External Control of Energetic-ion-driven MHD instabilities by ECH/ECCD in Heliotron J Plasmas

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Introduction

- ✓ Since redistribution and exhaust of alpha particles caused by energetic-ion-driven MHD instabilities lead to the reduction of fusion gain and damage of first wall, the methods to control the MHD instabilities are required, but they have not been established yet.

- ✓ ECH/ECCD are an ideal tool to control the MHD instabilities because they can provide highly localized ECH power/EC current with a known location and good controllability. e.g. mitigation of NTM by ECCD.

- ✓ The effect of ECH/ECCD on the MHD instabilities was experimentally found in some tokamaks and helical plasmas [1~4].

- ✓ In our study, we focus on the effect of continuum damping, which is related to the magnetic shear, in order to control the energetic-ion-driven MHD instabilities.

  ⇐ Heliotron J has weak magnetic shear and can vary it with the EC-driven plasma current.

[1] M.A. Van Zeeland, PPCF **50** (2008)
[2] M.A. Van Zeeland, NF **49** (2009)
[3] K. Nagasaki, NF **53** (2013)
[4] K. Nagaoka, NF **53** (2013)

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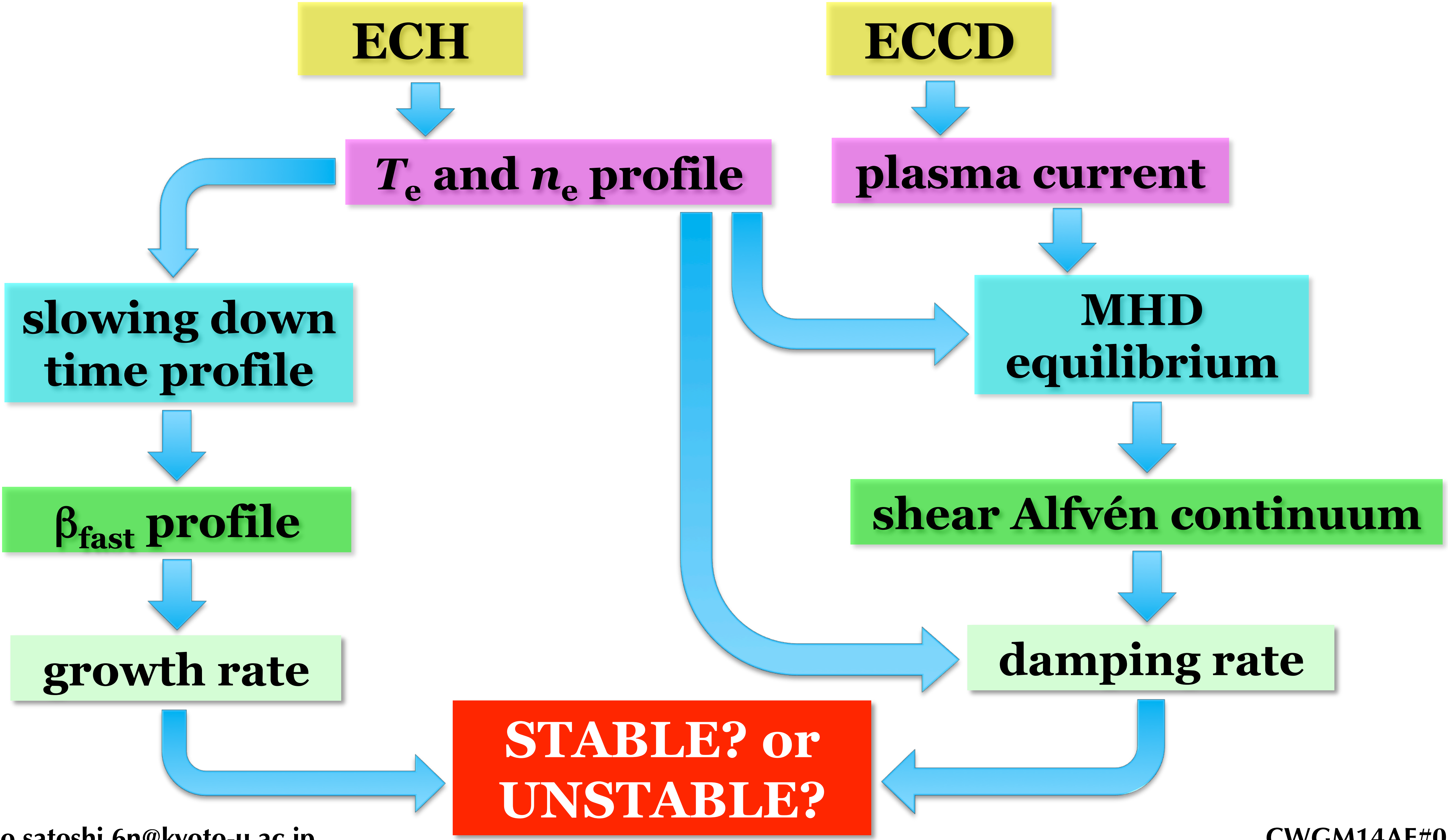
Effect of ECH/ECCD on AE

✓ ECH/ECCD affect T_e, n_e, and plasma current profile …



ECH

ECCD

T_e and n_e profile

plasma current

slowing down time profile

MHD equilibrium

β_{fast} profile

shear Alfvén continuum

growth rate

damping rate

STABLE? or UNSTABLE?

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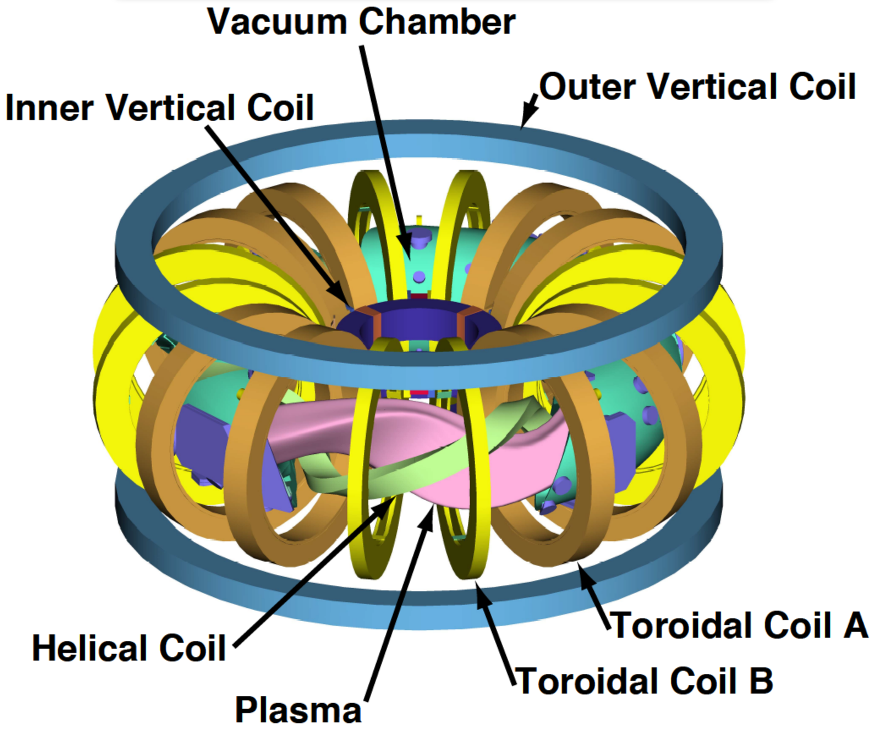
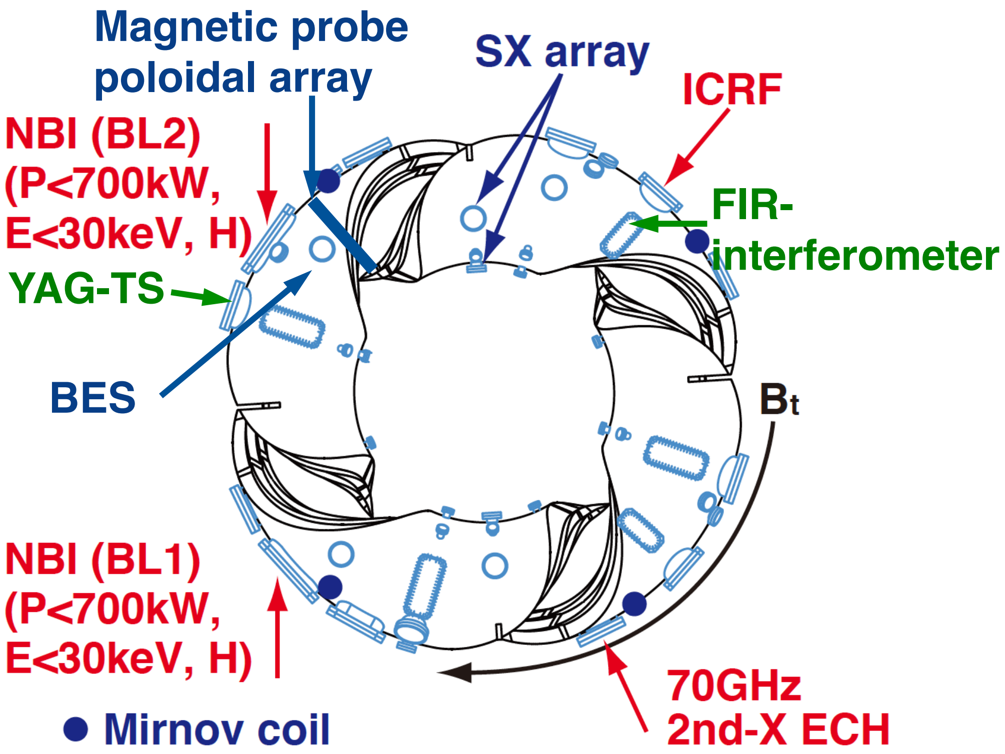
Heliotron J Device

Heliotron J





Device and Plasma Parameters

Coils for magnetic configuration	• Single helical coil ($l = 1$) • Two kinds of toroidal coils • Inner vertical coil • Outer vertical coil
Major radius R (m)	1.2
Minor radius a (m)	< 0.25
Magnetic field B (T)	< 1.5, operated at 1.25
Toroidal period N_p	4
ECH Power P_{ECH} (kW)	< 500
NBI Power P_{NBI} (kW)	< 700 x 2 (co. and ctr.)
NBI Energy E_{NBI} (keV)	< 30 [H]
Working gas	D
Rotational transform	0.4 ~ 0.7

Diagnostics for fluctuation study	
Magnetic probe array (B_r, B_θ)	Toroidal. 4ch / Poloidal. 14ch
Soft X-ray diode array	60ch for computer tomography
Beam Emission Spectroscopy	16ch in radial direction
Reflectometer (under develop.)	O-mode

