SUPPRESSION OF THE ENERGETIC PARTICLE DRIVEN INTERCHANGE MODE IN THE LARGE HELICAL DEVICE

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S. Ohdachi[1], J. Varela[2], K. Y. Watanabe[1], H. Nakano[1,3], H. Takahashi[1,3], Y. Suzuki[1,3], Y. Narushima[1,3], T. Bando[3], X. D. Du[4], T. Morisaki[1], and the LHD Experiment Group[1]

National Institute for Fusion Science, Toki, Japan[1]

Universidad Carlos III de Madrid, 28911 Leganes, Madrid, Spain[2]

The Graduate University for Advanced Studies, SOKENDAI, Toki, Japan[3]

General Atomics, PO Box 85608, San Diego, CA 92186-5608, USA[4]

ohdachi.satoshi@nifs.ac.jp

Contents of my talk

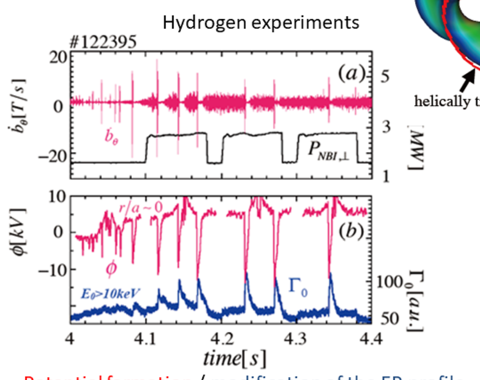
- A new type of the energetic particle driven MHD instability, EIC was found in LHD (X. D. Du, *et. al.*, Phys. Rev. Lett. **114** (2015), 155003) in the hydrogen plasma campaign.

1. The characteristics of the EIC in hydrogen/deuterium campaign.
   - Neutron emission rate is decrease by 50~60% by the excitation of EIC.
2. Excitation mechanism of EIC
   - Resonant of the MHD mode with the helically trapped particles motion is the key physics.
3. Suppression of the EIC
   1. ECH application (Resonant effects is reduced/Comparison with FAR3D)
   2. RMP application (Resistive interchange mode is stabilized?)

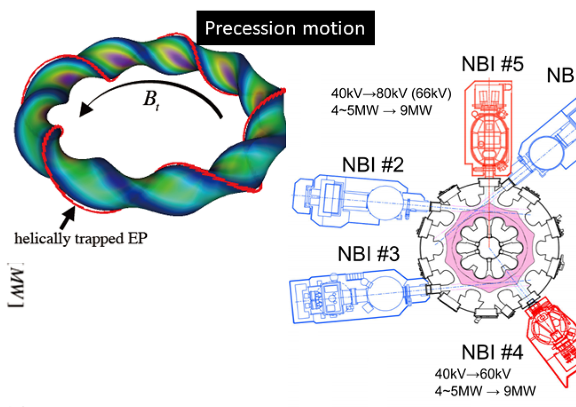
EIC in the hydrogen / deuterium campaign (1)

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)

