EX/4-4

Extension of High-Beta Plasma Operation to Low Collisional Regime

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Outline

- Background and purpose of this study
- Experimental Setup
- High-beta experiments
  - Global properties of high-beta operations in low-collisional regime
    - Characteristics of high-beta discharges
      - Multi-pellet operations
      - Quasi-steady state operations with improvement of particle confinement
- Summary

Strategy of high beta experiments

<β> of 5.1 % was achieved in previous experiments

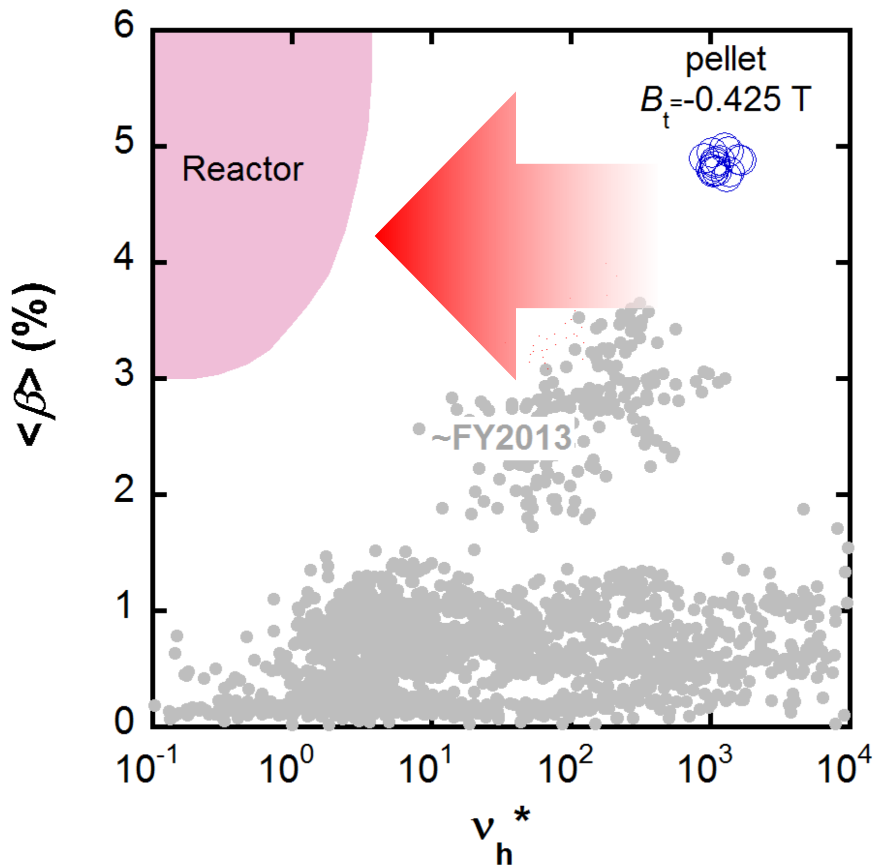
→ verify an ability in high beta plasma production in currentless plasmas

→ **Extension of database of non-dimensional parameters (β, S, ν^*, ρ^*)**

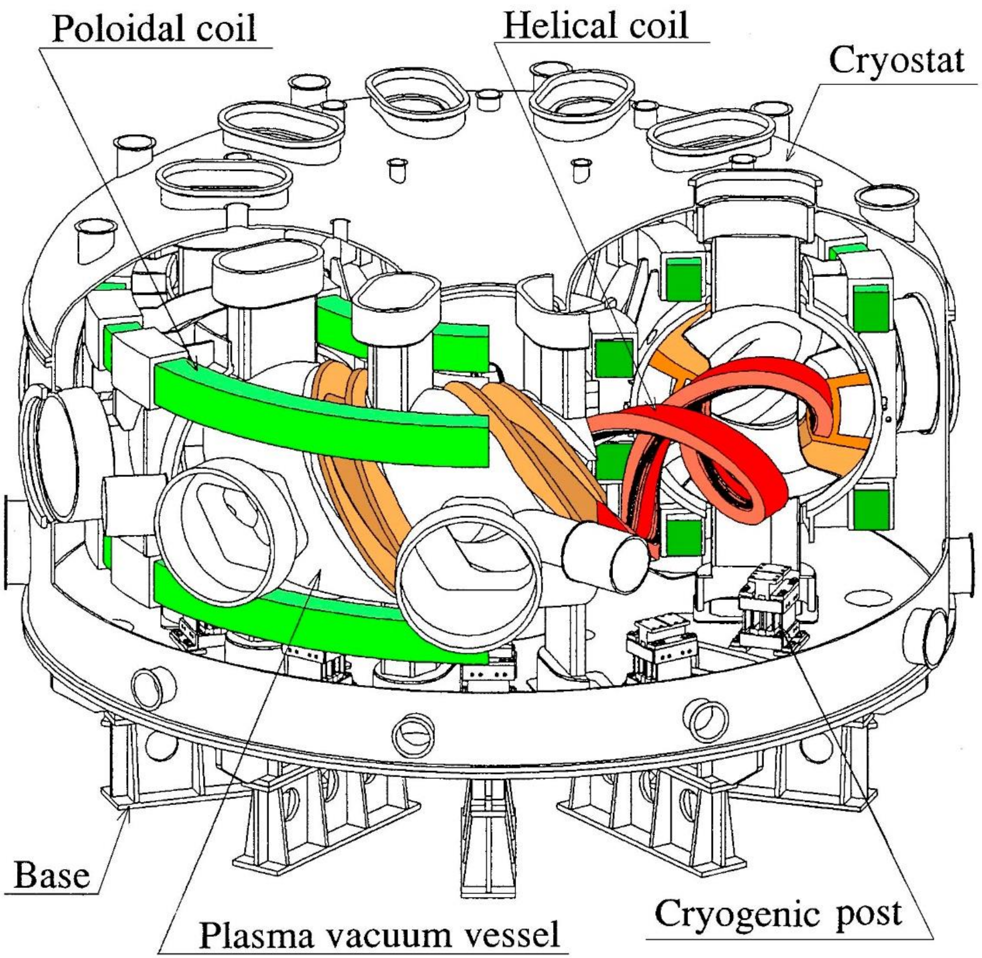
Physics Studies
Stability, Plasma confinement in ergodic regime, magnetic island dynamics, transport caused by turbulence etc.

⇒**high T and high β plasma is required**

Goal: <β> ~ 4 % at 1T
(**Final goal of LHD: 5 % at 1T**)



Large Helical Device (LHD)



- Experiments have been done since 1998
- All coils are superconductive.
- 10 pairs of RMP coils

Specification:

R = 3.5 ~ 4.1 m, a ~ 0.65 m

Maximum B_t ~ 3 T

Heating Power:

N-NBI 15 MW

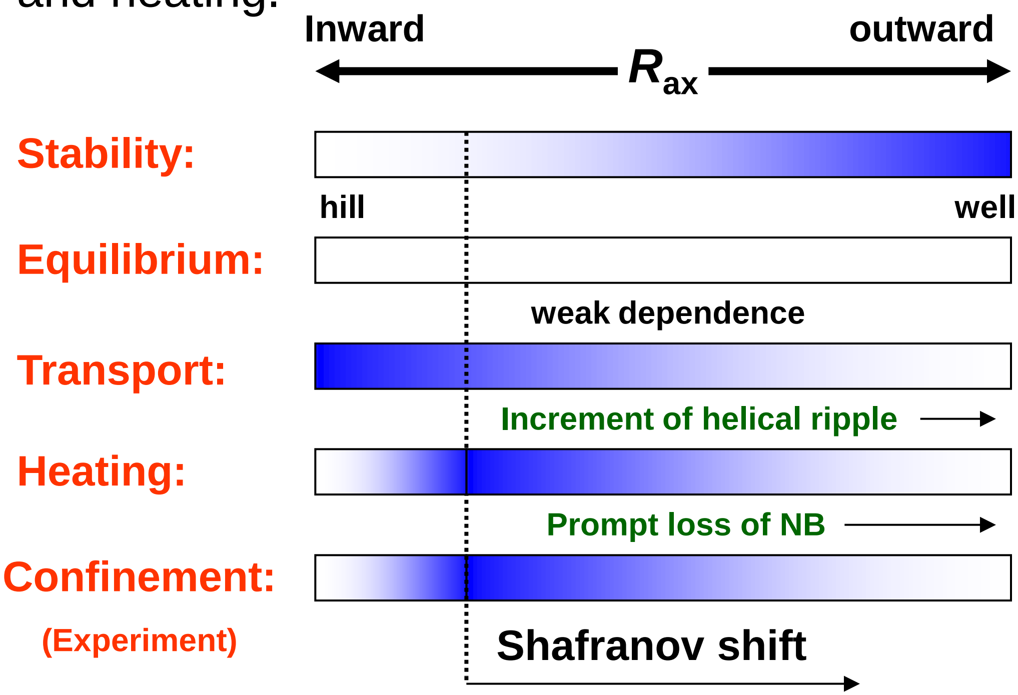
P-NBI (perp.) 10 MW

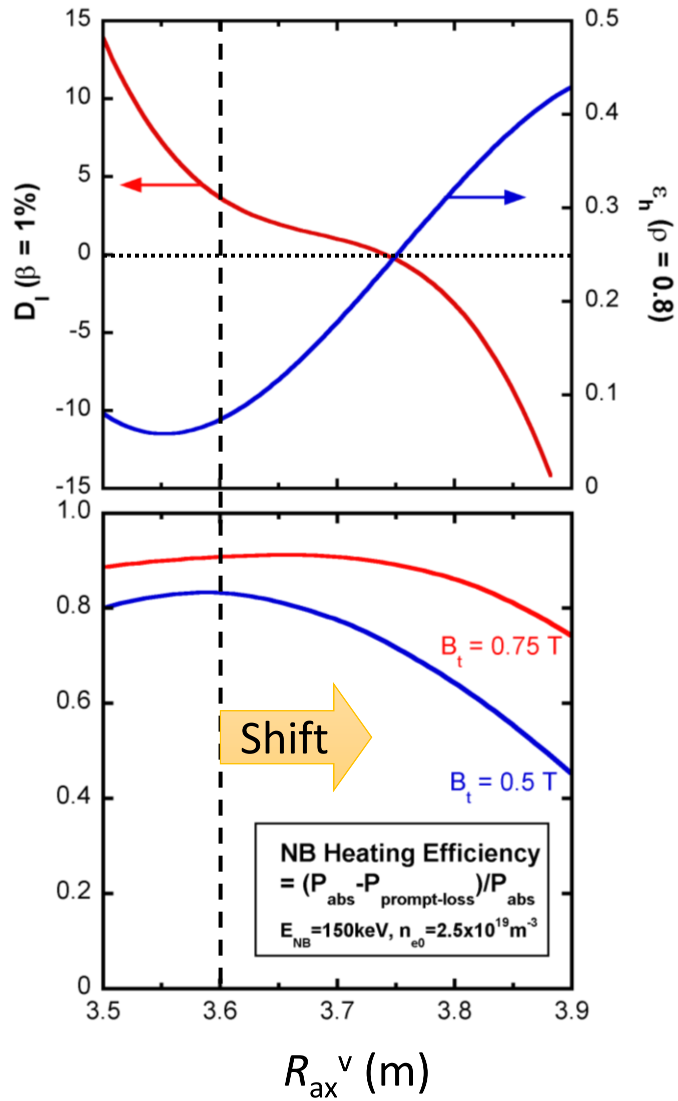
ICRF < 3 MW

ECH ~ 2 MW

R_{ax} is a key parameter for high-beta

R_{ax}^{v} (Magnetic axis in vacuum) is important for optimizing characteristics of MHD, transport and heating.





Shafranov shift deteriorates transport and heating efficiency, although it is valid for stability

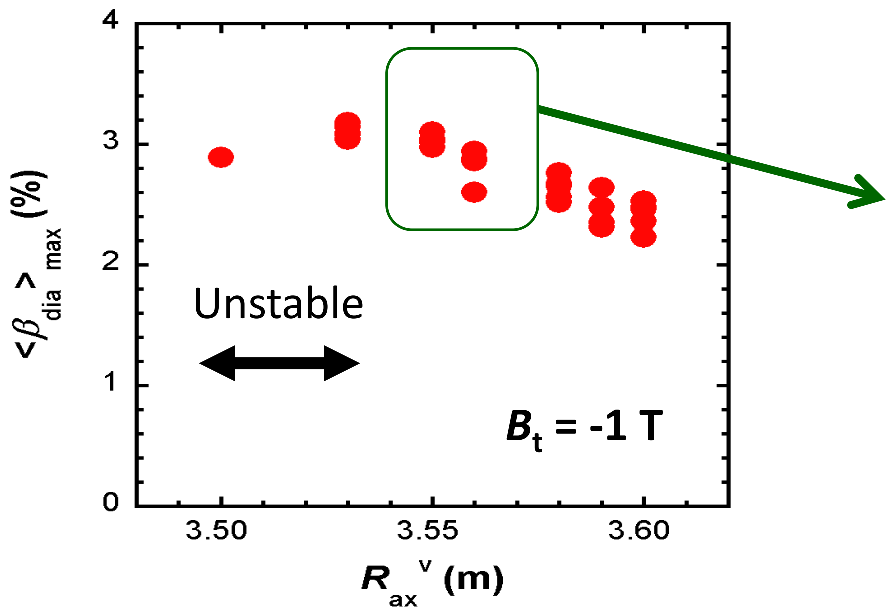
R_{ax}^{v} scan experiments for high-beta

- R_{ax}^{v} scan experiments were done in condition with constant heating power and electron density

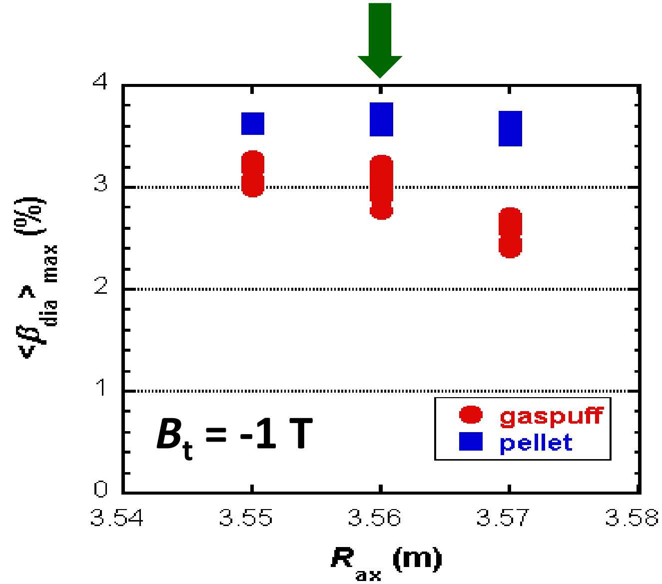
- Core instabilities were excited in the configuration with $R_{ax}^{v} < 3.55$ m

  ⇒R_{ax}^{v} of 3.56 m was selected

R_{ax}^{v} scan with n_e constant



Optimum R_{ax}^{v} for pellet and gas-puff



<β> of 4.1% was successfully achieved

High beta operation has been extended to low collisional regime

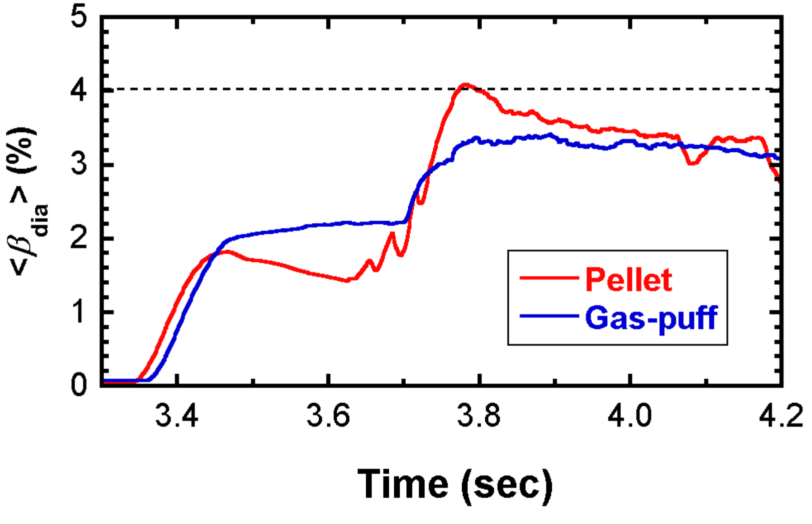
- ✓ Multi-pellet injections (Maximum beta)

