11th WORKSHOP
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Effects of global MHD instability on operational beta-regime in LHD and its control

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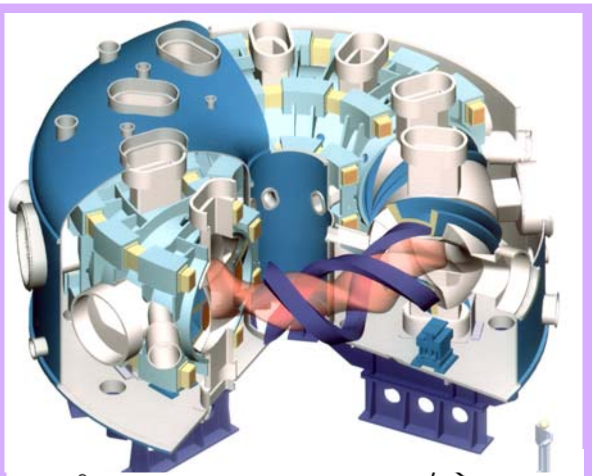
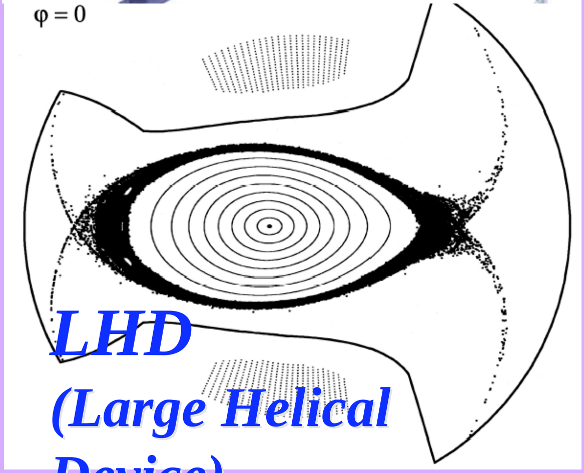
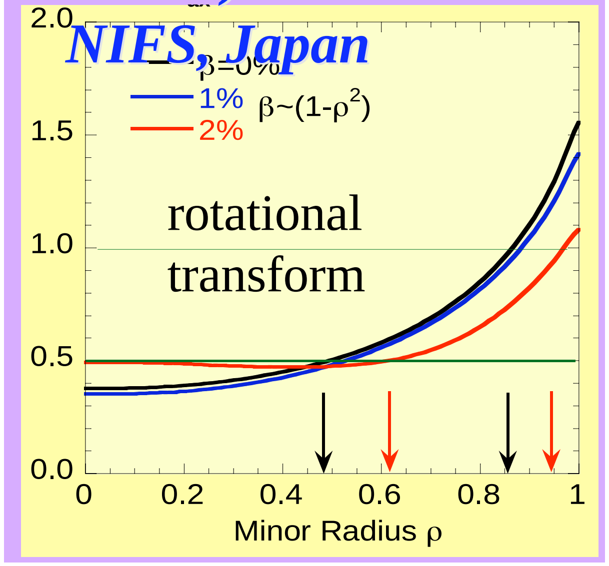
Special Thanks the LHD technical staff for their support of the experiments.

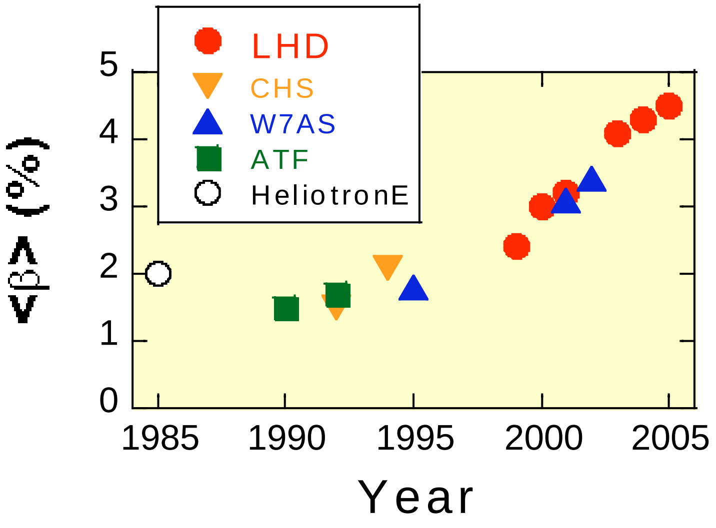




LHD
(Large Helical Device)
NIFS, Japan



Buck ground



Progress of achievement of max. beta in helical devices

For an economical fusion reactor, achievement and sustainment of high beta plasma (β~5%) is necessary.

In heliotron plasma like LHD (Large Helical Device, NIFS in Japan), it is predicted that the MHD instabilities appear in high beta regime because the magnetic hill exists in the finite beta gradients region.

Expected influence of MHD instabilities on confinement

1. global mode (low-n/m; limited resonant surfaces)
=> disruption or collapse; hard limit in operation range!?

2. localized mode (high-n/m; a lot of resonant surfaces)
=> turbulence or anomalous transport; soft limit!?

Contents

Main topics;

Effects of global MHD instability (low-n,m modes) on operational beta-regime in LHD

 # Characteristics of LHD configuration

 # Progress of high beta operation in LHD

 # Characteristics of 2 type of low-m (global) MHD activities and their effects on plasma confinement

1. commonly observed, increasing with beta

2. observed in a special config. with a minor collapse

 # On control of MHD instabilities with static error field coil

Ref.
[1] K.Y.Watanabe et al., Nucl. Fusion, 45, 1247-1254 (2005).
[2] S.Sakakibara et al., 15th ISW, Madrid, Oct., 2005.
[3] S.Sakakibara et al., 33th EPS, Rome, Jun. 2006.
[4] K.Y.Watanabe et al., ICPP2006, Kiev, May, 2006.
[5] S.Sakakibara et al., Ex/7-5 in 21th IAEA, Chengdu, Oct. 2006.

