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

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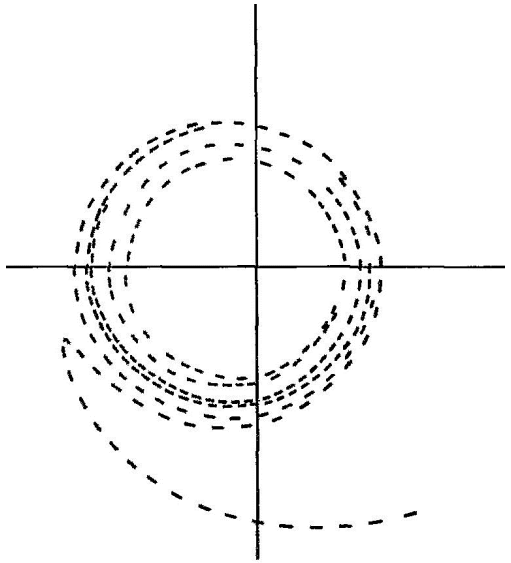
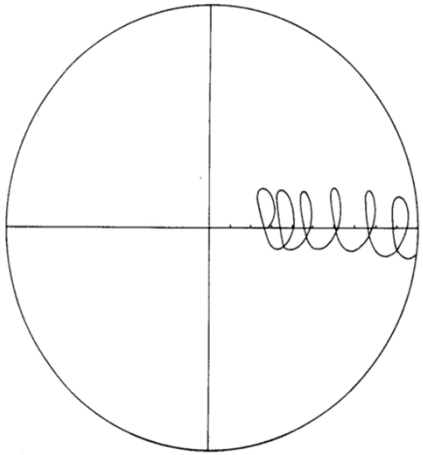
Introduction

Loss with convective type process [1]



Loss with diffusive type process [2]



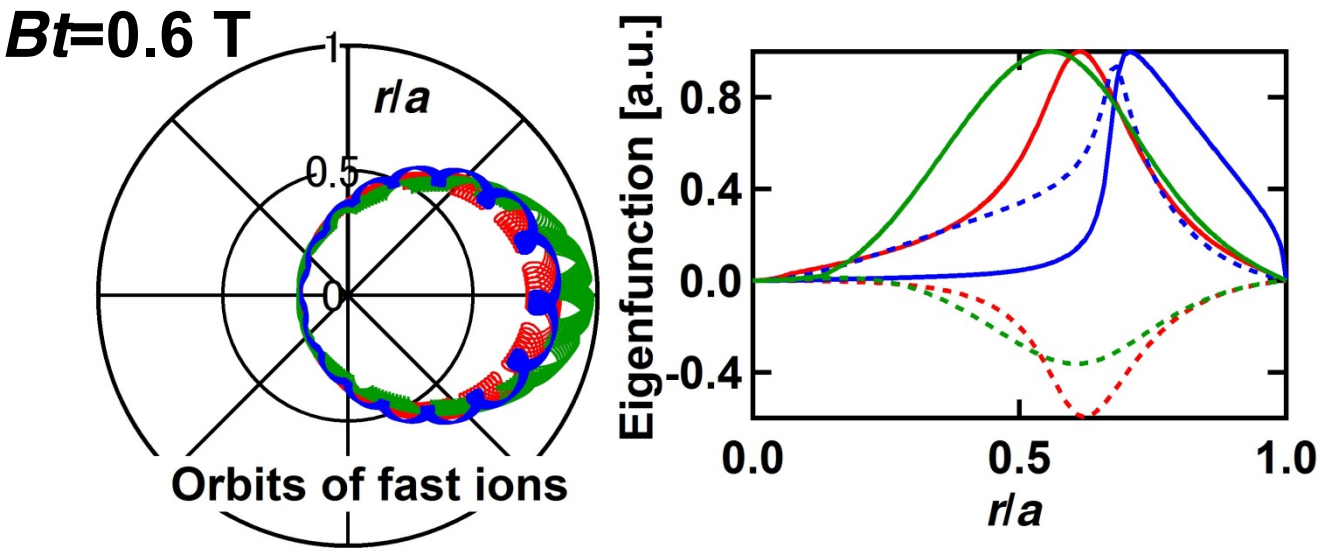
- TAE induced fast-ion loss process has been widely studied in tokamaks and heliotron/stellarator devices to find a method to reduce the α particle loss in fusion device.
- In LHD, characteristics of transport and loss of fast ions due to TAE have been studied.
  - Little attention has been given to 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.

