Effects of global MHD instability on operational high beta-regime in LHD

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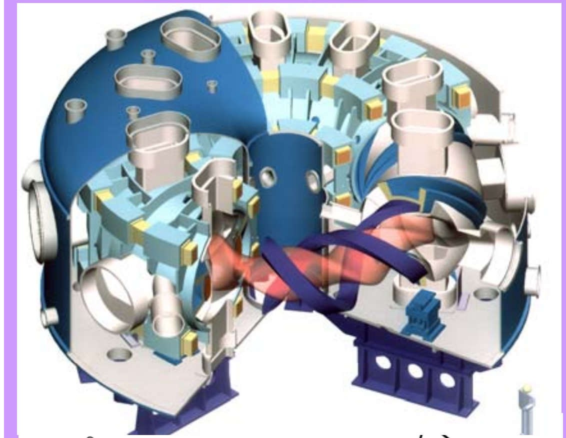
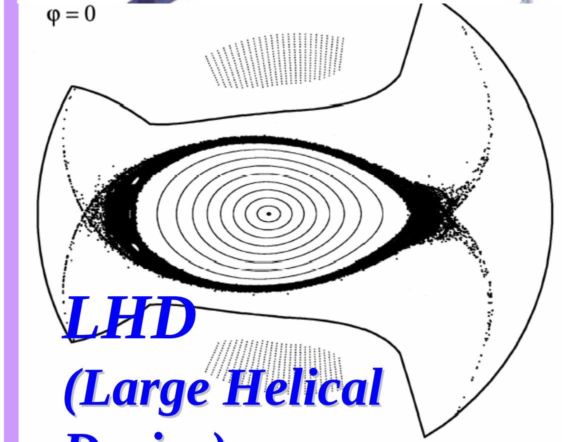
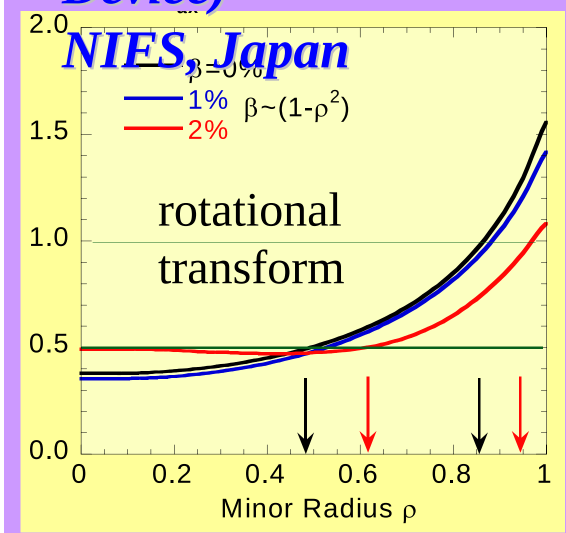




LHD (Large Helical Device) NIES, Japan



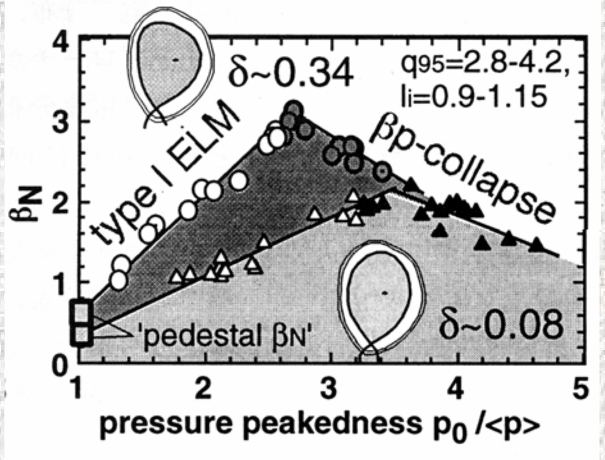
Background I --- ideal MHD effects on the beta limit ----

 # A Heliotron device is a probable candidate of thermonuclear fusion reactor under steady-state operation.
However, a disadvantage with respect to pressure driven MHD instabilities is theoretically predicted.

 # How do MHD instabilities limit the operational regime in high beta plasmas?   It is very important issue in heliotron devices.

 # Tokamaks; well known
The operational beta limits are quite consistent with theoretical predictions of ideal linear MHD theory.

 # Stellarator/helotrons; there were a few experimental studies
The ideal MHD effects on the beta limit (the operational regime) were not clear.



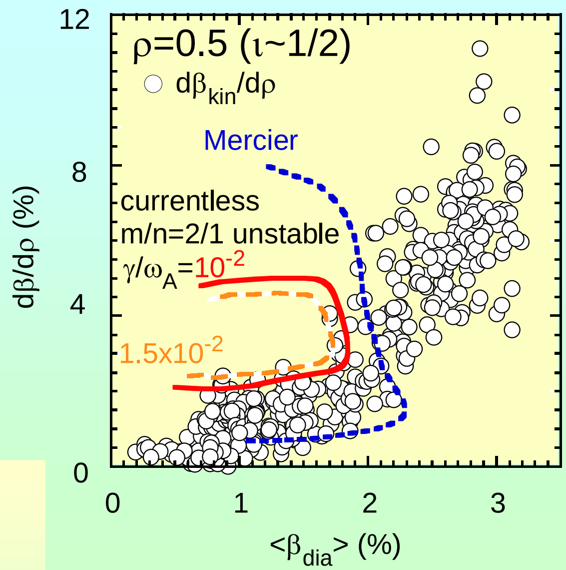
Profile and shape dependence of β_N in JT-60U.

[Kamada et al, 16th IAEA proc.]

Background II *--- Related previous study in LHD ----*

1. In Core region,
Comparison between observed $d\beta/d\rho$ and the theoretical ideal MHD stability analysis,
=>
The observed $d\beta/d\rho$ are limited by the ideal global MHD instability in the intermediate beta range.

[WATANABE, K.Y., et al, Fusion Sci. Tech. 2004]

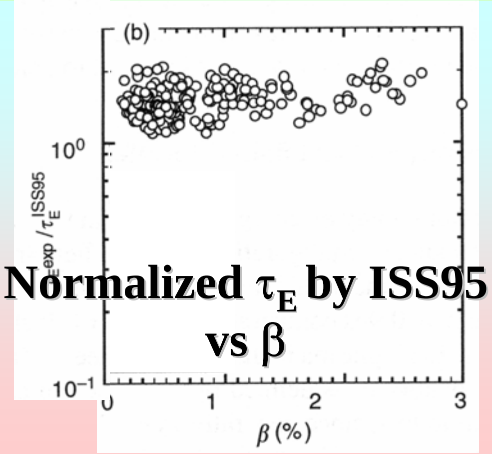


2. When only core resonant magnetic fluctuation disappears, the plasma stored energy gains. However, the gain is ~5% of W_p.

