I-7

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

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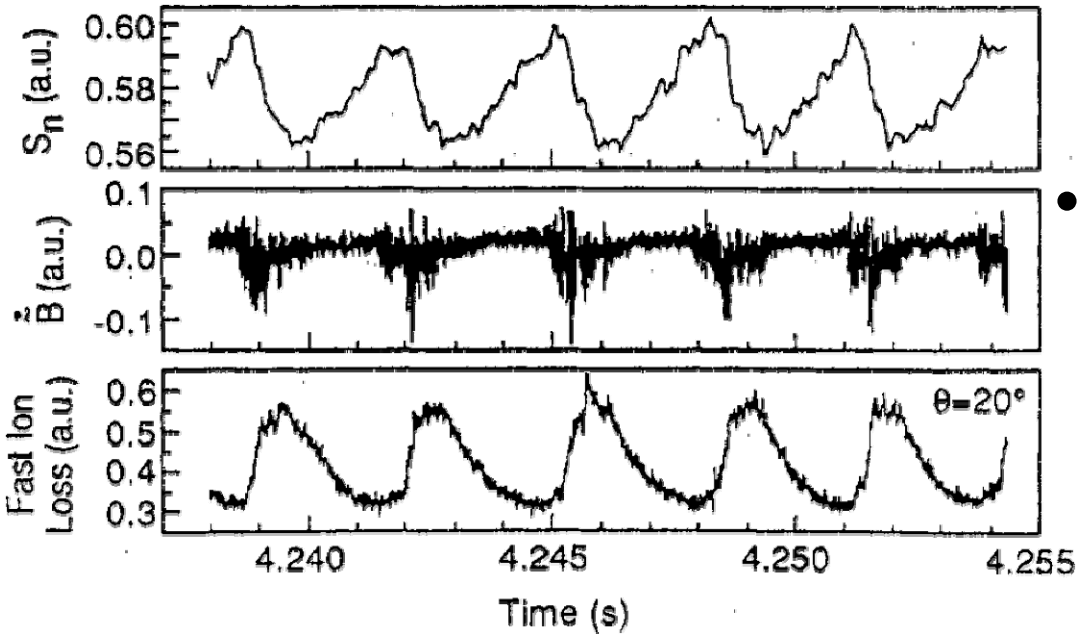
Contents

Introduction

GAE induced loss in TFTR [1]

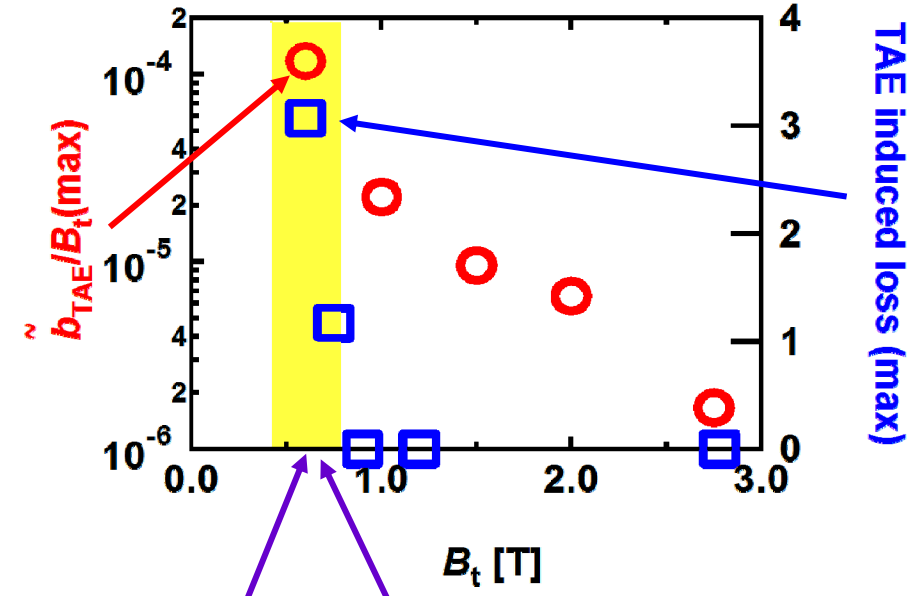


- **It is crucial issue for fusion device to understand on AEs induced loss**
  - **Important to reduce the damage of PFC.**
- **Scintillator-based lost-fast ion probe is widely used to measure E/χ of lost fast ions.**
  - **Fast ion lost due to GAE together with neutron drops in TFTR.**

[1] D.DARROW *et al.*, NF (1997)

Study on TAE in High Beta LHD Plasmas

TAE fluctuation amplitude and TAE-induced loss dependence on B_t



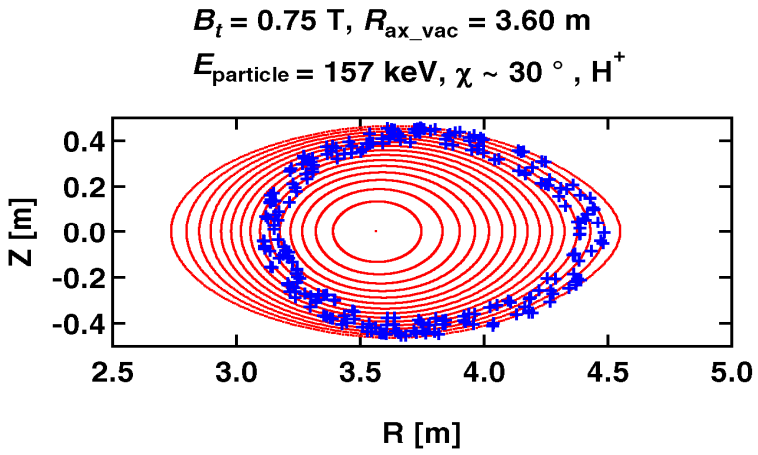
Loss flux is observed and Strong TAE excited

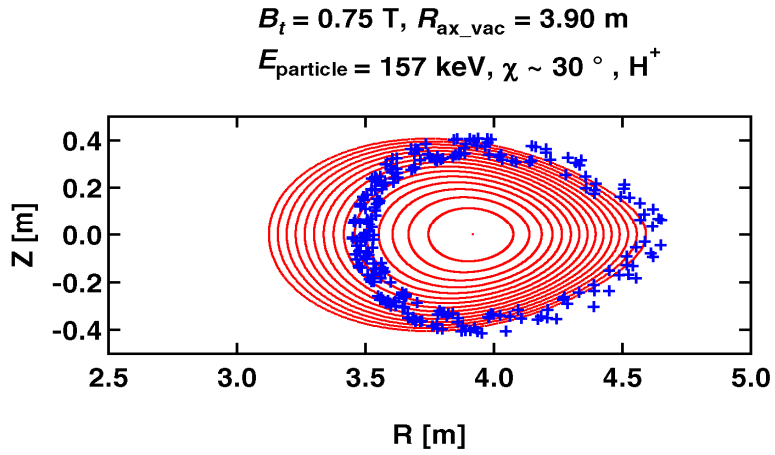
relatively high β plasma

- **TAEs are excited by NB ions in LHD.**
- **Very weak toroidal mode coupling on TAE**
  - **->Very similar to TAEs in Tokamaks**
- **Obvious fast-ion losses by TAEs are observed only at relatively low-B_t region (B_t < 0.75 T) : <β> = 1.0 ~ 2.0 %**
- **Co-going fast-ion losses induced by TAE using bi-directional scintillator-based lost-fast ion probe being studied.**

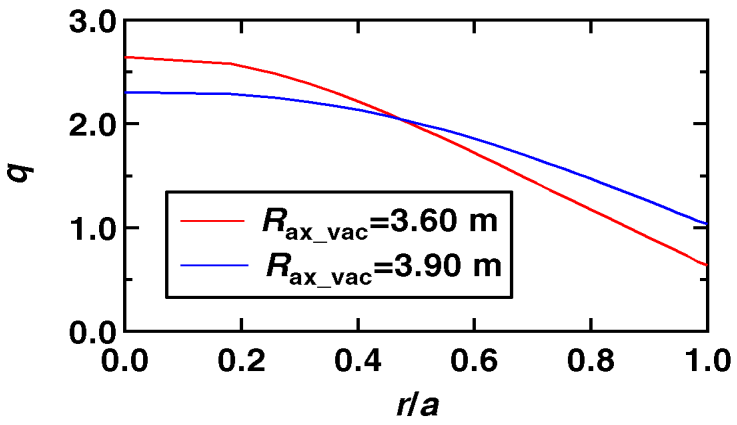
Configuration effect on orbit and safety factor on LHD

- Poincaré plots of passing fast ion orbit at R_{ax_vac} of 3.60 m, and 3.90 m with vacuum field





Safety factor profile

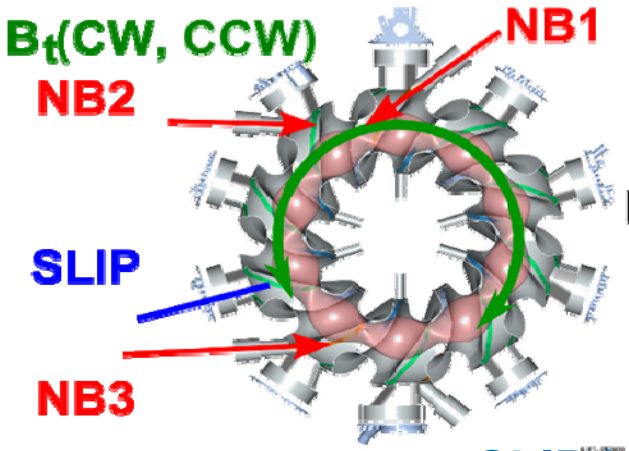


- Large deviation of orbit from the flux surface.
  - High-energy of fast ions
  - Low-B_t experiment.
  - Become large as R_{ax_vac} shifted.
- Safety factor profile becomes flat as R_{ax_vac} shift.
  - Affect the profile of instability
- Charge exchange loss of fast ion (~180 keV) is small.

