Energetic Particle Driven Resistive Interchange Mode in the Deuterium LHD Experiments

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Content of my talk

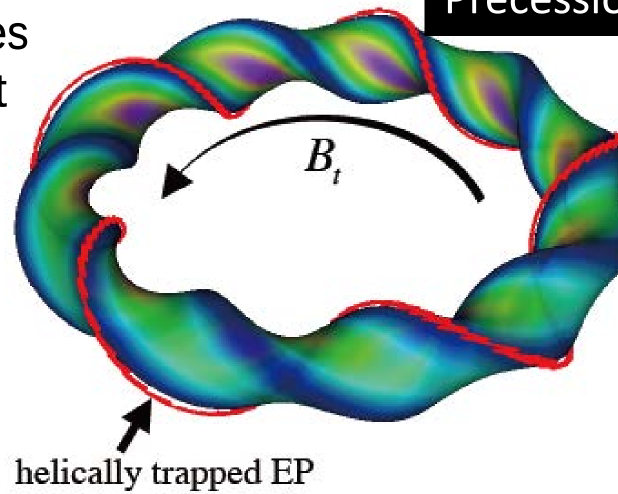
- A new type of the energetic particle driven MHD instability, EIC was found in LHD (X. D. Du, *et. al.*, Phys. Rev. Lett. **114** (2015), 155003) in hydrogen heating campaign.
- Observation of the EIC in the new deuterium heating campaign, by which our understanding of the EIC is improved, will be discussed.

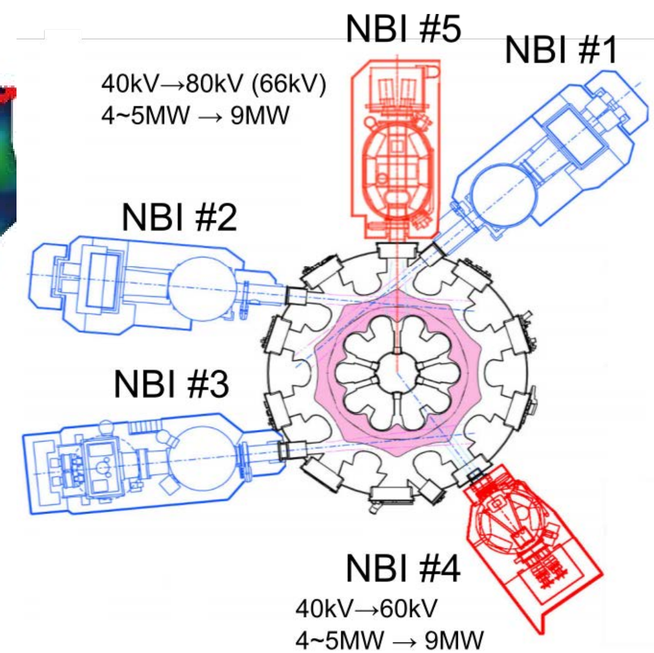
1. The characteristics of the EIC in deuterium experiment.
   Stability of EIC with deuterium beam injection.
2. The effect of the EIC on the energetic particle and the bulk plasma.
3. Strategy to control the EIC.
   1. EIC suppression with ECH heating.
   2. EIC suppression with RMP.

EIC in the hydrogen / deuterium campaign (1)

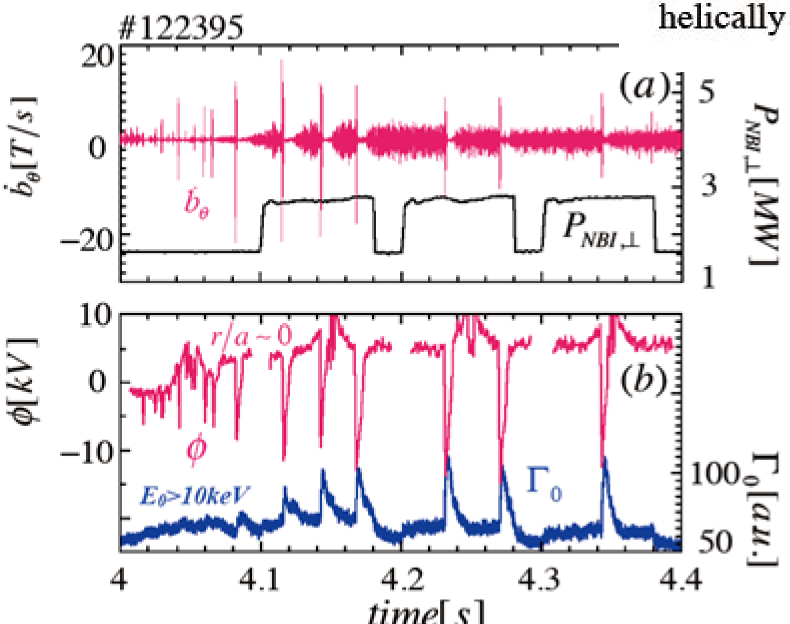
EIC: Energetic particle driven resistive InterChange mode

- 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

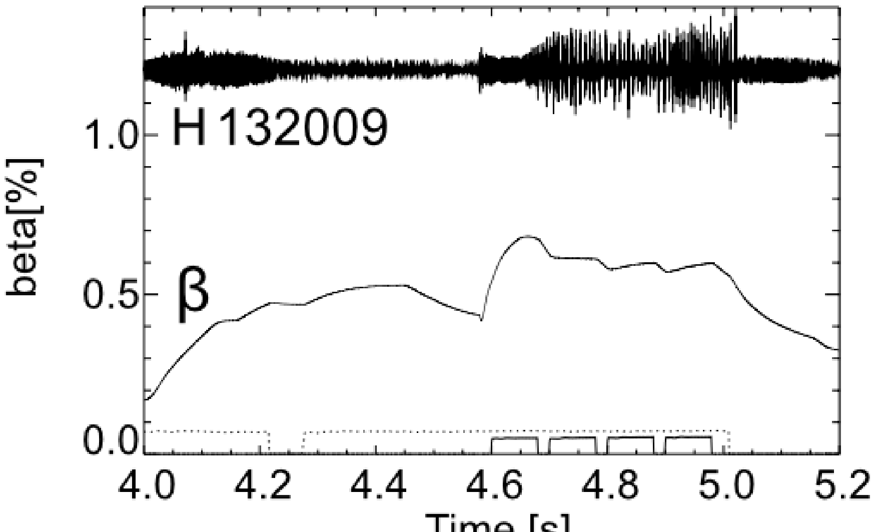


- EIC behavior when deuterium perpendicular injected NBIs are used is reported. It is noted that neutron emission rate is a good measure of the amount of the trapped particles, since the beam-plasma reaction is the dominant in LHD.

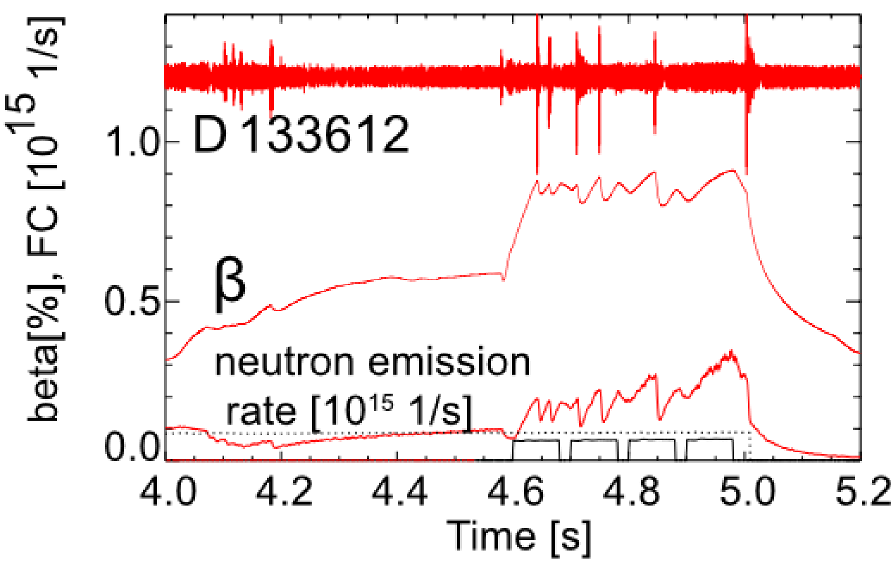
Potential formation / modification of the EP profile

EIC in the hydrogen / deuterium campaign (2)

Hydrogen Campaign

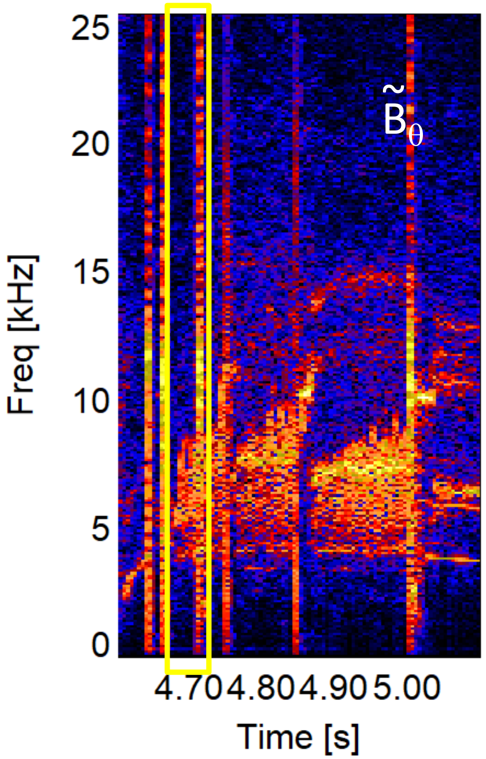


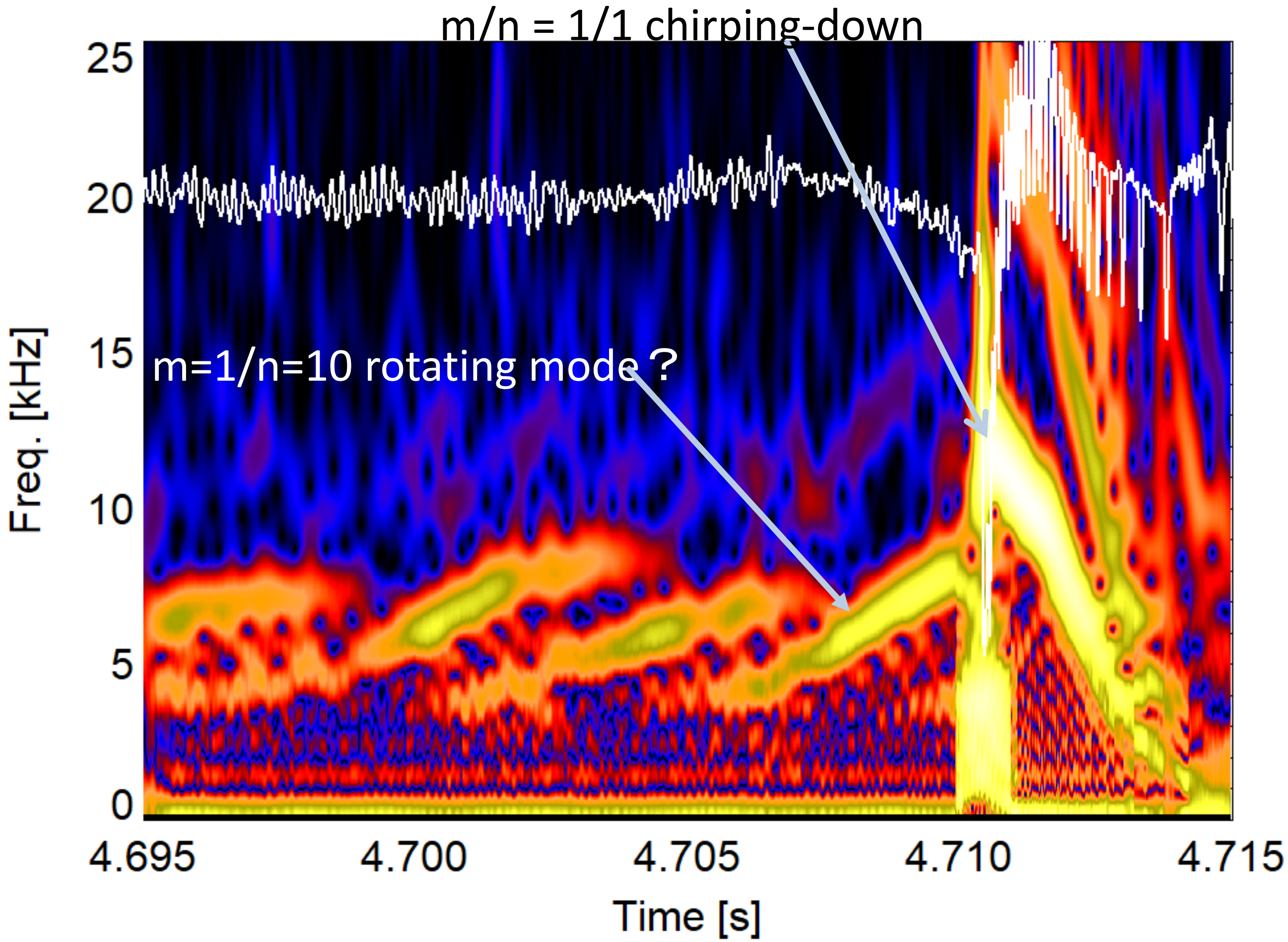
Deuterium Campaign (only Perp. Beams)

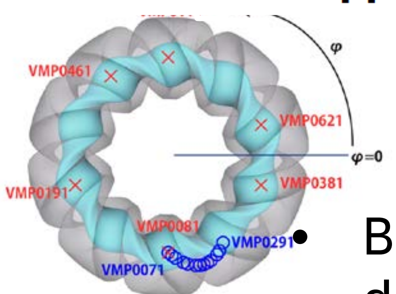


- EICs becomes unstable when the perpendicularly injected NBI power is increase.
- Bursts of MHD activities less frequently activated are observed in deuterium campaign.
- Impact of each EIC burst is larger, as seen in the time evolution of beta than that observed in hydrogen campaign.
- Total neutron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