[SAKAKIBARA, S., Nucl. Fusion 2001]

3. On the global energy confinement time, a disruptive degradation of the improvement factor had not been observed up to $<\beta_{dia}>$ ~3%

[YAMADA, H., et al., Plasma Phys. Control. Fusion 2001]



Normalized τ_E by ISS95 vs β

Topics of Talk

In order to make clear the effects of the global ideal MHD instabilities on the operational regimes in stellarator/ heliotrons, the MHD analysis and the transport analysis are done in a high beta range up to ~4% in the LHD.

Outline

0. Background

1. On a typical discharge in the extended beta range up to ~4% in the LHD

2. Effect of the global confinement on the beta value

3. Relationships between predicted global ideal MHD modes and transport analysis

4. Discussion

--- Index for the limitation of an operational regime in the LHD (as a stellarator/heliotron device)

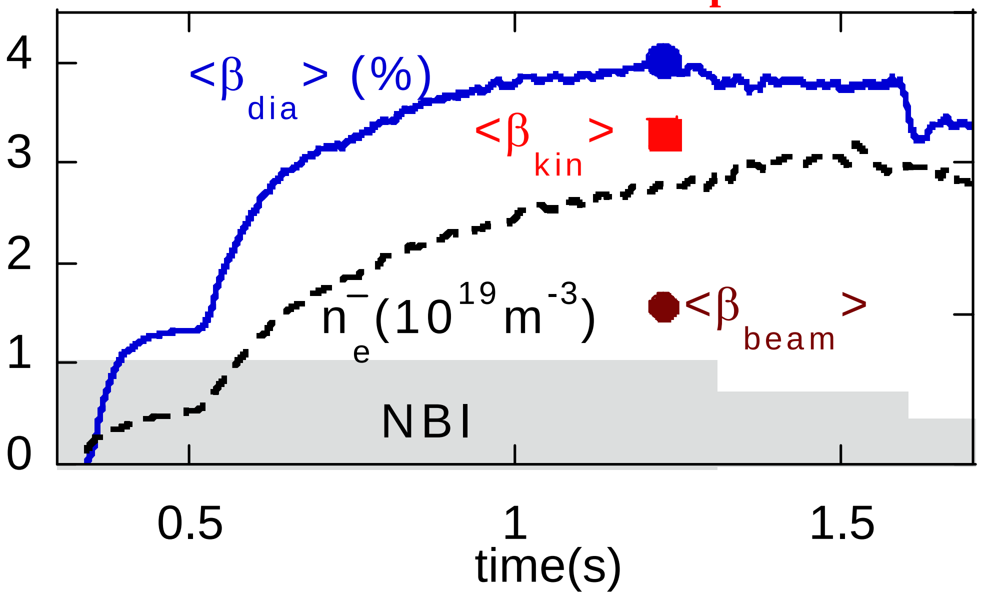
--- Beam pressure effects on the pressure driven MHD instability

5. Summary

On a typical discharge in the extended beta range (I)

Wave form for a high β discharge

0.45T, R_{ax}^{V}=3.6m, A_p=6.3



When <β_{dia}> reaches 4%,

NBI Power

Port through ; 11.2MW

Deposition ; 6.2MW(Cal.)

<β_{kin}> ; *3.3%*

<β_{beam}> ; *1.5%* (Cal.)

<β_{dia}> ; based on the diamagnetic measurement.
defined as $(2W_{dia}/3V_{p0})/(B_{av0}^2/2\mu_0)$.
B_{av0} and V_{p0} are based on a vacuum calculation.

Beam pressure is fairly large.

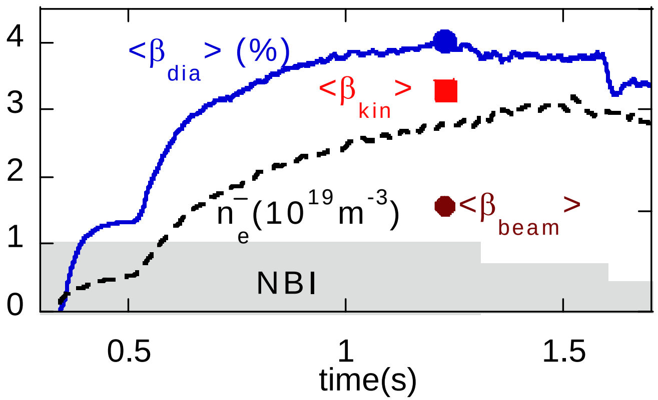
<β_{kin}>; based on the T_e and n_e profile measurements
Z_{eff}=1 and T_i=T$_e$ are assumed.

(When Z_{eff}=2.5, <β_{kin}>~2.8%, <β_{beam}>$_{perp}$~0.8%, <β_{beam}>$_{para}$~0.7%)

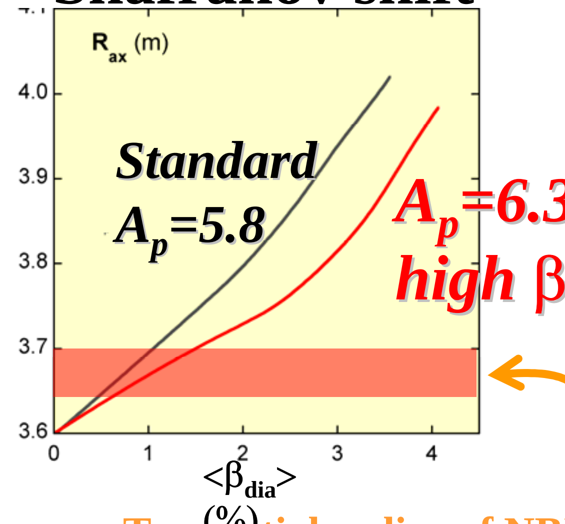
<β_{beam}> ; based on the calculation
with Monte Carlo technique and the steady state Fokker-Plank solution.