- 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)

LHD and Position of SLIP

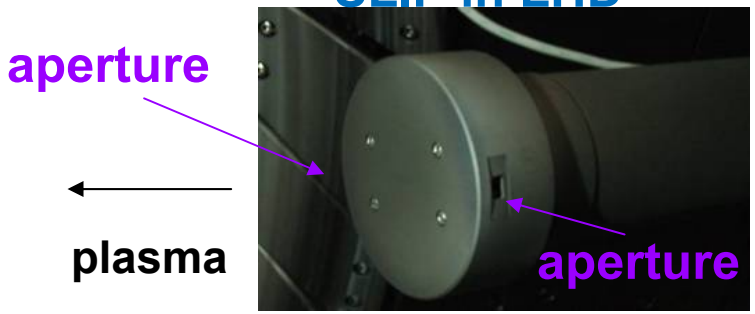


B_t= 0.4 ~ 3.0 T

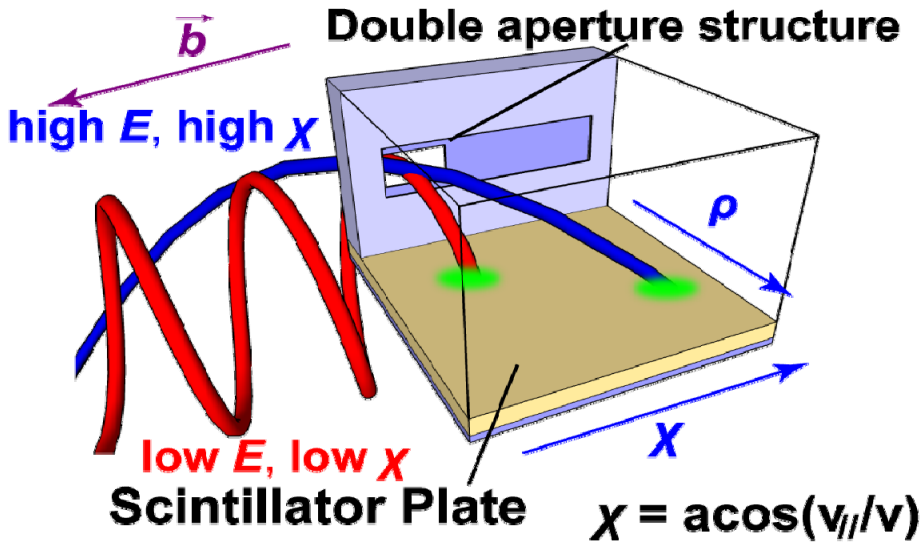
R/a = 3.9 m/0.6 m

V_{NBACC}~190 keV

SLIP in LHD



Model of scintillator head

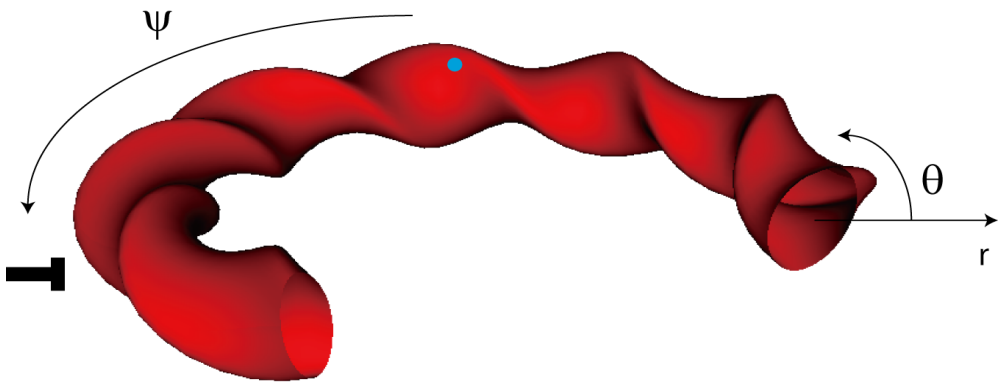


E: energy of ion, χ : pitch angle

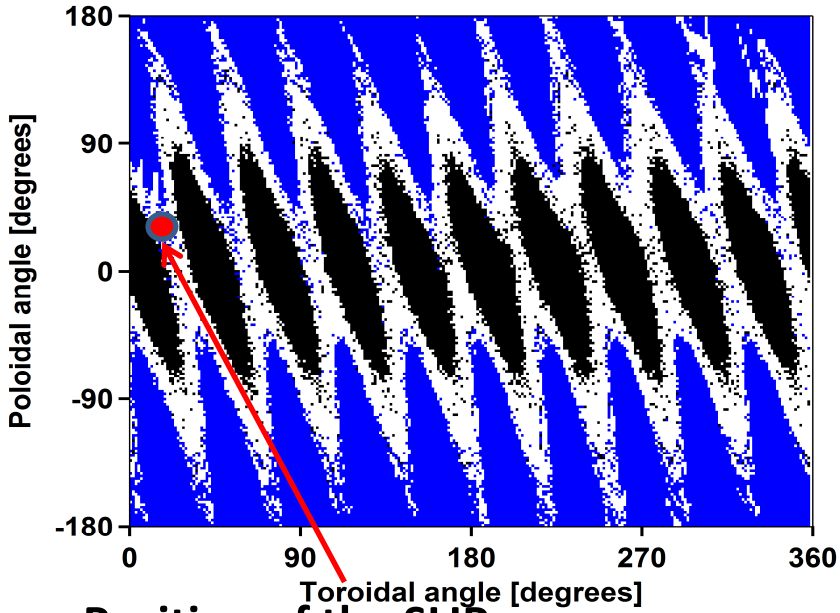
- Double aperture structure has a role in discriminating E/χ of detectable ions
- Scintillation point gives the information of *E* and χ of lost ions
  - Scintillation points are measured with a CMOS camera and a 4×4 PMT array.
- The scintillator probe can collect wide region.

Whether fast ions reach the SLIP or not

Condition for evaluation



Classification of reaching point

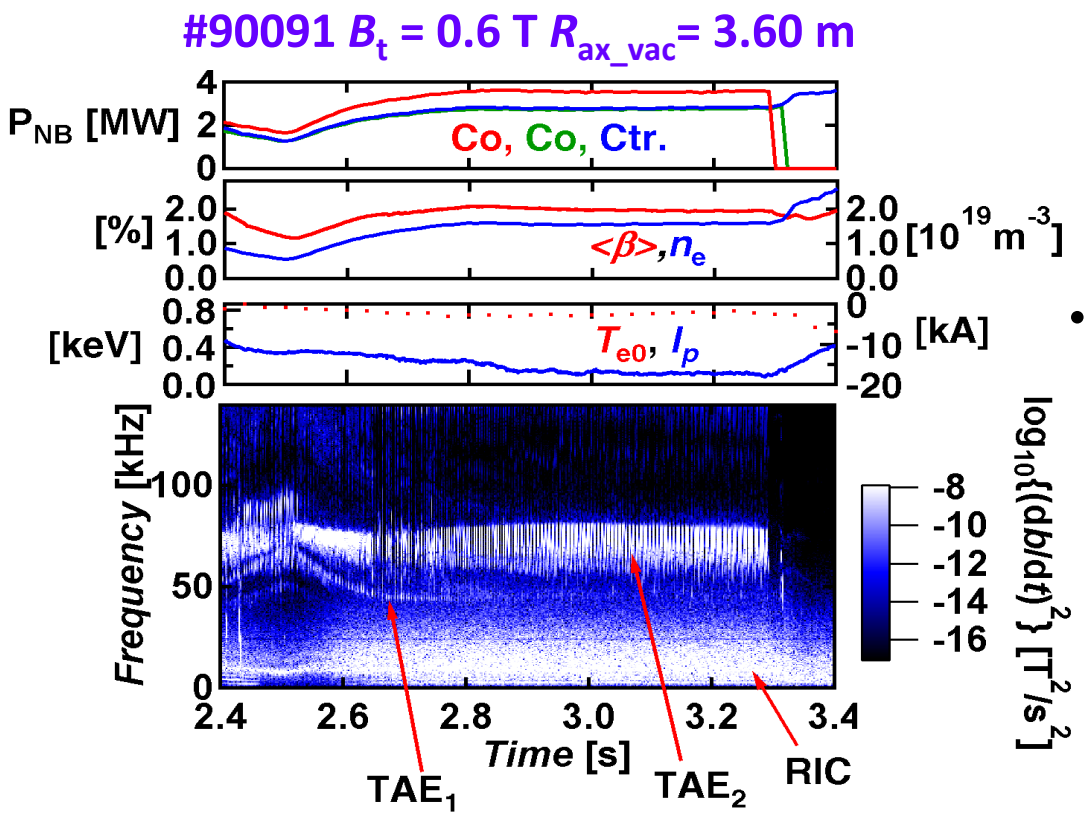


Position of the SLIP

- **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, χ~40degrees**
    - **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_{ax_vac}=3.6 m



