[EX/1-3Ra]

Impact of ECH/ECCD on Fast-ion-driven MHD Instabilities in Helical Plasmas

S. Yamamoto *et al.*, (Kyoto University, Japan)

[EX/1-3Rb]

Excitation mechanism of the energetic particle driven resistive interchange mode and strategy to control the mode in the Large Helical Device

S. Ohdachi *et al.*, (NIFS, Japan)

Heliotron J

Laboratorio
Nacional
Fusión

NIFS

27th IAEA Fusion Energy Conference (FEC 2018)
22~27 Oct. 2018, Gandhinagar, India

EX/1-3Ra

Impact of ECH/ECCD on Fast-ion-driven MHD Instabilities in Helical Plasmas

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Acknowledgement : D.A. Spong (ORNL, USA), N.B. Marushchenko (IPP, Germany)

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Outline

1. Introduction
2. Heliotron J, TJ-II and LHD
3. Shear Alfvén spectra in helical plasmas
4. Impact of ECCD on AEs
5. Impact of ECH on AEs
6. Conclusion

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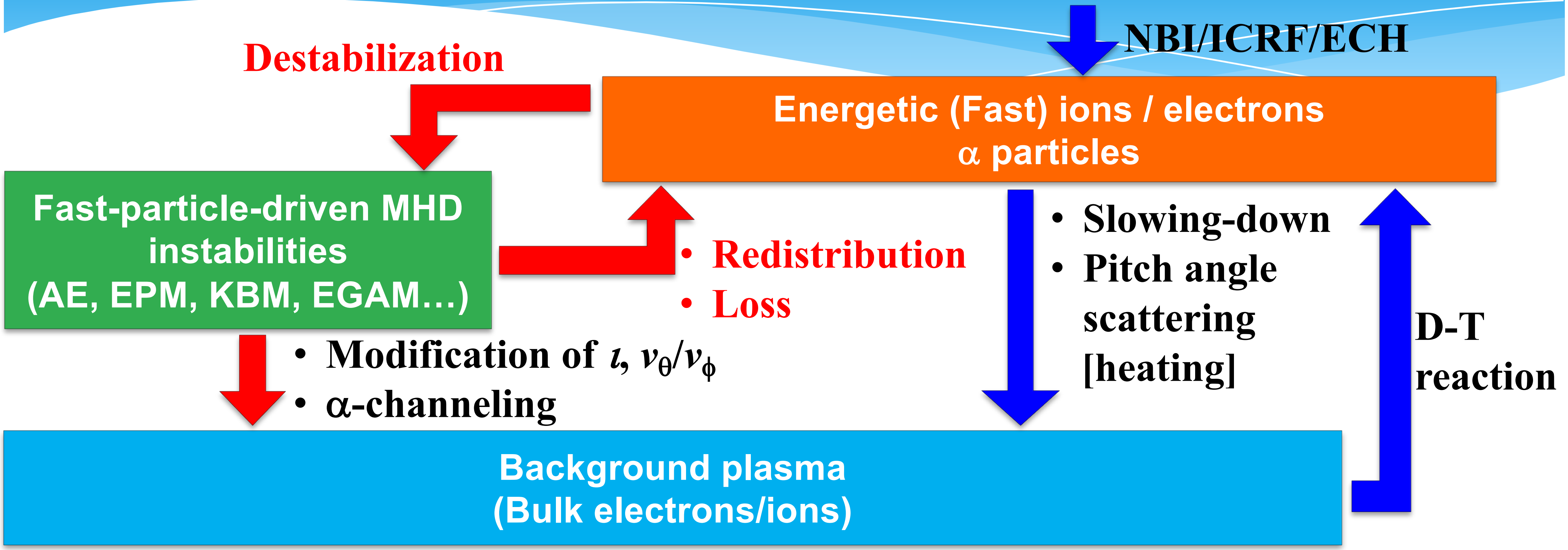
Introduction



NBI/ICRF/ECH

Destabilization

Energetic (Fast) ions / electrons
α particles

Fast-particle-driven MHD instabilities
(AE, EPM, KBM, EGAM…)

- Redistribution
- Loss

- Slowing-down
- Pitch angle scattering [heating]

D-T reaction

- Modification of ι, v_θ/v_ϕ
- α-channeling

Background plasma
(Bulk electrons/ions)

✓ Since redistribution and exhaust of alpha particles caused by fast-particle(FP)-driven MHD instabilities lead to the reduction of fusion gain and damage of first wall, the methods to control the FP-driven MHD instabilities are required.

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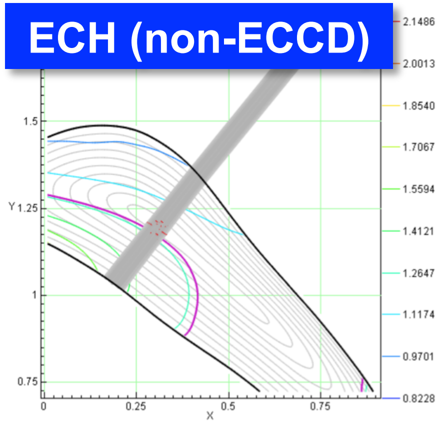
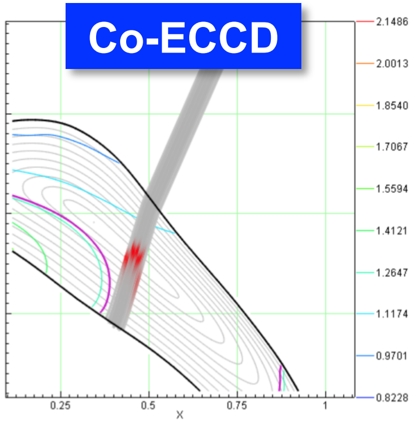
Introduction (cont'd)

- ✓ ECH/ECCD are an ideal tool to control MHD instabilities.
  - ➢ Highly localized ECH power/EC current with a known location.
  - ➢ Good controllability.
- ✓ The effect of ECH/ECCD on FP-driven MHD instabilities was experimentally found in some tokamaks and helical plasmas [1~6].
- ✓ To **have a comprehensive understanding of suppression of FP-driven MHD instabilities in a toroidal plasma due to similarities and differences**.
- ✓ Among three stellarator/heliotron (S/H) devices, **Heliotron J, TJ-II and LHD**.

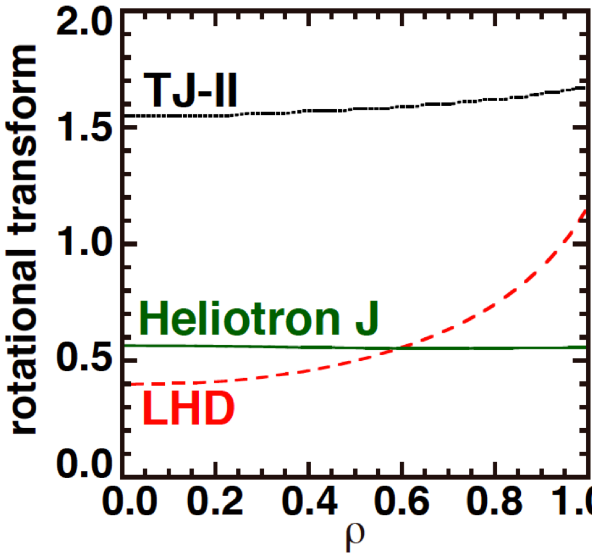

ECH (non-ECCD)


Co-ECCD

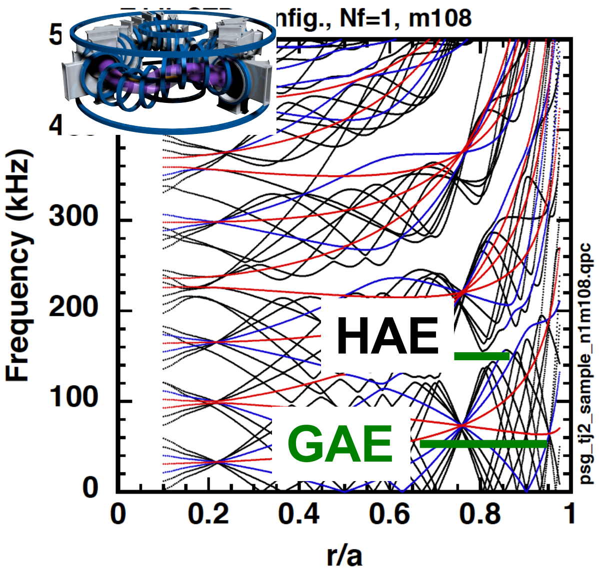
[1] A. Lazaros, PoP **9** (2002)
[2] M.A. Van Zeeland, PPCF **50** (2008)
[3] M.A. Van Zeeland, NF **56** (2016)
[4] K. Nagasaki, NF **53** (2013)
[5] K. Nagaoka, NF **53** (2013)
[6] S. Yamamoto, NF **57** (2017)

Shear Alfvén Continua in S/H

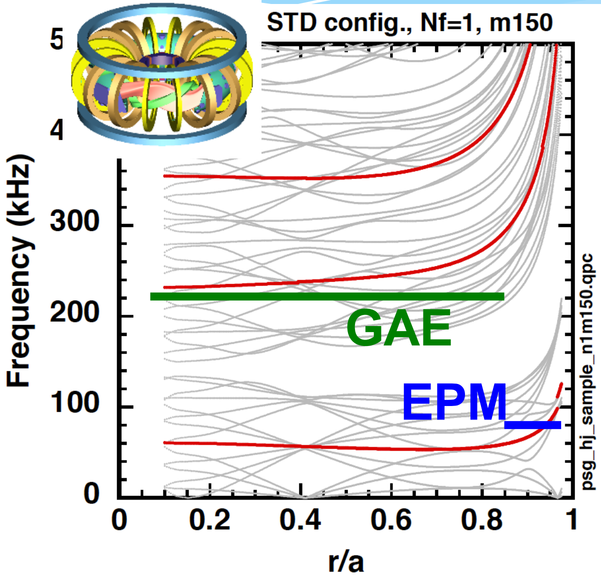
Profile of iota (1/q)



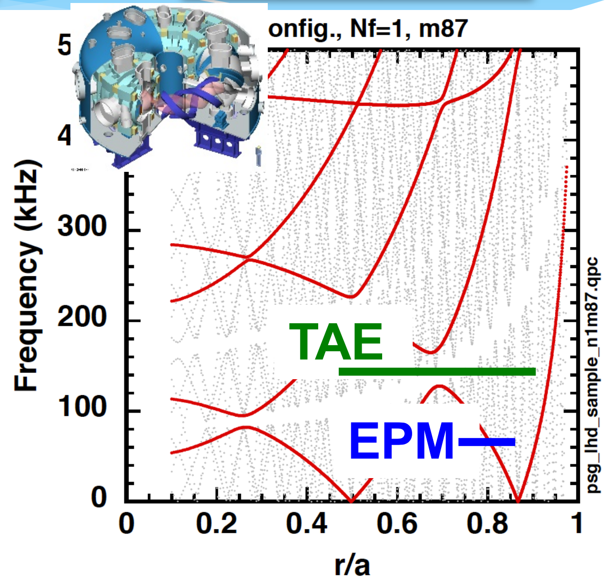
Low *s* / High ι (TJ-II)



Low *s* / Low ι (Heliotron J)



High *s* (LHD)

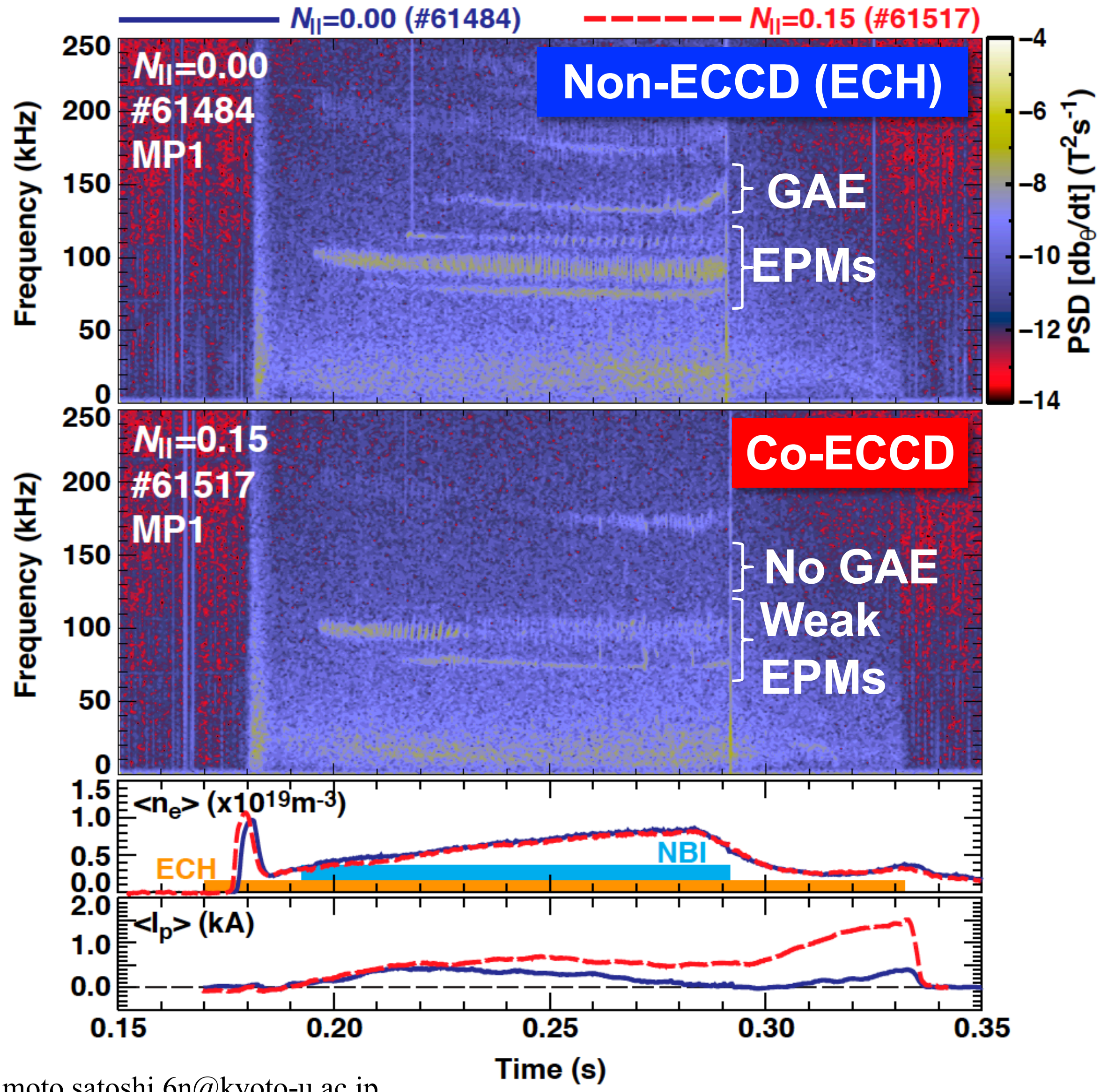


✓ Observed (identified) FP-driven MHD instabilities.

[1] S. Yamamoto, FST **51** (2007)
[2] K. Nagaoka, NF **53** (2013)
[3] R. Jiménez-Gómez, NF **51** (2011)
[4] A. Melnikov, NF **52** (2012)
[5] S. Yamamoto, NF **45** (2005)
[6] K. Ogawa, NF **50** (2010)

- Heliotron J (**low s**, **low ι**, **low period**) : Global AE (GAE), Energetic particle mode (EPM) [1,2]
- TJ-II (**low s**, **high ι**, **low period**) : GAE, Helical AE (HAE) [3,4]
- LHD (**high s**, **low/high ι**, **high period**) : Toroidal AE(TAE), HAE, EPM [5,6]

Suppression of GAE/EPM by ECCD in HJ



- ✓ When $N_{||}$ = 0.0 (non-ECCD), **EPMs/GAEs** are excited in Heliotron J.
- ✓ Plasma current is consisted of only ECCD. (can ignore BS and NBCD)
- ✓ Mitigation of EPMs/GAEs are observed when both co- /ctr- ECCD is applied.
- ✓ **No difference of plasma parameters** T_e, n_e in $N_{||}$ scan experiment **except for** I_p.
- ✓ When lower density (< $0.5x10^{19}m^{-3}$), **EPM is fully stabilized by ECCD**.

