



Indication of bulk-ion heating by Energetic particle driven Geodesic Acoustic Mode on LHD

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 - c. Confinement improvement with the mode.
 - d. Anomalous ion-heating with the mode.
4. SUMMARY



Background & Motivation

- Zonal Flow(ZF) and Geodesic Acoustic Mode(GAM) get much interests recently, since it could be a knob to regulate turbulence in plasmas and to reduce anomalous transport. Moreover, additional heating by GAM is theoretically pointed out (GAM channeling).*
- Energetic-particle(EP) induced GAMs are observed in several toroidal devices, such as JET, DIII-D and LHD**. Effect of GAMs on the energetic particle behaviors needs to be investigated.
- Recently, an influence of EP induced GAM on bulk-ions was observed on LHD.

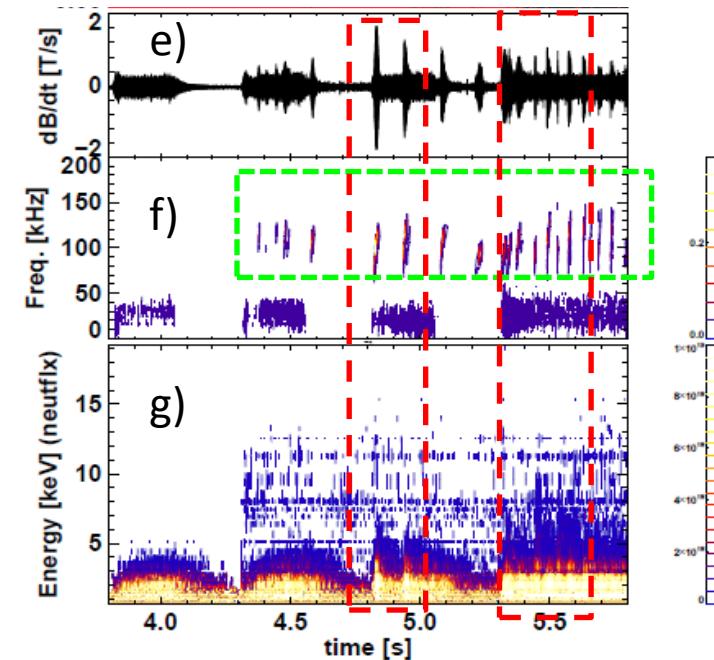
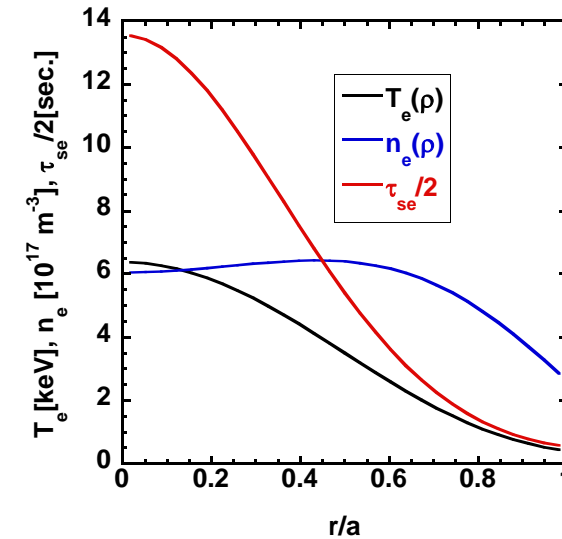
*M.Sasaki, et.al., PPCF **53**(2011)085017

H.L.Berk, et.al., Nucl. Fusion **46, S888, C.J.Boswell, et.al., Phys. Lett. A , **358**, 154, R.Nazikian, PRL 101, 185002, G.Y.Fu, PRL 101, 185002, K.Toi: 22nd IAEA-FEC, EX P8-4, T.Ido : 23rd IAEA-FEC



On LHD, increase of low energy neutrals are observed with up-sweeping n=0 modes by tangential NPA at low density plasmas.

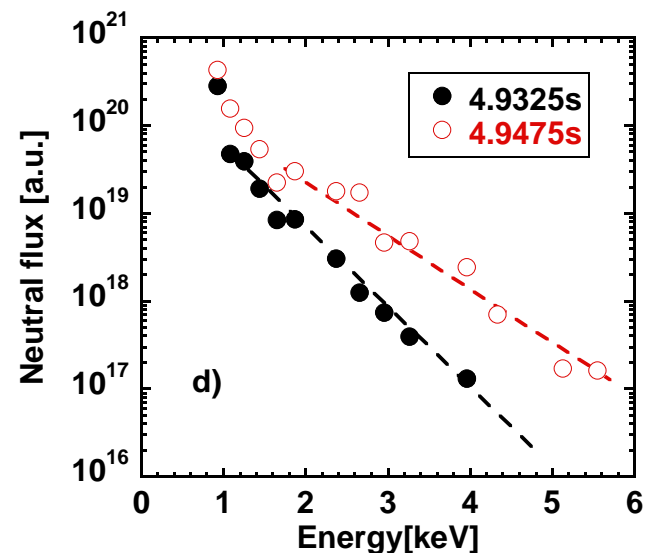
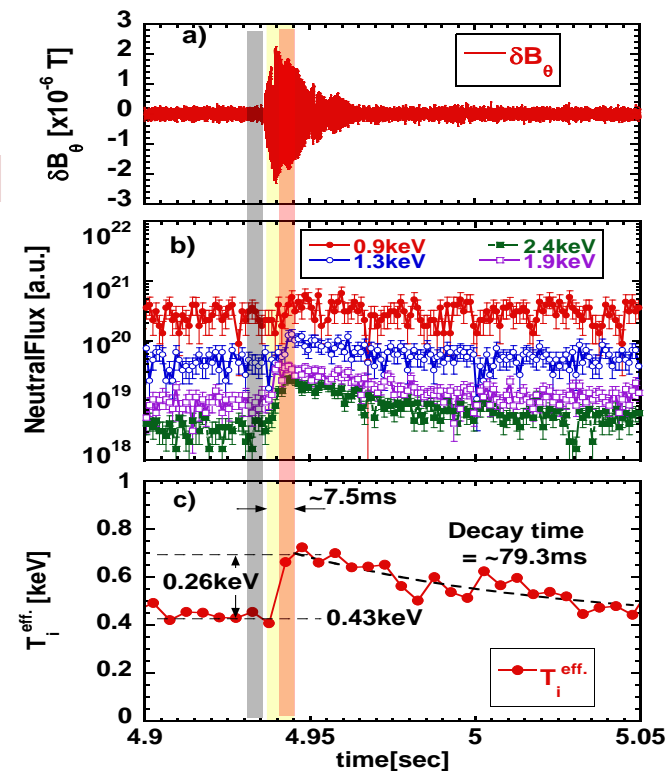
- The mode was only excited during counter-NB injection phase.
 - Superposition of ECH seems to be effective to excite the mode.
 - The typical initial frequencies of the mode are 50 -100kHz. The flux increase was associated with relatively large amplitude modes.
 - No significant increase of H α -signals were observed.
- => Measured increase in neutral flux are due to the low energy ion behaviors.
- Typical slowing-down time is estimated to be ~ 10 [s] at the core



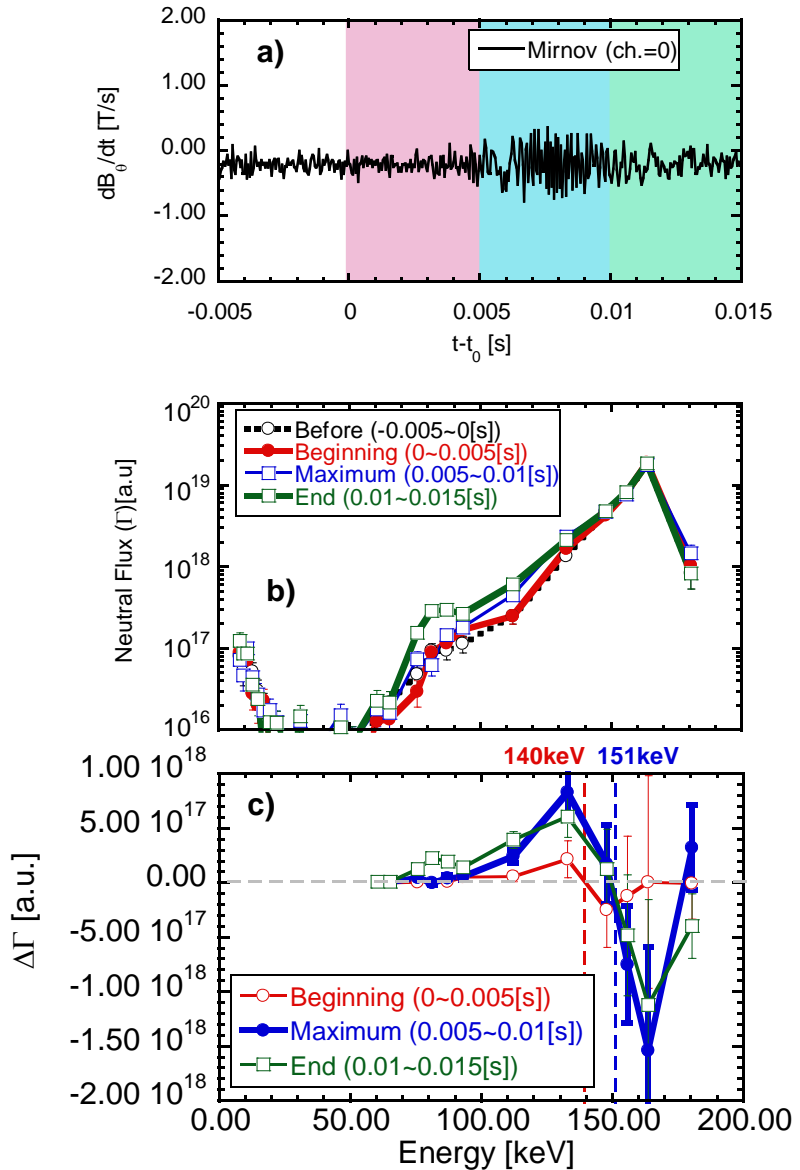
Bulk-ion behavior

- Neutral flux close to the bulk-ion energies are starts to increase after the mode excitation.
- The effective ion temperature also starts to increase after the mode excitation.

Either confinement property of bulk-ions or bulk-ion heating mechanisms seem to be changed with the mode excitation.



Fast-Ion Behavior



The flux increase and its decay were observed with the mode activity.

➤ Decay times of the increased flux were order of 10-100 ms.

⇒ The fast-ions influenced by the mode activity were not promptly lost and were circulating on confined orbits.

➤ The decay times were smaller than the expected slowing-down time of fast-ions and almost no-delays of decays were found at each energy.

⇒ They were lost before they undergo slowing-down process.

➤ The decay times have energy dependence. They became smaller as the energy decreases.

⇒ By comparing the decay time with charge exchange cross section, the charge exchange loss was found to be the dominant loss process.

The charge exchange loss process produces the positive gradients in the energy spectra.

⇒ Source of instability drive.