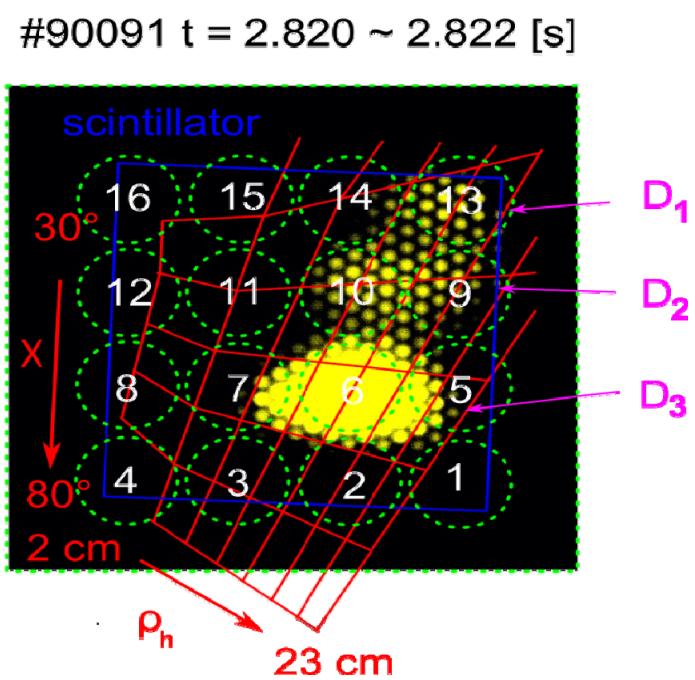
TAE: toroidal Alfvén eigenmode
RIC: resistive interchange mode

- Experimental condition.
  - B_t=0.6 T (CCW)
  - <n_e> ~ 1.5 x10^{19}m^{-3}
  - <β>~ 2.0 %
  - R_{mag}~3.86 m
  - <β_{fast}>~1.0 %
  - v_{beam}/<v_A>~1.6
- Instabilities observed with pickup coil
  - TAE(m~1/n=1)
    - Frequency ~70 kHz
    - Amplitude of magnetic fluctuation: ~0.5x10^{-4} T
    - peak of eigenfunction :r/a~0.6[1]
  - Bulk plasma pressure excites instability
    - RIC (mainly: m=1/n=1)
    - Frequency:~2 kHz
    - Amplitude of magnetic fluctuation: ~3.0x10^{-4} T
    - Peak of eigenfunction :r/a~0.9[2]

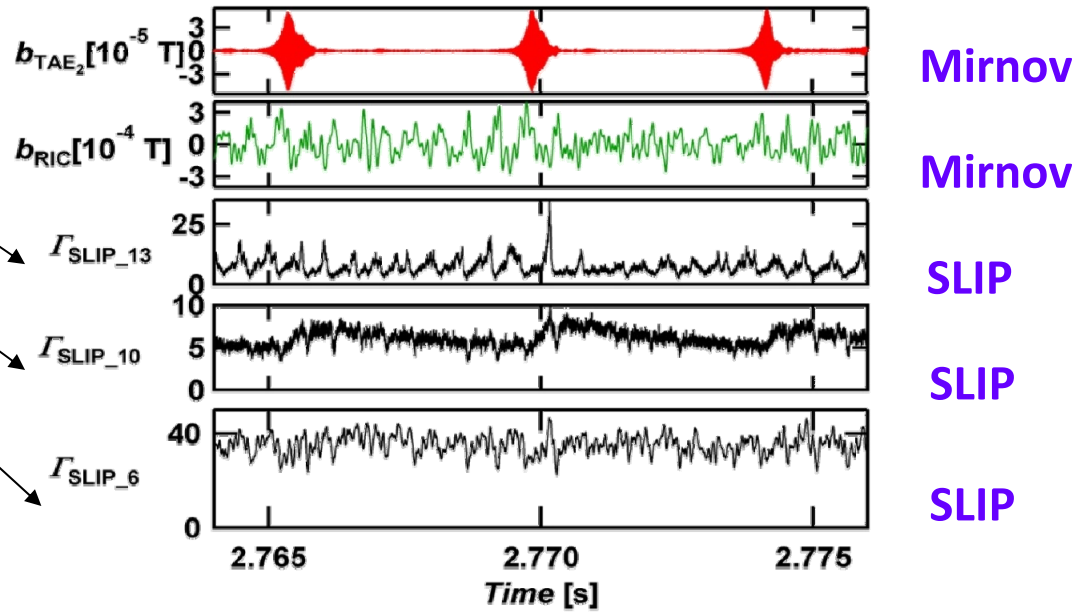
[1] K. OGAWA *et al* PPCF 30 (1988) 1023
[2] K. OGAWA *et al* NF 30 (1990) 1023

Energy and pitch angle of lost ion due to TAE/RIC

Image of scintillator plate



Time trace of TAE_2, RIC and Γ_{SLIP}(#90091)



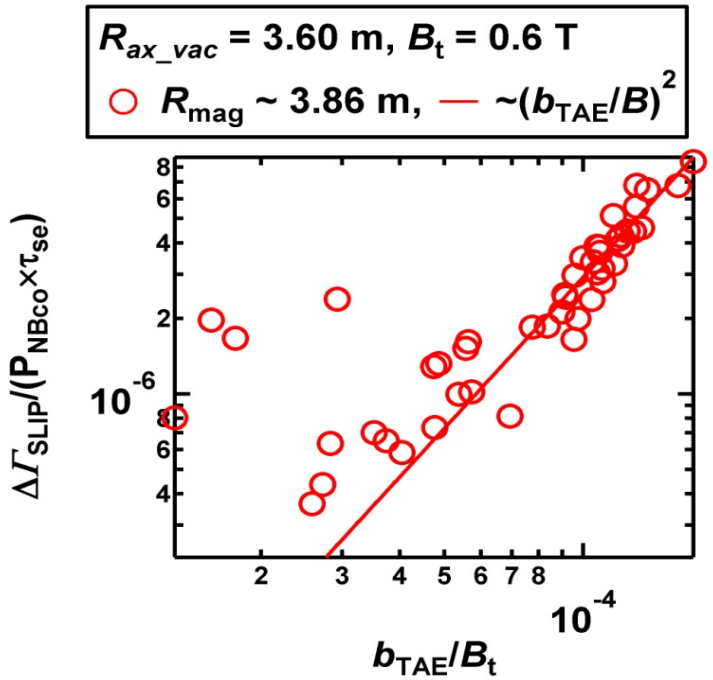
- **Three domains are observed. (D_1 ~ D_3)**
- **D_1: E=80~150 keV, χ =25~35° D_2: E=50~190 keV, χ =35~45°**

  D_3: E=50~190 keV, χ =45~60°
- **D_1: mainly RIC loss, D_2: mainly TAE loss, D_3: mainly collisional loss**

RIC: resistive interchange mode

TAE induced loss dependence on magnetic fluctuation amplitude on MP position at R_{ax_vac}=3.6 m w/large shift

