Stability in High-β Plasmas of LHD

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Outline

- Subjects on MHD study
- Magnetic configurations of LHD
- Development of high-β experiments
- **Ideal-stable regime**
  - **- High-beta discharge**
  - **- Parameter dependence of resistive mode**
- **Significance of "ideal limit" of interchange mode**
  - **- Effect on plasma confinement and its control**
- Discussion
- Summary

Motivation

Production of high-β plasma is the common subjects in magnetic confinement systems

Optimization → **Economical Reactor**

Experimental Verification ↑

Production of High-β Plasmas ↔

- **Transport**
  NC, turbulence etc.
- **MHD Stability**
  growth of MHD mode
- **MHD Equilibrium**
  finite-β effects

What has limited the β-value?

Tokamak: NTM, RWM, ELM... **Helical**: Stability? Equilibrium? Transport?

Understanding of high-β physics related with β-limit

Subjects of MHD Study

Major subjects of MHD study in high-β heliotron

Equilibrium

- disorder of peripheral magnetic surface due to finite-β effects
- growth or healing of magnetic island → limit confinement region

  → comparison between experiment and calculation

Stability

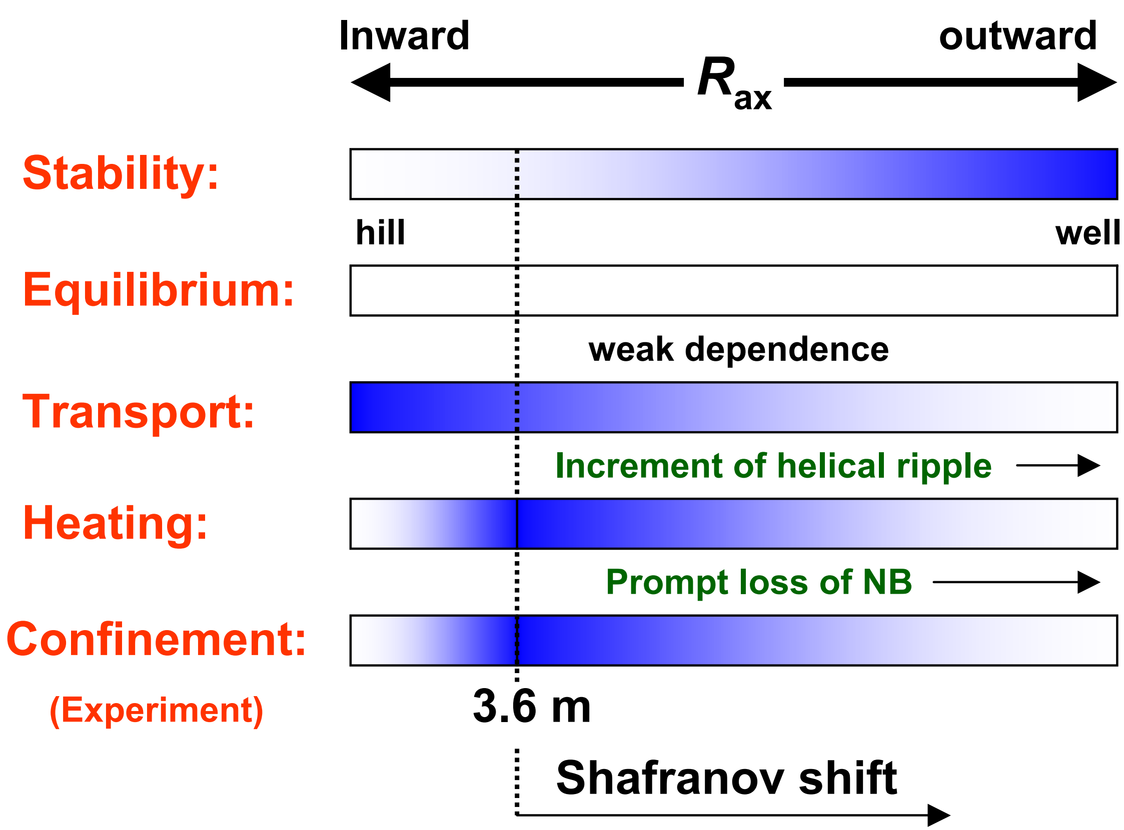
- enhanced magnetic hill in periphery and weak magnetic shear in core
- many resonances, especially, in periphery

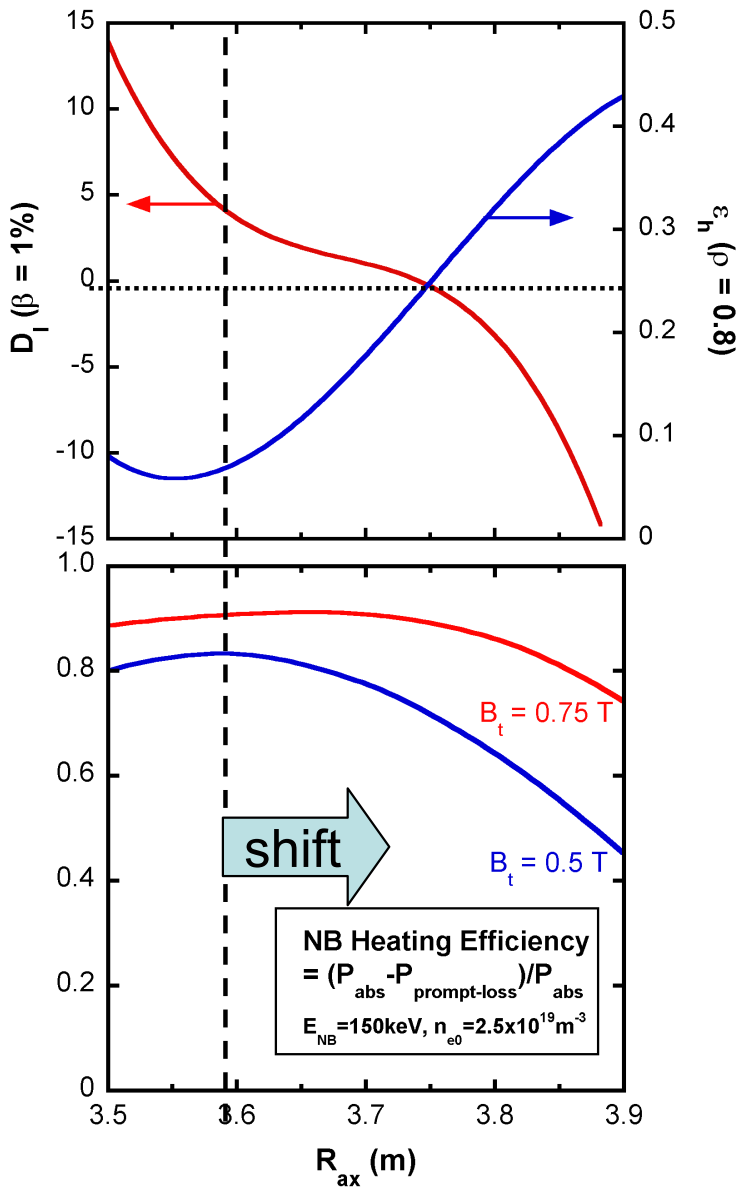
  → effects of pressure-driven modes on profile and confinement
- verification of linear stability boundary and mechanism of mode saturation
- interpretation of "ideal" and "resistive" instabilities

further extension of β range is required for experimental interpretation of these subjects and extrapolation of the knowledge to reactor-plasma.

Configuration Optimization – R_{ax} –

Magnetic axis position is one of configuration parameters characterizing MHD and transport:





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

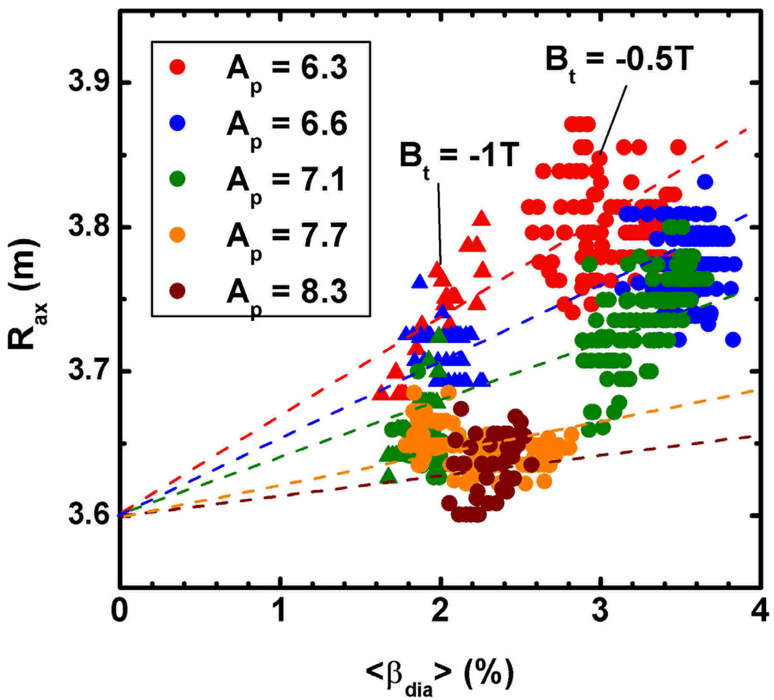
→ control of aspect ratio

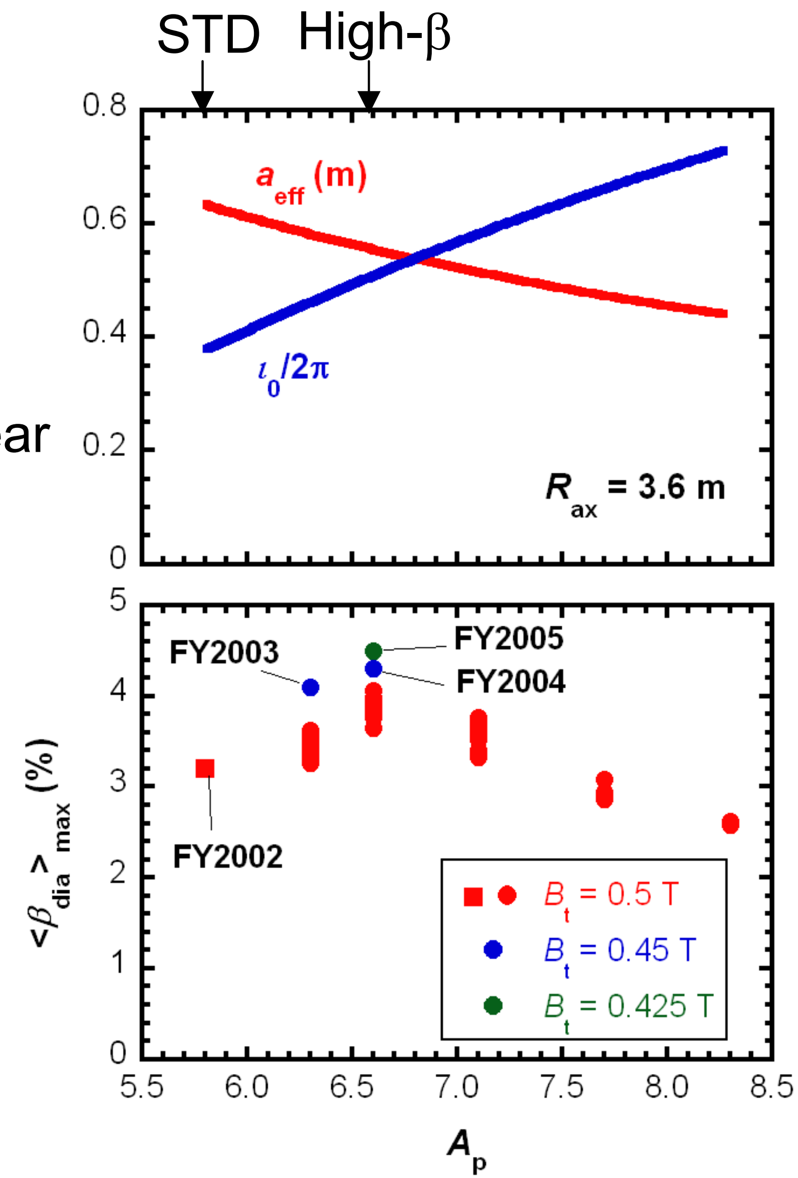
Optimization of Aspect Ratio

Shafranov shift can be restricted by increasing plasma aspect ratio.