High-aspect ratio Config. for High β

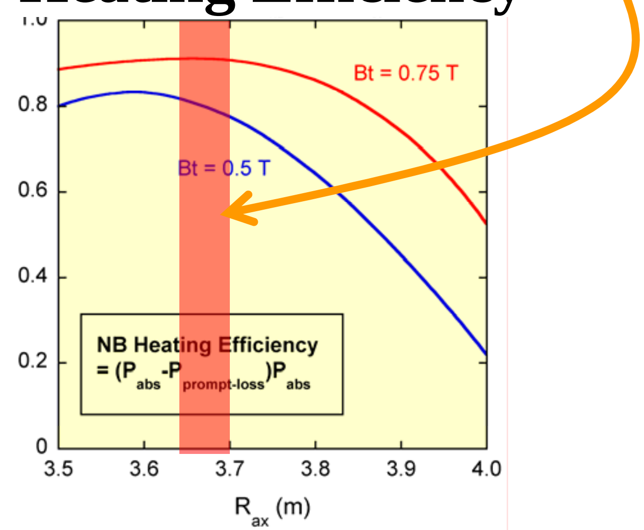
0.45T, R_{ax}^{V}=3.6m, A_p=6.3



Shafranov shift



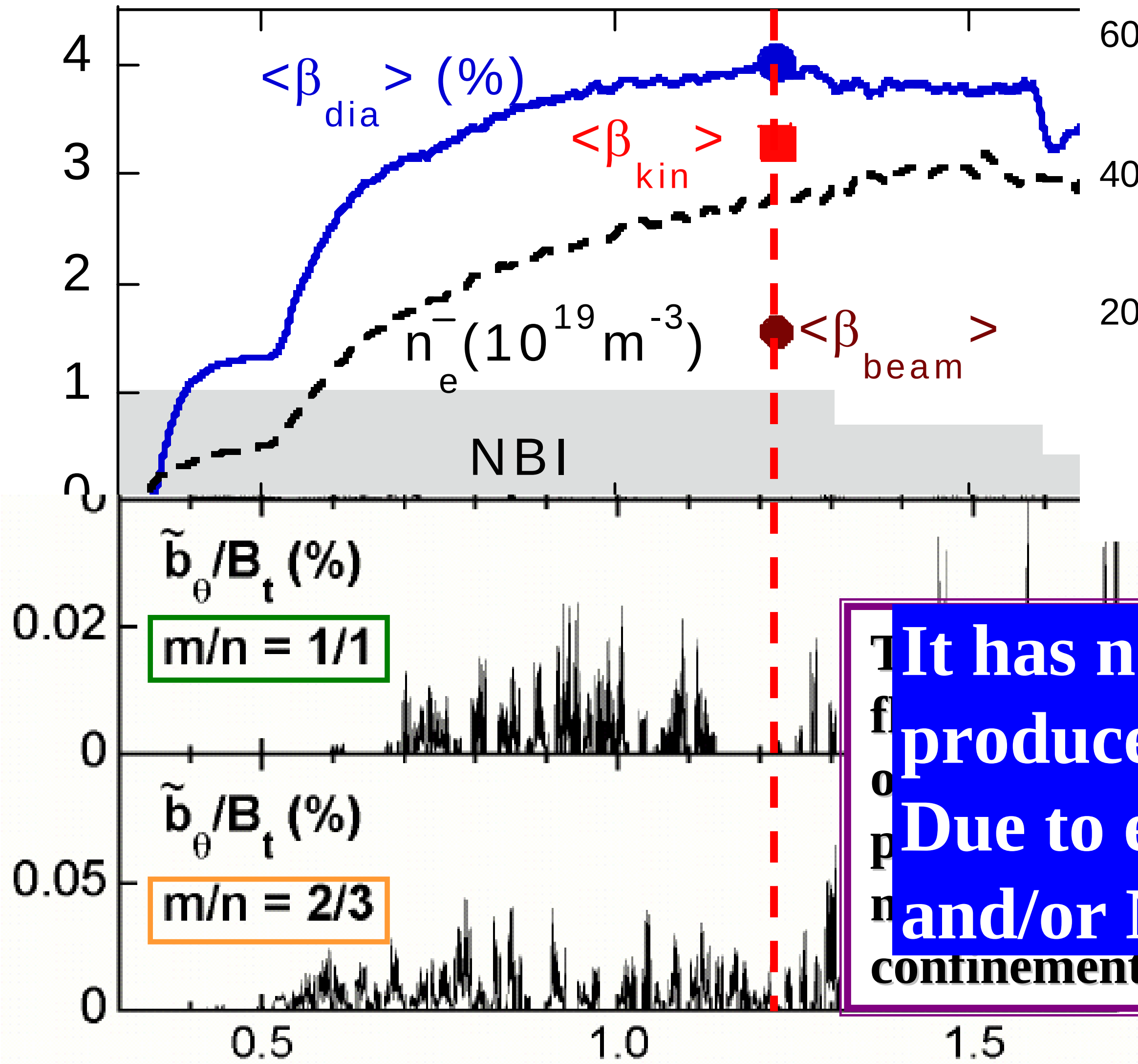
Heating Efficiency

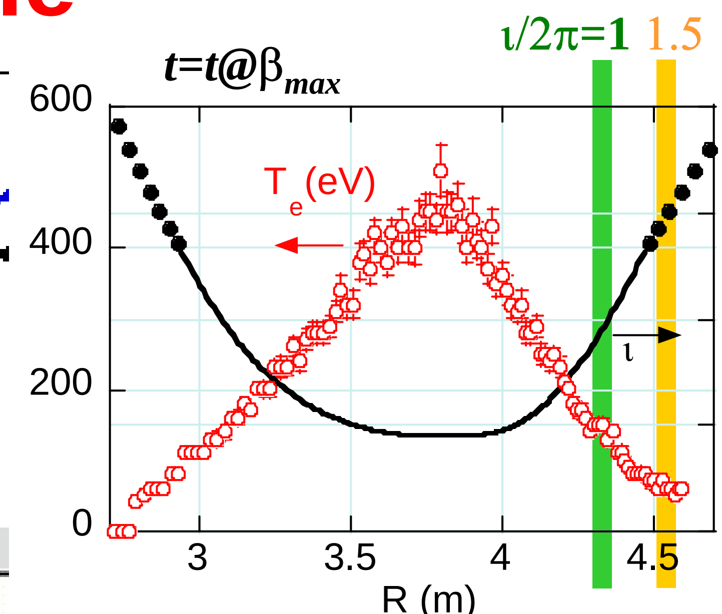


High-aspect ratio config.
=> high ι, Reduced shafnanov shift
=> Retains a good heating efficiency
in high beta discharges

The config. is unfavorable for MHD stability
<= reduces the formation of magnetic well
in high beta regimes..

Magnetic fluctuation and ... T_e profile

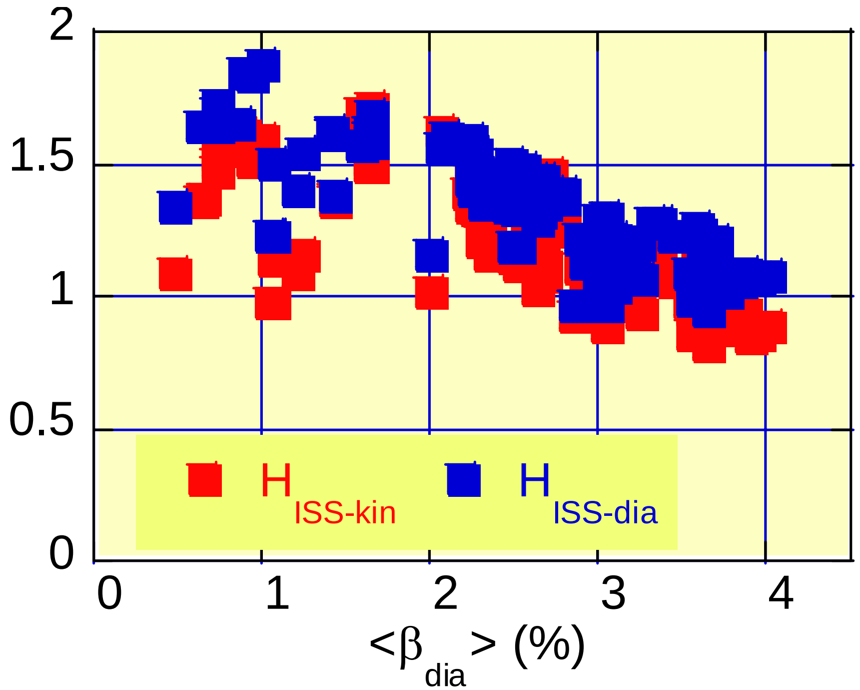




It has not been clear what produces the fine structure. Due to equilibrium current and/or MHD activity??

confinement.