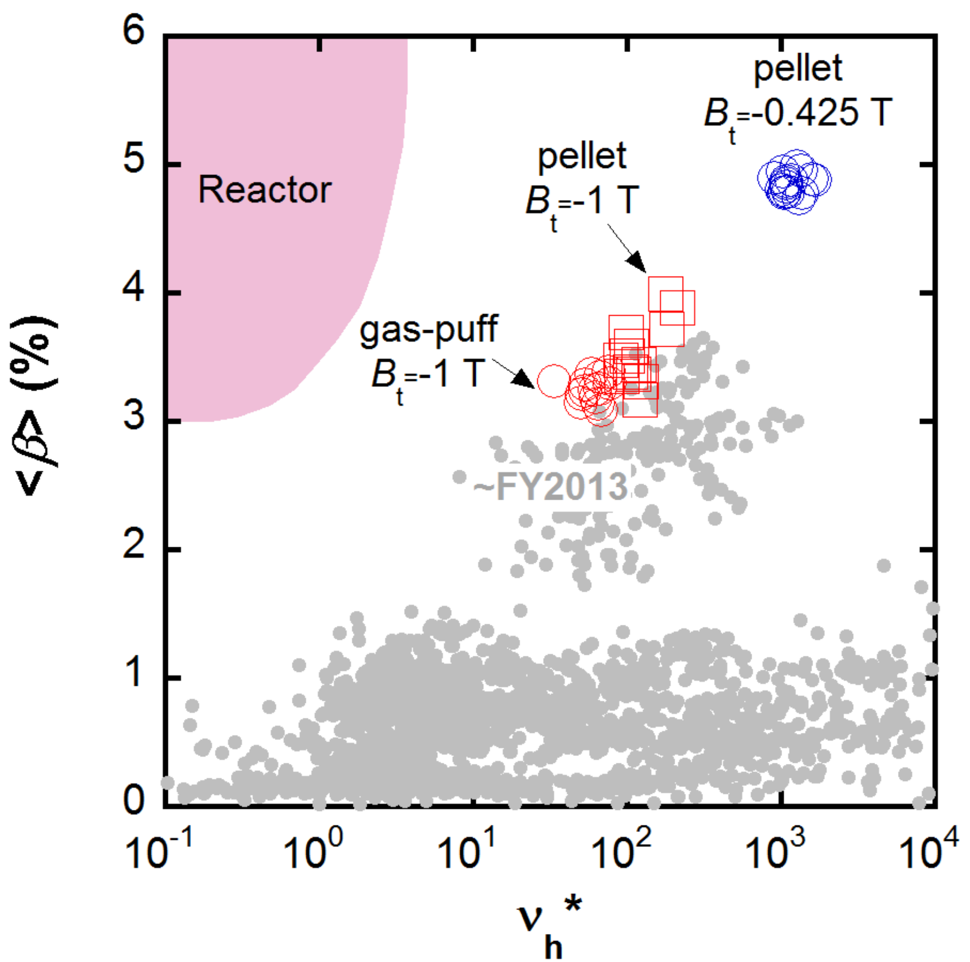
  ⇒**4.1** % (T_{e0} = 0.9 keV, n_{e0} = 6 × 10^{19} m^{-3})

- ✓ Gas puff (Quasi-steady state)

  ⇒**3.4** % (T_{e0} = 1.2 keV, n_{e0} = 3 × 10^{19} m^{-3})

R_{ax}^{v} = 3.56 m, B_t = -1T, A_p = 5.8

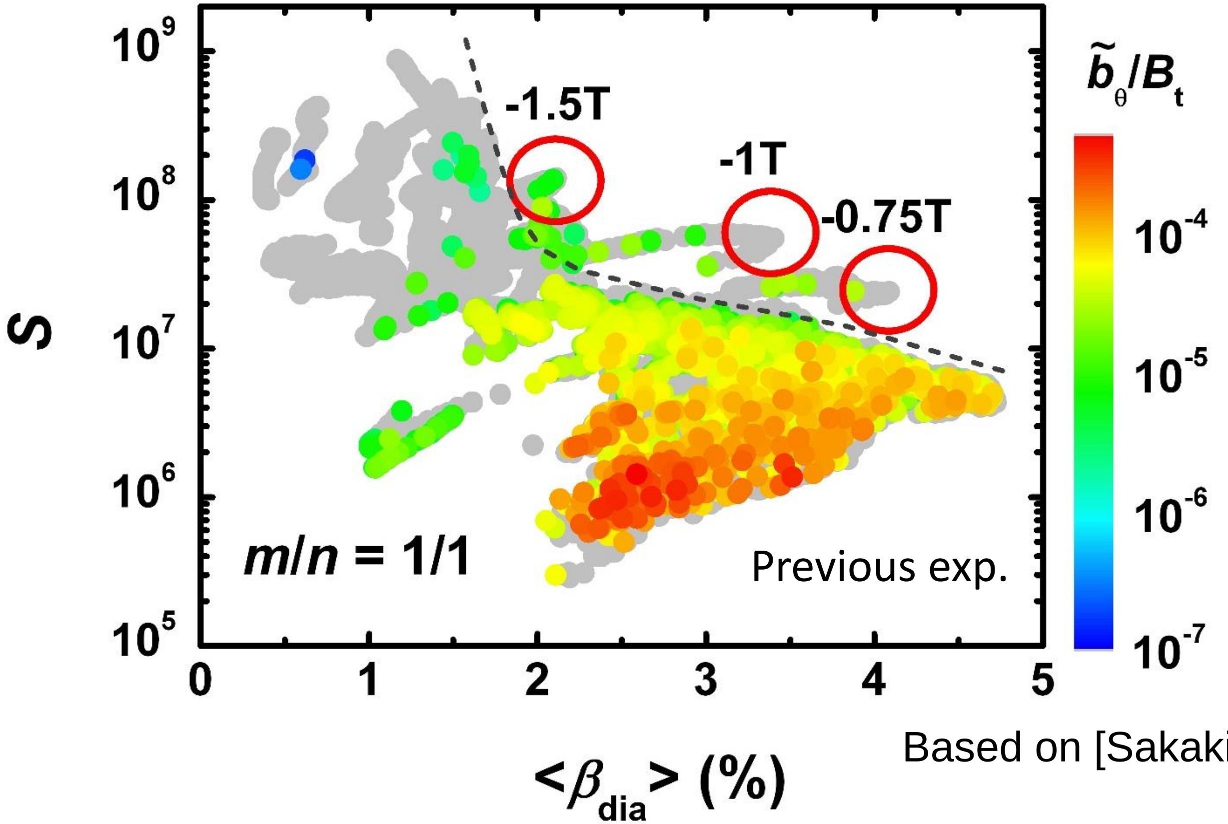




Low-*n* instabilities are suppressed with the increase in *S*

Increase in *S* suppresses the amplitude of low-*n* mode

- ✓ The amplitude of low-*n* modes depend on the beta and magnetic Reynolds number, *S*, which is consistent with prediction of linear theory.
- ✓ Results of low-ν* (high-*S*) experiments emphasize the obtained knowledge.



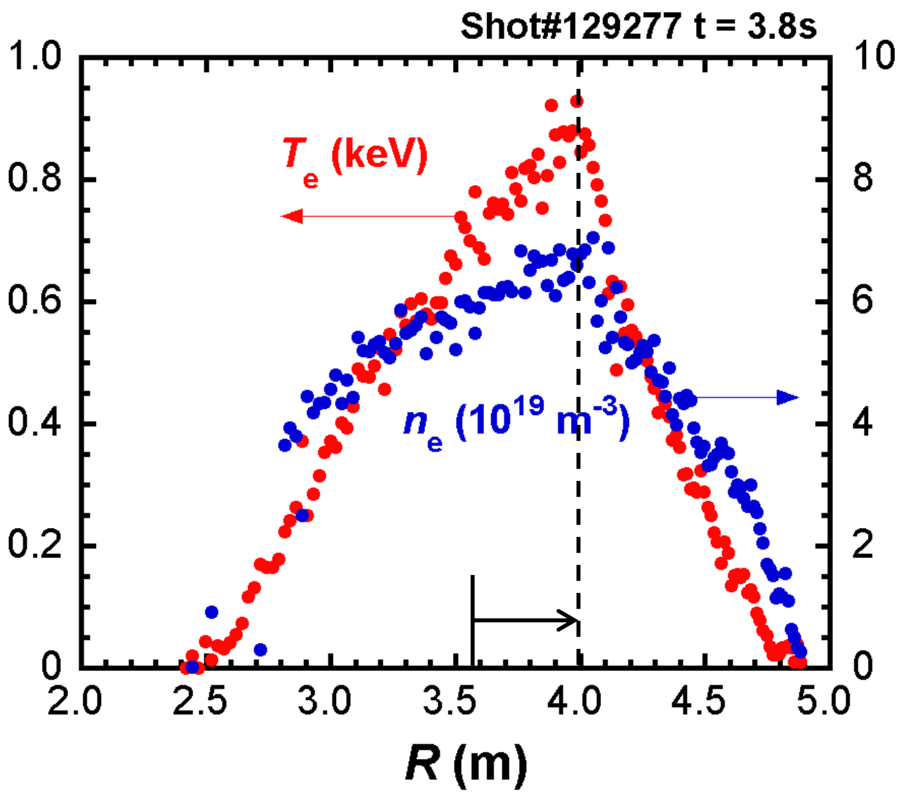
Based on [Sakakibara PPCF2008]

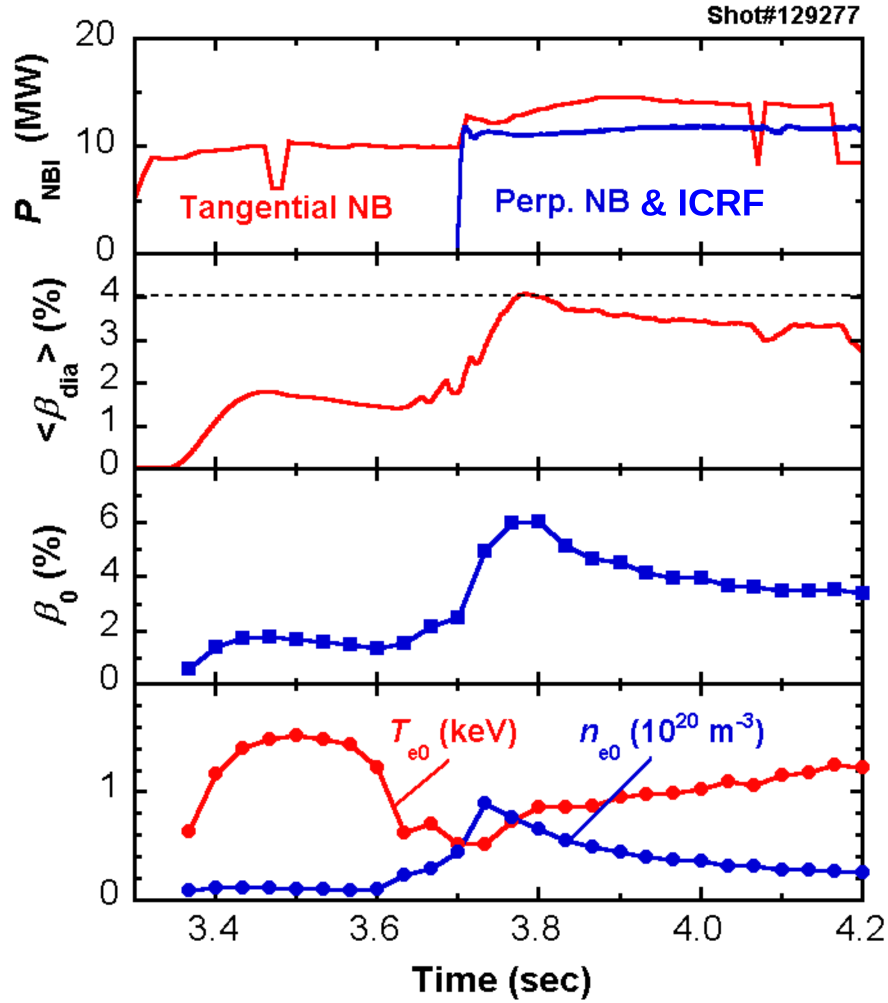
Comparison between Pellet and Gas-puff

	Pellet discharge	Gas-puff discharge
Achieved <β>	**4.1** %	**3.4** %
Duration time	< 0.1 s	> 0.5 s (limited by heating)
T_{e0}	**0.9** keV (0.2 keV at B_t = 0.425 T)	**1.2** keV (< 0.5 keV at B_t = 0.425 T)
n_{e0}	6×10^{19} m^{-3}	3×10^{19} m^{-3}
P Profile	Peaked profile	Broaden profile
R_{ax} shift	～0.44 m	～ 0.29 m
Improvement of particle confinement	Unclear (short duration)	**Clear**
Stability	Core instability	Edge instability
subjects	Long time duration	Stability control Fueling to core

High-beta discharge with pellet injections

- ✓ Pellets were injected in NB and ICRF plasma
  - → Peaked n_e and T_e profiles were formed
- ✓ Central beta ~ 7%
- ✓ Shafranov shift ΔR : ~ 0.44 m