Loss dependence on mode amplitude at R_{mag} of 3.86 m

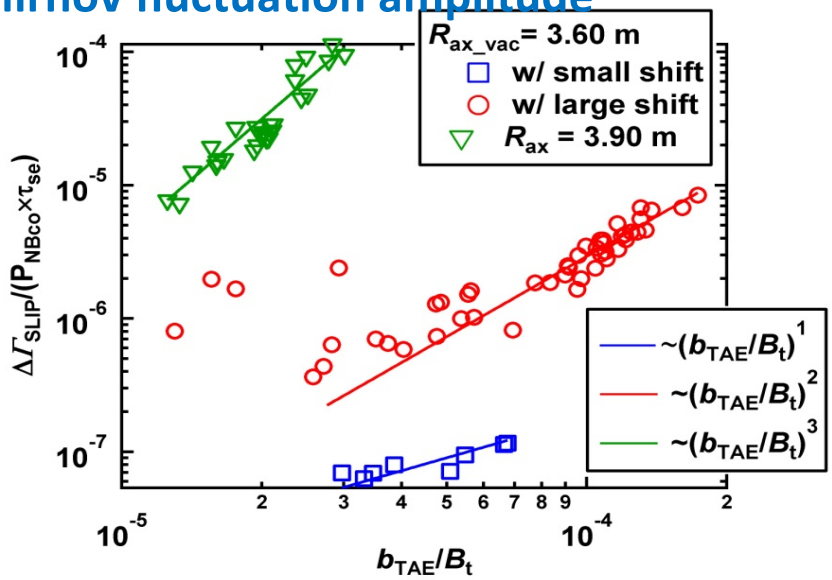


$<\beta_{dia}>$ ~ 2 %
R_{ax_vac}=3.60 m
Large Shafranov shift case

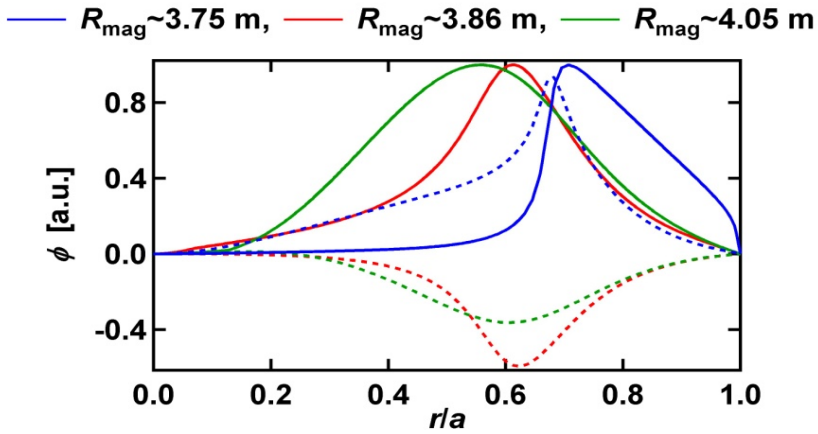
- b_{TAE} is magnetic fluctuation amplitude measured by pickup coil.
- $\Delta\Gamma_{SLIP}$ is increment of loss induced by TAE.
  - $\Delta\Gamma_{SLIP}$ is evaluated with removing RIC effects.
- Loss flux is proportionate to fast ion density ~ P_{NBco}xτ_{se}
  - Loss signal is normalized by fast ion density.
- Diffusive type of loss is observed.

TAE induced loss dependence on Mirnov fluctuation amplitude on various R_{mag}

TAE induced loss dependence on Mirnov fluctuation amplitude



Eigenfunction of TAE in each configuration

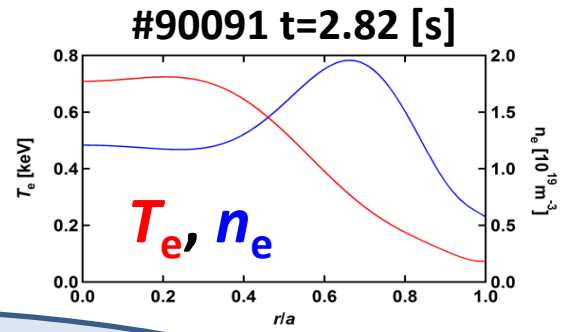


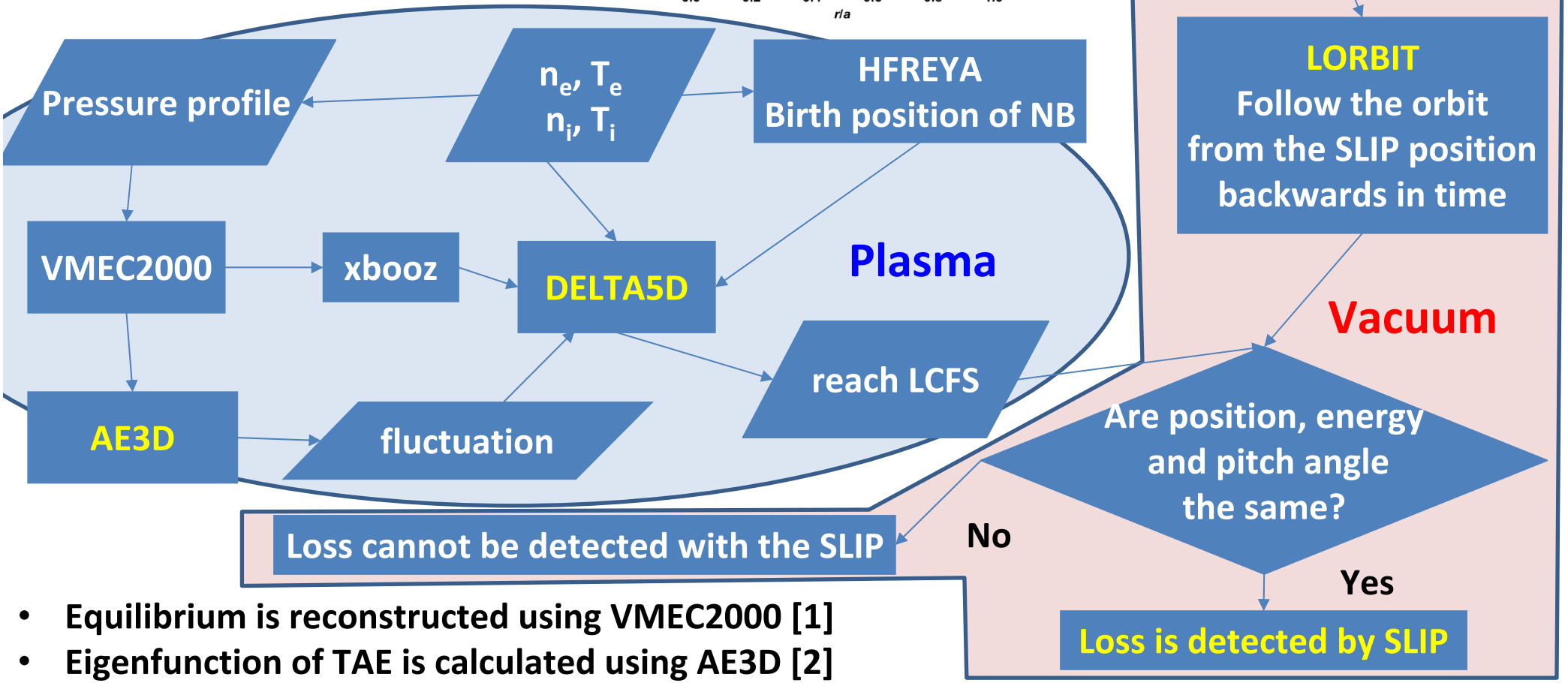
- Number of loss grows as R_{mag} shifted.
- The dependence becomes steeper as R_{mag} shifted.
  - The convective loss process (s=1) changes to diffusive (s=2) as R_{mag} shifted.
  - Finally to a stochastic transport of particle orbits in phase space.
- Eigenfunction of TAE becomes wider as R_{mag} shifted.
- Fast ions stays away from loss cone can be lost due to TAE with wide eigenfunction.

- The effect of Shafranov shift at R_{ax_vac} of 3.60 m on TAE induced loss is simulated.

Calculation of TAE induced loss using Orbit following model

Scheme of the numerical simulation



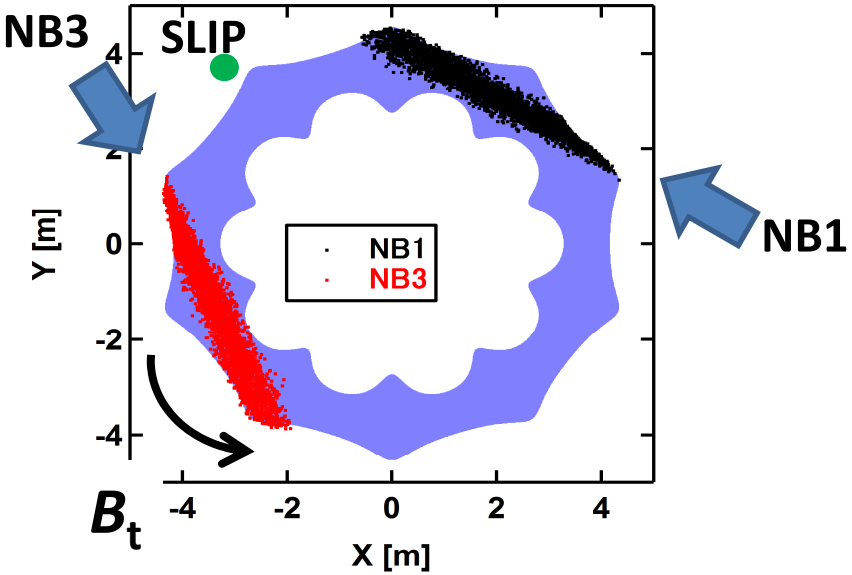


- Equilibrium is reconstructed using VMEC2000 [1]
- Eigenfunction of TAE is calculated using AE3D [2]
- Guiding center orbit in a plasma region is followed using DELTA5D [3]
  - It is the simple modeling at ρ/a ~ 0.1.
- Lorentz orbit at the outside of the plasma is followed using magnetic field in vacuum.