⇒ restricts reduction of heating efficiency and increment of transport

⇒ restricts spontaneous formation of magnetic well and decreases magnetic shear





Maximum beta of 4.5 % was achieved

- Maximum averaged beta : 4.5 %
- long sustainment of 4 % plasma
- Shafranov shift Δ/a_{eff} ~ 0.25

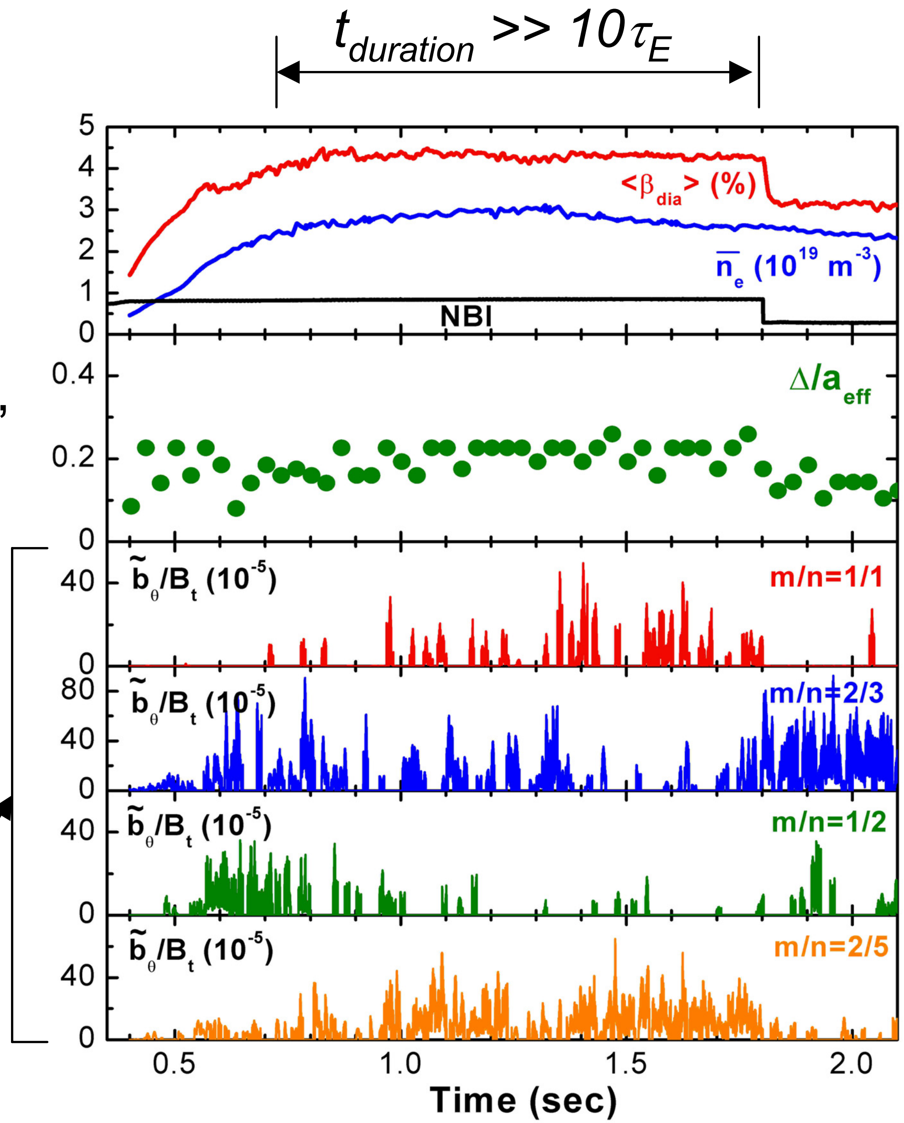
Low-*n*,*m* activities

- *m*/*n* = 2/3 and 1/2 modes appear (< 4 %), but behave intermittently with increasing beta

(*A.Komori,S.Sakakibara, POP2004*)

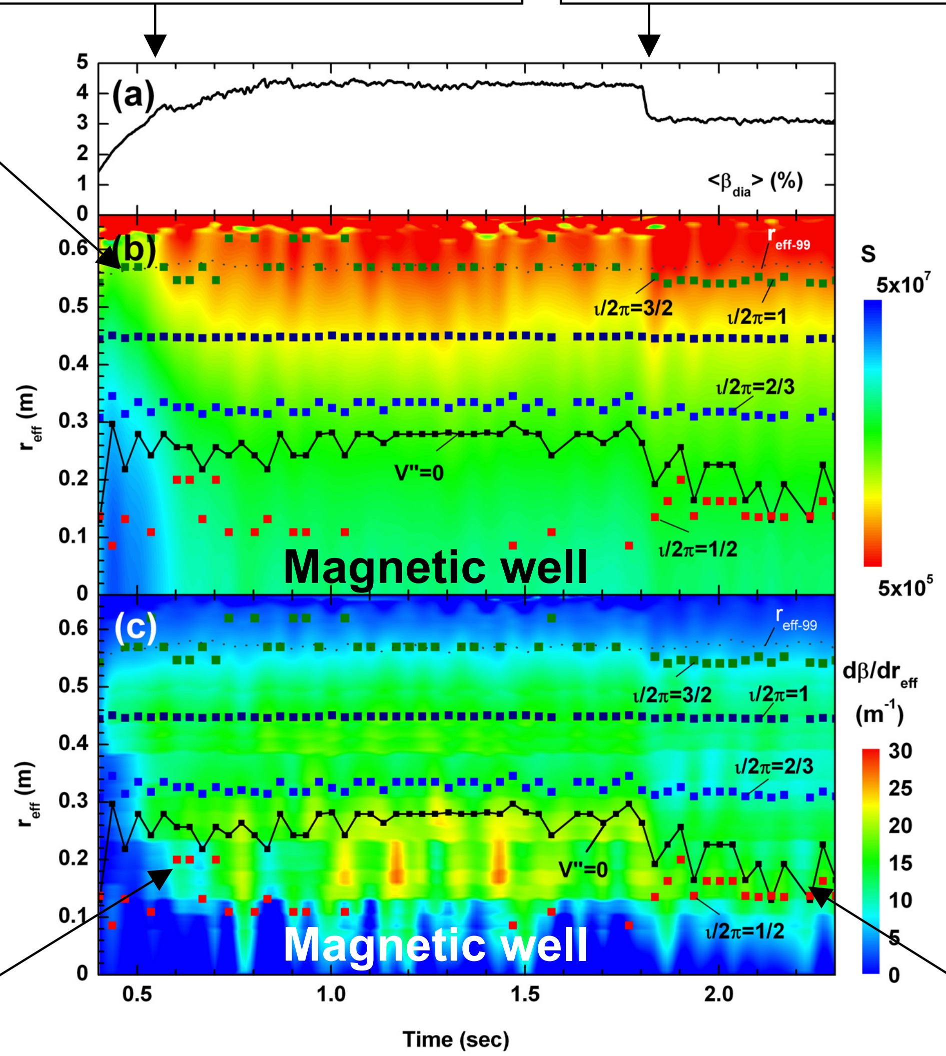
- Outermost-resonant mode is enhanced
- Mercier criterion $D_I < 0.2$

Resonances are located outside ρ ~ 0.9



Time Evolution of Config. Parameters

- The reduction of S seems to destabilize 2/3 and 1/2 modes rather than beta gradient
- 2/1 resonance enters the magnetic well region
- High pressure gradient inside V"=0



Magnetic Reynolds Number S

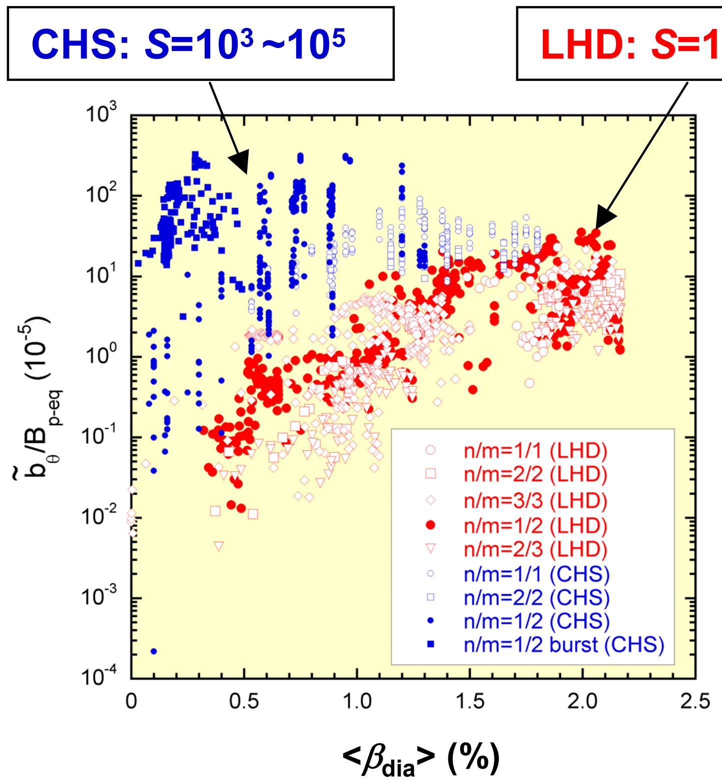
$$S = \frac{\tau_R}{\tau_A} \propto \frac{aBT_e^{3/2}}{ZA^{1/2}\sqrt{n_e}}$$