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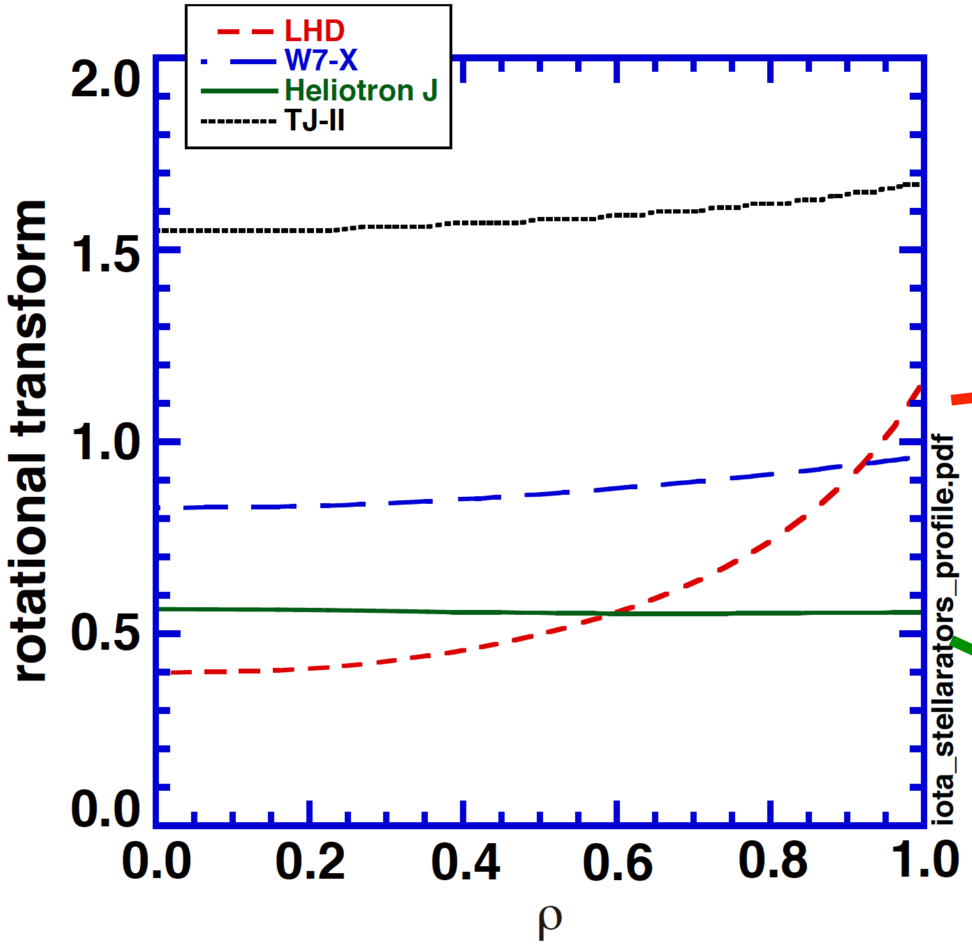
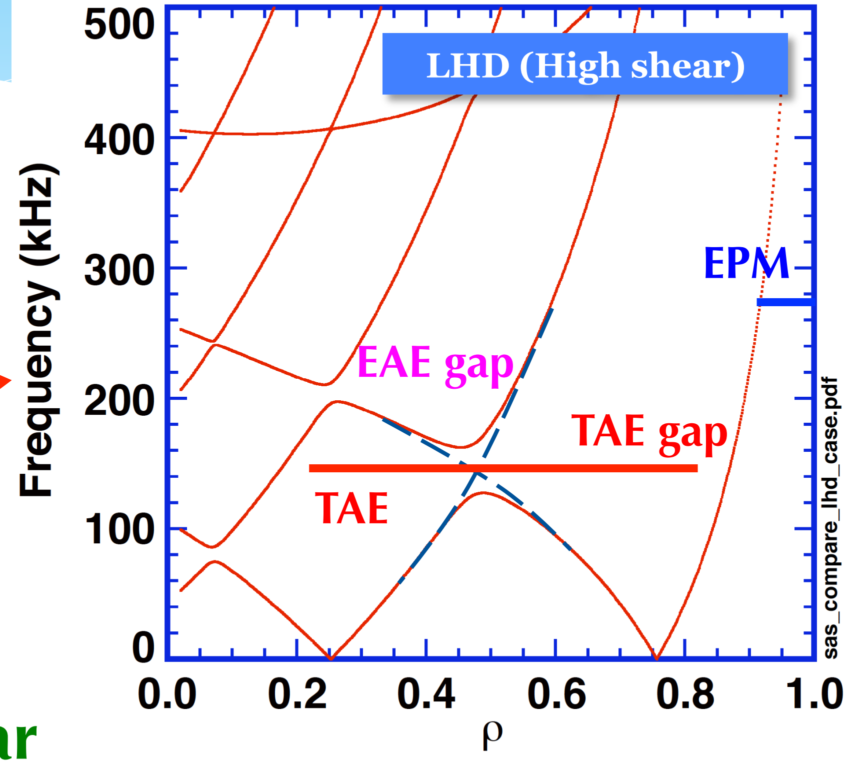
Shear Alfvén Continua of Helical Plasmas

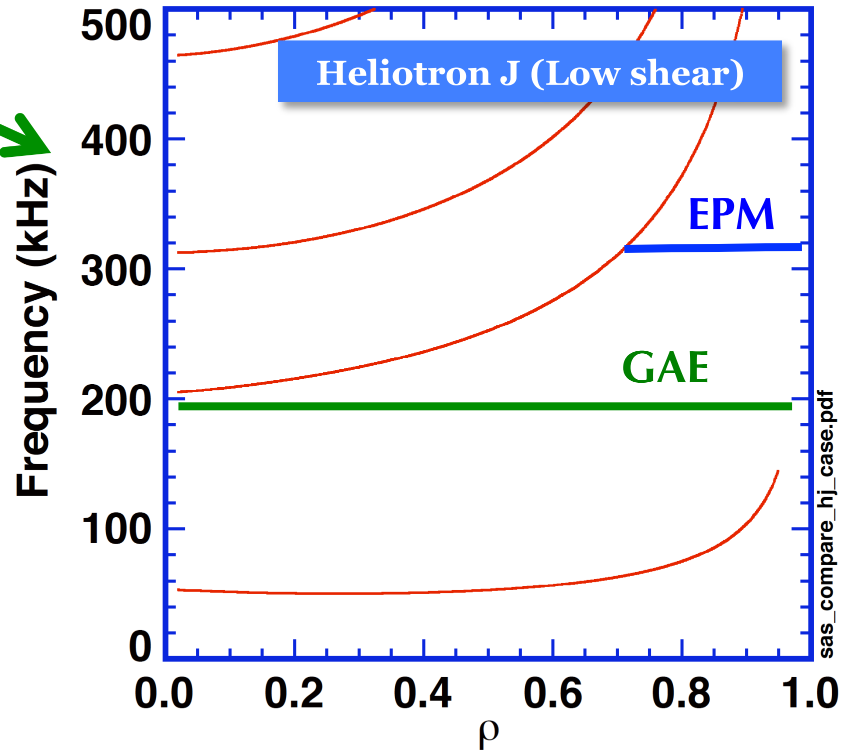
Profile of rotational transform (iota)



High shear



Low shear



- ✓ In **low magnetic shear** configuration, **Global AE (GAE)** can lie below and/or above the continuum instead of TAE with low-m/n.
- ✓ **Energetic particle mode (EPM)** which is a kinetic MHD instability, is observed in low-density plasmas of both Heliotron J and LHD.

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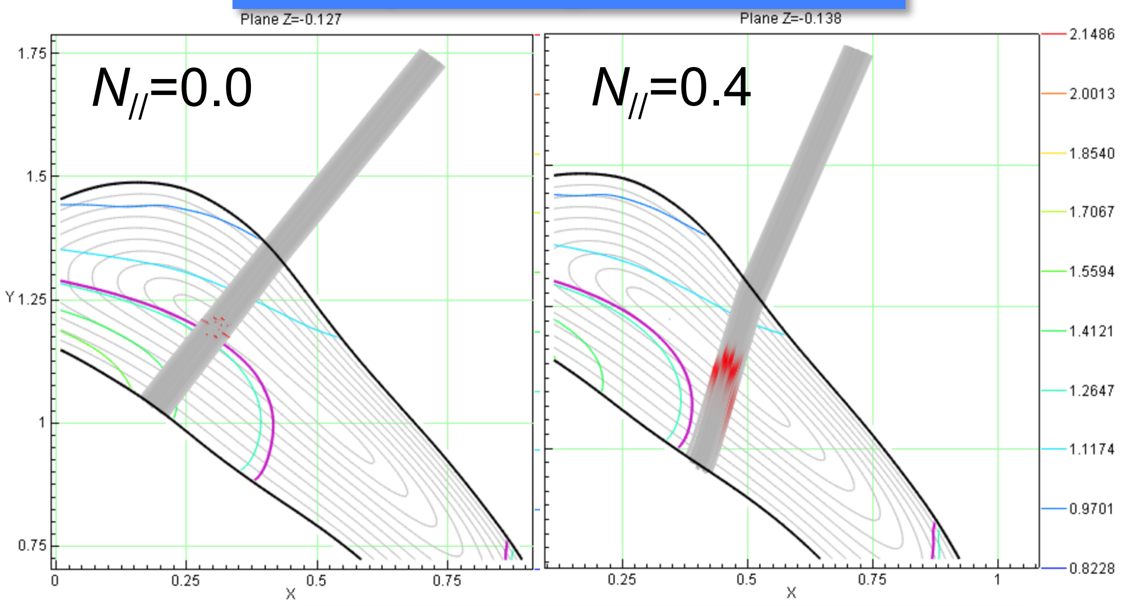
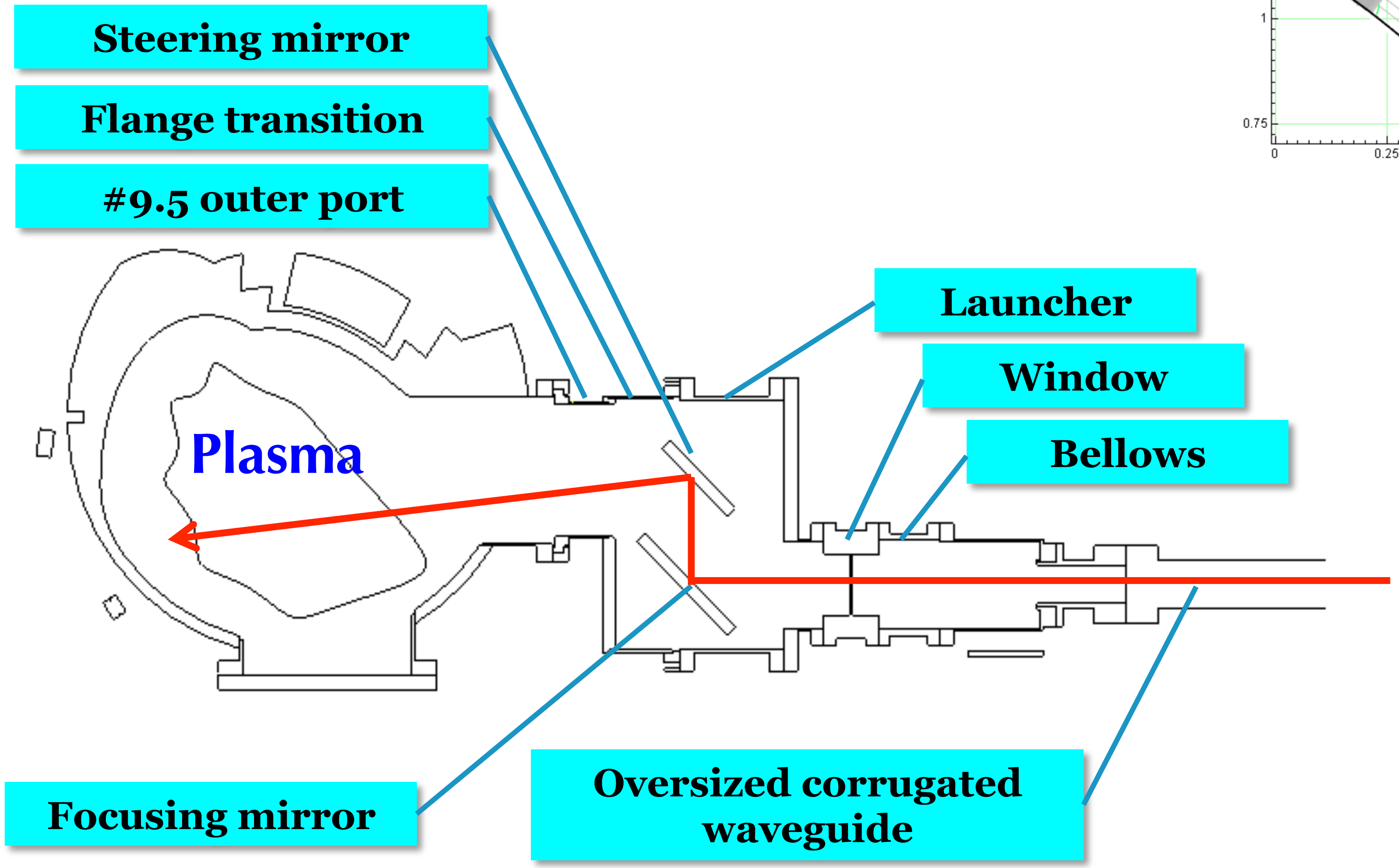
ECH/ECCD system on Heliotron J