Large Helical Device (LHD, NIFS, Japan)

Exp. started at
F.Y.1998
Shot
#66053
(Up to Feb.2006)

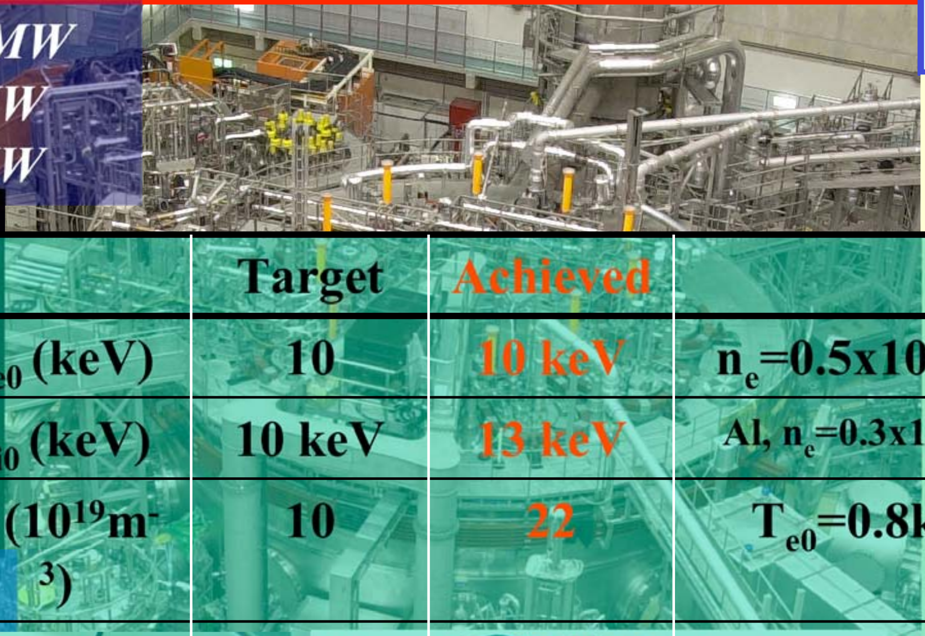
Largest helical and super conducting machine in the world

Magnetic energy	1 GJ
Cryogenic mass(-269℃)	850 t
Tolerance	< 2mm

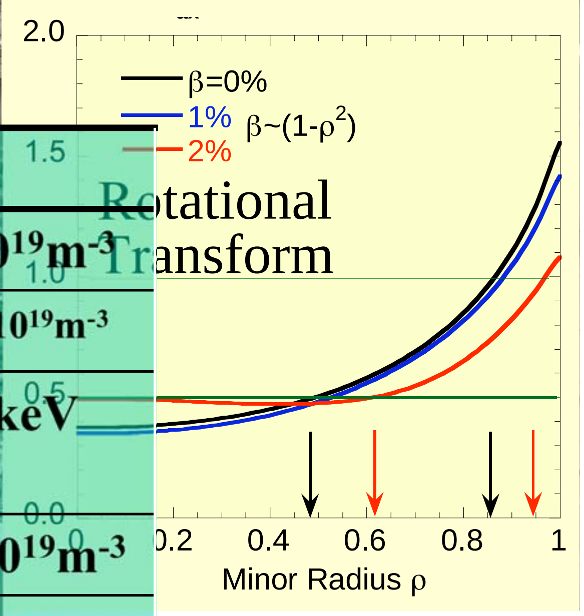
External dia.	**13.5 m**
Plasma Maj. R.	**~3.7 m**
Plasma Min. R.	**~0.6 m**
Plasma Vol.	**~30 m³**
Magnetic field	**3 T**
Total weight	**1,500 t**

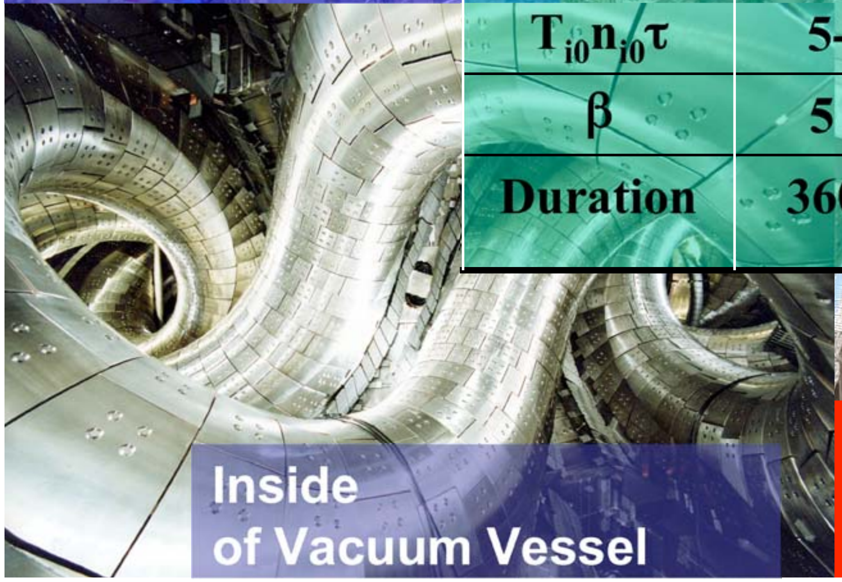
ECH	**84 – 168 GHz/*~2MW***
ICH	**25-100 MHz/*~3MW***
NBI	**para.+perp./*~15MW***

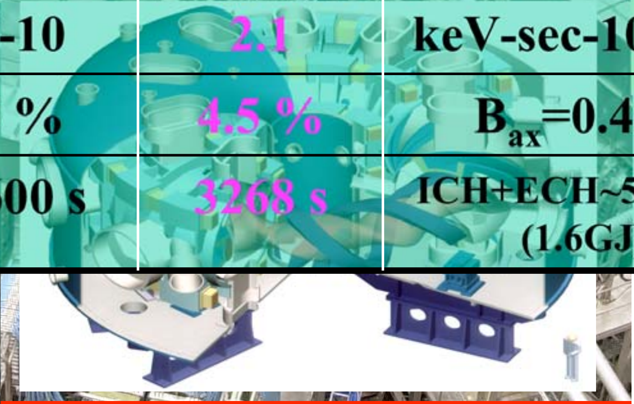
Light from plasma

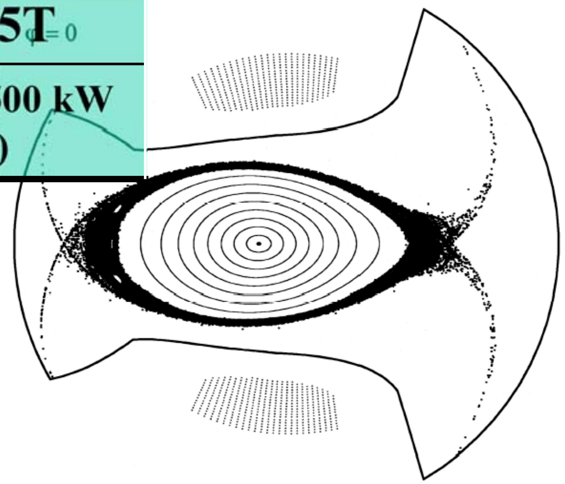


	Target	**Achieved**	
T_{e0} (keV)	10	10 keV	$n_e=0.5\times10^{19}m^{-3}$
T_{i0} (keV)	10 keV	13 keV	Al, $n_e=0.3\times10^{19}m^{-3}$
n_e ($10^{19}m^{-3}$)	10	22	$T_{e0}=0.8$keV
$T_{i0}n_{i0}\tau$	5-10	2.1	keV-sec-$10^{19}m^{-3}$
β	5 %	4.5 %	$B_{ax}=0.45$T
Duration	3600 s	3268 s	ICH+ECH~500 kW (1.6GJ)