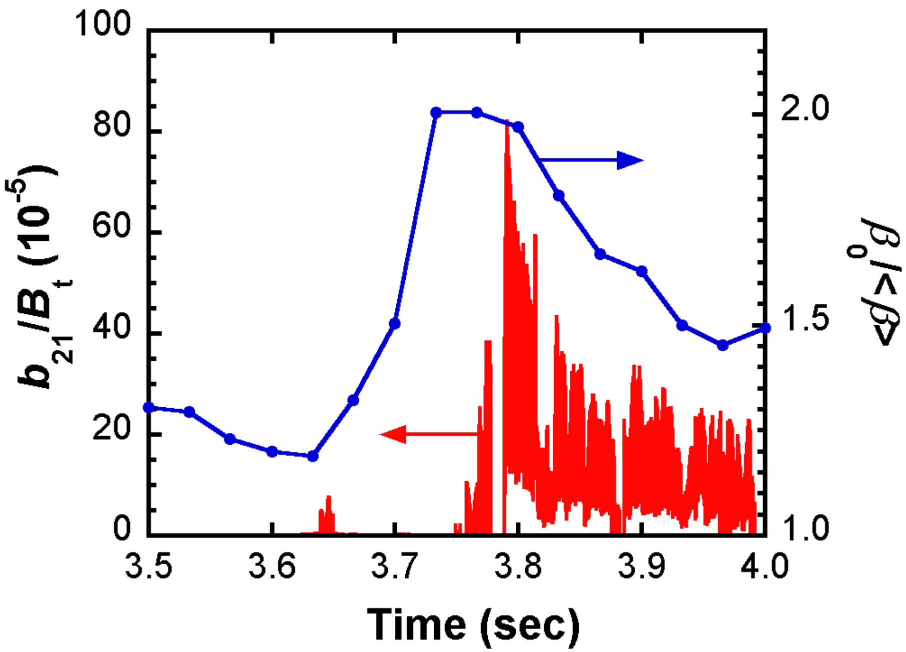


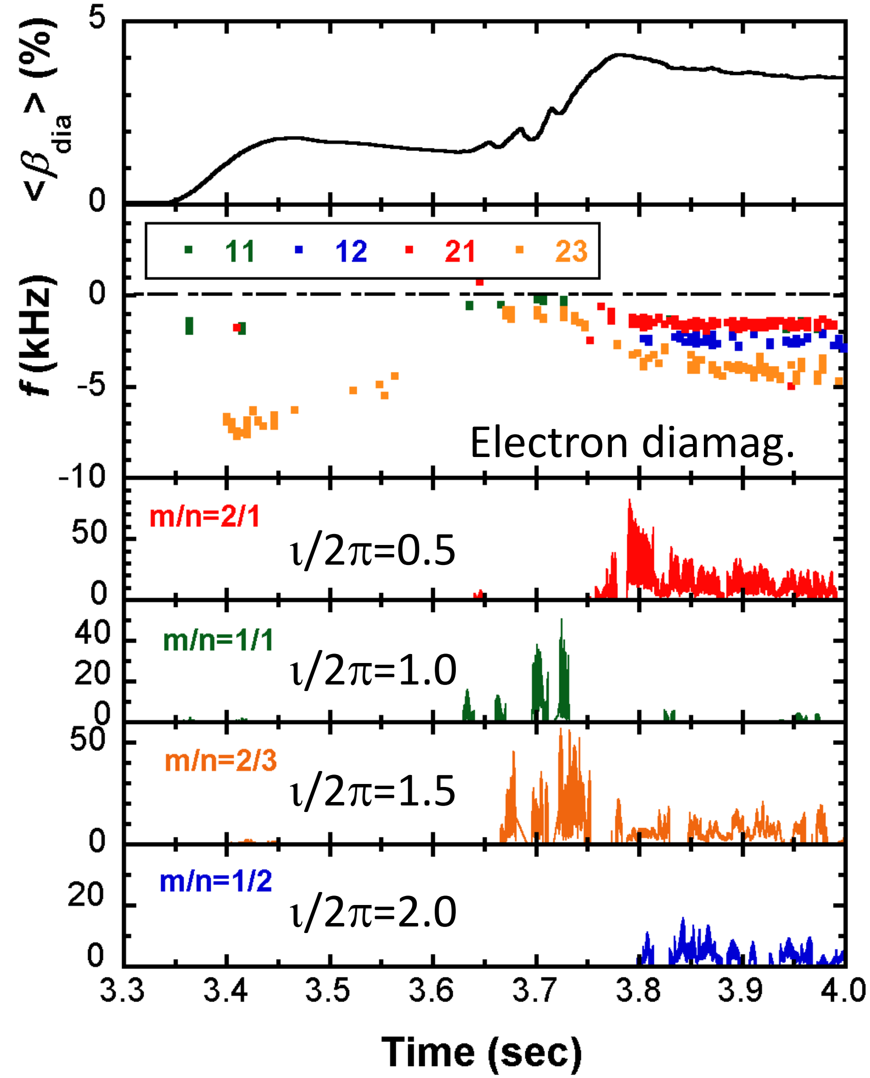


Appearance of Core MHD mode

- Pellet Discharge -

- ✓ Peaking of pressure profile leads to destabilization of core mode
  - → no profile flattening
  - → Increase in beta can stabilize the mode by Shafranov shift?
- ✓ No significant edge instability

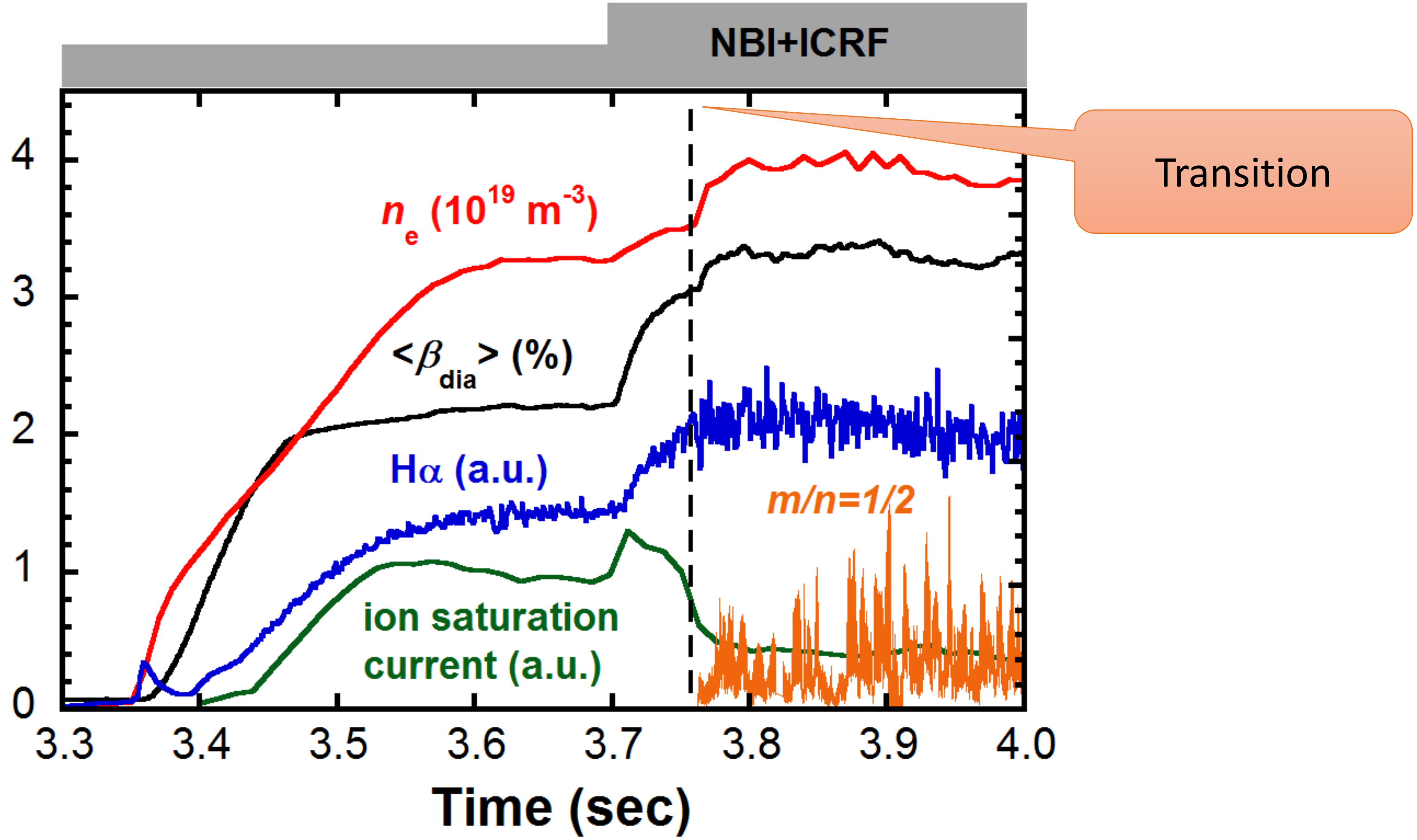




Quasi steady-state high beta discharge with more than 3% - Gas-puff -

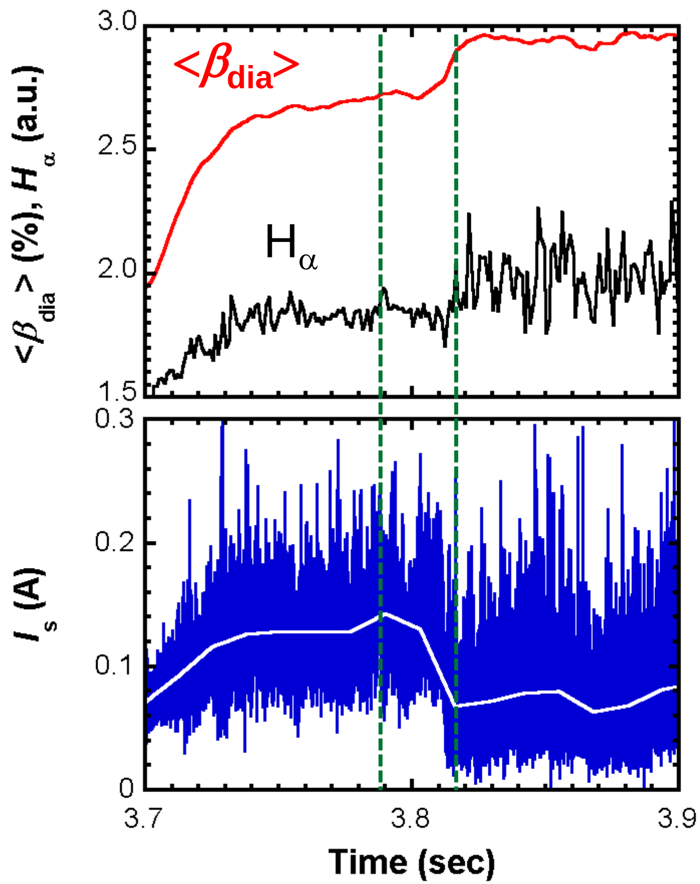
Transition phenomenon appears in quasi-steady state operation

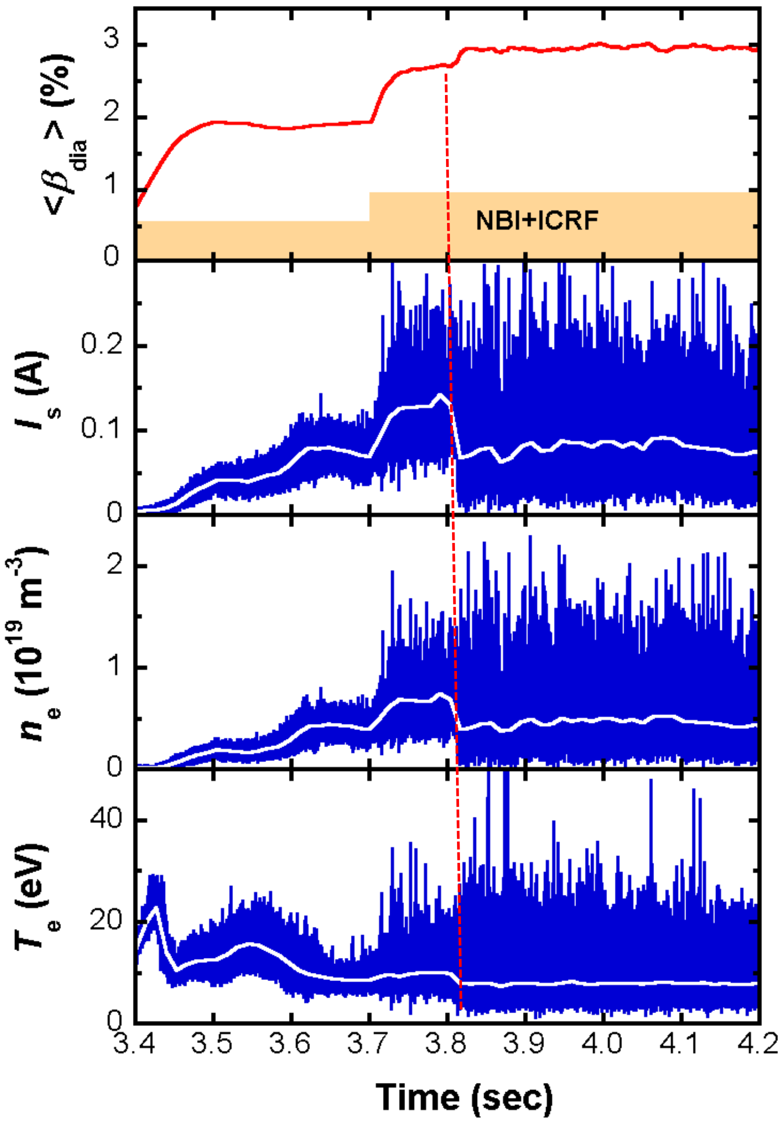
- ✓ Strong fluctuation appears ⇒limits the increase in beta
- ✓ Density fluctuation correlates with magnetic one



Particle flux to divertor reduces after the transition

- ✓ Ion saturation current and density reduce after the transition.
- ✓ Hα starts to decrease with IS current before transition.



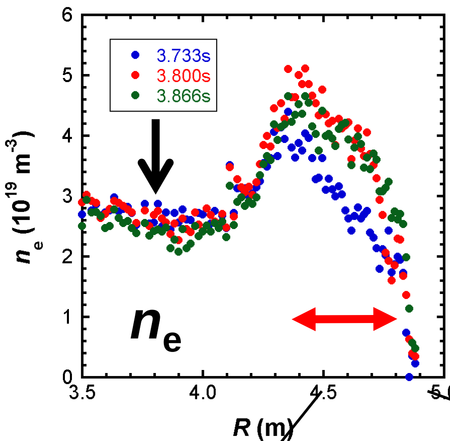


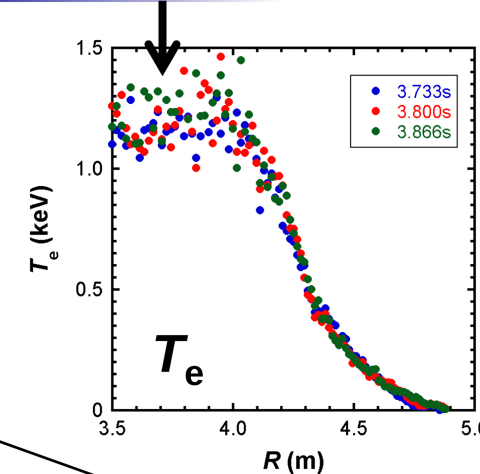
Changes of plasma profiles before and after transition

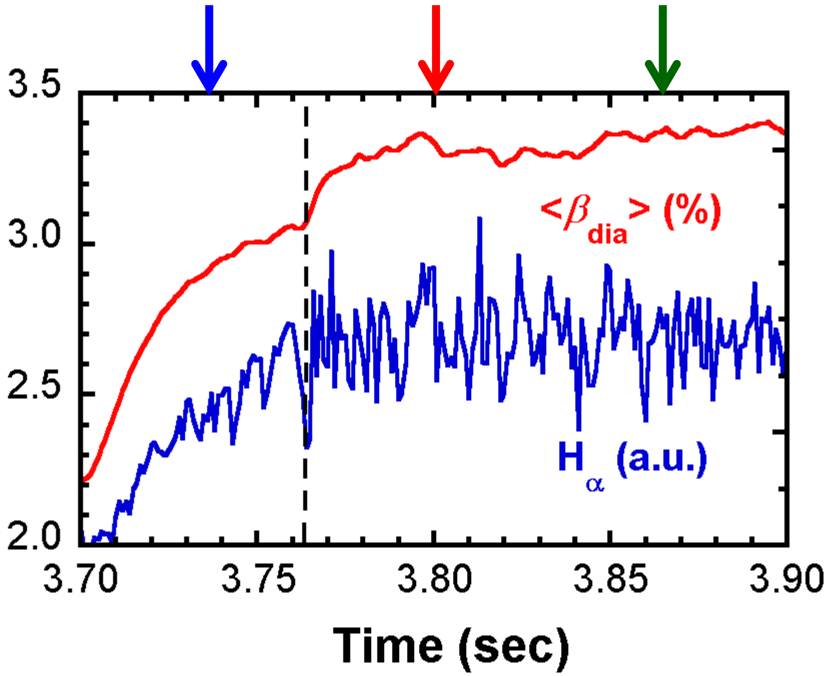
Increment of edge density after the transition [Toi, FST2010]

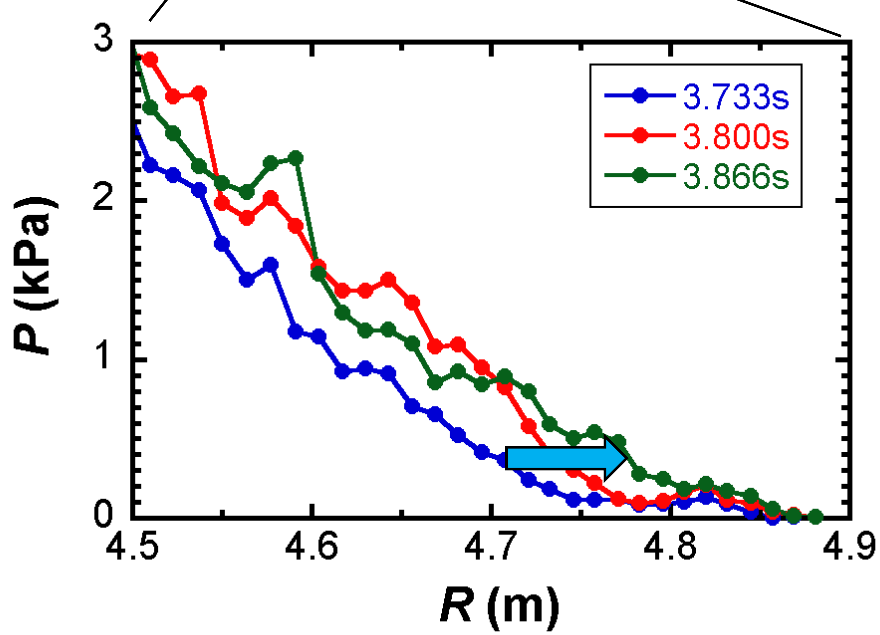
- ✓ No change of core density
- ✓ Extension of confinement region

⇒ Magnetic field structure is changed?