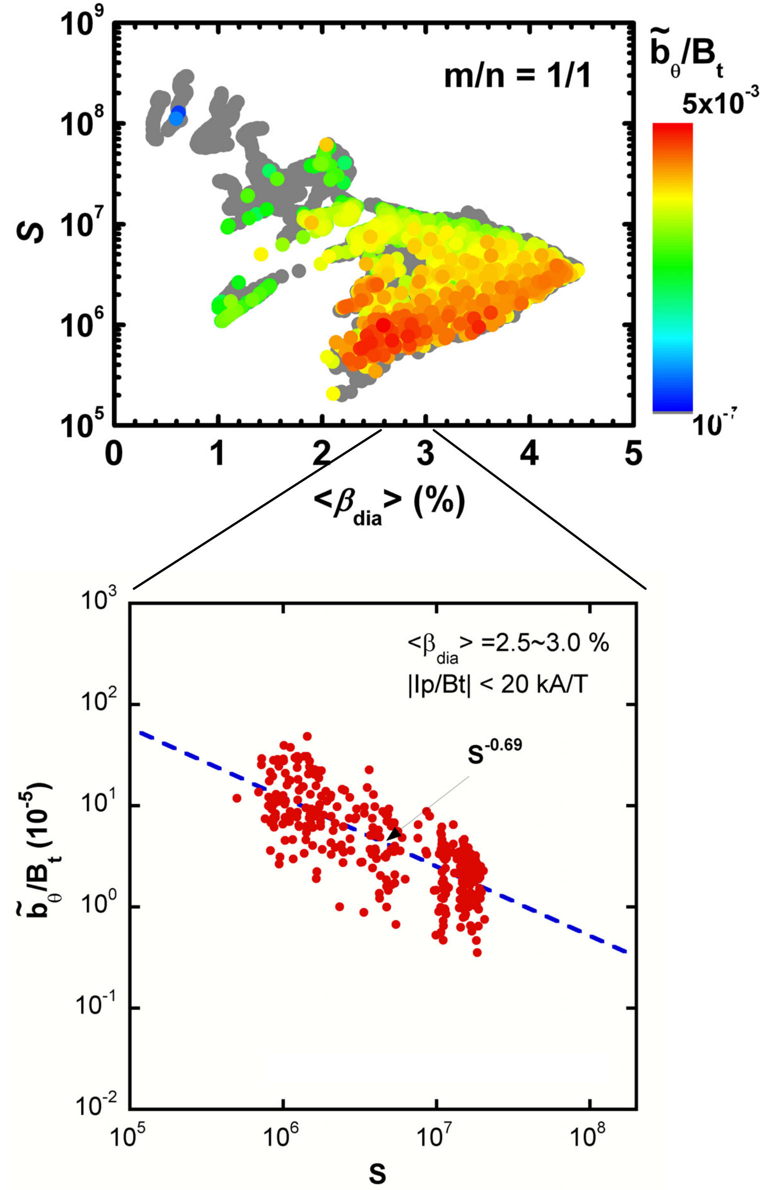
Beta gradient

$d\beta/dr_{eff}$

S Dependence of MHD mode

- S dependence of island width ($w \propto (\tilde{b}_{11}/B_t)^2$) is similar to that of linear growth rate ($\gamma \propto \beta^{2/3} S^{-1/3}$) of resistive interchange mode.
- Amplitudes in LHD (high-*S*) are much smaller than that in CHS (low-*S*).





Discussion on High-β MHD

• Clear S dependence of saturation of the mode was found out, which is similar to that of linear growth rate of resistive interchange mode. Also, it has been found out that the mode onset strongly depends on S and D_R [1].

⇒ Local heating in vicinity of resonances is valid for the stabilization?

• Observed modes are suppressed or intermittently behave when $<\beta>$ exceeds a certain value. The understanding of change of equilibrium due to finite-β effects is required for making the mechanism clear.

⇒ equilibrium study (finite-β effect)

• Averaged beta increases with heating power, whereas degradation of plasma confinement with $<\beta>$ has been observed [2]. Experiments suggest that it is caused by an increment of transport rather than low-n MHD activity.

• If the increment of transport is caused by outward-shift of R_{ax}, the real-time control of R_{ax} is valid for the suppression. In case of turbulence due to (high-n) resistive-g mode, production of high-S plasma leads to the reduction of the transport.

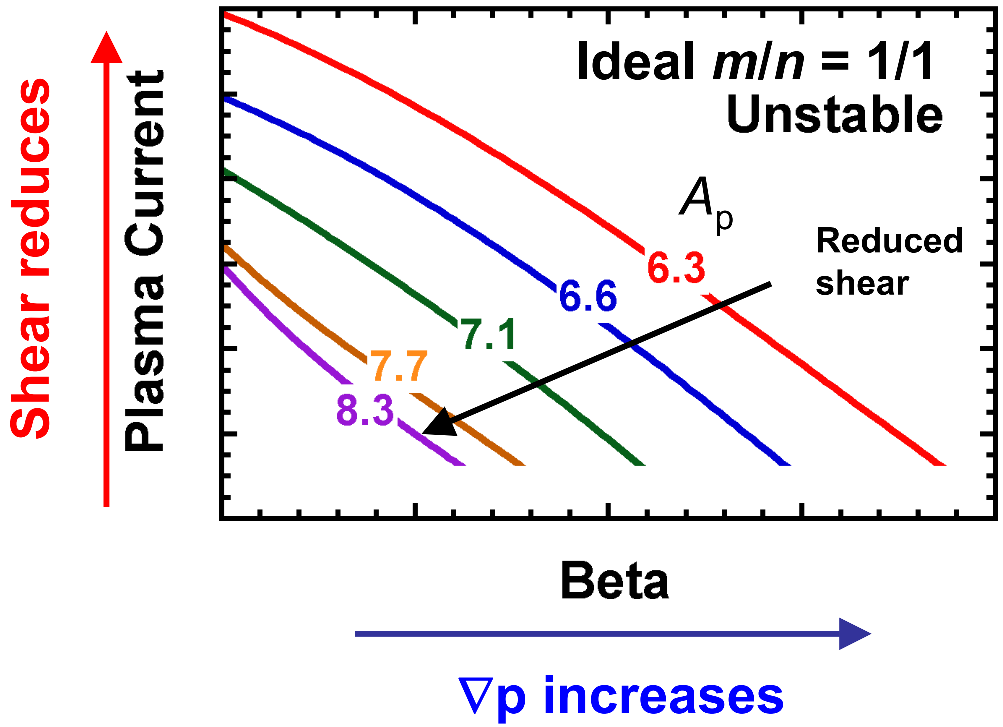
[1] *S.Sakakibara, PFR 2006,* [2] *K.Y.Watanabe, IAEA2004,* [3] *H.Funaba, FST 2006.*

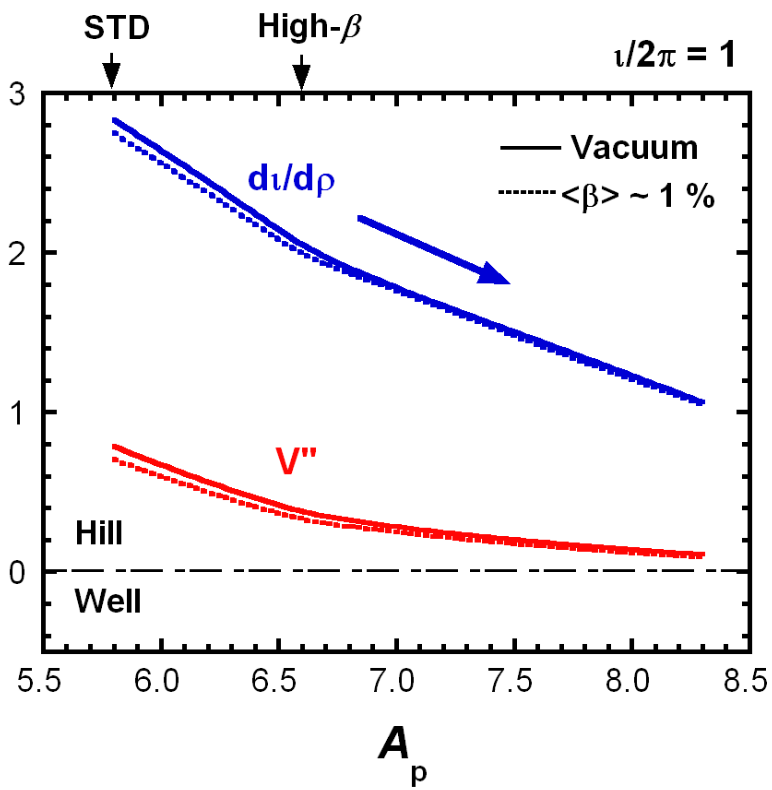
How about “ideal limit”?

- Usually, “resistive” mode is saturated and leads to no collapse of the plasma.

  ⇒ How about plasma close to “ideal” limit?

- It is possible to bring the plasma close to “**ideal limit**” by increasing A_p





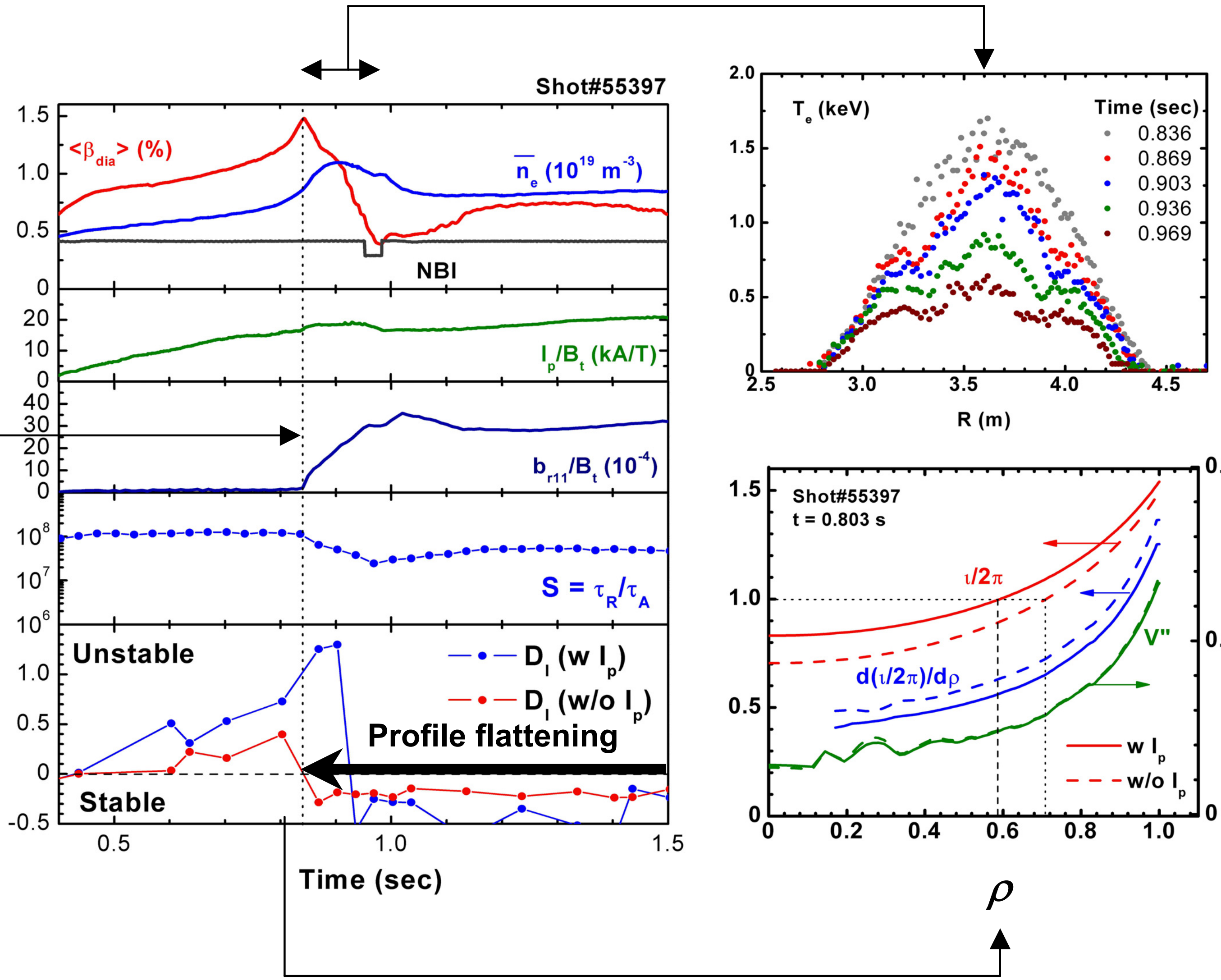
Minor Collapse due to *m*/*n* = 1/1 Mode

The strong m/n = 1/1 mode caused minor collapse.