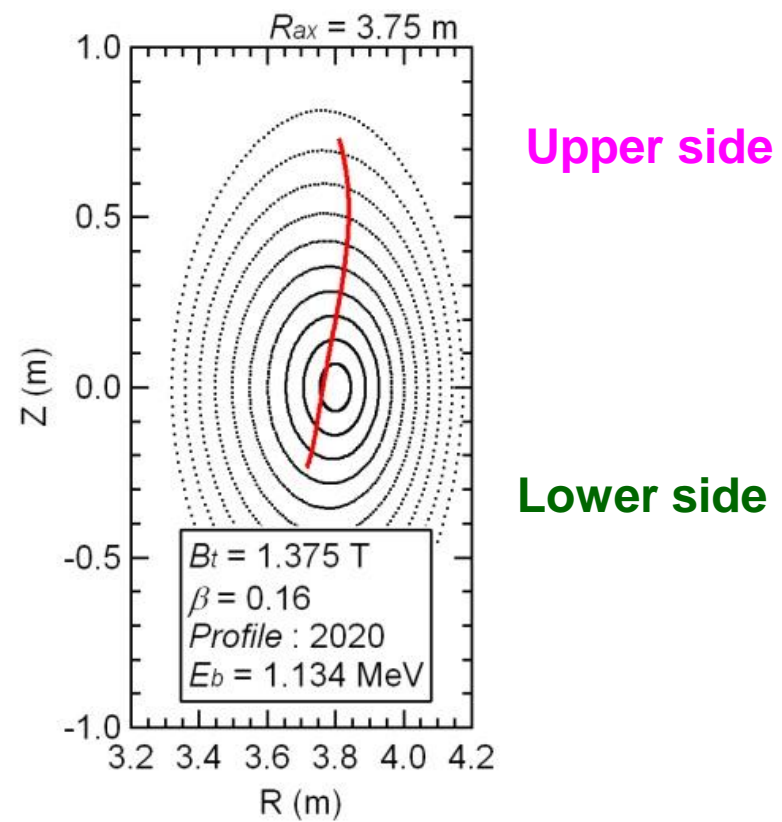
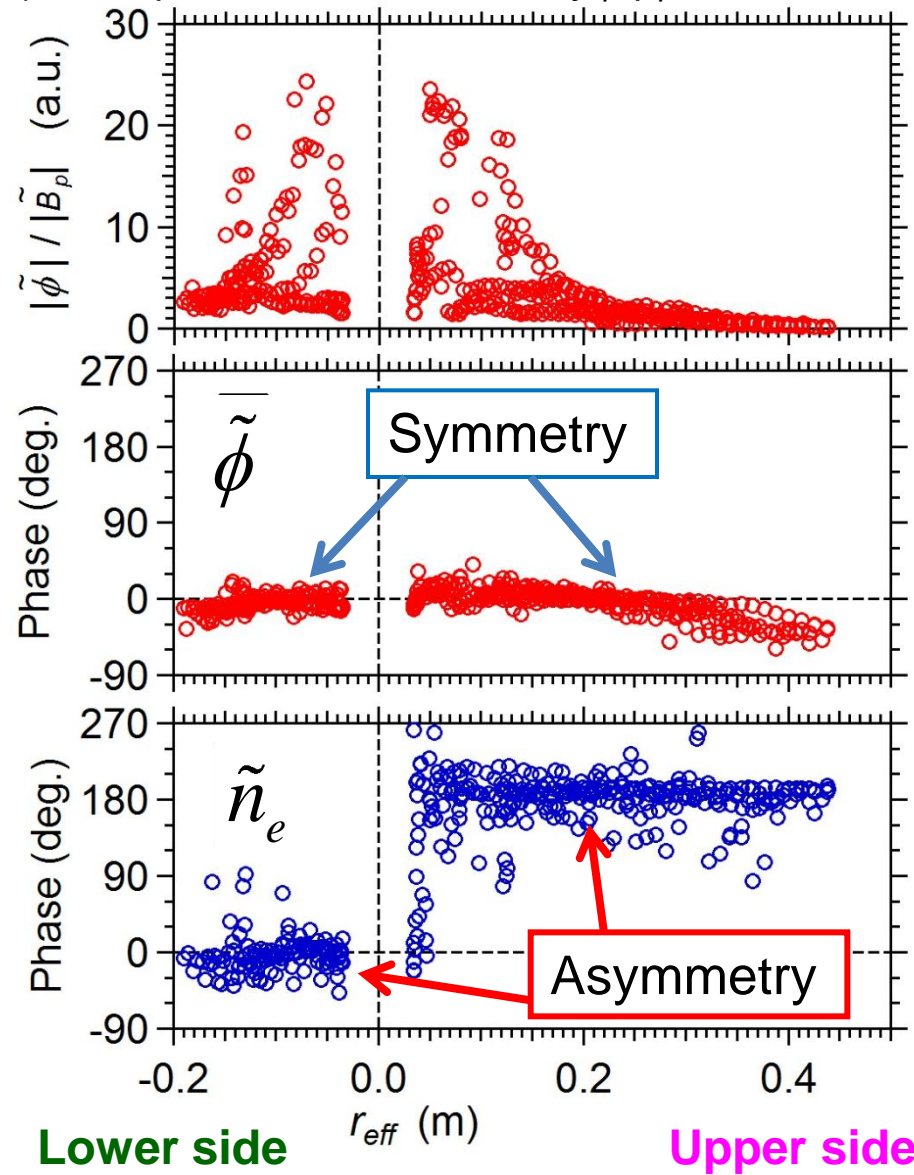
⇒ Induces clump-hole formation in the energy spectra.

MODE STRUCTURE AND ITS FREQUENCY

Evaluation of poloidal mode structure by HIBP measurement.

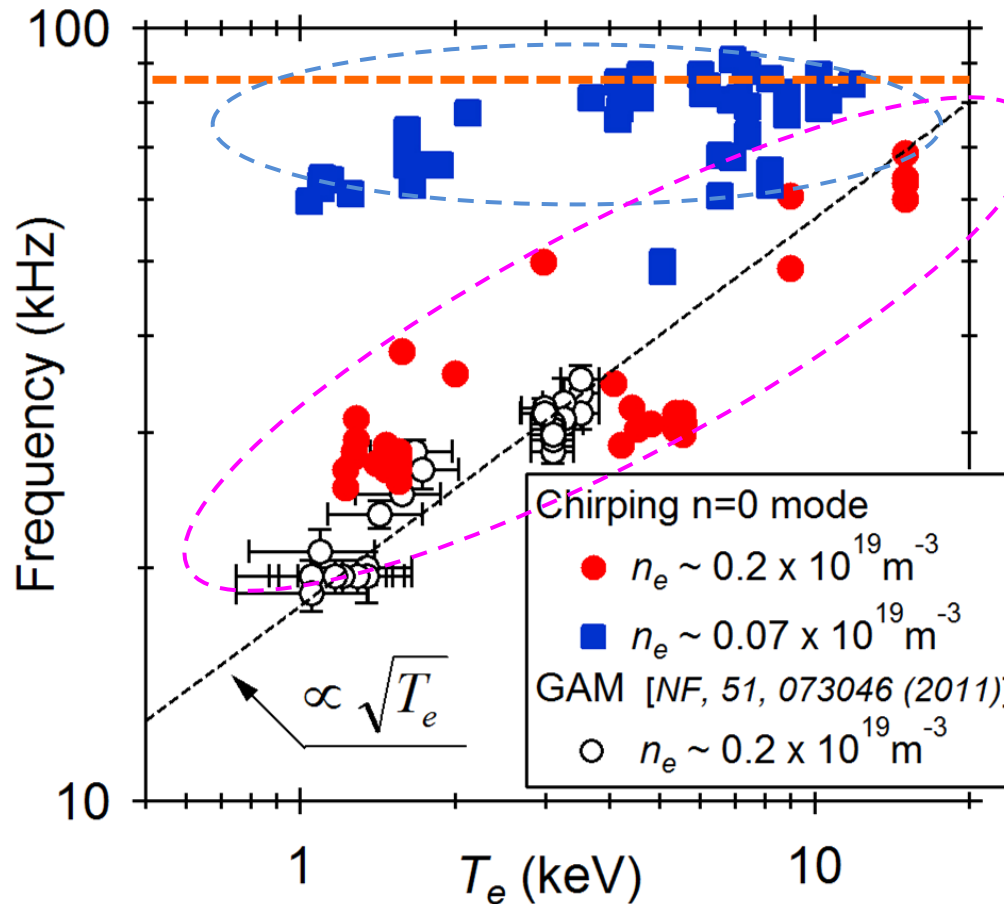
T.Ido, et.al.

(The amplitudes are normalized by $|B_p|$ to remove variation among events.)



•The spatial structures are consistent with the structures of the GAM. ($\tilde{\phi} : m \sim 0, \tilde{n}_e : m \sim 1$)

T_e dependence of the initial frequency of $n = 0$ mode

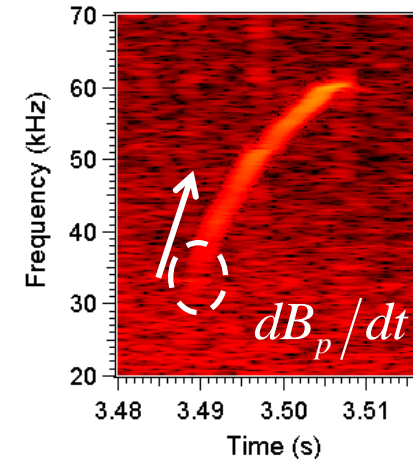


$$f_{b,0} = \frac{v_{NB,0} \tau}{2\pi R}$$

T.Ido, et.al.

85 kHz, where $E_b = 175 \text{ keV}$,
 $\tau = 0.35$, $R = 3.75 \text{ m}$

$$f_{GAM} \propto \sqrt{T_e + \frac{7}{4} T_i}$$



1. One has the $T_e^{0.5}$ -dependence of the mode frequency. (\Rightarrow GAM)
2. The other mode has weak T_e -dependence of the frequency. The mode frequency is much larger than the usual GAM, and is close to the orbital frequency of the fast-ions produced by the NBI.

The FI affects the GAM frequency

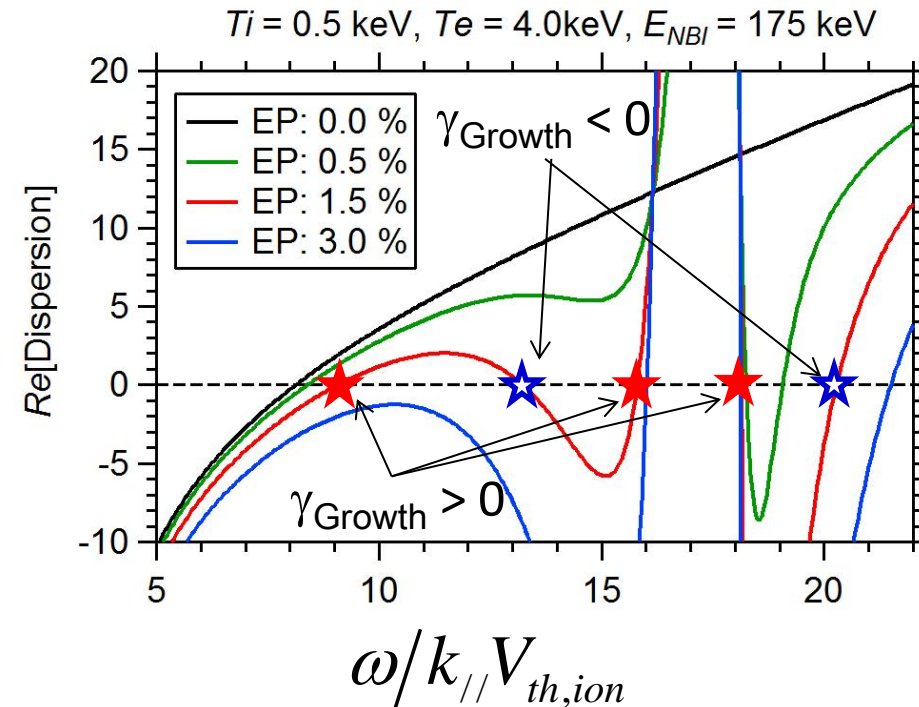
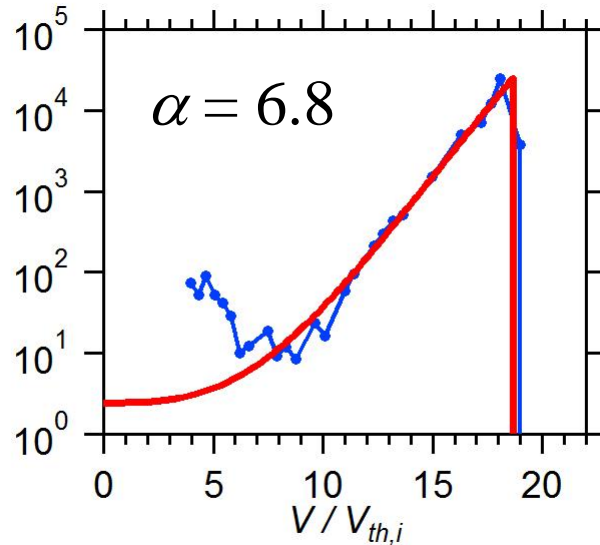
The GAM frequency is modified by FIs. (G.Y.Fu, PRL, 101, 185002 (2008))