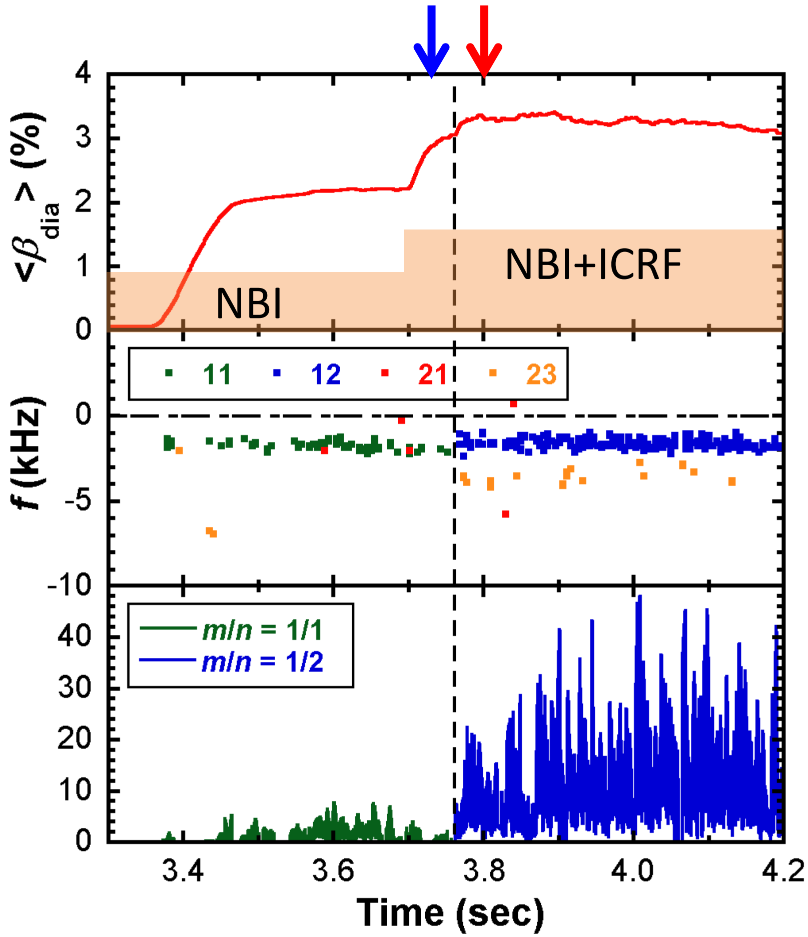


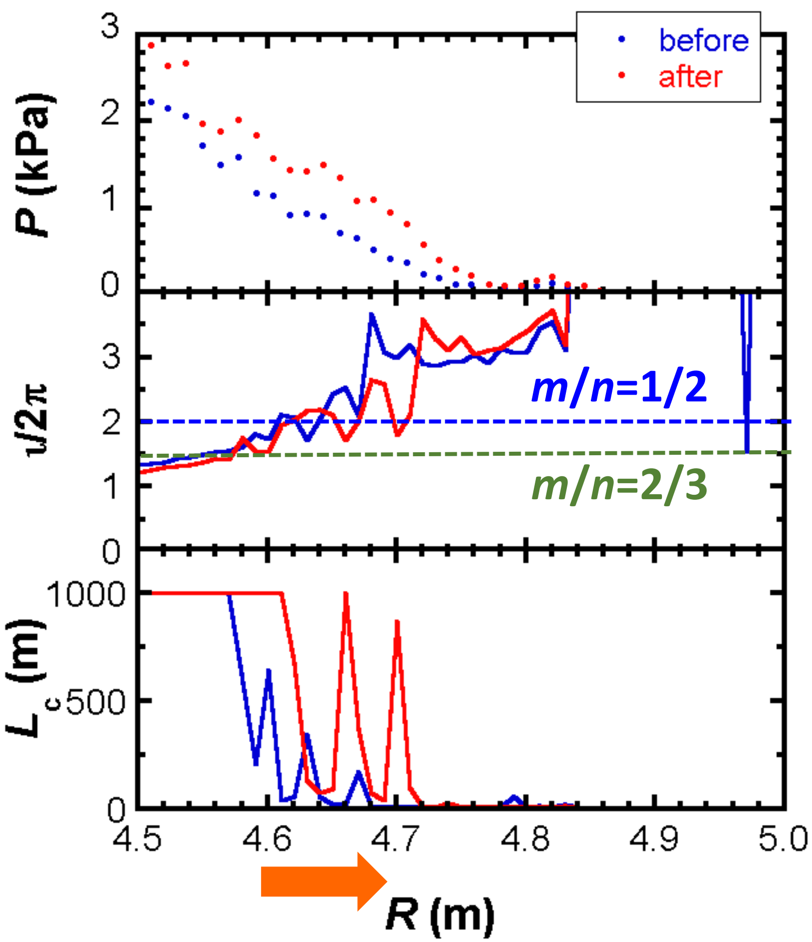




Confinement region is extended to the outward

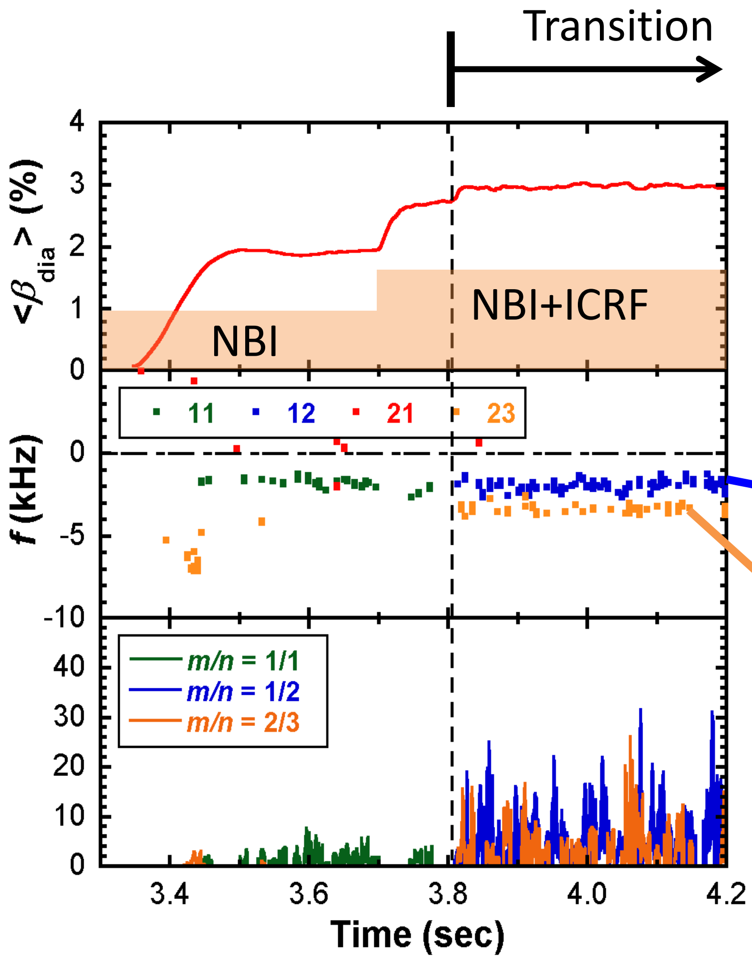
- ✓ Long L_c around $\iota/2\pi=2$ ⇒extension of confinement region
- ✓ New edge MHD instability is excited ⇒ limits the increase in β

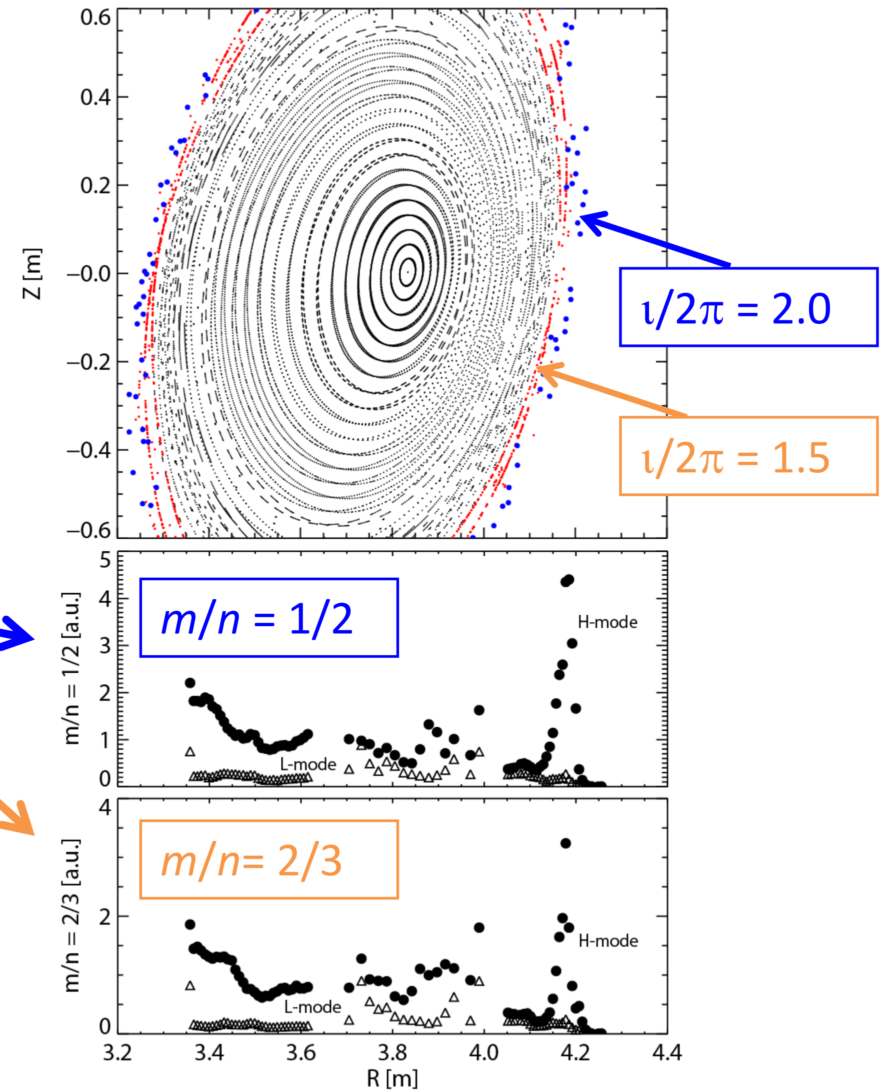




Radial structures of the modes measured with CO_2 interferometer

Observed modes are localized near edge





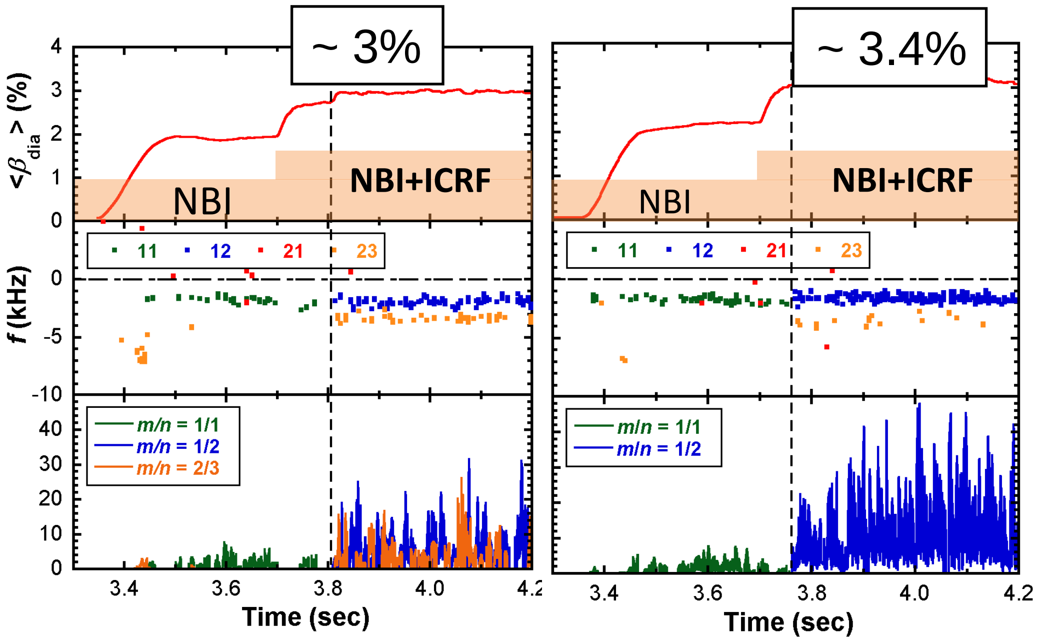
Change of dominant mode with beta

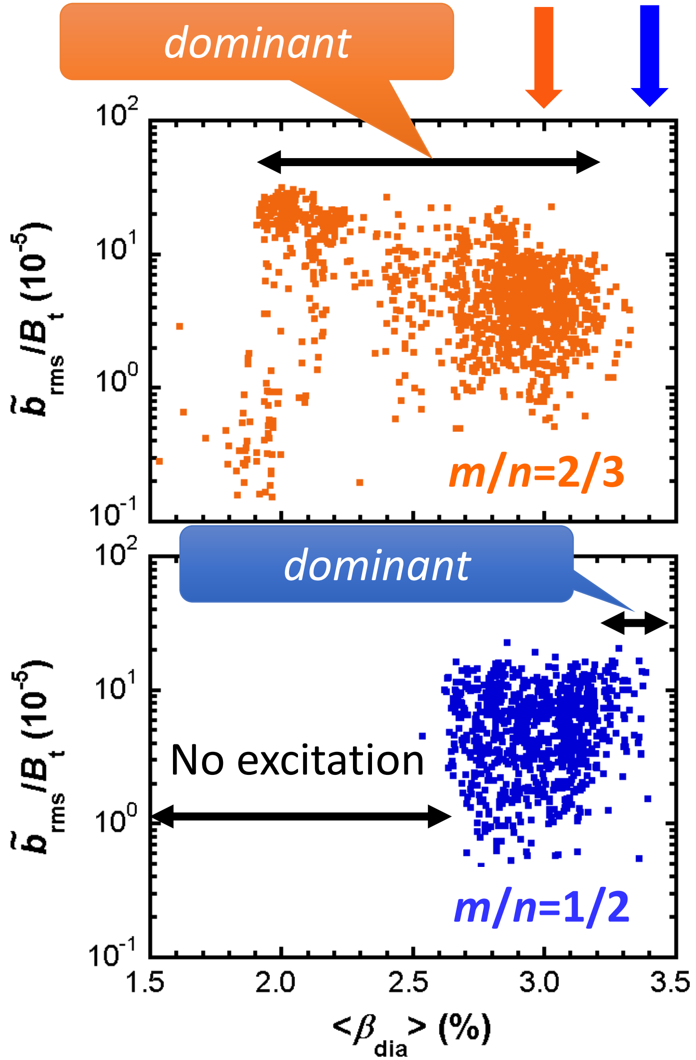
Resonance of the dominant mode : ι/2π=3/2→ 2/1

Extension of confinement region leads to appearance of new resonant surface.