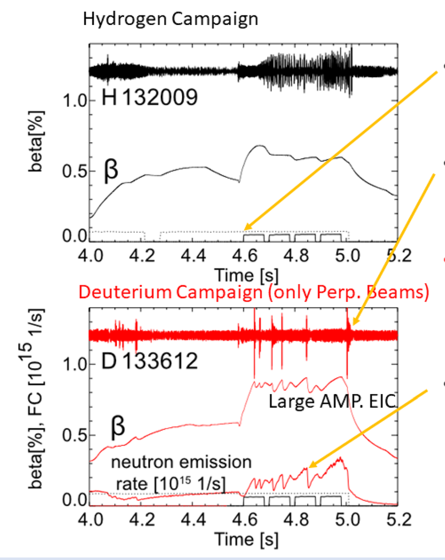


Potential formation / modification of the EP profile



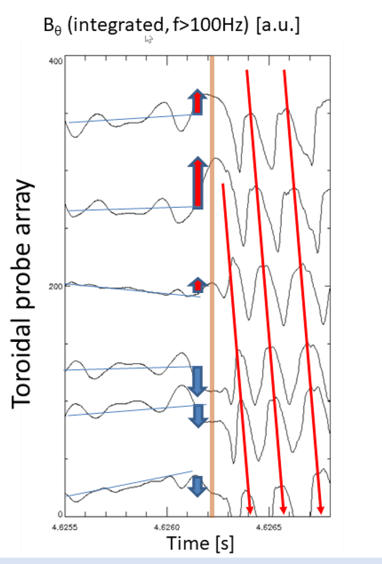
- It is noted that neutron emission rate is a good measure of the amount of the trapped particles, since the beam-plasma reaction is the dominant in LHD.

EIC in the hydrogen / deuterium campaign (2)

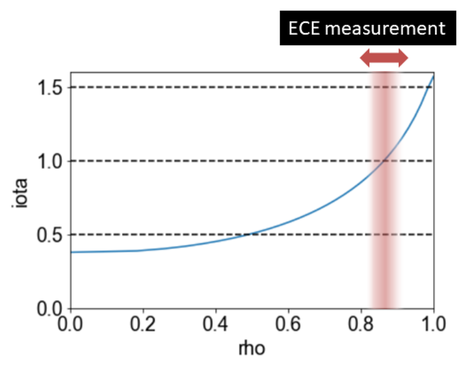


- EICs becomes unstable when the perpendicularly injected NBI power is increased.
- Bursts of MHD activities, less frequently activated, are observed in deuterium campaign.
- Impact of each EIC burst is larger, as seen in the time evolution of beta than that observed in hydrogen campaign.
- Total neutron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

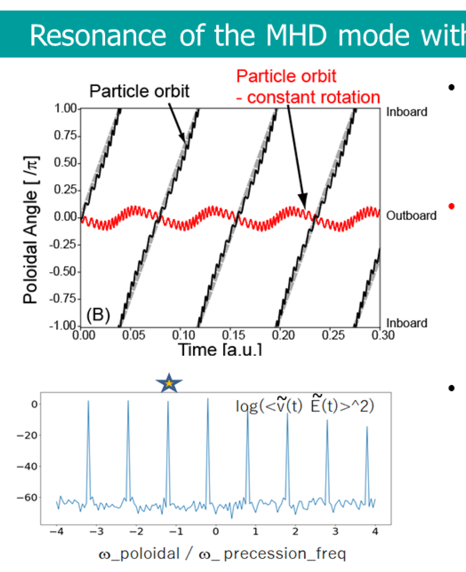
Onset of the EIC followed by the chirping down mode



- First, a large deformation with n = 1 occurs, and the m/n = 1/1 structure start rotating.
- The perturbation is quite localized on the iota = 1 rational surface (-> interchange mode).



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.)

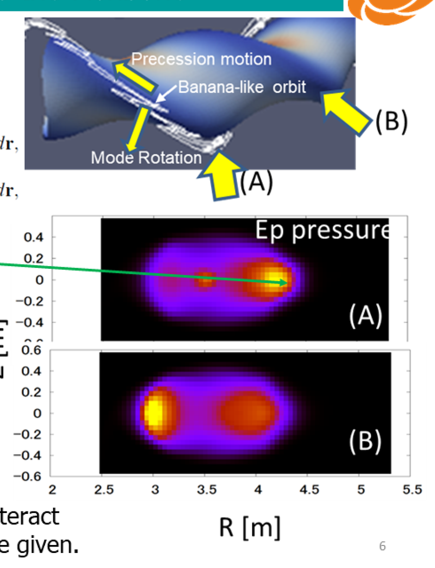
Ya. I. Kolesnichenko, et. al., Phys. Rev. Lett. **82**(1999) 3261, Phys. Plasma **9** (2002), 517