[1] K. Nagasaki, NF **50** (2010)
[2] N.B. Marushchenko, PFR **2** (2007)

- ✓ Focused Gaussian beam : w = 30 mm
- ✓ $|N_{//}| < 0.6$
- ✓ Available to inject along magnetic axis
- ✓ Ray tracing code TRAVIS[2] can predict EC driven plasma current

Ray tracing (TRAVIS)





Steering mirror

Flange transition

#9.5 outer port

Plasma

Launcher

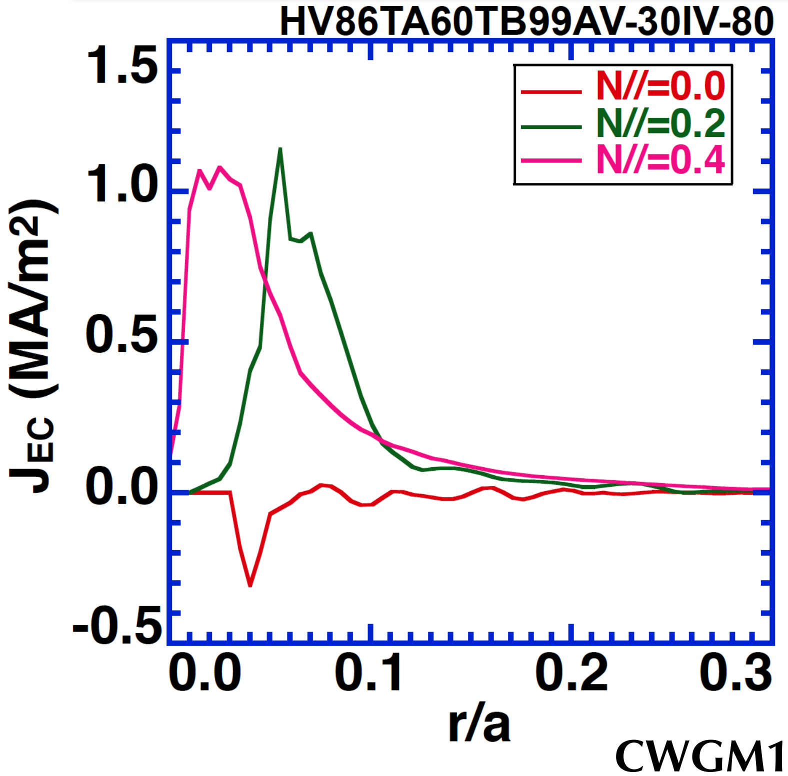
Window

Bellows

Focusing mirror

Oversized corrugated waveguide

Profile of EC driven current



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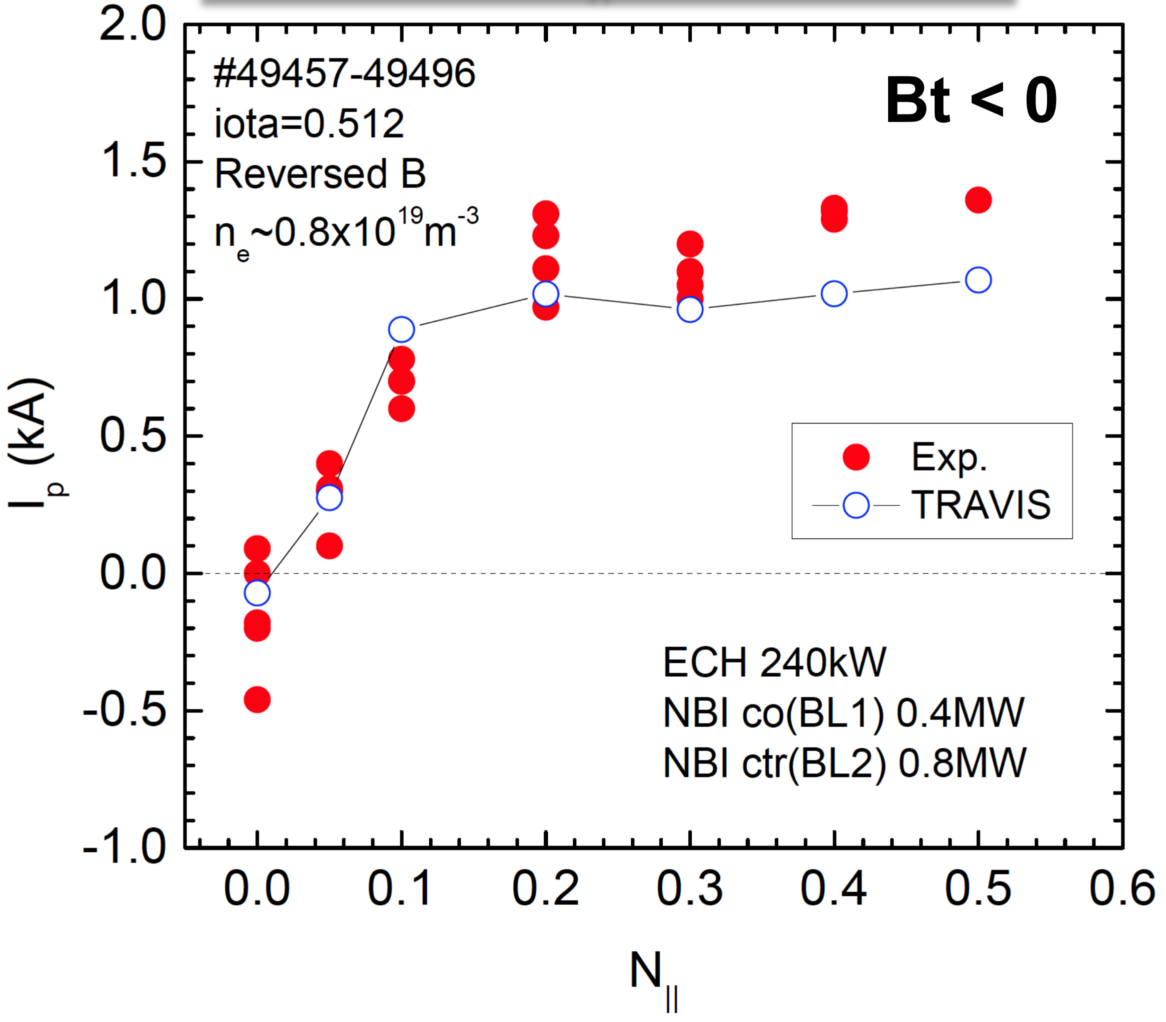
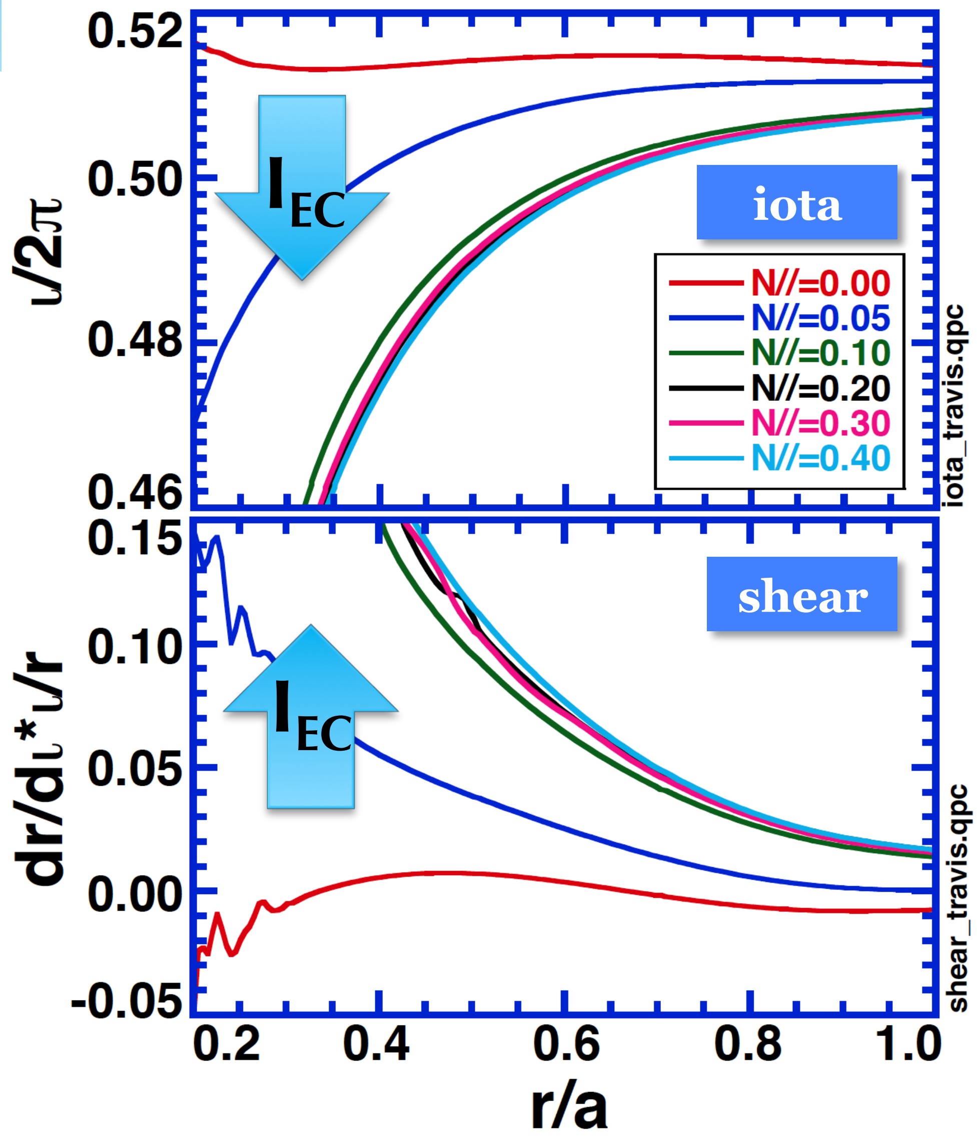
Plasma Current Control by ECCD