Magnetic fluctuations with an EIC event

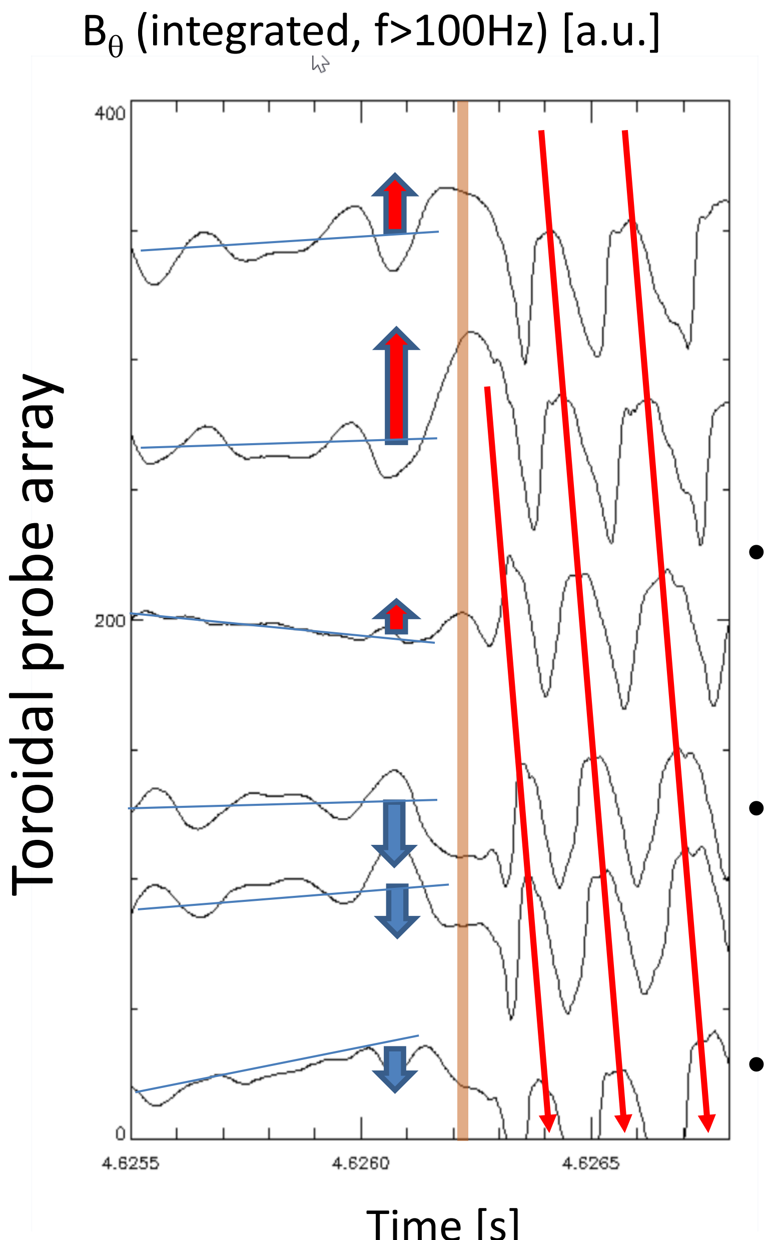


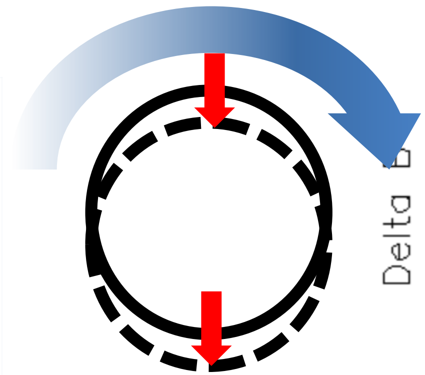


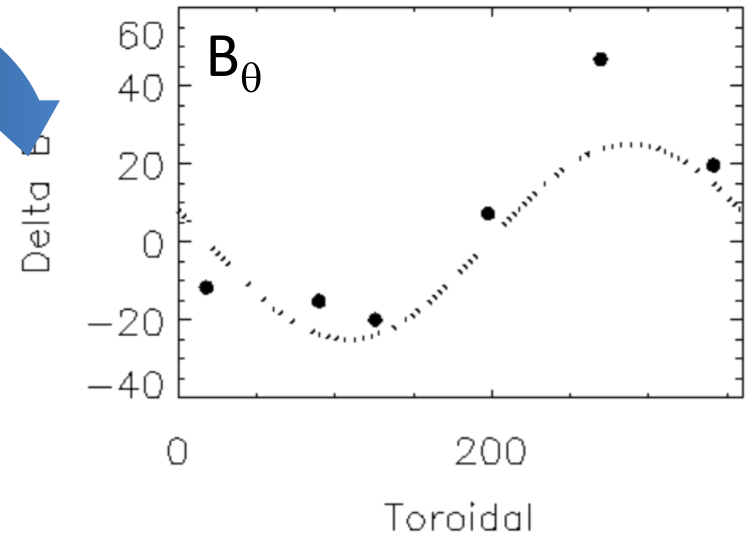


- Bursting MHD activities together with the m/n = 1/1 chirping-down MHD mode is observed.
- The precursors-like oscillations before the onset of the EIC is quite complicated. (There are several patterns.)

Onset of the EIC and chirping down mode





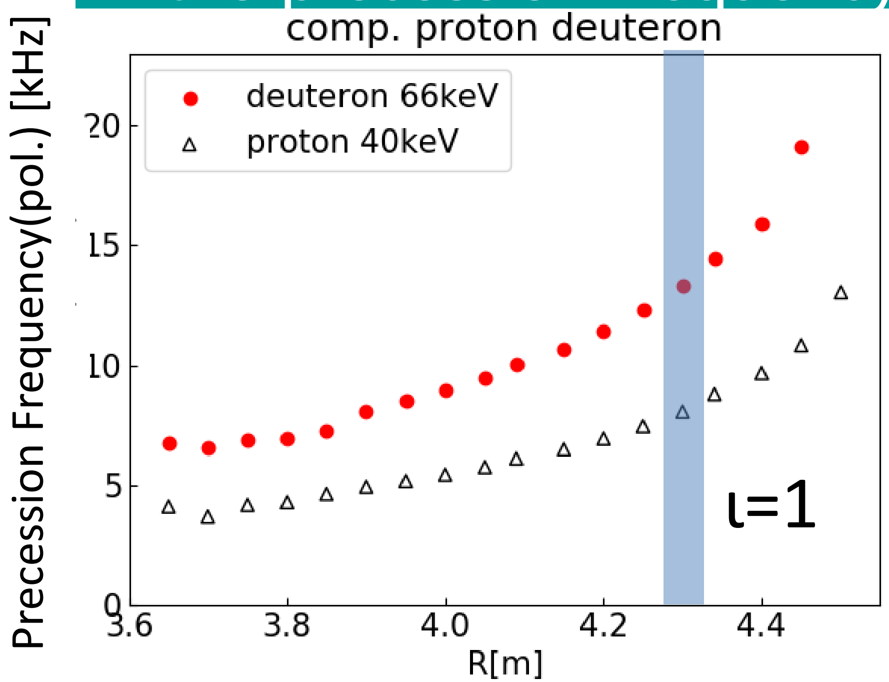


- First, a large deformation with n = 1 occurs, and the structure rotating into the direction the precession motion.
- The perturbation is quite localized on the iota = 1 rational surface (-> interchange mode).

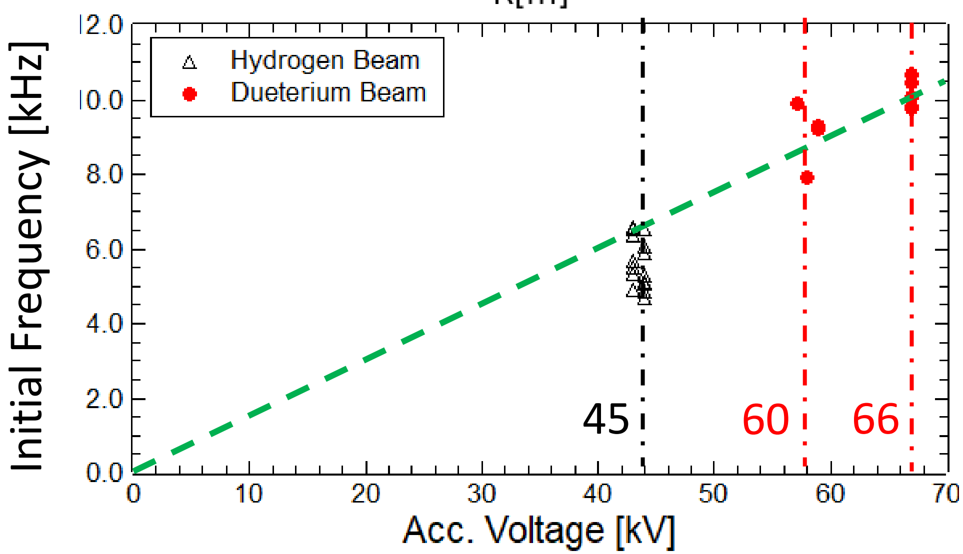
ECE measurement

- The rotation frequency is similar to the frequency of the precession frequency of the EPs (-> EP driven mode).

The observed frequency of EICs is proportional to the precession frequency of helically trapped EPs



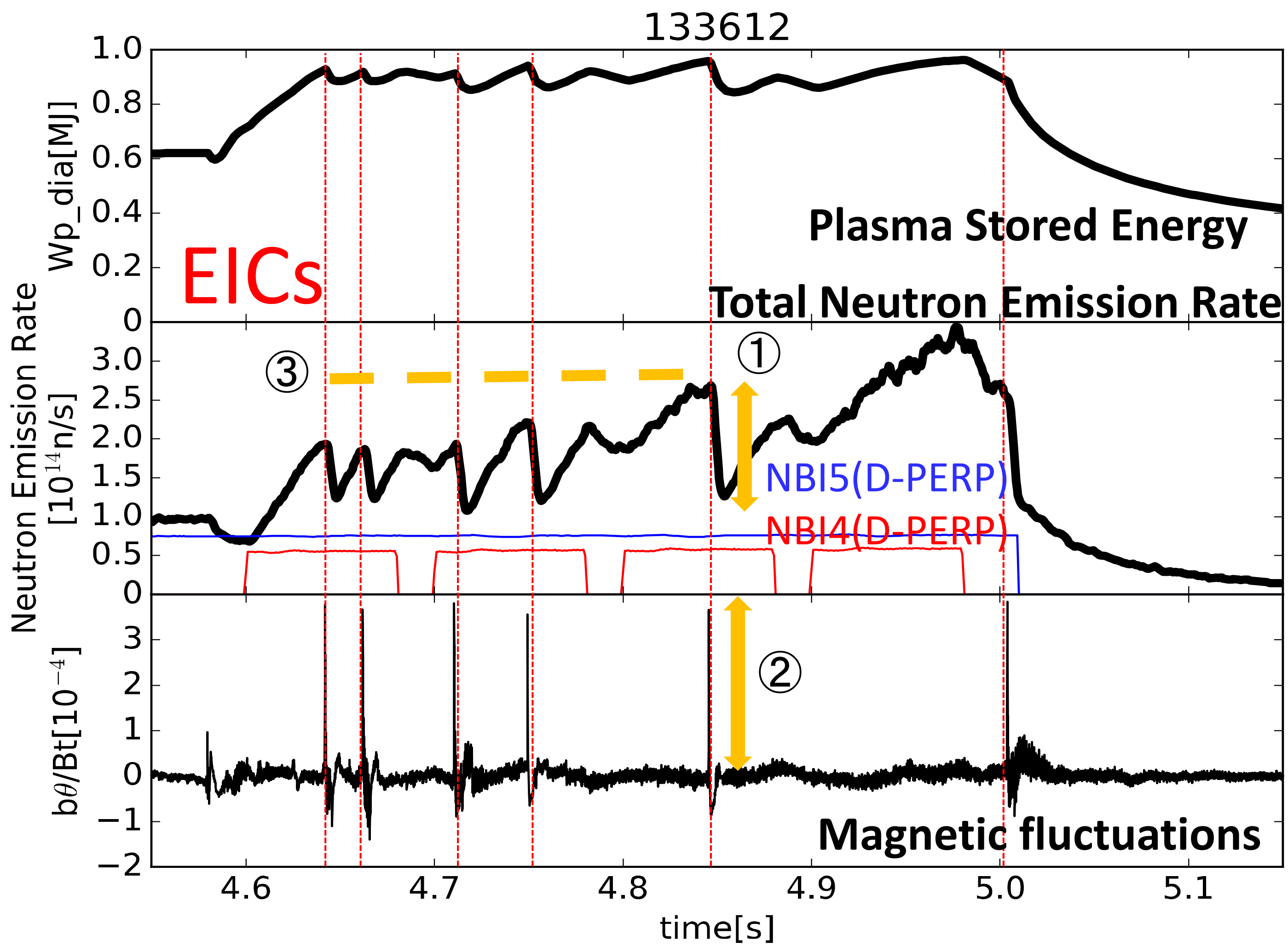
- Precession frequency is proportional to the energy of EPs and does not depend on kinds of particles. The chirping down frequency is similar to the frequency of the precession frequency



- EICs by PERP NBIs with 66 kV has the larger frequency than that with 60 kV and 45 kV.
- Initial frequency dependence strongly supports that the EIC is driven by the pependiculaly injected EP discussed in ref [1].

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

Parameter dependence of the EICs



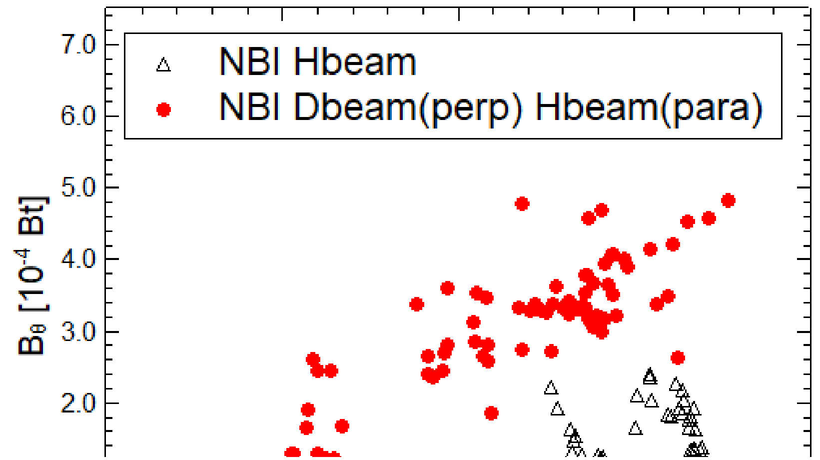
①Drop of neutron emission rate (fraction of the lost Eps dSn/Sn),

②Amplitude of the magnetic fluctuations B_θ(scale of the events dB_θ/Bt), and

③Neutron emission rate Sn before EIC burst (EP pressure before the events

Amplitude is 2-3 times larger with D beams

- EICs are observed relatively low density plasma.
- Larger scale collapse with D beams, shown by the large magnetic fluctuations, occurs in the same density regime.
- Content of Eps before EIC is larger in larger event.