[1] D. Sigmar PoFB 1992 [2] R. White PoF 1983

Experimental setups

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

R_{mag}=3.75 m (Case A), 3.86 m (Case B), 4.00 m (Case C)



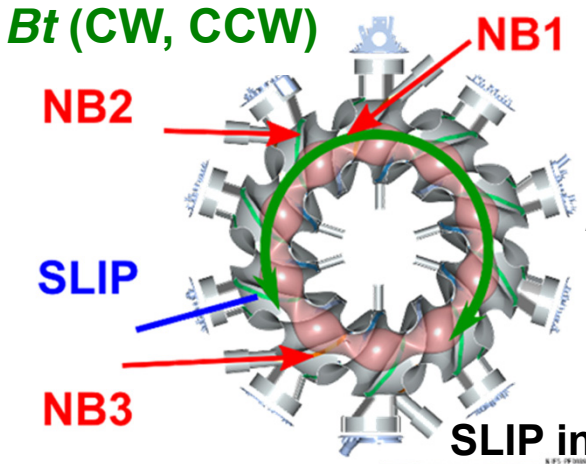
- **Small magnetic axis position at finite beta R_{mag}**
  - **Smaller deviation of fast-ion orbit from magnetic flux surface**
  - **Strong magnetic shear**

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

    -> Wide TAE gap -> Wide radial extent of TAE mode

Scintillator-based lost-fast ion probe (SLIP)