Excitation Condition of EIC – analogy to the Fishbone

Energy Principal with Energetic particle

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

Bulk plasma — From Energetic Particle



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

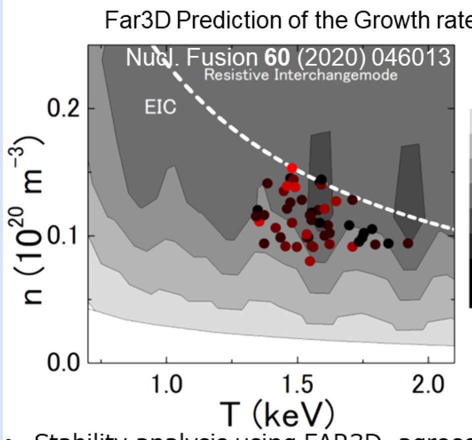
- EP pressure gradient at the rational surface can be large estimated from the deposition profile.

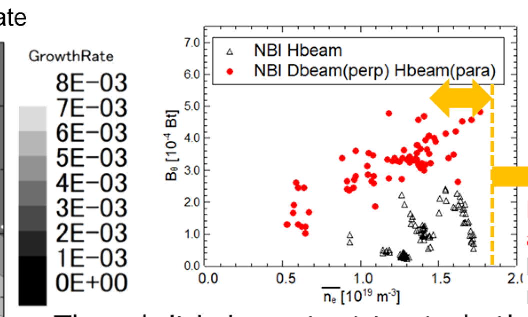
EP motion resonant with MHD mode

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

Linear Growth Rate / Effects on plasma

Far3D Prediction of the Growth rate





In high density discharges, amplitude is large.

EIC does not appear in higher density regime.

- Stability analysis using FAR3D agrees well with the region of EIC appearance. Amplitude is larger near the boundary.
- Though it is important to study the non-linear evolution of the mode, characteristics of the evolution is not easy to be analyzed since non-linear code is quite heavy.
- Analysis based on the study for Fishbone mode , **Heidbrink et. al. Phys. Fluids B Vol. 5(1993) 2177**, is introduced here.

Predator-Prey model for the EP driven modes

$$\frac{dA}{dt} = (\gamma_f - \gamma_{damp})A.$$

A: Mode amplitude is proportional to the number of the energetic particles.

$$= \gamma_{damp}(\frac{N_b}{\bar{N}_b} - 1)A, \text{ where } \gamma_f = \frac{N_b}{\bar{N}_b}\gamma_f.$$

$\bar{N}_b$ EP particle number at marginally stable condition

$$S = P_b/E_b - \bar{N}_b/\tau_{th}.$$

Particle balance of the EPs

$$\frac{N_b}{dt} = \gamma_{loss}\bar{N}_b A^\nu.$$

Loss is proportional to the A^ν

$$y \equiv \left(\frac{S}{\bar{N}_b}\nu\gamma_{damp}\right)^{\frac{1}{2}} t.$$

$$n \equiv \frac{N_b - \bar{N}_b}{\bar{N}_b}\sqrt{\frac{\bar{N}_b}{S}\nu\gamma_{damp}}.$$