- Dominant MHD mode is changed from inner region to outer one when β is increased.

[A.Komori, POP2004]





Discussion on Improvement of particle confinement

Experimental observation

- The transition with the spontaneous increase in <β> is found in high-beta regime, which is caused by the increase in peripheral electron density
- After the transition, particle flux to divertor plate is obviously reduced
- Plasma boundary is shifted to the outward (Thomson scattering)
- Edge MHD instabilities are abruptly excited

Speculations

- **Extension of plasma boundary**

  magnetic field structure with short-Lc is changed to that with long-Lc (HINT2 calculation) → confinement region is extended → good particle confinement

- **Excitation of Edge MHD instabilities**

  → Appearance of new rational surface due to extension of long-Lc region

Change of magnetic topology is a key (ν*, β, configuration etc.)

[S.Sakakibara NF2013, PPCF2013]

Summary

High-beta experiments have been done in order to extend operation regime to low collisional one.

- ✓ Volume-averaged beta value of 4.1 % was achieved at 1 T by multi-pellet injections, and 3.4 % could be maintained for a long time by gas-puff fueling.
- ✓ Strong instability excited in the core was observed in multi-pellet discharges, which is expected to be stabilized by magnetic well formation due to the increase in beta.
- ✓ Maximum beta in steady-state discharge (gas-puff) is realized by improvement of particle confinement. The reduction of particle flux to divertor is obviously observed after the transition.
- ✓ Edge MHD instabilities excited after the transition limit the achieved beta.

Reference Materials

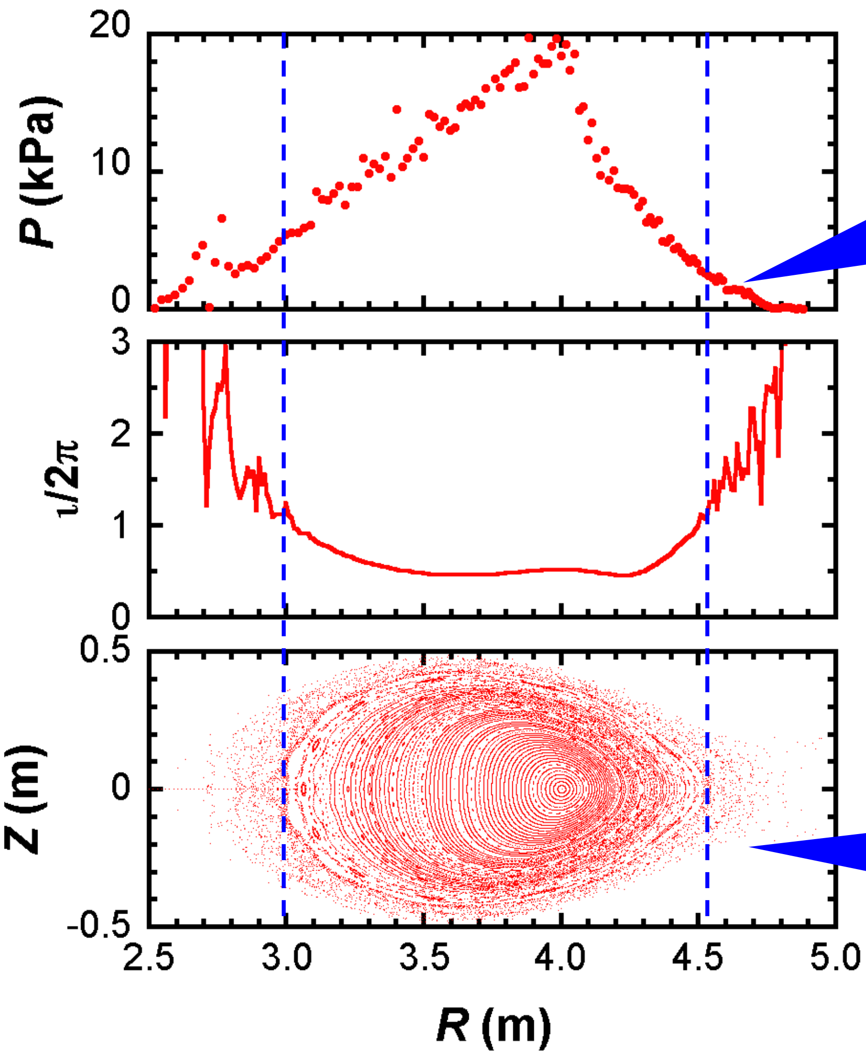
MHD Equilibrium in Pellet discharge

✓ HINT2 predicts extension of stochastic regime

Pressure profile

$\iota/2\pi$

Magnetic field structure



Plasma is confined in stochastic regime

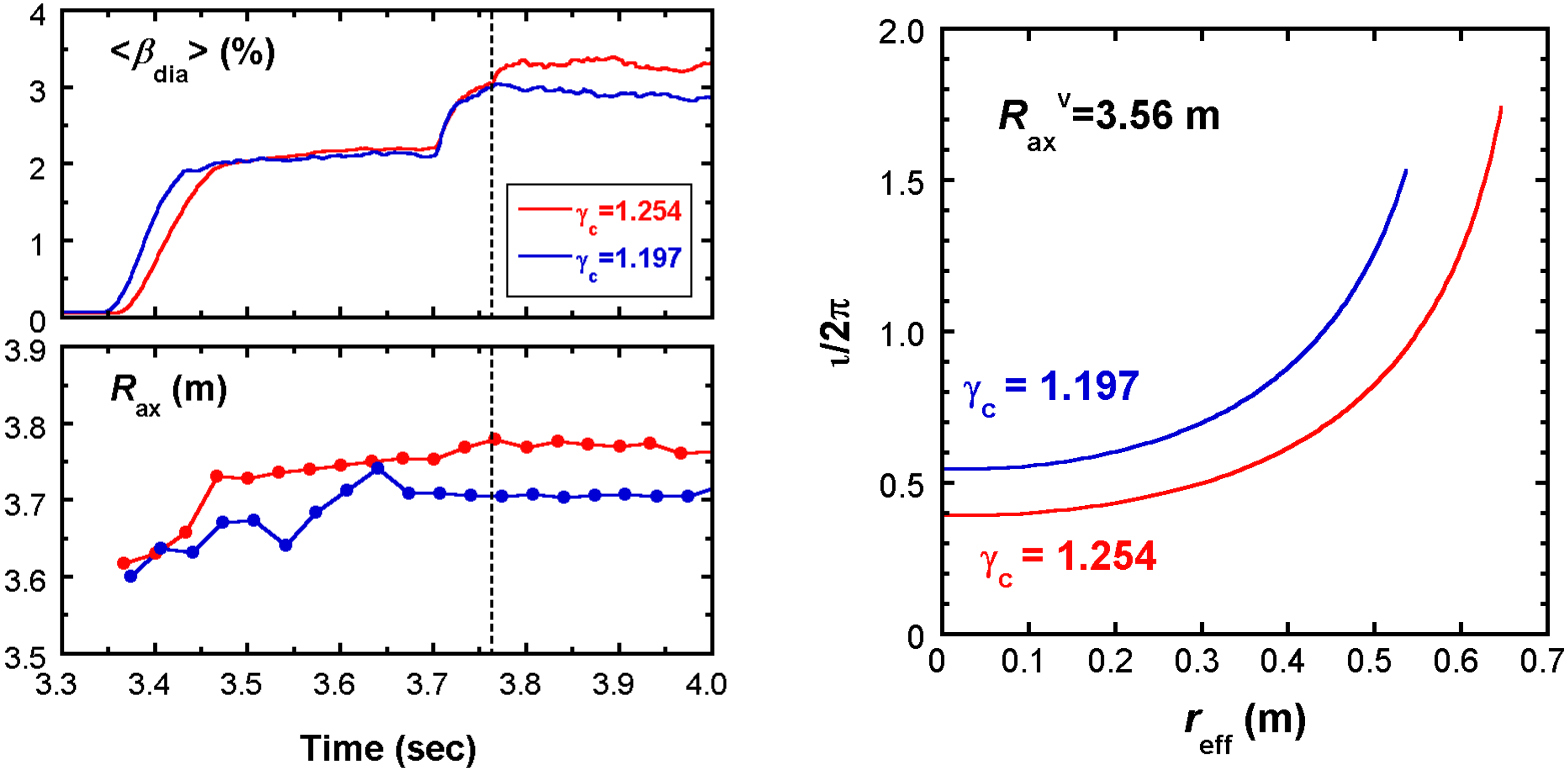
Disturbance of magnetic field line

A_p= 6.6 and 5.8 (R_{ax} = 3.56m, 1T)
- Comparison of discharges -

Beta value before transition is almost the same in both cases

- The transition is observed only in A_p = 5.8

・Shafranov shift in A_p = 6.6 is smaller than that in A_p = 5.8



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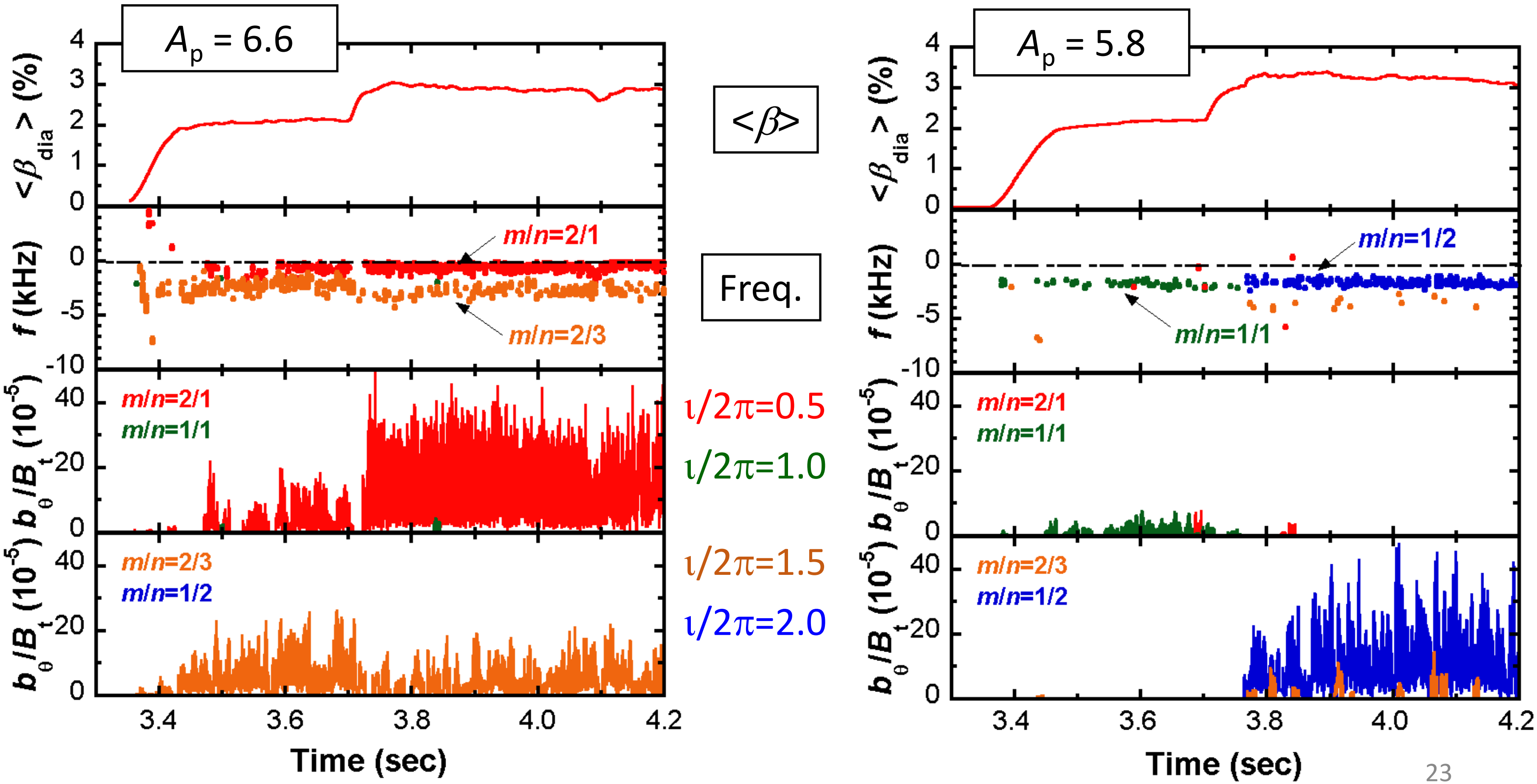
No transition and strong instabilities in core and edge at $A_p = 6.6$

Excited modes are quite different despite β and *P*-profile are almost the same

- ✓ A_p = 6.6 : core and edge instabilities are unstable
- ✓ R_{ax} = 3.56 m configuration is not suitable for high-beta plasma production