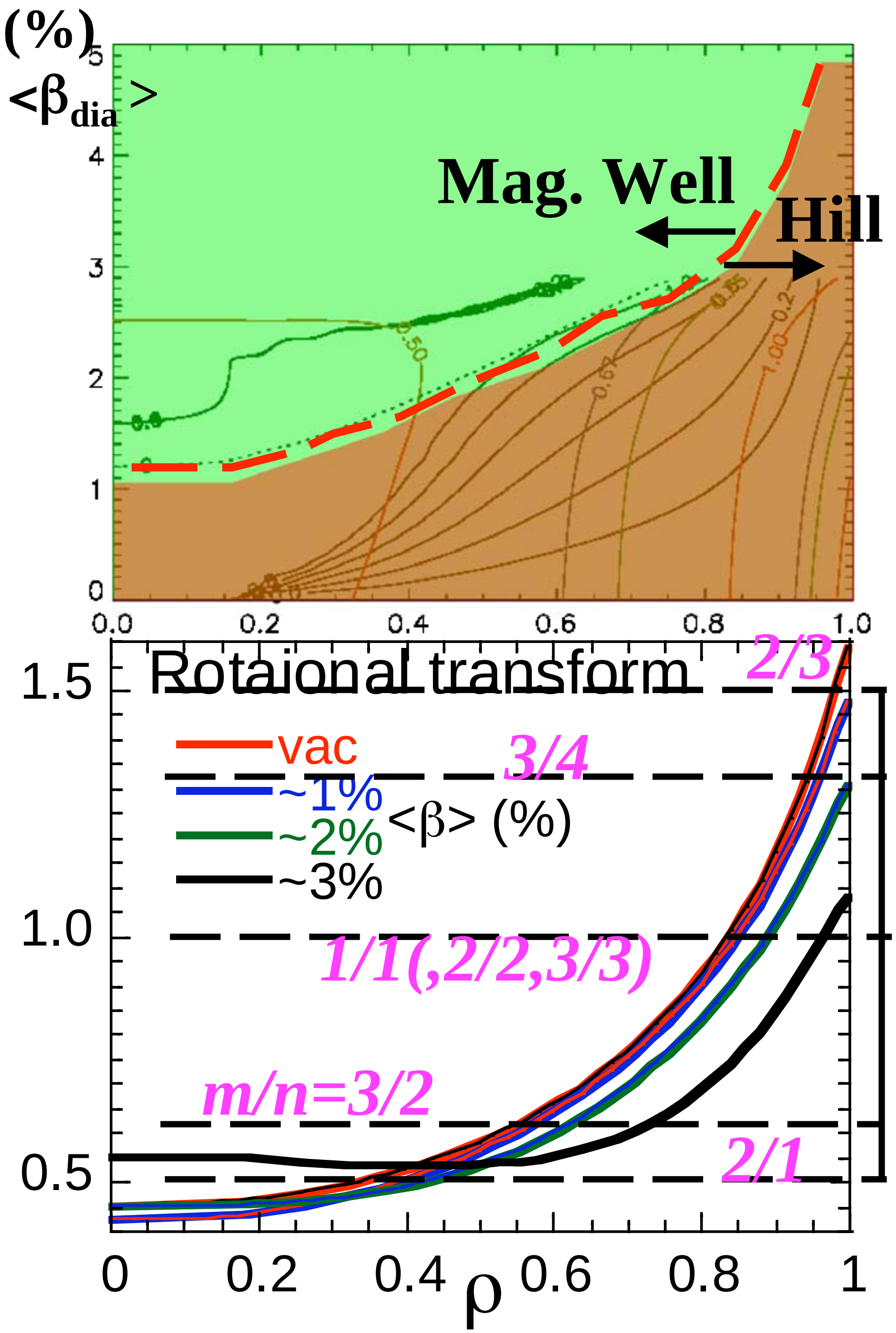








Characteristics MHD equilibrium related to stability



A_p=6.2, p~(1-ρ^2)(1-ρ^8)

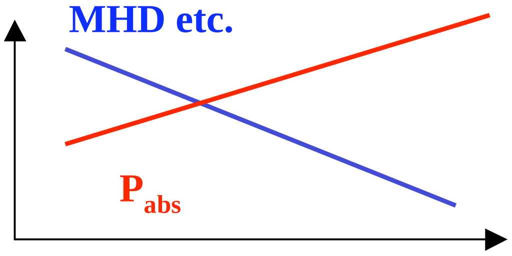
Magnetic hill exists in the finite beta gradients region
=>
MHD instabilities (interchange/ pressure driven) would appear in high beta regime.