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$$f_{EP} = \frac{A_2}{v^3 + v_c^3} \left(\frac{v_0^3 + v_c^3}{v^3 + v_c^3} \right)^{-\alpha} \exp\left(-\frac{P_\phi}{e\Delta\Psi}\right) \exp\left[-\left(\frac{\Lambda - \Lambda_0}{\Delta\Lambda}\right)^2\right] \quad \Lambda = \frac{\mu B}{E}$$

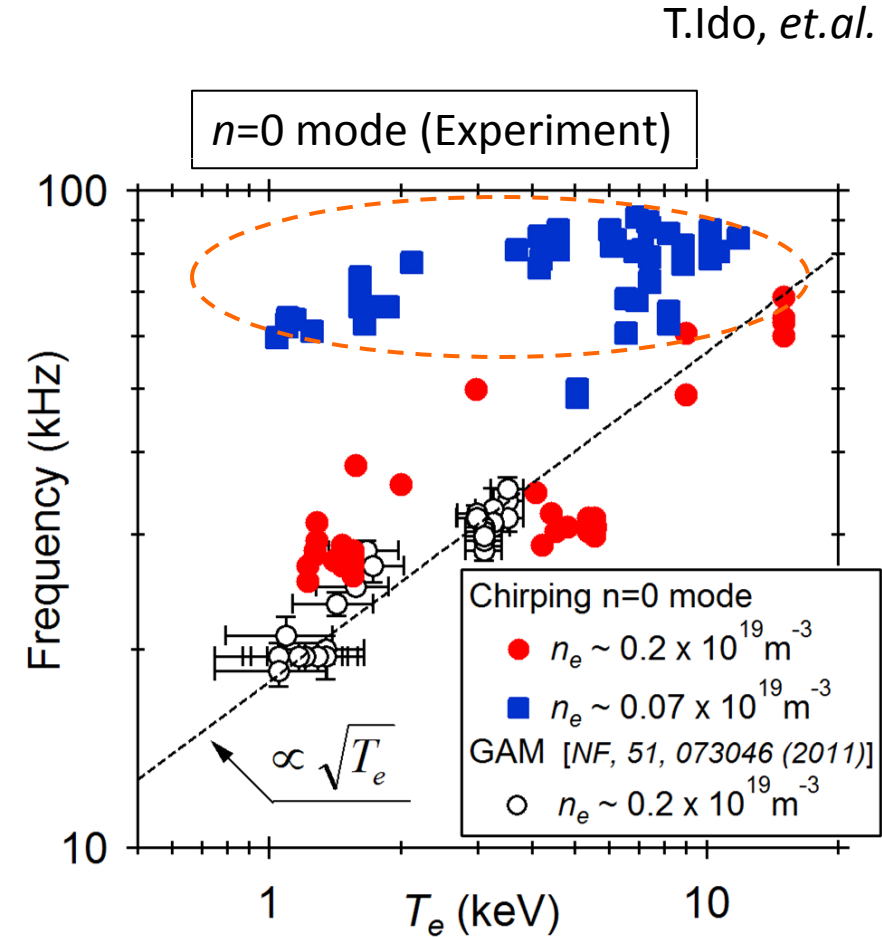
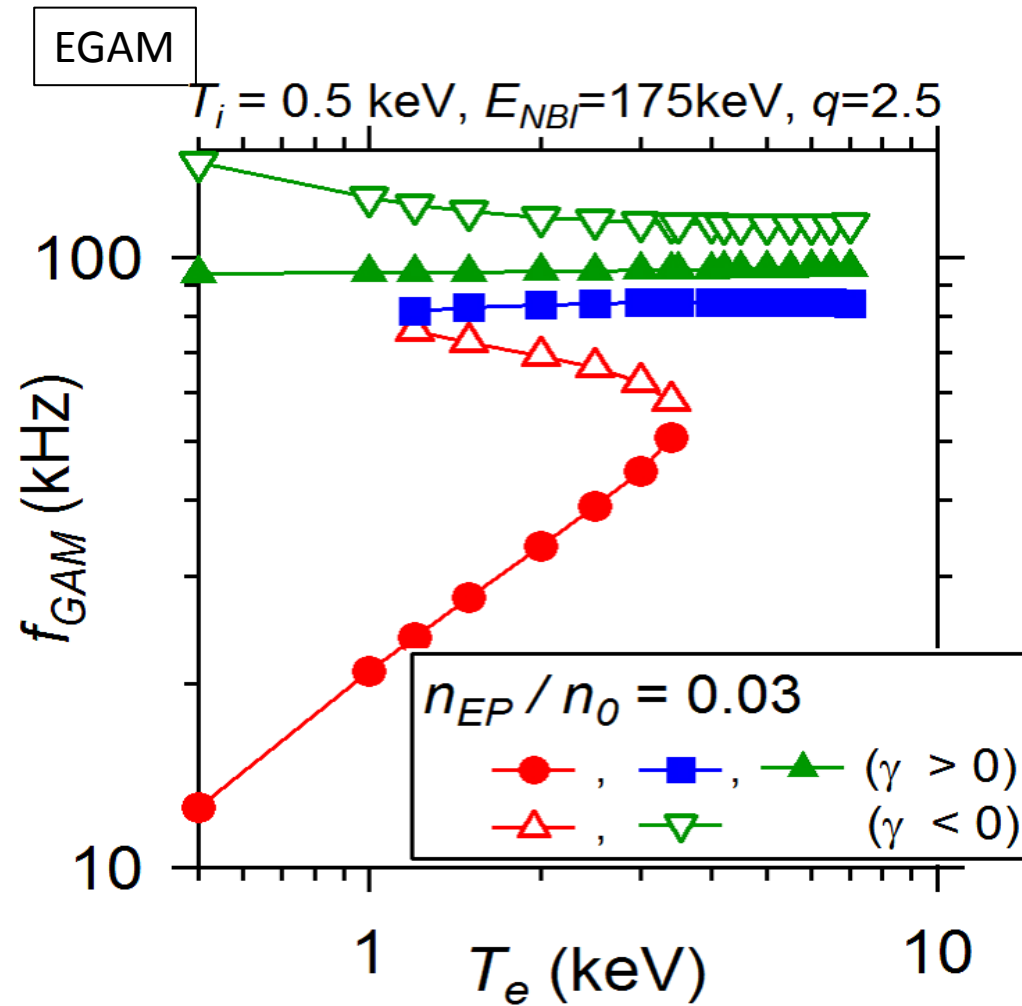
$$\nabla \cdot (J_{geodesic}^{bulk} + J_{polarization}) = 0 \quad \rightarrow \quad \nabla \cdot (J_{geodesic}^{bulk} + J_{geodesic}^{FI} + J_{polarization}) = 0$$

(T.Watari, et al, PoP, 13, 062504 (2006))



The freq. of FI-driven GAM can be much higher than the ordinary GAM freq.

Observed n=0 mode with weak Te-dependence is also identified as GAM



More detailed analysis based on numerical simulation can be found at [H.Wang TH/P1-12](#)



Mechanisms which might explain this phenomenon

1. Change of orbit topology by the GAM. activities
2. Enhanced ion-heating by the classical collision process due to the deformation of fast-ion spectra by the GAM
3. Improvement in bulk-ion energy confinement with the mode
4. Enhanced ion-heating with the mode



Mechanisms which might explain this phenomena

1. Change of orbit topology by the GAM. activities
2. Enhanced ion-heating by the classical collision process due to the deformation of fast-ion spectra by the GAM
3. Improvement in bulk-ion energy confinement with the mode
4. Enhanced ion-heating with the mode

These effects were examined by numerical calculations:

- ✓ The first one was examined by orbit calculations with perturbed electrostatic potential by $\delta\psi$.
 - The effect was small. Thus, it was ruled out.
- ✓ The second one was examined by TASK-3D calculation with an artificial spectral deformation, which reproduces the experimental observation.
 - The effect was also small. Thus, it was ruled out.



Mechanisms which might explain this phenomena

1. Change of orbit topology by the GAM. activities
2. Deformation of fast-ion energy spectra by the mode and the enhancement of ion-heating by classical collision process.
3. Improvement in bulk-ion energy confinement with the mode
4. Enhanced ion-heating with the mode

The effects of confinement improvement and enhanced ion-heating were evaluated by 0-D power balance model

- To investigate the possibility of these effects, typical values of characteristic numbers, P_i (ion-heating power density) and $\tau_E^{eff.}$ (effective ion energy confinement time) were examined in a simple power balance model with an assumption of constant ion-density.

$$\frac{dT_i^{eff.}}{dt} = \frac{P_i}{(3n_i/2)} - \frac{T_i^{eff.}}{\tau_E^{eff.}}$$

$n_e = n_i$ assumed

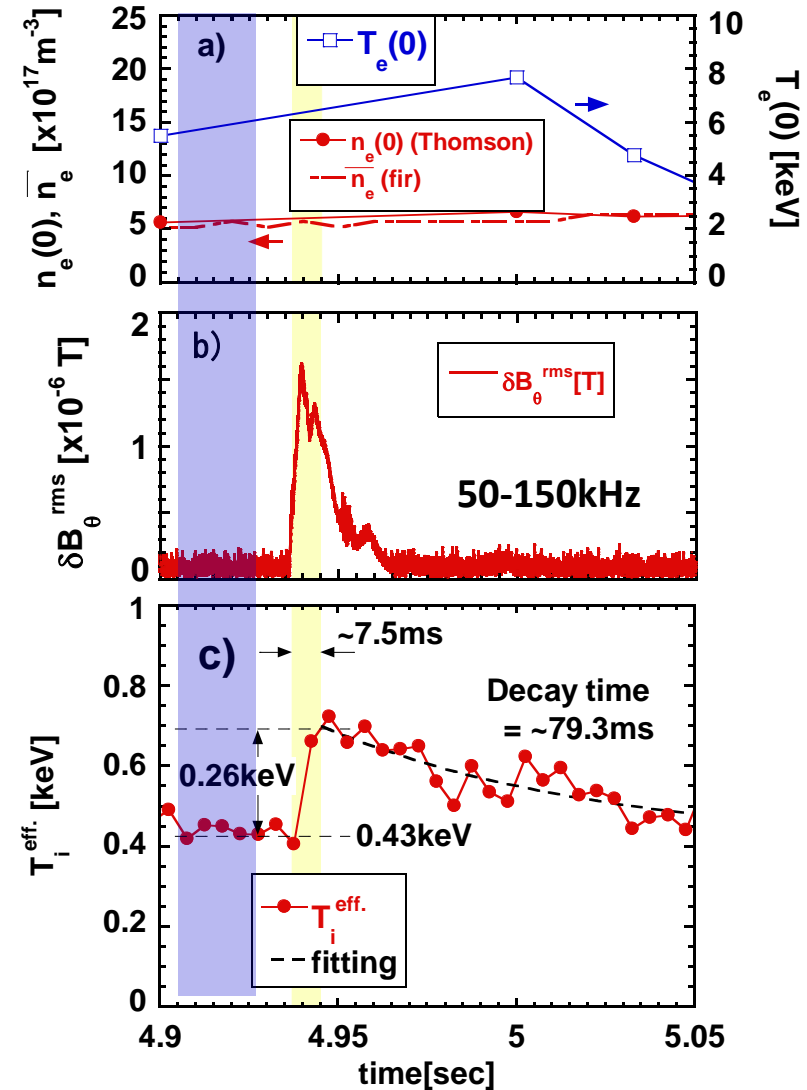
Original value of P_i and $\tau_E^{eff.}$ can be evaluated from:

- (i) Ion heating power estimated by TASK3D:

$$P_i = 170 \text{ W/m}^3 \Rightarrow \tau_E^{eff.} = 364 \text{ ms}$$

- (ii) Ion temperature decay:

$$\tau_E^{eff.} = \sim 80 \text{ ms} \Rightarrow P_i = 774 \text{ W/m}^3$$

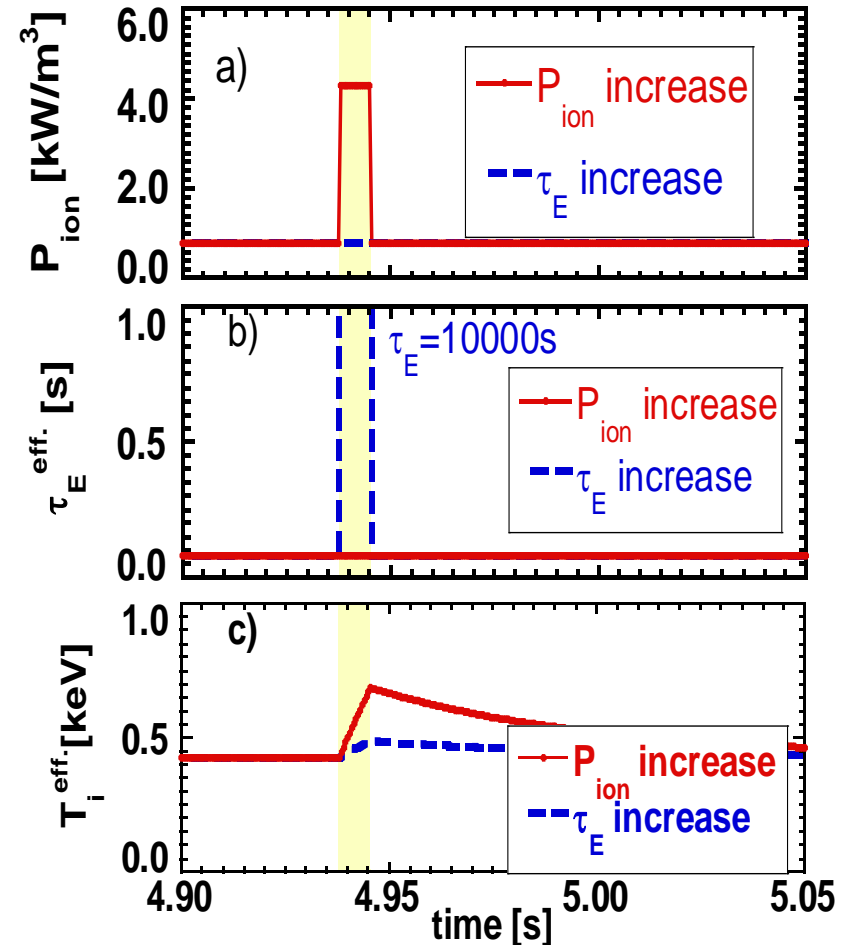




Evaluation of the enhanced ion-heating case and the confinement improvement case

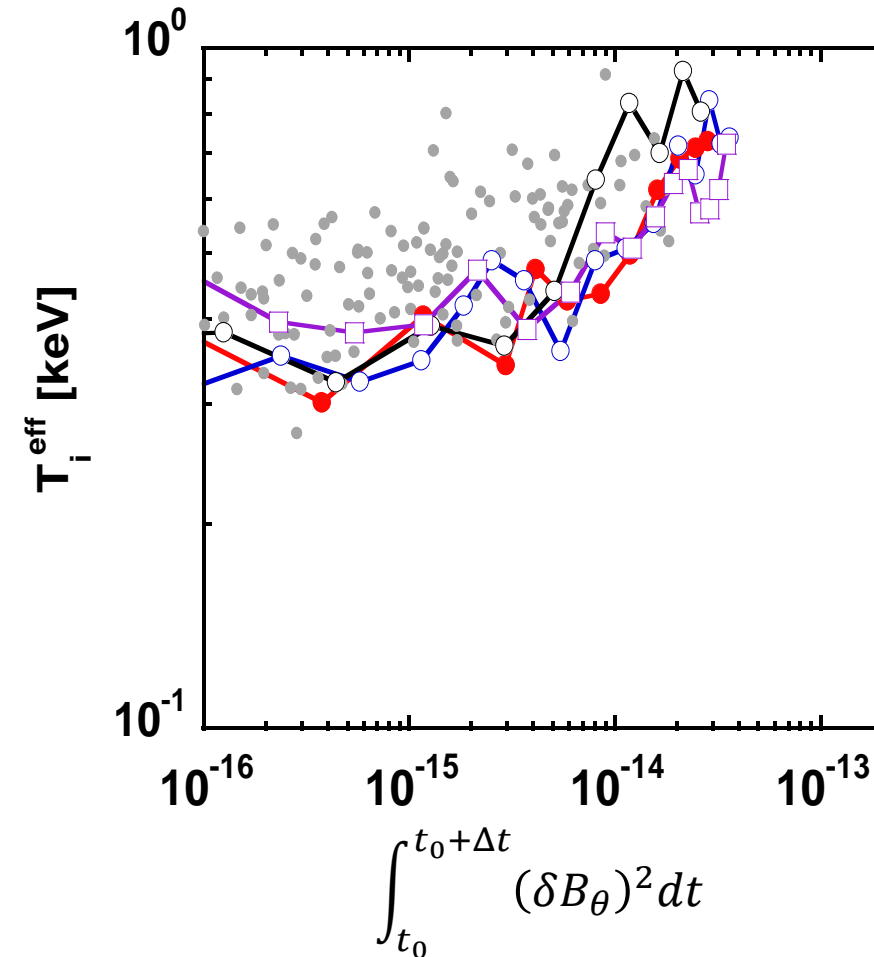
- In the enhanced ion-heating case, the observed ion temperature was reproduced by assuming $4.3[\text{kW}/\text{m}^3]$ of ion heating power during the mode activity.
- In the case of improved confinement case, the observed ion temperature behavior could not be reproduced even if the confinement time of infinitely large number was assumed ($\tau_E \sim 10000[\text{s}]$).

The candidate of “confinement improvement” was ruled out. Thus, “the ion heating enhancement” becomes most probable candidate.



Ion temperature behavior with the time integrated value of mode amplitudes

- Although clear response of the flux increase was observed with the mode activity, the correlation between the mode amplitude and the temperature behavior was not clear.
- If we assume, the ion-heating power is related to the mode amplitude, the stored energy would correspond to its time integrated value.



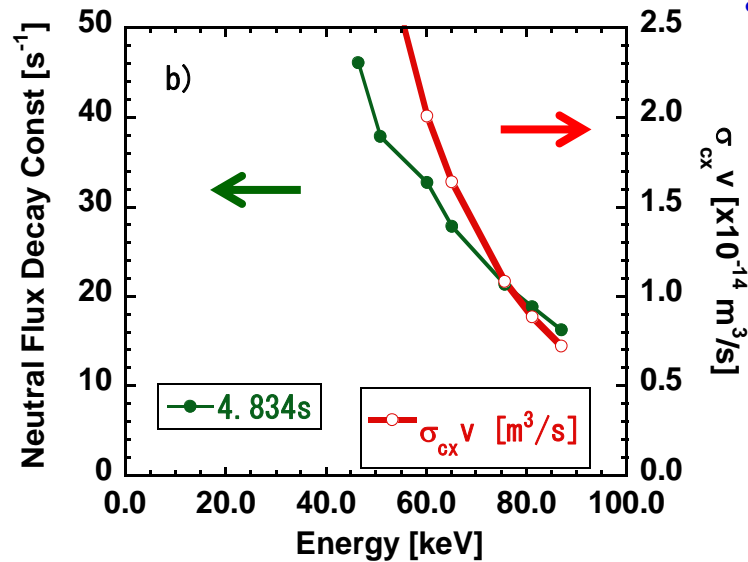
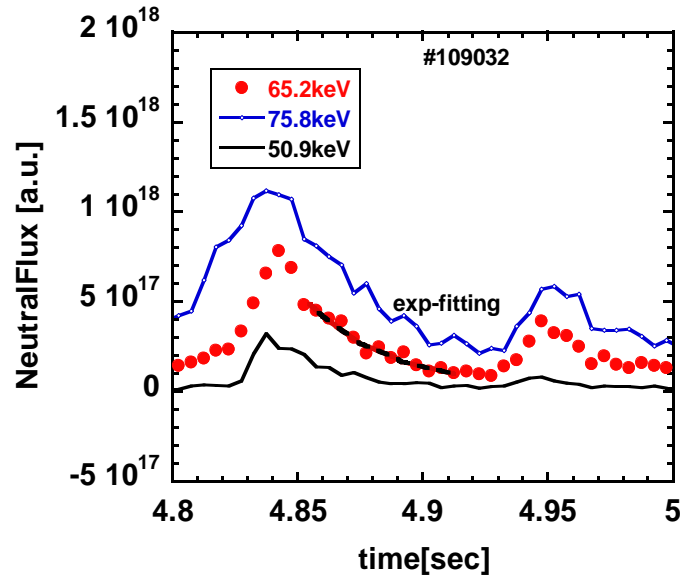


SUMMARY

- On LHD, phenomena indicating **the ion-temperature increase associated with FI induced n=0 mode was observed by tangential NPA at very low density plasmas.**
- Its poloidal mode structure was examined by the HIBP measurement, and were consistent to the GAM.
- According to the T_e -dependence of the frequency, mode can be classified into two categories, i.e., **one has $T_e^{1/2}$ -dependence** and **the other has weak T_e -dependence.** The frequency of the latter mode are almost equal to the orbital frequency of fast-ions.
- Considering the positive gradient in the energy spectra of fast-ions, these frequency features can be explained in the framework of GAM. Thus, observed mode was identified to be GAM.
- **Four candidates were proposed to explain the phenomena; (1) change of measured ion spectra due to the orbit topology change, (2) increase of classical ion heating power by the deformation of energetic particle spectra, (3) improved energy confinement, and (4) enhanced ion heating with the mode activities.** Among them, **the enhanced ion heating with the mode activities becomes most probable candidate.**
- But, the heating mechanism was left as an open question for the future studies.

BACKUP VIEWGRAPHS

Charge Exchange loss was seems to be significant at the discharge.