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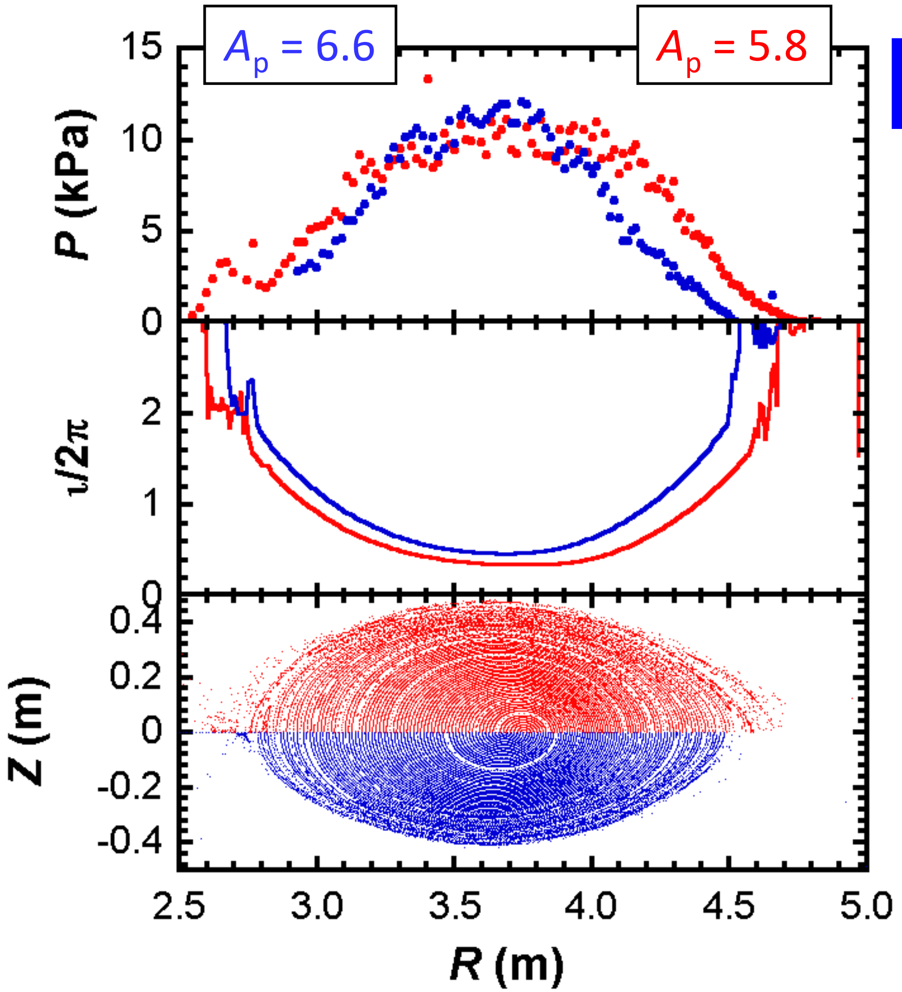
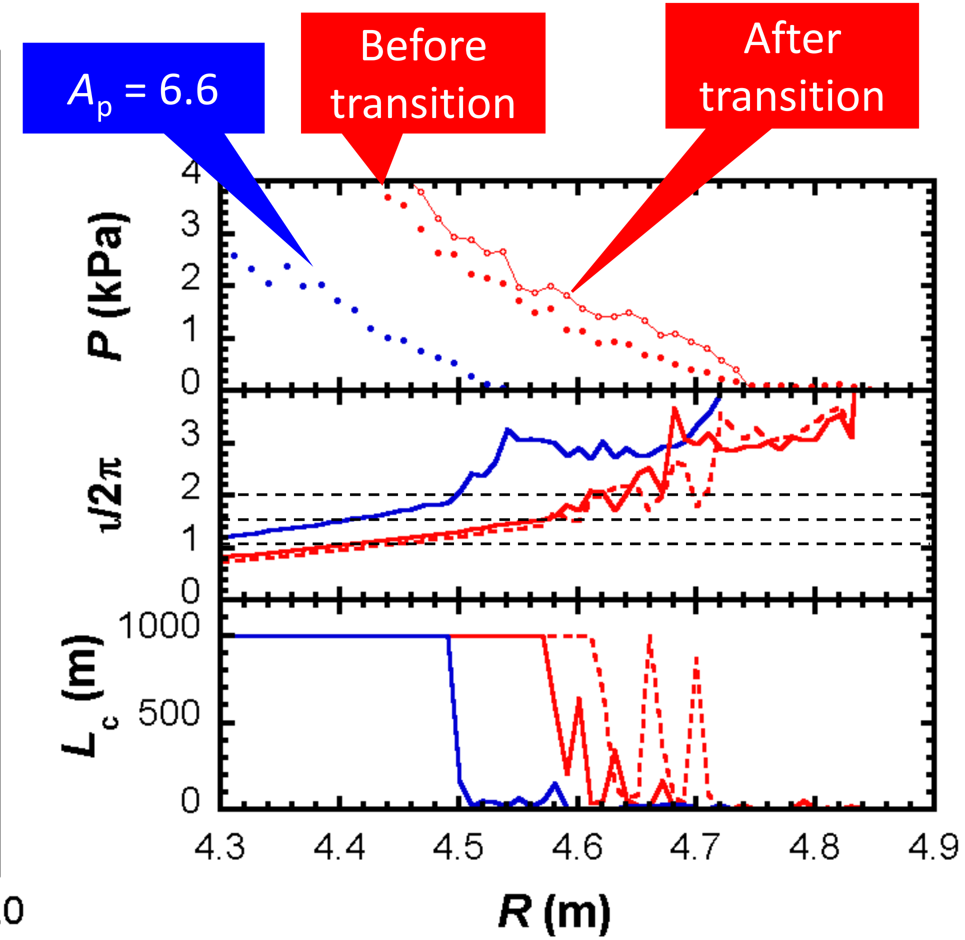
A_p = 6.6 and 5.8 (R_{ax} = 3.56m, 1T)
- MHD Equilibrium -

P$_0$ and pressure profile are almost the same

- A_p = 6.6: $\iota_a/2\pi$ ~ 2, A_p = 5.8: $\iota_a/2\pi$ ~ 3

A_p = 6.6 and 5.8 (before and after transition)





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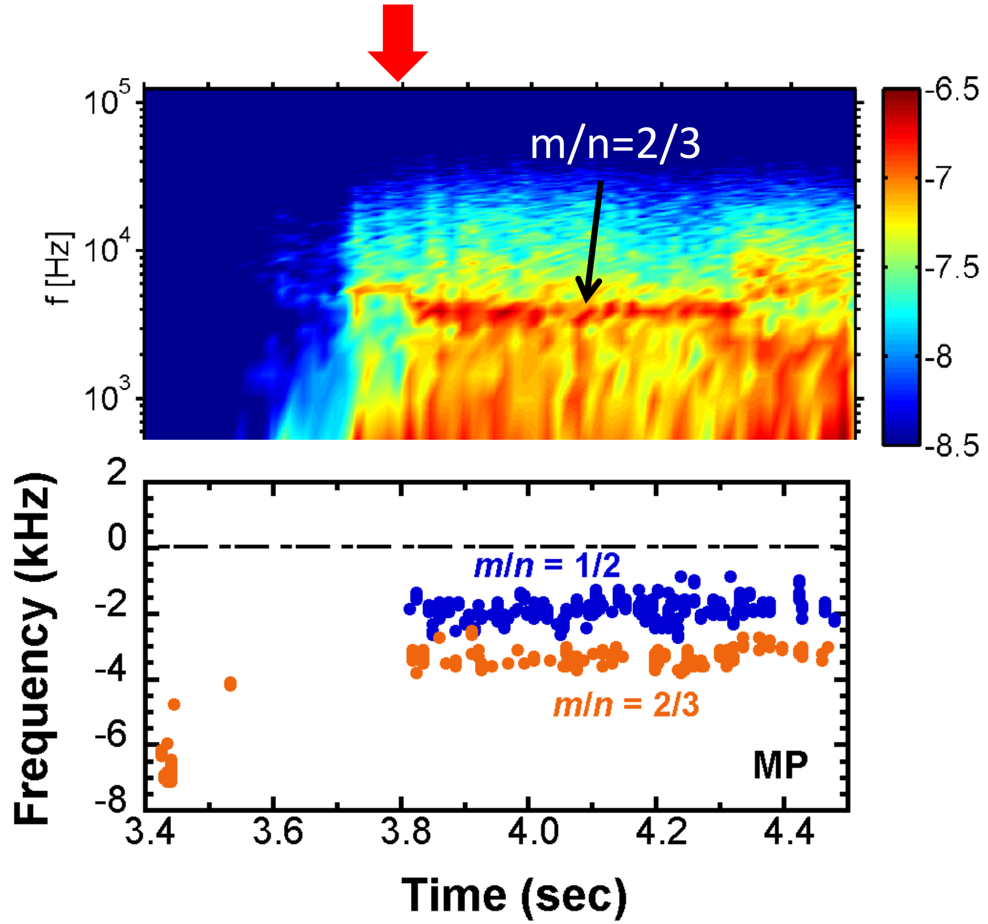
Fluctuation at divertor synchronizes with MHD mode

- ✓ Fluctuation of ion saturation current is enhanced during the transition
- ✓ Strong correlation with *m*/*n* = 2/3 MHD mode

Fluctuation of ion saturation current

Magnetic Fluctuation



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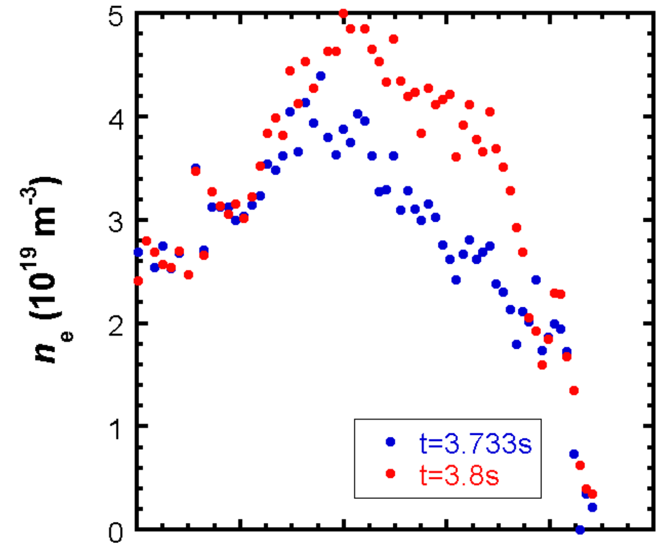
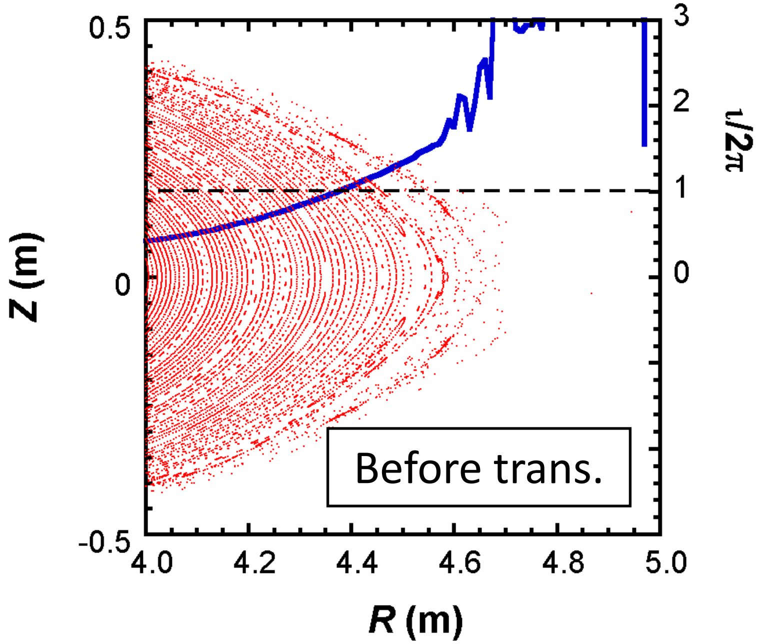
Shielding by magnetic island?

Increment of density is observed only in periphery

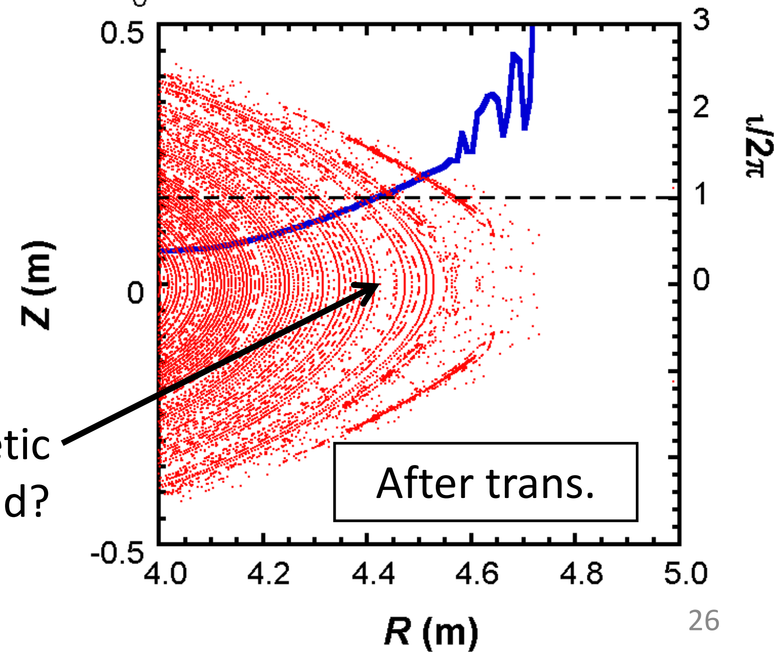
- ✓ Magnetic island appears around $\iota/2\pi=1$ surface after the transition

  → suppress influx of particles to core?

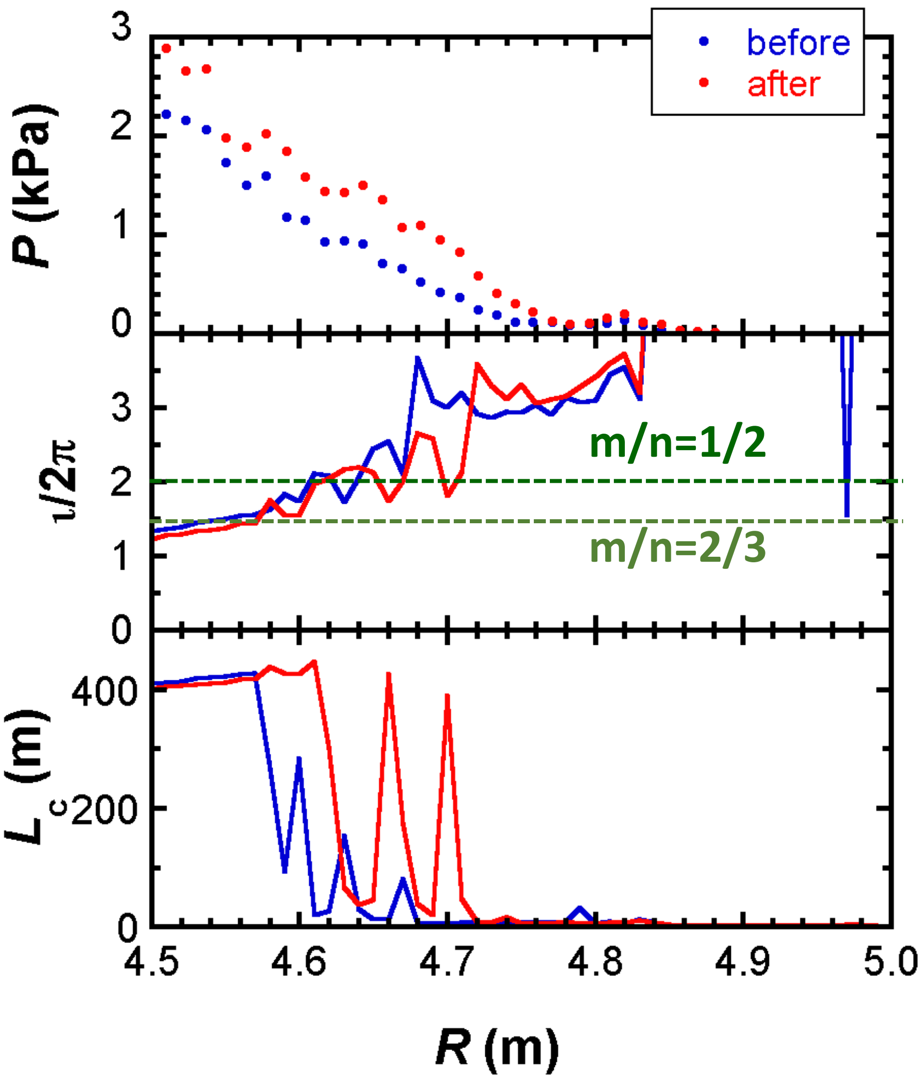


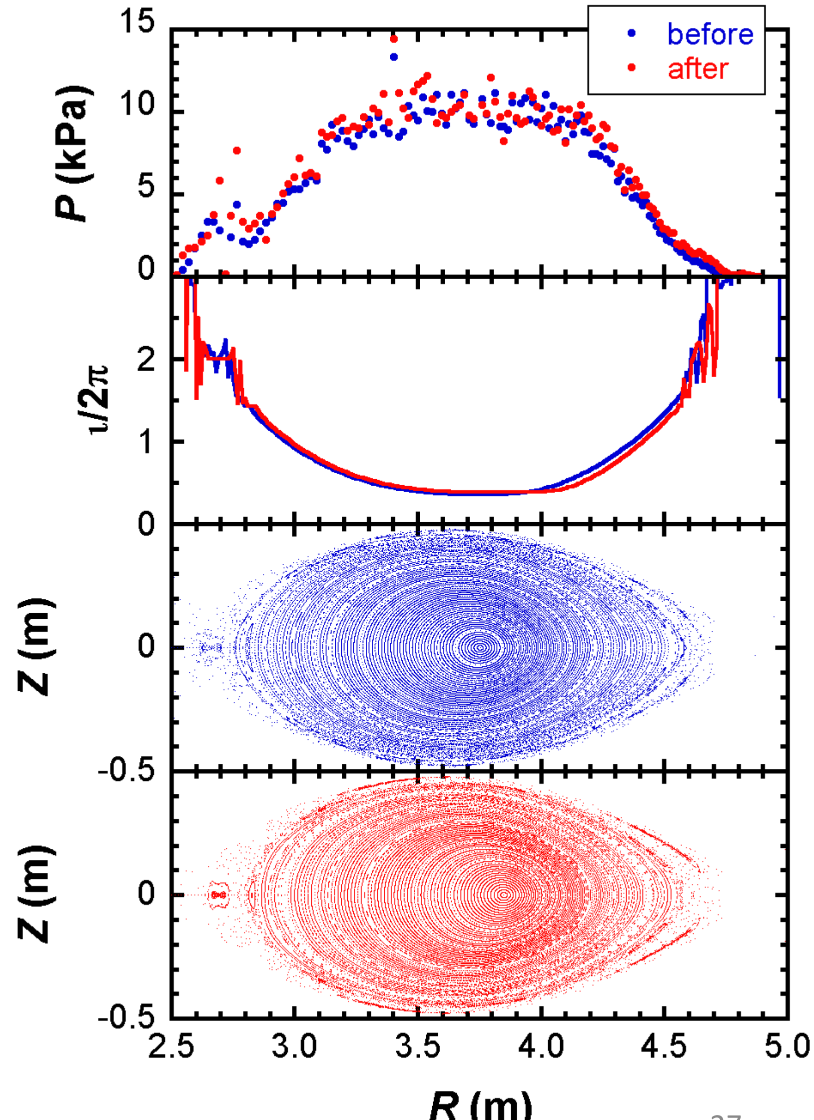


Magnetic island?