LHD & Position of SLIP

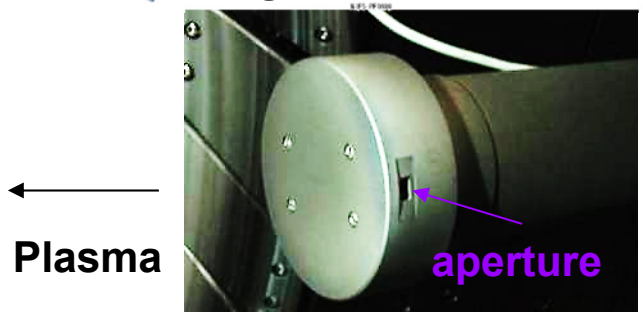


Bt = 0.4 T- 3.0 T

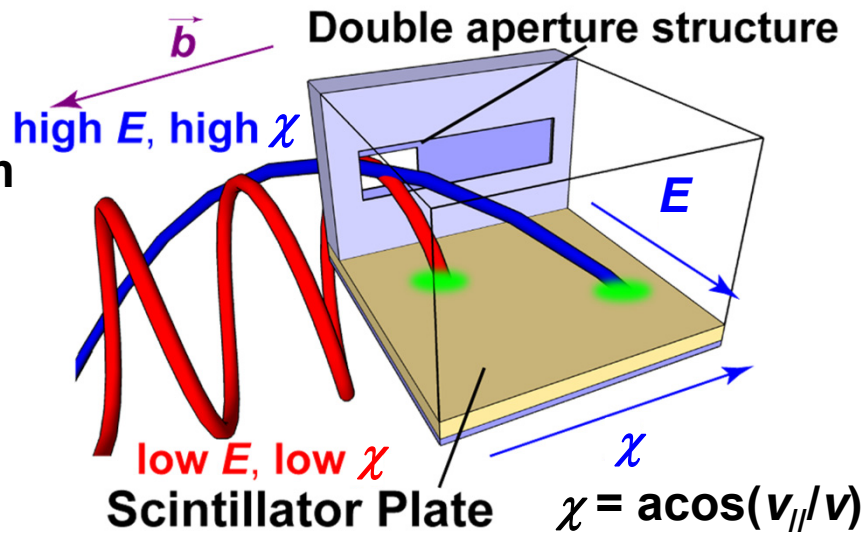
R/*a* = 3.9 m / 0.6 m

V_{NBinj} ~ 180 keV

SLIP in LHD



Model of scintillator head

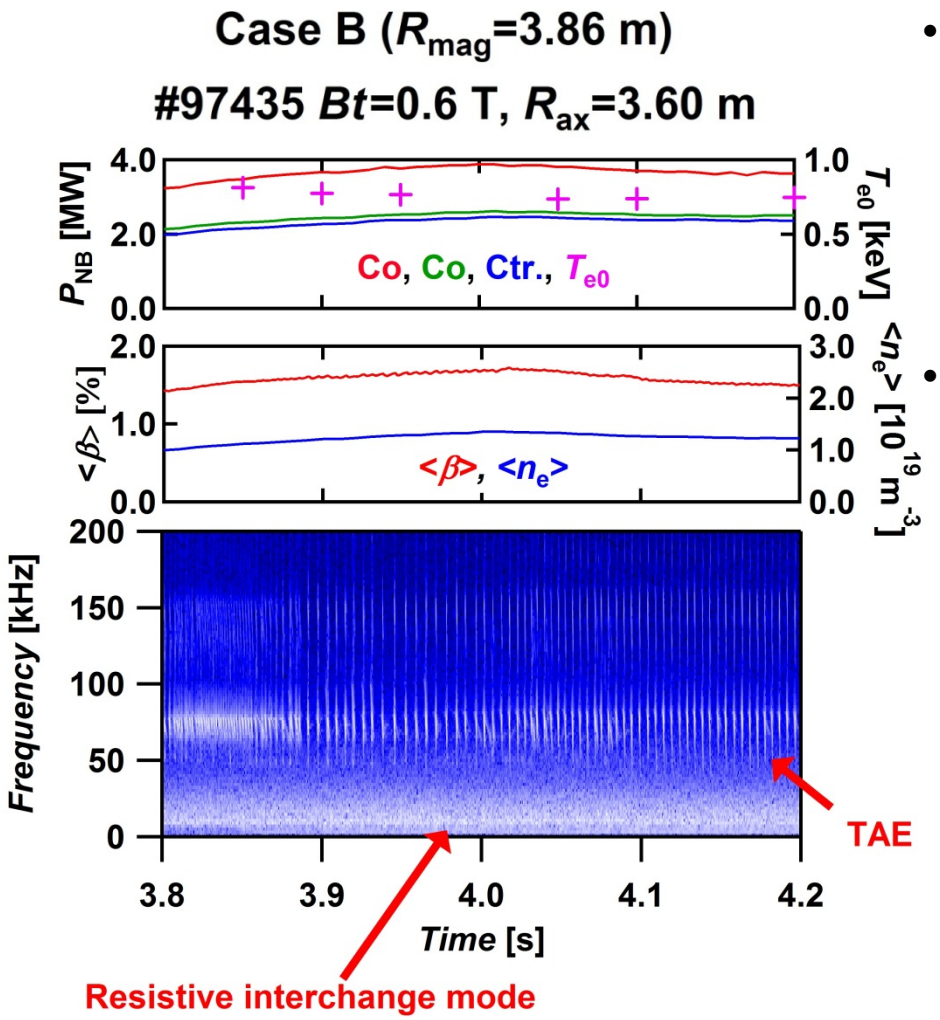


E: Energy of ion, χ : Pitch angle

- A set of apertures has a role in discriminating *E* and χ of detectable fast ions.
- Scintillation points give the information of *E* and χ of lost-fast ions.
- Photomultiplier (PMT) array : Each PMT views particular region of *E* and χ on the screen. The time response is high enough to observe TAE-induced fast-ion loss.