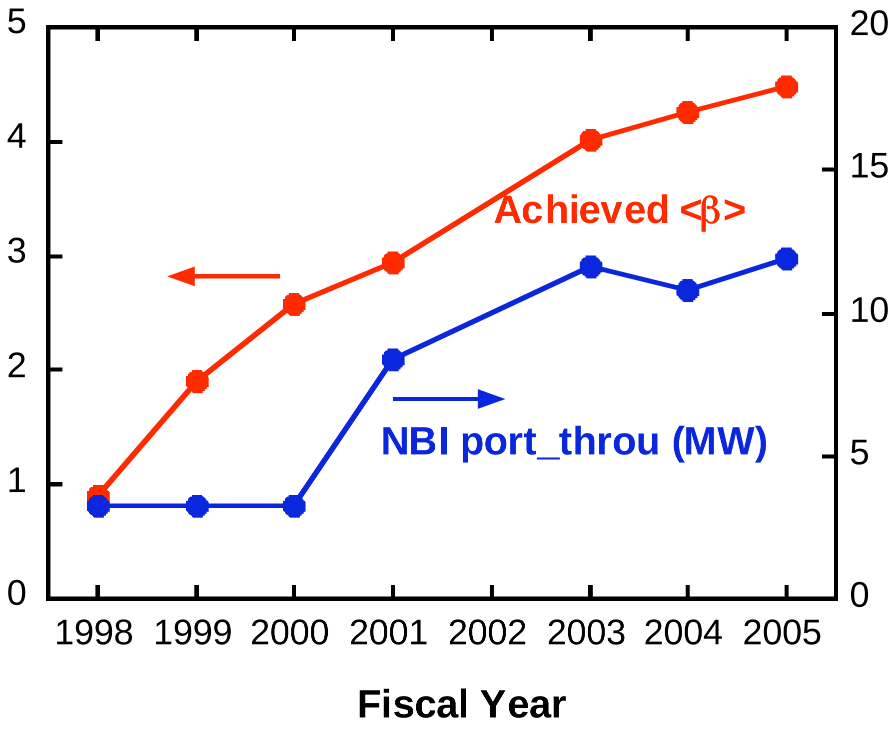
Low order rational surface m<=3

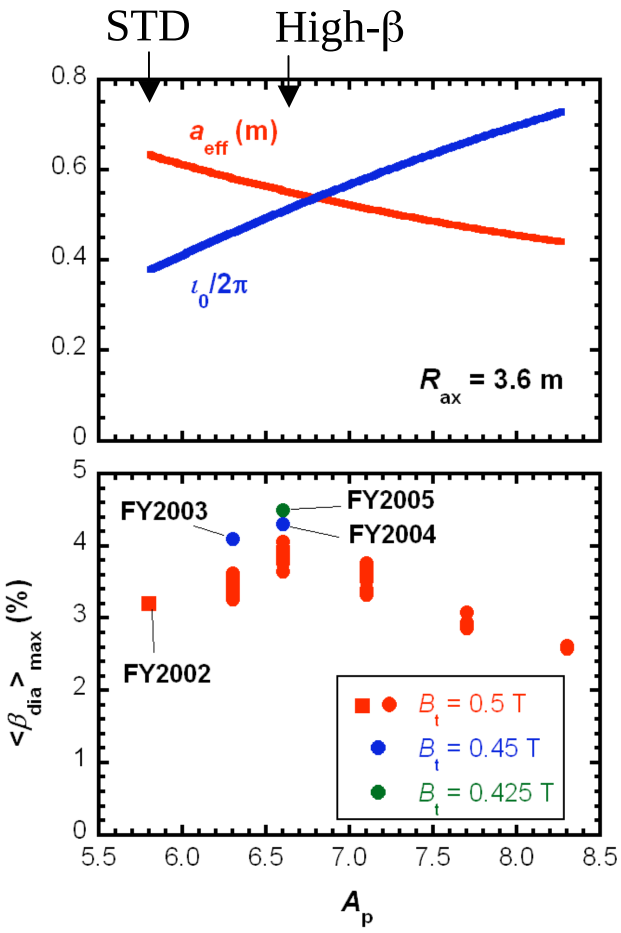
m/n=2/1, 3/2,1/1(,2/2,3/3), 3/4,2/3

Extension of the operational high-β range in LHD

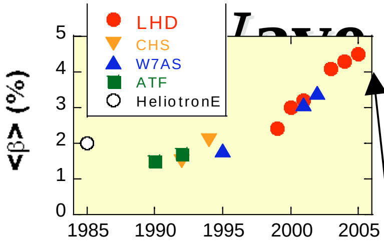
FY2002 (Standard) : 3.2 % (1.25, 0.5 T)
FY2003 (Reduced A_p) : 4.1 % (1.22, 0.5 T)
FY2004 (Optimized A_p) : 4.3 % (1.20, 0.45T)
FY2005 (Finely turn B_0) : 4.5 % (1.20, 0.425 T)

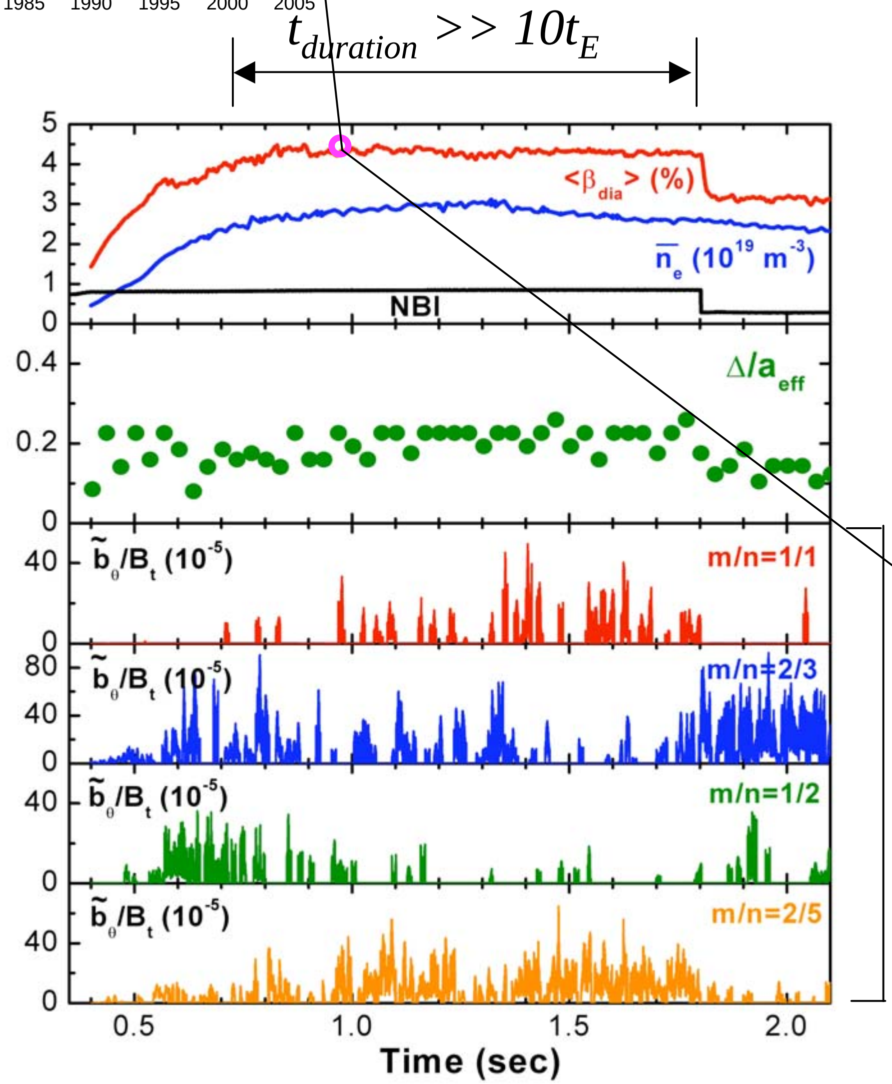






Disruptive phenomena have not been observed in high beta operation with <β_{dia}> >4%