Minor collapse due to abrupt profile-fattening near *m*/*n* = 1/1 resonance

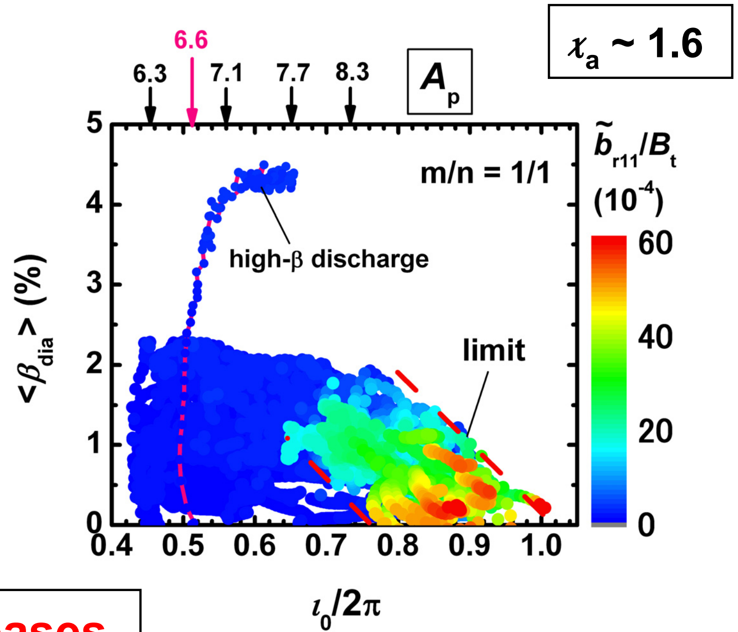
Growth of radial component of *m*/*n* = 1/1 mode

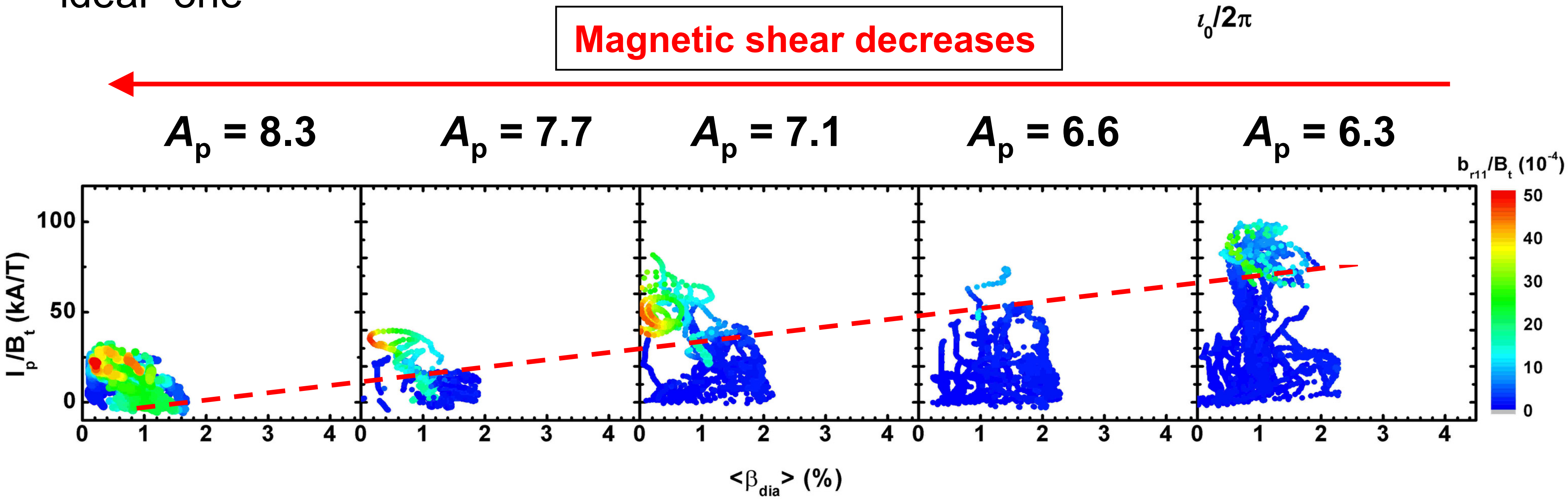
$D_I > 0.2$ even in currentless plasma



Magnetic Shear Dependence

- Appearance of the mode obviously depends on A_p and I_p
- The mode appears even in low- A_p if I_p exceeds a threshold.
- A threshold of the plasma current decreases with increasing A_p
- Operation limit is qualitatively consistent with "ideal" one





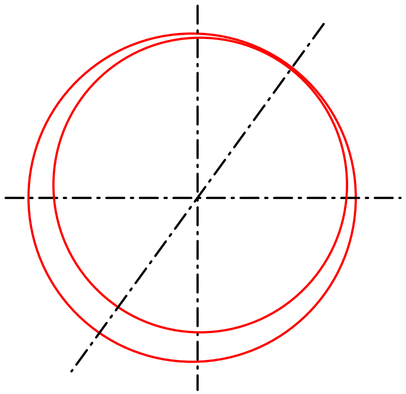
Attempt of suppression of the mode

- The m/n = 1/1 mode has **no rotation** and grows in **specific location** (error field), which is different from "resistive" mode

$\Rightarrow$ **Is it possible to suppress the mode by resonant magnetic field?**

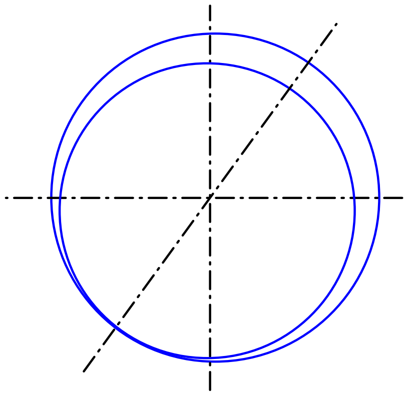
- LHD has the compensation coil system to cancel out the error field and to perform advanced divertor scenario (LID)
- Dominant Fourier component is m/n = 1/1.

$I_{LID}/B_t < 0$

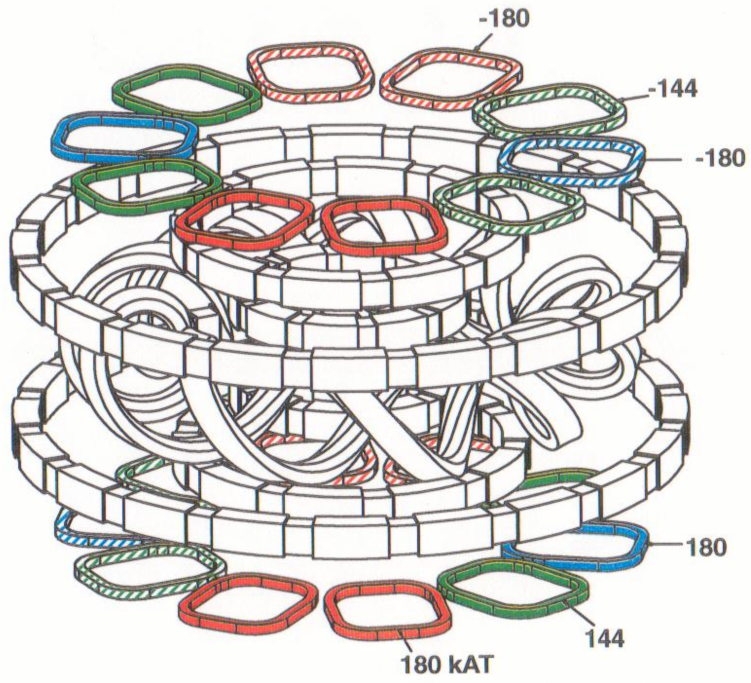


O-point (ϕ = -126°)

$I_{LID}/B_t > 0$



O-point (ϕ = 54°)



Suppression of *m*/*n* = 1/1 Mode

The mode could be suppressed by giving optimal perturbation field, and <β> recovered.

• The location and saturation-level of the mode strongly depends on those of given perturbation field.

$\Rightarrow$ similar to error field locked mode?

- relation with ideal interchange mode and/or magnetic shear

- measurements of plasma rotation and radial electric field

(Torque balance)

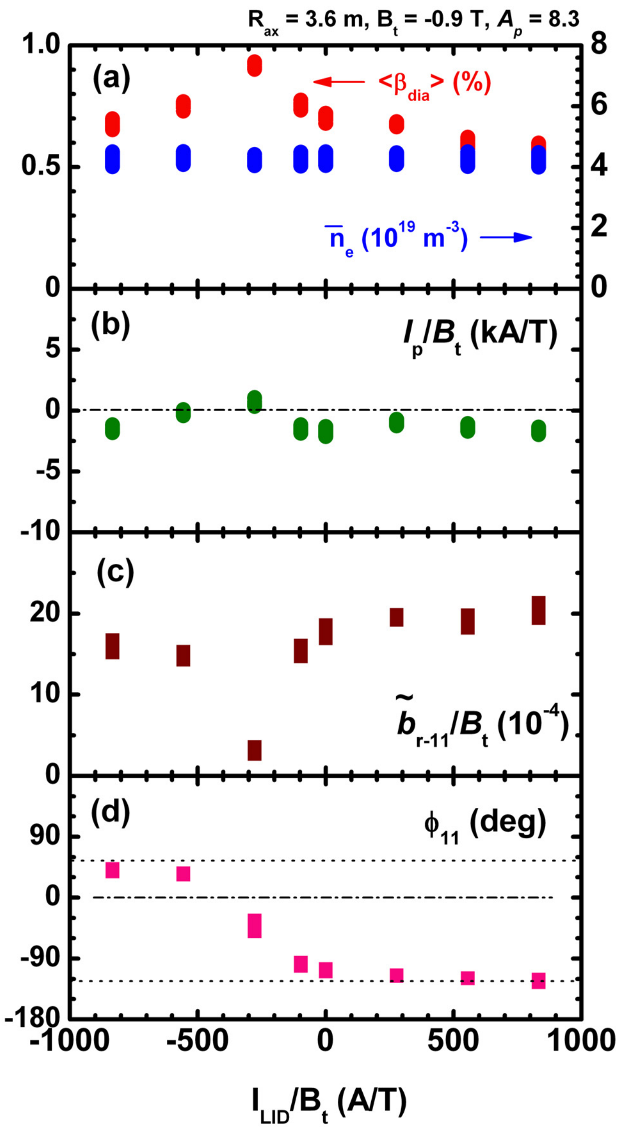
- threshold of “seed” island

<β> recovers at fixed n_e

I_p ~0

The mode is suppressed at specific field

Island phase is the same as external field



Summary

• The volume averaged beta value of 4.5 % was achieved by optimizing the magnetic configuration from a viewpoint of MHD characteristics, transport and heating efficiency of neutral beam.