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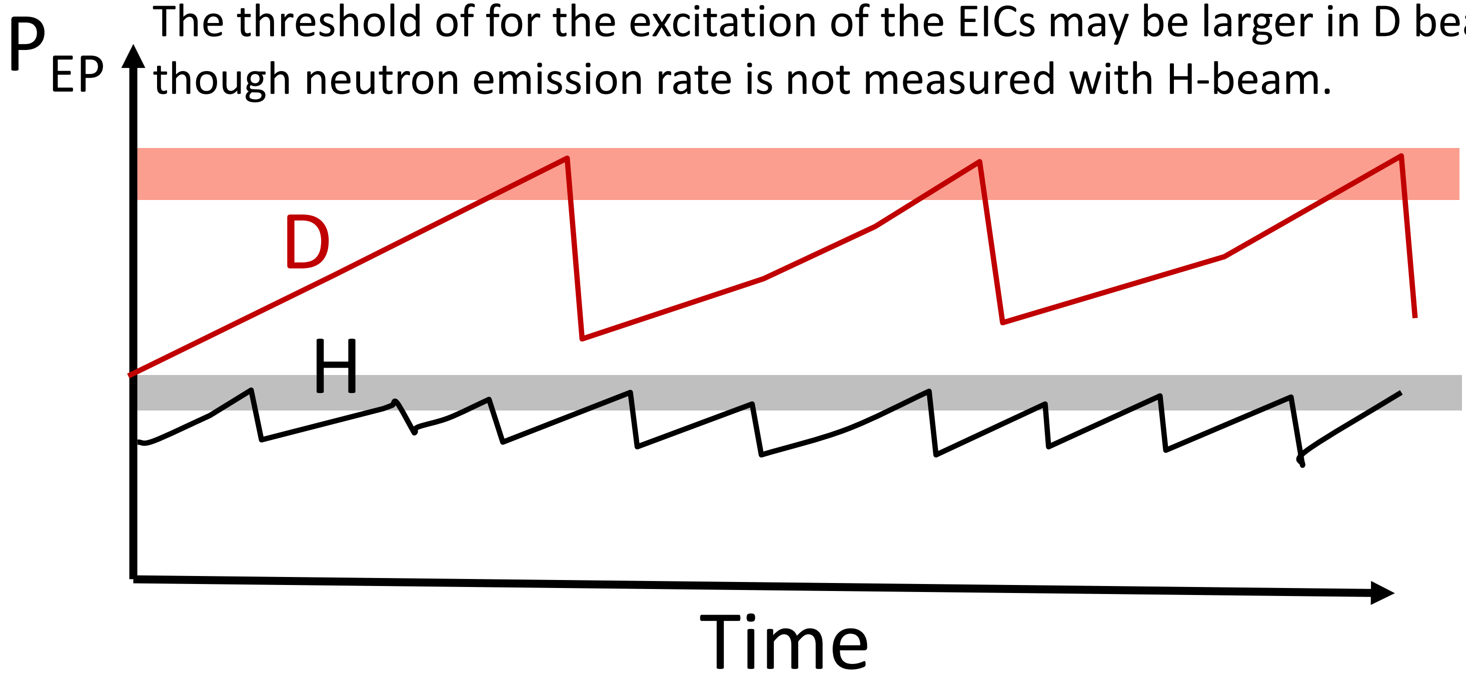
The threshold of for the excitation of the EICs may be larger in D beams, though neutron emission rate is not measured with H-beam.



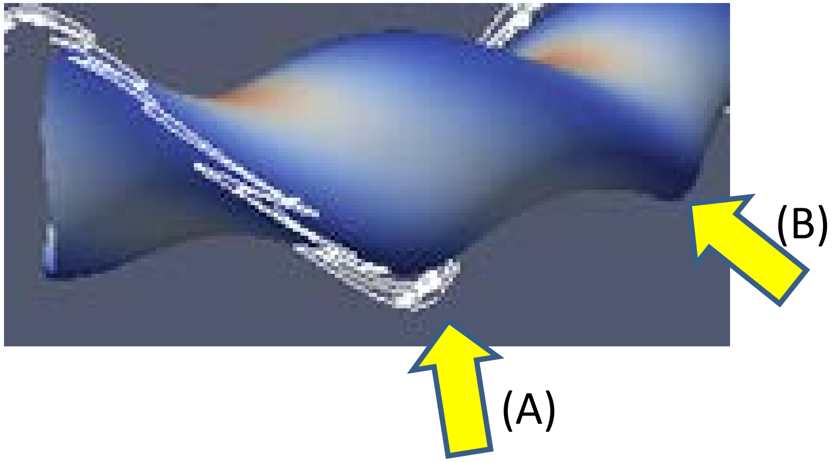
EIC excitation – analogy to the Fishbone

Energy Principal with Energetic particle

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

Bulk plasma

From Energetic Particle



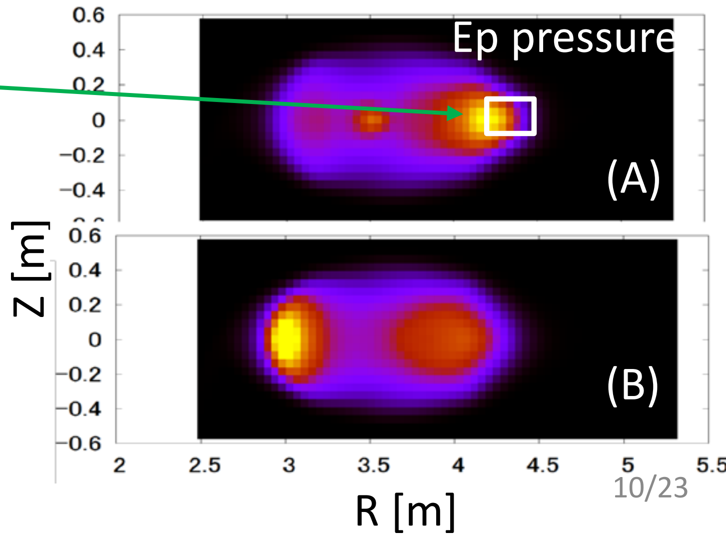
$$\delta I = -\frac{\omega^2}{2}\int \rho_m |\xi|^2 d\mathbf{r},$$

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

- The injected beam is deposited at the outer region. The pressure of the energetic particle is larger in only one valley of the weak magnetic field.

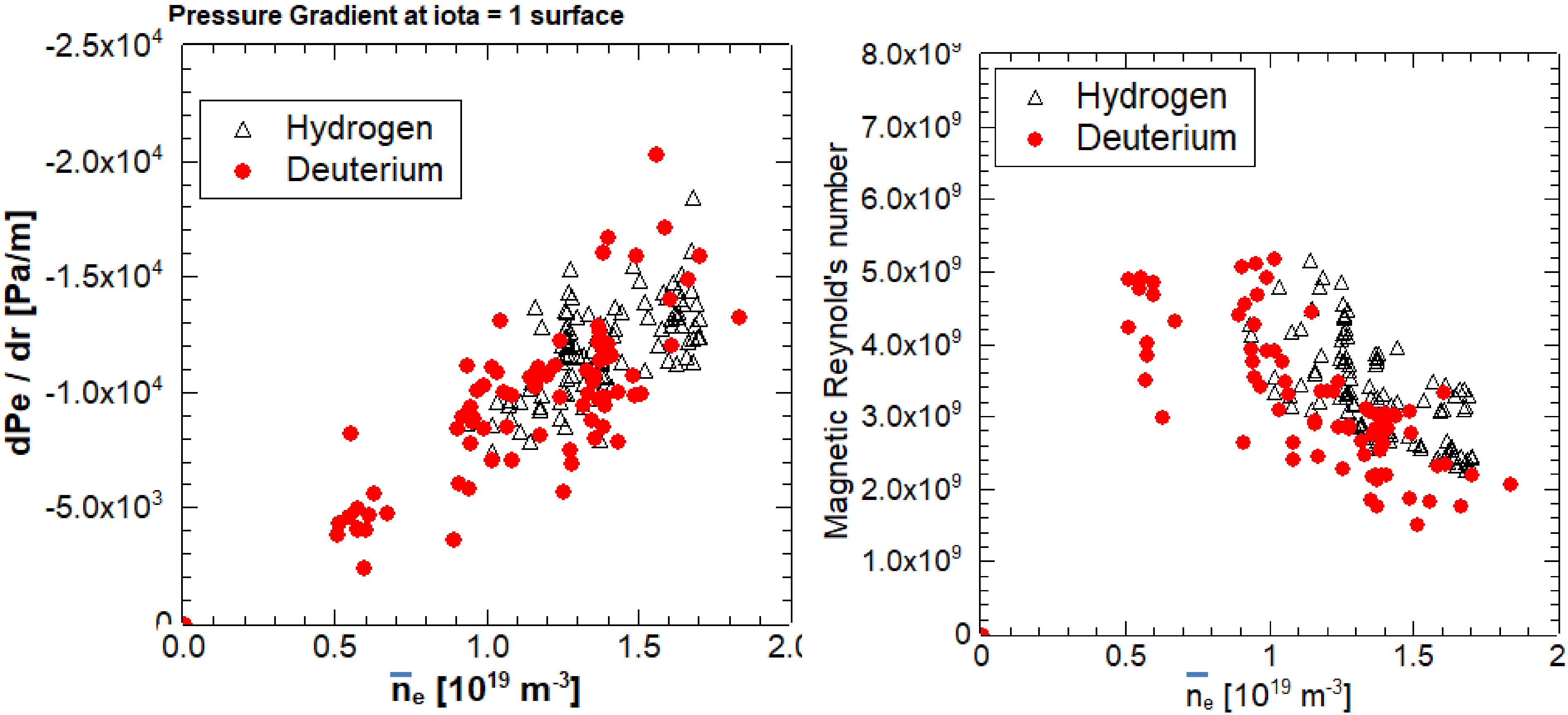
$$-\frac{\partial \beta_h}{\partial r} > C_{th}$$

In order to fulfill the dispersion relation



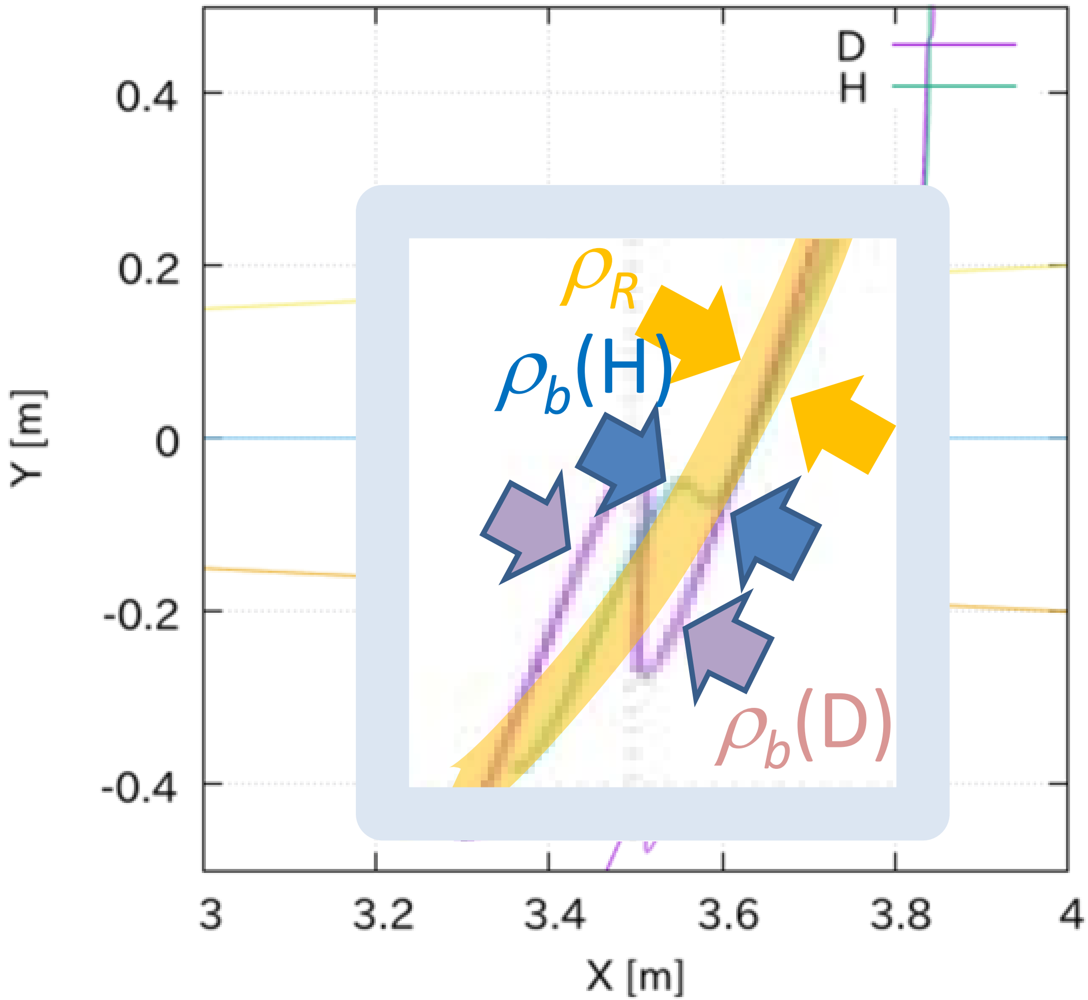
- It is expected that larger power D beam produces larger pressure gradient of energetic particle.
- Why is EIC with D beam more stable?

Pressure gradient of the bulk plasma is not changed



- The pressure gradient which drive the pressure driven mode is not changed in H/D experiment.
- Why is EIC more stable in D beam heating?

Mode width resistive Interchange mode and width of the banana orbit



- Banana width (ρ_b) is proportional to the mass of the particle.
- Width of the deuteron is wider than that of proton.
- It is predicted[2] that the threshold for excitation is increased by

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

- where the mode with of the resistive interchange mode is ρ_R
- This is one possible explanation that EIC with D beam is more stable.

[2]H. Bigrari, and L Chen, Phys Fluids **29** (1986), 2960

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- Excitation and suppression of the EIC in the deuterium heating campaign will be discussed by this talk.