MHD equilibria before and after transition





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Change of MHD activities with β

Suppression of $\iota/2\pi < 1$ modes → β↑ → Suppression of $\iota/2\pi \leq 1$ modes → β↑ → Suppression of $\iota/2\pi \leq 2$ modes

$<\beta_{dia}>$, n_e

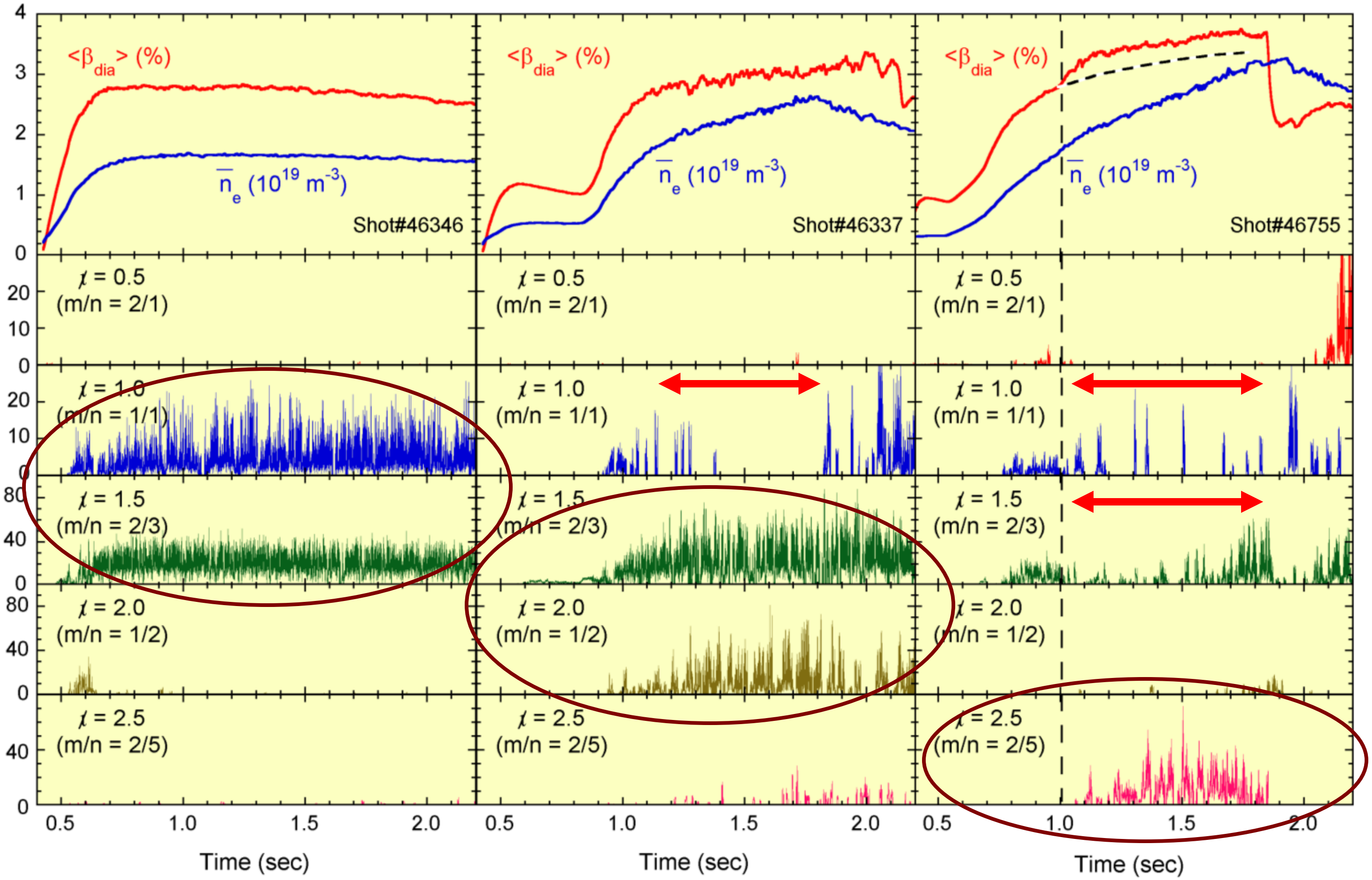
$\iota/2\pi = 1/2$

$\iota/2\pi = 1$

$\iota/2\pi = 3/2$

$\iota/2\pi = 2$

$\iota/2\pi = 5/2$



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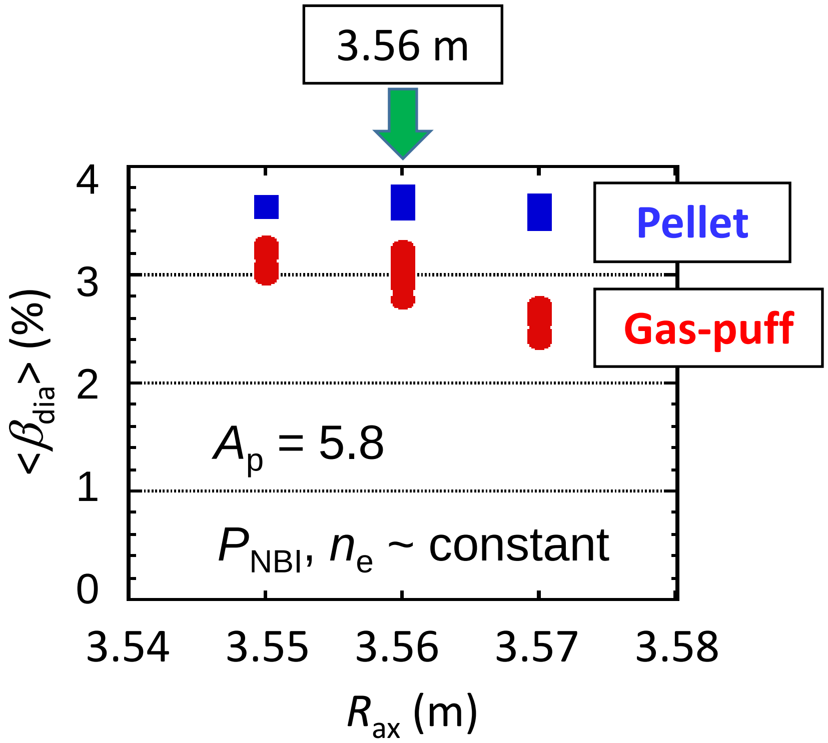
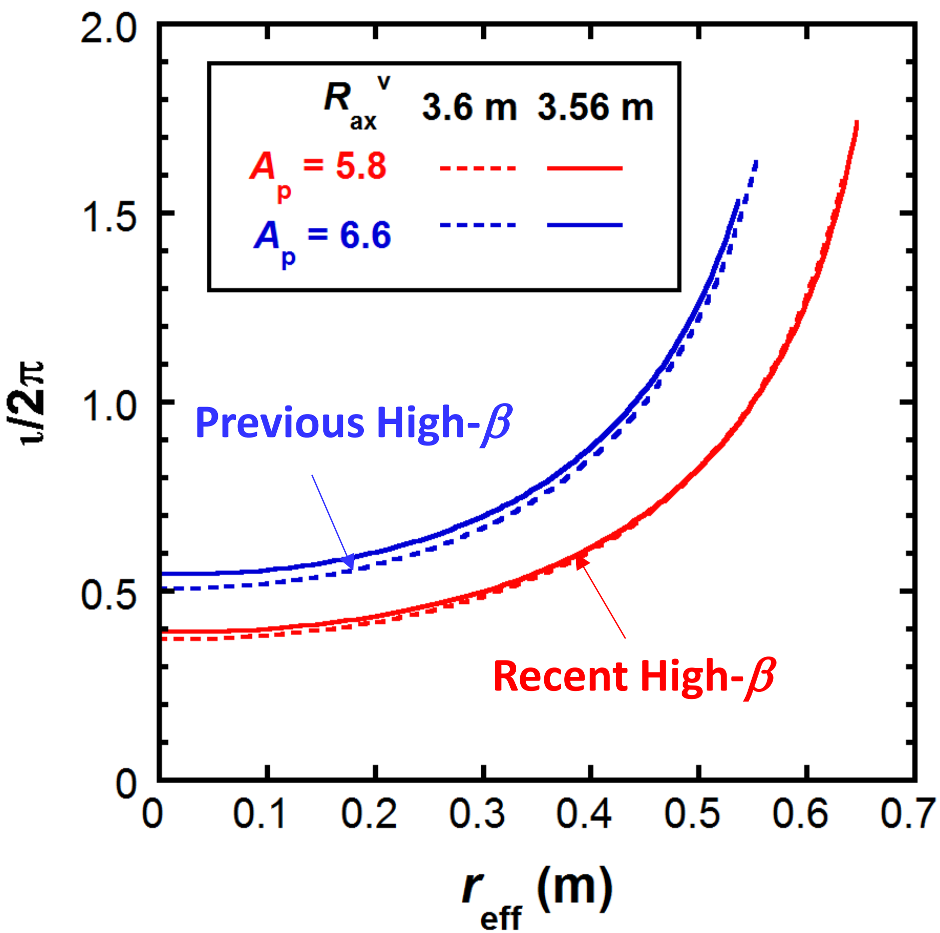
Magnetic Configuration for high-beta

Magnetic configuration was decided based on R_{ax}^{v} scan experiments with constant P_{NBI} and n_e.

- A_p = 6.6 in previous high-ν* exp.
- A_p = 5.8 in recent low-ν* exp.

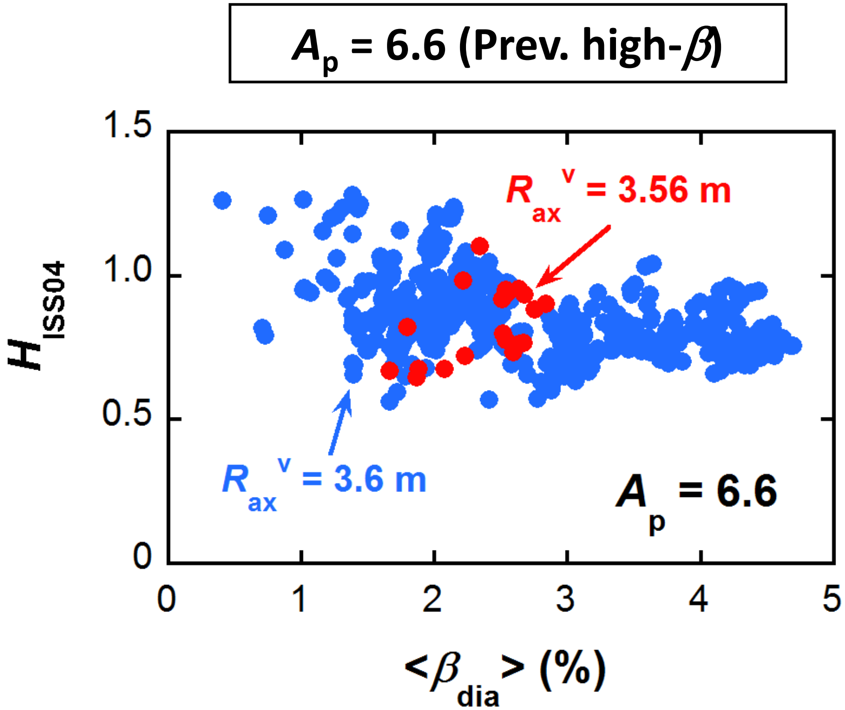


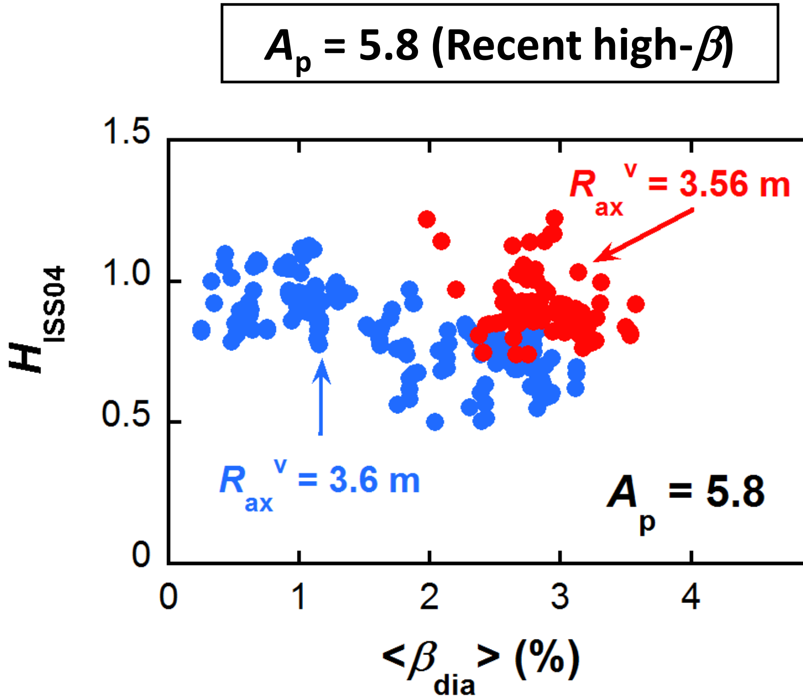


Global Energy Confinement property

Inward shift of R_{ax}^v recovers confinement property (A_p = 5.8)

- **A_p = 5.8**: Improvement of particle confinement is one of reasons for recovery of global energy confinement property
- **A_p = 6.6**: The confinement property is almost the same
  (No improvement of particle confinement, strong instabilities…)