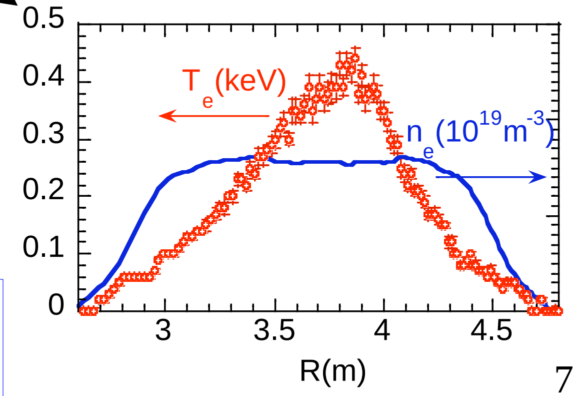
\# Achieved max. averaged beta : 4.5 %

\# Long sustainment of 4 % plasma

\# Shafranov shift D/a_{eff} ~ 0.25

\# Low-*n*,*m* activities

- *No observation of core resonant modes.*
- *m*/*n* = 2/3 and 1/2 modes (peripheral resonant surfaces, *Resonances are located outside ρ ~ 0.9*) appear (< 4 %), but behave intermittently with increasing beta.
- Mercier criterion D_I < 0.2 @ι=1/ρ~0.9



Though some flattening and asymmetric structures are observed in the T_e profile, they are not large enough to affect a global confinement.

Ideal MHD stability in peripheral region

As the β becomes higher,,,,,,

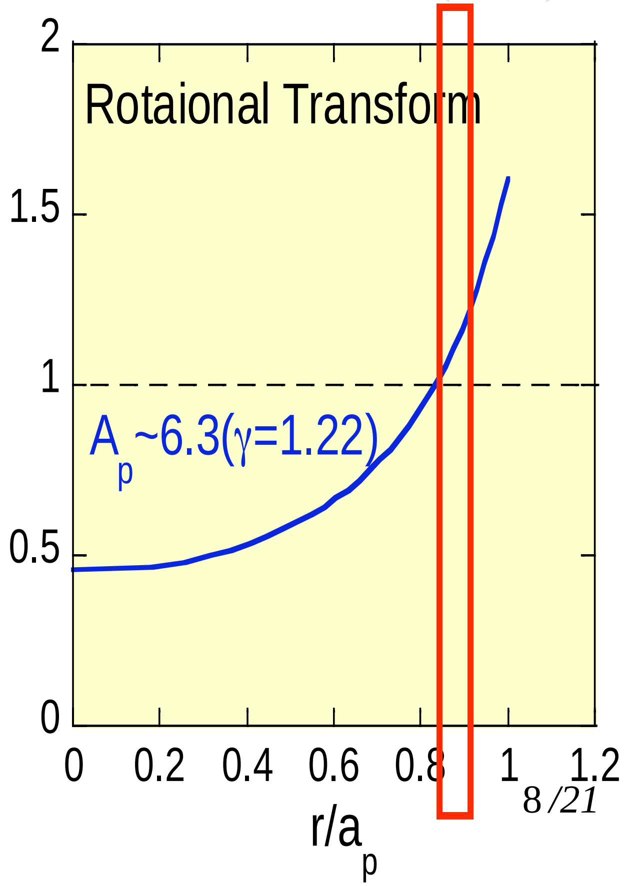
Instability in the peripheral region is more unstable.

The instability might limit the operational beta range.

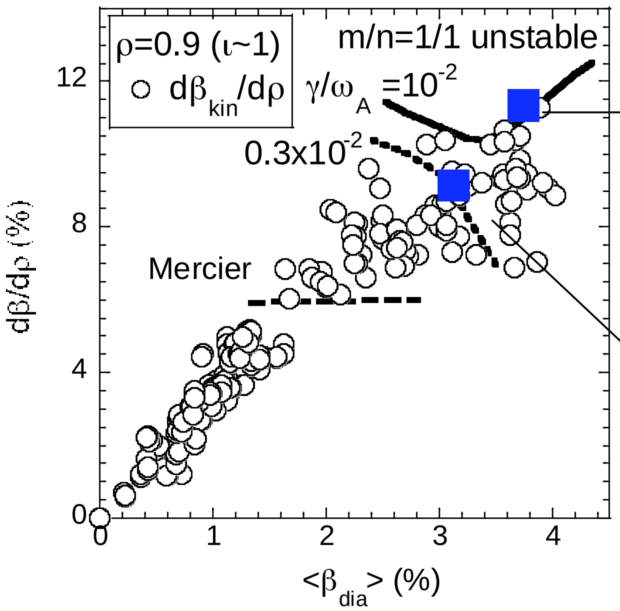
(Core interchange modes are more stable due to the well formation.)

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

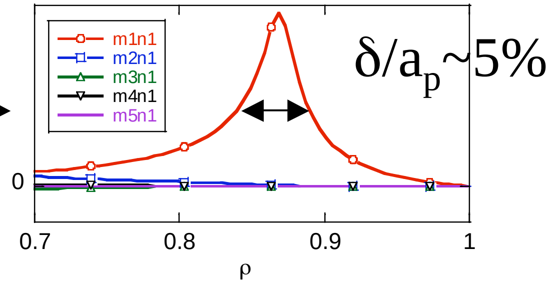
ρ=0.9
(ι~1)



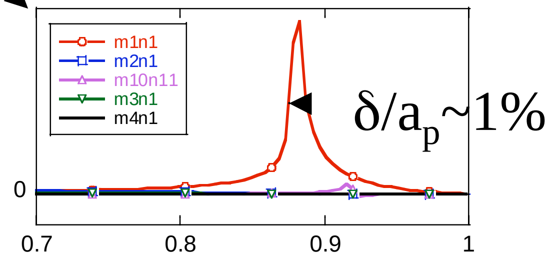
Relationships between predicted global ideal MHD modes and observed beta gradients



Observed kinetic beta gradients are plotted on a contour of growth rate of low-n ideal MHD mode by Terpsichore code