Scan of $N_{//}$ for ECCD



TRAVIS



- ✓ Plasma current can be **controlled by the ECCD** due to the change of parallel refractive index $N_{//} = 0.0 \sim 0.6$.
- ✓ Plasma current is composed of **BS (<0) and NBCD (bal.) and ECCD (>0)**.
- ✓ Produced ctr. current ($I_p > 0$, $B_t < 0$) **decreases the iota and induces shear.**

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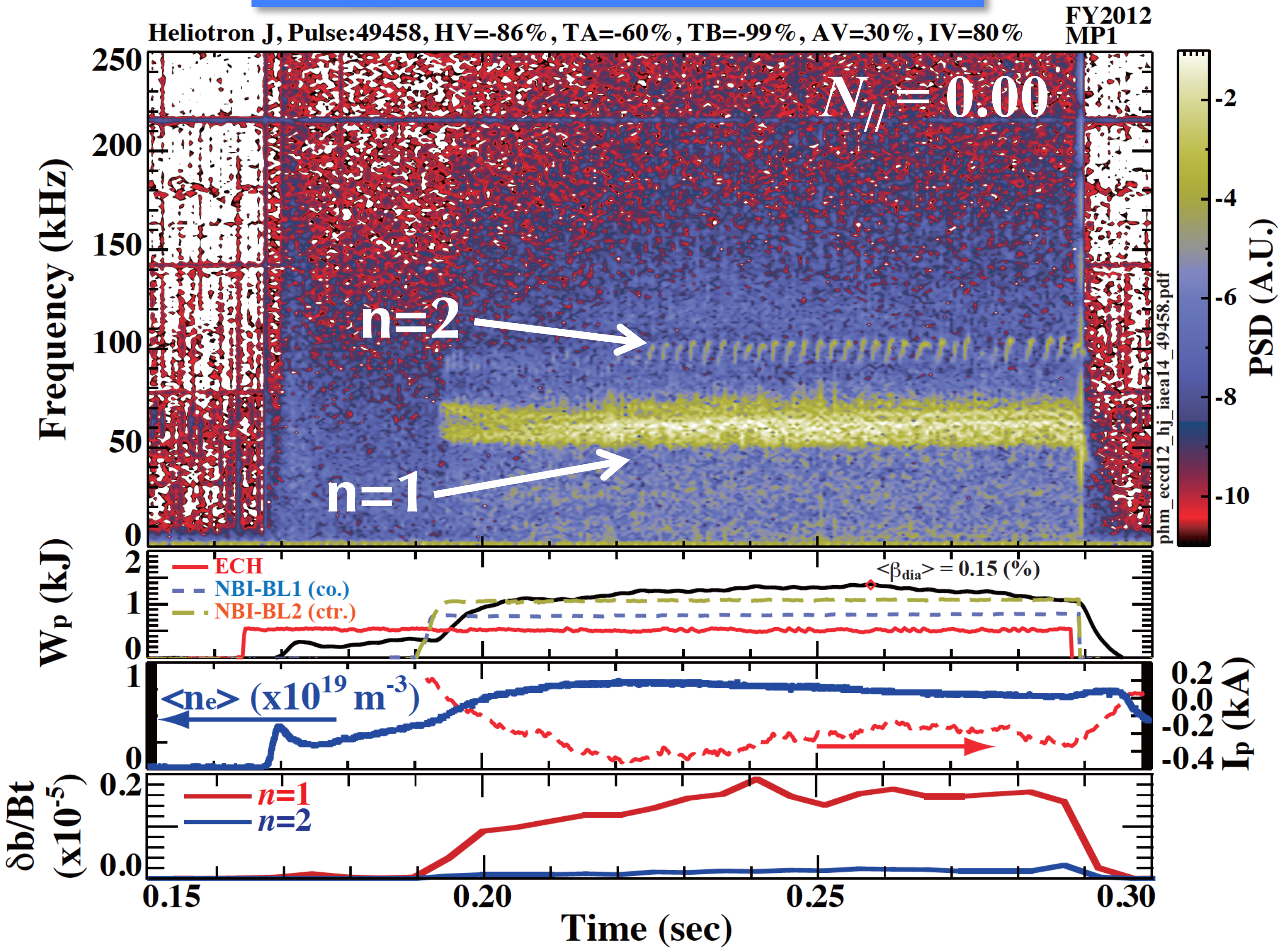
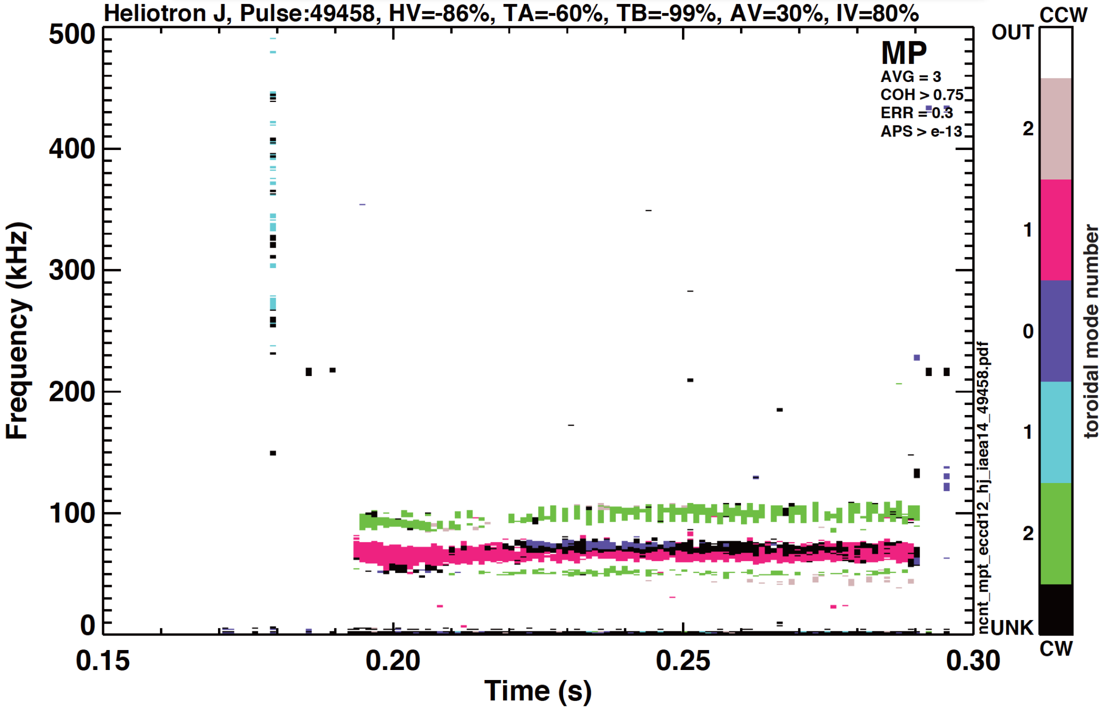
Observation of EPMs

Typical observation of EPMs



Toroidal mode number



- ✓ In NBI-heated Heliotron J plasmas, **energetic-ion-driven MHD instabilities including GAEs and EPMs are usually observed.**
- ✓ Especially, in low-density plasmas, **EPMs are observed with low-*m*/*n*.** e.g. *m*~2/*n*=1, *m*~4/*n*=2.
- ✓ EPMs are destabilized by both co- and counter-going passing ions.

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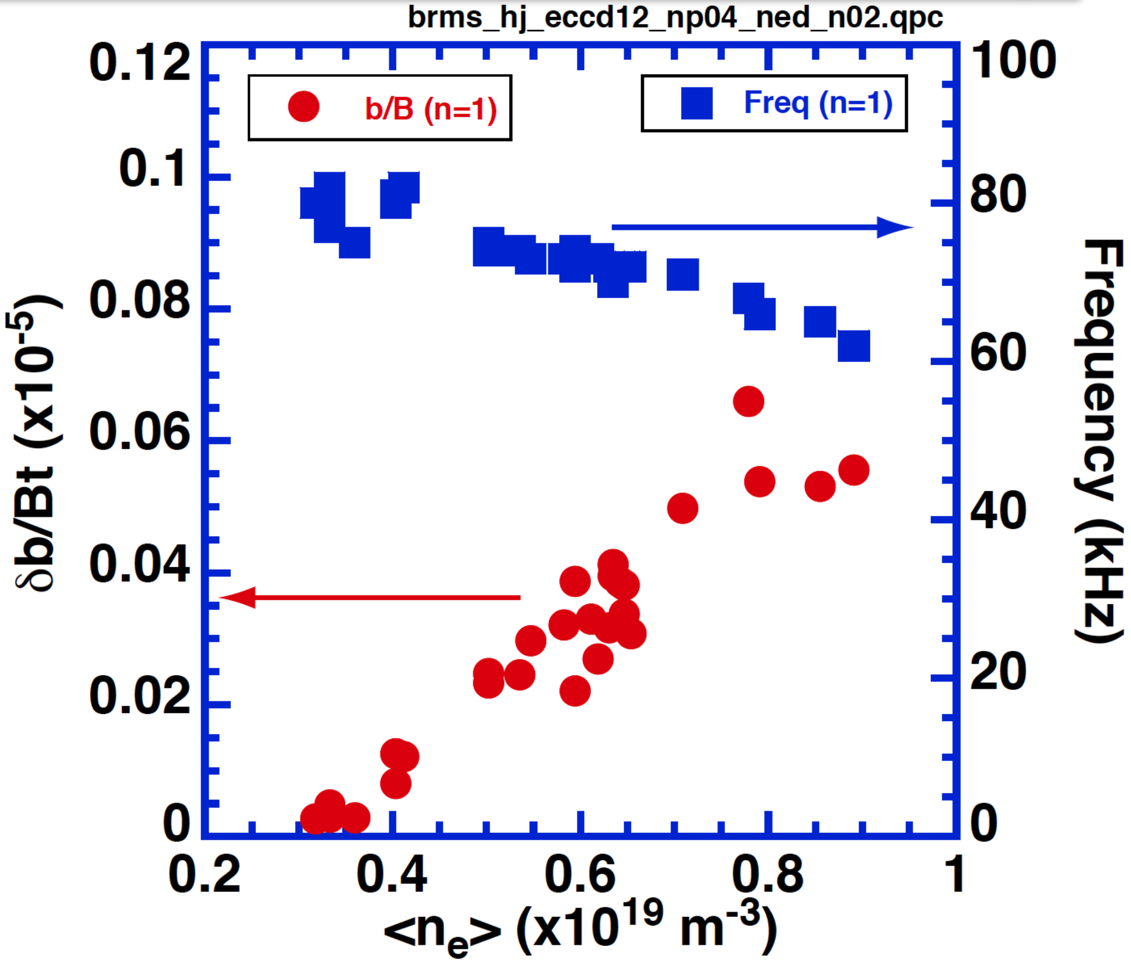
Characteristics of EPMs