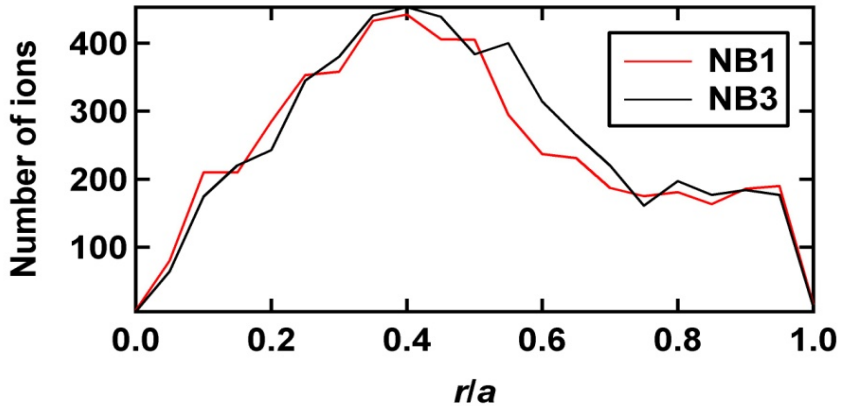
[1] S.Hirshman Pof 1983, [2]D. Spong PoP 2010, [3] D. Spong BAPS 1999

Birth profiles and pitch angle of fast ions

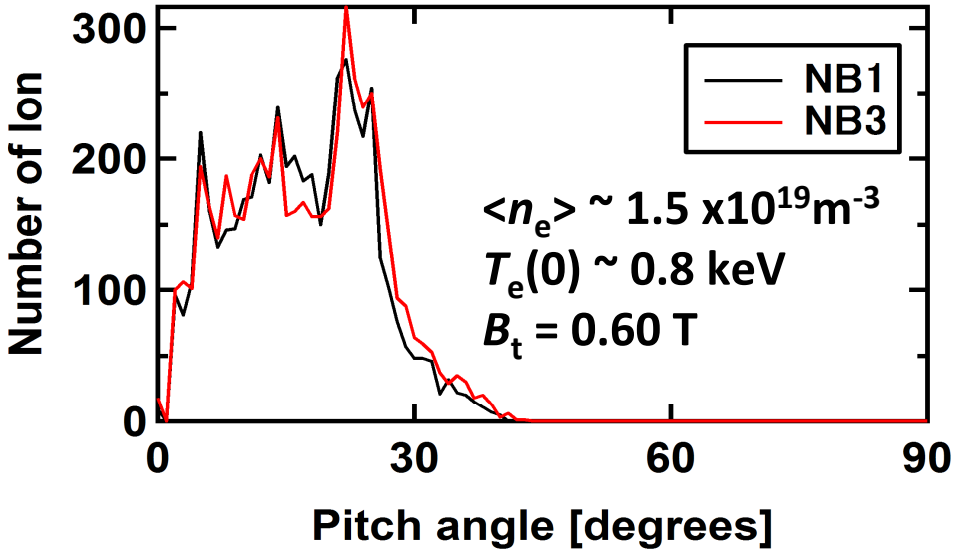
Birth positions of the beam ions



Birth profile of fast ion



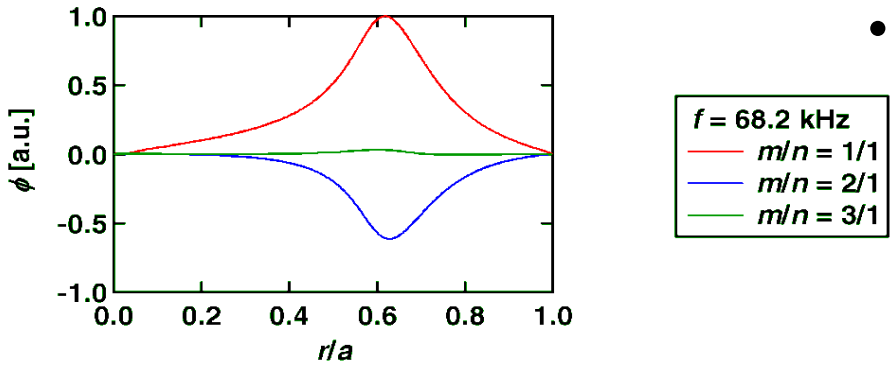
Initial pitch angle distribution of beam ions



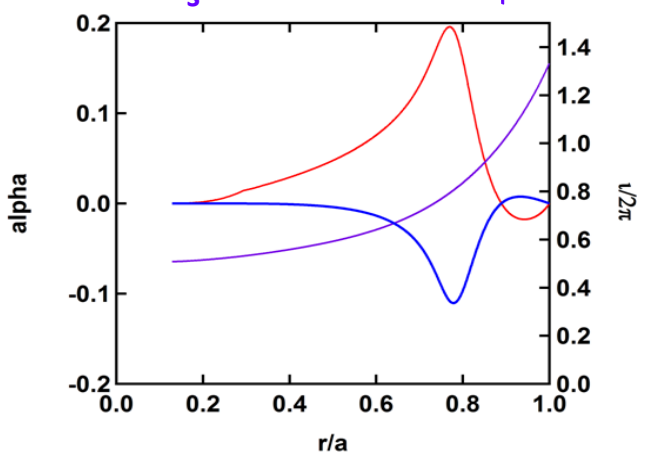
- **Fast ion created by NB#1 and NB#3 are considered in this calculation.**
  - **NB#2 is injected on the CW direction producing Ctr.-going ion.**
  - **SLIP installed at outboard side cannot detect Ctr.-going ions.**
- **Pitch angle of fast ions are less than ~30 degrees**
  - **All of them are co-going ions.**

Model of the fluctuation

ϕ of TAE mode



α_s derived with ϕ



[1] D. Sigmar PFB 1992

- **Fluctuation of the TAE is mostly perpendicular to the magnetic field line.**
- **Fluctuation is modeled as[1]**

$$\delta \mathbf{B} = \nabla \times (\alpha \mathbf{B})$$

$$\alpha(\psi,\theta,\zeta) = \sum_l \alpha_s(\psi) \sin(n_l \zeta - m_l \theta - \omega_{real} t)$$

$$\alpha_s(\psi) = \nabla_{//}\phi = \alpha_{k0}\left(\frac{n_l}{m_l} - \iota\right) e^{-(\psi-\psi_{peak})^2/\Delta^2}$$

  - ϕ is calculated with AE3D
  - Effect of electric field due to fluctuation is neglected