Experimental results

Typical discharge with TAE



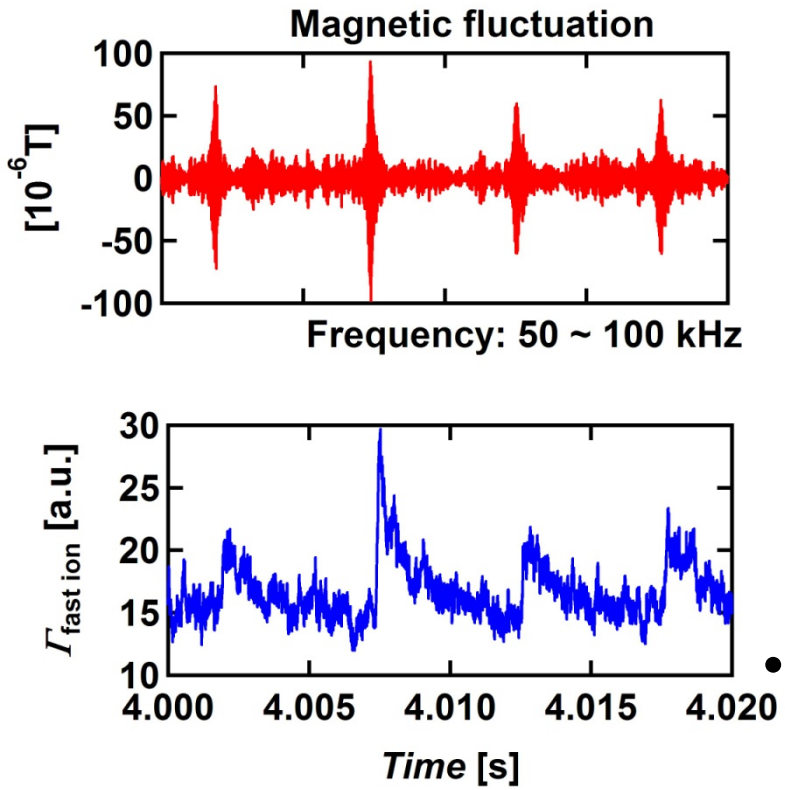
- **Experimental condition**
  - Bt=0.6 T (CCW)
  - $\langle n_e \rangle \sim 1.2 \times 10^{19} m^{-3}$
  - $\langle \beta \rangle \sim 1.5$ %
  - $\langle \beta_{fast} \rangle \sim 0.7$ %
  - $v_{beam}/\langle v_A \rangle \sim 1.5$
- **Instabilities observed with Mirnov coil**
  - TAE (m~1/n=1)
    - Frequency ~70 kHz
    - Amplitude of magnetic fluctuation: ~0.5×10^{-4} T
    - Peak of eigenfunction :r/a~0.6[1]
  - Bulk plasma pressure excites instability
    - Resistive interchange mode (mainly: m=1/n=1)
    - Frequency:~1 kHz
    - Peak of eigenfunction : r/a~0.9[2]

[1] K. Ogawa NF 2010 [2] F. Watanabe PFR 2007

Increase of fast-ion loss due to TAE

Case B (R_{mag}=3.86 m)