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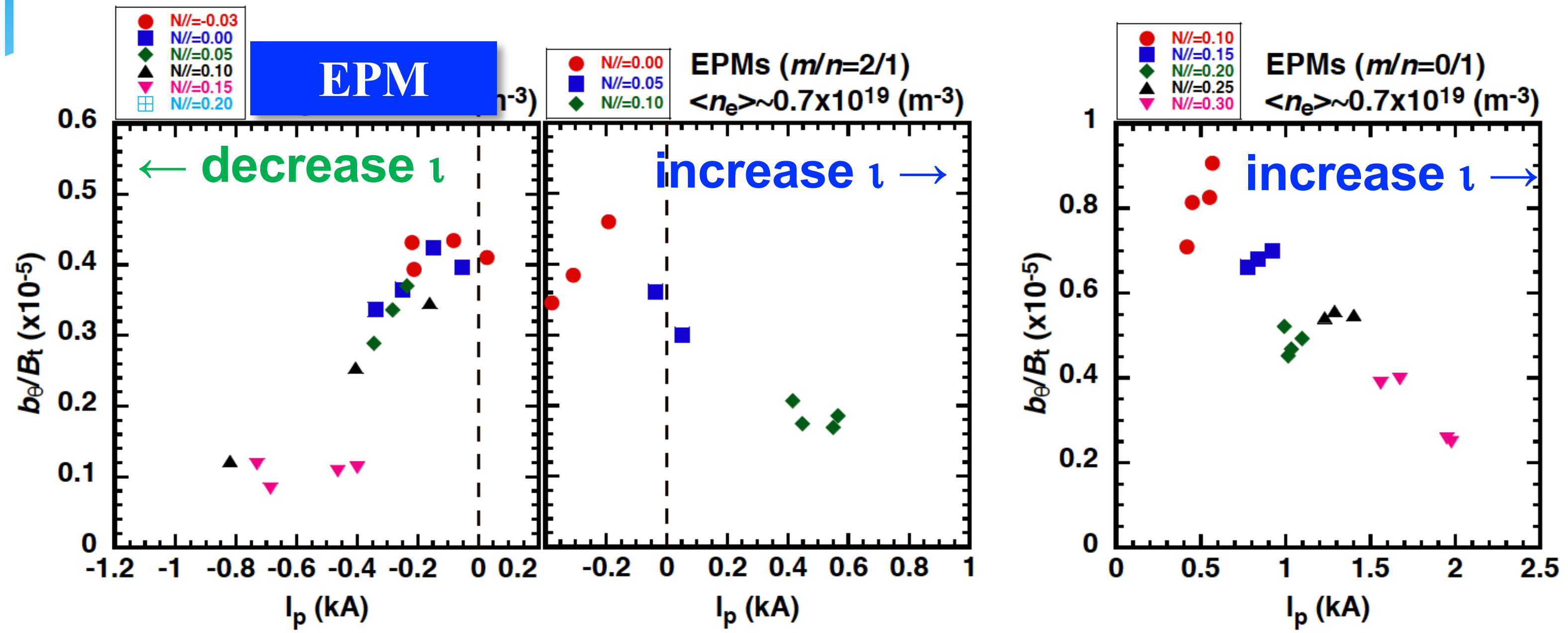
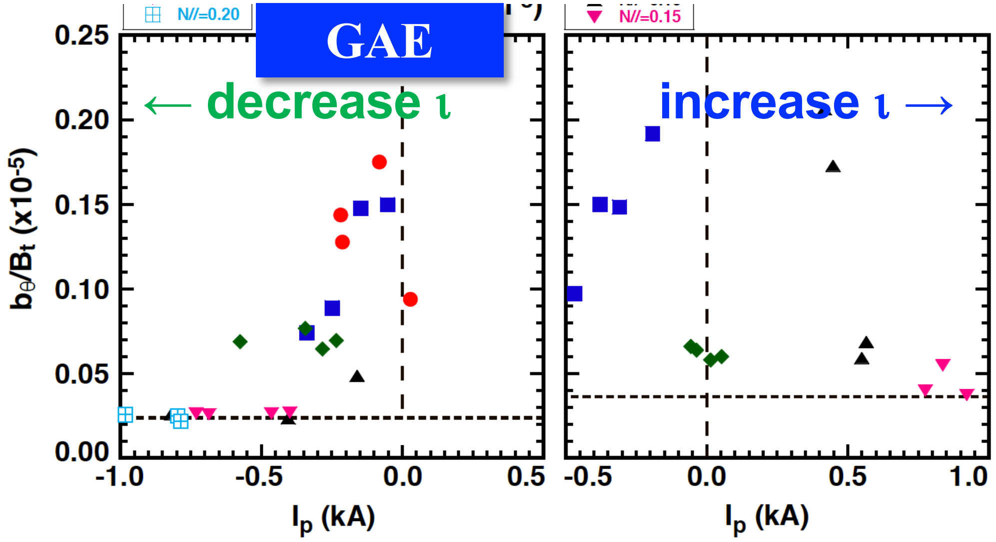
Dependence of EPM/GAE upon EC-driven Current

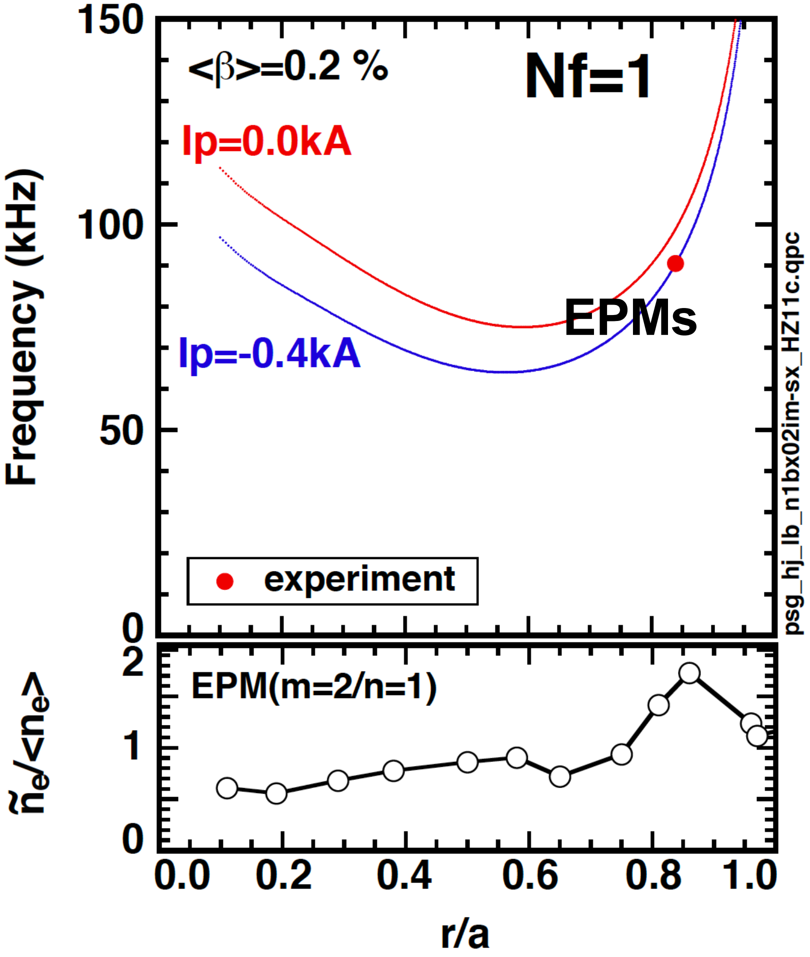




- ✓ EC-driven current **enhances magnetic shear**. (s ~ 0 in vacuum)
- ✓ **Amplitude of EPMs/GAEs obviously decreases by the increasing I_p regardless of its sign**.
- ✓ EPM is shear Alfvén continuum.
  - ➔ **Continuum damping rate is proportional to magnetic shear**
  - ➔ **Increase of shear leads to suppression of EPMs**.
- ✓ GAE seems to suffer from continuum damping.

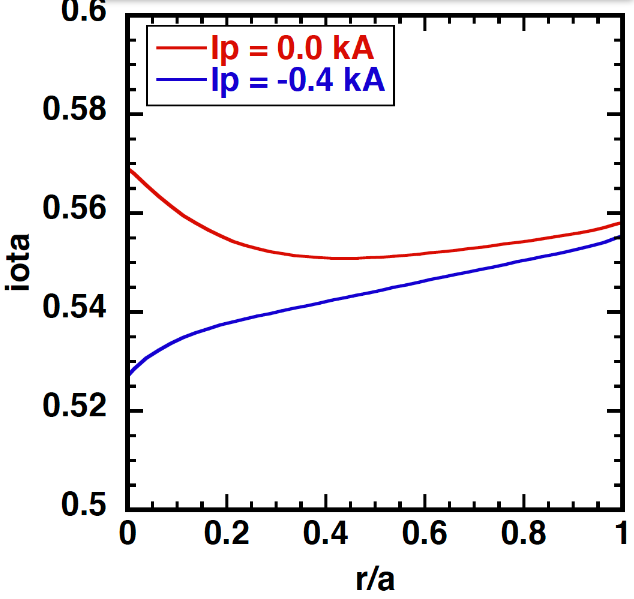
Change in Shear Alfvén Spectra in HJ

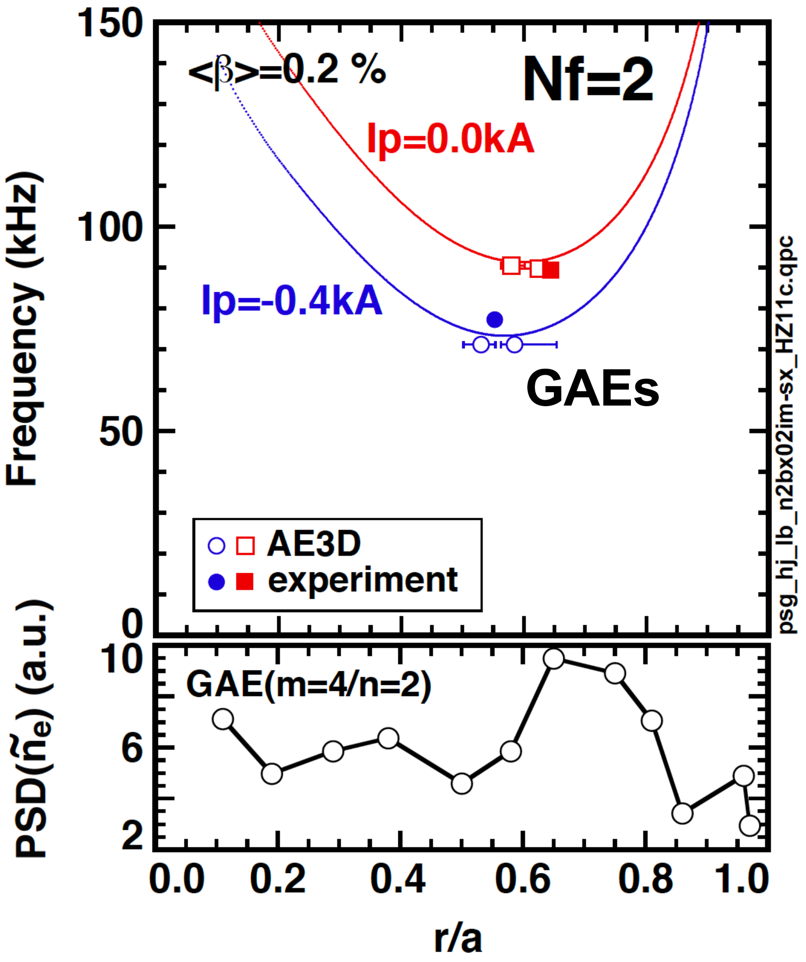
STELLGAP/AE3D (D.A. Spong PoP 17 (2019)) calculation



✓ Agree with experiments

Profile of iota (1/q)





✓ Landau, inverse landau and radiative damping seem to be constant in $N_{||}$ scan.

→ **EMPs/GAEs suffer from continuum damping**.

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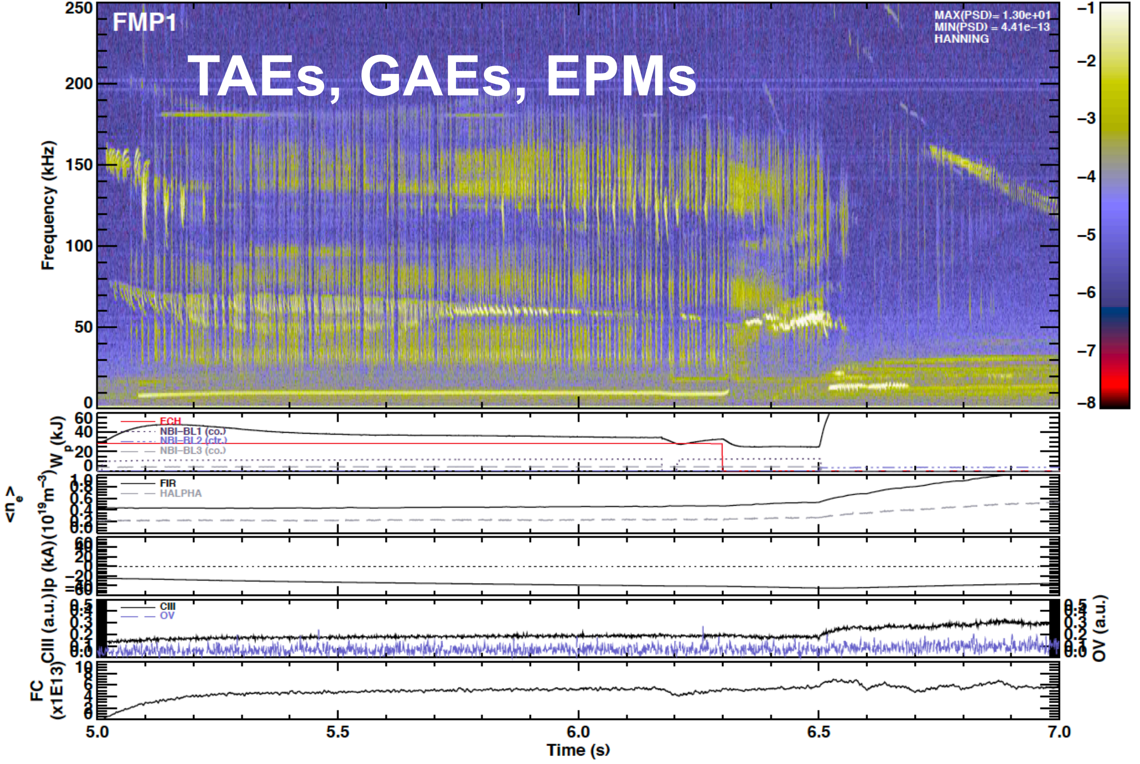
Suppression of AE/EPM by ECCD in LHD

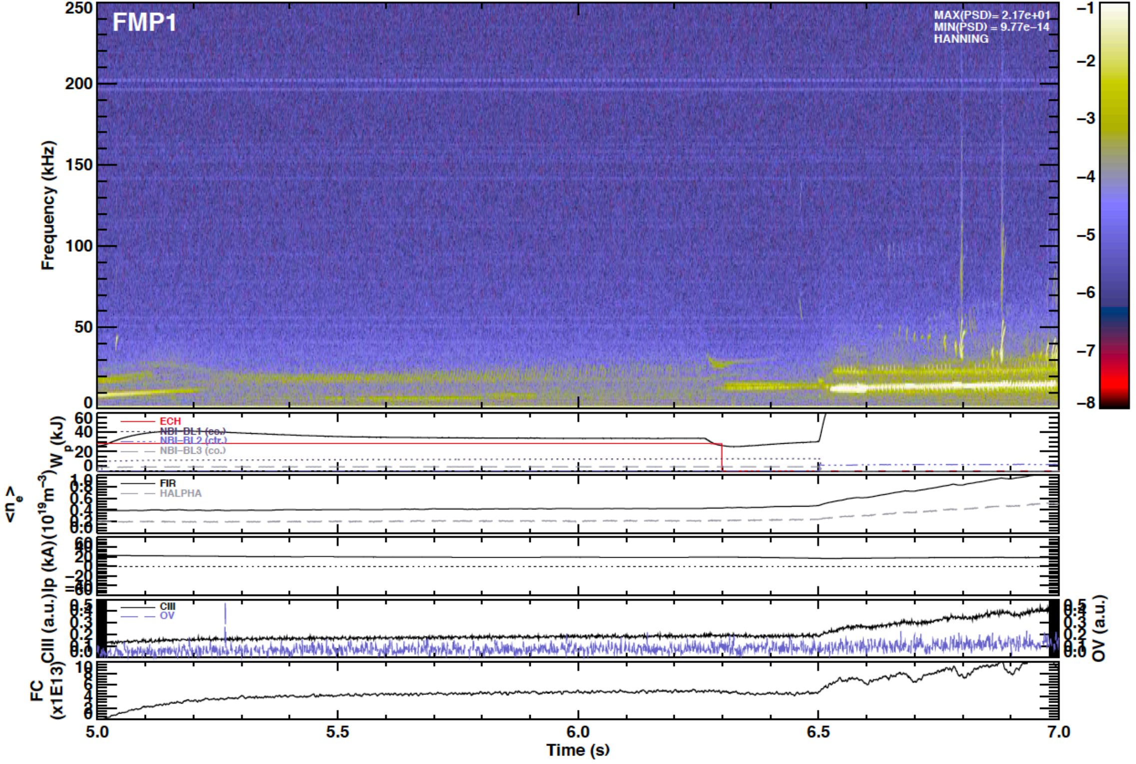
$P_{(BL1+BL3)}$~4MW

Co-ECCD ($N_{||}$ = -0.32)



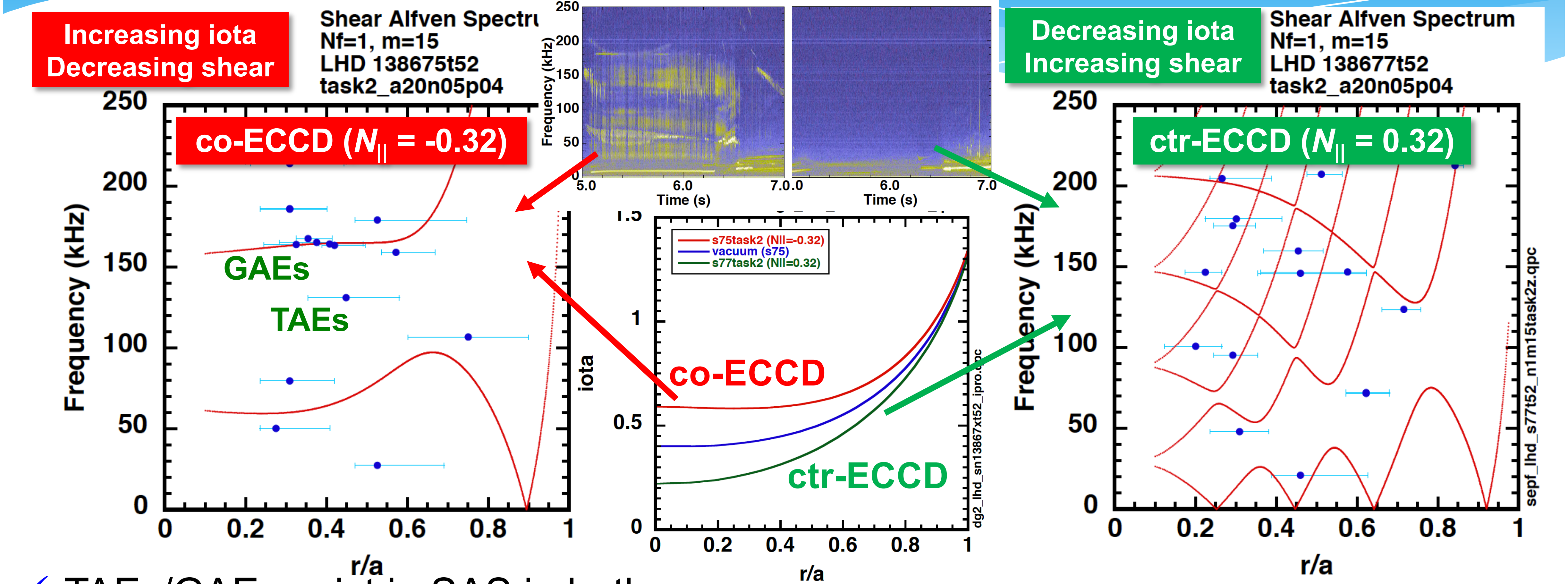
$P_{(BL1+BL3)}$~4MW

Ctr.-ECCD ($N_{||}$ = 0.32)