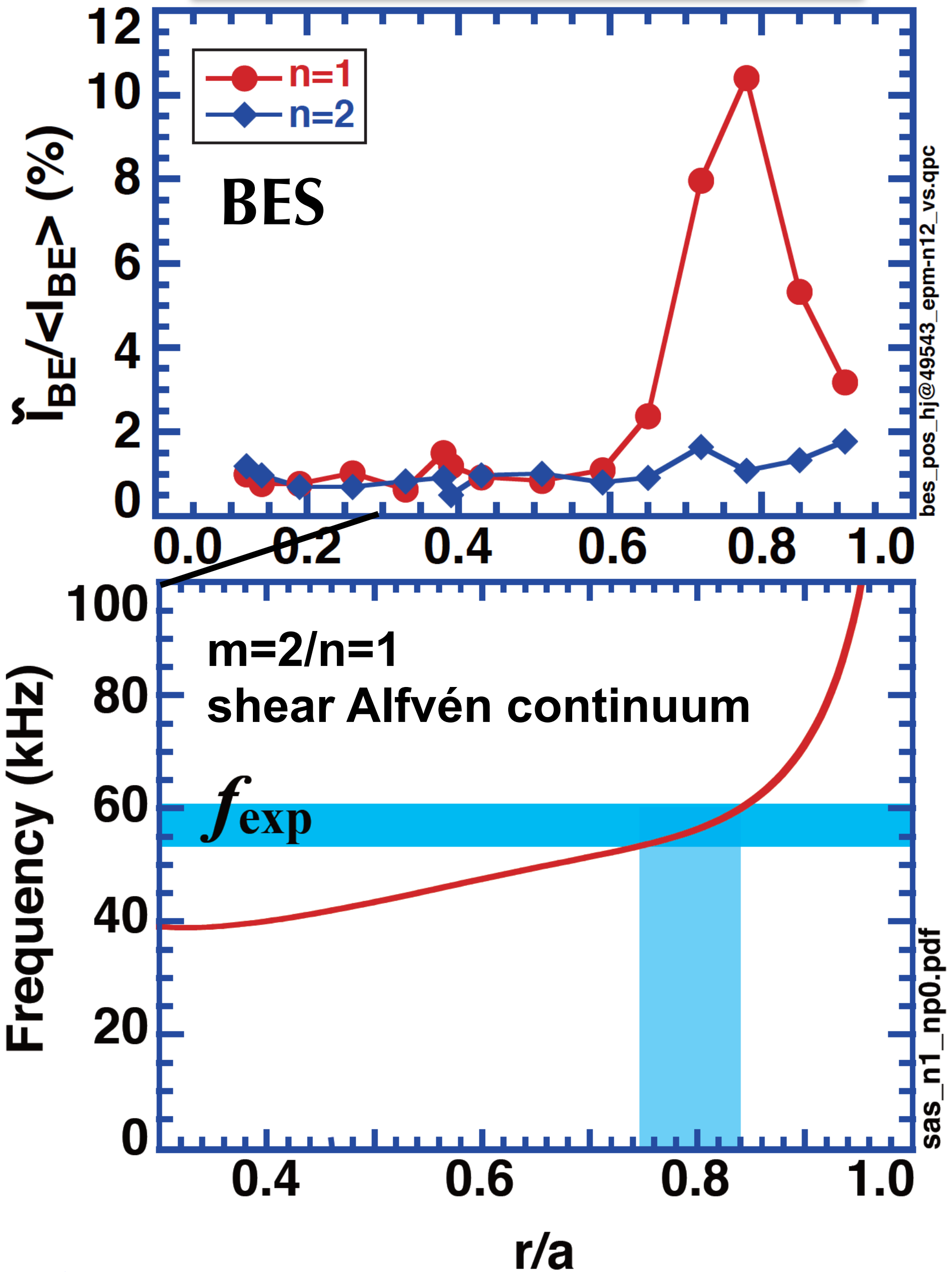
Dependence of amplitude, frequency on n_e



- ✓ Observed frequency is **not proportional to Alfven velocity** v_A.
  ➔ Not AE.
- ✓ Observed frequency of EPM is generally consistent with theoretically predicted EPM frequency ω for passing ions.

$$\omega = (k_{//} \pm 1/qR)v_{//}$$

Radial structure of mode



- ✓ Peak position corresponds to intersection point between continua and mode frequency ω

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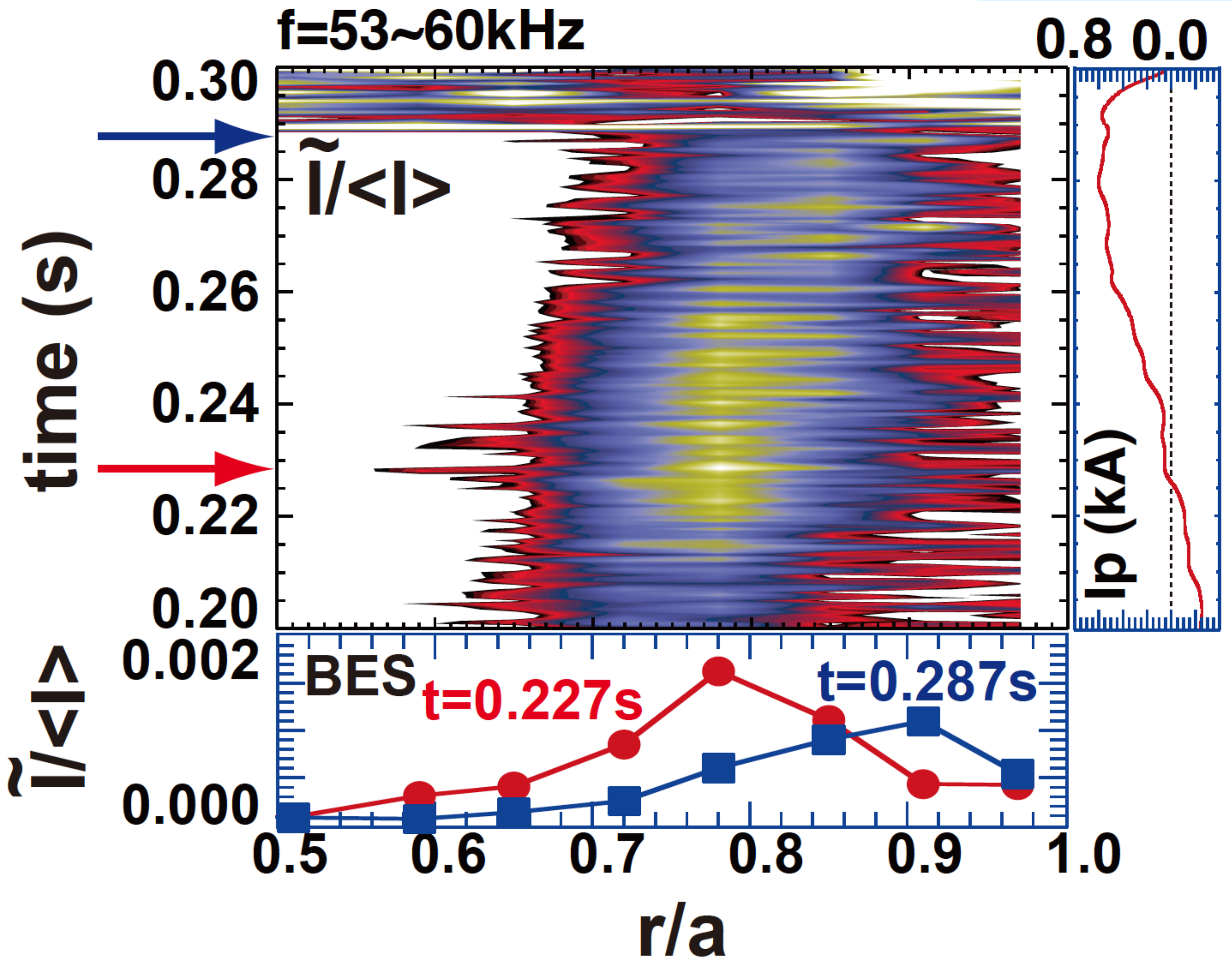
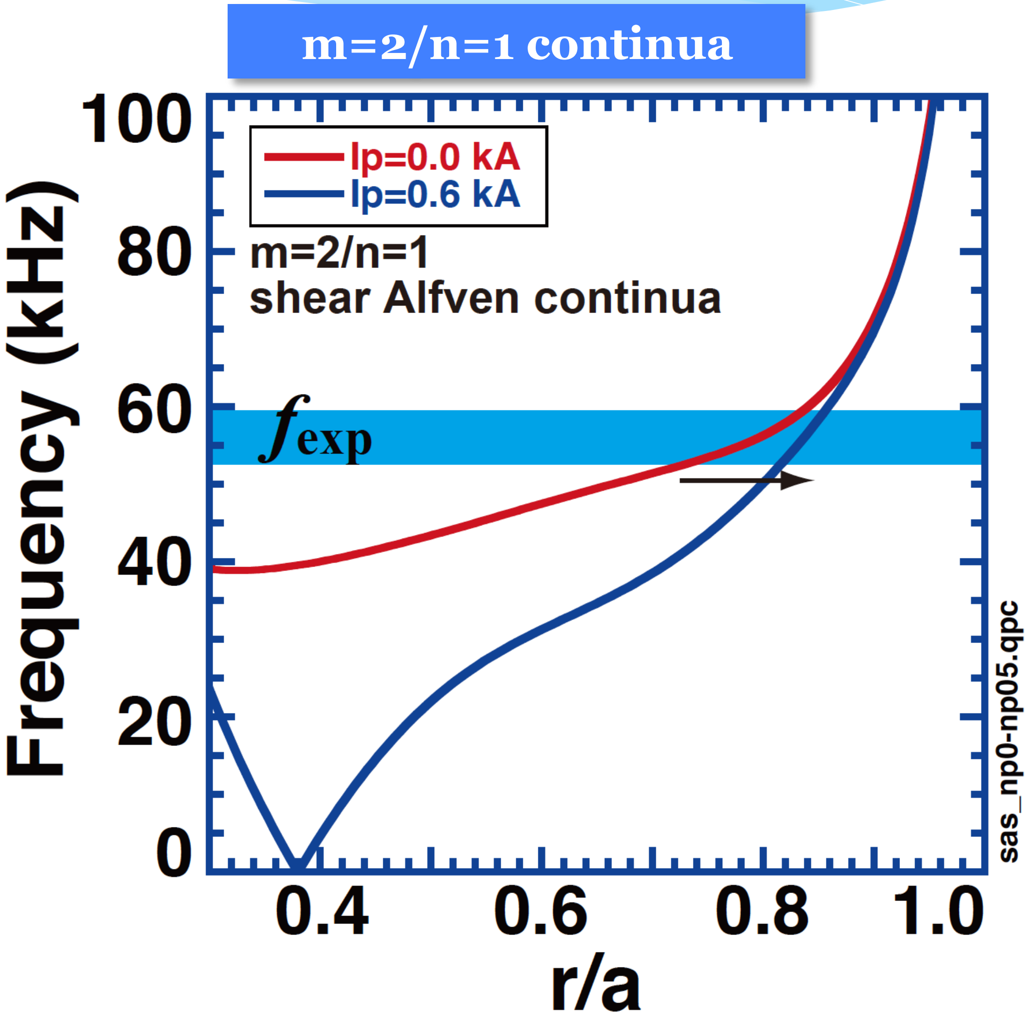
Movement of EPM due to EC Driven Current




m=2/n=1 continua

- ✓ **Outward movement of EPM** with n=1 during the ramp-up phase of plasma current is observed in BES measurements $(\tilde{n}_e/\langle n_e \rangle)$.
- ✓ The movement can be explained by **the change of shear Alfvén continuum** due to the increase of plasma current (change of MHD equilibrium).