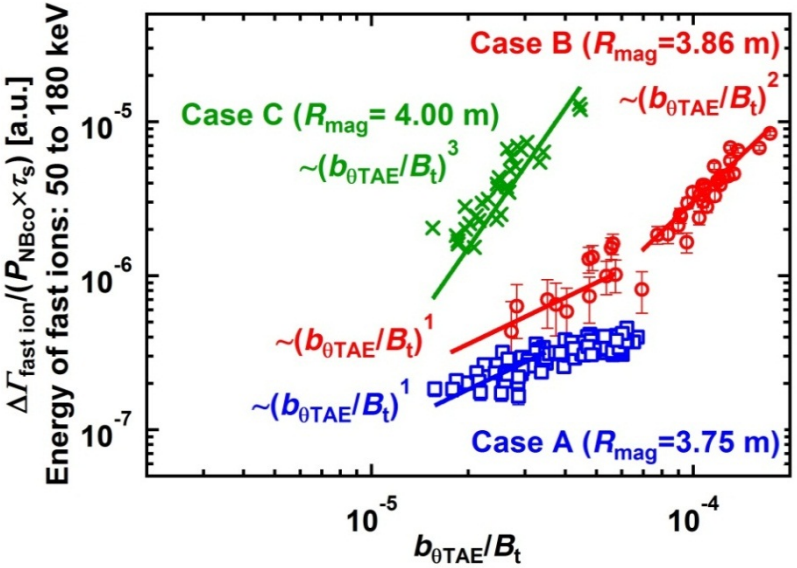
#97435 Bt=0.6 T, R_{ax}=3.60 m



Frequency from 0.8 kHz to 1.2 kHz is excluded.

- **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 χ 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 χ.**
  - **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 $\Gamma_{\text{fast ion}}$.**

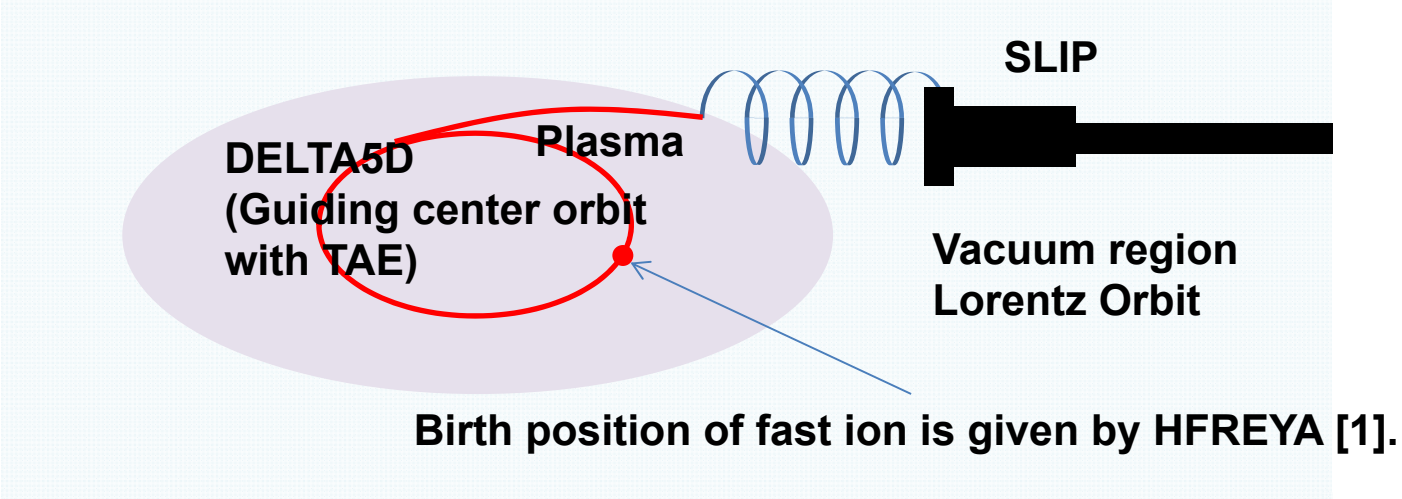
Dependence of fast-ion loss flux on TAE fluctuation amplitude