- **Additional term due to TAE is…**

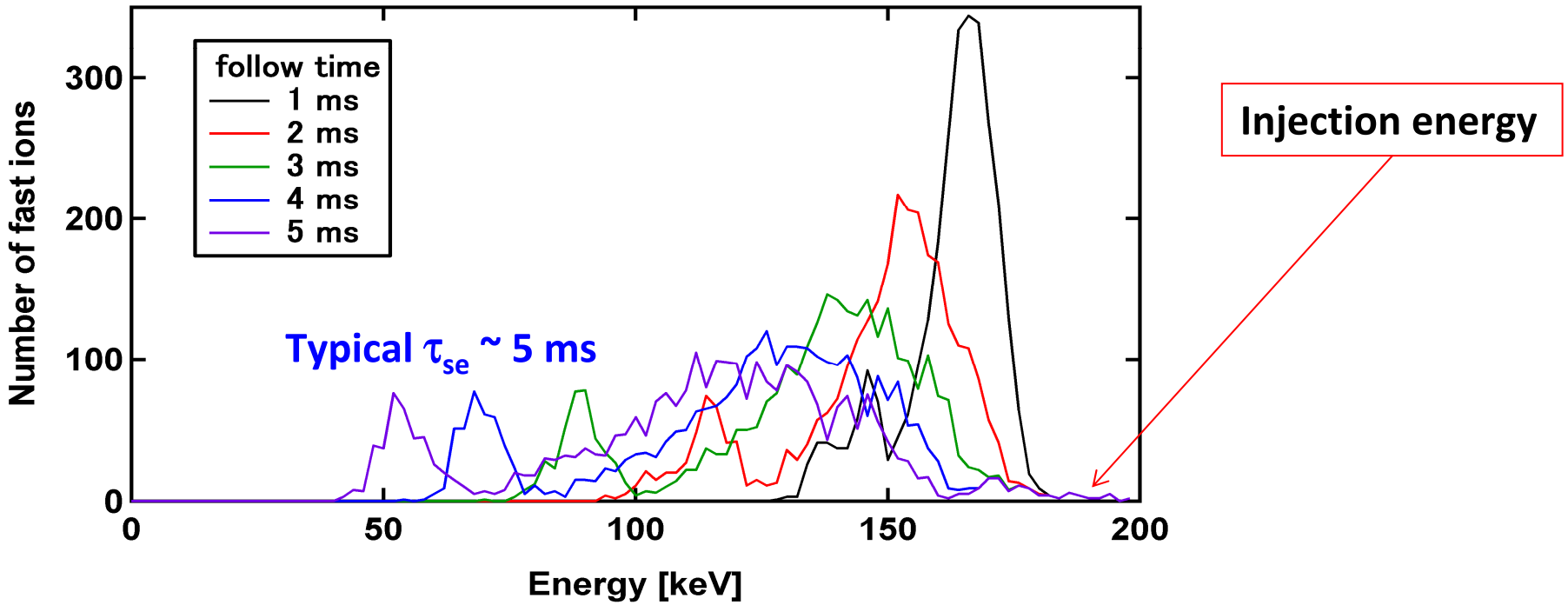
$$\frac{d\theta}{dt} = \cdots + e v_{//} B \frac{\partial \alpha}{\partial \psi}\frac{\partial \psi}{\partial P_\theta}$$

$$\frac{d\psi}{dt} = \cdots + e v_{//} B \frac{\partial \alpha}{\partial \psi}\frac{\partial \psi}{\partial P_\zeta}$$

$$\frac{d\rho_{//}}{dt} = \frac{\bar{\iota} - (\rho_{//} + \alpha) g'}{D}\dot{P}_\theta + \frac{\bar{\iota} - (\rho_{//} + \alpha) I'}{D}\dot{P}_\zeta + \frac{d\alpha}{dt}$$

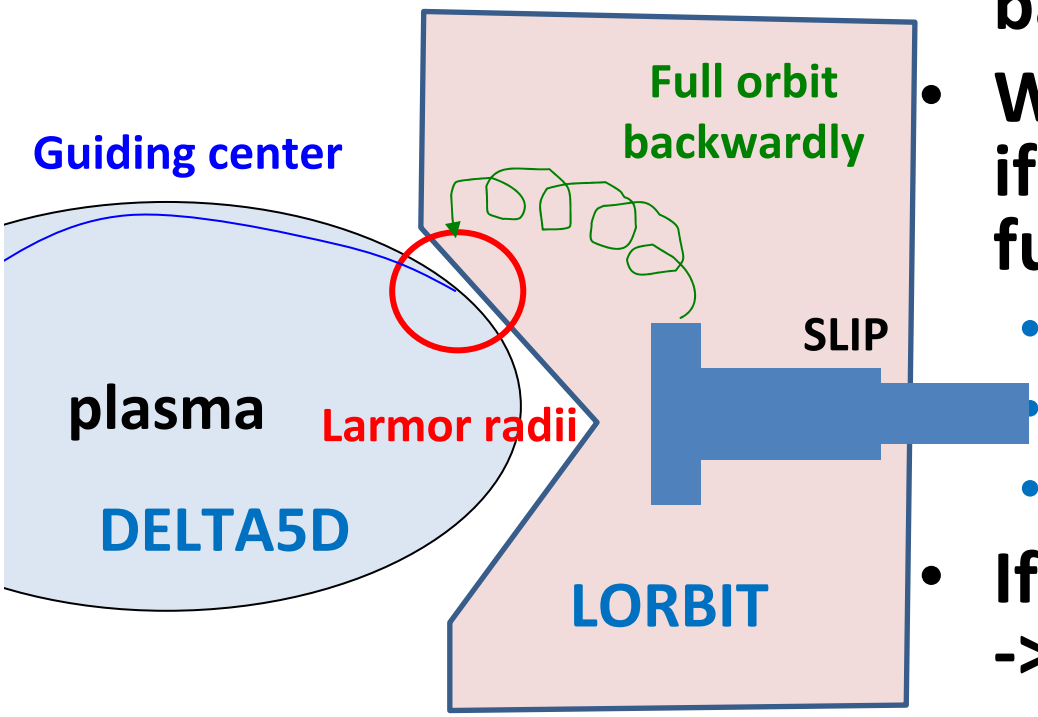
Slowing-down distribution

Slowing down distribution of beam ion injected into the plasma



- 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.

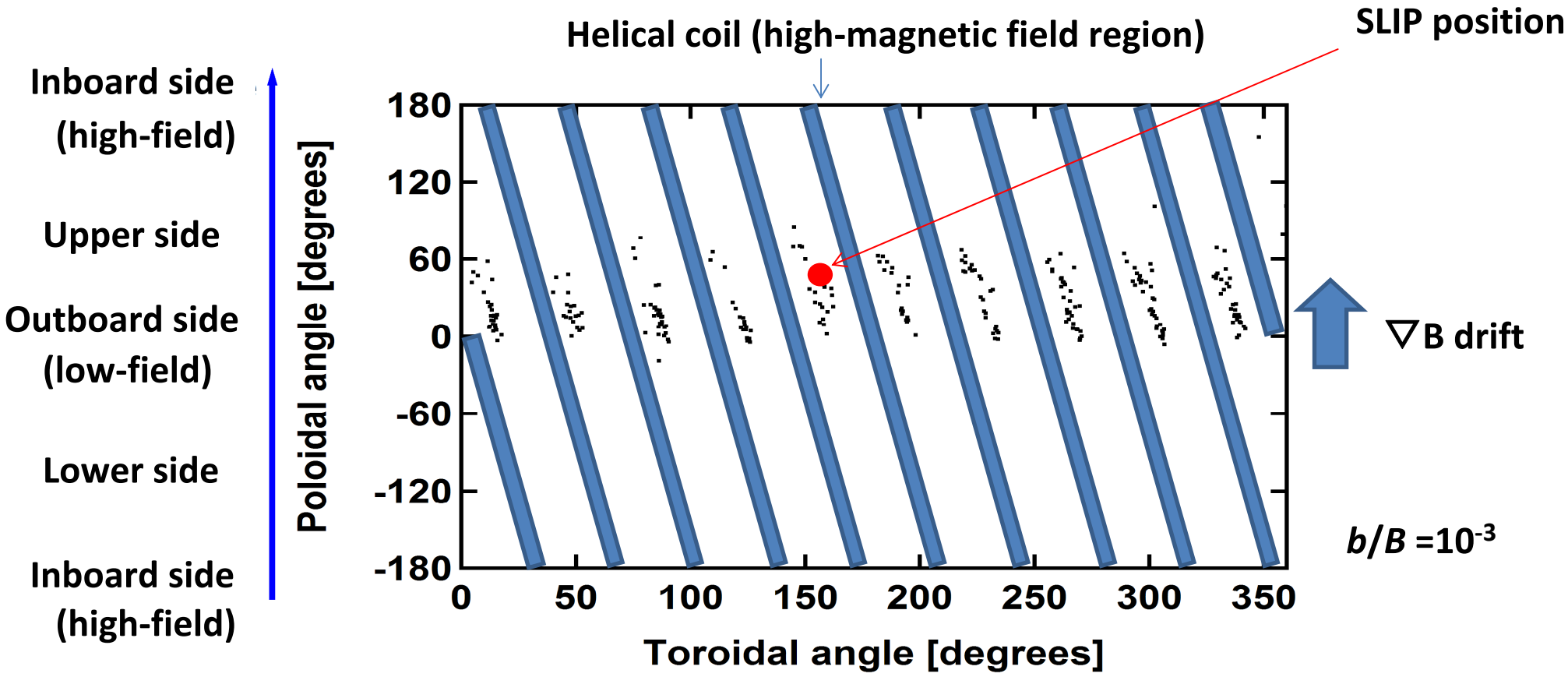
Connecting procedure between DELTA5D and Lorentz orbit