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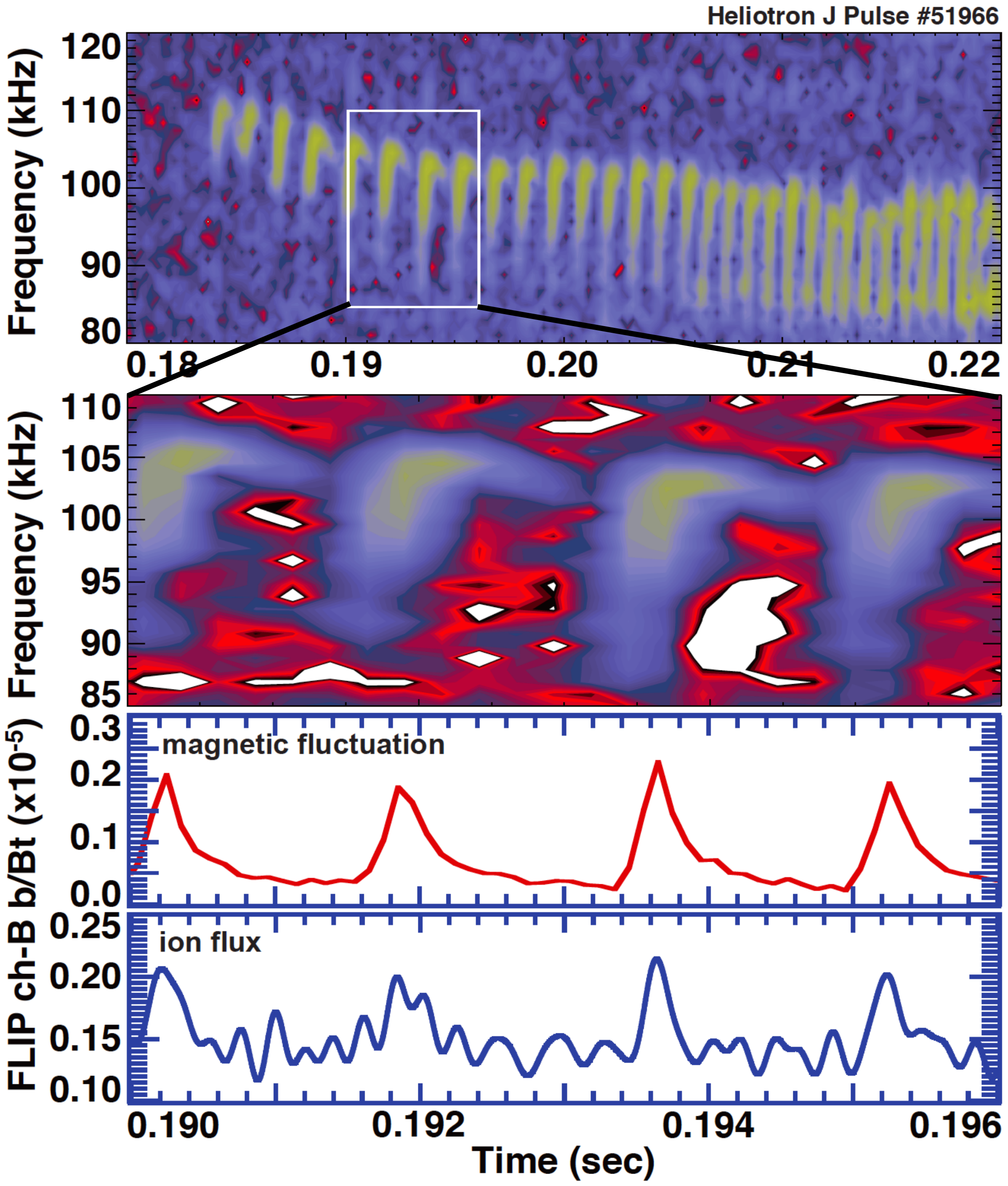
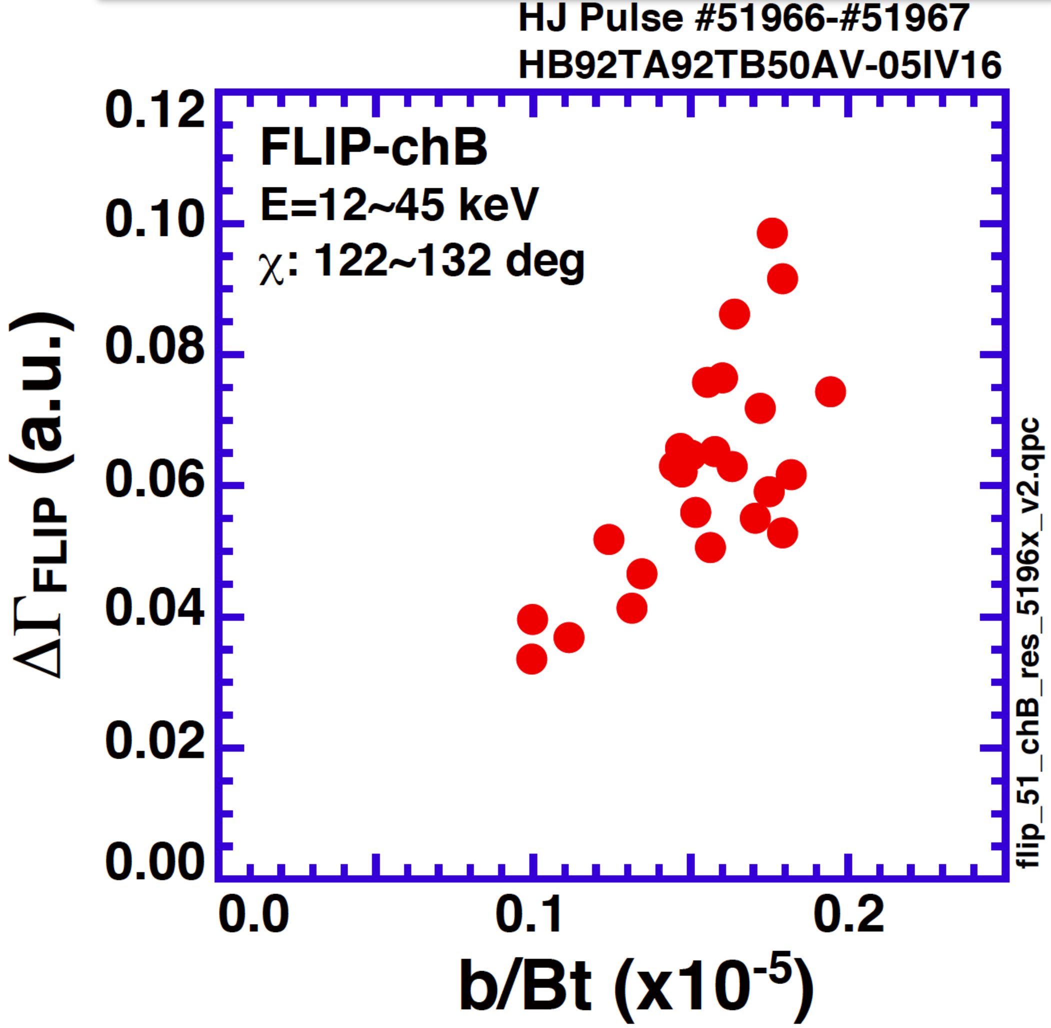
Observation of energetic ion loss caused by EPMs

- ✓ Bursting EPMs having intense magnetic fluctuation enhance the transport and/or induce loss of the energetic ions in Heliotron J plasmas.



Dependence of lost ion flux on EPM



- ✓ FLIP: Faraday-cup-type lost ion probe
- ✓ Amount of lost ion flux is related to the amplitude of bursting EPM.