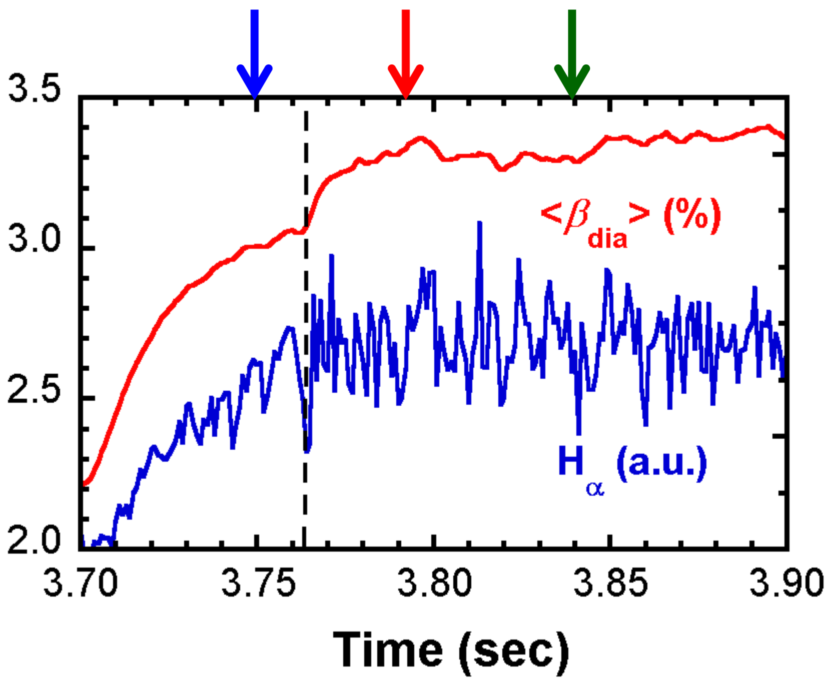


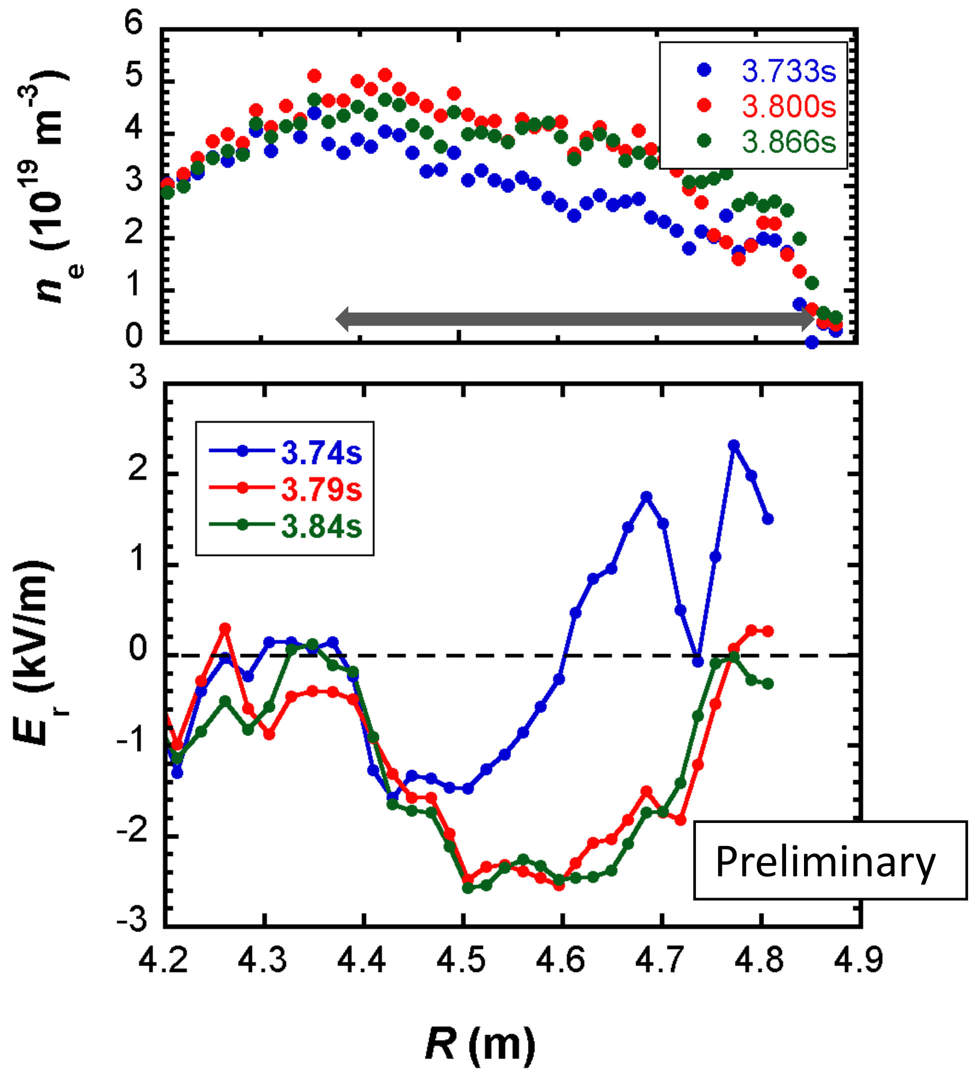


Negative electric field is formed after the transition

Profile of electric field is clearly changed after the transition

- E_r is significantly changed at R > 4.4 m



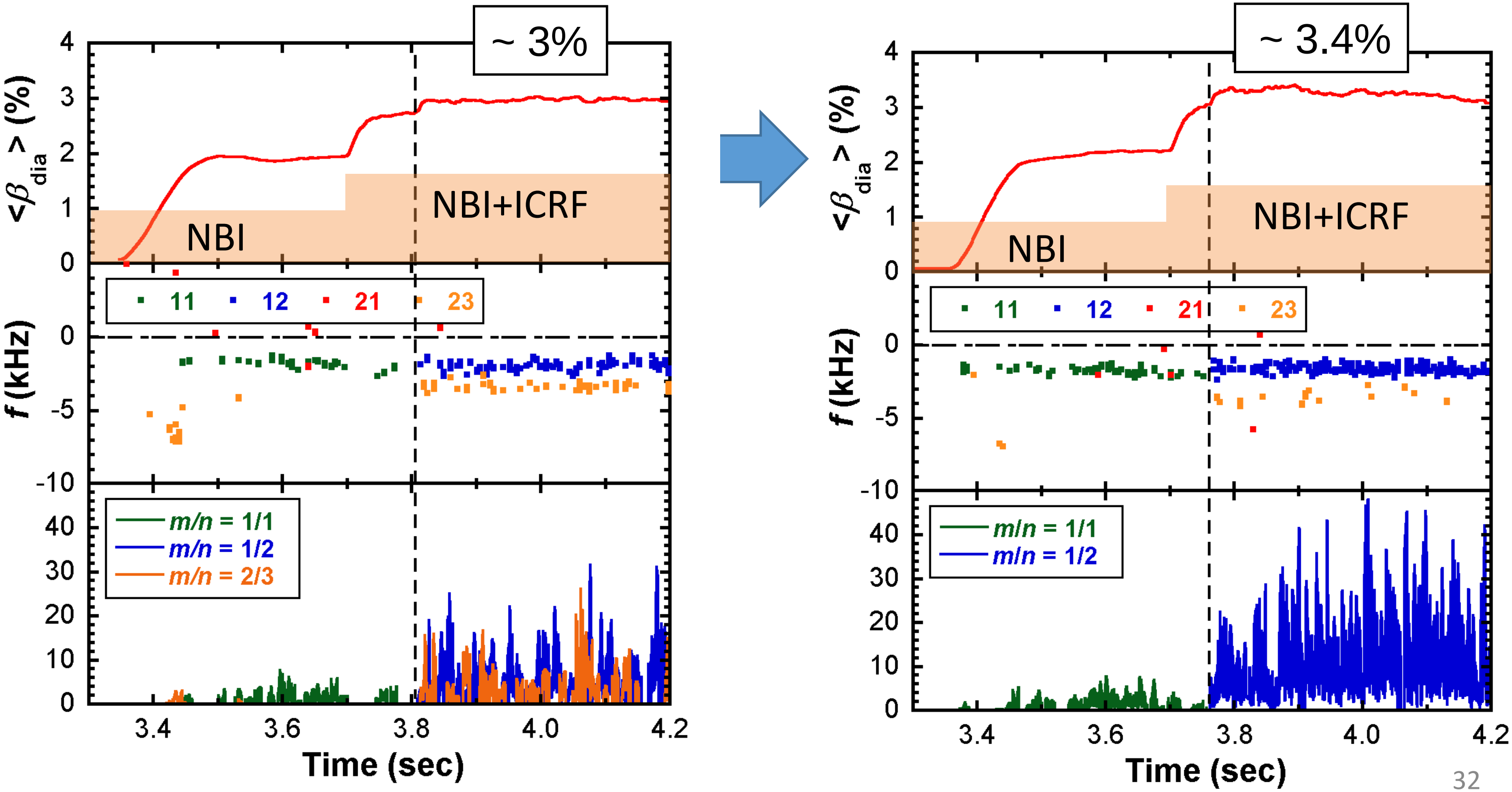


Change of dominant mode with beta

Excitation of edge MHD mode (*m*/*n* = 1/2, 2/3) just after the transition

⇒ Extension of confinement region leads to appearance of new resonant surface.

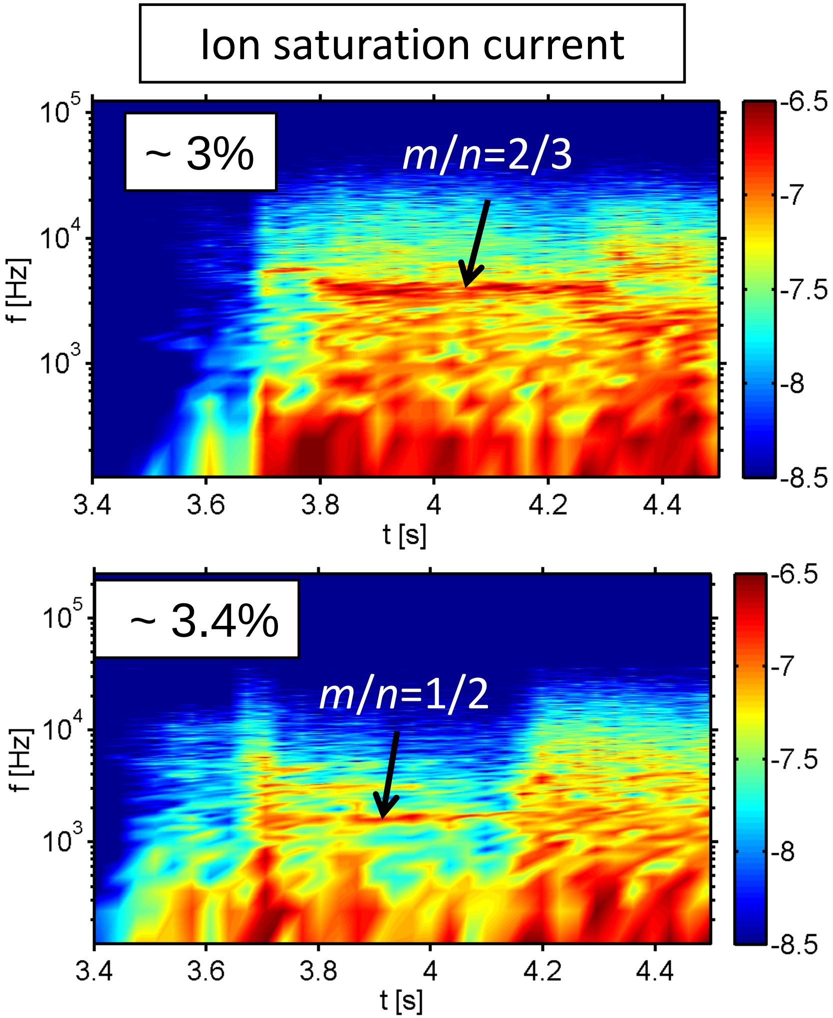
- Resonance of dominant mode is changed from inner region to outer one [A.Komori et al., POP2004]

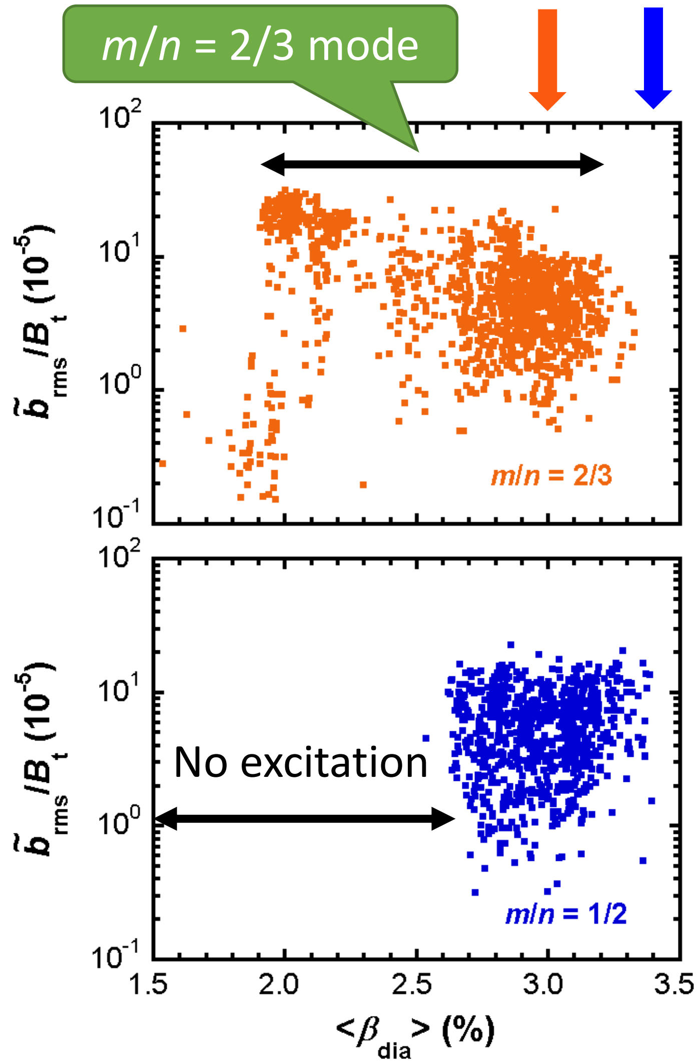


Change of dominant mode with beta

Resonance of the dominant mode : $\iota/2\pi$=3/2→ 2/1

- Consistent with extension of plasma confinement region





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Strategy of high-beta Experiments in LHD

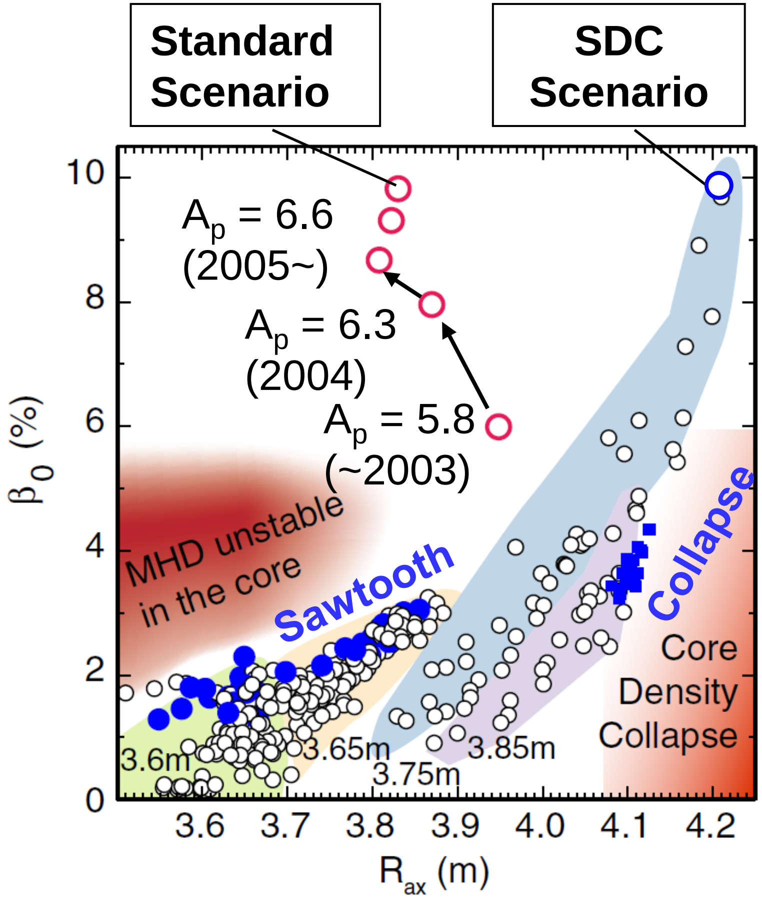
High beta operation has been realized by two scenarios

Standard scenario (broaden P-profile)

- High A_p configuration for optimizing heating efficiency, transport and MHD
- <β> of 5.1 % was obtained at low-field

Super Dense Core scenario (peaked P-profile)

- Peaked P profile by multi-pellet injections
- High density (> 10^{20} m^{-3})
- Central β of 10 % was realized at high-field



- Steady-state high-beta discharge was realized in optimized configuration

→ Verification of ability in high beta plasma production in heliotron