 3.86 m.
- Energy of lost ion is from 120 keV to 180 keV.
- Lost ions come to three domains.
  - Each pitch angle corresponds to that of observed in experiments.
- Fast ion having pitch angle of 40 degrees lost from the plasma/detected by SLIP due to TAE.
- Pitch angle of 30 to 45 degrees treated as a TAE induced loss measured by the SLIP.
TAE induced loss dependence on fluctuation amplitude

- Clear increase of loss is observed when $b_0/B > 3.0 \times 10^{-4}$ at large shift case.
- Increment of loss due to TAE is quadratically increase as observed in experiments.
- The dependence is the same as that of fast ion reaching LCFS due to TAE.
  - The SLIP can collect most of ions transported to the LCFS by TAE.
TAE induced loss dependence on fluctuation amplitude in various $R_{\text{mag}}$

- **Loss flux dependence on fluctuation amplitude.**
  - $b_0$ indicate the fluctuation amplitude at peak position in a plasma
- **Relation between $b_0$ and $b_{\text{TAE}}$ observed in experiment have a certain relationship in each configuration.
- **Loss flux dependence on fluctuation amplitude have some relation as that of at LCFS.
- **Loss flux dependence on fluctuation amplitude is similar as observed in experiments in both cases.**
Summary

• Lost fast ion is measured at relatively low $B_t$ experiment in the LHD
• TAE induced loss grows with increasing TAE fluctuation
• $R_{mag}$ shift induce...
  – TAE induced loss growing
  – Loss dependence on TAE fluctuation becomes steeper
• TAE induced loss is simulated based on orbit following models.
  – Same tendency as experiments at $R_{ax_vac}$ of 3.60 m
    • $R_{mag}$ shift induce TAE induced loss growing
    • $R_{mag}$ shift induce loss dependence on TAE fluctuation becomes steeper
  – Fast ion reaching the SLIP due to TAE
    • same dependence as fast ion transported to LCFS.

• Effect of electric field due to TAE on fast ion loss will be include.
• Comparison the fluctuation amplitude inside/outside a plasma
• TAE induced loss at $R_{mag}$ of 4.00 m will be simulated.