• Peripheral MHD modes excited in the magnetic hill are dominantly observed, and the dependence of the amplitudes of their modes on magnetic Reynolds number is close to that of linear growth rate of resistive interchange mode.

• When the magnetic shear was decreased and the plasma was close to m/n = 1/1 ideal stability boundary, the m/n = 1/1 mode was excited and led to a minor collapse in the core region.

• The results suggest the significance of magnetic shear and a validity of a linear theory on ideal mode.

• The mode can be stabilized easily by using external resonant field.

Previous Works on High-β MHD

MHD instability concerning high-β

- Core modes near ideal stability boundary effects the pressure profile and degrade confinement

(*S.Sakakibara, NF 2001, PPCF 2002, PFR 2006*)

- Stabilization of peripheral modes from inner region to outer one in high-β range with > 3 %

(*S.Sakakibara, EPS 2004, A.Komori, POP 2005*)

- Onset of peripheral mode is quantitatively consistent with linear theory on resistive mode

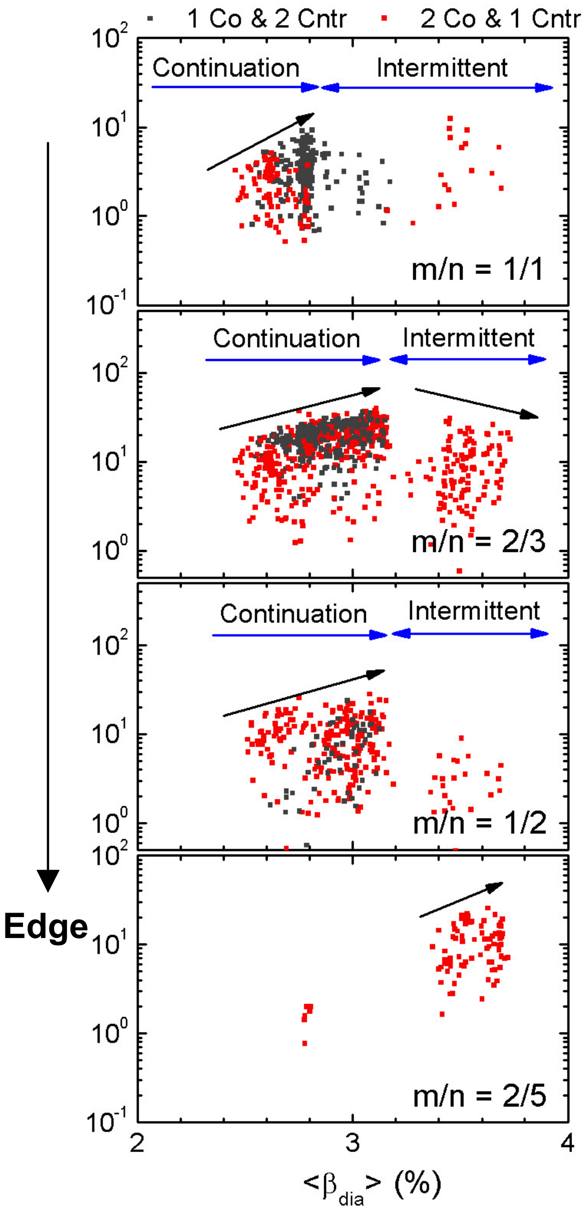
(*S.Sakakibara, PFR 2006*)

- Peripheral MHD Activities in High-β plasmas

(*S.Sakakibara, FST 2006*)

- Relationship between the thermal transport, ideal mode and turbulence due to resistive-g mode, in high-β

(K.Y.Watanabe NF2005, *H.Funaba, FST 2006*)



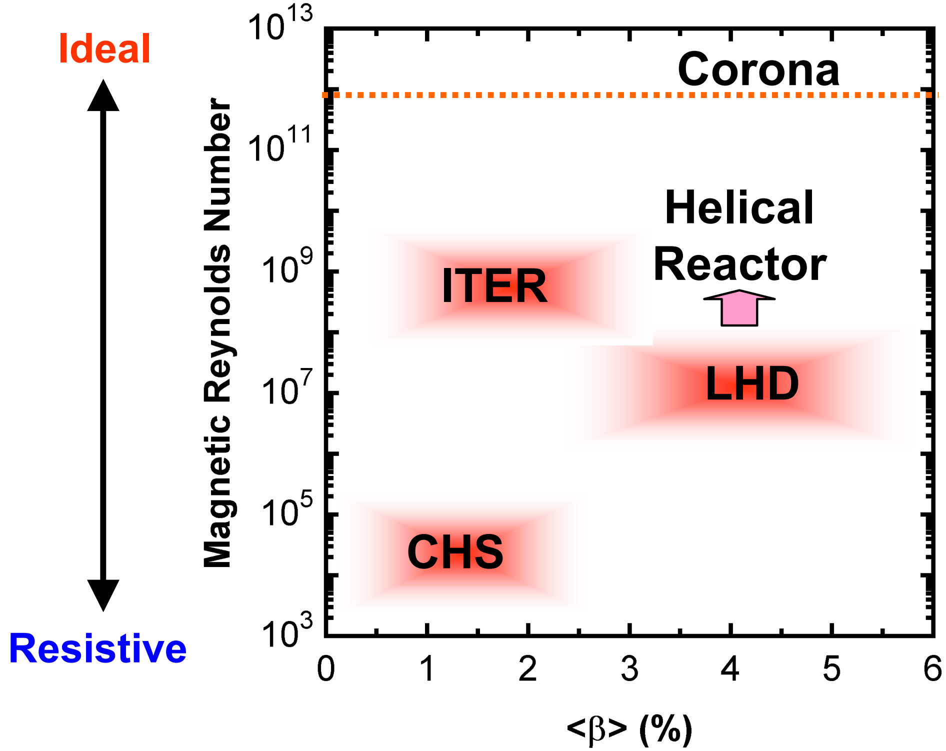
Magnetic Reynolds Number

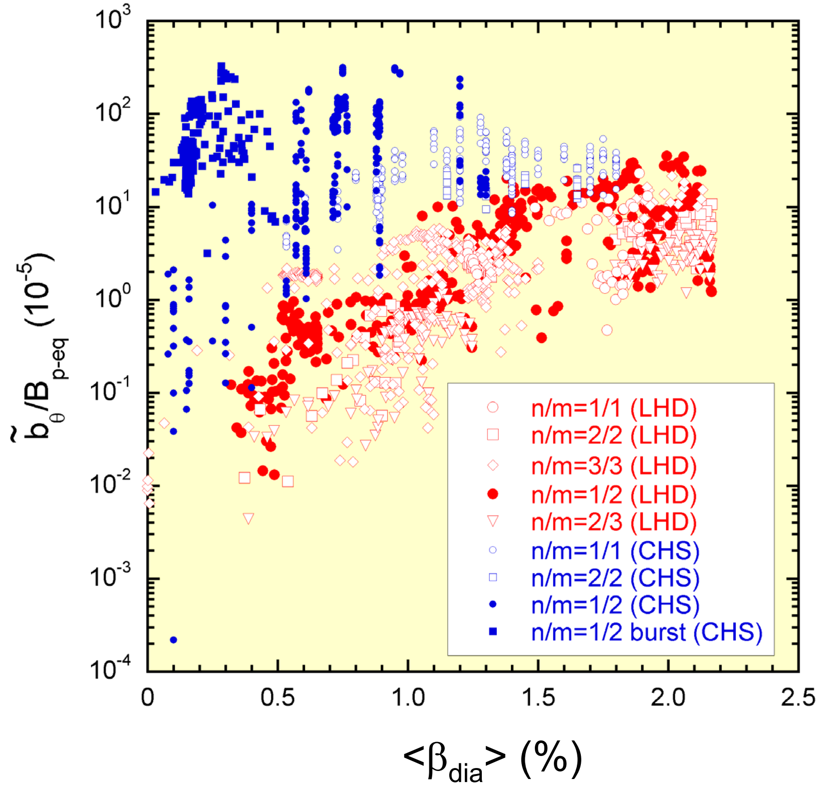
Magnetic Reynolds number is related with growth of resistive mode ($\gamma \propto \beta^{2/3} S^{-1/3}$), the change of topology (reconnection) and so on.

CHS: $S=10^3 \sim 10^5$

LHD: $S=10^6 \sim 10^8$

$$S = \frac{\tau_R}{\tau_A} \propto \frac{aBT_e^{3/2}}{ZA^{1/2}\sqrt{n_e}}$$





Comparison of MHD activities in between LHD and CHS

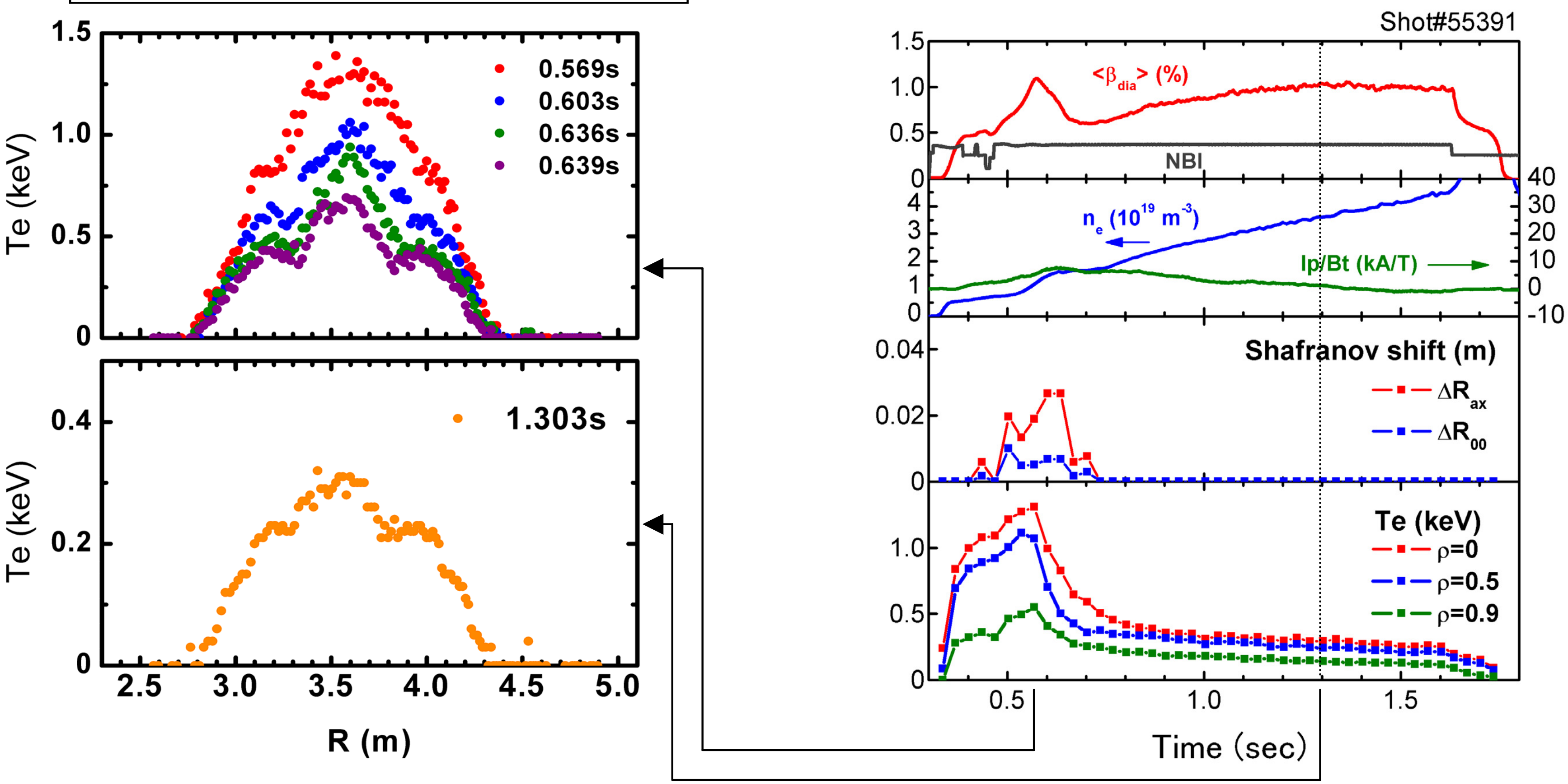
(S.Sakakibara et al., NF 2000)

Occurrence of Minor Collapse

- Minor Collapse in core region was observed in High-A_p configuration
- Profile flattening near $\iota/2\pi$ = 1 surface occurs with the collapse.