- ✓ ECCD ($N_{||}$ = -0.44 ~ +0.5) with P_{ECH} = 560 kW induces ~ ±20 kA current in LHD.
- ✓ **Suppression of TAEs and EPMs is observed for only ctr.-ECCD**. (decreases ι)

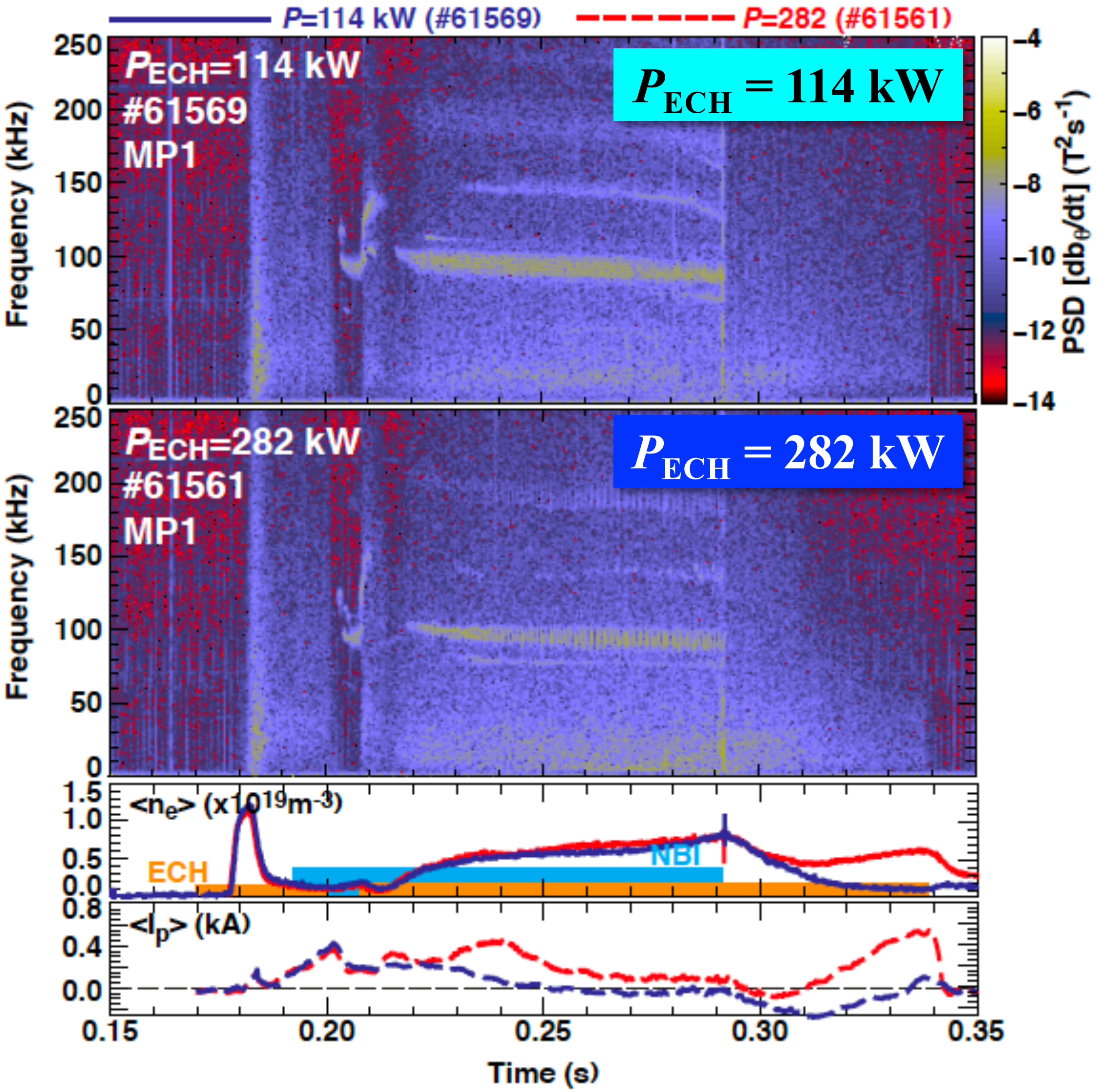
EC-driven Current Modify SAS in LHD



STELLGAP/AE3D calculation

- ✓ TAEs/GAEs exist in SAS in both cases.
- ✓ AEs intersect with continua in ctr-ECCD. Gap is radially aligned in co-ECCD.
- ✓ Change in SAS by EC-driven current contributes to **suppression of AEs**

ECH Effect on GAE/EPM in HJ



- ✓ On axis ECH (non-ECCD) affects EPM/GAE amplitude.
- ✓ **Amplitude of EPMs/GAEs decreases by the increasing ECH power**.
- ✓ Mode behavior changes from continuous to bursting when ECH power is increased.
- ✓ Overserved increasing T_e should lead increase of fast-ion beta, and then **mode amplitude should increase. But we observed mitigation of the modes**.

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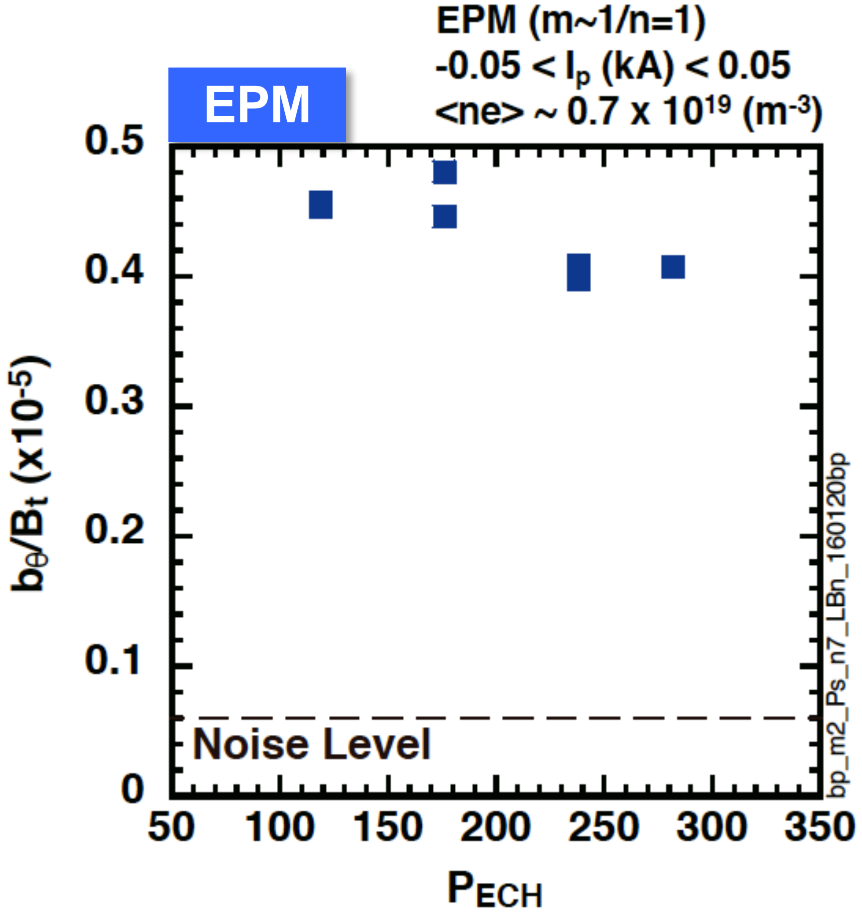
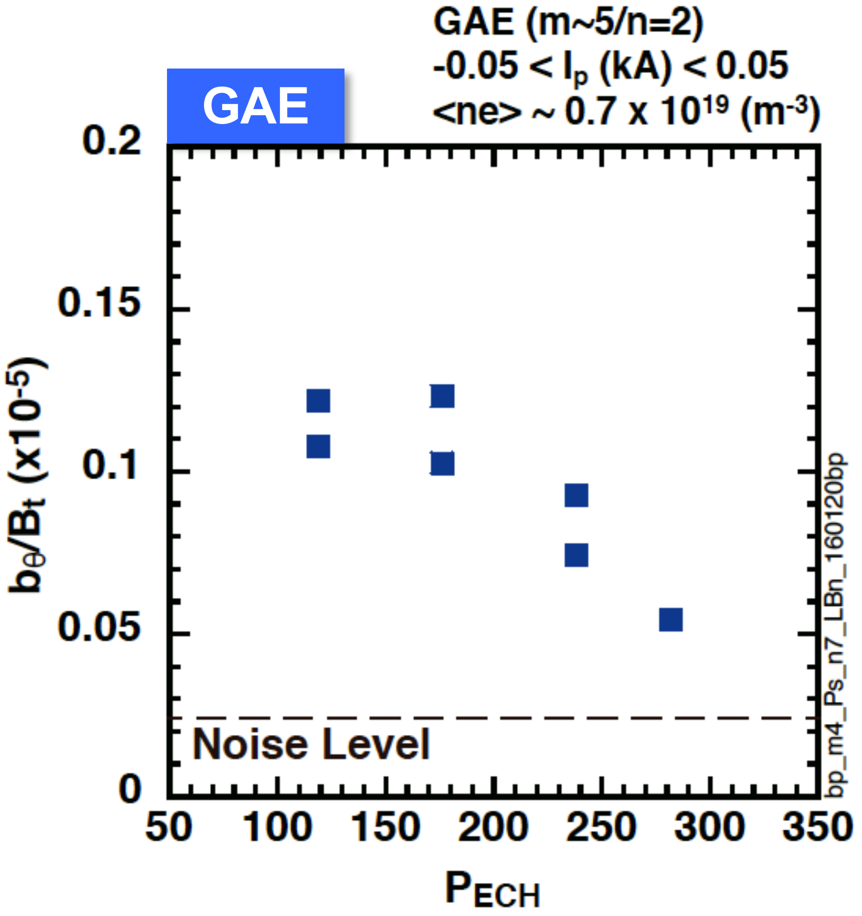
Dependence of GAE/EPM upon P_{ECH}

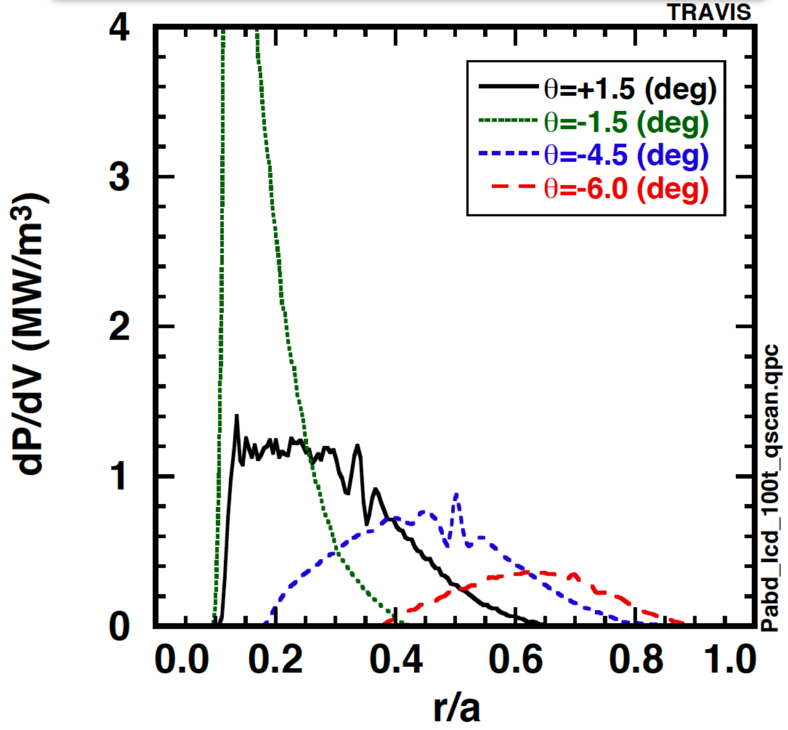


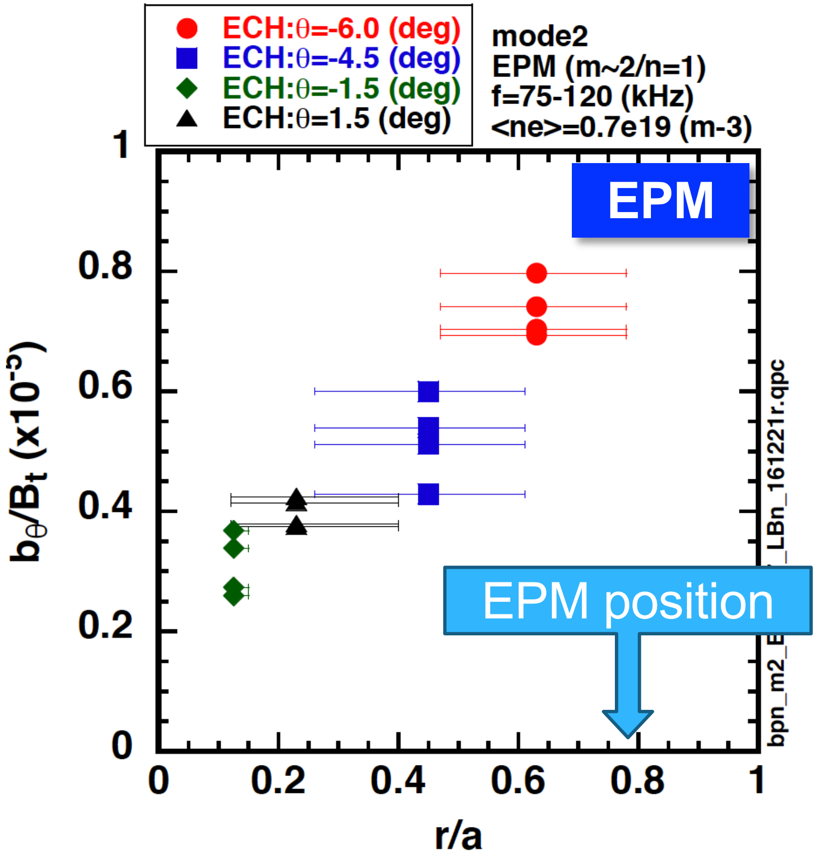


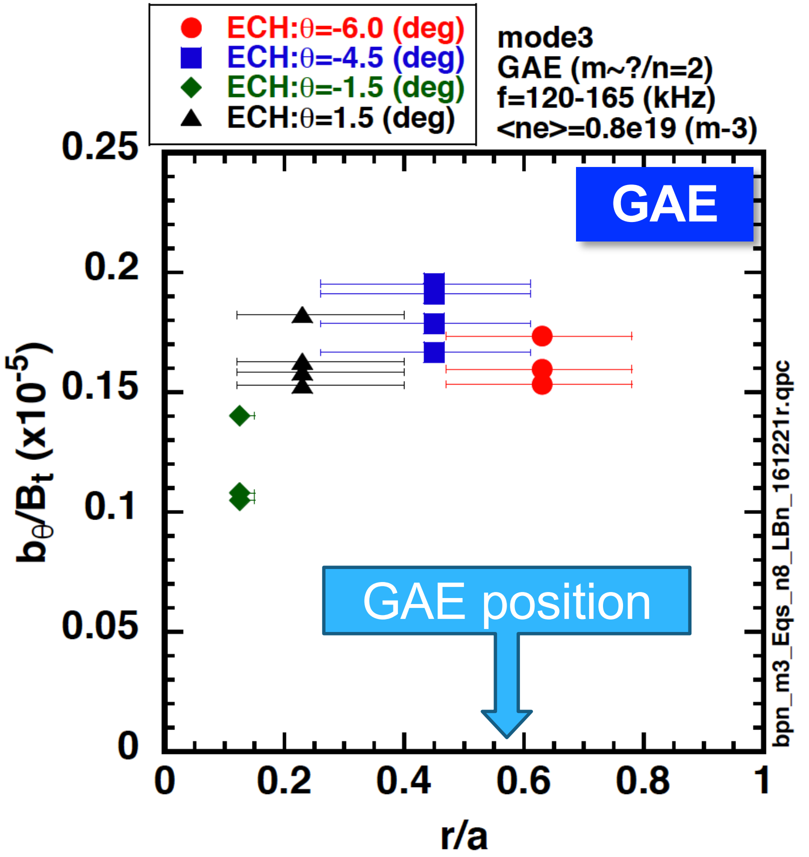
- ✓ Increasing ECH power induces a change of behavior from continuous to bursting.
- ✓ **GAE amplitude decreases with the increasing P_{ECH} with on-axis ECH**.

Effect of ECH Deposition

ECH deposition profile in θ scan







- ✓ ECH deposition can be scanned by poloidal angle scan of ECH mirror.
- ✓ **Edge ECH increases amplitude of EPMs/GAEs** localizing at edge.
  - ➟ **Modification of $<\beta_{fast}>$ profile** by ECH affects EPM/GAE amplitude.
  - ➟ Deposition scan affect production of trapped electron ➟ **Collisional damping**.