τ_E normalized by ISS95 scaling



A disruptive degradation has not been observed up to $\langle\beta_{dia}\rangle$ ~4%, in both τ_E based on the diamagnetic energy and the kinetic energy .

However, the enhancement factors are gradually reduced as beta increases.

How about the ideal MHD effects?!

Ideal MHD stability in peripheral region

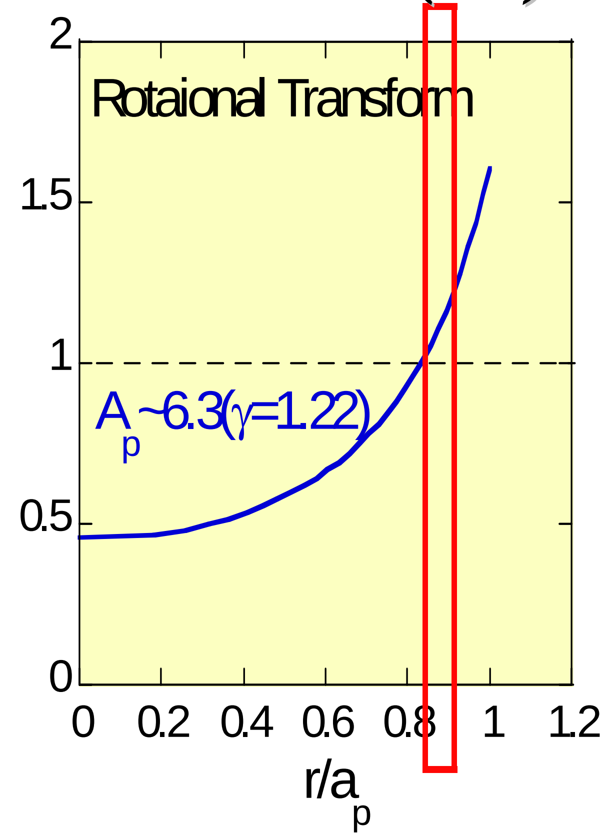
As the β becomes higher,,,,,,

Instability in the peripheral region is more unstable.

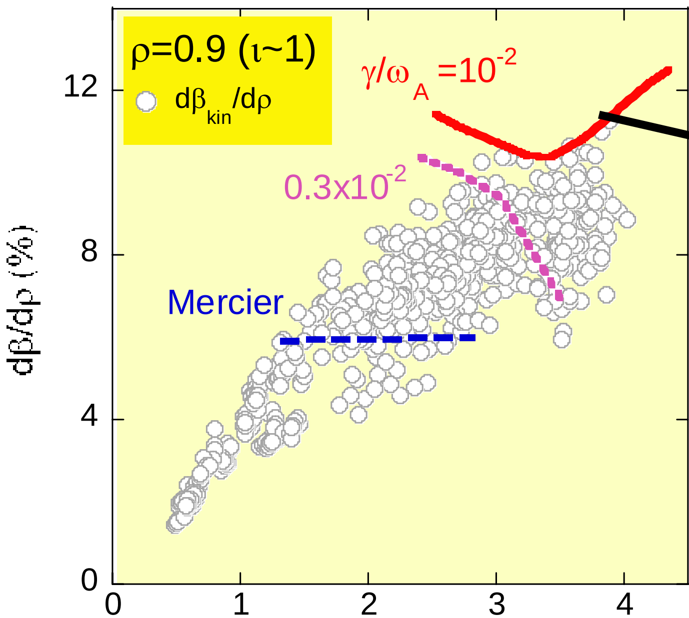
The instability might limit the operational beta range.

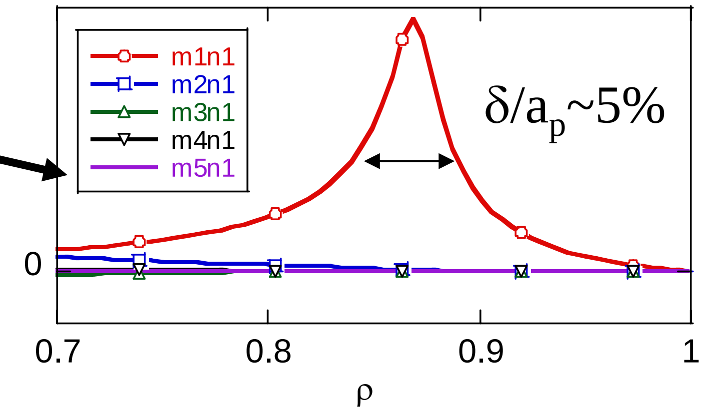
ρ=0.9 (ι~1)

Here ρ=0.9 (ι~1) surface is focused to analyze the relationships between observed beta gradients and the prediction of ideal MHD instability.