Calculated radial structure of ideal MHD mode



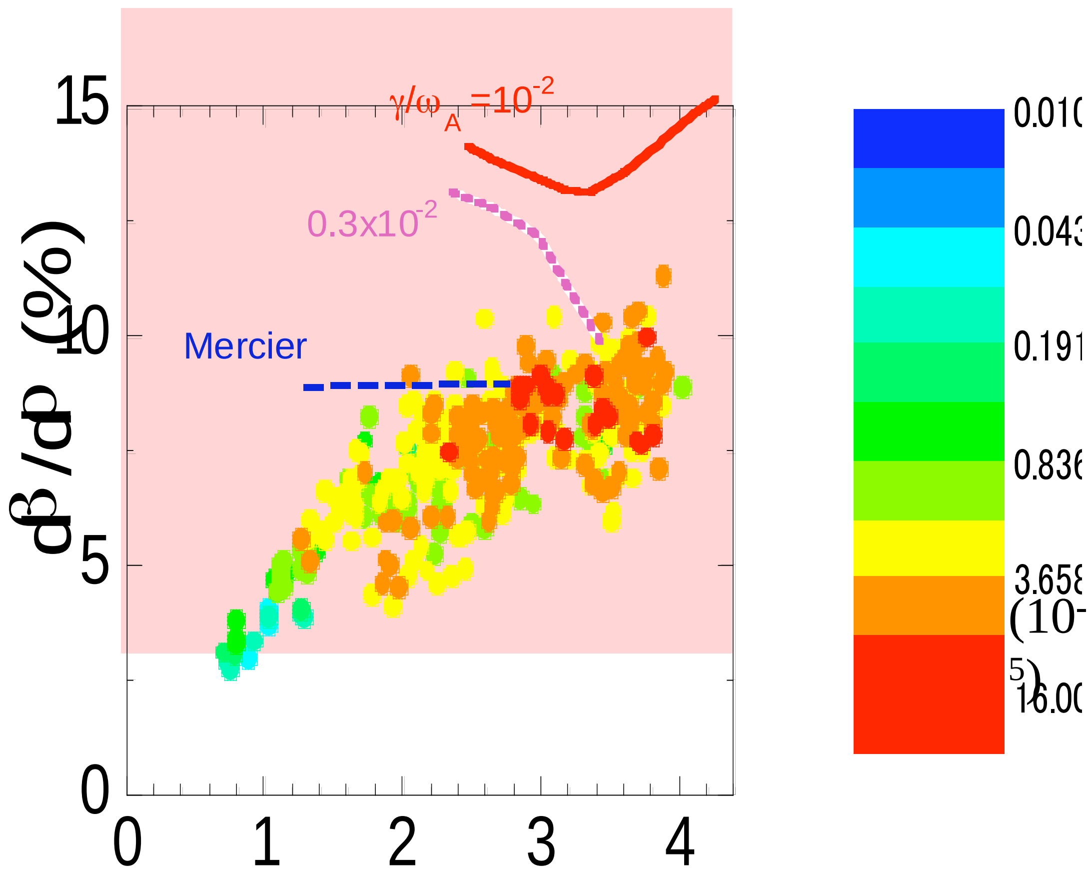
Radial mode structure is relatively narrow in high beta discharge with $\langle\beta_{dia}\rangle$ >3% because the mag. shear is fairly large in peripheral region in LHD highest beta discharges.

The plasmas with $\langle\beta_{dia}\rangle$ >3% is predicted that an ideal interchange type MHD modes are marginally unstable. The radial width and the growth rate are δ/a_p~5% and $\gamma/\omega_A=10^{-2}$ at $\langle\beta_{dia}\rangle$ ~4%.

Relationships between predicted global ideal MHD modes and observed fluctuation

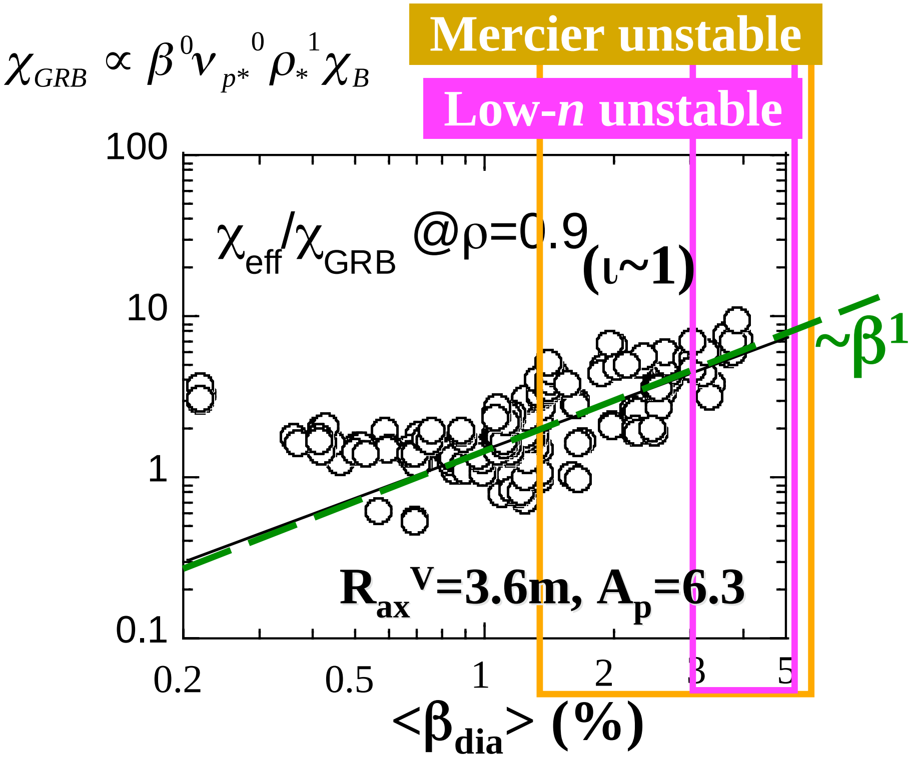
Amplitude of $\tilde{b}/B_0$ of m/n=1/1 mode

Typically rotating in the e-diamag. direct. with several kHz.



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.

Beta dependence of peripheral local transport


$\chi_{GRB} \propto \beta^{0} \nu_{p*}^{\ 0} \rho_{*}^{\ 1} \chi_{B}$

Normalized thermal conductivity by GB (Gyro-reduced Bohm) model （Global property of GB is quite similar with ISS95)

χ/χ^{GRB} at β~1% is 4~10 times larger than that at β~4%.

There is no abrupt degradation of transport around β~4%. However χ/χ^{GRB} decreases with β in more than 1%.

 # MHD instabilities affect the transport!?

1.Mercier modes are unstable in the beta range of $<\beta_{dia}>$ >1.5%.

2.Resistive interchange mode always unstable in finite beta.