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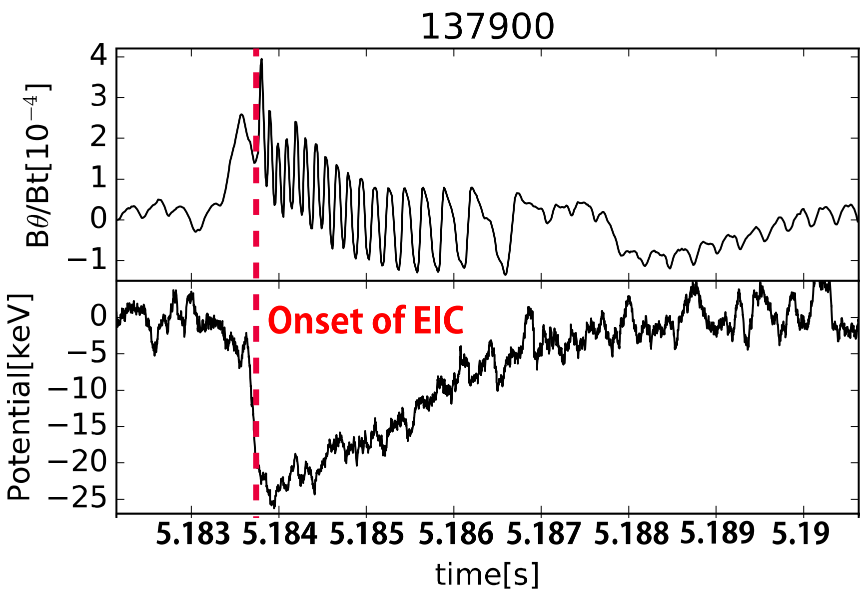
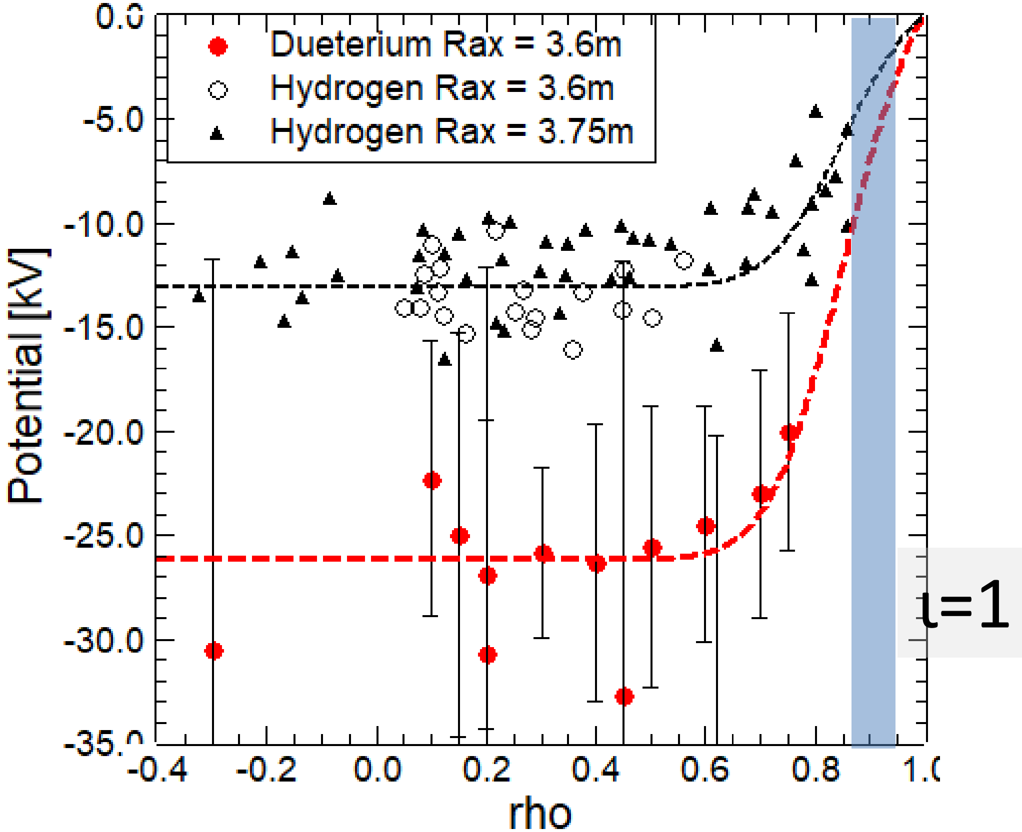
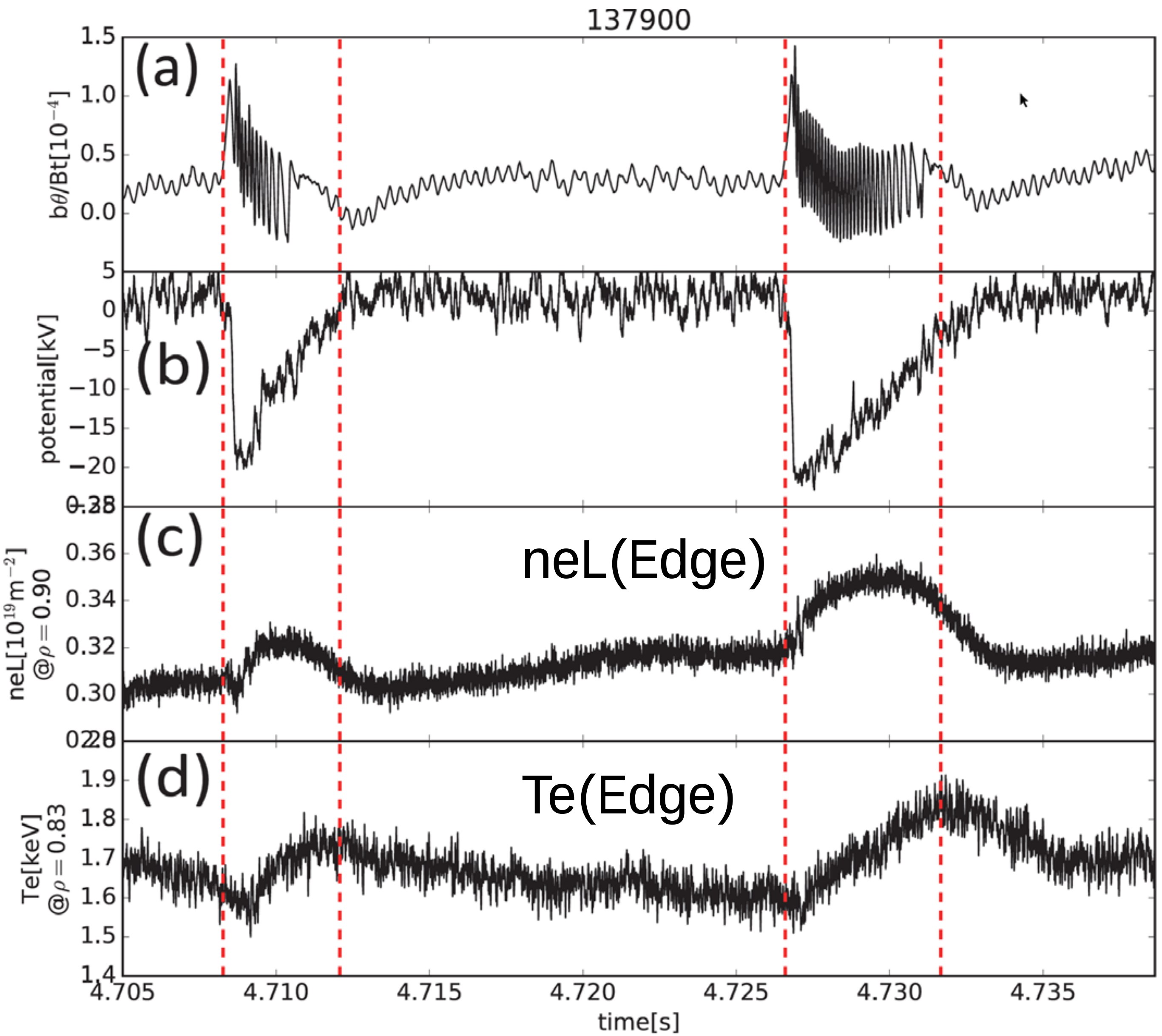
Formed electrostatic potential is larger in deuterium experiments





- The large negative electrostatic potential, ~25kV, is formed with expelling of EPs by EICs.
- The formed potential is about two times larger than that of hydrogen experiments. The variation of potential occurs around ι=1 surface.
- Change of the distribution of the energetic particle is observed by the CNPA and neutron profile measurement. (K. Ogawa's talk (Thursday))

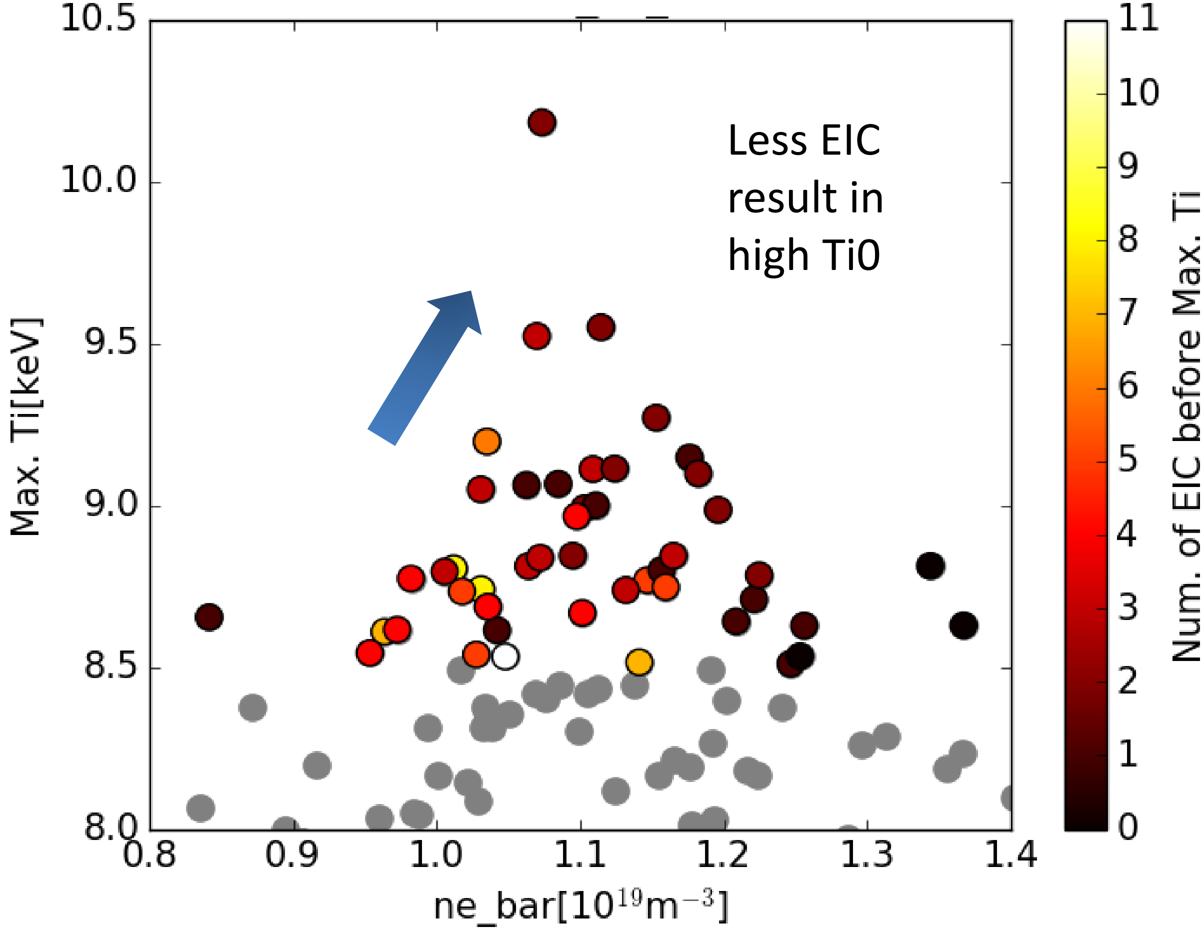
Transport of the edge plasma is affected transiently



- While the strong Er or Er shear is formed, increase of the edge electron density. (It may be casued by the Er shear formation.)

- The electron temperature is also increased.
- Inrease of Wp is also observed transiently.

The effect on the core transport?



- The effect on the core plasma is not obvious 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.

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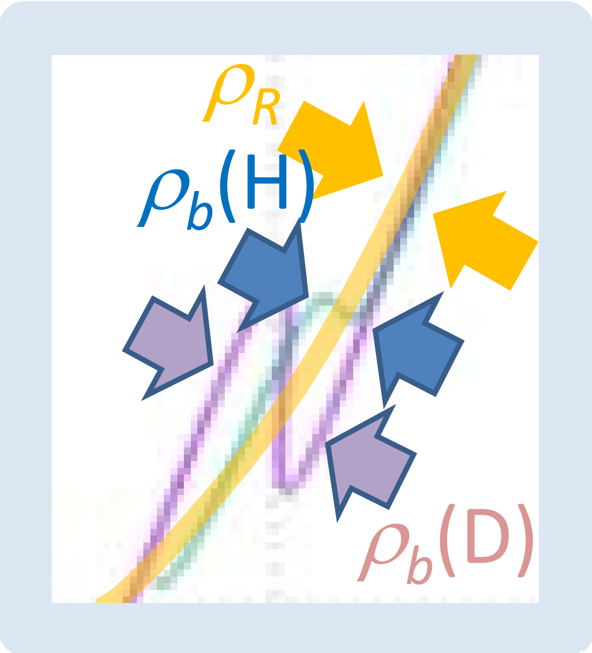
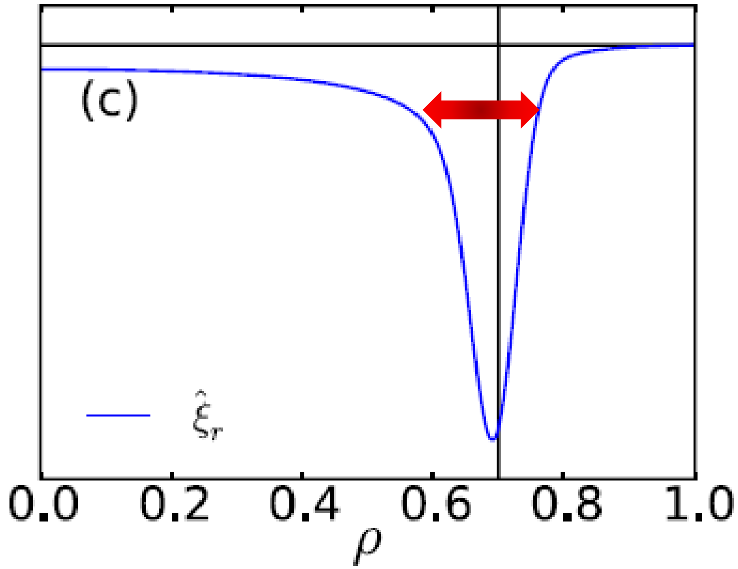
Control of the EIC with narrower mode width



Typical displacement of the Interchange Mode

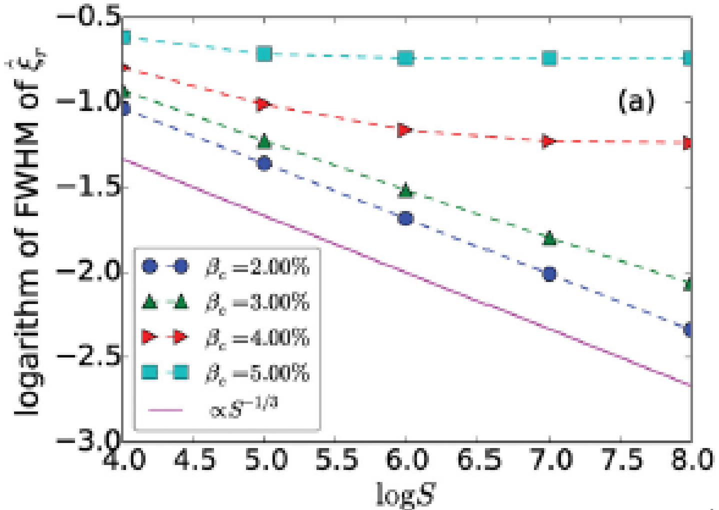


$$\rho_R \sim \left(\frac{q^2}{S\hat{s}^2}\right)^{1/3}\left(\frac{\beta\kappa_n}{L_p}\right)^{1/6}$$