Te profile measured with Thomson

A_p = 8.3 and low-I_p (I_p/B_t< 10 kA/T)



Characteristics of m/n = 1/1 mode

Several differences of characteristics of the mode in different configurations.

Experiments	High-A_p, and/or large I_p	Standard, high-β
radial location	ρ ~ 0.7 (currentless)	ρ ~ 0.9
configuration	weak shear, magnetic hill	magnetic hill
observation	*Ideal unstable*, $D_R > 0$	*Ideal stable*, $D_R > 0$
frequency	DC ~ several Hz	several kHz
spatial location	ϕ~ -120 deg (near natural error field)	rotating
S dependence	Not clear	strong

Interaction of the modes with resonant magnetic field

Increment of Radial Flux

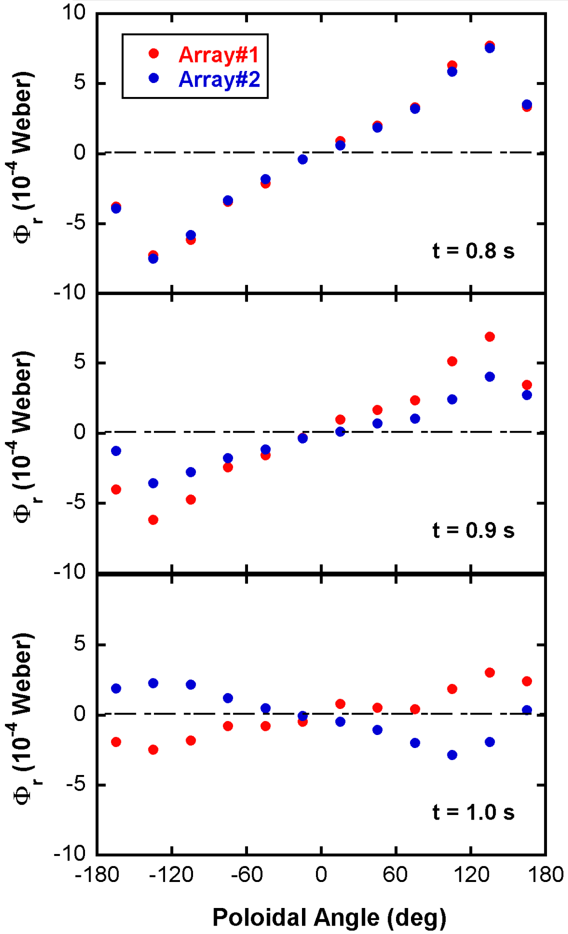
Increment of radial magnetic flux with minor collapse

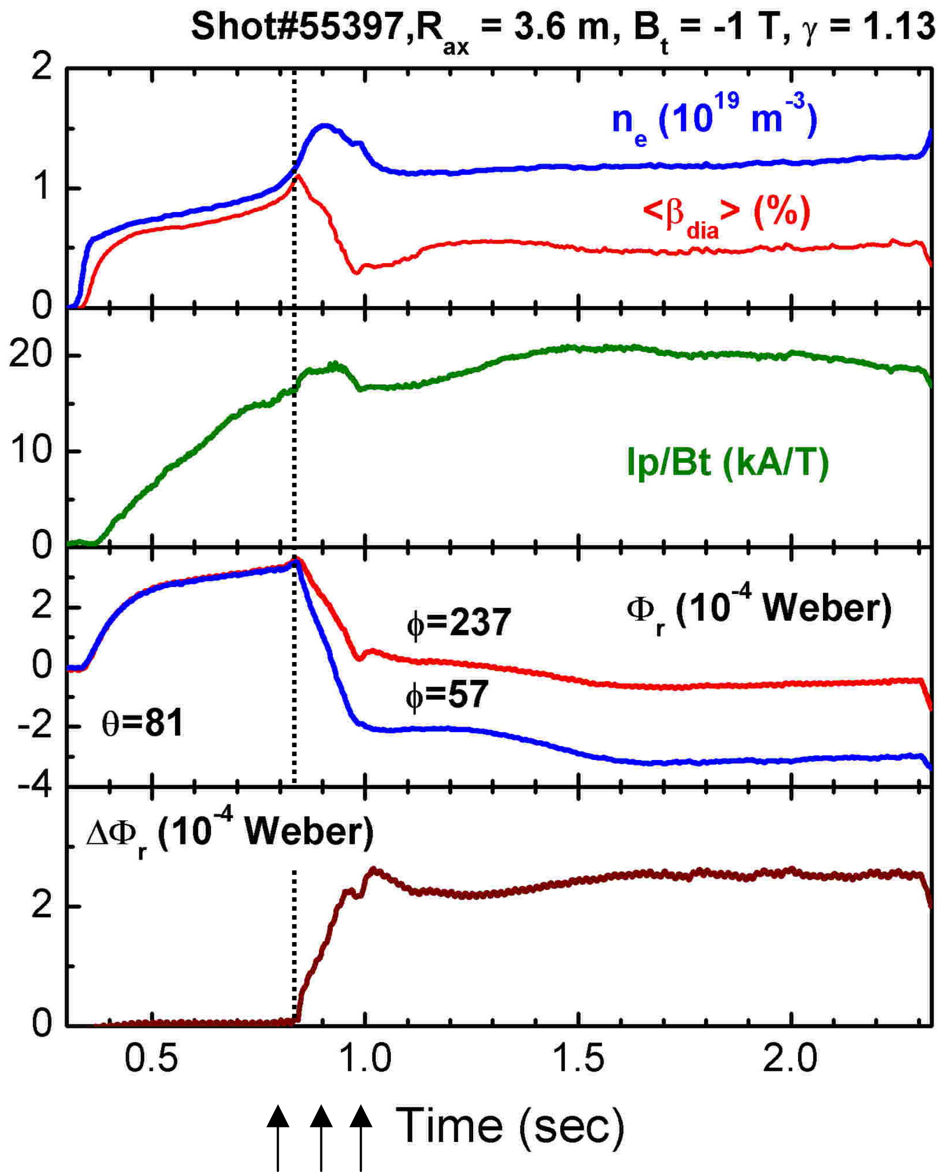
Poloidal Arrays of Saddle Loops (ϕ = 0, 180°)

Before

Growth

Saturation





Increment of $B_{r\text{-}1/1}$ component

- m/n = 1/1 mode structure is identified through comparison between flux loop signals and the multi-filament calculation.

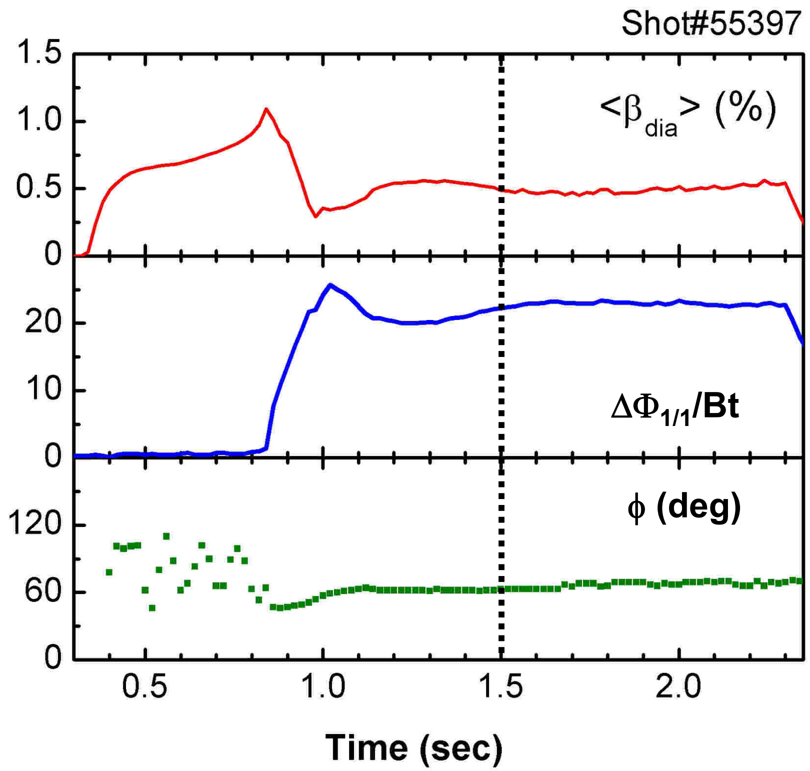
- Parameter $\Delta\Phi_{1/1}/B_t$ is related with w^2

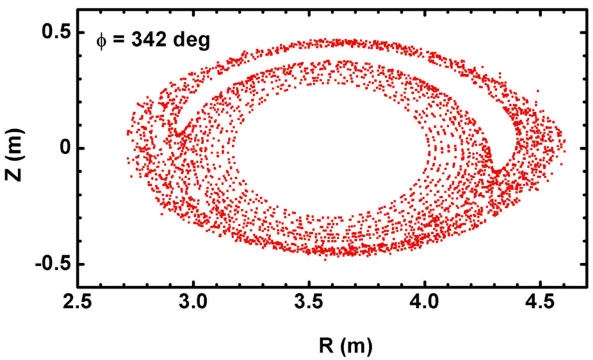
$$\mathbf{w/a = 4(|1/\Theta|\delta B_r/mB_0)^{1/2}}$$

$$\mathbf{\delta B_r/mB_0 \propto \Delta\Phi_{1/1}/B_t}$$

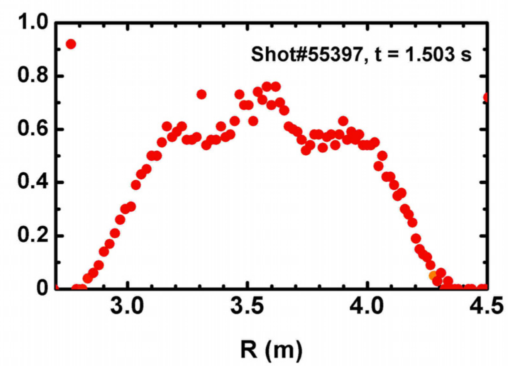
- The beta signal synchronizes with $B_{r1/1}$ component.