(β dependence of χ is similar to a turbulence model based on a resistive interchange modes)

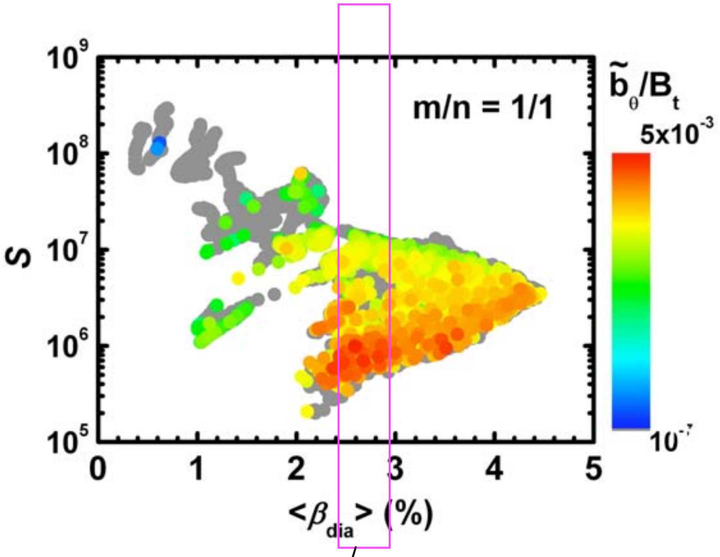
=> high m,n MHD modes would affect it!

Other possibilities:

 # Invasion of stochastic region with beta is predicted!

Degradation due to high n (high density)

S (Reinolds#) dependence of MHD mode

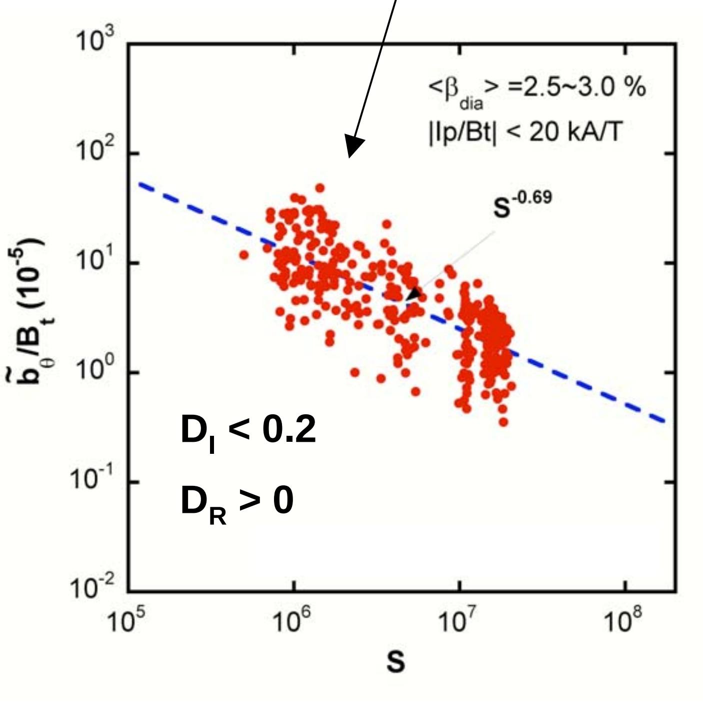


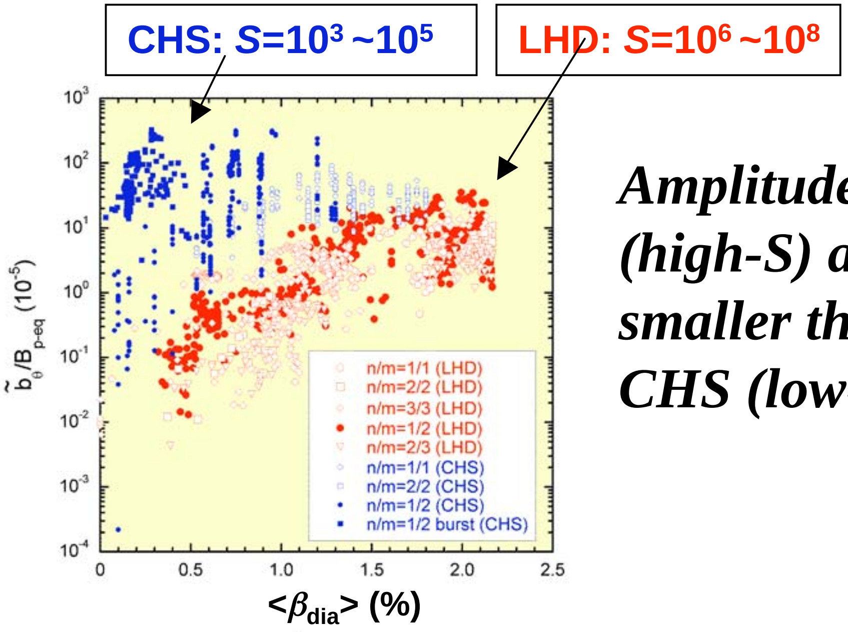
Saturation of peripheral MHD mode strongly depends on S parameter. If w ~ $(b_\theta/B_t)^{1/2}$, S dependence of w is close to that predicted by linear theory of resistive interchange mode (w ∝ $\beta^{1/6}S^{-1/3}$).

=>

Commonly observed modes in LHD

=> resistive (interchange) modes



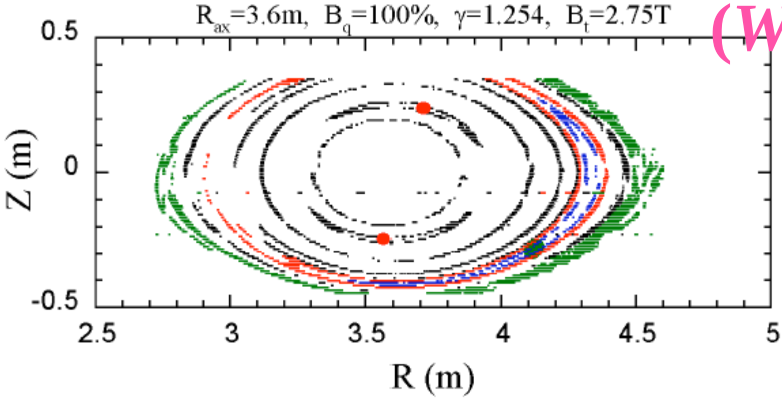


Amplitudes in LHD (high-S) are much smaller than that in CHS (low-S).

Resonant magnetic field

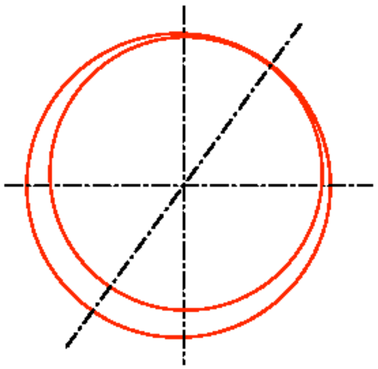
- LHD has the compensation coil system to cancel out the error field and to perform advanced divertor scenario (LID)
- Dominant Fourier component is $m/n = 1/1$.
- Negative coil current can cancel out the natural error field with $m/n = 1/1$.