Position of experimental region

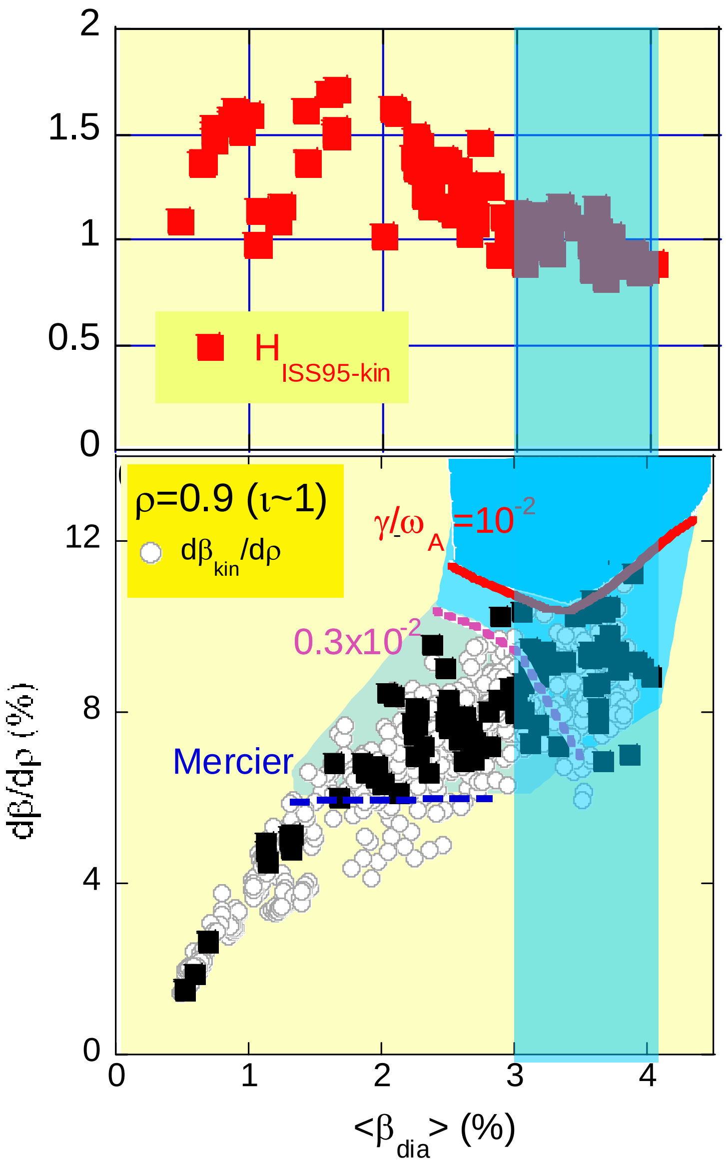




Radial structure of ideal MHD mode calculated by **TERPSICHORE code**

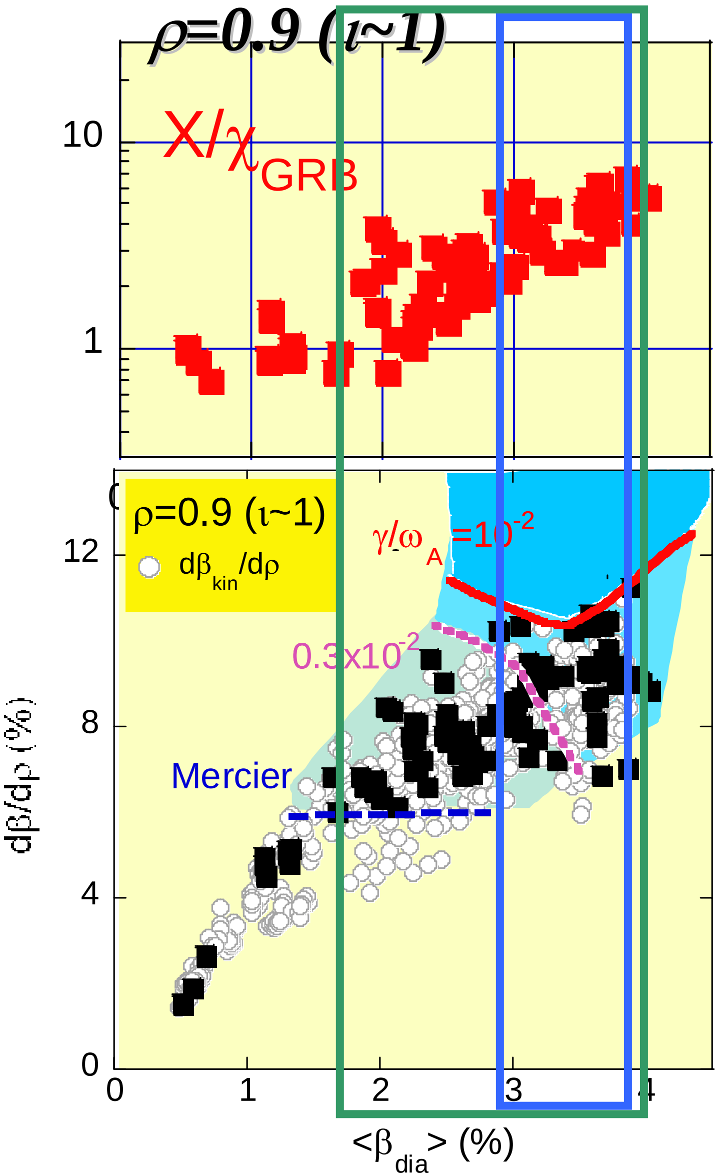
Though beta value and its gradients reach the global mode unstable region where the predicted radial width of the ideal MHD mode reaches δ/a_p=5%, the disruptive degradation of global confinement has not been observed.

Ideal MHD effects on global confinement



In the global MHD mode unstable region (β=3~4%), No disruptive degradation!!

Ideal MHD effects on local transport



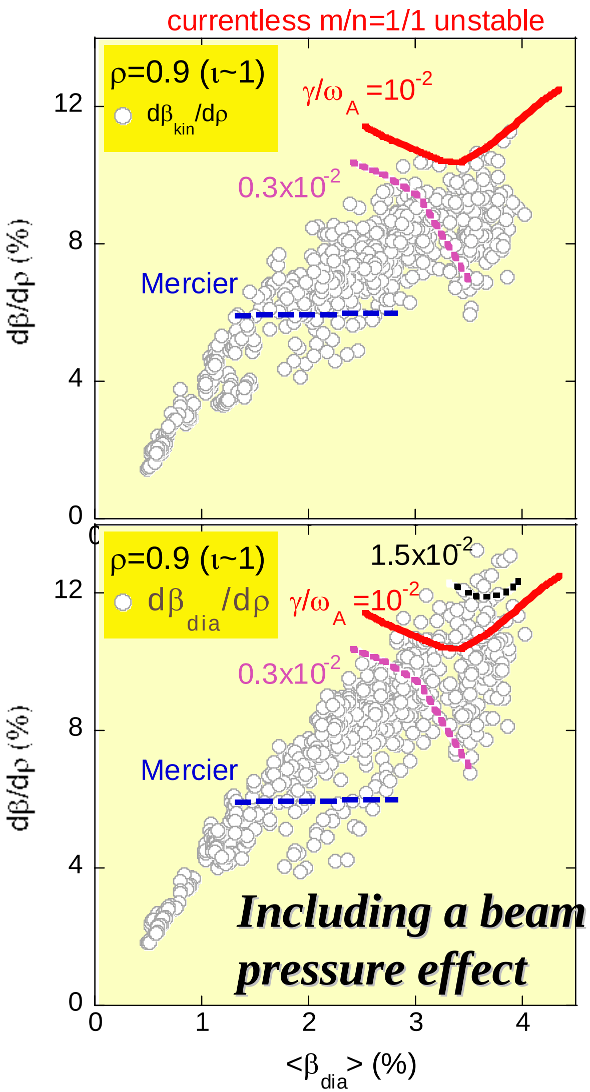
$$X = \left.\frac{Q}{S}\right|_{\rho=0.9} \Bigg/ \left(-\left.\frac{\partial \beta_{kin}}{\partial r}\right|_{\rho=0.9} \frac{B^2}{2\mu_0} \right)$$

No disruptive degradation in the global mode unstable region!!