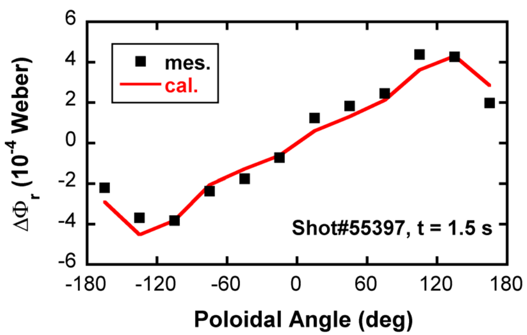
-The toroidal angle (O-point at outer torus) is almost constant to the end of discharge.





Example plot (A_p = 5.8)





Characteristics of non-rotating mode

When the "non-rotating mode" grows, it obviously limits the beta.

Characteristics of the mode:

[1] spatial location

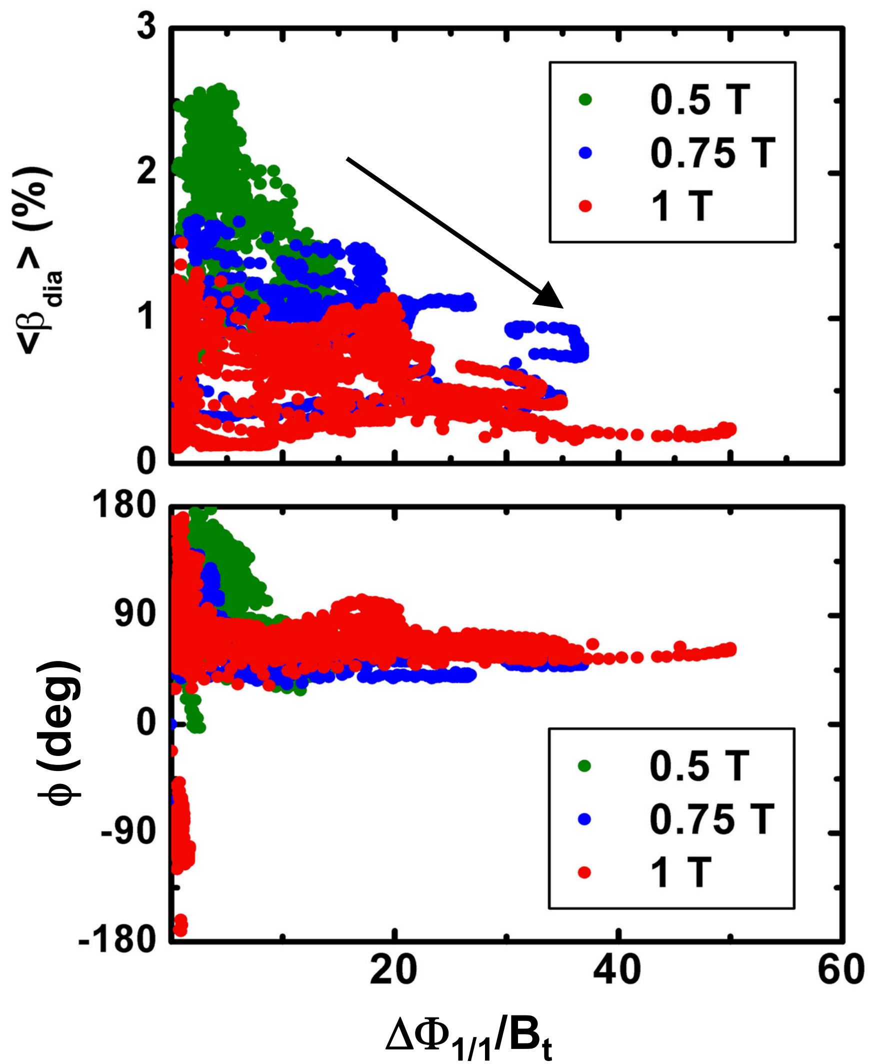
- almost constant
- O-point in outer torus: ϕ ~ 60 deg.

[2] growth time

- 0.05 ~ 0.1 s (~ τ_E)
- fast growth → nonlinear ?

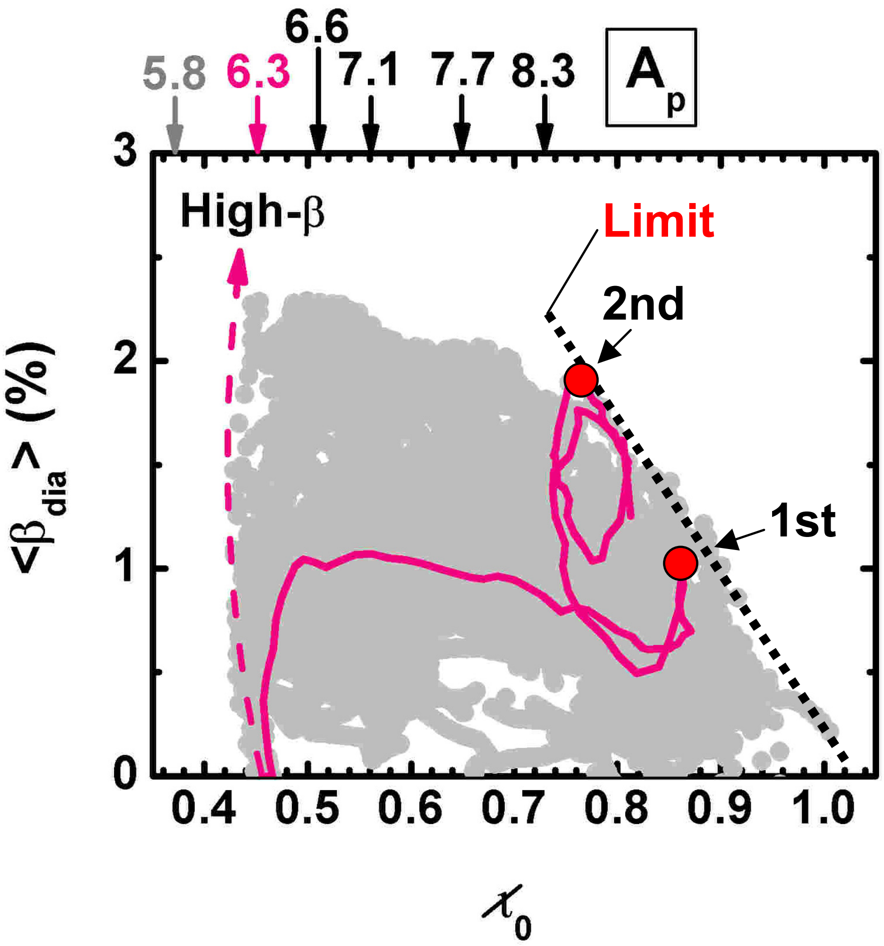
[3] precursor

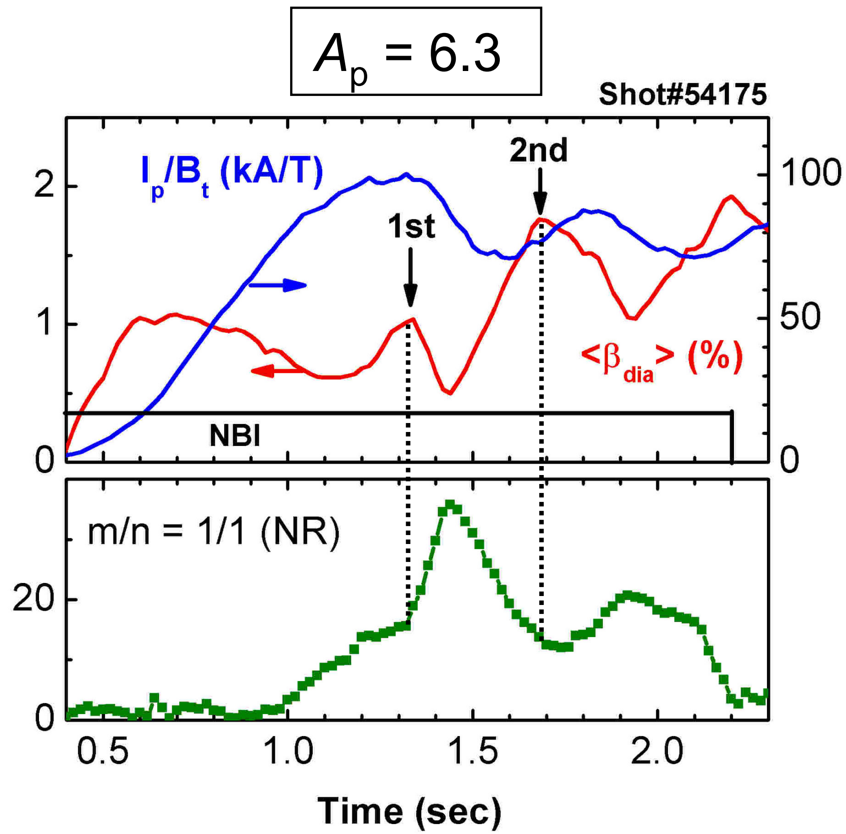
- Obvious precursor is not identified yet.



Plasma rebounded against “Limit”

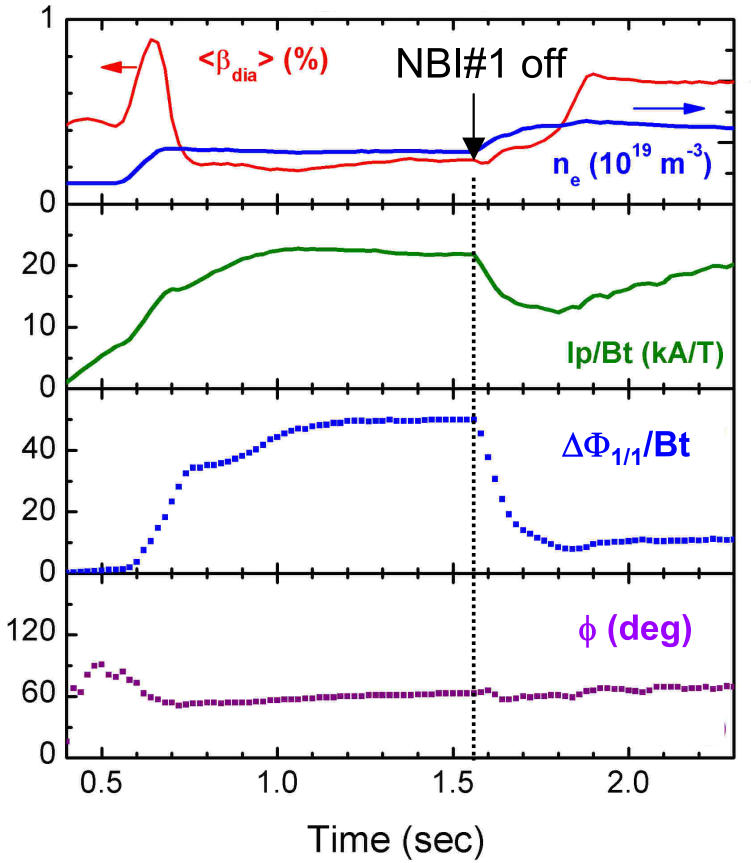
- Even if A_p is sufficiently low, the I_p causes the minor collapse
- Plasma is rebounded from “limit” twice.