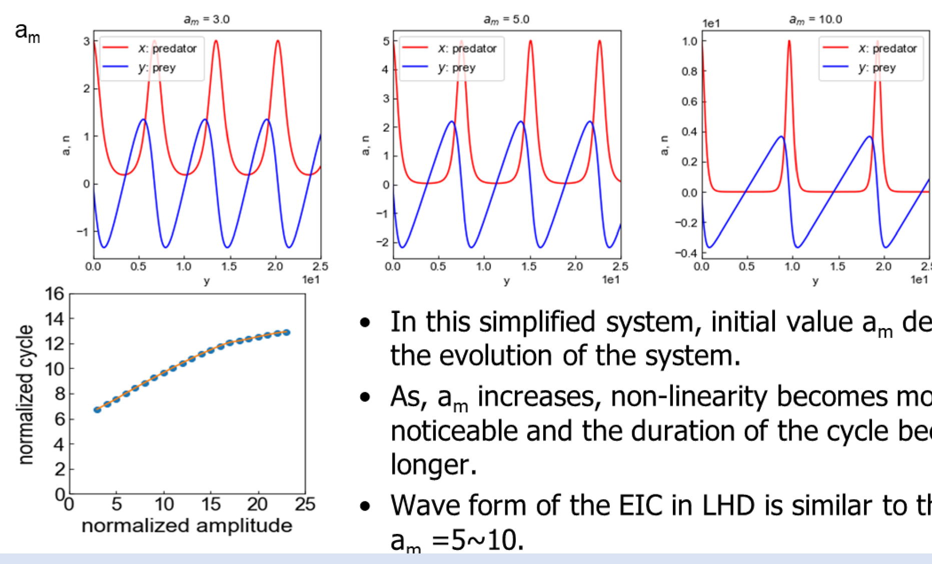
$$a \equiv (\gamma_{loss}\frac{\bar{N}_b}{S})A^\nu.$$

Normalize

$$\frac{da}{dy} = na.$$

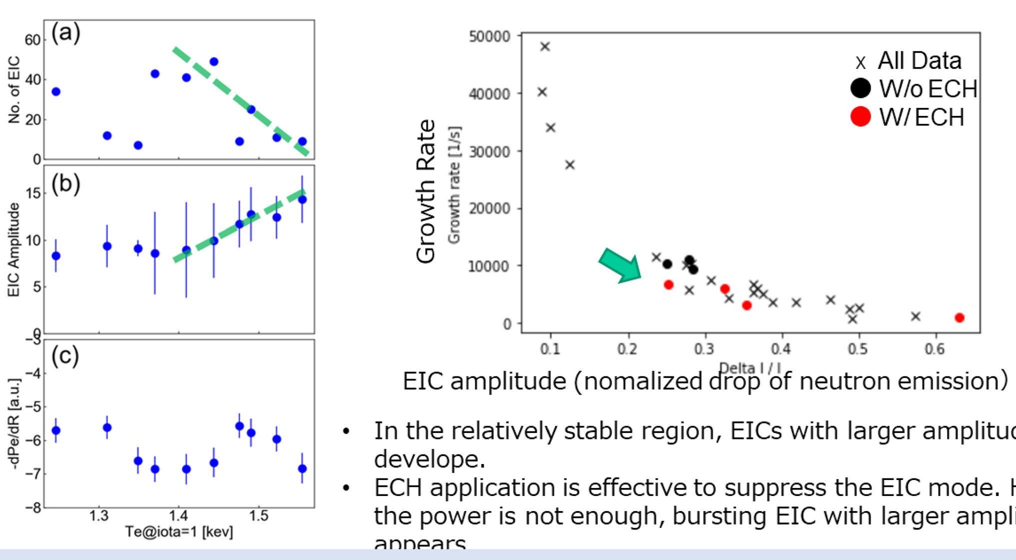
$$\frac{dn}{dy} = 1 - a.$$

Time evolution of the simplified model



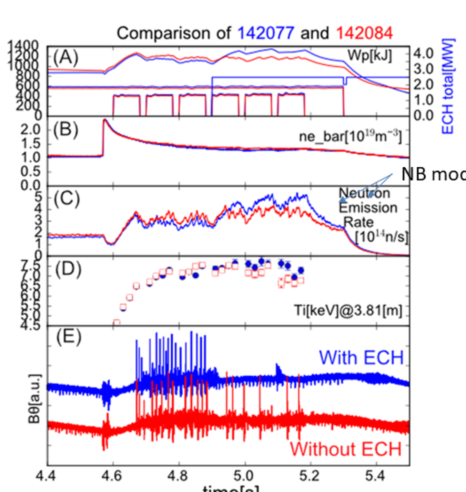
- In this simplified system, initial value a_m determines the evolution of the system.
- As, a_m increases, non-linearity becomes more noticeable and the duration of the cycle becomes longer.
- Wave form of the EIC in LHD is similar to the case of a_m =5~10.