- **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

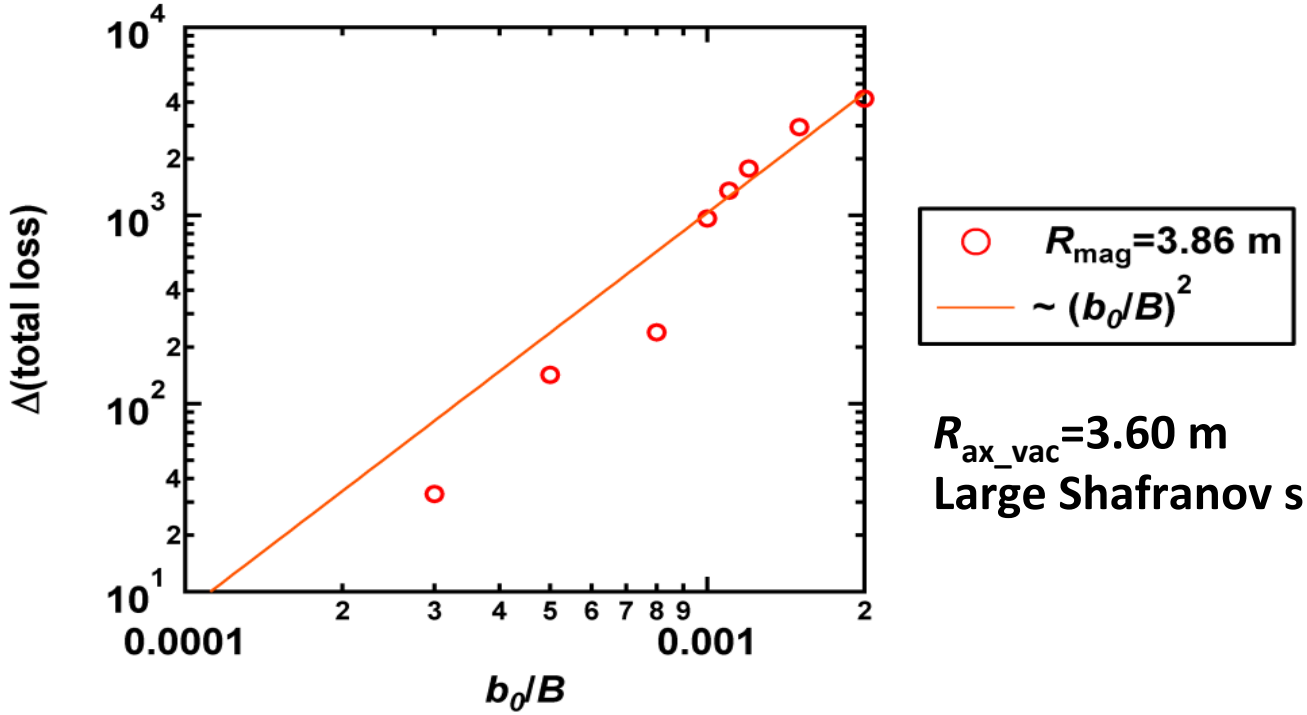
The points that fast ions transported to LCFS



- 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_{ax_vac}=3.60 m with large shift

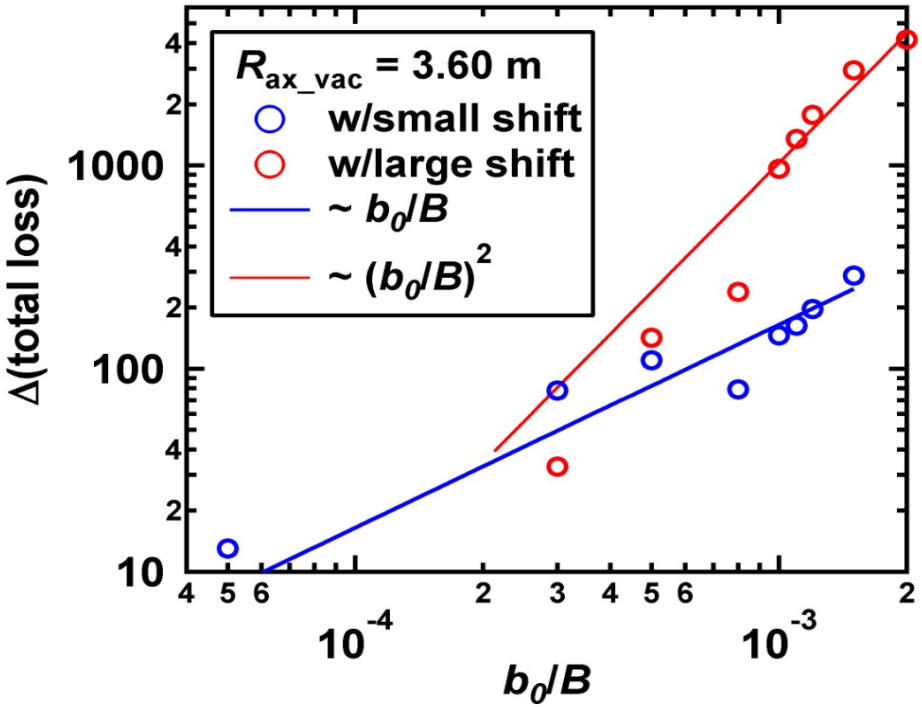
Fast ions come to LCFS due to TAE



- **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 $b_0/B < 3.0\times10^{-4}$
- **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.

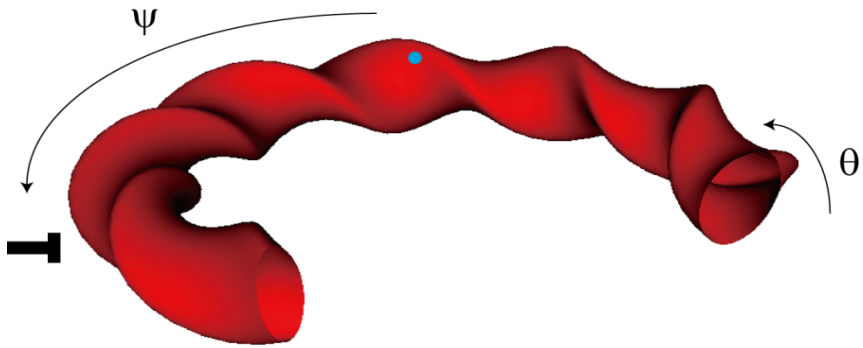


- **Number of particle reaching the LCFS grows with increasing b_0.**
- **Shafranov shift induce…**
  - **Growing number of loss**
  - **Steeper dependence**
    - **Linearly to quadratically.**

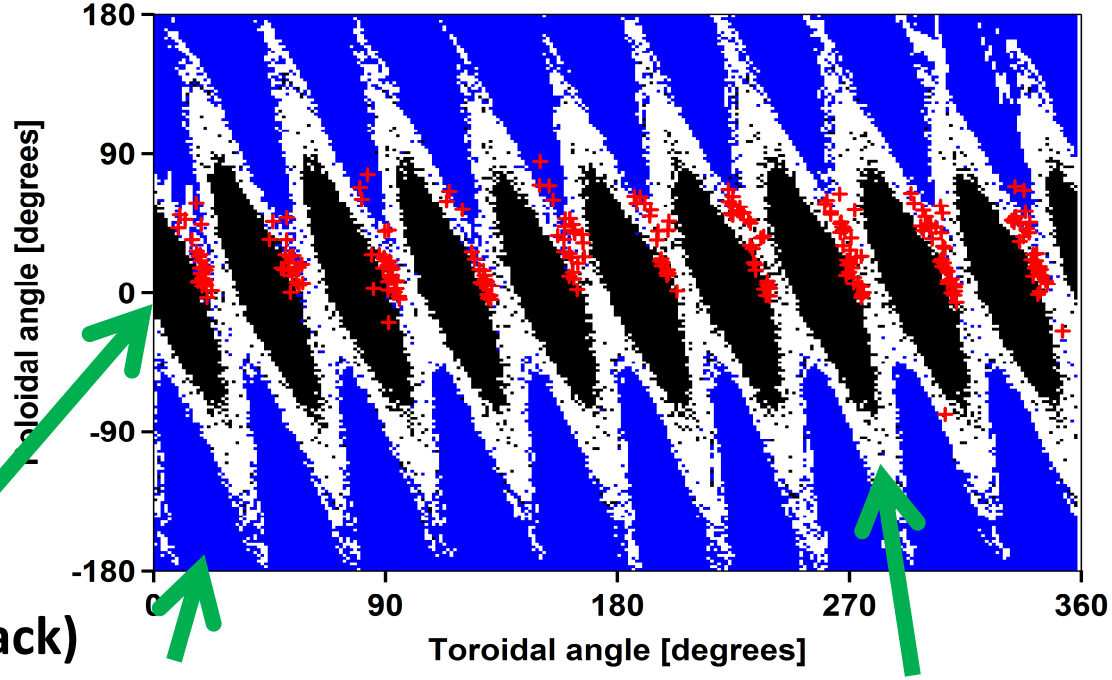
Fast ion lost due to TAE measured by the SLIP

Compare the region covered by SLIP and reaching points

Condition for evaluation



Classification of orbit and reaching points



Confine (Black)

Loss w/o detect (Blue)