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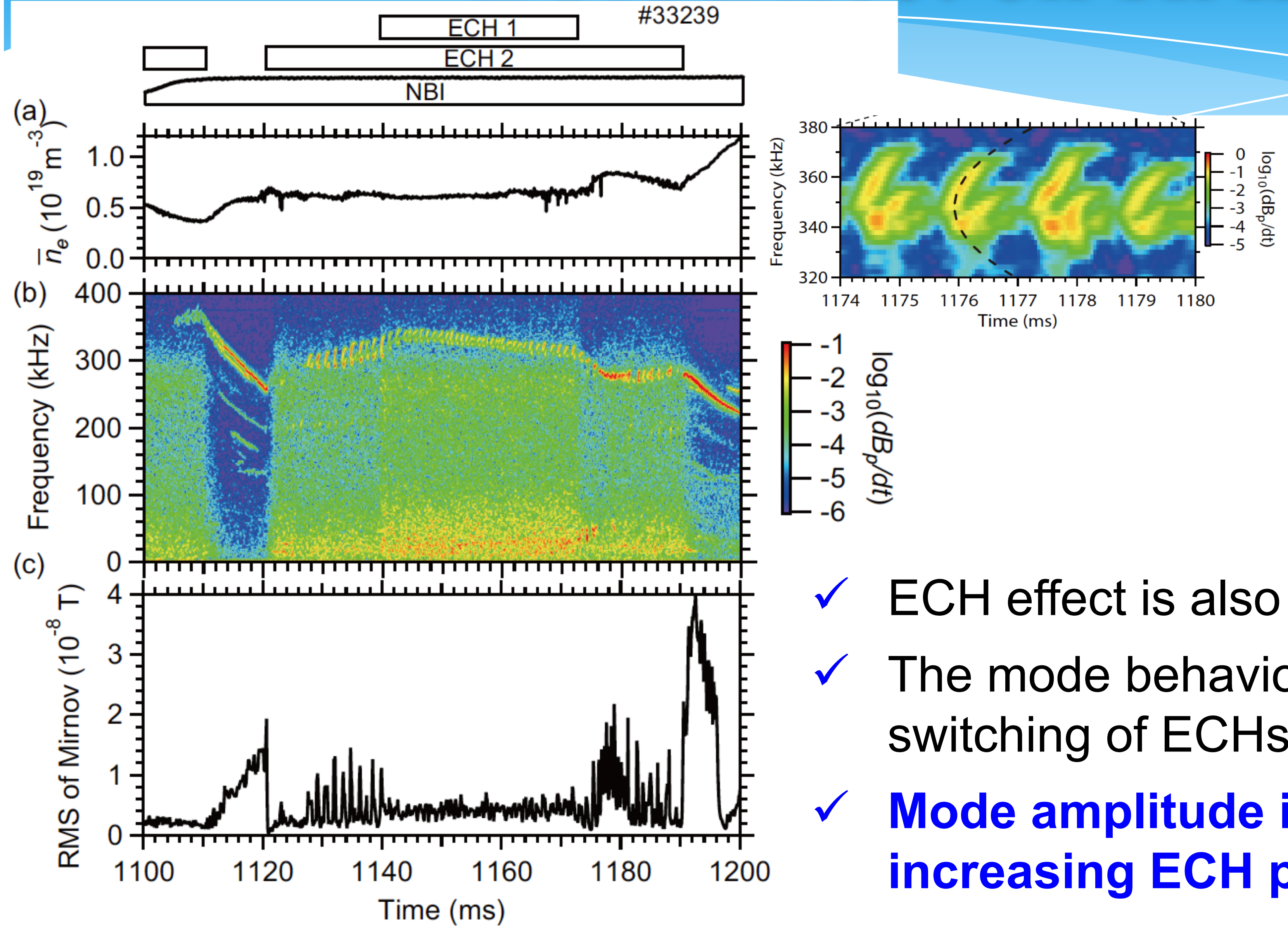
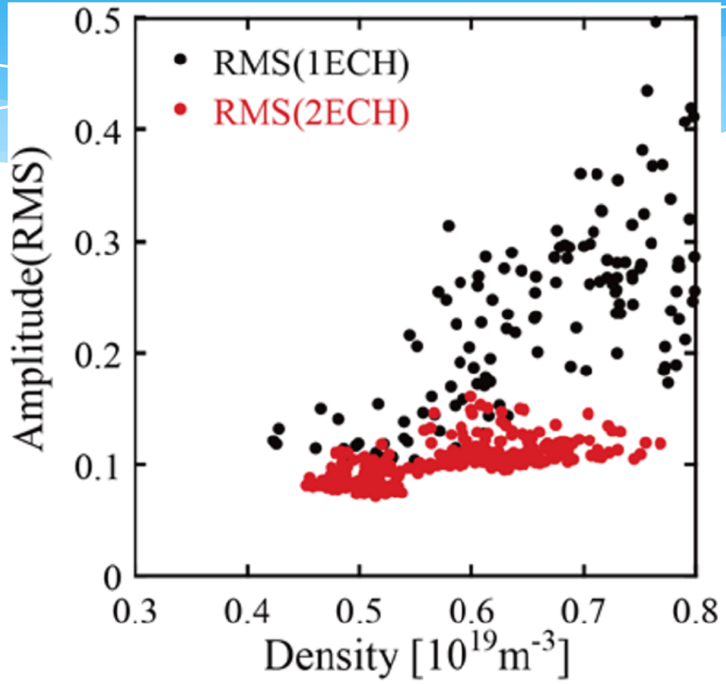
ECH Effect on HAEs in TJ-II





- ✓ ECH effect is also observed in TJ-II.
- ✓ The mode behaviors are clear seen in the switching of ECHs. e.g. burst to continuous
- ✓ **Mode amplitude is decreased with increasing ECH power**.

Discussion

Growth/Damping	**Effect**	**ECCD**			**ECH**
		HJ (low s/low ι)	TJ-II (low s/high ι)	LHD (high s)	HJ/TJ-II/LHD
Inverse Landau damping	Destabilizes AEs by <b> gradient				✓?
Shear Alfven Structure	AEs tend to intersect with continua or not		✓	✓	
Continuum damping	Alfvén resonance	✓	✓		
Electron Landau damping	Landau damping by electron				
Ion Landau damping	Landau damping by fast and bulk ions				
Radiative damping	Mode conversion by kinetic effect				
Collisional damping	Collision with fast electrons				✓?

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Conclusion

- ✓ In order to develop the method to control the observed EPMs and AEs in Stellarator/Heliotron, we investigate the effect of ECH/ECCD on EPMs/AEs in three devices, LHD, TJ-II and Heliotron J based on the similarities and differences.
- ✓ The increasing continuum damping of the modes by increase in magnetic shear due to EC-driven plasma current is effective for GAE and EPM (non-frequency gap modes).
- ✓ The modification of shear Alfvén continuum is more important effect than continuum damping for TAE and HAE (frequency gap modes)
- ✓ ECH (non-ECCD) also impact on FP-driven EPMs/AEs. A candidate to explain this phenomenon is modification of $<\beta_{fast}>$ and/or collisional damping by trapped electrons.

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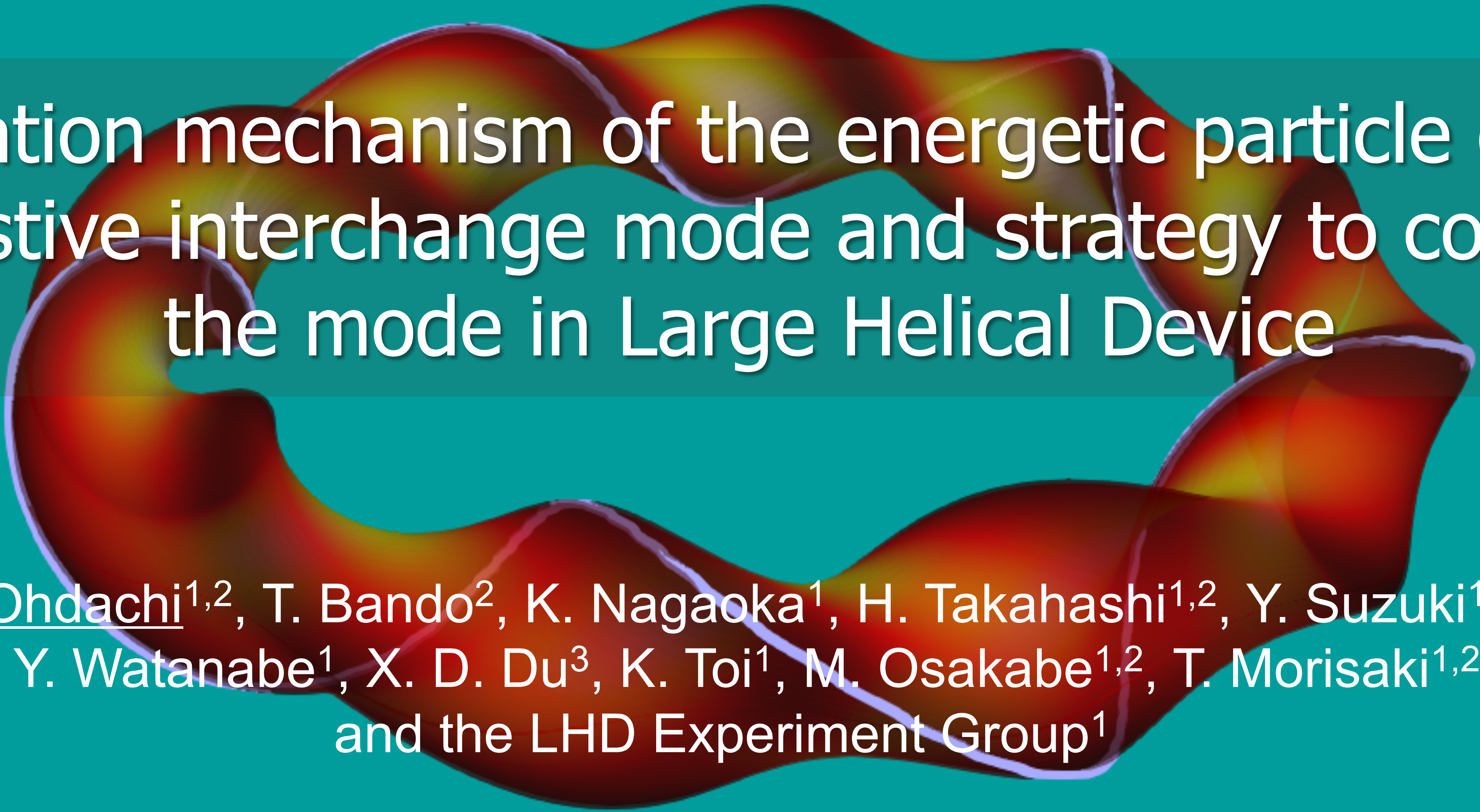
EX/1-3Rb



Excitation mechanism of the energetic particle driven resistive interchange mode and strategy to control the mode in Large Helical Device

S. Ohdachi[1,2], T. Bando[2], K. Nagaoka[1], H. Takahashi[1,2], Y. Suzuki[1,2],
K. Y. Watanabe[1], X. D. Du[3], K. Toi[1], M. Osakabe[1,2], T. Morisaki[1,2],
and the LHD Experiment Group[1]

[1]National Institute for Fusion Science,
[2]Sokendai (The Graduate University of Advanced Studies)
[3]General Atomics, USA.

Contents of my talk

- A new type of the energetic particle driven MHD instability, EIC was found in LHD (X. D. Du, *et. al.*, Phys. Rev. Lett. **114** (2015), 155003) in the hydrogen plasma campaign.

1. The characteristics of the EIC in deuterium campaign.

2. Excitation mechanism of EIC
    - Resonant of the MHD mode with the helically trapped particles motion is required.

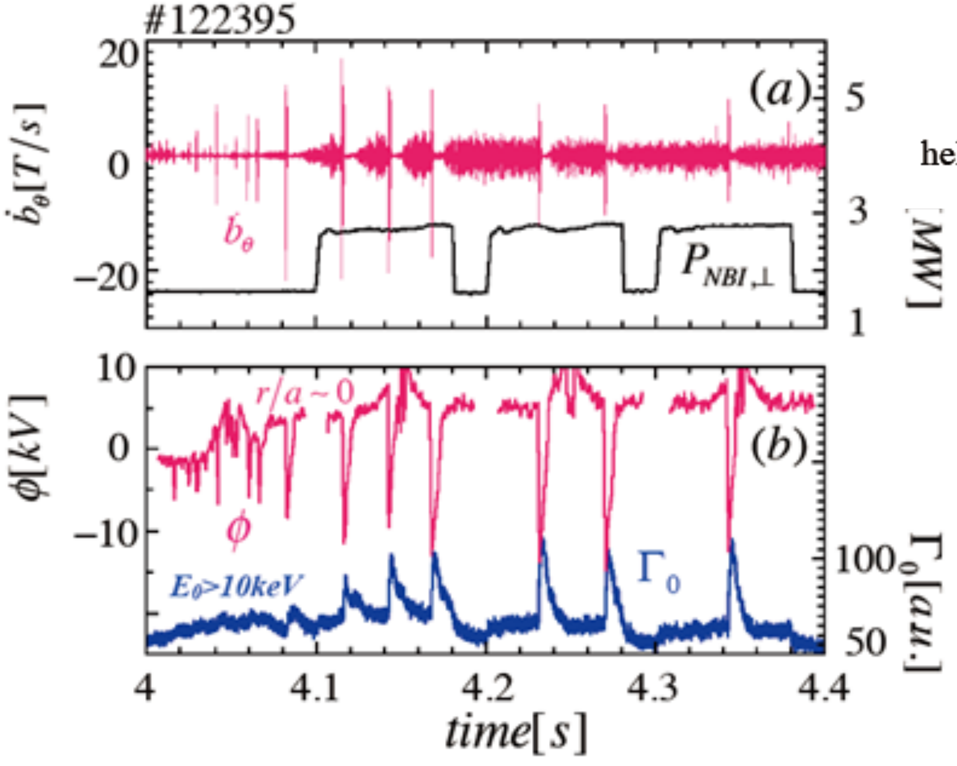
3. Control of the EIC
    1. ECH application (Resonant effects is reduced)
    2. RMP application (Resistive interchange mode is stabilized?)

EIC in the hydrogen / deuterium campaign (1)

EIC: Energetic particle driven resistive InterChange mode

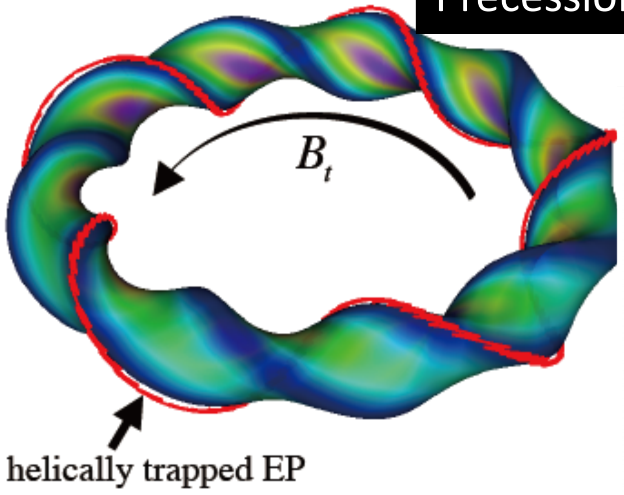
- With the excitation of the EIC, the energetic particles are lost rapidly. The effect on the plasma is quite large, e.g., formation of the negative potential. (ϕ>10kV)

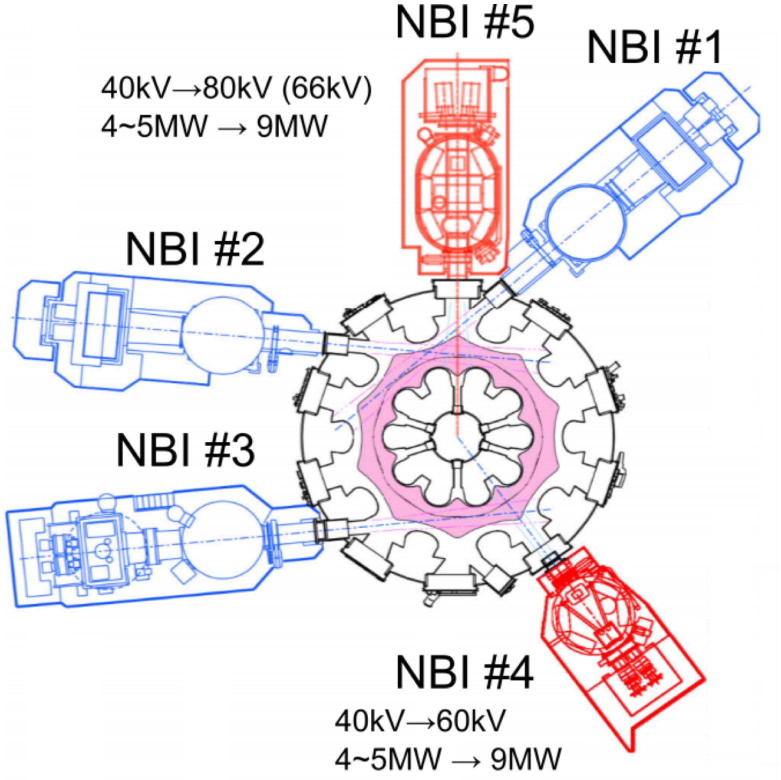
Hydrogen experiments



Potential formation / modification of the EP profile

Precession motion

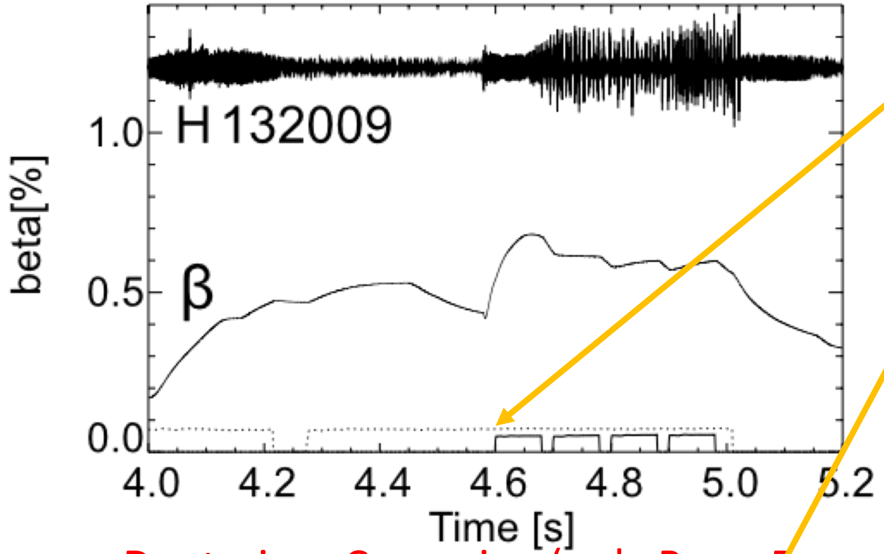




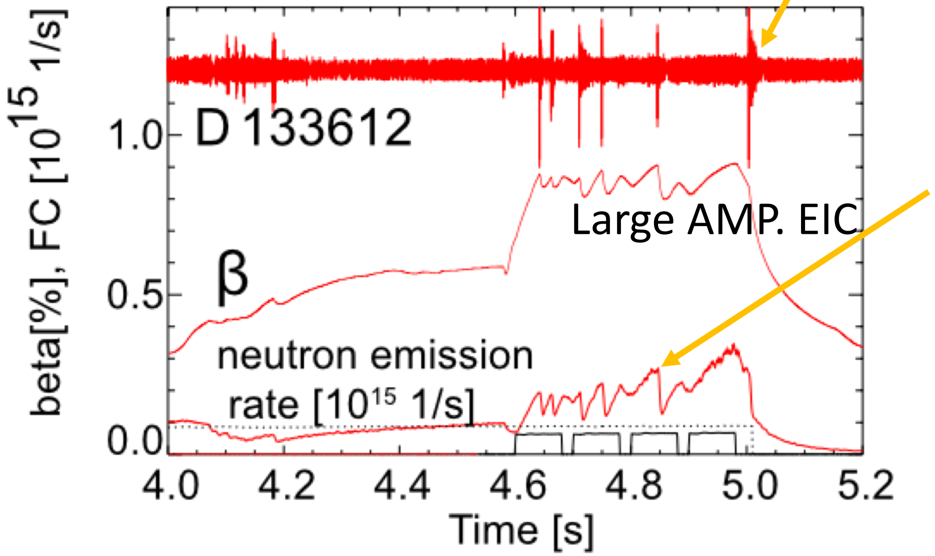
- It is noted that neutron emission rate is a good measure of the amount of the trapped particles, since the beam-plasma reaction is the dominant in LHD.