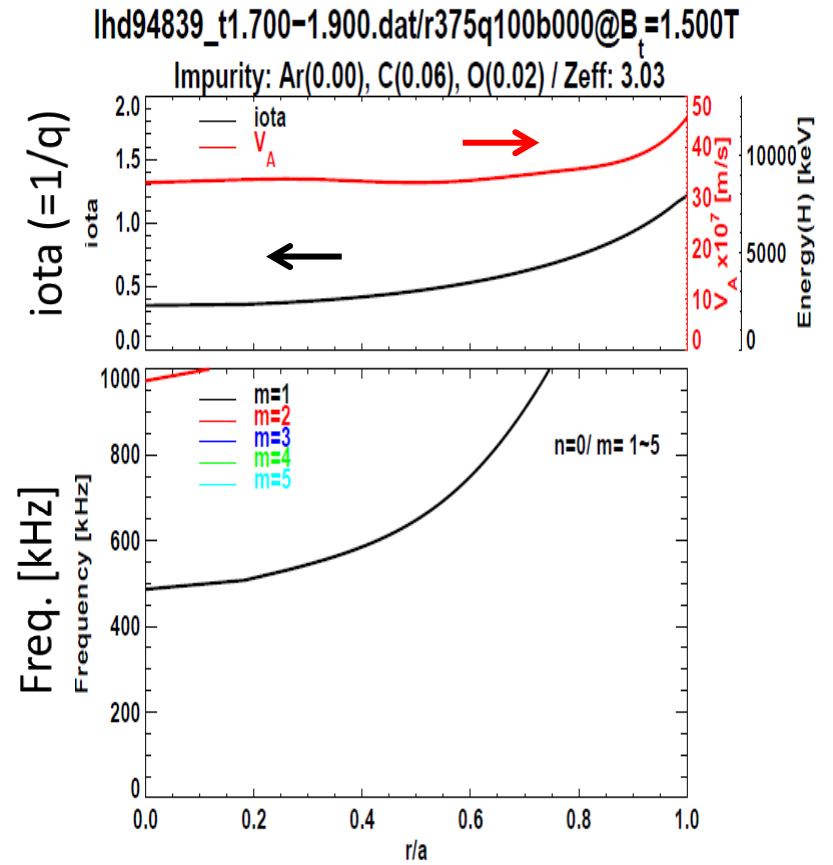
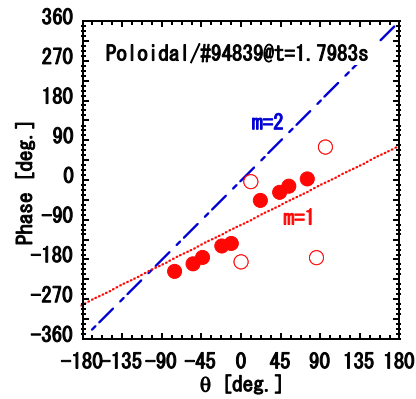
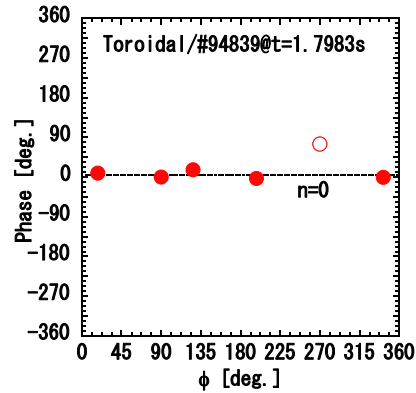
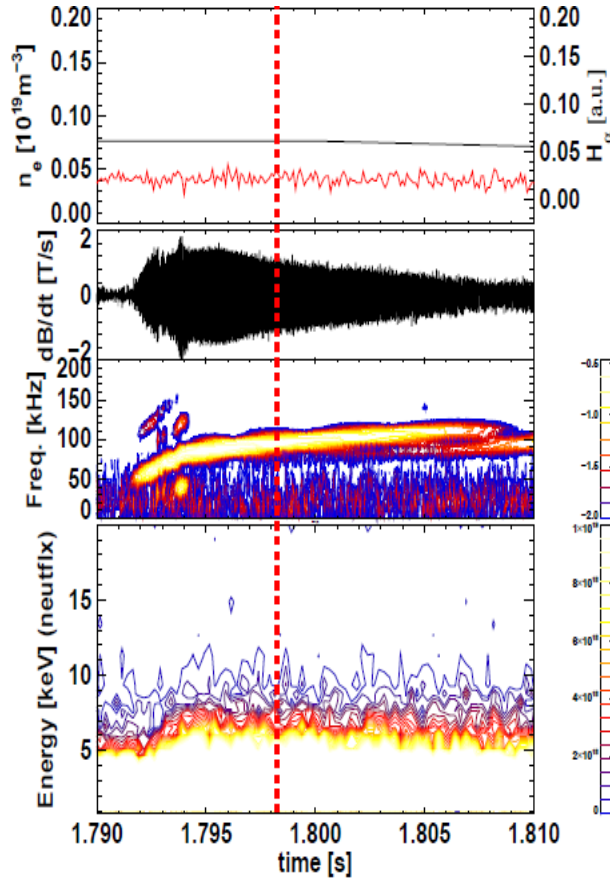
- Decay constants of the neutral flux show similar energy dependence to the reactivity($\sigma_{cx}v$) for Charge eXchange (CX) loss with Hydrogen neutrals.
- If we assume the neutral density is $\sim 2 \times 10^{15} [m^{-3}]$, the decay constants agree the CX-loss time, qualitatively.
- The evaluated neutral density is consistent to the neutral density calculation by AURORA-code.
- The CX-loss is the major loss process of the clump.
- Evaluated CX-loss time (10- 100ms) is much smaller than the slowing-down time(order of 1s) of fast-ions



- The CX-loss of the fast-ions diminishes the slowing-down feature of the clump.
- Positive-gradient in the energy spectra can be formed by CX-loss.



Toroidal mode number is $n=0$

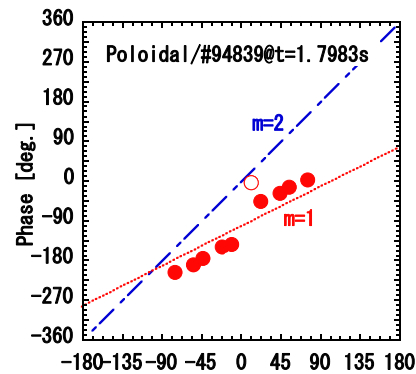
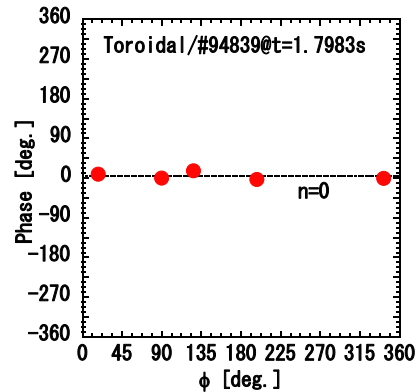


The initial frequency of the mode is much smaller than expected $n=0$ GAE frequencies ($f > 500$ kHz).



Toroidal mode is zero. Phase for poloidal structure has a slope of unity, but ..

a phase jump was observed at around $\theta=0$ [deg]. This indicates a formation of standing-wave like structure.



- Standing wave is formed by the sum of two modes having a same mode number and propagating opposite to each other.
 - ✓ In the case of $m \geq 3$, we should observe more than three nodes.
 - ✓ In the case of $m=1$, it is difficult to have a node like structure with a slope of $m=1$.

The $m=2$ is the most likely in this case.

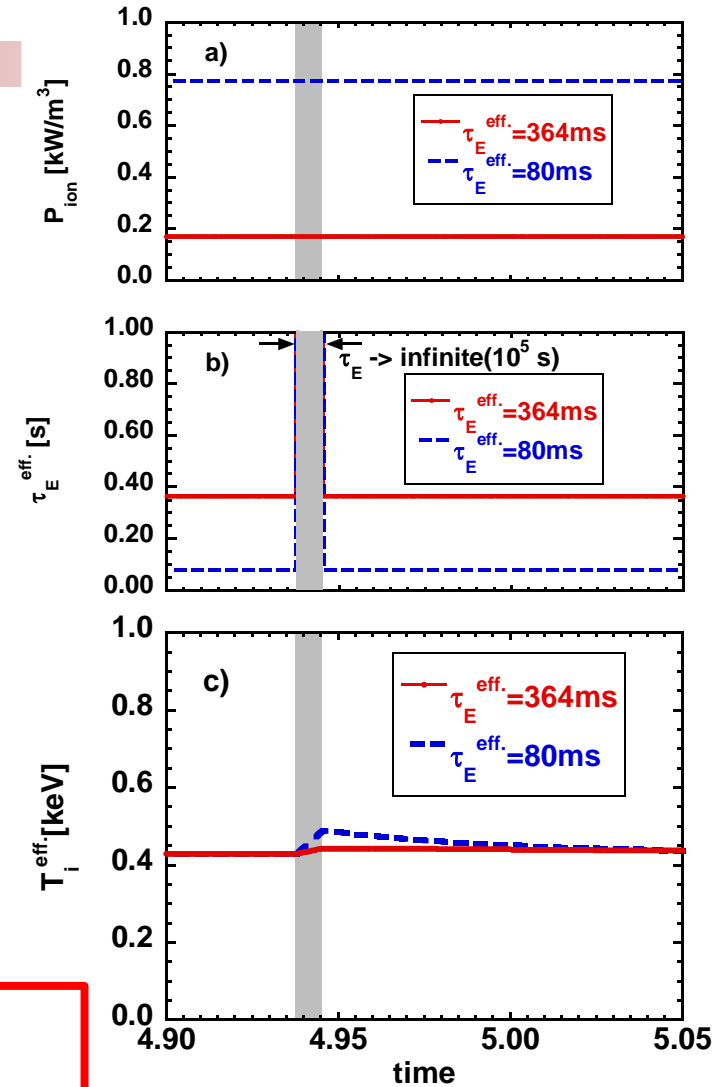
*Consistent to theoretical prediction for poloidal mode of Magnetic component of GAM; Zhou D, PoP, 14, 104502 (2007)

Confinement improvement case

- P_{ion} constant model -

- Energy confinement was assumed to be improved to infinite number during the mode activity.
- Estimated temperature rise was smaller than the experimental observation.
- Charge-exchange loss time of 5~100ms for bulk ions with background neutrals ($10^{14} \sim 10^{15} m^{-3}$) will also suppress the confinement improvement.

Confinement improvement can not explain the measured temperature rise.