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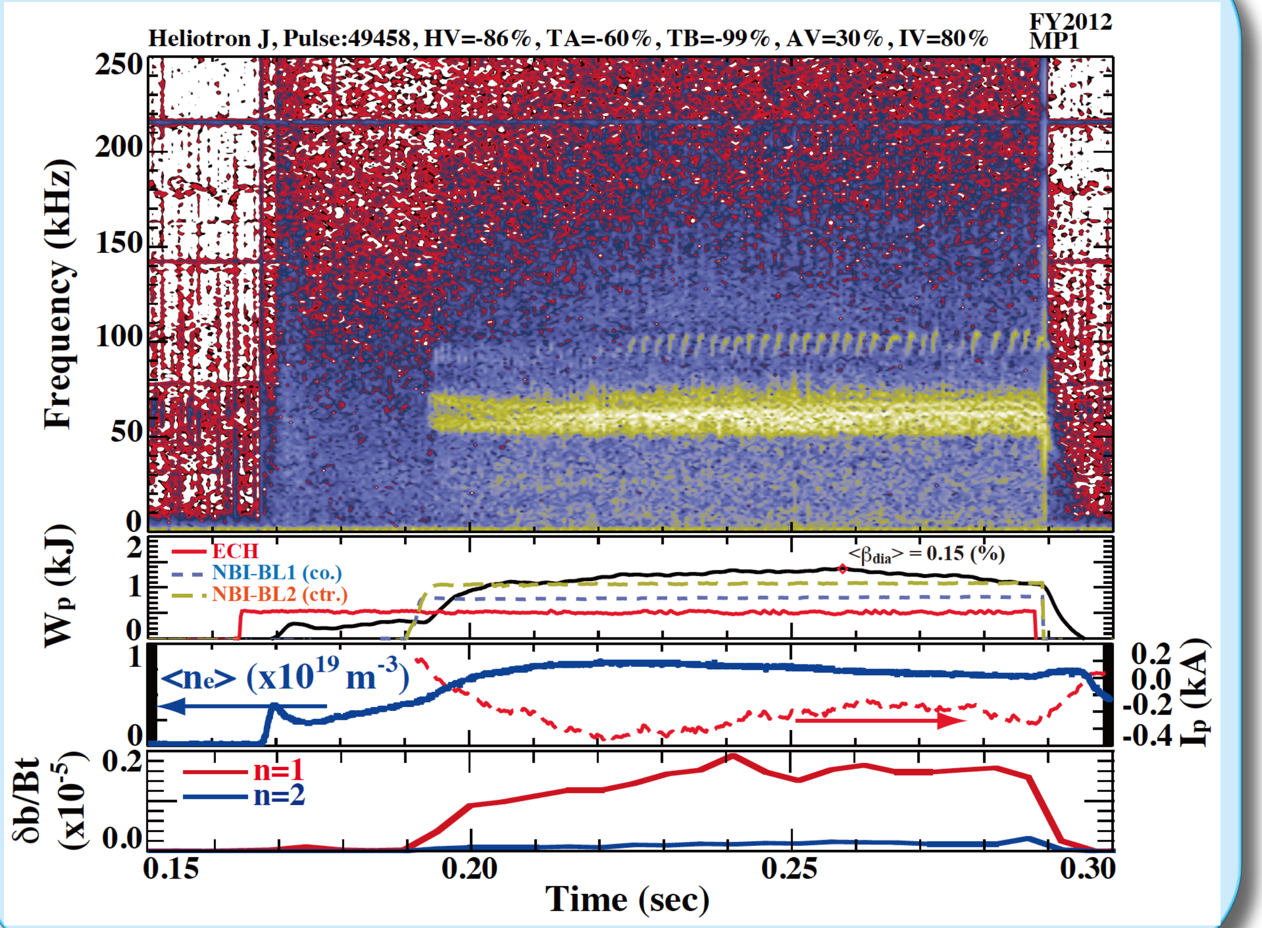
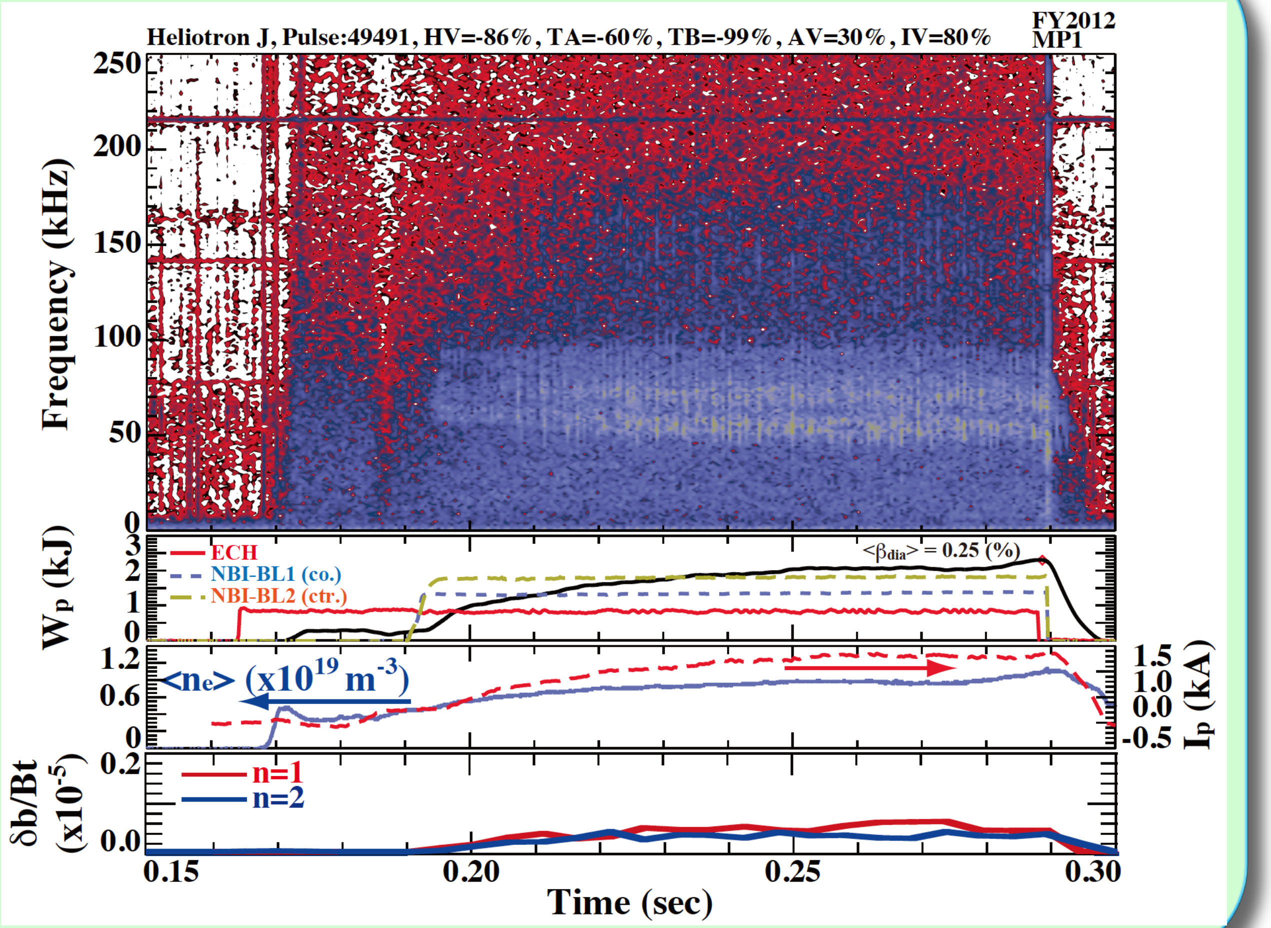
EC Current Mitigates EPMs

$N_{//}$=0.0 (Non ECCD)



$N_{//}$=0.4 (Ctr. current)



- ✓ In the case of $N_{//}$=0.0 corresponding to the non-ECCD, EPMs with n=1 and 2 are excited.
- ✓ The amplitude of EPMs are obviously reduced by ECCD.
- ✓ In the case of lower density($\sim 0.4\mathrm{x}10^{19}\mathrm{m}^{-3}$), EPM is fully stabilized by ECCD

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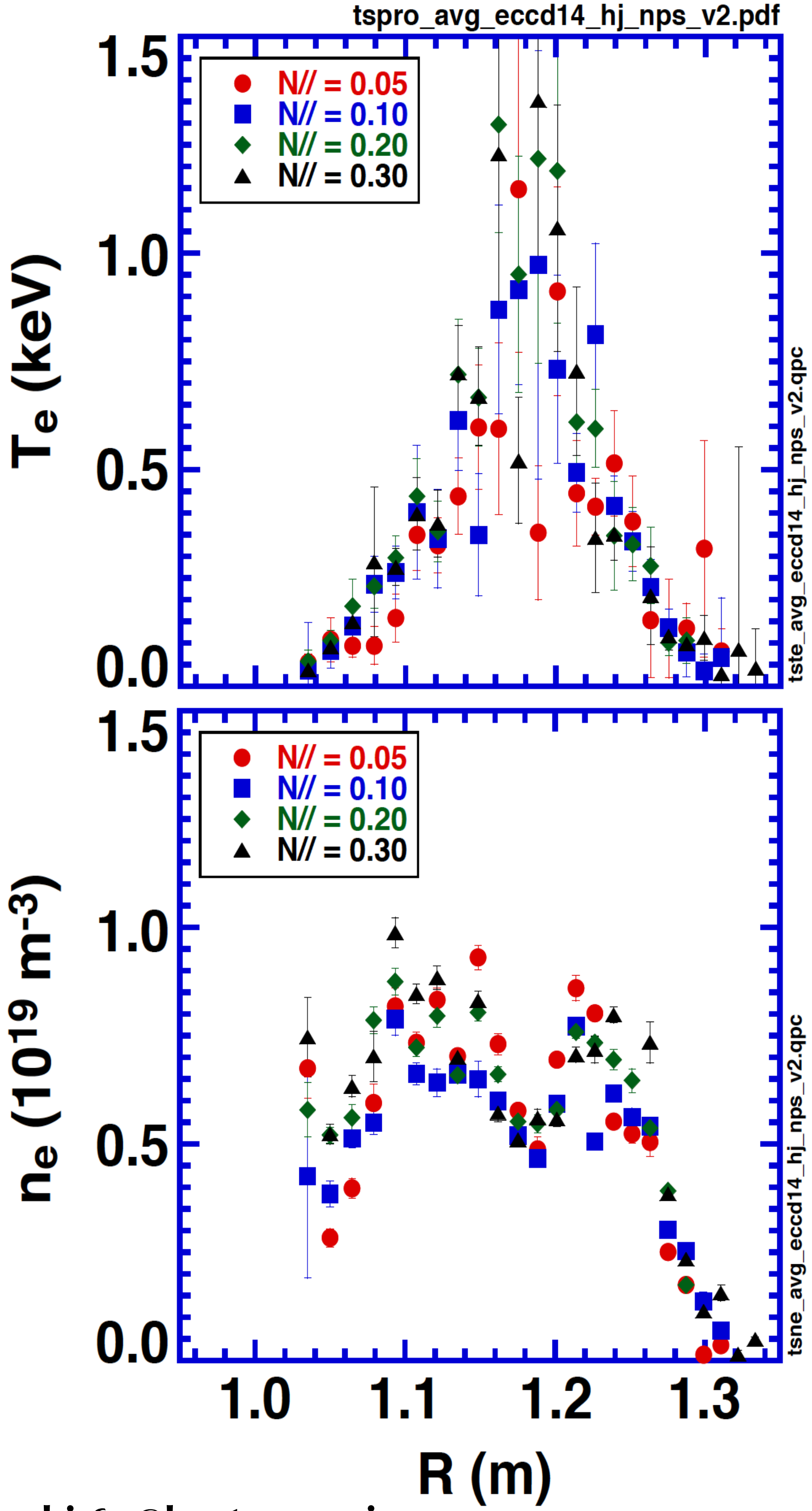
Electron temperature and density



- ✓ We basically fixed experimental conditions such as NBI power and electron density in the $N_{//}$ scan experiment.
- ✓ There are no difference of electron temperature and density at edge region in each condition of $N_{//}$.
- ✓ Electron Landau damping is not significant in these experiment.
- ✓ Main difference in each $N_{//}$ is plasma current induced by ECCD.

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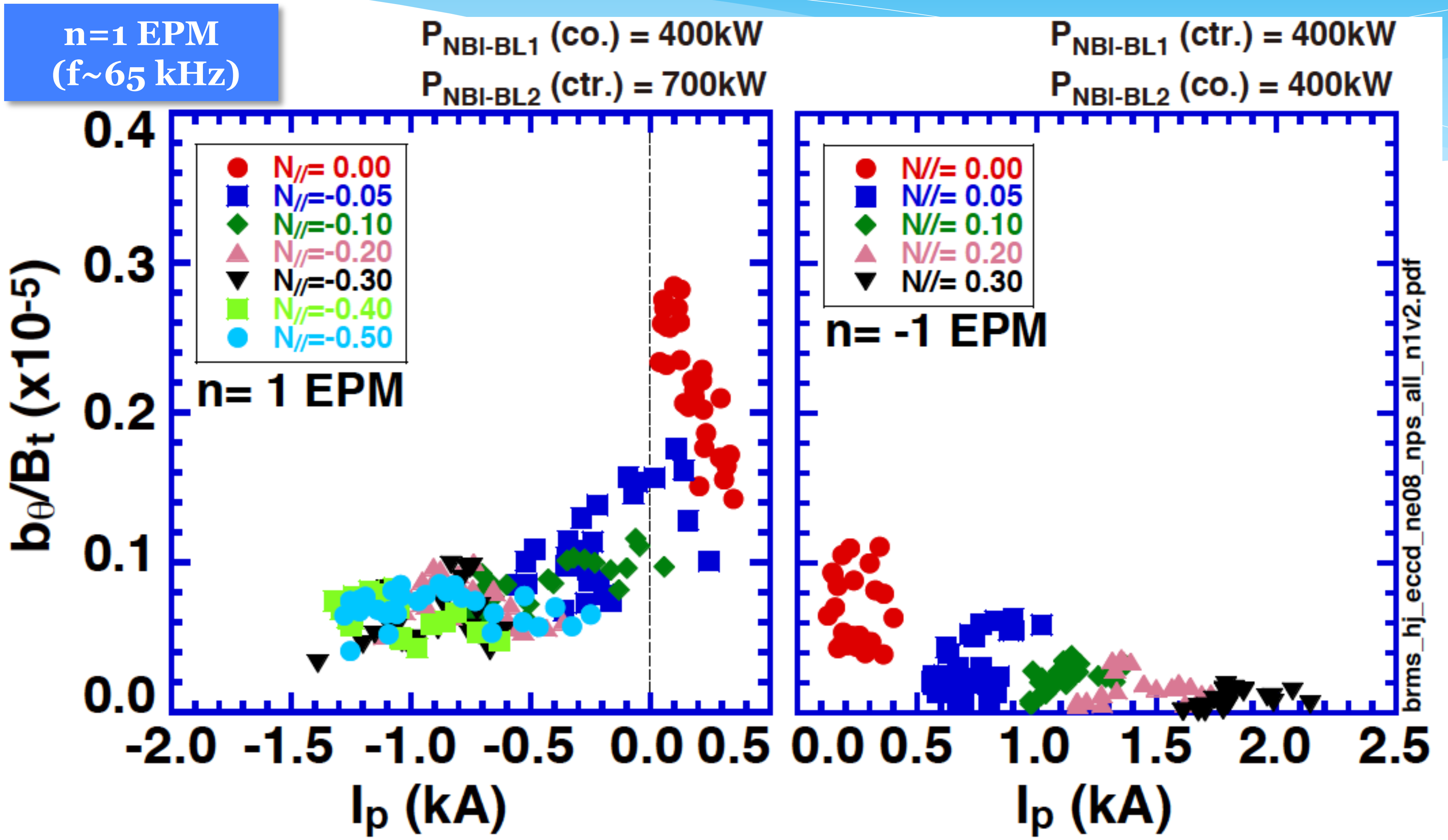
Dependence of Mode Amplitude on Ip, n=1