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

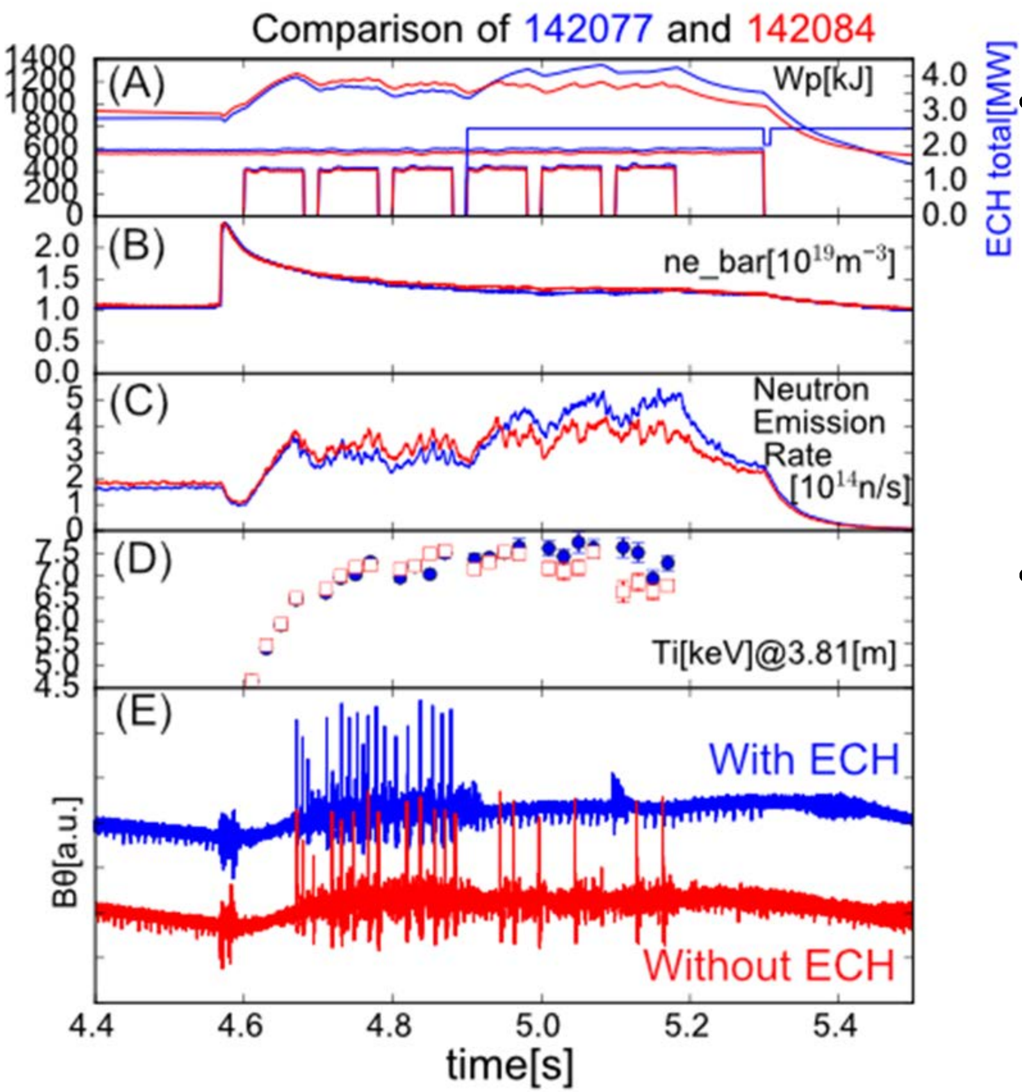
$\hat{S}$: Magnetic shear

- In order to increase the threshold of the EIC excitation, reduction of the mode width is also effective to isolate the effect of the EPs.
- The mode width of the resistive interchange mode is sensitive the magnetic Raynold's number.



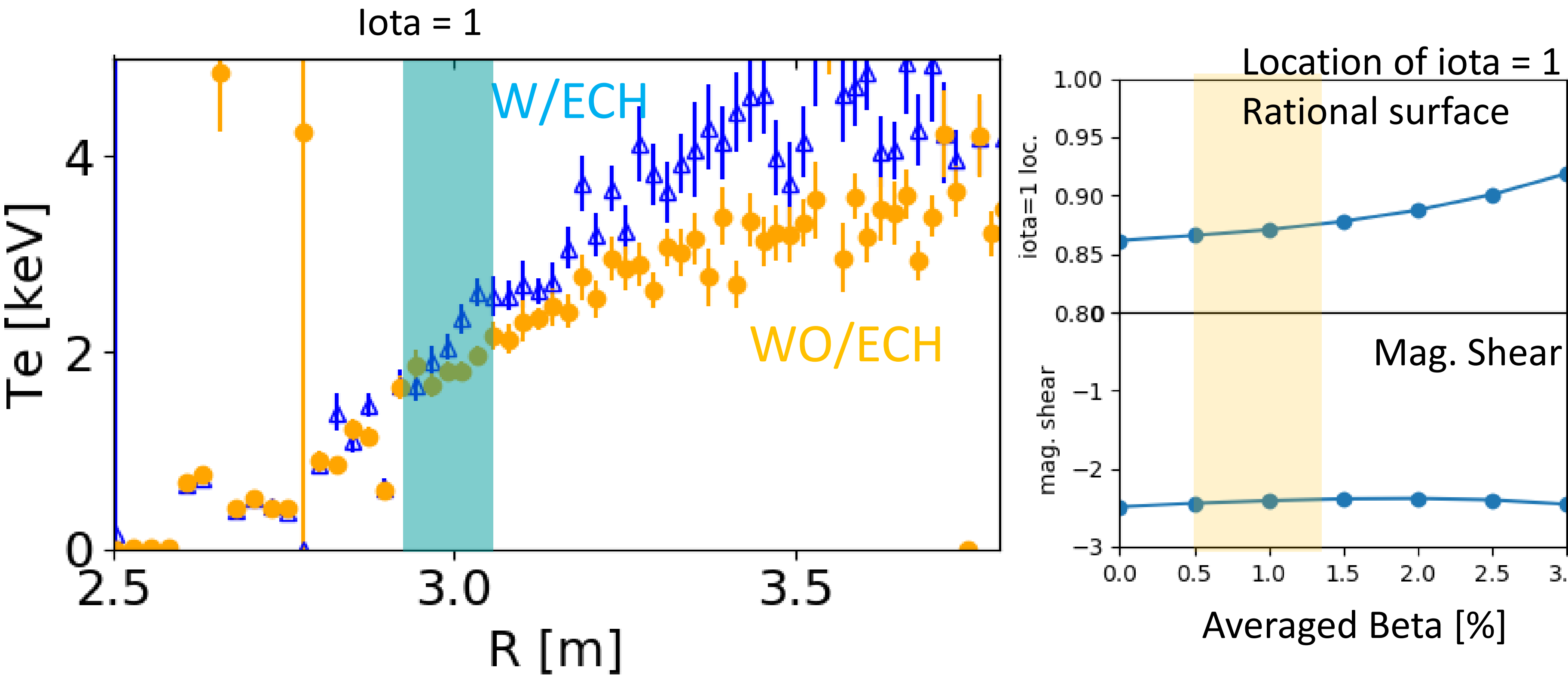
R. Ueda, et.al, POP **21**, 052502 (2014)

Control of EIC in High-Ti Deuterium exp.



- The control of the EIC using ECH 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 EC heating at the center in the in deuterium campaign of high-Ti discharge condition. No reduction of the neutron emission rated is observed.

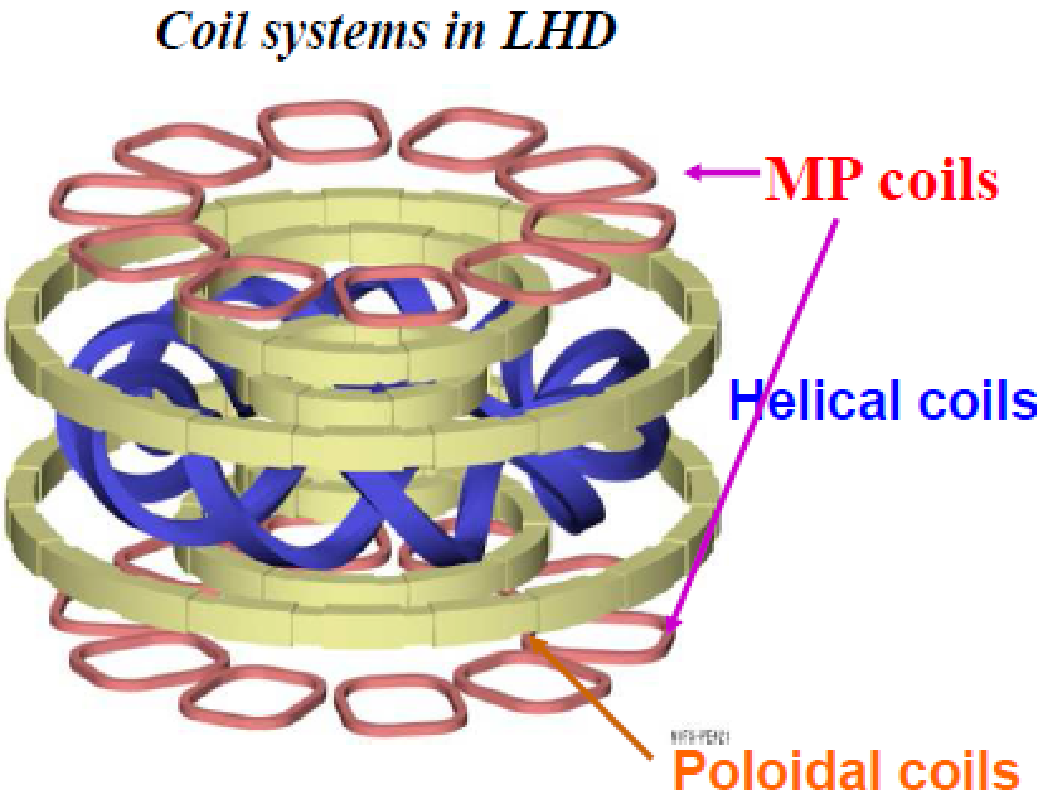
Change in the Te w/wo ECH

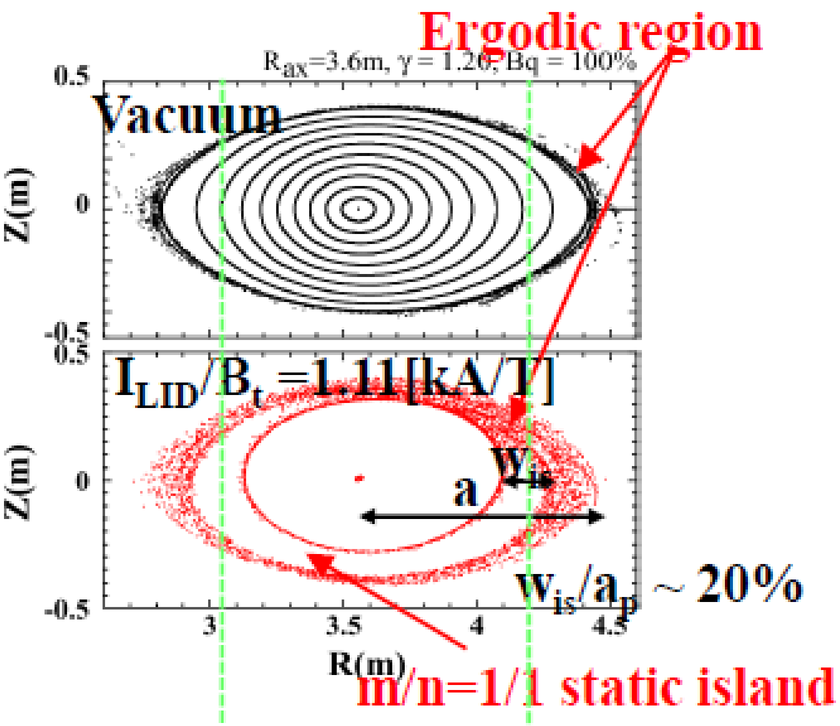


- The electron temperature at iota = 1.0 is slightly increased.
- Change of the magnetic shear can be another candidate for the suppression.

- Comparison of the radial mode width should be done to clarify the stabilization.

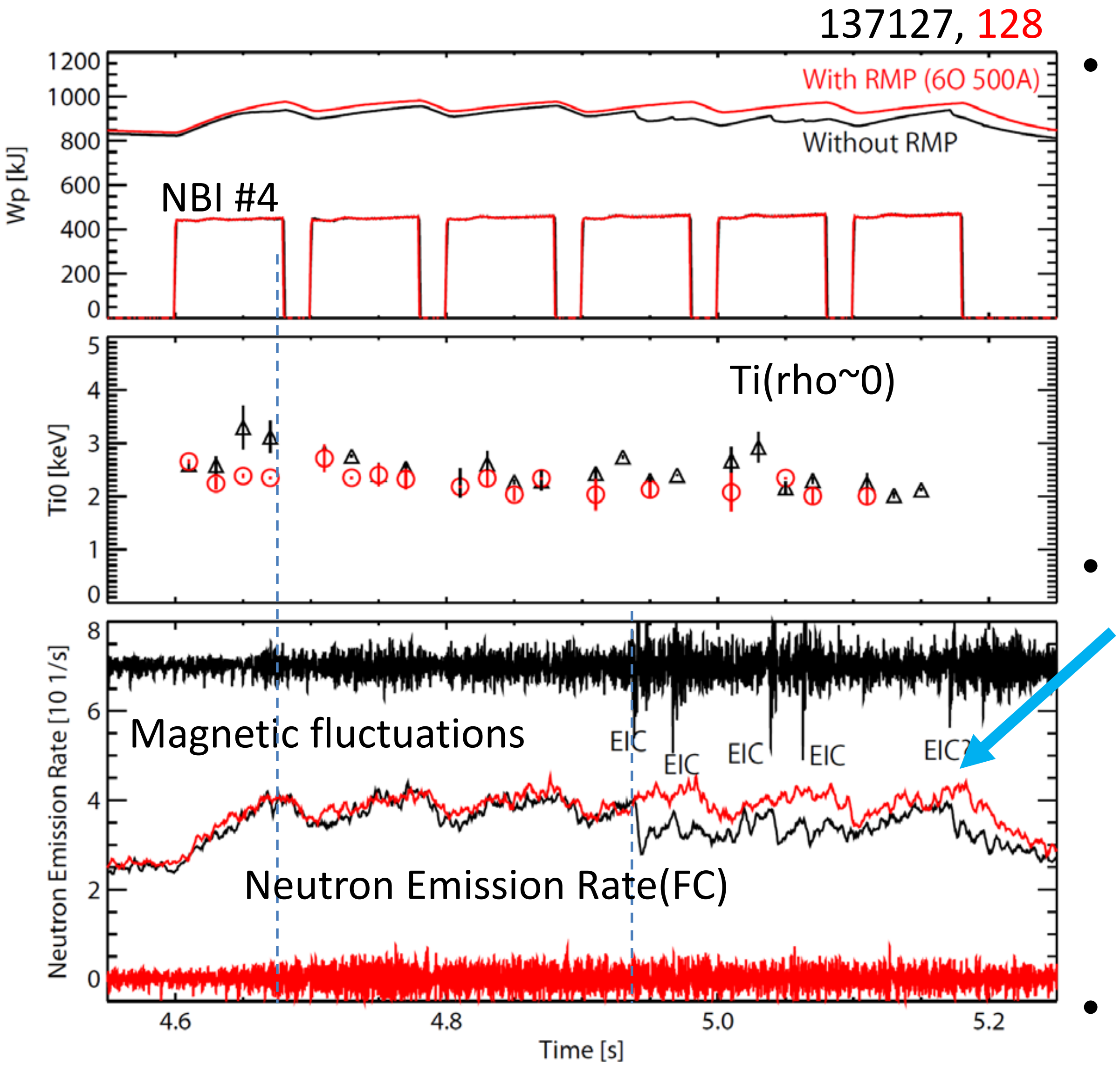
RMP field by LID-coil and island formation





- RMP field resonant with iota = 1 rational surface can be applied.