EIC Amplitude and Growth rate



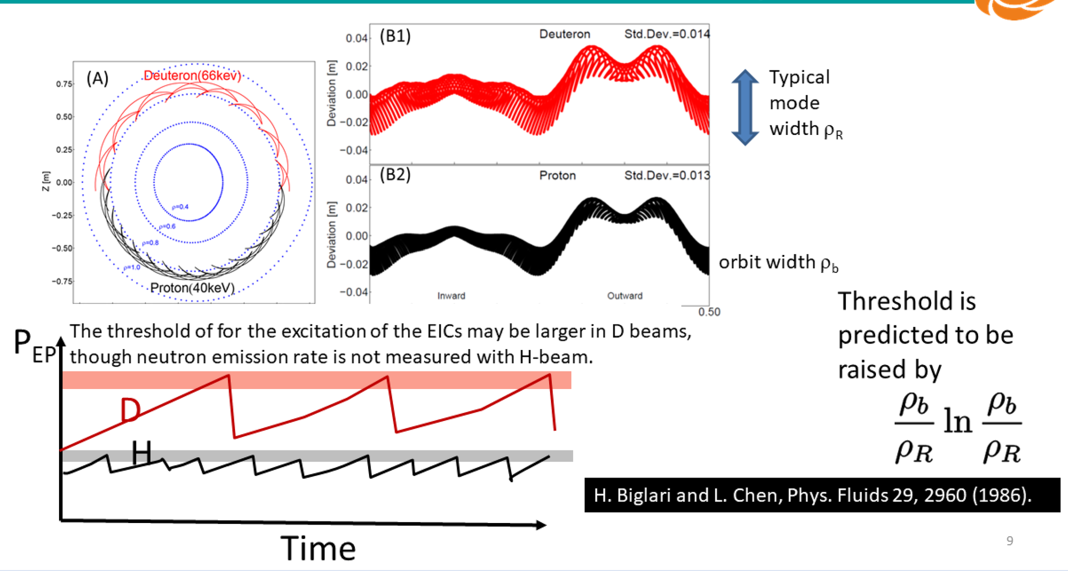
- In the relatively stable region, EICs with larger amplitude develop.
- ECH application is effective to suppress the EIC mode. However, the power is not enough, bursting EIC with larger amplitude appears.

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 ECW heating at the center in the high-Ti discharge condition. No reduction of the neutron emission rated is observed with ECH.