- ✓ Amplitude of n=1 EPMs obviously decreases with increasing |Ip|.
  ⇐ EC-driven plasma current enhances magnetic shear.
- ✓ EPMs will suffer from strong continuum damping whose rate is proportional to magnetic shear.
  ⇒ Increment of magnetic shear leads to the mitigation of EPMs with n=1.

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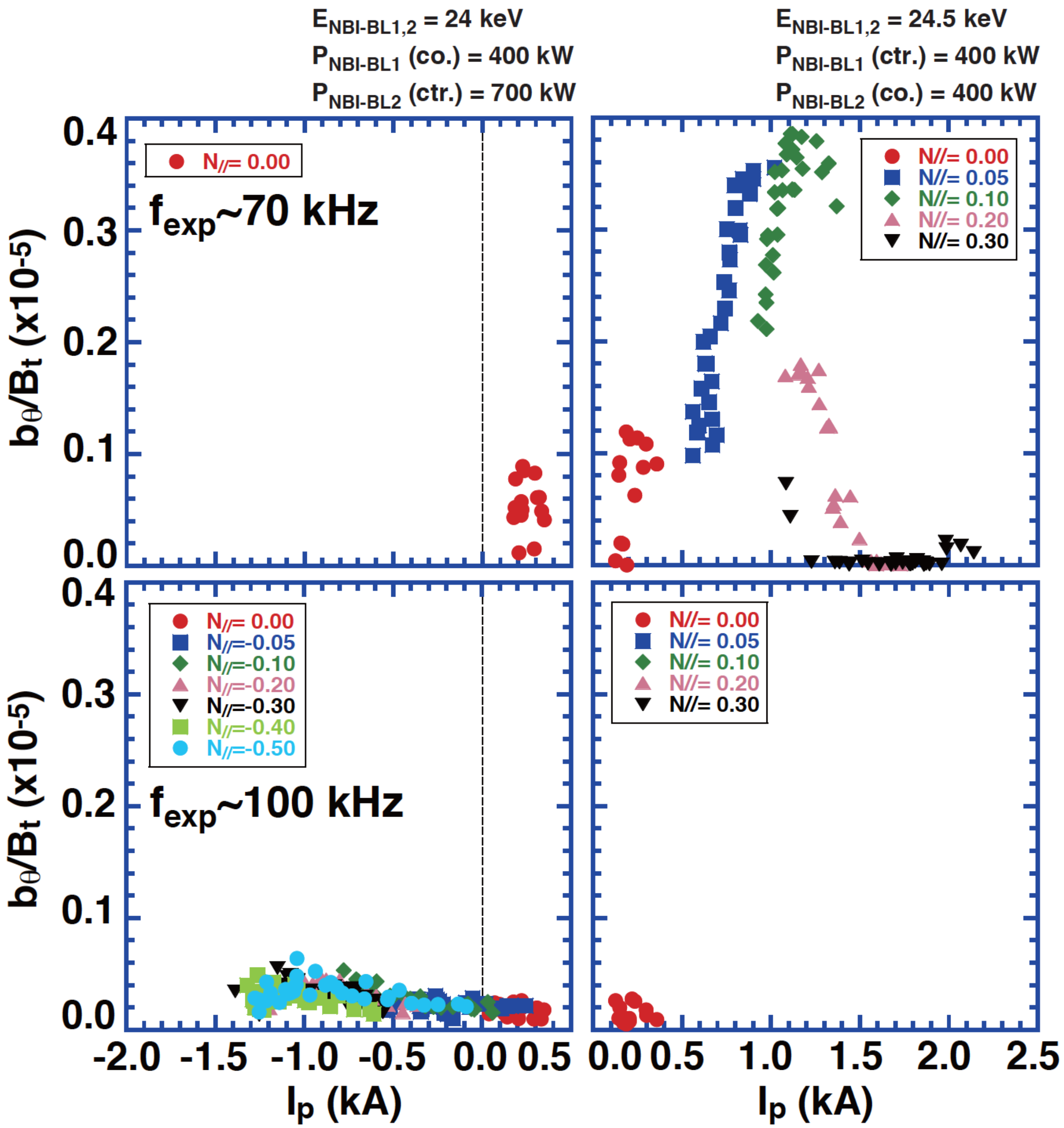
Dependence of Mode Amplitude on Ip, n=2



- ✓ We also observed two *n*=2 EPMs whose frequencies are *f*~70 and 100 kHz.
- ✓ The EPMs with *n*=2 and *f*~70 kHz are only observed in the plasma with $N_{//} > 0$.
- ✓ EPMs are stabilized at I_p < 0 and > 1.5 kA, although EPMs has a peak at I_p = 1.0 kA.
- ✓ Effect of magnetic shear on *n*=2 EPMs is different from *n*=1 EPMs

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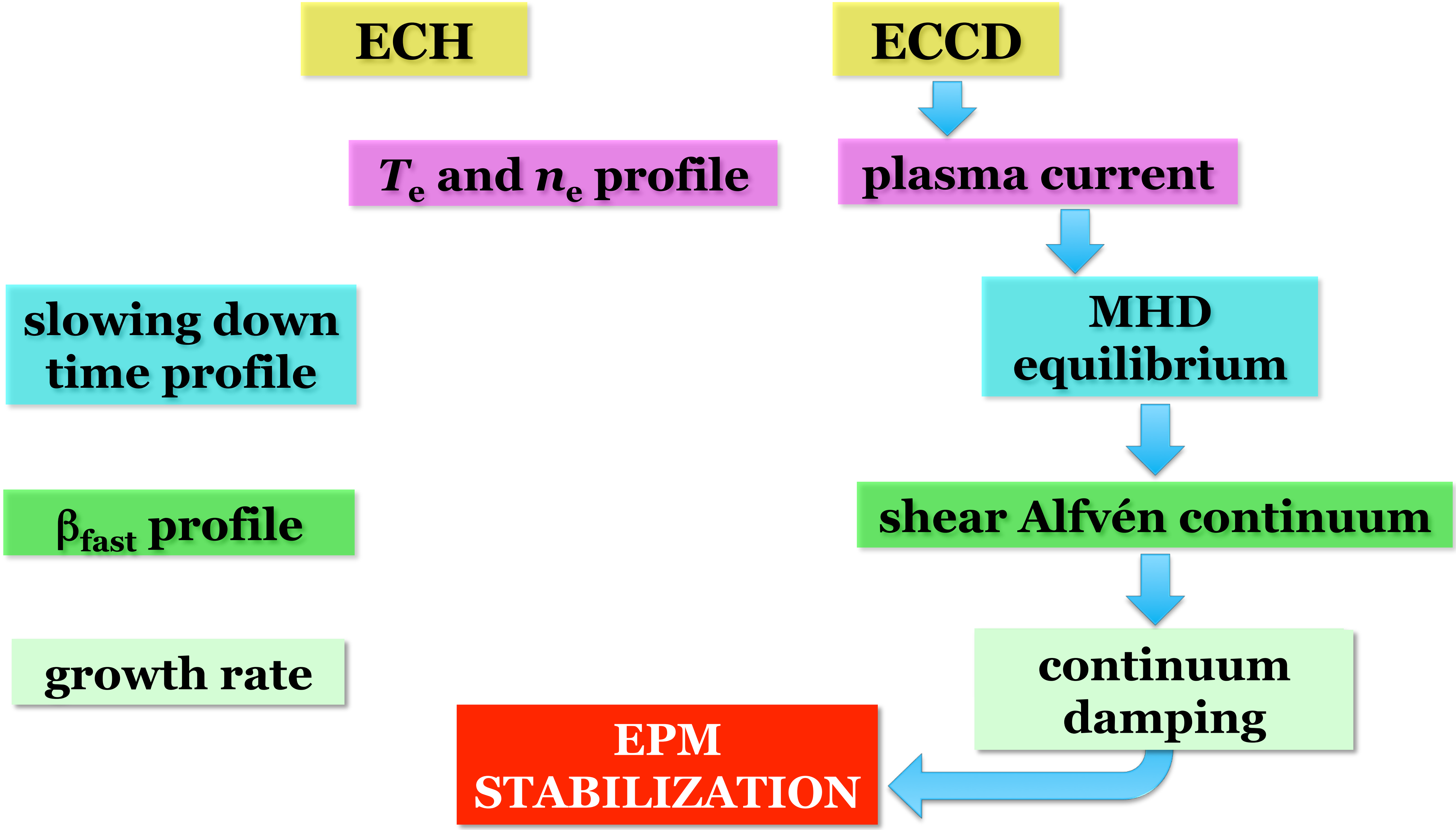
Stabilization of EPM by ECCD in Heliotron J

✓ EPM is mitigated by the change of magnetic shear due to ECCD where continuum damping is the main mechanism to stabilize it in Heliotron J.



ECH

ECCD

T_e and n_e profile

plasma current

slowing down time profile

MHD equilibrium

β_{fast} profile

shear Alfvén continuum

growth rate

continuum damping

EPM STABILIZATION

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Conclusion

- ✓ In order to control the observed EPMs in NBI-heated Heliotron J plasmas, we applied ECCD, which modified the rotational transform and magnetic shear.
- ✓ The continuum damping is an important factor, whose damping rate is related to the local magnetic shear at EPM position.
- ✓ We scanned $|N_{//}|$ from 0.0 to 0.4 and changed magnetic field for the purpose of scanning EC driven plasma current in the range of -2.0 to 2.5 kA.
- ✓ We successfully modified the magnetic shear s ranging from 0.06 to -0.08 at EPM position (r/a ~ 0.8) by EC driven plasma current and the resultant shear mitigated the observed EPMs by the increase in continuum damping rate.
- ✓ The mitigation of EPM amplitude is observed in both positive and negative shear.

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