X/χ_{GRB} gradually increases in Mercier unstable region.

High-n and/or low-n localized ideal interchange modes affect a local transport!?

How does beam pressure affect the pressure driven MHD instability ?



Assumption;

$d\beta_{beam}/d\rho$ is proportional to $d\beta_{kin}/d\rho$.

$<\beta_{dia}> - <\beta_{kin}> \Rightarrow <\beta_{beam}>$

Predicted maximum growth rate exceeds $\gamma_{low\text{-}n}/\omega_A = 1.5\mathrm{x}10^{-2}$.

Growth rate is fairly large!!

To make clear the beam effects, we need more detail analysis.
=> Future subject

Summary

1. In LHD, the operational highest beta value has been expanded from 3.2% to 4% in last two years by increasing the heating capability and exploring a high aspect configuration.

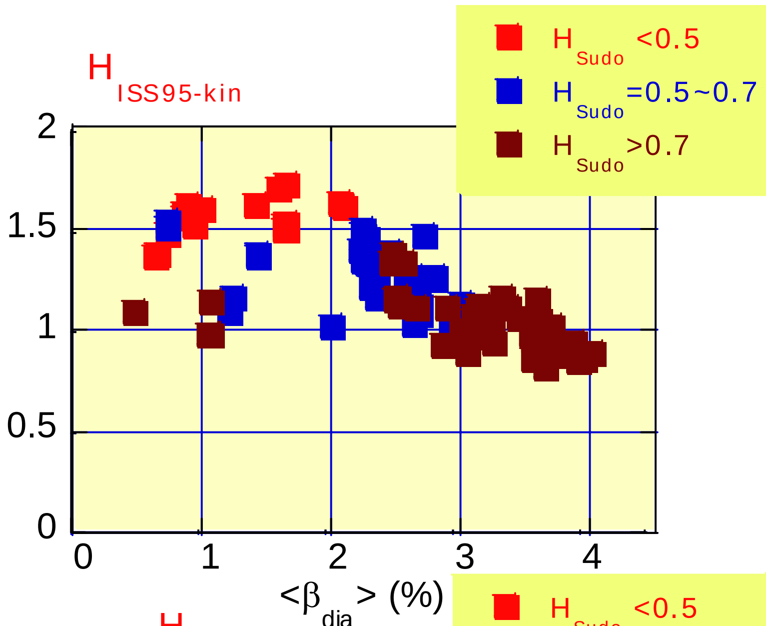
2. In order to make clear the effect of the global ideal MHD instabilities on the operational regimes, the MHD analysis and the transport analysis are done in the high beta range up to 4%.

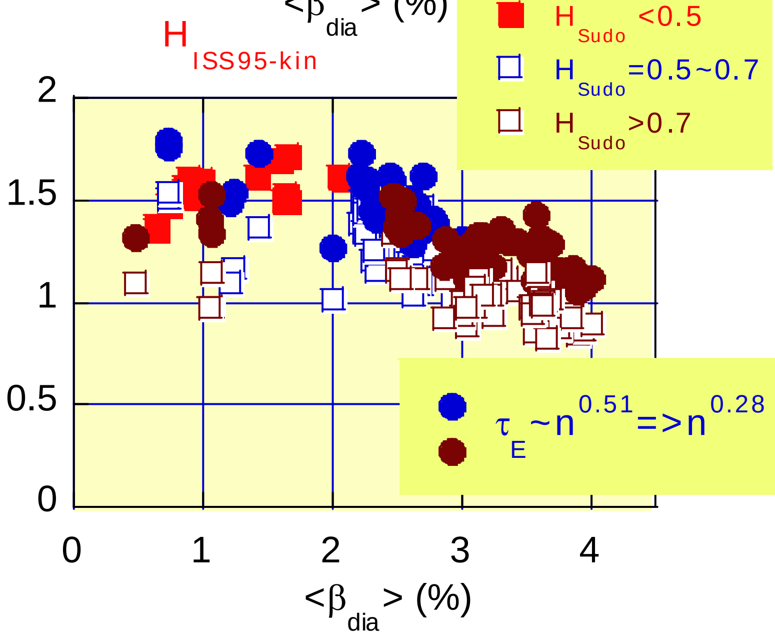
In a high beta range of more than 3%, the maxima of the observed peripheral thermal pressure gradients are marginally unstable to a global ideal MHD instability.

Though a gradual degradation of both the peripheral local transport and the global confinement has been observed as beta increases, a disruptive degradation does not appear in the beta range up to ~4%.

3. There is a possibility that the beam pressure gradient effect on the operational limits will be a key issue for a further extension of the beta range in LHD.

Effect of ideal MHD mode on the global confinement (II)





The high beta discharges with β>3% are done near a density limit, $\boldsymbol{H_{Sudo}}$>0.7.

$$H_{Sudo}=\bar{n}_e/\bar{n}_{e\_lim},\ \bar{n}_{e\_lim}\sim(P_{abs}B/V)^{0.5}.$$

According to a recent transport study in the LHD high collisional regime,
τ_E scales as $n_e^{0.28}$
(In the ISS95 scaling, $\tau_E \sim n_e^{0.51}$)