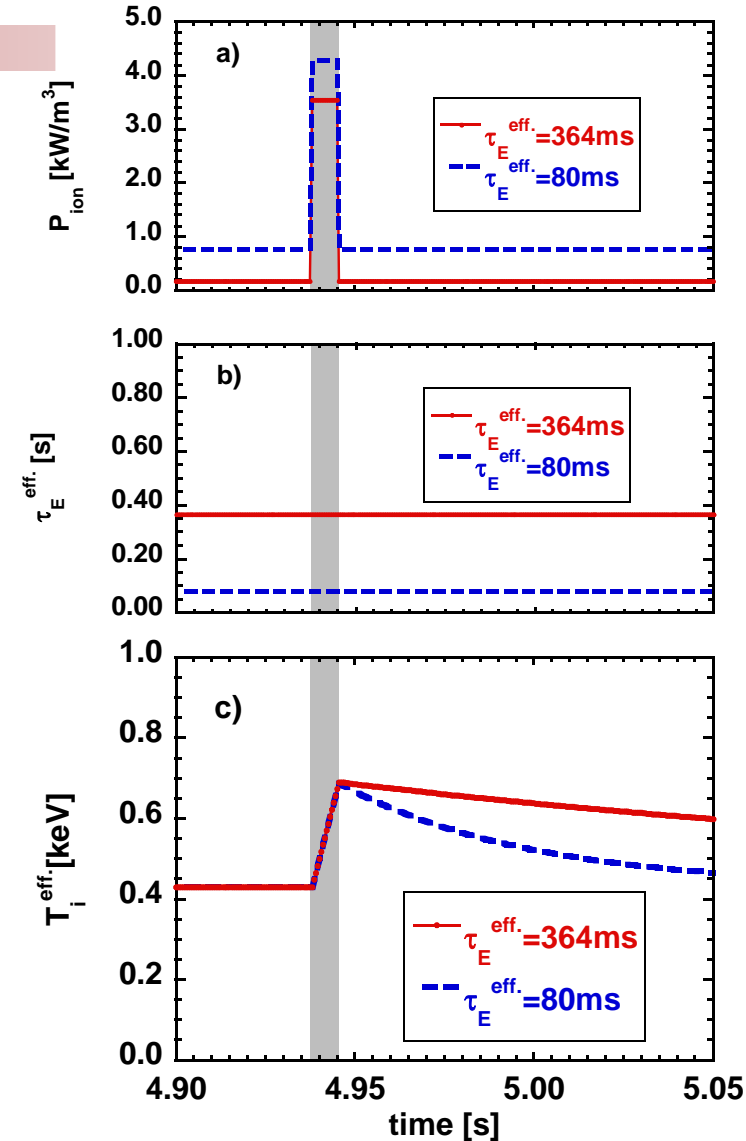


Enhanced ion-heating case

- Constant confinement time model -

- Ion heating power was assumed to be increased during the mode activity.
- The amount of heating power was determined so that the observed temperature rise was reproduced.
- The P_i enhancement factors of;
 - 21 ($P_i=3.6\text{kW/m}^3$) for $\tau_i^{\text{eff.}}=364\text{ms}$, and
 - 5.6 ($P_i=4.3\text{kW/m}^3$) for $\tau_i^{\text{eff.}}=80\text{ms}$.are necessary to explain the observed temperature rise.

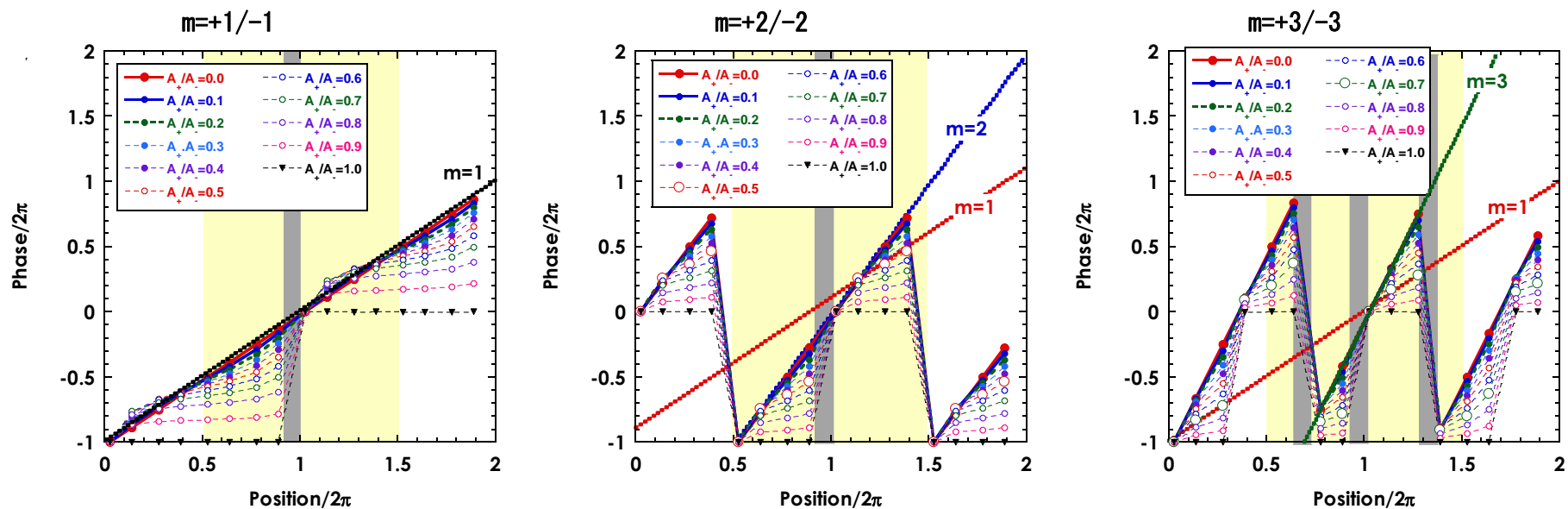
Indication of enhanced ion-heating power during the mode activity.





Combination of $m=2/-2$ mode might explain the observed phase structure*.

- In the case of $m \geq 3$, we should observe more than three nodes in the poloidal phase diagram.
- In the case of $m=1$, it is difficult to have a node like structure with a slope of $m=1$.



Further investigation is necessary since it sometimes show $m=1$ structure without node.

*Consistent to theoretical prediction of poloidal mode of Magnetic component of GAM; Zhou D, PoP, **14**, 104502 (2007)

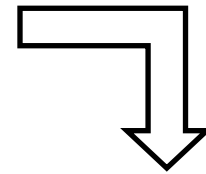
The EP affects the GAM frequency

The GAM frequency is modified by FIs. (G.Y.Fu, PRL, 101, 185002 (2008))

T.Ido, et.al.

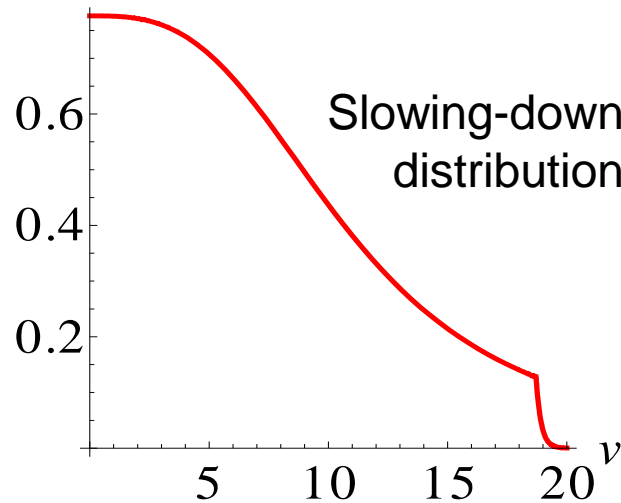
$$f_{EP} = \frac{A_1}{v^3 + v_c^3} \exp\left(-\frac{P_\phi}{e\Delta\Psi}\right) \exp\left[-\left(\frac{\Lambda - \Lambda_0}{\Delta\Lambda}\right)^2\right]$$

$$\Lambda = \frac{\mu B}{E}$$

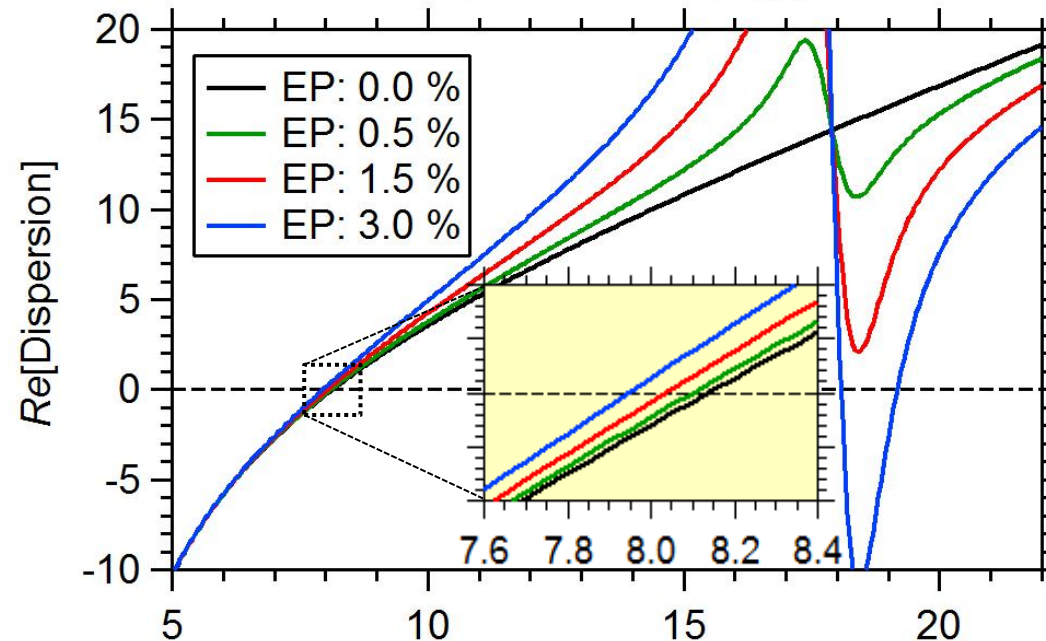


$$\nabla \cdot (J_{geodesic}^{bulk} + J_{polarization}) = 0 \quad \rightarrow \quad \nabla \cdot (J_{geodesic}^{bulk} + J_{geodesic}^{EP} + J_{polarization}) = 0$$

(T.Watari, et al, PoP, 13, 062504 (2006))



$T_i = 0.5 \text{ keV}$, $T_e = 4.0 \text{ keV}$, $E_{NBI} = 175 \text{ keV}$



The EP affects the GAM frequency

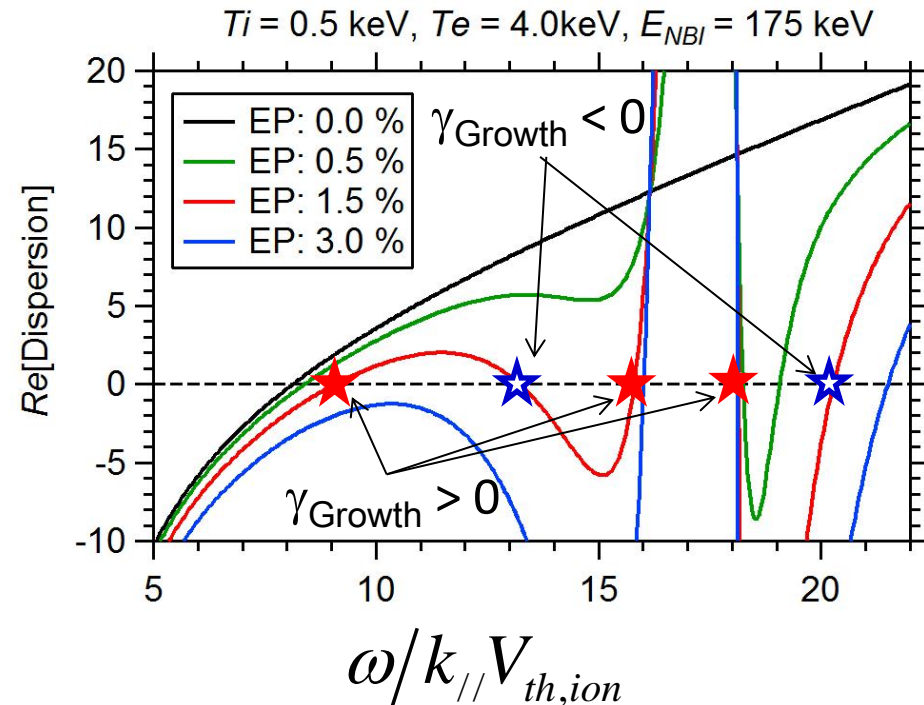
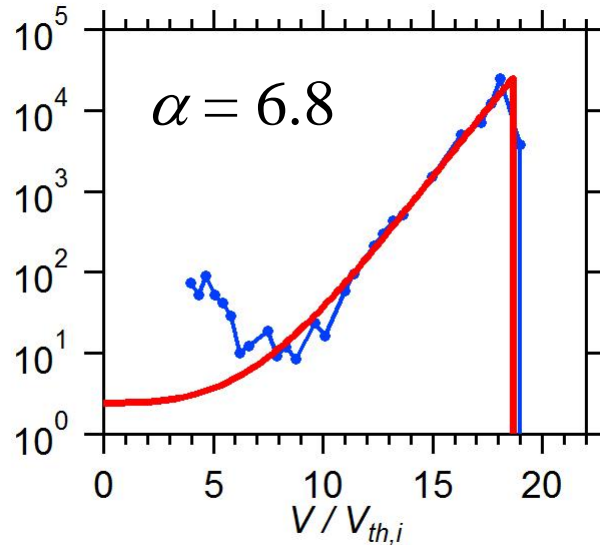
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The freq. of EP-driven GAM can be much higher than the ordinary GAM freq.