EIC behavior with RMP field



- When the EICs are marginally unstable, RMP application control the EIC excitation. Penetration of the external field to the plasma is required.
- Total amount of the trapped EPs (estimated from FC) is not modified significantly since the Neutron Emission rate is not changed so much.
- Orbit of the EPs with RMP field will be investigated.

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 amplitude and the effects of an EIC events on plasma is enhanced in deuterium experimental campaign. From the comparison of the result with D and H, mechanism of the EIC excitation is confirmed.

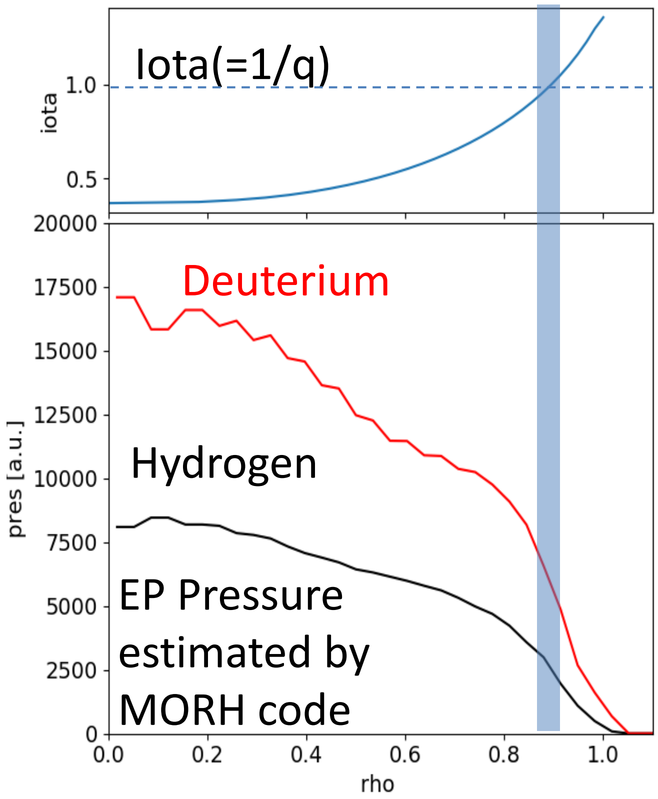
- Since the effect of the EIC is quite large, two methods to control EIC are performed.
  - ECH injection.

    Disappearance of the bursting EIC is observed. Instead of EIC, complicated MHD activities appears. However, the energetic particles are well confined and not expelled by these activities.
  - RMP (m/n = 1/1) application.

    When the external field penetrate the plasma, disappearance of the bursting EIC is observed without reducing the total amount of trapped EPs.

BACKUP SLIDES

EIC excitation and strategy for the stabilization



Energy Principal with Energetic particle

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

Bulk plasma (δW_{MHD})

From Energetic Particle (δW_k)

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

In order to fulfill the dispersion relation

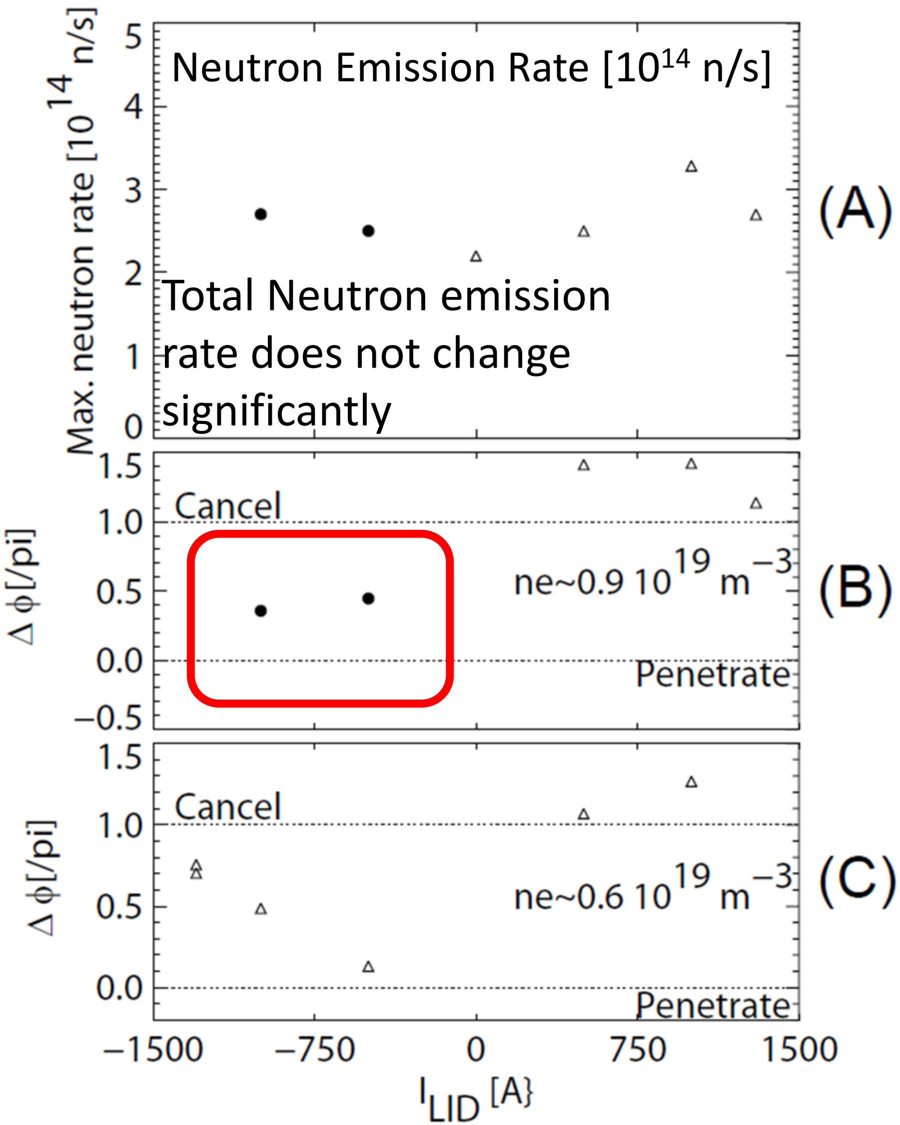
$$\delta I = -\frac{\omega^2}{2}\int \rho_m |\xi|^2 d\mathbf{r},$$

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

To stabilized the mode,

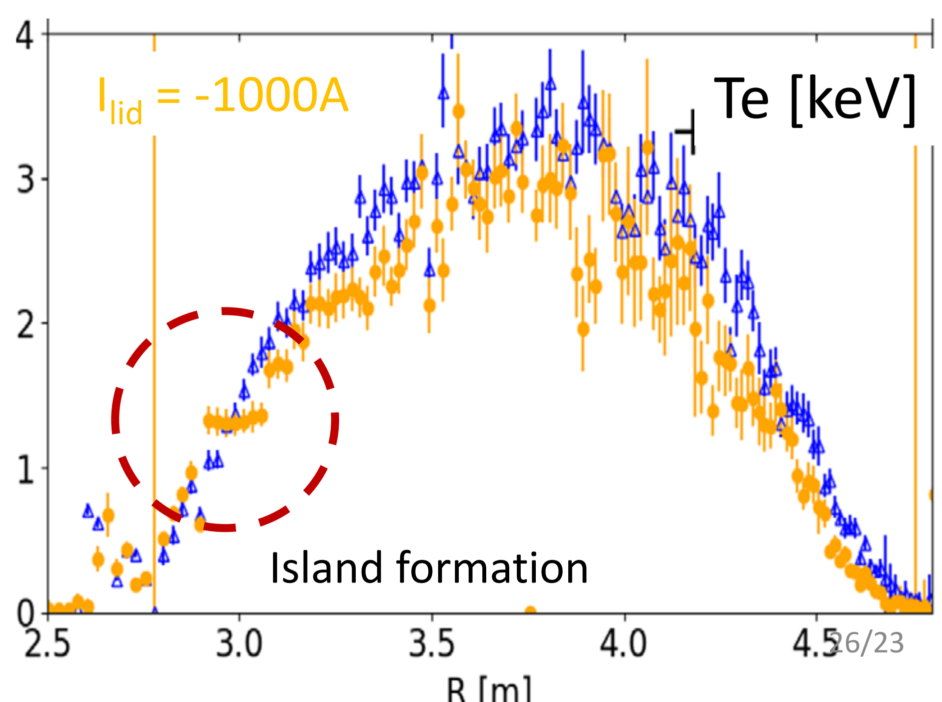
1. Reduce the pressure gradient of the EPs. (not preferable for heating)
2. Decouple the MHD and EPs. (ECH heating)
3. Stabilized the resistive interchange mode. (RMP application)

Scan of the RMP field with 2 density range

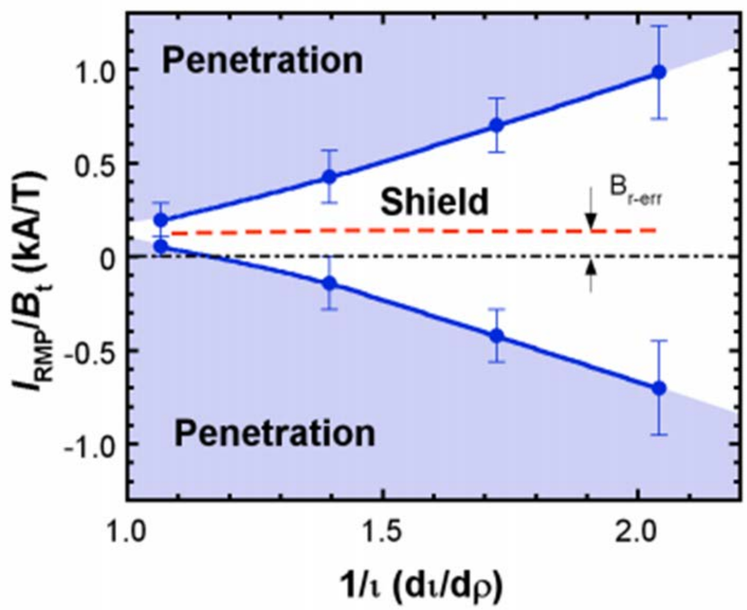


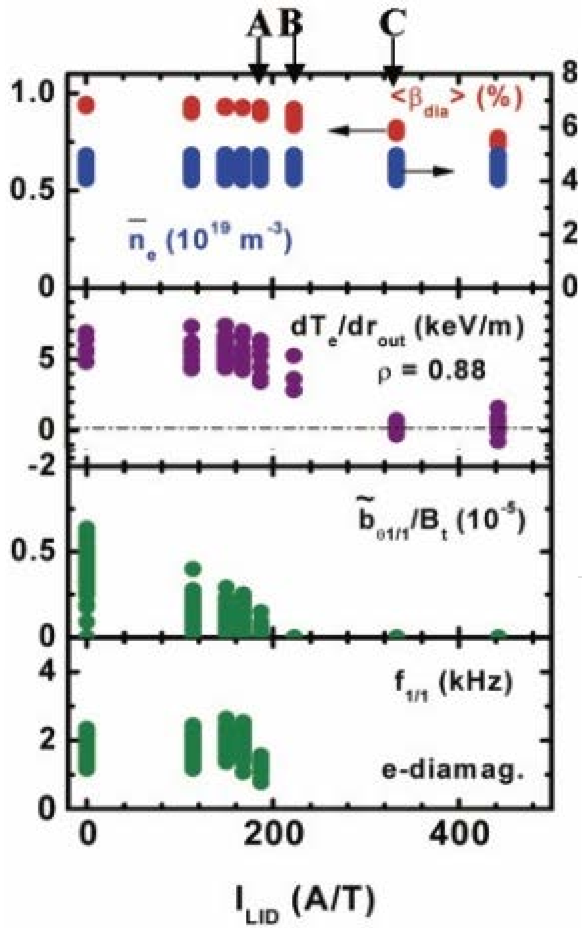
- EIC bursts disappears when the external field penetrate the plasma.

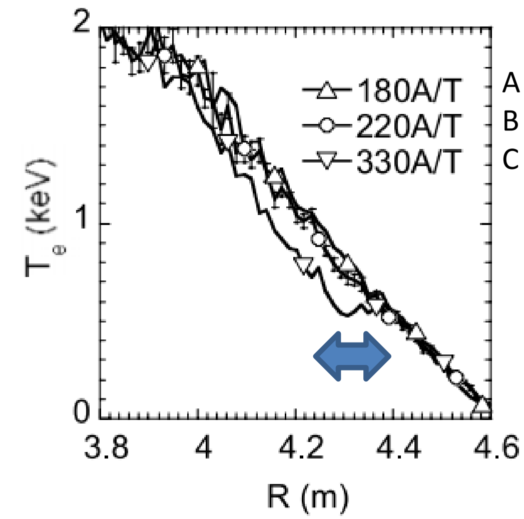
- In lower density regime, where EIC is more unstable, RMP does not affect the appearance of the EIC.