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

Setups for orbit-following simulation including TAE fluctuation

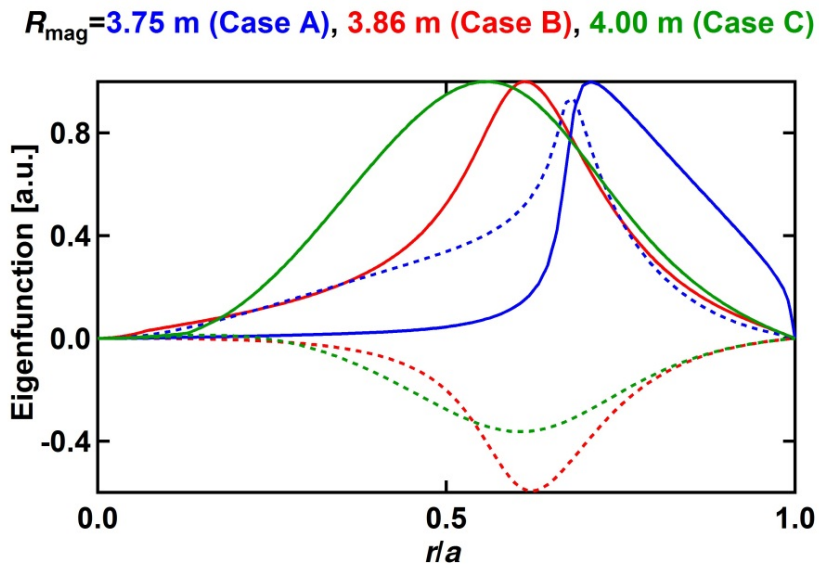
Setups for orbit-following simulation



- **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 χ of fast ions according to Larmor motion.

[1] S. Murakami TFT 1995 [2] D. A. Spong BAPS 1999 [3] S. Hirshman JCP 1991

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**

$$\delta B = \nabla \times (\alpha B)$$

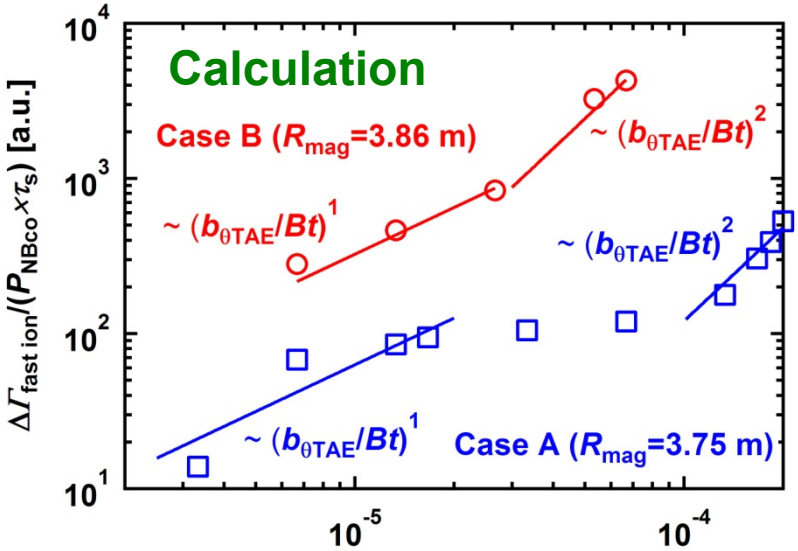
$$\alpha \propto \frac{m}{\omega_{TAE}} \phi(\psi) \sin(n\zeta - m\theta - \omega_{TAE} t)$$

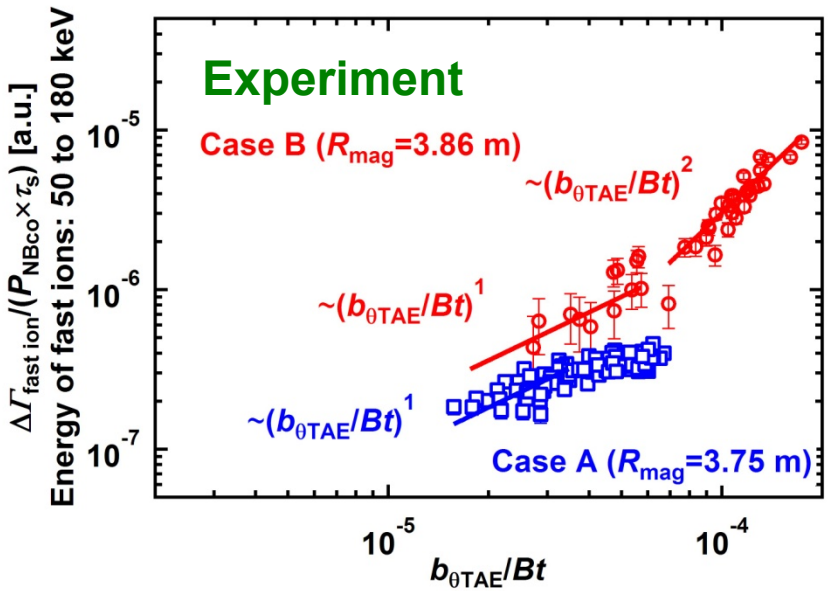
- **Eigenfunction ϕ is calculated with AE3D [1].**
  - **The profile of TAE agrees with that obtained in experiment [2].**
- **Frequency chirping down rate is 20 kHz/ms.**