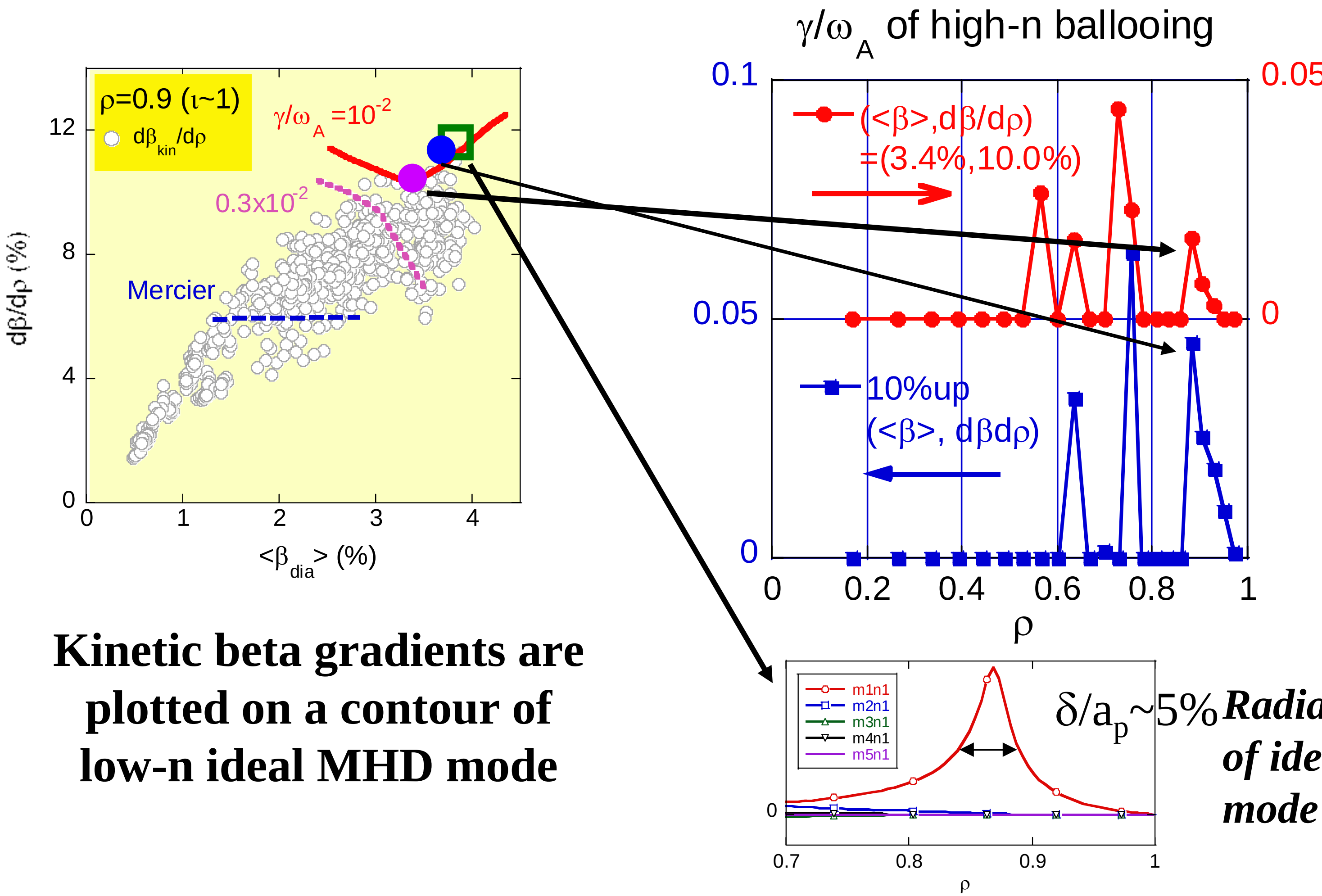
Applying the above collection near a density limit

=>
In a low beta regime,
the scattering of the data is reduced.
In a high beta regime,
the gradual degradation of the global confinement on β still remains.

How about the ideal MHD effects?!

Discussion IV

Example of ideal ballooning stability analysis in high β range



Kinetic beta gradients are plotted on a contour of low-n ideal MHD mode

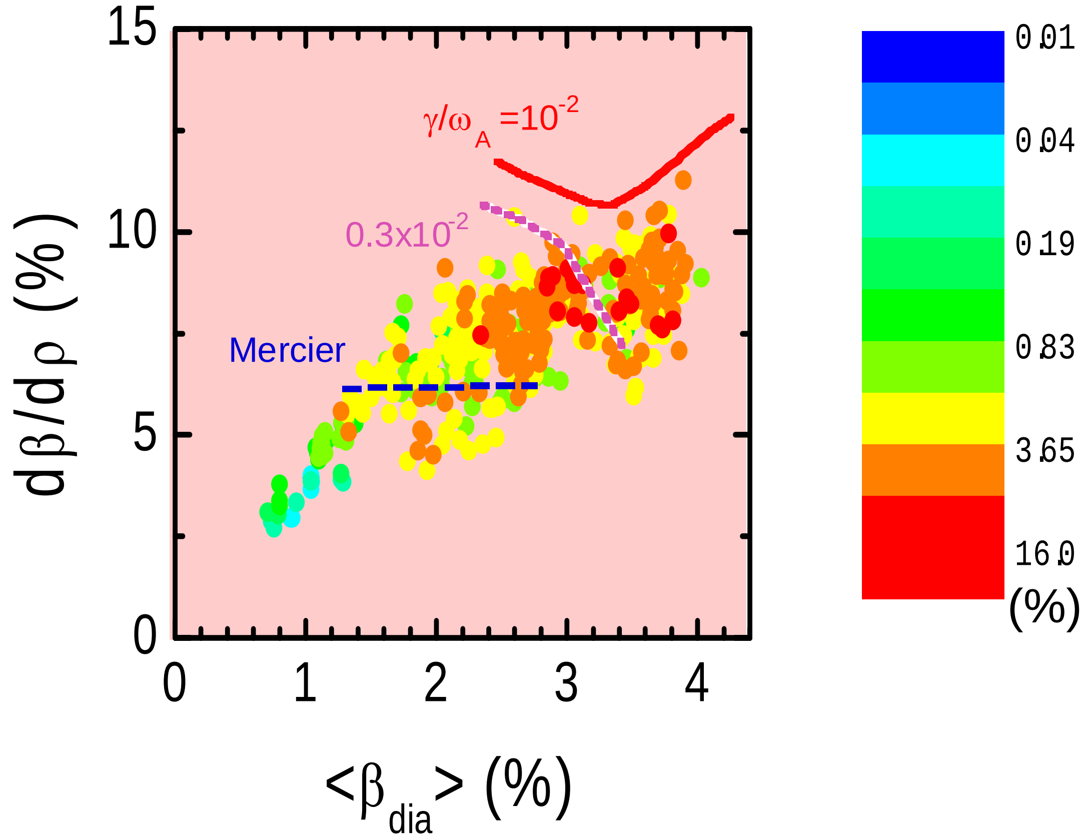
Radial structure of ideal MHD mode

Predicted high n ballooning modes are as unstable as ideal interchange modes in high beta range of β=3~4%.