EIC in the hydrogen / deuterium campaign (2)

Hydrogen Campaign



Deuterium Campaign (only Perp. Beams)



- EICs becomes unstable when the perpendicularly injected NBI power is increase.
- Bursts of MHD activities less frequently activated are observed in deuterium campaign.
- Impact of each EIC burst is larger, as seen in the time evolution of beta than that observed in hydrogen campaign.
- Total neutron emission rate is decreased as much as 60%.

➔ This difference might be caused by the excitation mechanism of EIC.

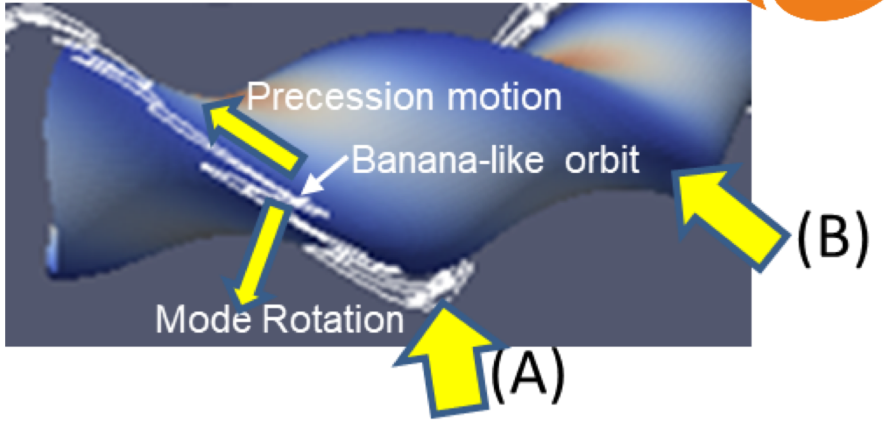
Excitation Condition of EIC – analogy to the Fishbone

Energy Principal with Energetic particle

$$\underbrace{\delta I + \delta W_{MHD}}_{\text{Bulk plasma}} + \underbrace{\boxed{\delta W_k}}_{\text{From Energetic Particle}} = 0$$

$$\delta I = -\frac{\omega^2}{2}\int \rho_m |\xi|^2 d\mathbf{r},$$

$$\delta W_k = \frac{1}{2}\int \xi \cdot \nabla \cdot \tilde{\mathbf{P}}_{\mathbf{h}} d\mathbf{r},$$



Three requirements for EIC excitation

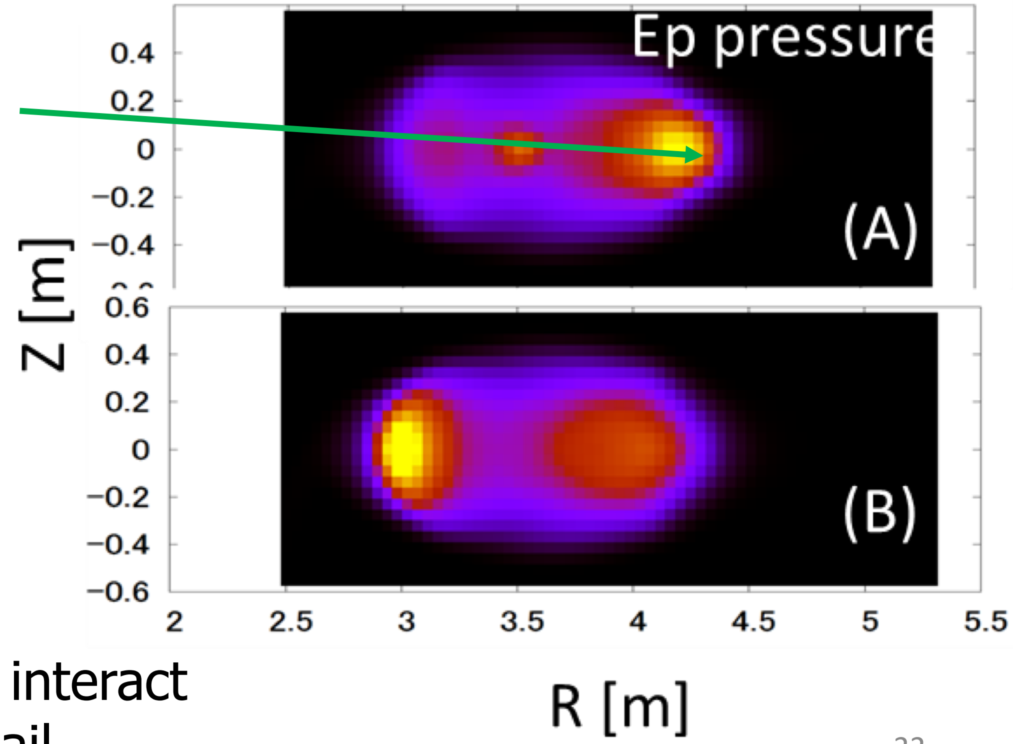
Pressure driven mode is marginally stable/ weakly unstable

- This condition is always satisfied in inward shifted configuration where EICs appear.

Pressure gradient of th EPs is large

$$-\frac{\partial \beta_h}{\partial r} > C_{th}$$

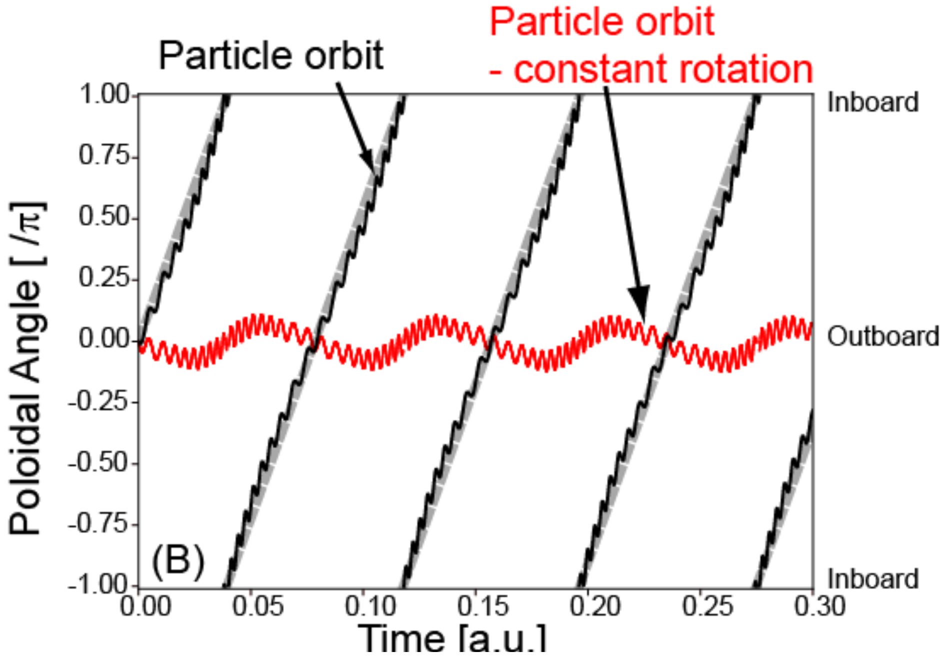
- EP pressure gradient at the rational surface can be large estimated from the deposition profile.

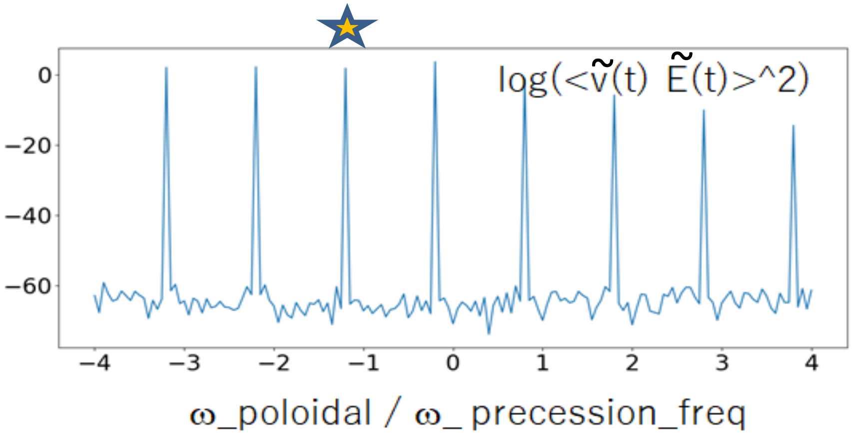


EP motion resonant with MHD mode

- Precession frequency (5~12kHz) is slow enough to interact with pressure driven mode. will be discussed in detail.

Resonance of the MHD mode with Helically trapped EP



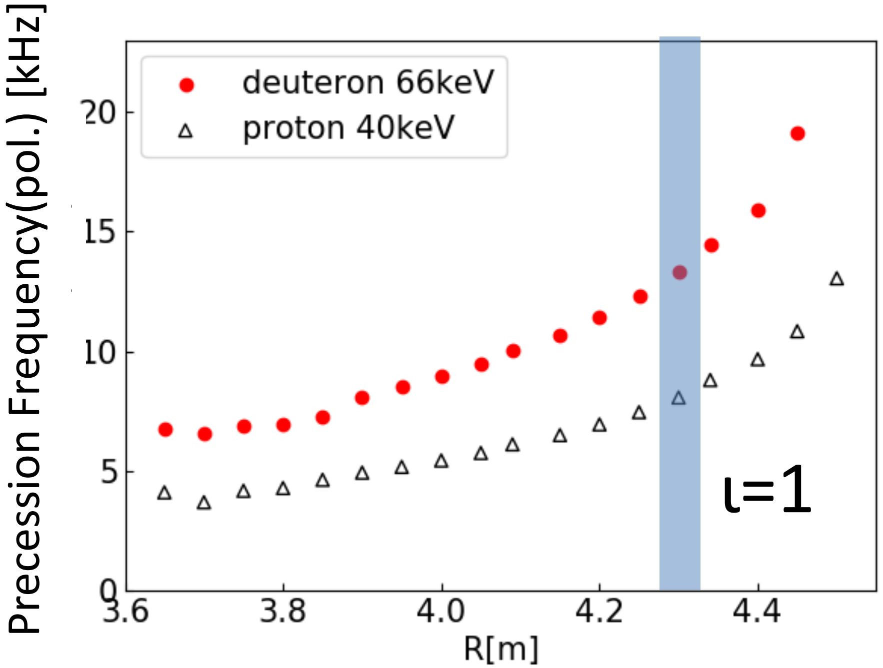


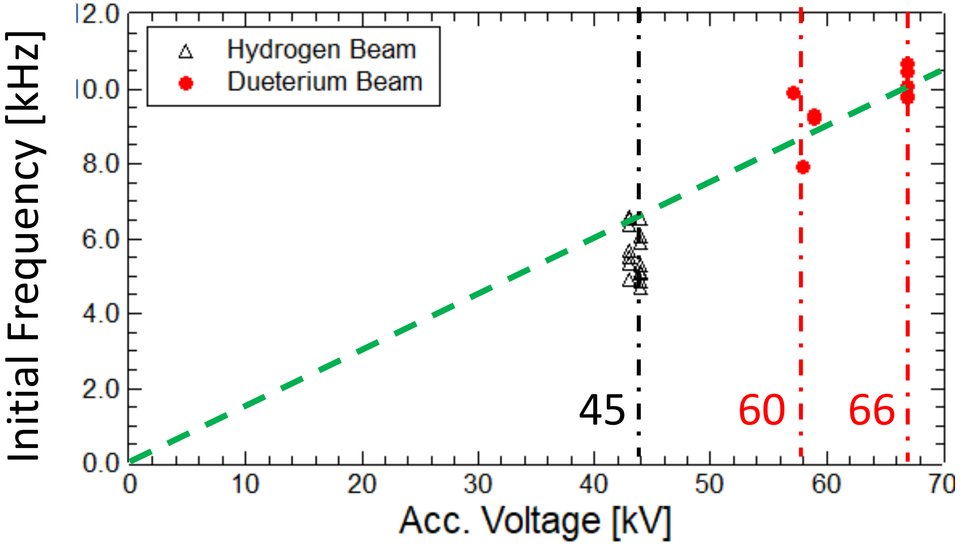
- There is an acceleration section at the inward side and a slowing down section at the outward side (GCR code is used).
- This variation of the velocity is the reason why the helically trapped EP can be coupled with the MHD instabilities having the mode number of m/n = 1/1.

- Energy transfer from the EP to the mode is estimated by evaluating the correlation of the fluctuating component of the precession motion and the MHD mode. Resonance is found at -1.2 x ω(prec.freq.)

Ya. I. Kolesnichenko, et. al., Phys. Rev. Lett. **82**(1999) 3261, Phys. Plasma **9** (2002), 517

Evidences supports EIC excitation mechanism

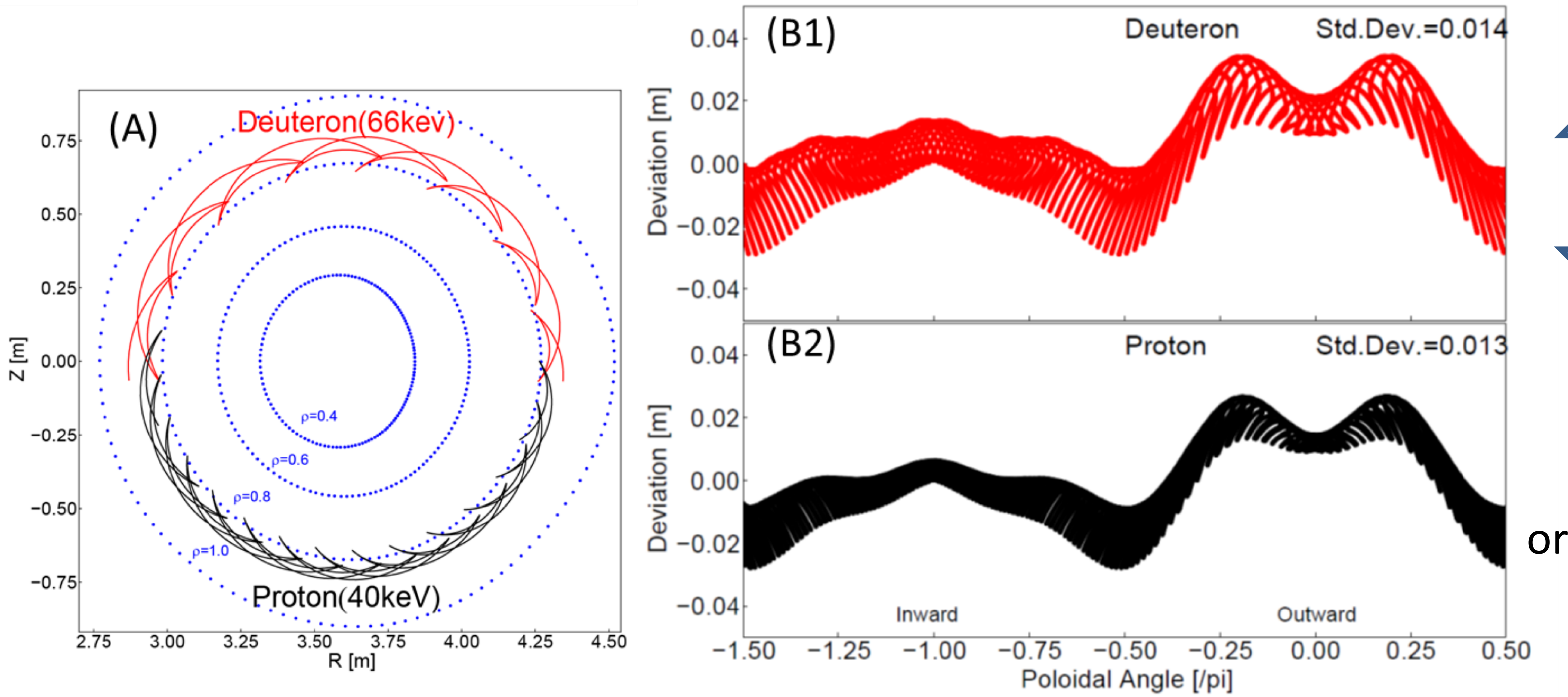




[1] X. D. Du, *et al.*, Phys. Rev. Lett. **114**(2015), 155003

- Precession frequency is proportional to the energy of EPs. The initial frequency of the EIC is similar to the frequency of the precession frequency.
- EICs caused by the PERP NBIs with 66 kV has the larger frequency than those with 60 kV and 45 kV.
- Initial frequency dependence strongly supports that the EIC is driven by the resonance of the perpendicularly injected EPs as discussed in ref [1].

MHD / EP resonant effects and stability



Typical mode width ρ_R

orbit width ρ_b

- This orbit width / mode width effects might be the reason why the EIC is more stable in D beam heating. EIC excitation threshold is raised when the orbits of the EPs are larger than the mode width of the resistive interchange mode.
- Excitation of EIC requires more EP pressure with D heating. ⇒ Less frequently excited and the amplitude is larger.

Threshold is predicted to be raised by

$$\frac{\rho_b}{\rho_R}\ln\frac{\rho_b}{\rho_R}$$

H. Biglari and L. Chen, Phys. Fluids 29, 2960 (1986).

Strategy to control the EIC

Energy Principal with Energetic particle

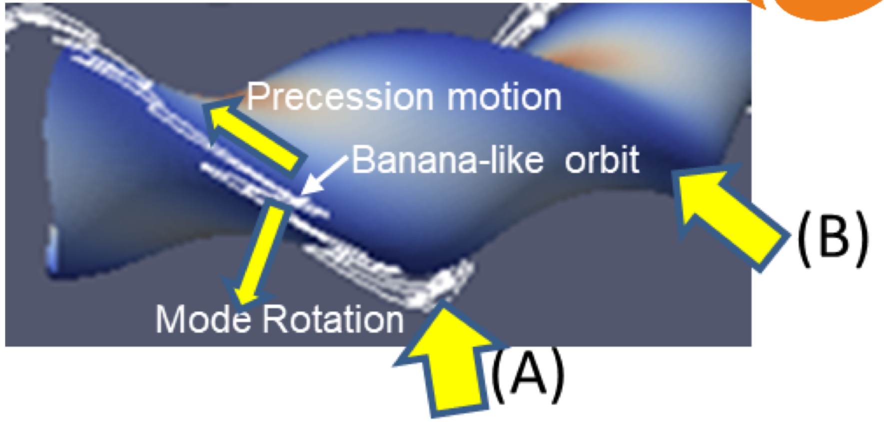
$$\delta I + \delta W_{MHD} + \boxed{\delta W_k} = 0$$

Bulk plasma

From Energetic Particle

$$\delta I = -\frac{\omega^2}{2}\int \rho_m |\xi|^2 d\mathbf{r},$$

$$\delta W_k = \frac{1}{2}\int \xi \cdot \nabla \cdot \tilde{\mathbf{P}}_{\mathbf{h}} d\mathbf{r},$$



(2) RMP

Pressure driven mode is marginally stable/ weakly unstable

$$-\frac{\partial \beta_h}{\partial r} > C_{th}$$

- This condition is always satisfied in inward shifted configuration where EICs appear.