Penetration of the RMP field and MHD instability







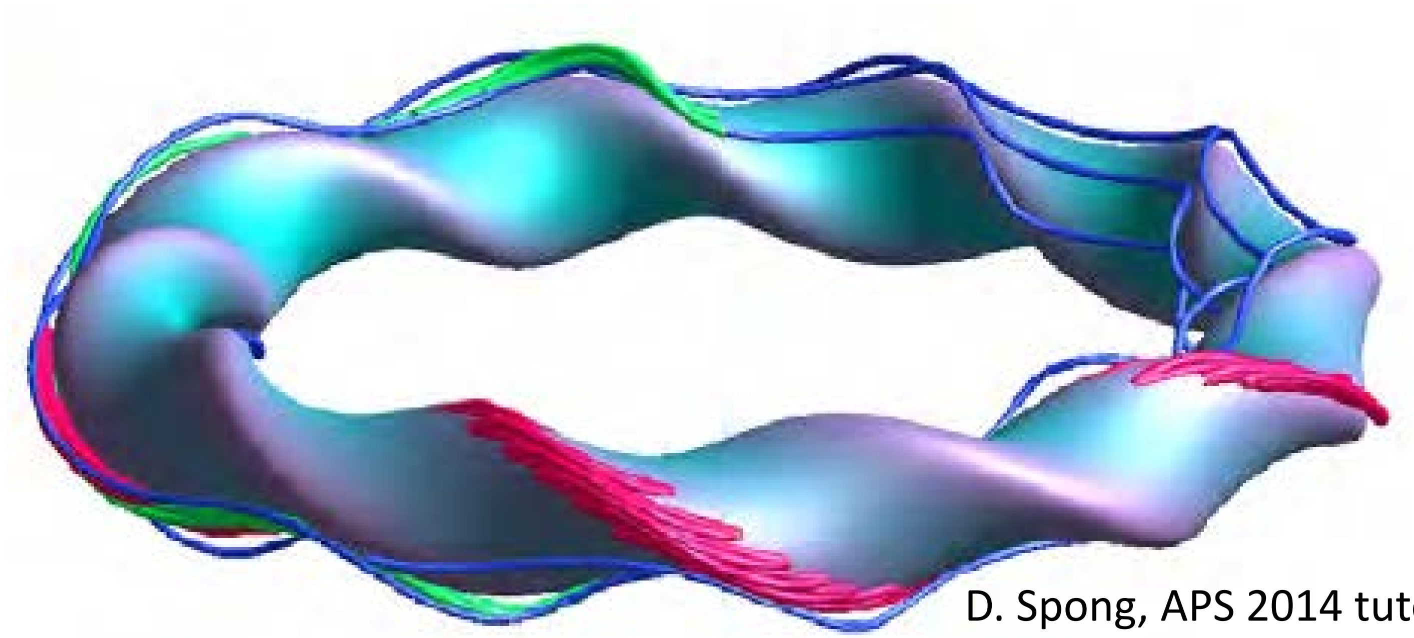
Case A: magnetic island is formed.

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.

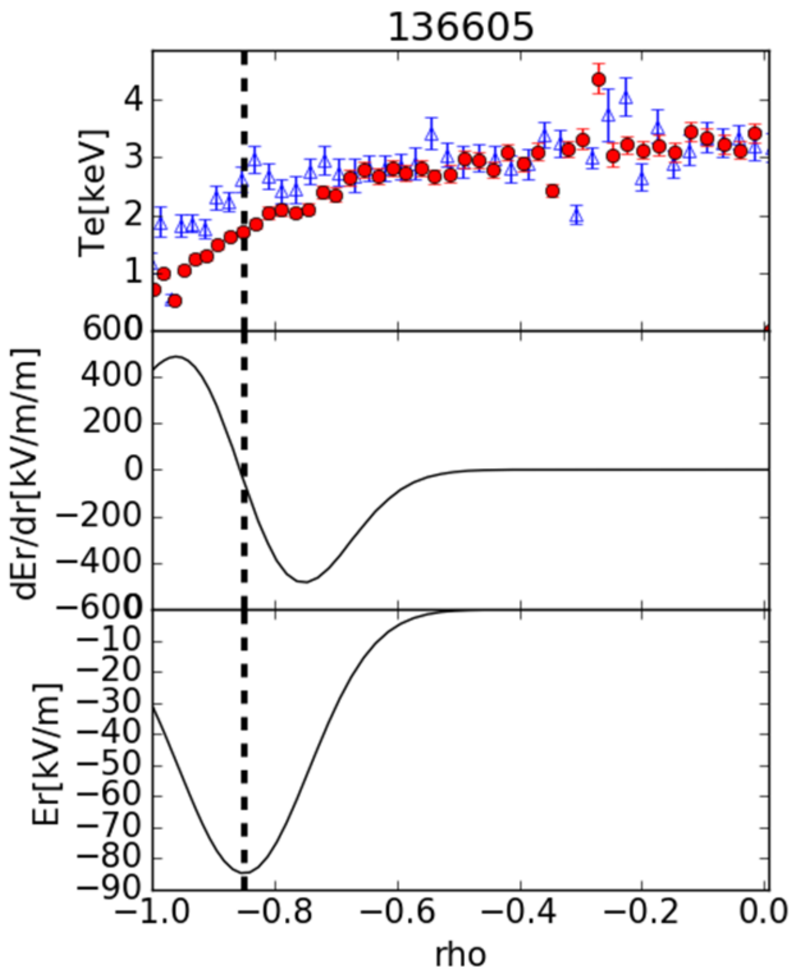
Magnetic field of LHD and EP orbit



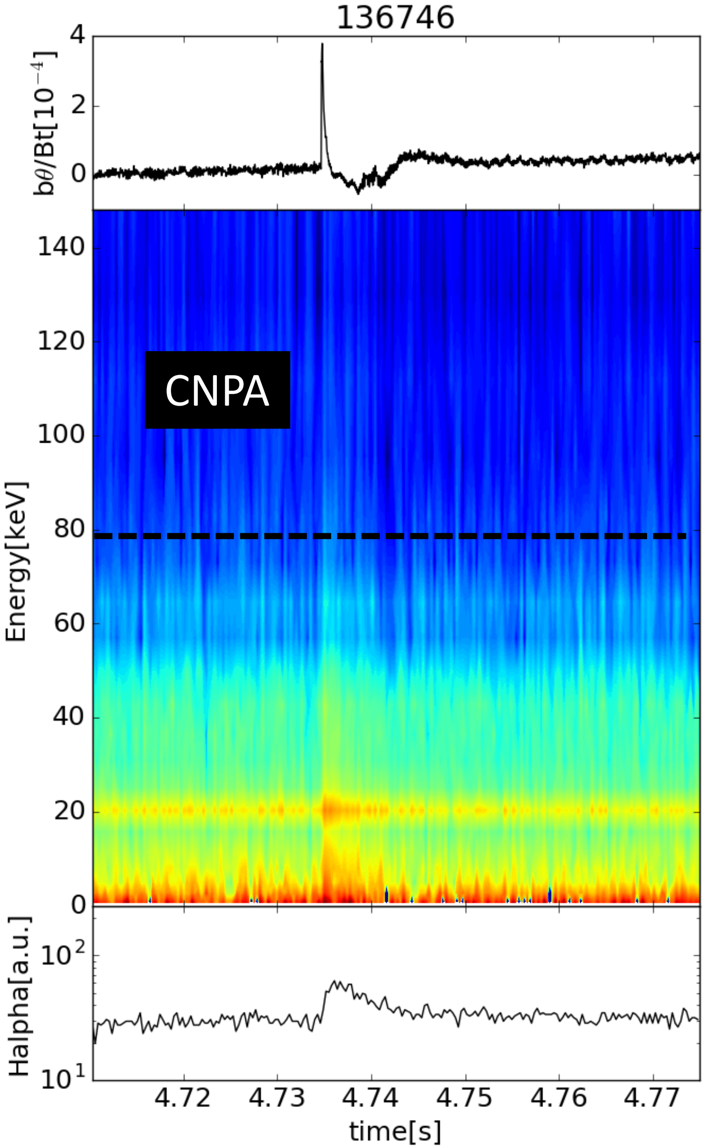
D. Spong, APS 2014 tutorial talk.

- There are three type of the orbit in Heliotron-type device, such as LHD.
- The passing, the helically trapped and the transitional particles.

- The interaction between precession motion of the Eps and the MHD mode (resisitive interchange mode at iota =1 rational surface) is somewhat similar to Fishbone and off-axis Fishbone in Tokamaks.

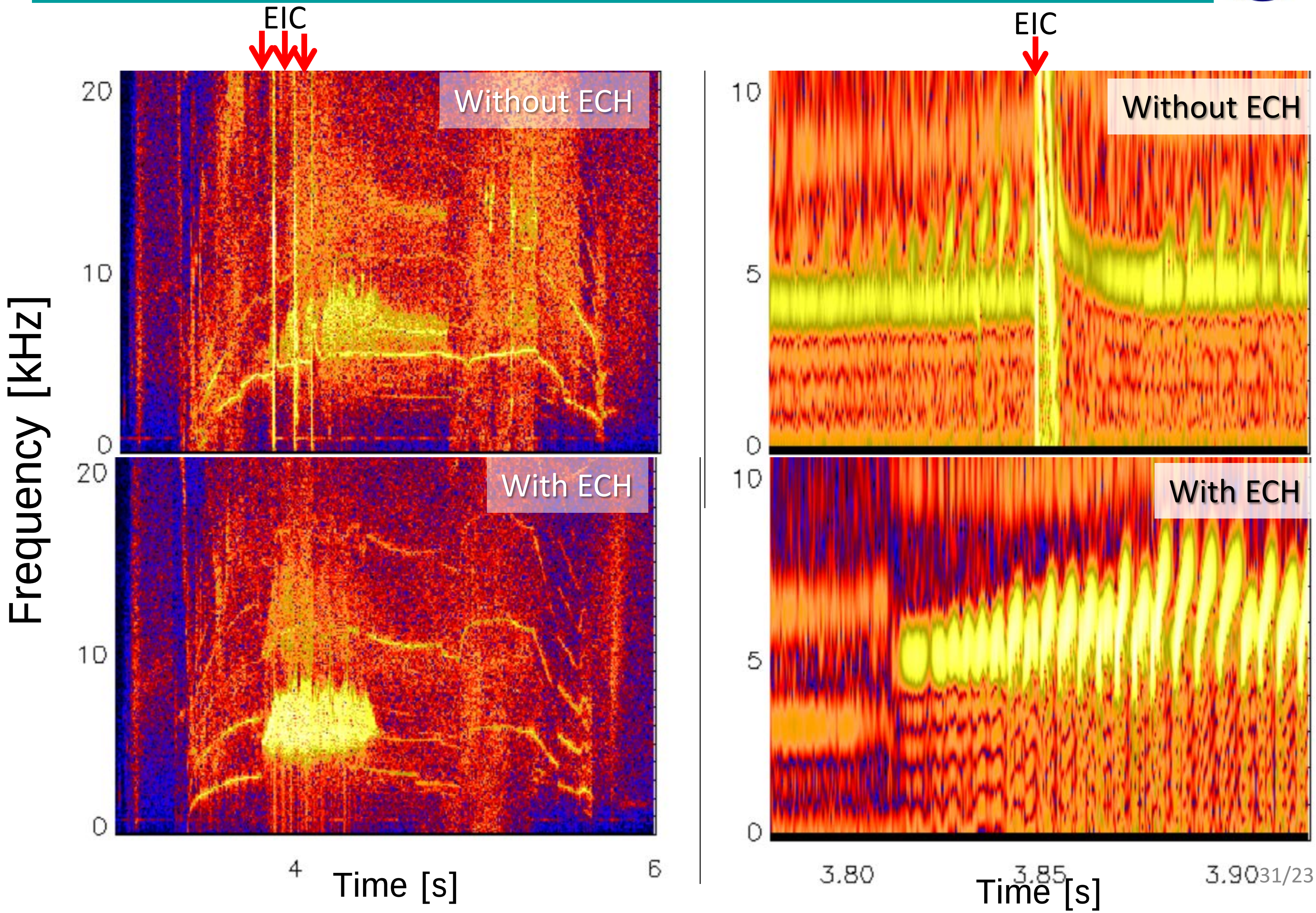

136605
Te[keV]
dEr/dr[kV/m/m]
Er[kV/m]
rho

Signals from CNPA seems to be response to EPs (~65keV)

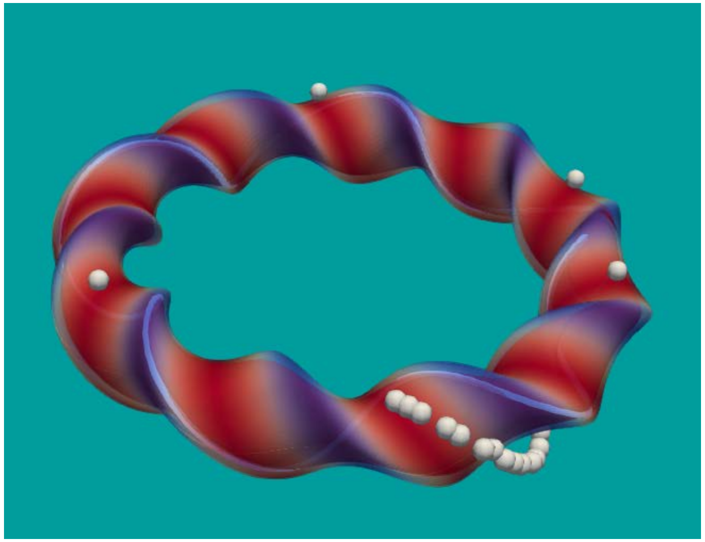


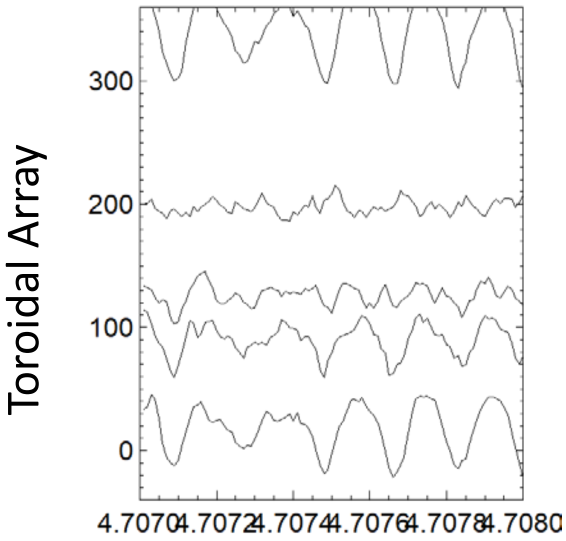
- When the EICs occur, the neutral flux measured by CNPA up to 60 keV increases when the injection beam energy of PERP-NBI is E_b ~65keV.
- Though the simultaneous increase of H/D alpha signals are observed, the increase of the neutral flux in higher energy region (60 ~150keV) is not observed.
- The increase of the neutral flux which energies are less than 60 keV may come from the change of the distribution of EPs caused by the EIC events.