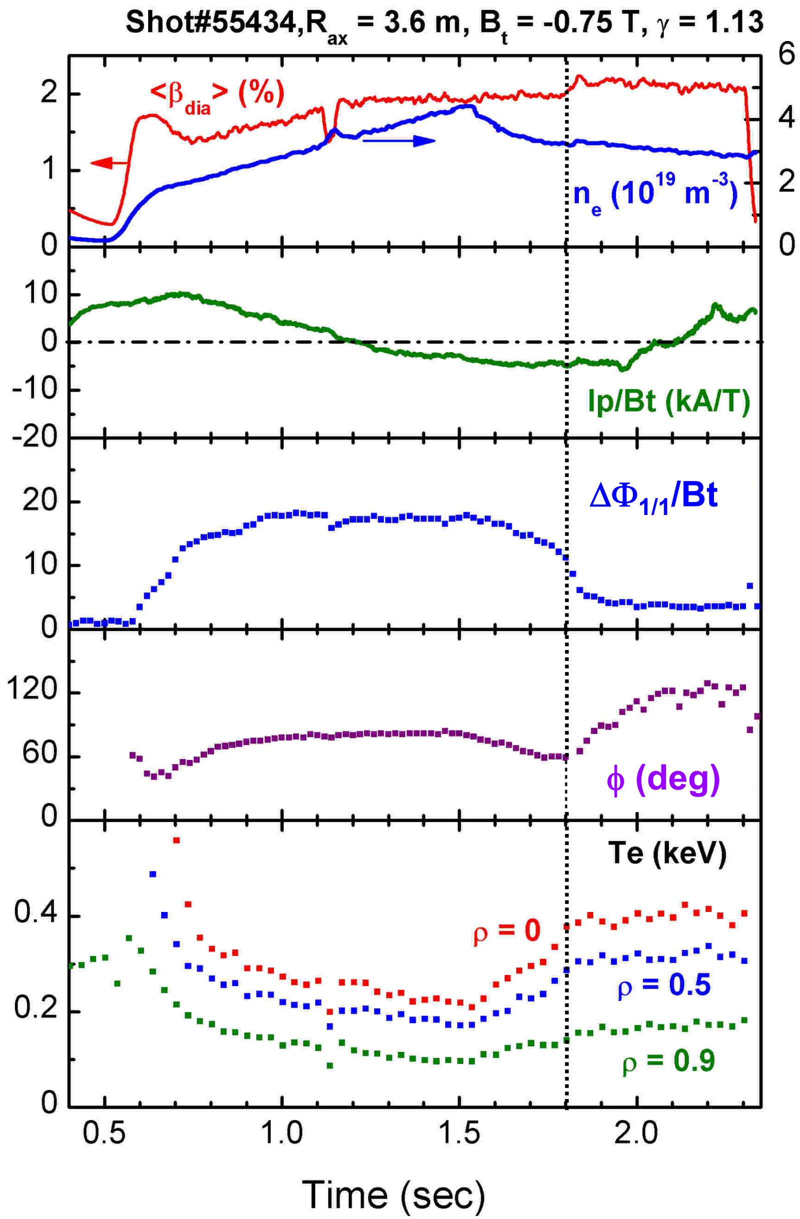




Recovery from *m*/*n*=1/1 restriction

- Recovery of β from *m*/*n* = 1/1 activity is observed in some conditions
- In the large I_p case, β degradation is so large





Discussion on the Minor Collapse

• The appearance of *m*/*n* = 1/1 mode is qualitatively consistent with theoretical prediction on ideal MHD instability.

⇒ comparison of the mode structure between experiments and calculation

• The mode has no rotation and stays at the same location

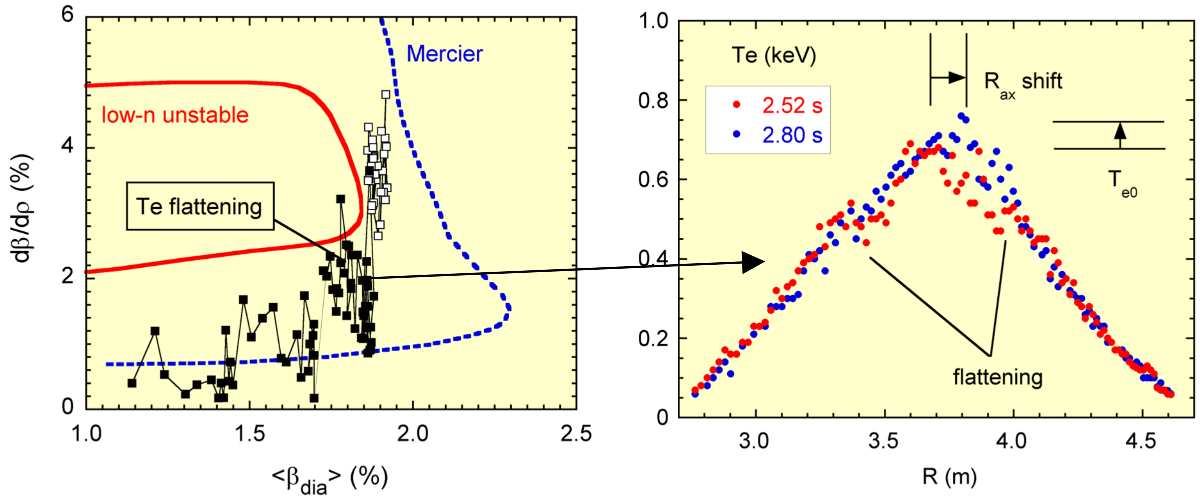
• When the mode has the rotation, minor collapse is not observed.

⇒ stabilization effect due to rotation

⇒ measurement of bulk rotation (radial electric field)

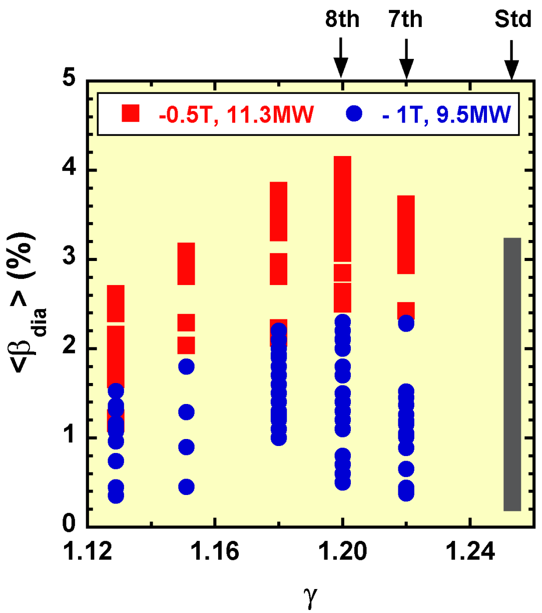
• The impact of m = 1 mode to plasma confinement is much larger than the m = 2 mode case.

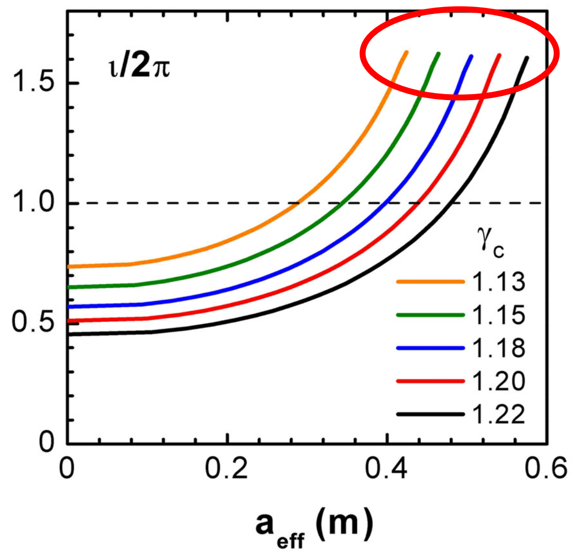
⇒ important knowledge on the design of configuration in the future.

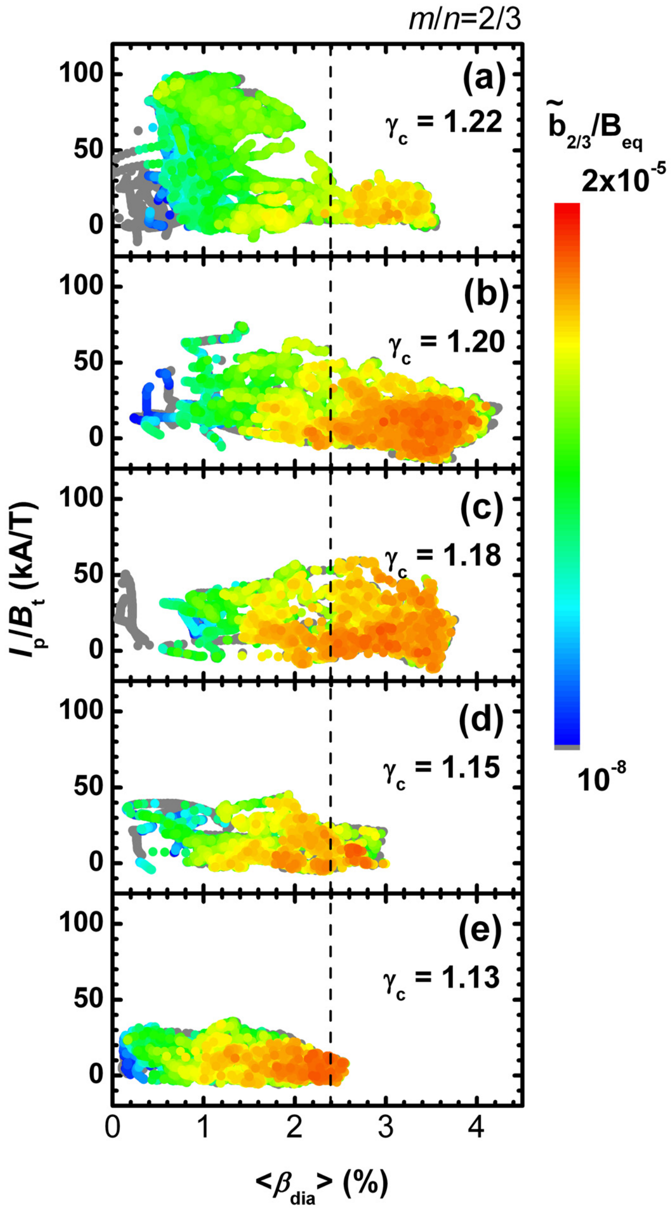


Enhancement of Edge low-*n* mode

- The m/n = 2/3 mode is enhanced with the decrease in γ_c., and it is one of the reasons for degradation of confinement with the reduction of γ_c.
- The resonance is located near edge in any γ_c (low-*S* region).
- Magnetic hill is enhanced with reduction of γ_c.







High-β Experiments in LHD

FY2002 (Standard) : 3.2 % (1.25, 0.5 T)

FY2003 (Reduced γ_c) : 4.1 % (1.22, 0.5 T)

FY2004 (Optimized γ_c) : 4.3 % (1.20, 0.45T)

FY2005 (Increment of P_{NBI}) :

4.5 % (1.20, 0.45 T)

- No power degradation.