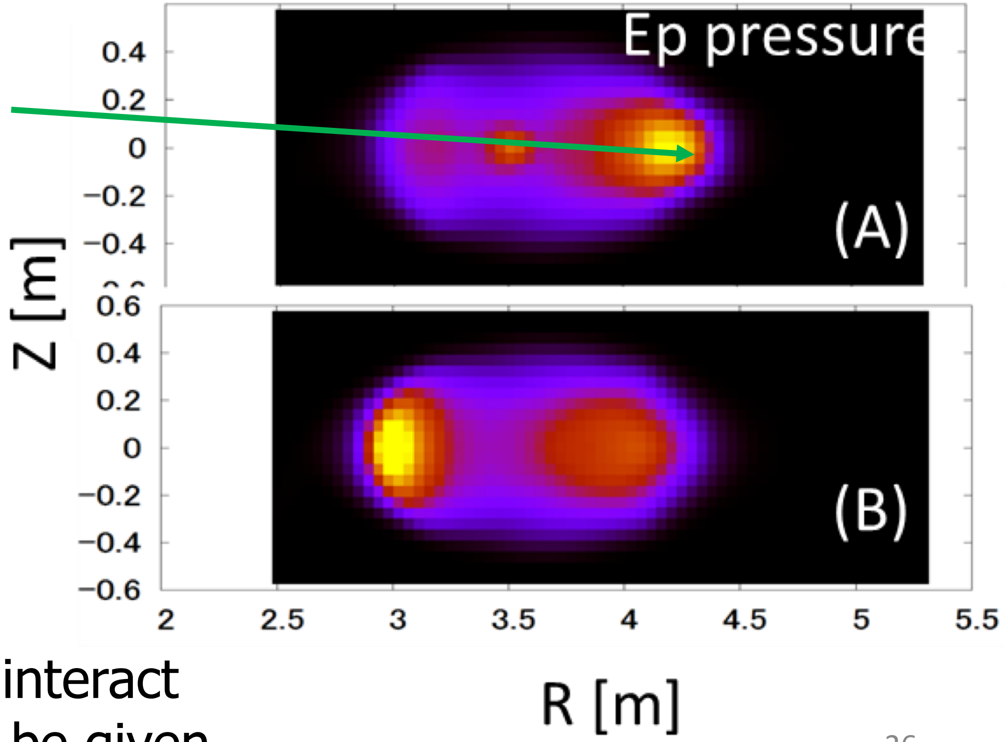
Pressure gradient of th EPs is large

- EP pressure gradient at the rational surface can be large estimated from the deposition profile.

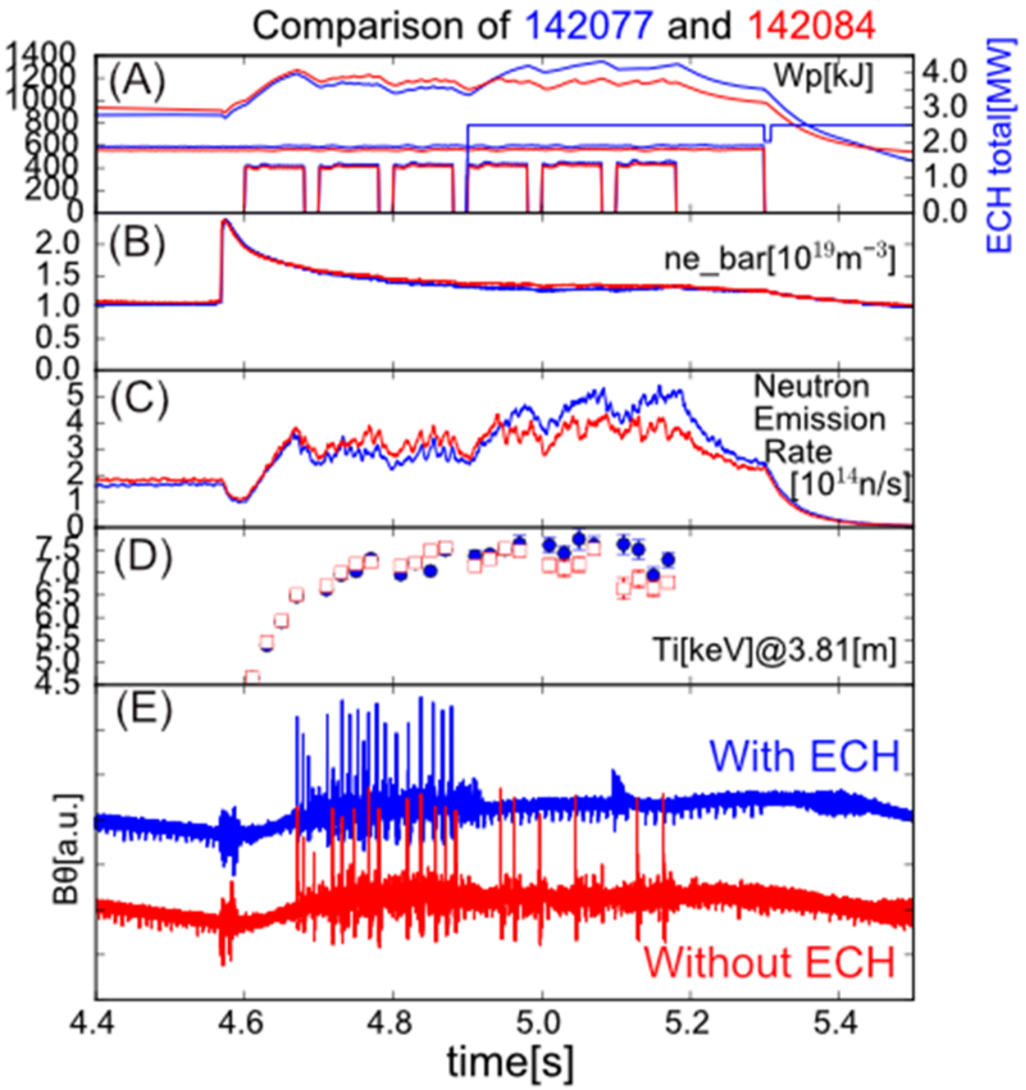
(1) ECH

EP motion resonant with MHD mode

- Precession frequency (5~12kHz) is slow enough to interact with pressure driven mode. Discussed in detail will be given.



Control of EIC in High-Ti Deuterium exp.



- The mode width of the resistive interchange mode is reduced with the increase of the electron temperature or the magnetic shear due to the larger Shafranov shift. ⇒ Reduction of the interaction of EP with the interchange mode.

- The control of the EIC using ECW was already reported in lower ion temperature regime. (X. D. Du et. al. Phys. Rev. Lett. **118** (2017), 125001)

- Clear disappearance of the EICs are observed with on-axis ECH in the high-Ti discharge condition. No reduction of the neutron emission rated is observed.

Summary

- From the resonance of the precession motion of the helically trapped particle and resistive interchange mode, so-called EIC mode appears in the Large Helical Device.
- The threshold of the energetic particle pressure for the EIC excitation is larger with D beam. The amplitude and the effects of an EIC events on plasma is thereby enhanced in deuterium experimental campaign.
- Trial to control the EIC with ECH and RMP application is investigated.
- Both ECH and RMP application successfully suppress the EIC without reducing neutron emission rate, i.e. EP pressure. Suppression by ECH might be explained by the reduction of the radial mode width. Suppression by RMP might be caused by the stabilization of the resistive interchange mode.

	Resistive interchange mode stability	**EP Pressure at EIC bursts**	**Resonance**	**EIC behavior**
D-Beam	Marginal	Small	Small	Larger Bursts
H-Beam	Marginal	Large	Large	Frequent Small Bursts
D with ECH	Marginal	Not changed	Smaller	Suppressed
D with RMP	Marginal to stable	Not changed	Not changed	Suppressed (only found in higher n_e)

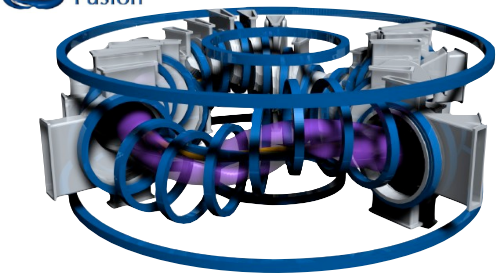
Backup

Heliotron J / TJ-II / LHD

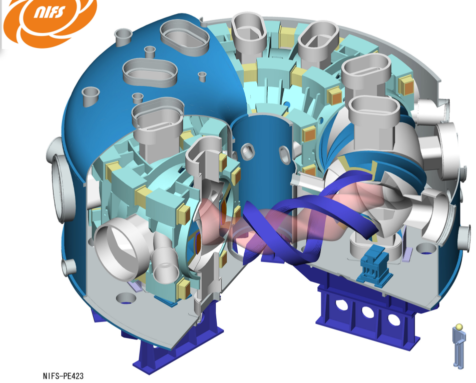
Heliotron J

TJ-II

Laboratorio
Nacional
Fusión



LHD



	HJ	TJ-II	LHD
	Helical axis Heliotron	Flexible Heliac	Planar axis Heliotron
Major radius R (m)	1.2	1.5	3.9
Minor radius a (m)	< 0.25	< 0.22	< 0.65
Magnetic field B (T)	1.25	0.95	< 3.0
Toroidal period N_p	4	4	10
ECH Power P_{ECH} (kW)	< 300	< 300 x 2	< 600 (77GHz)*
NBI Power P_{NBI} (kW)	< 700 x 2	< 700 x 2	< 2000 x 3*
NBI Energy E_{NBI} (keV)	< 30 [H]	< 40 [H]	< 80 [D]*
Working gas	D	H	D
Magnetic shear	LOW	LOW	HIGH
Rotational transform [1/q]	0.4 ~ 0.7	0.9 ~ 2.2	0.3 ~ 1.5 [high s]

* For our experiments

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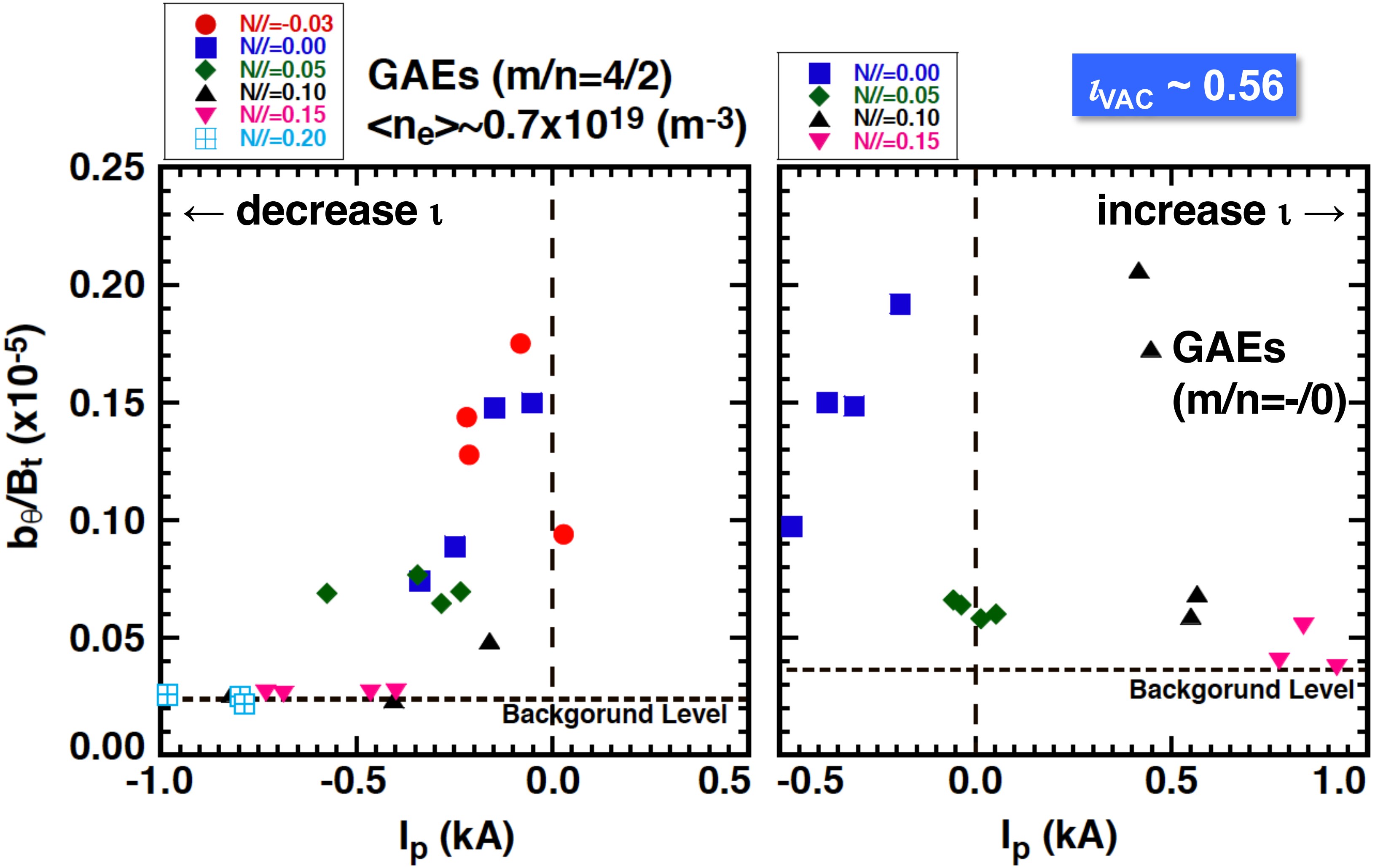
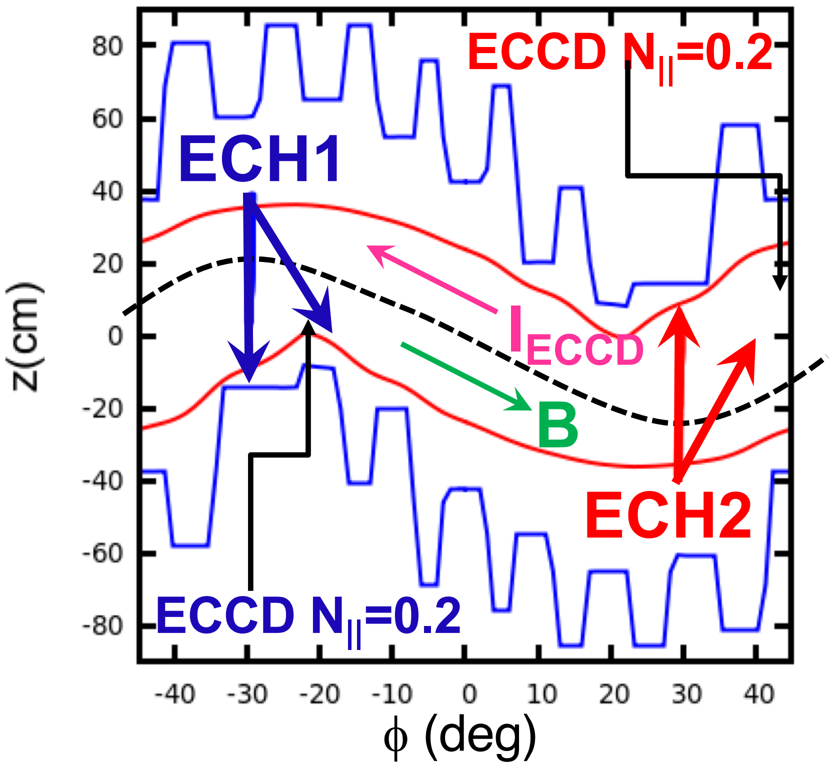
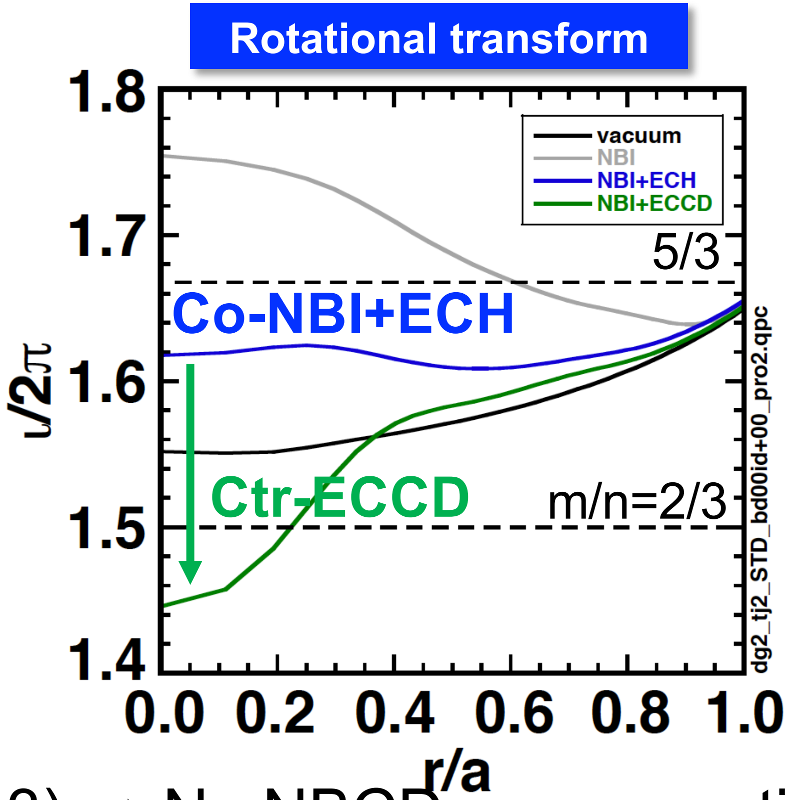
Dependence of GAE upon EC-driven Current