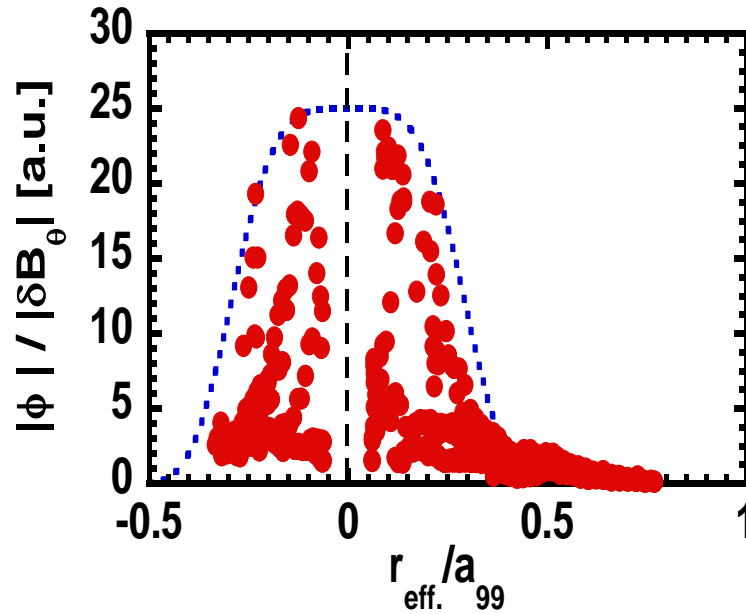


Mechanisms which might explain this phenomena

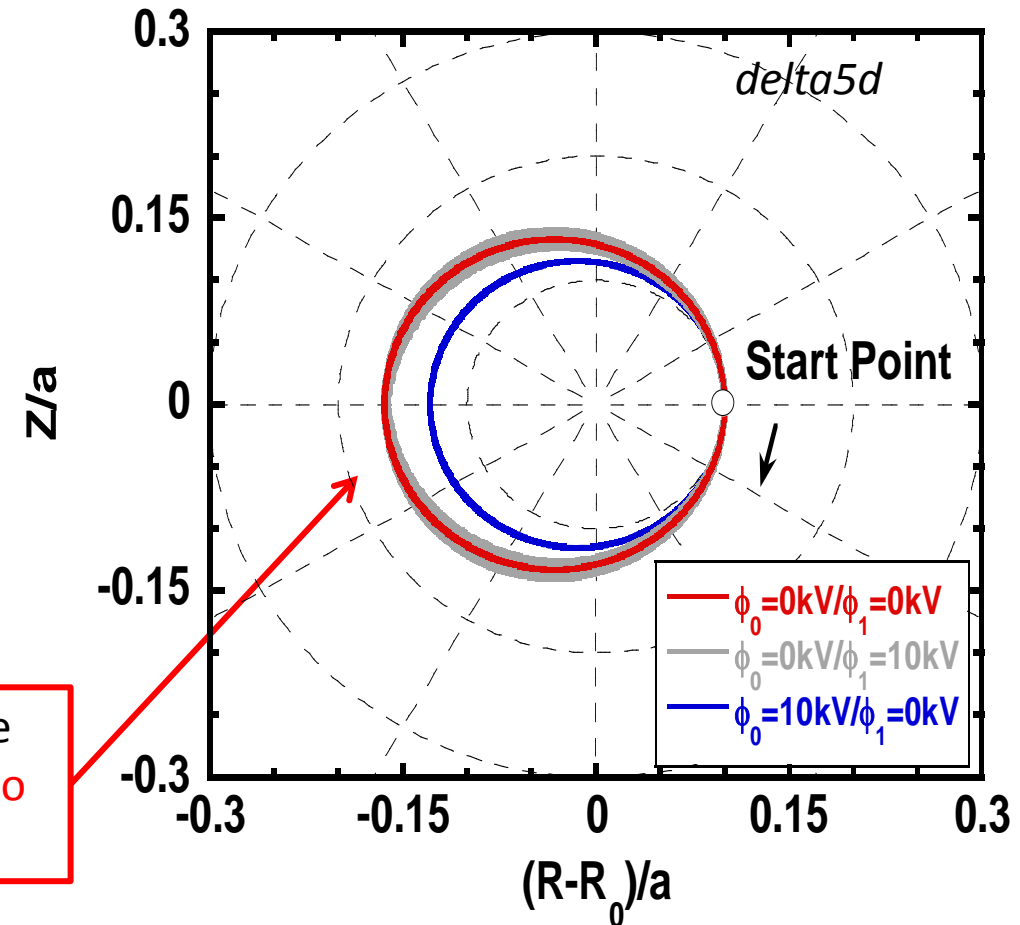
1. Change of orbit topology by the GAM. activities
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Effect of electrostatic potential on the topology of particle orbit

$$\phi(\psi_N, t) = \phi_0 \exp(-(\psi_N - b_0)^2/a_0^2) + \phi_1 \exp(-(\psi_N - b_1)^2/a_1^2) \sin(-\omega t)$$

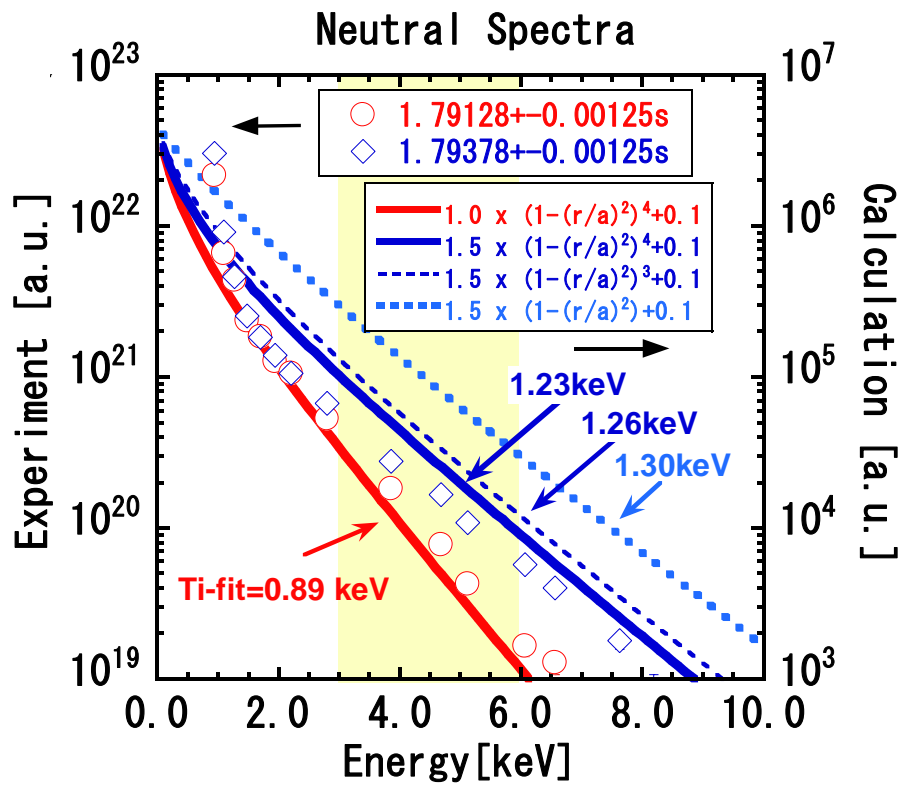


Effect of ExB-drift on the deviation of particle orbit is small. Thus, it seems to be difficult to claim this is responsible to the phenomena.

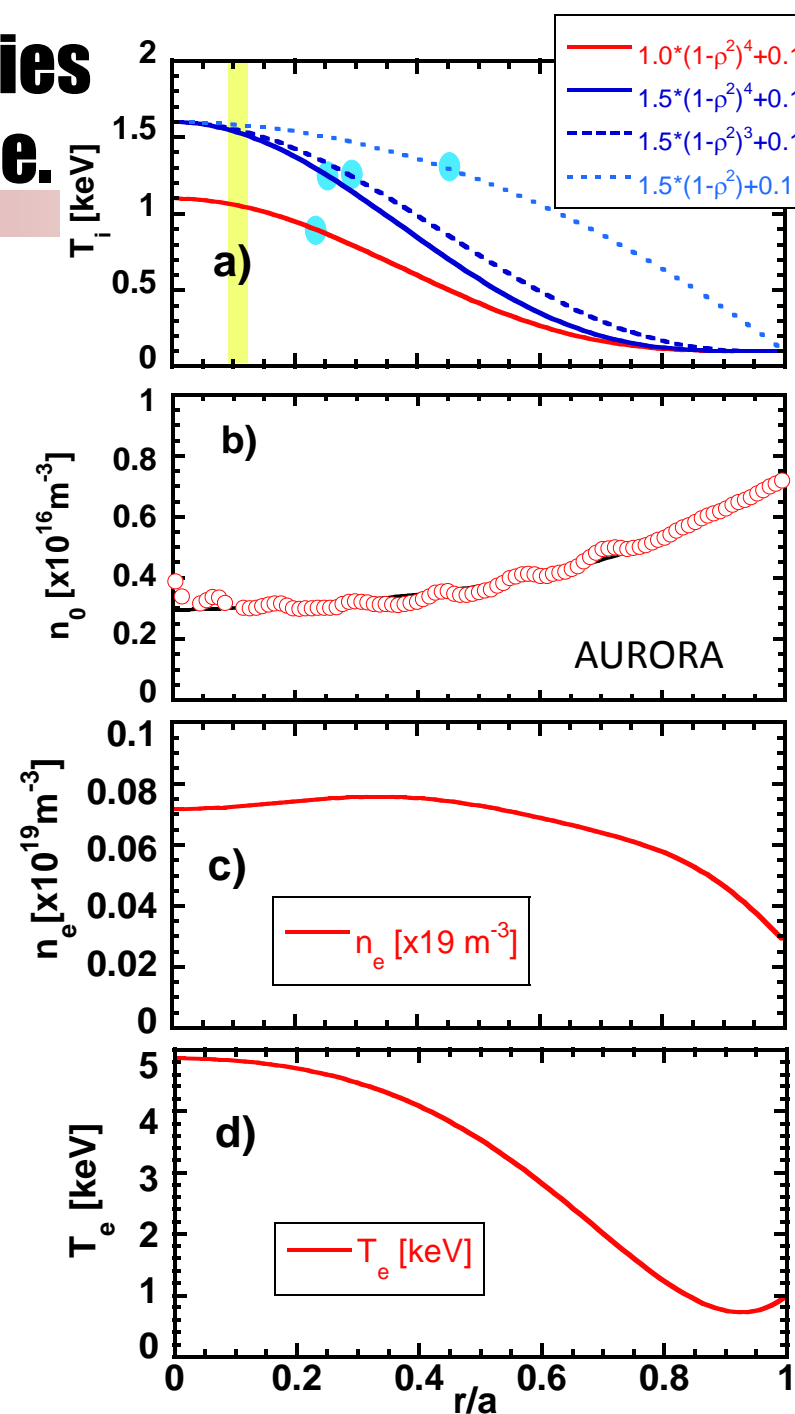




The change of orbit topologies would change the Ti-profile.