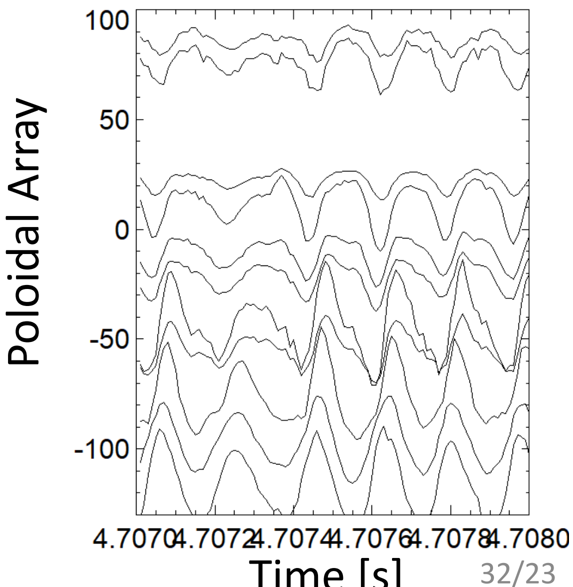
Magnetic fluctuations w/wo ECH



Precursor-like oscillation

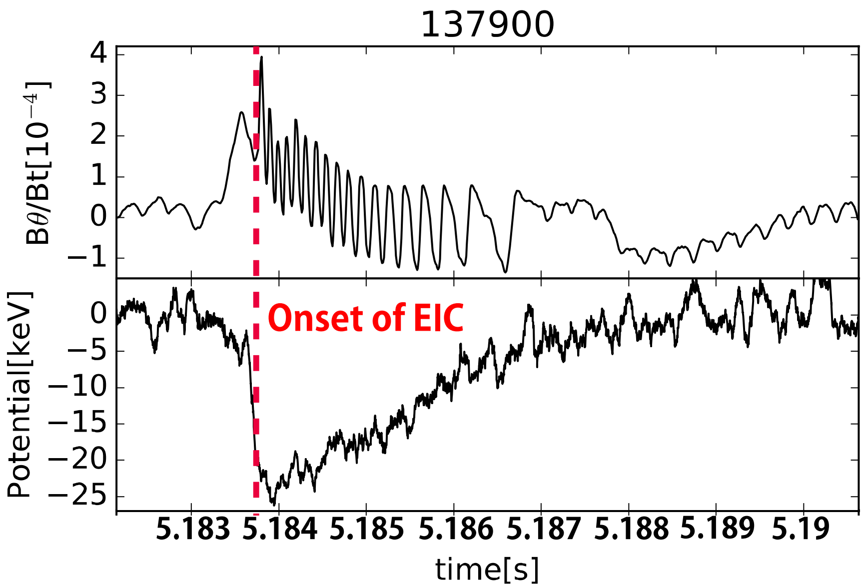


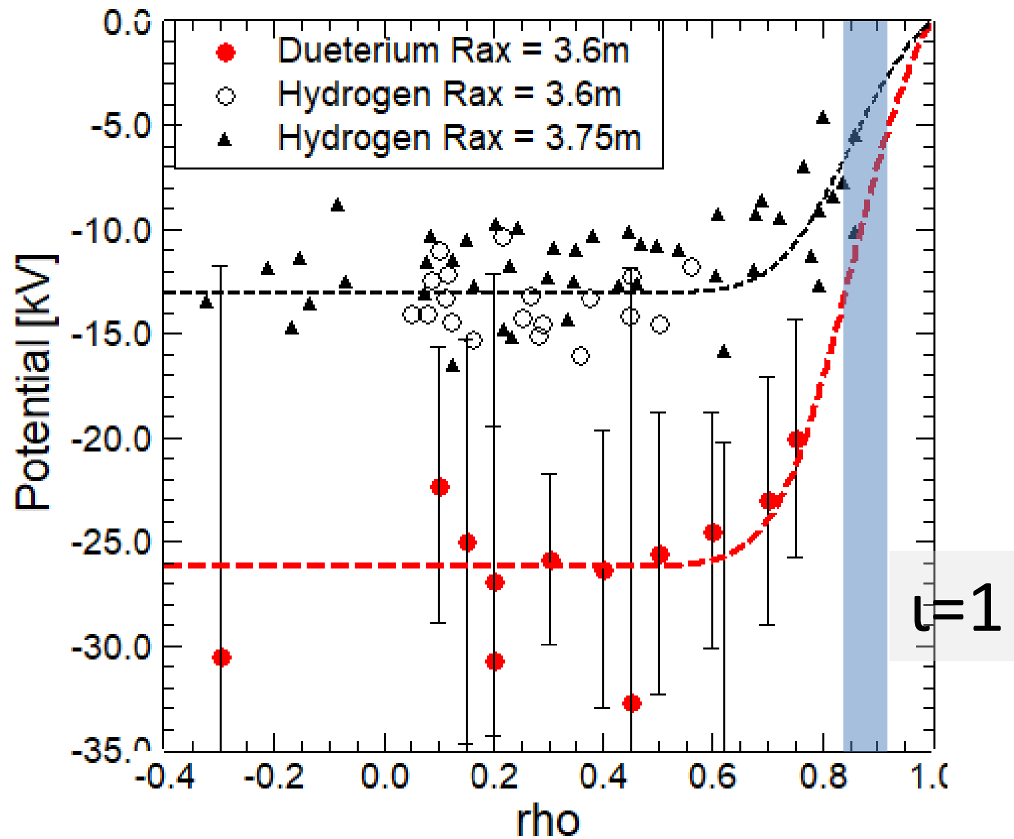




- Quite complex and not easy to understand.
- Stationary oscillation in toroidally and rotating poloidally.
- Sometimes it rotates toroidally.
- n=10, m=1???. (From the orbit,

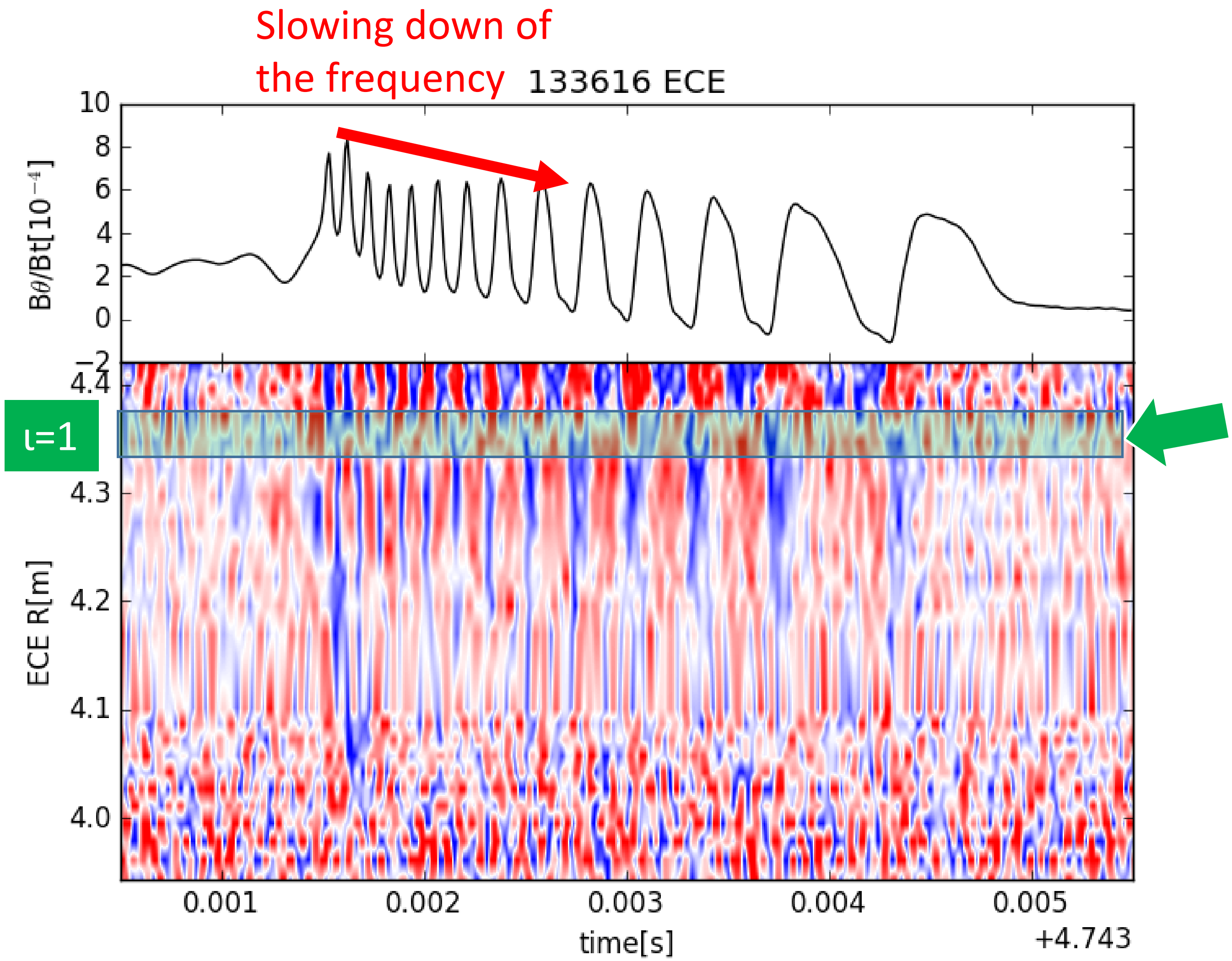
Formed electrostatic potential is larger in deuterium experiments





- The large negative electrostatic potential, ~25kV, is formed with expels of EPs by EICs.
- The formed potential is about two times larger than that of hydrogen experiments. The variation of potential occurs around ι=1 surface.

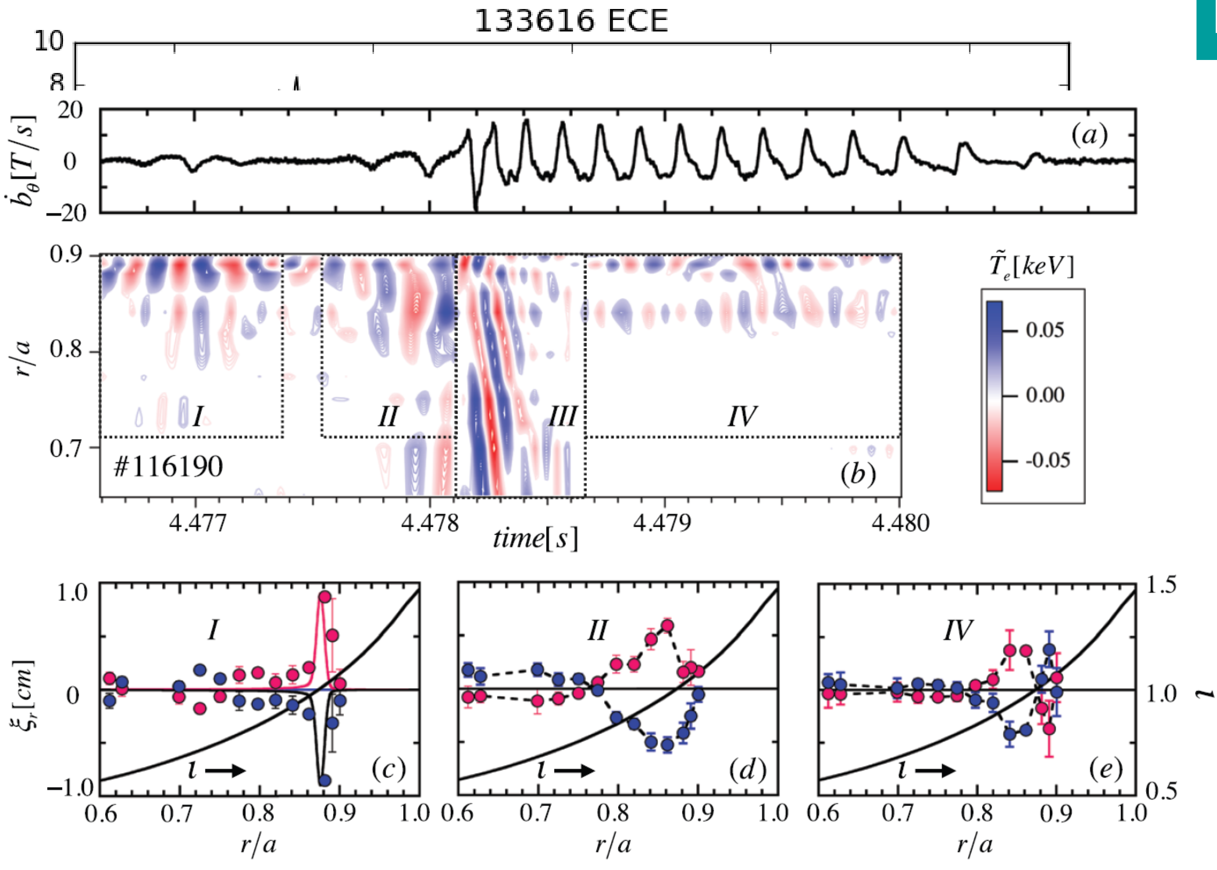
EICs localize at ι=1 surface

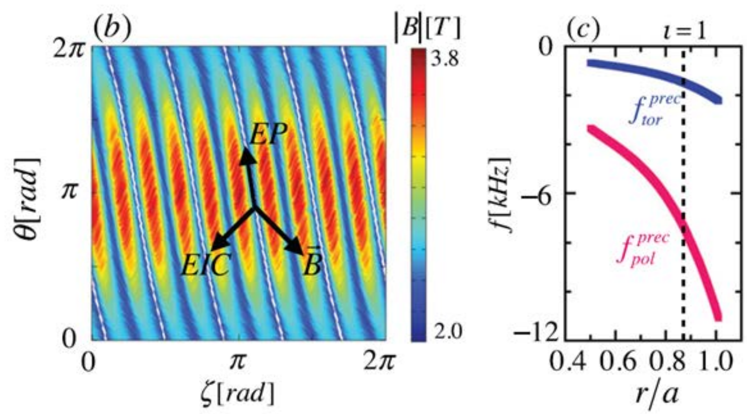


◆Chirping down oscillation with m/n=1/1 structure which localizes around ι=1 surface appears.

◆The eigenfunction has tearing parity same as hydrogen case.

ECE


133616 ECE
(a)
$\dot{b}_\theta[T/s]$
(b)
#116190
I
II
III
IV
r/a
time[s]
4.477
4.478
4.479
4.480
$\tilde{T}_e[keV]$
0.05
0.00
-0.05
(c)
(d)
(e)
$\xi_r[cm]$
r/a
ι


(b)
|B|[T]
3.8
2.0
EP
EIC
$\vec{B}$
θ[rad]
ζ[rad]
(c)
ι=1
f_{tor}^{prec}
f_{pol}^{prec}
f[kHz]
r/a

The threshold of for the excitation of the EICs may be larger in D beams, though neutron emission rate is not measured with H-beam.