[1] D. A. Spong PoP (2010) [2] K. Ogawa NF (2010)

Results of orbit-following simulation

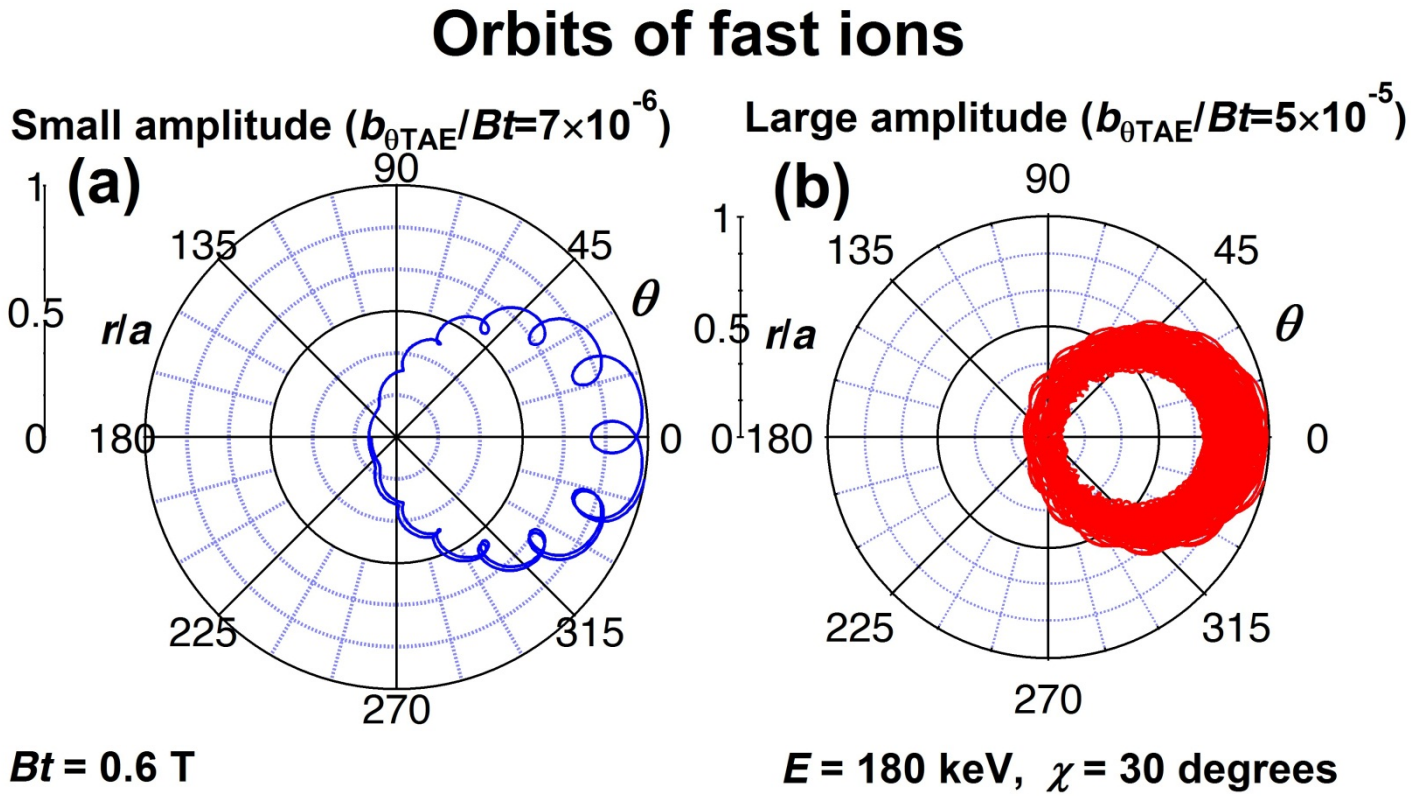
Dependence of fast-ion loss flux on TAE fluctuation amplitude