The observed change seems to correspond to the increase of Ti central value rather than the change of the shape.





Mechanisms which might explain this phenomena

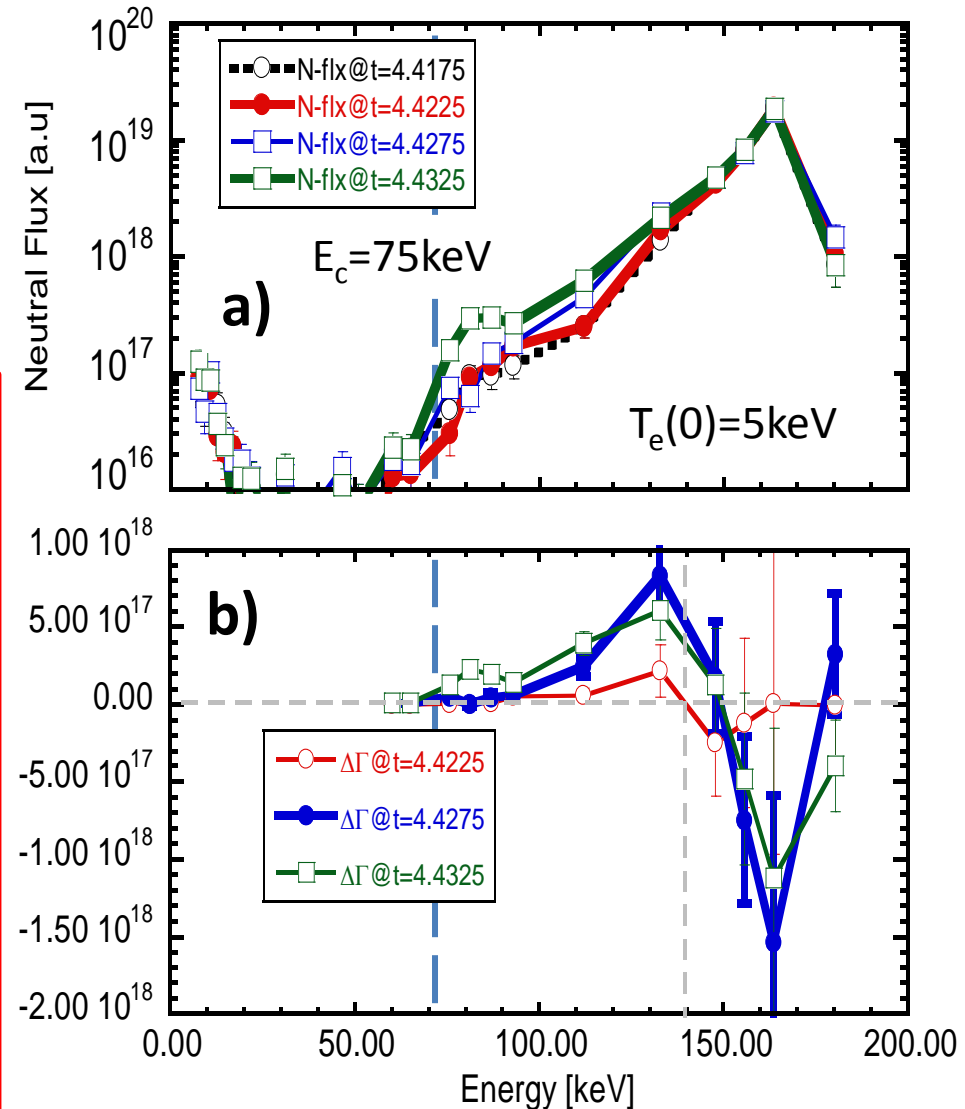
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When the energetic particle spectra was deformed, it might increase ion-heating power, classically.

Because, the population of energetic particles close to the E_c ($\sim 15Te$) would increase by the deformation. Thus, the ion-heating rate might increase.

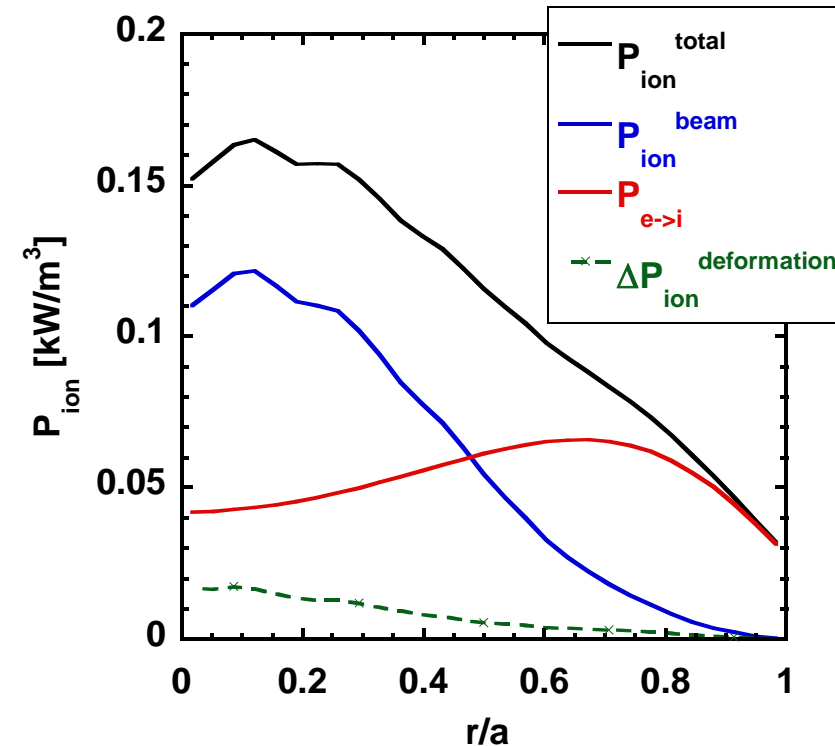
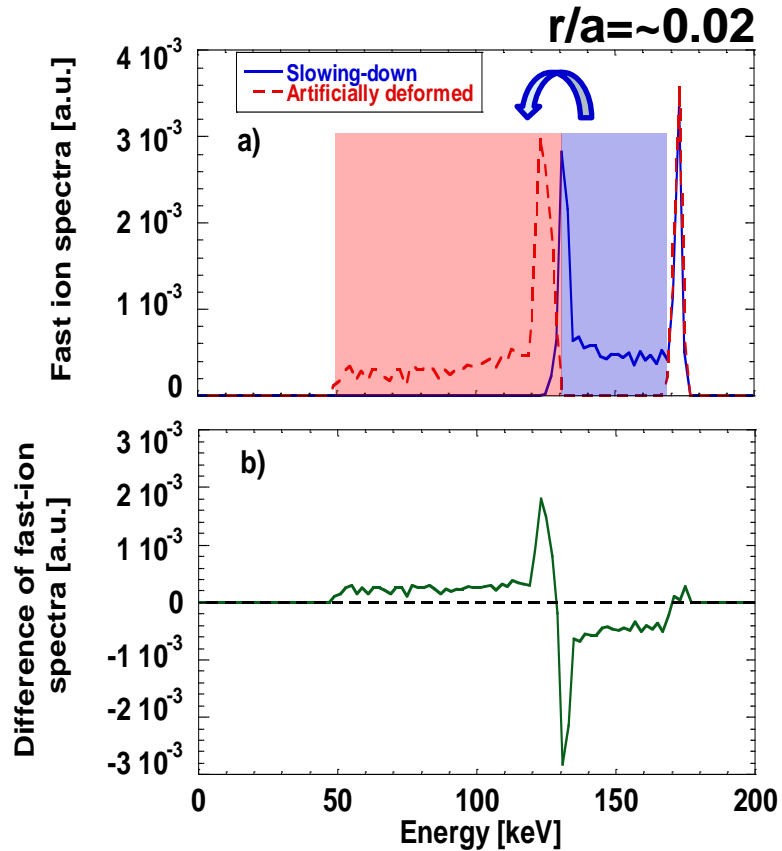
Time-dependent analysis of NB heating power was performed based on TASK3D-code to evaluate the classical bulk-ion heating power by EPs .
The possible increase of the heating power by the deformation was examined by introducing artificial deformation of the spectra in the calculation.





Increment of classical ion heating power by the deformation of the spectra is too small to cause observed increase of the ion temperature.

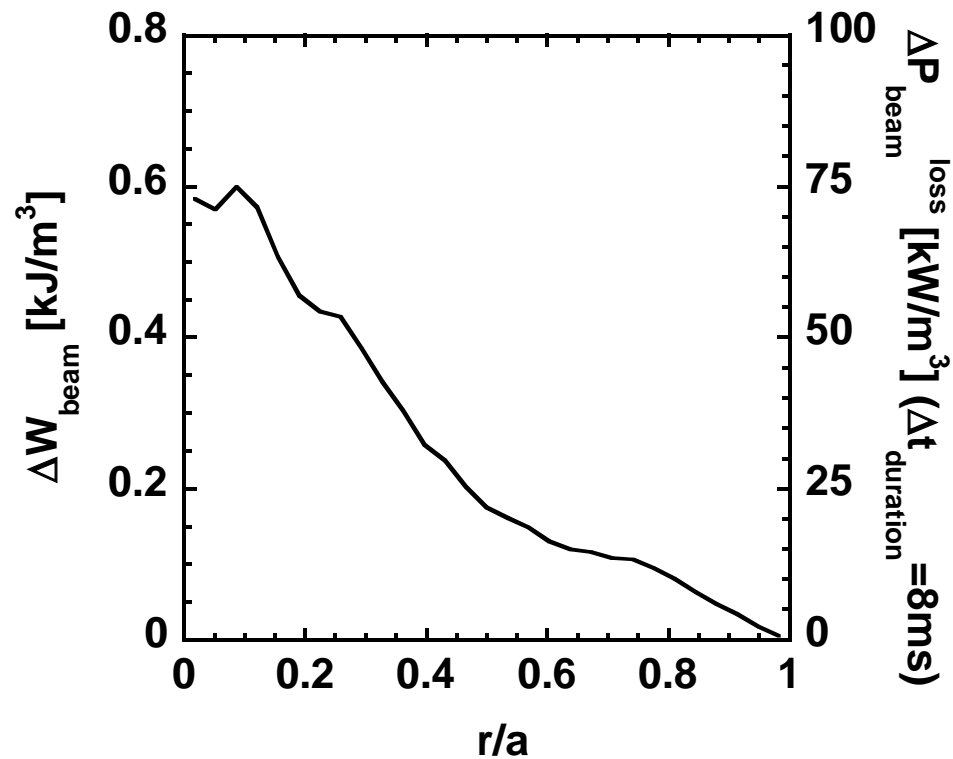
- Energetic particle spectra at $t=4.94\text{s}$ with classical slowing-down spectra were evaluated by TASK3D code.
- The spectra was artificially deformed to reproduced the observed clump-hole formation. The increment of ion heating power by the deformation was examined.



This candidate is also ruled out.

Evaluated energy loss of EP by the deformation of the spectra reaches to $0.6[\text{kJ}/\text{m}^3]$ at the core.

- Considering the duration time of the mode ($\sim 8[\text{ms}]$), the average power loss of EPs are $\sim 75[\text{kW}/\text{m}^3]$, which is larger than the necessary ion heating power ($\sim 4[\text{kW}/\text{m}^3]$).



During the GAM bursting activity, the Clump-Hole formation was observed in high energy part, and the ion temperature increase was observed for the low energy part.