- ✓ **GAE amplitude decreases with increasing *I*$_p$.**
- ✓ Mode frequency and position do not change so much ➟ **growth rate should remain unchanged**.
- ✓ When *I*$_p$ > 0.5 (kA), other **GAEs are appeared and also decrease with increasing *I*$_p$.**

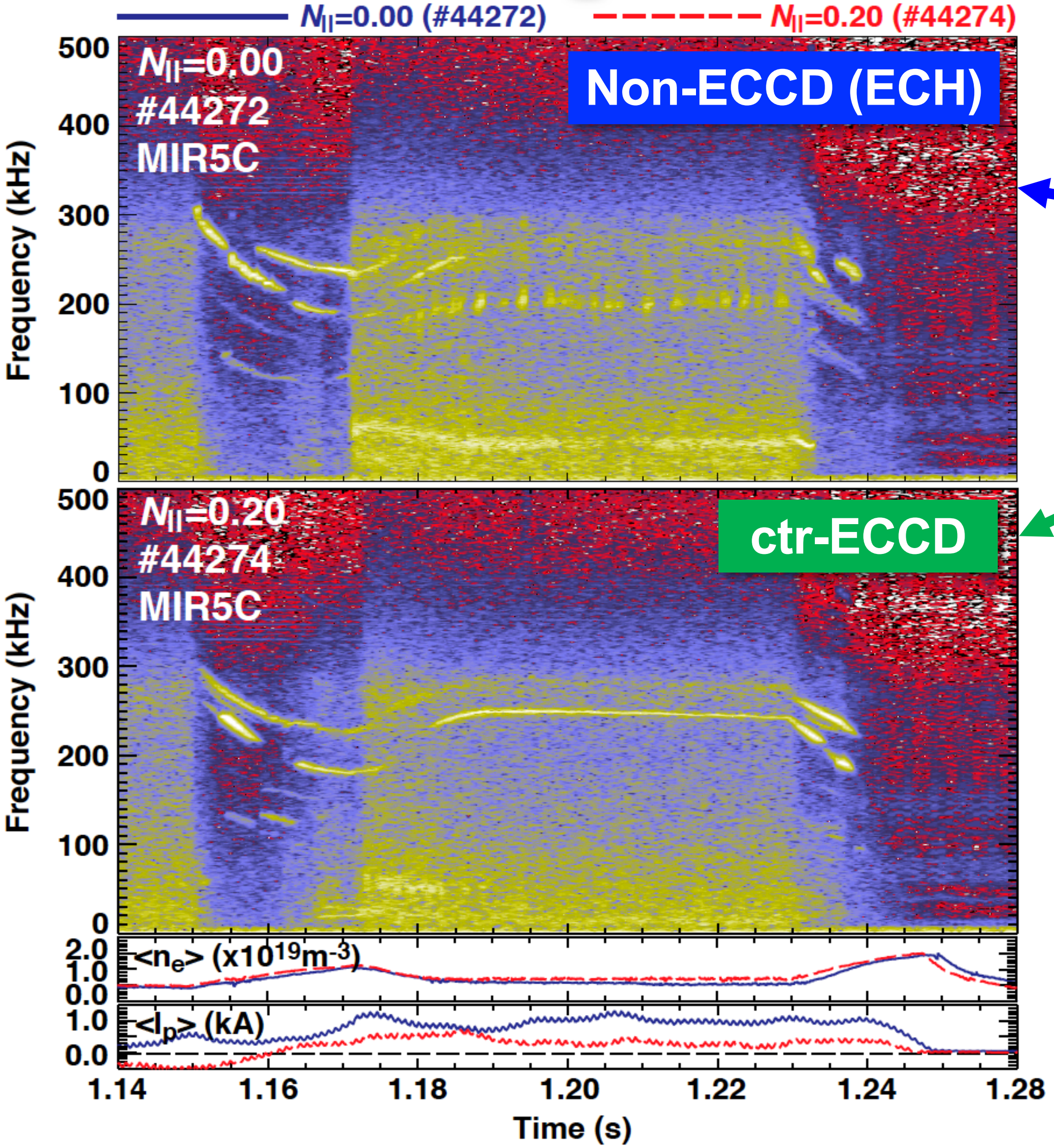
ECCD Modify Configuration in TJ-II

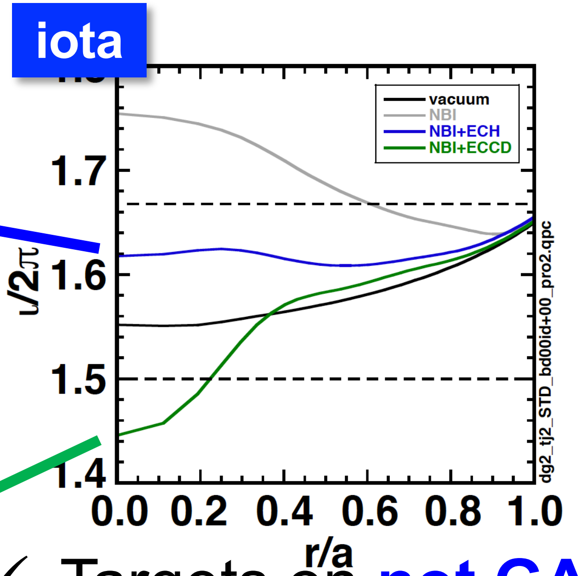


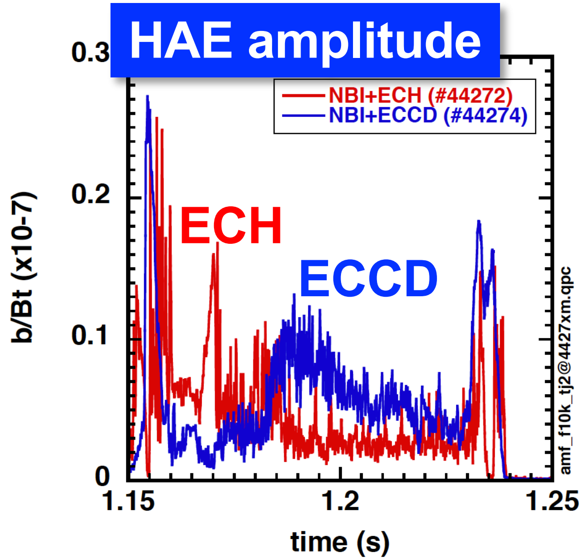


- ✓ Co-NBI: 30 kV / 0.7 MW /H^0 (v_b/v_A ~ 0.2 - 0.3) → No NBCD compensation
- ✓ Two ECH (ECH1 & ECH2). $P_{ECRH} \approx$ 250 kW each.
- ✓ On-axis ctr.-ECCD ($N_{||}$ = 0.2) induces ~ - 0.5 ~ -1.0 kA, decreases iota.
- ✓ Change of rotational transform → **impacts on shear Alfvén spectra**

Impact of ECCD on AEs in TJ-II







- ✓ Targets on **not GAE but HAE** in TJ-II.
- ✓ **ECCD decreases I_p** composed of BS and NBCD.
- ✓ **Continuous HAEs in ECCD+NBI**.
- ✓ **Bursting HAEs in ECH+NBI**.
- ✓ **Increases shear induces increase of HAE amplitude**.

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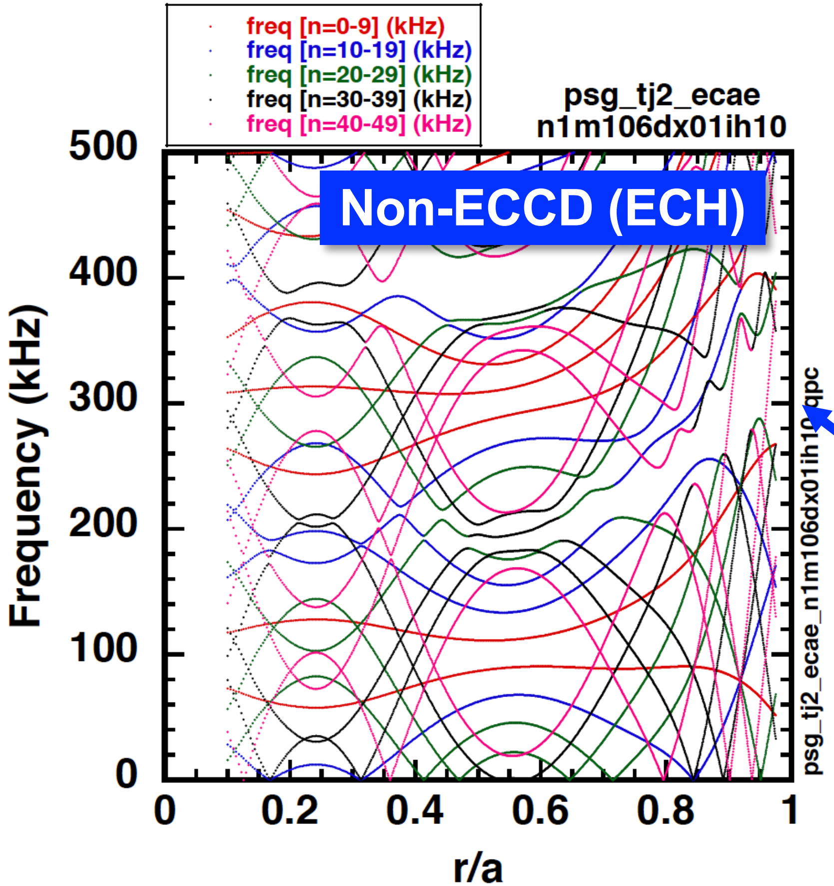
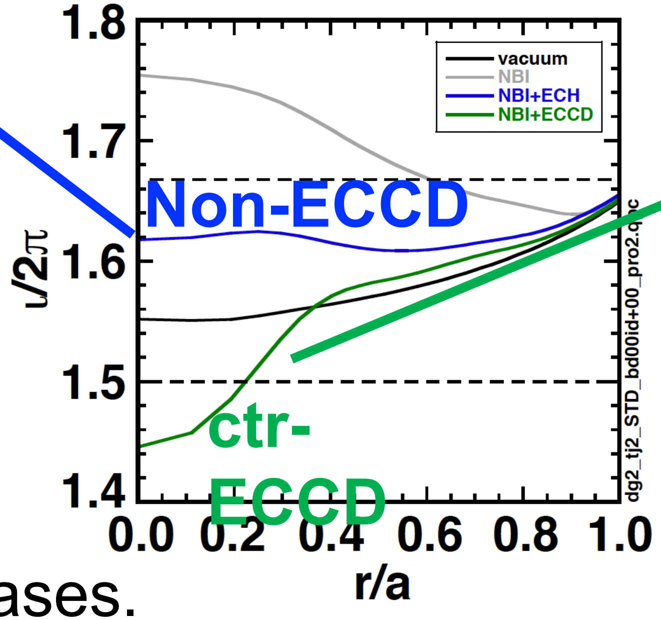
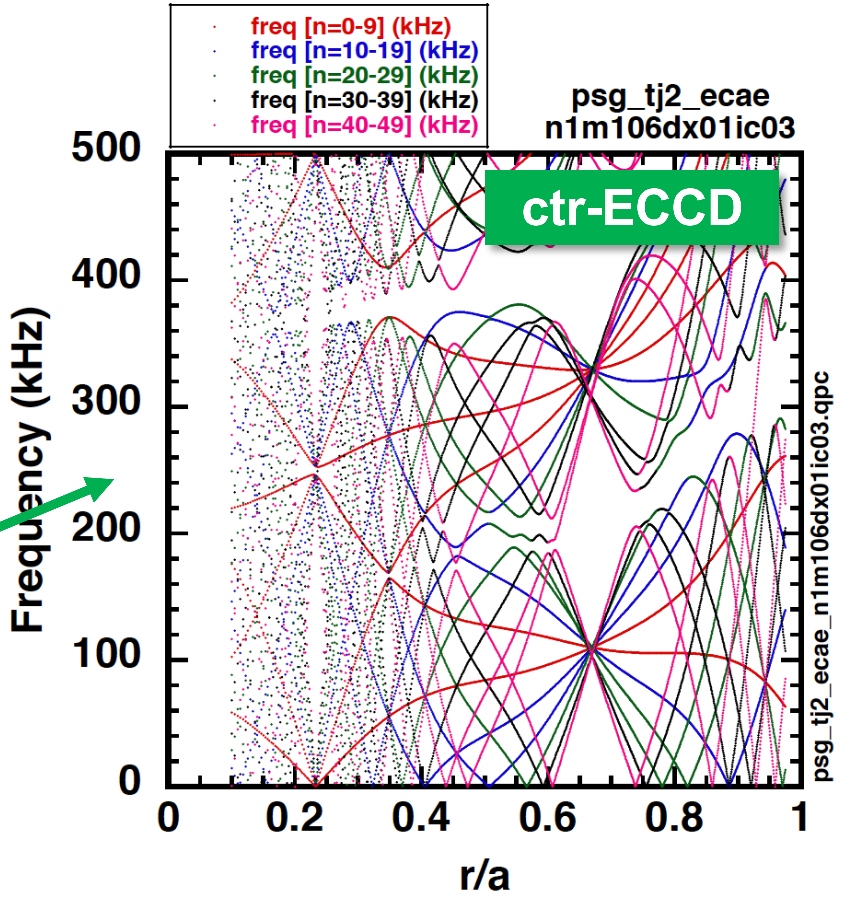
Change in Shear Alfvén Spectra in TJ-II







STELLGAP/AE3D calculation

- ✓ HAEs exist in SAS in both cases.
- ✓ Small change in iota lead to **change in SAS structure, especially for HAE gap**.
- ✓ Change in SAS by EC-driven current contributes to **suppression of AEs**.

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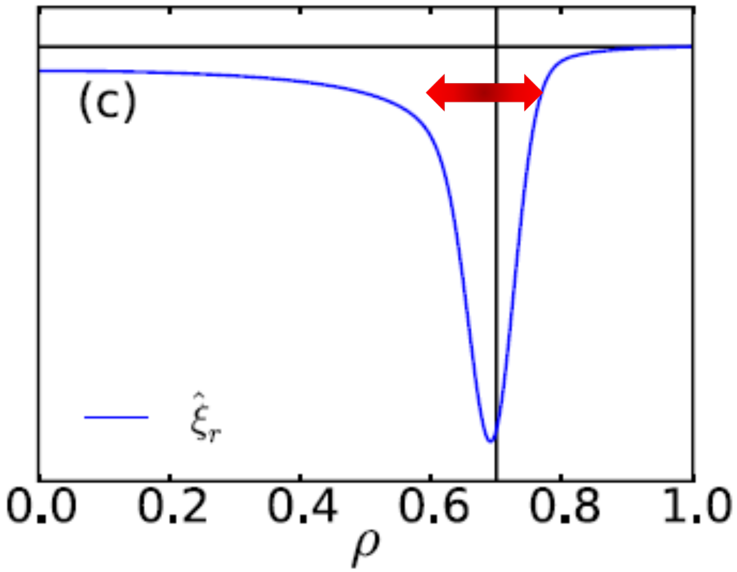
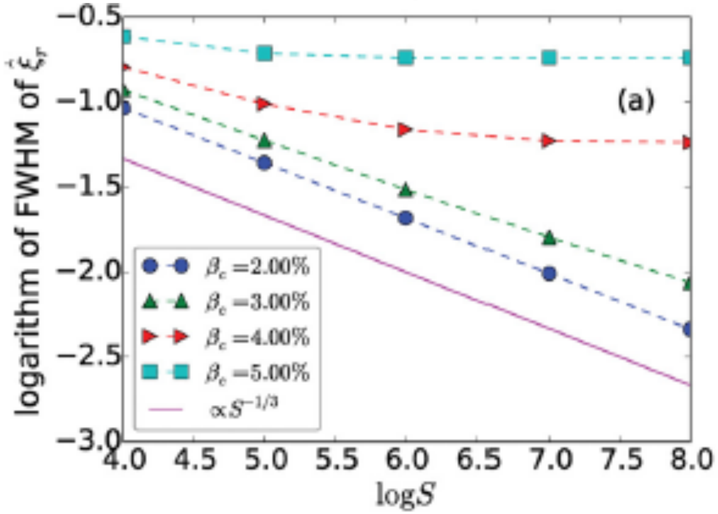
Mode width of the resistive interchange mode

Typical displacement of the Interchange Mode





R. Ueda, et.al, POP **21**, 052502 (2014)

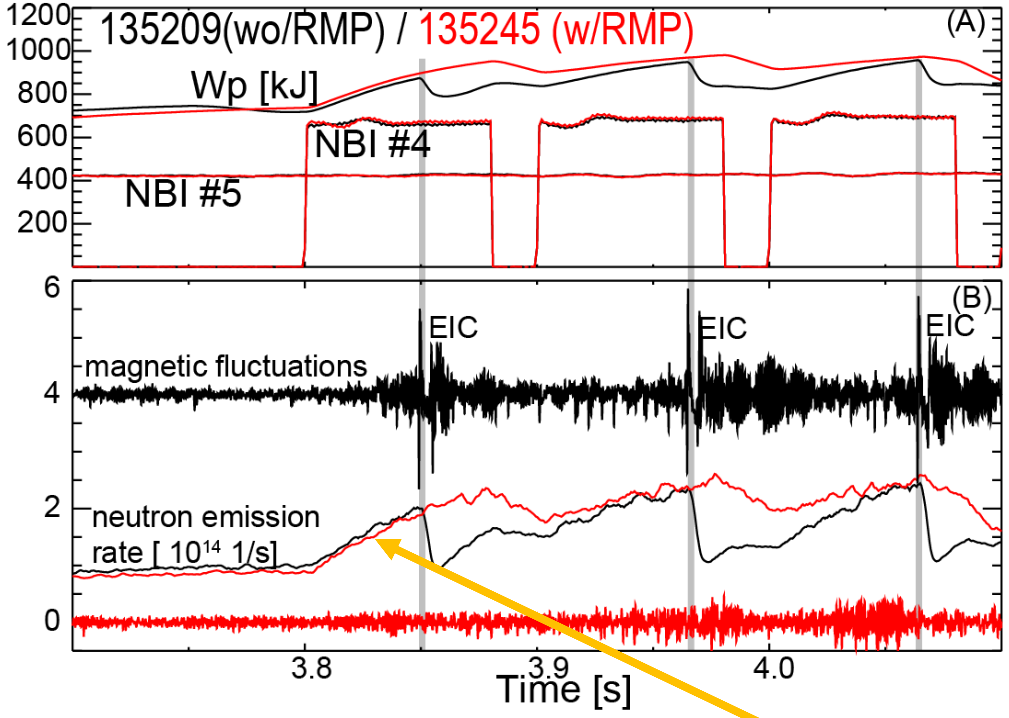
$$\delta w \sim \left(\frac{q^2}{S\hat{s}^2}\right)^{1/3}\left(\frac{\beta\kappa_n}{L_p}\right)^{1/6}$$

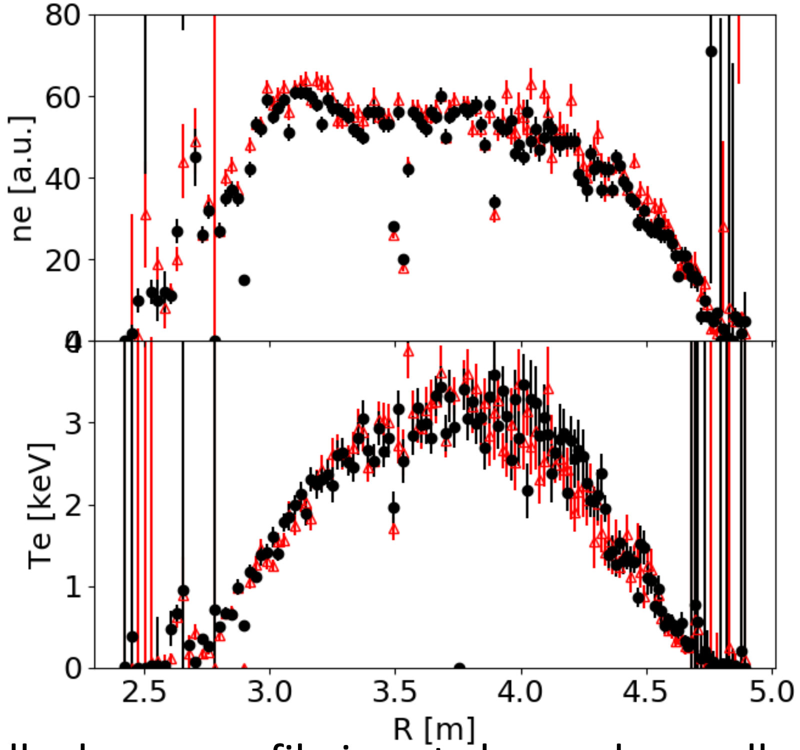
S : Magnetic Reynolds Number $\propto T_e^{3/2}\, n_e^{-1/2}$

$\hat{S}$: Magnetic shear

- Mode width of the resistive interchange mode depends on the magnetic Reynold’s number S.
- Mode width is narrower with higher electron temperature.