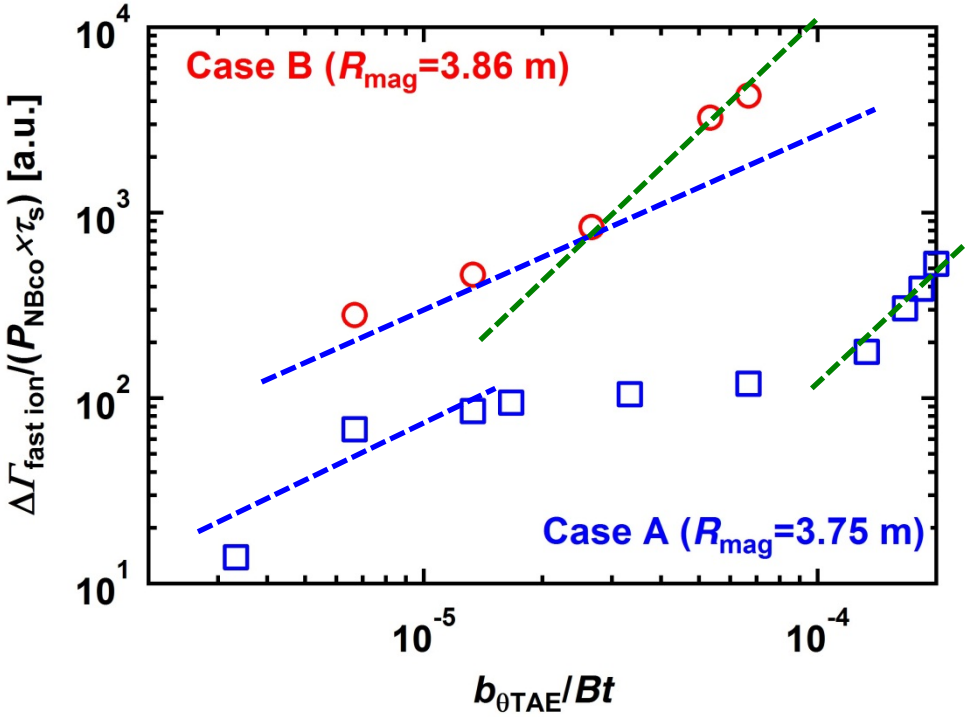
- The E of lost-fast ion : 120-180 keV
  - cf. EXP: 50-180 keV
- The χ of lost-fast ion : 30-40˚
  - cf. EXP: 35-45˚
- In case B
  - The change of dependence is reproduced.
  - The critical $b_{\theta TAE}/Bt$ is 3×10^{-5}.
  - Same order as experiment : 7×10^{-5}
- In case A
  - The dependence is similar 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).**

Possible explanation of the phenomenon



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

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

[1] D. Sigmar PoFB 1992

- Small TAE: barely confined fast ions are lost -> convective process is dominant.
- $b_{\theta TAE}$ increases -> orbits of fast ions existing interior region is expanded, then finally, lost from the plasma.
- Diffusive loss increases with $b_{\theta TAE}$ -> 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.

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_{mag} =3.86 m).**
  - **Low $b_{\theta\text{TAE}}$ region : $\Delta\Gamma_{\text{fast ion}}/(P_{\text{NBco}}\times\tau_s) \propto b_{\theta\text{TAE}}/Bt$**
  - **High $b_{\theta\text{TAE}}$ region : $\Delta\Gamma_{\text{fast ion}}/(P_{\text{NBco}}\times\tau_s) \propto (b_{\theta\text{TAE}}/Bt)^2$**
- **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.**