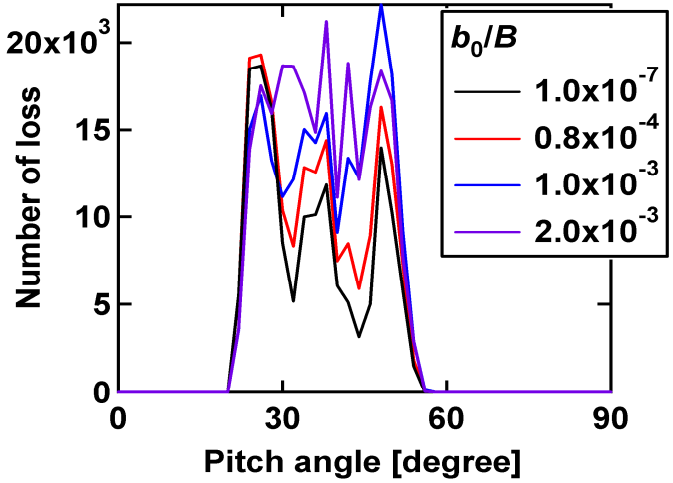
Reach SLIP (White)

+ : Reaching point of fast ion on LCFS

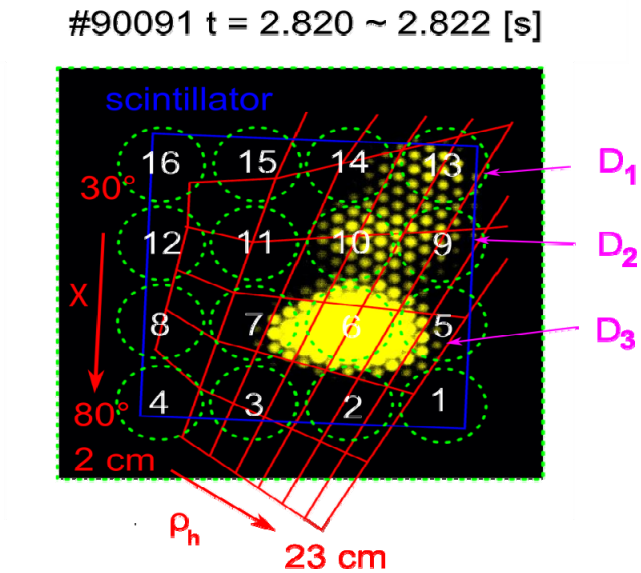
- Comparison between reaching points on LCFS and the LCFS region which fast ions having pitch angle of ~ 40 degrees goes to the SLIP.
- The SLIP can catch most of ions transported to the LCFS due to TAE.

Pitch angle distribution of TAE induced loss detected by SLIP

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



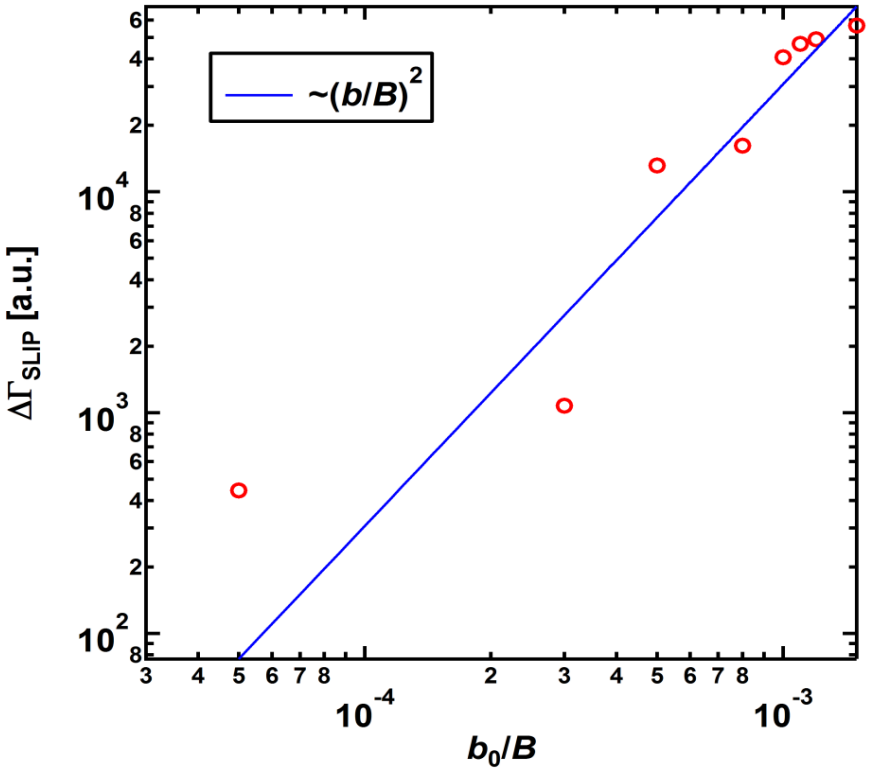
Energy/pitch angle distribution in experiment



- **Pitch angle distribution of lost ion reach the SLIP at R_{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

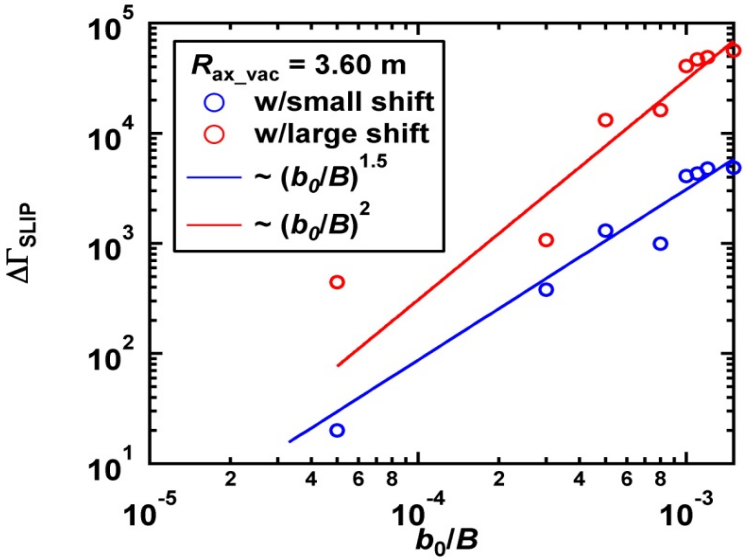
b_0 dependence on lost ion at R_{ax_vac}=3.60 m with large shift



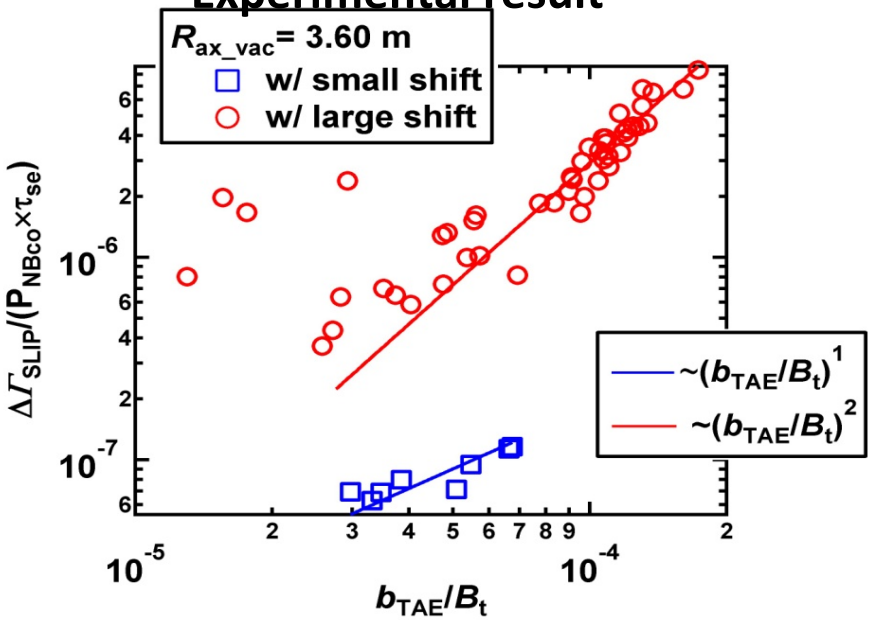
- **Clear increase of loss is observed when b_0/B > 3.0x10^{-4} at large shift case.**
- **Increment of loss due to TAE is quadratically increase as observed in experiments.**
- **The dependence is the same as that of fast ion reaching LCFS due to TAE.**
  - **The SLIP can collect most of ions transported to the LCFS by TAE.**

TAE induced loss dependence on fluctuation amplitude in various R_{mag}

Calculation result



Experimental result



- **Loss flux dependence on fluctuation amplitude.**
  - **b_0 indicate the fluctuation amplitude at peak position in a plasma**
- **Relation between b_0 and b_{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.