MHD / EP resonant effects and stability

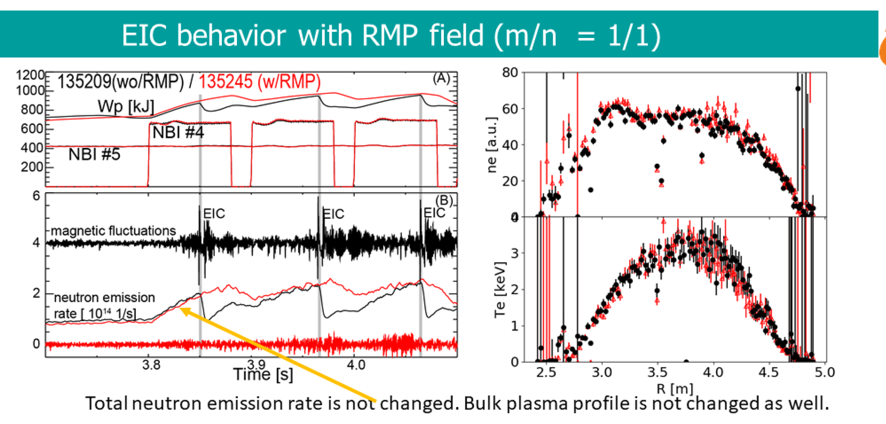


Threshold is predicted to be raised by

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

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

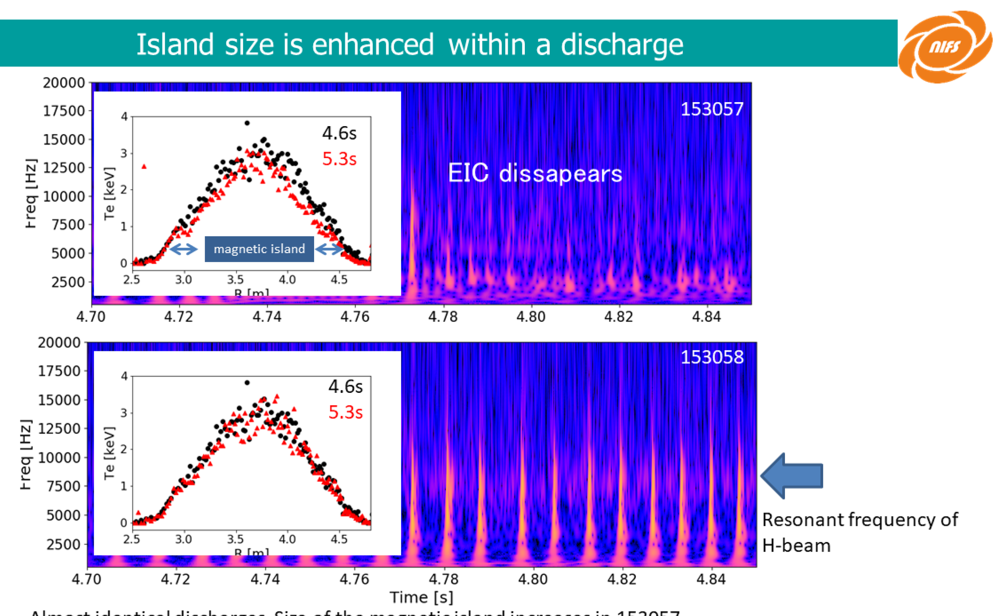
EIC behavior with RMP field (m/n = 1/1)



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.

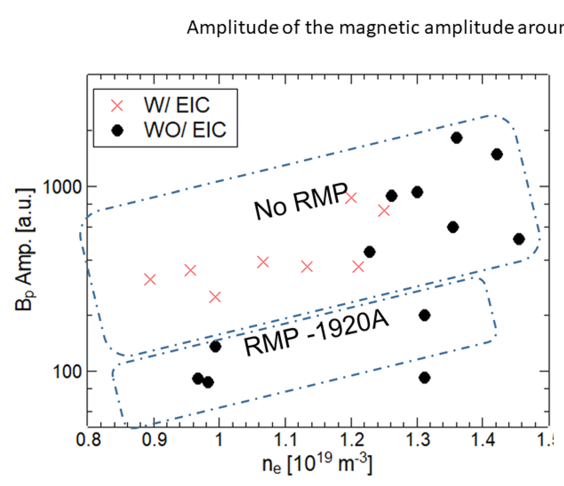
Island size is enhanced within a discharge



Almost identical discharges. Size of the magnetic island increases in 153057.