Discussion III

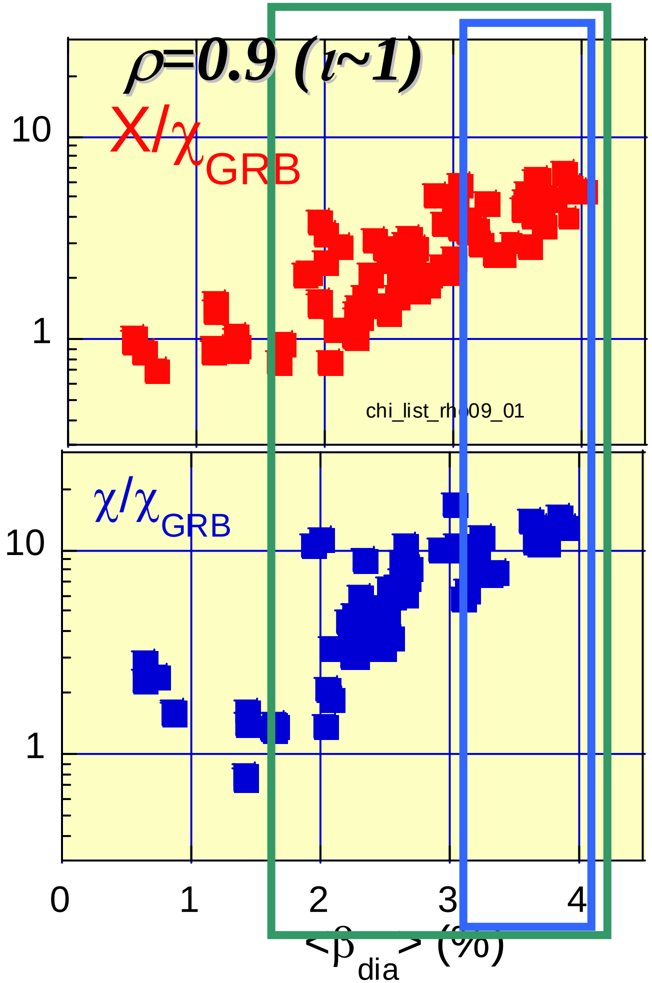
$\tilde{b}/B_0$ on $d\beta/d\rho$ and global ideal MHD unstable region

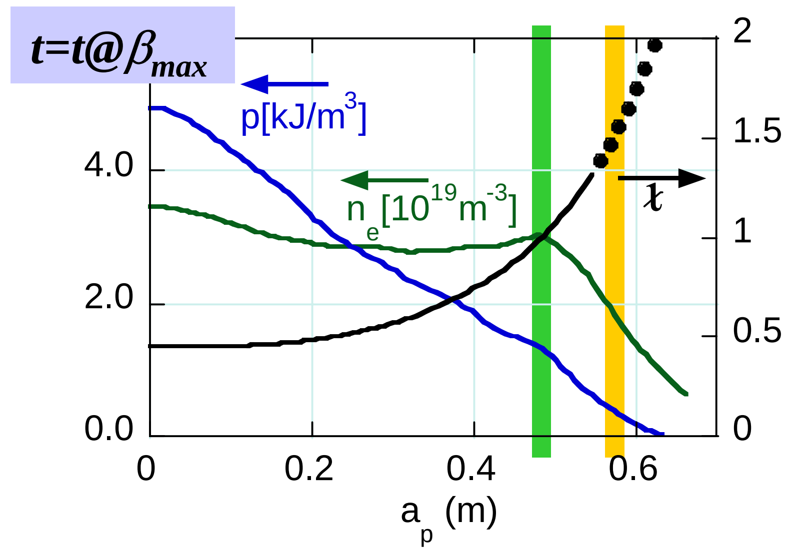
Amplitude of $\tilde{b}/B_0$ of m/n=1/1 mode



The m/n=1/1 mode is observed even in the Mercier stable region. Amplitude of the m/n=1/1 mode increases as beta and the gradients increase.

Ideal MHD effects on Electron thermal transport (II)





No disruptive degradation is observed in the global ideal MHD modes, $<\beta_{dia}>$=3-4%.

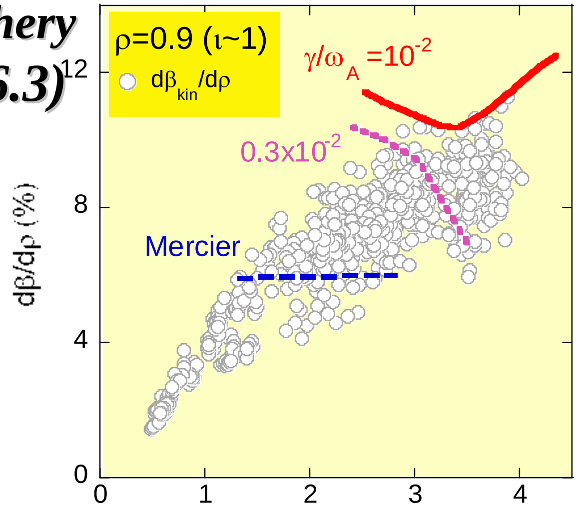
Maxima of χ/χ_{GRB} increases when the beta gradients are in Mercier unstable region. High-n and/or low-n localized ideal interchange modes affect a local transport!?

There high-n ideal ballooning and resistive interchange/ballooning modes might be also unstable. ***A future subject!!***

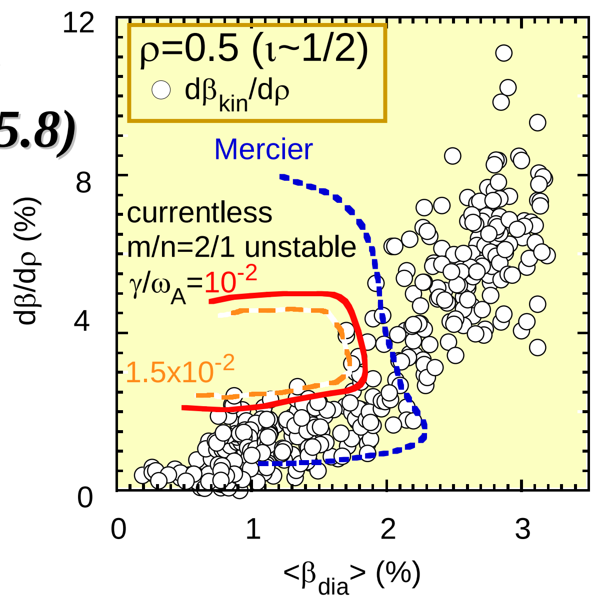
Discussion II

What is a good index for the limitation of the operational regime in stellarator/heliotron?

Periphery (A_p=6.3)



Core (A_p=5.8)



Though the observed pressure gradients are in non-linear saturation phases, a linear MHD theory could be a reference for more complicated non-linear analyses, and/or a criterion for a reactor design.

Peripheral region: the maxima of the achieved pressure gradients are less than $\gamma_{low\text{-}n}/\omega_A = 10^{-2}$.
Core region; the maxima of the achieved pressure gradients saturate against the contour of $\gamma_{low\text{-}n}/\omega_A = 1.5\text{x}10^{-2}$ in the range of $\langle\beta_{dia}\rangle$ = 1~1.8%.

Roughly speaking, $\gamma_{low\text{-}n}/\omega_A = 1\sim1.5\text{x}10^{-2}$ is considered a good index to determine the condition that the global ideal MHD instability limits the LHD operational regime.

For further verification, we need to extend the above comparative analyses between the experimental results and the theoretical prediction based on a linear theory to many magnetic configurations in LHD!!

Aspect-ratio Control in LHD

Aspect ratio of plasma can be optimized by the control of the central position of HC current.

- Aspect-ratio of 5.8 ~ 8.3 is available in the R_{ax}^{V} = 3.6 m configuration.
- High aspect-ratio configuration has high rotational transform which suppresses.