EIC behavior with RMP field (m/n = 1/1)

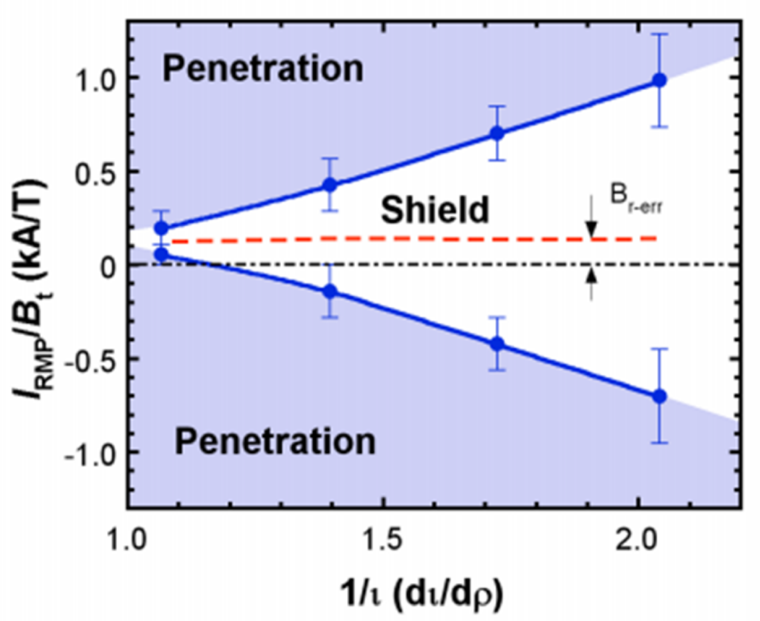




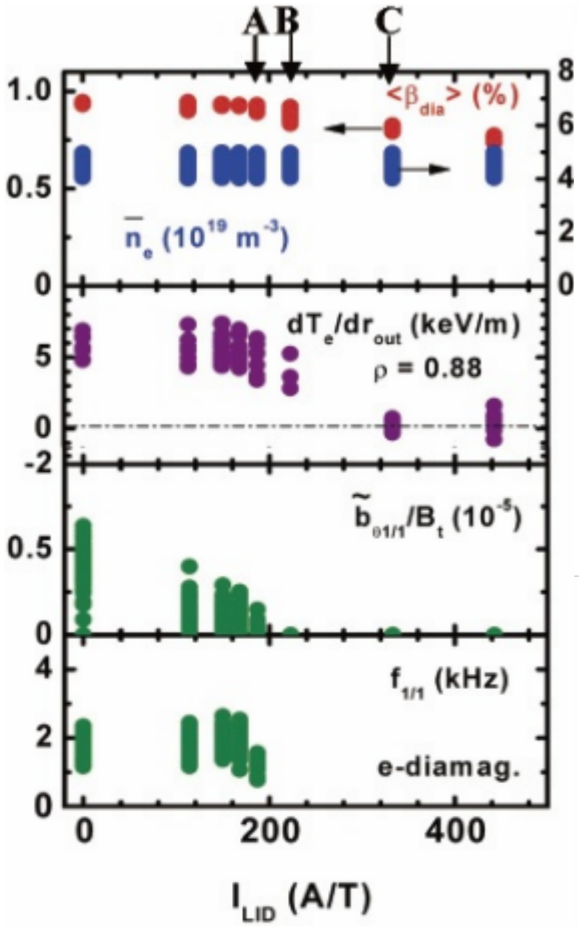
Total neutron emission rate is not changed. Bulk plasma profile is not changed as well.

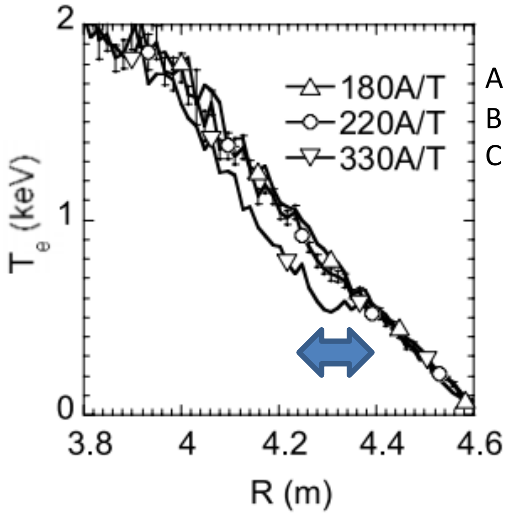
- Application of the RMP field is effective to control the EIC. The mechanism has not been clarified so far.
- Energetic particles (perp) are less affected by the RMP since the orbit is m/n = 1/5 type and do not resonant with RMP field.
- Change of the stability of the resistive interchange mode with RMP and or change of the pressure gradient of EP (parallel component) might cause this suppression.

Penetration of the RMP field and MHD instability



When the external field is applied, field is shielded with small field. External field penetrates the plasma and make magnetic island(m/n = 1/1).



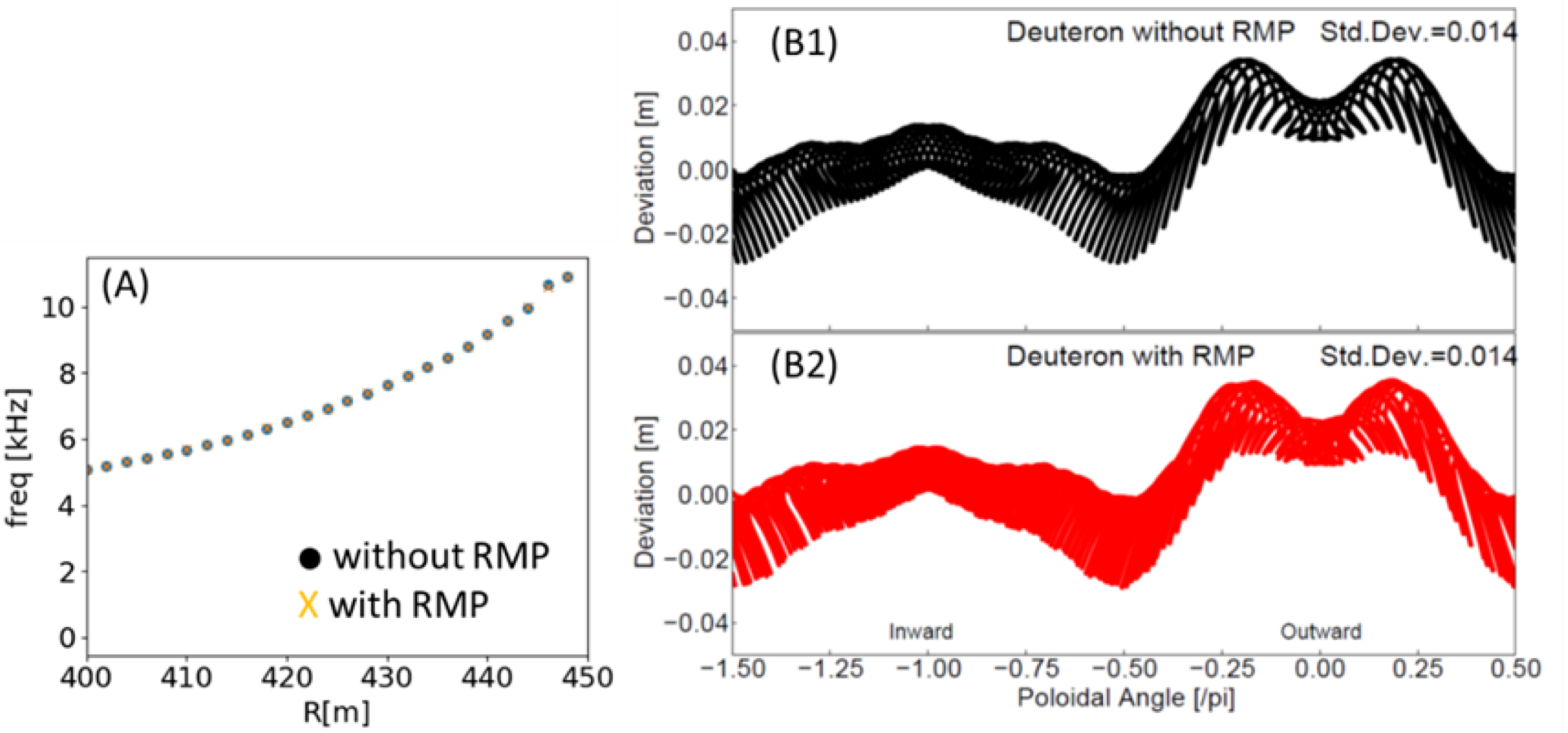


Case A: magnetic island is formed.

S. Sakakibara et al., Proc. in 33th EPS, Rome, Jun. 2006 ECA Vol. 301, p-4.113 (2006).

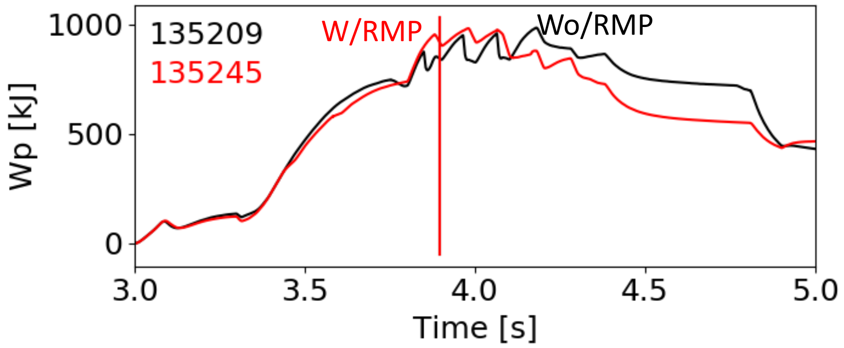
- RMP application affects the resistive interchange mode.
- When the field penetrates and pressure gradient is reduced (island formation), resistive interchange modes disappear.
- Even the external field is partly shielded, MHD activities are suppressed to some extent.

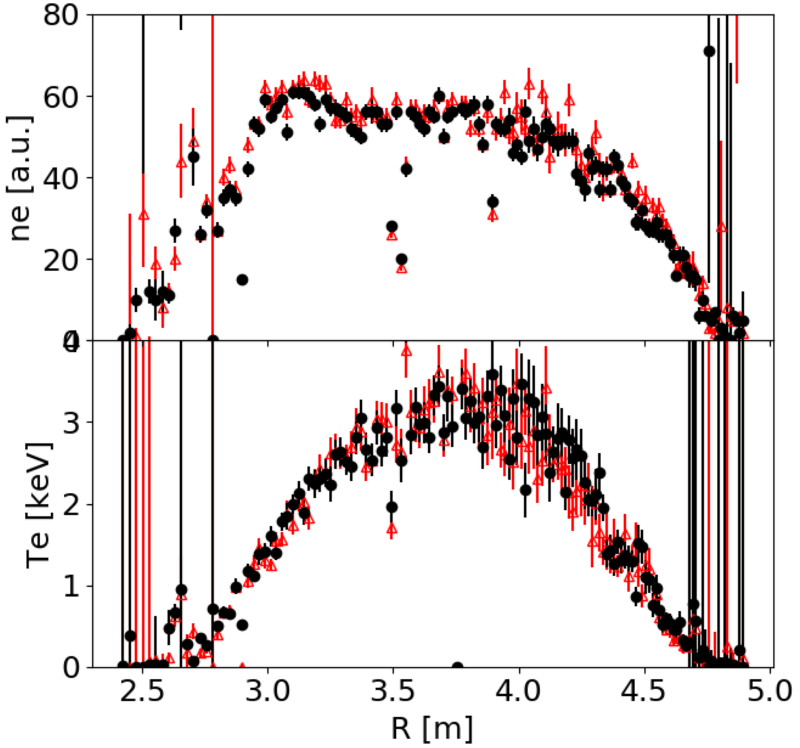
Can not be explained by the orbit effect



- Though the detailed orbit is slightly perturbed if we compare the Fig. (B1) and Fig. (B2), this perturbation is much smaller than the typical size of the banana like orbit of the EP. It is, therefore, not likely this stabilization is caused by the change of the EP orbit.

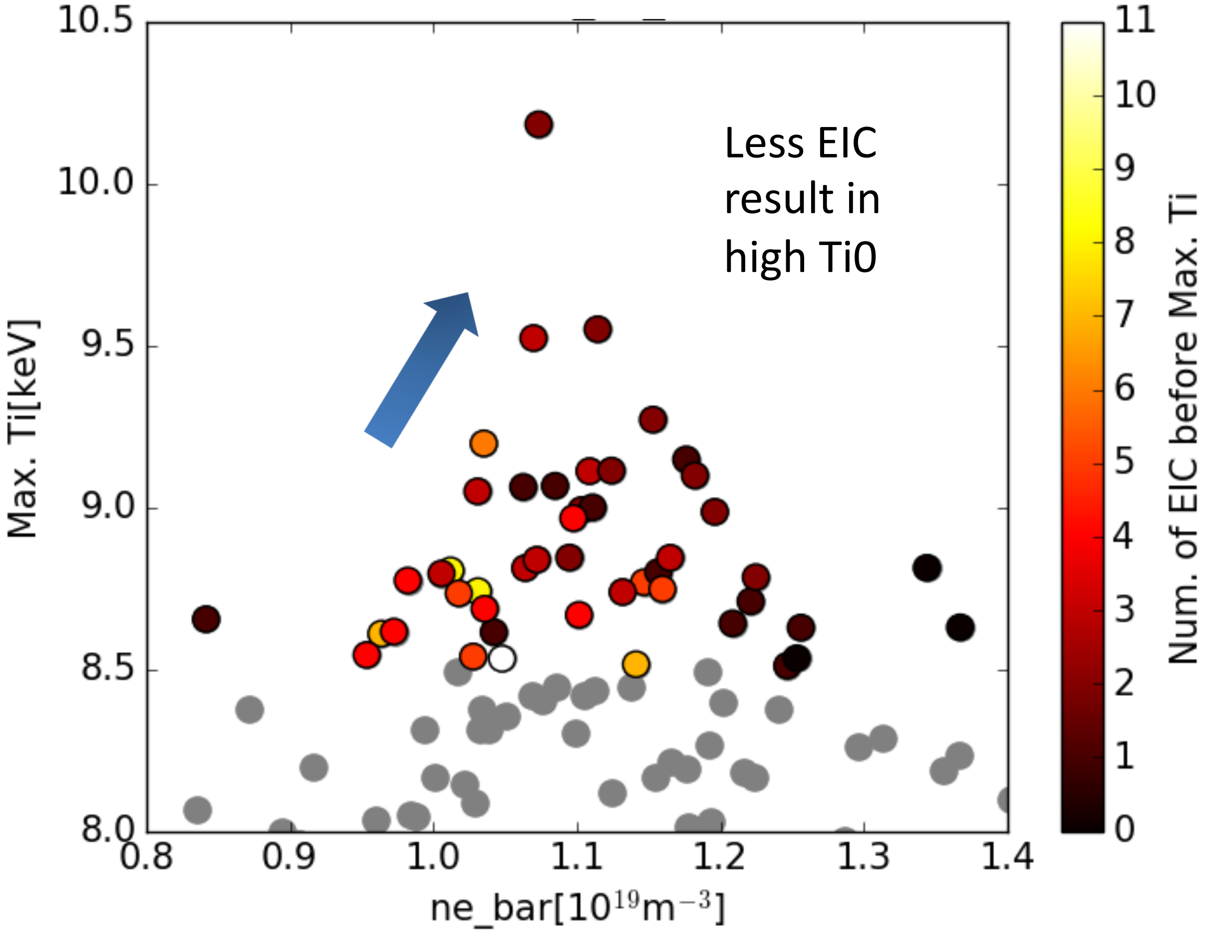
Profile with and without RMP





- Bulk pressure profile is almost identical with RMP and without RMP.

High central ion temperature with less EIC events



- The effect on the core plasma has not been fully understood since only the energetic particles in the edge region are affected by the EIC. However, In order to achieve high central temperature, reduction of the EIC is needed. ⇒ Control of the EIC is required.