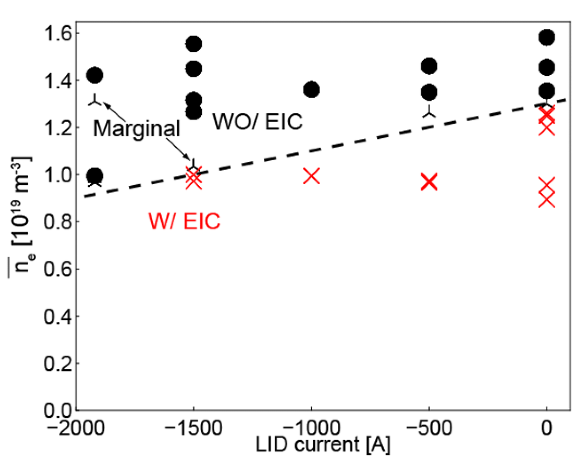
With RMP application, MHD activites resonant with Energetic beams reduces in low density regime

Amplitude of the magnetic amplitude around 7kHz.



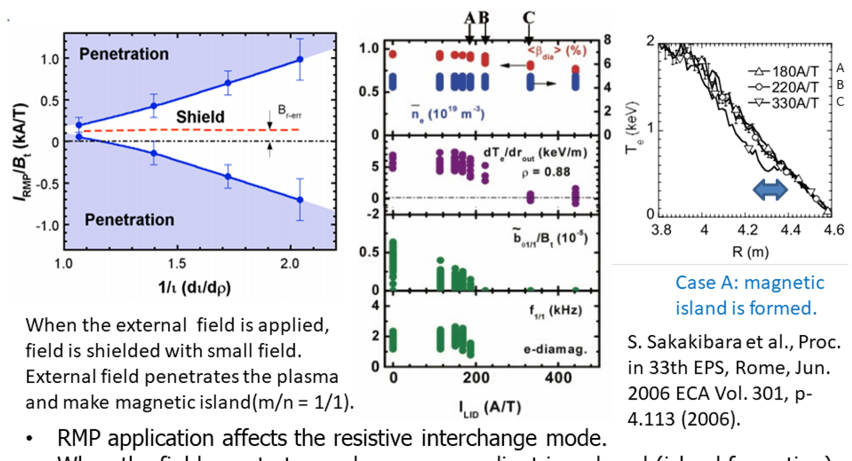
- Amplitude of the activities which can be resonant with the EP precession frequency is reduced.
- The mode can not evolve into the bursting the mode which make significant loss of the EPs.

RMP application: Scan of the RMP amplitude



- Application of the RMP affects the density limit smaller.
- Operational region is thereby increased.

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).

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

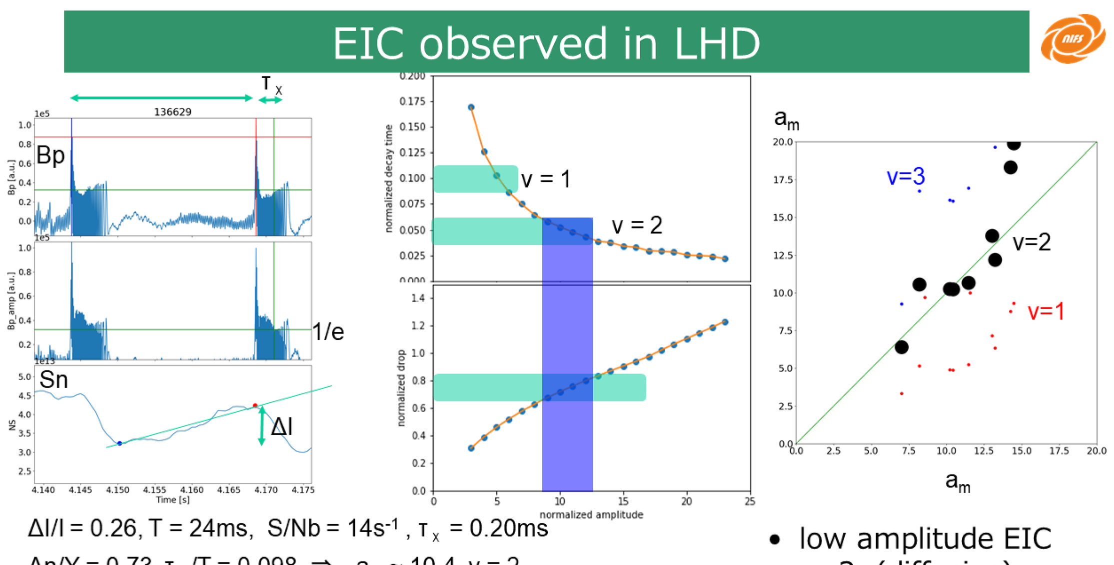
- RMP application affects the resistive interchange mode.
- When the field penetrates and pressure gradient is reduced (island formation), resistive interchange modes disappear.
- Even the external field is partly shielded, MHD activities are suppressed to some extent.

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.
- Trials to control the EIC with ECH injection and RMP application is performed.
- Both ECW injection and RMP application successfully suppress the EIC without reducing neutron emission rate, i.e. EP pressure. 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

EIC observed in LHD



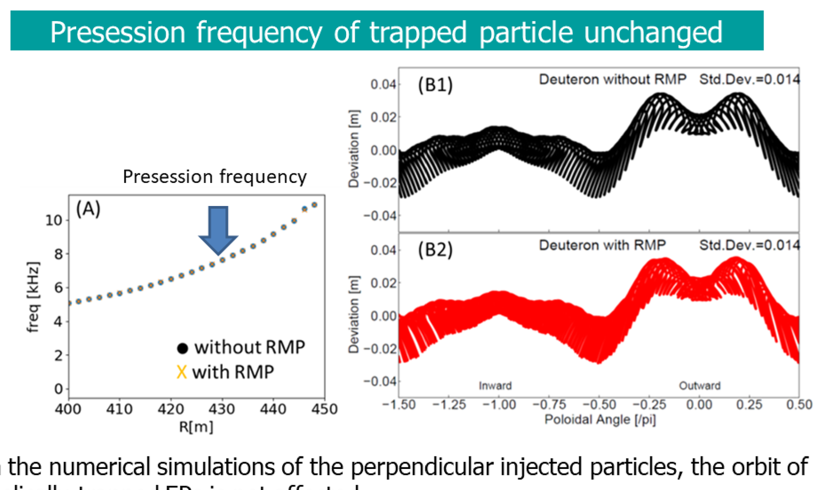
ΔI/I = 0.26, T = 24ms, S/Nb = 14s⁻¹, τ_x = 0.20ms

Δn/Y = 0,73, τ_x /T = 0.098 ⇒ a_m ~ 10.4, v = 2

γ~1.15x10⁴ [1/s]

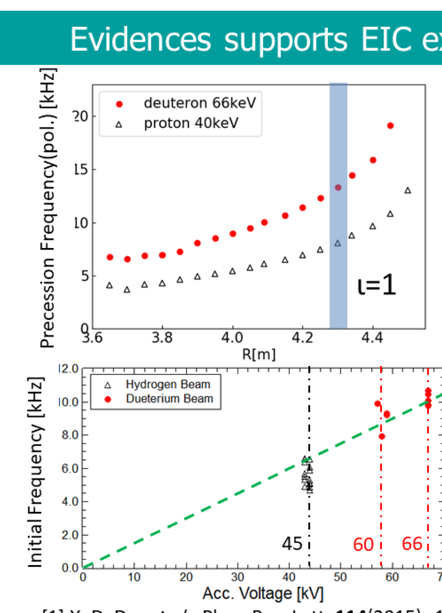
- low amplitude EIC v=2 (diffusive).

Presession frequency of trapped particle unchanged



- From the numerical simulations of the perpendicular injected particles, the orbit of the helically trapped EPs is not affected.
- Therefore the number of the particles that remains in the helically shaped weak magnetic region is not reduced with RMP. That means the mitigation effects are not caused by the change of the number of beam ions.

Evidences supports EIC excitation mechanism



- 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].

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