Natural island : ϕ = -90° ~ -126°



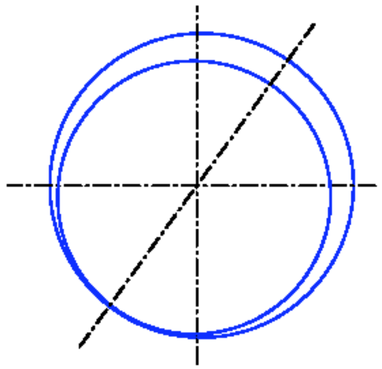
$(W/a_p \sim 0.11)$

$I_{LID}/B_t < 0$

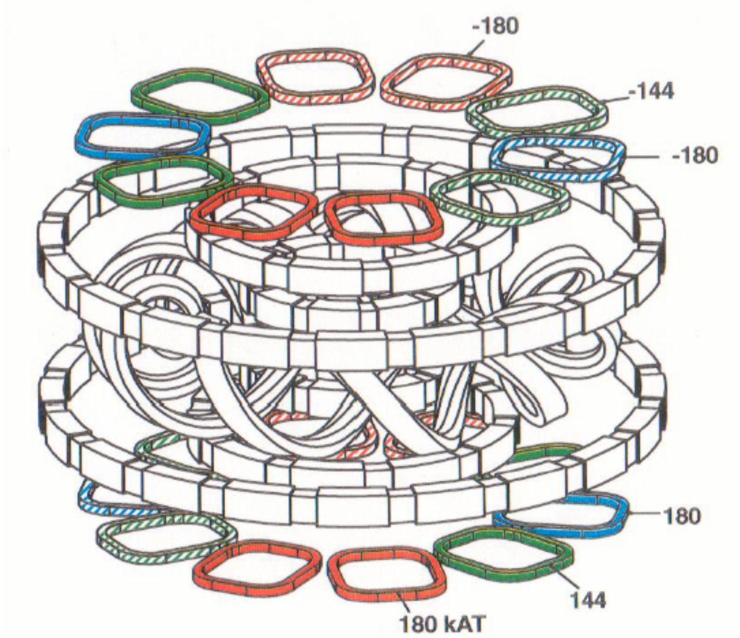


O-point (ϕ = -126°)

$I_{LID}/B_t > 0$



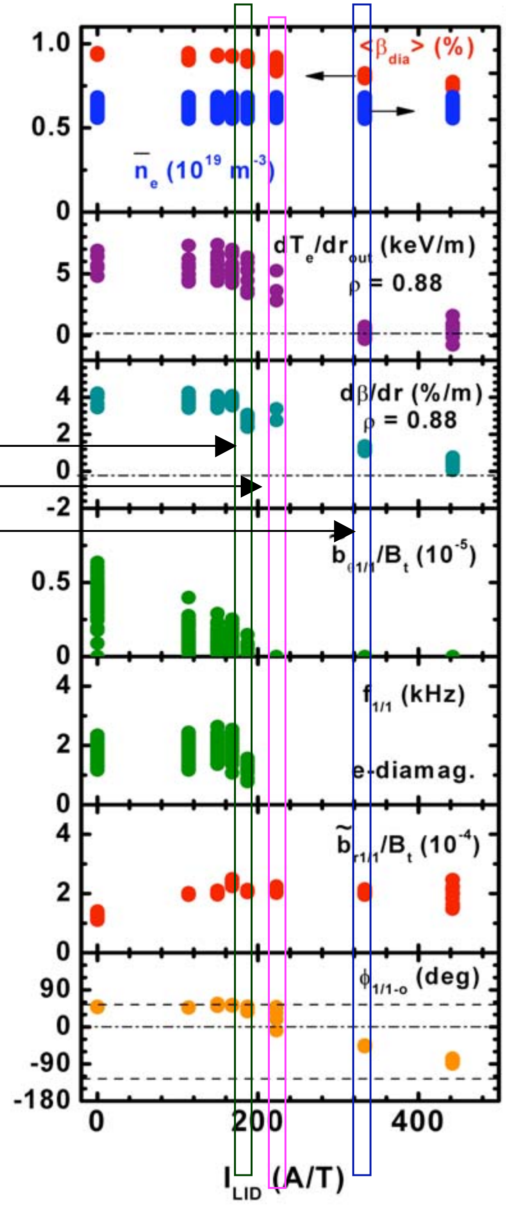
O-point (ϕ = 54°)

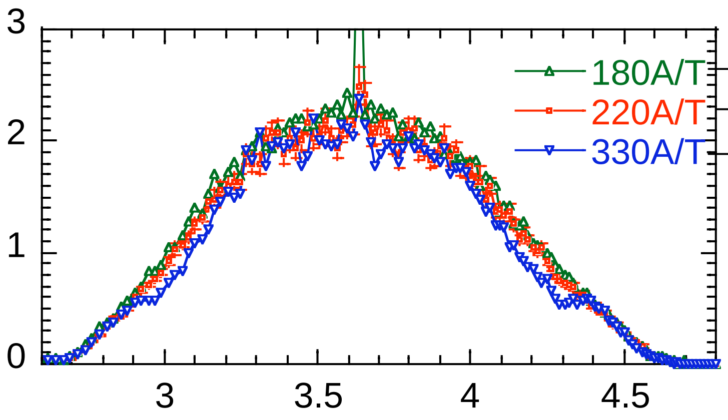


Suppression of *m*/*n* = 1/1 mode by resonant magnetic field

At I_{LID} =220 A/T (W/a_p~0.20), the mode disappears despite finite gradient still remains finite pressure gradient near ι =1 surface exists despite finite gradient still remains.

R_{ax} = 3.6 m, B_t = 2.75 T, A_p=5.7, NBI, $\langle\beta\rangle$~1%, D_I<0, D_R>0, S~10^7



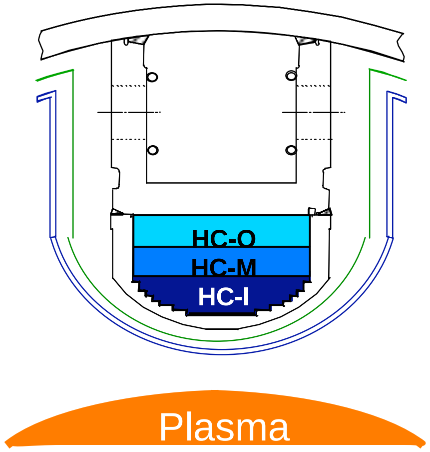


Finite pressure gradient near ι=1 surface exists till I_{LID} ≤ 220 A/T, whereas it gradually decreases with I_{LID} .

Amplitude of the mode decreases with reduction of the gradient. Then the mode frequency slowed down.

Effect of “ideal” mode on the plasma confinement ?

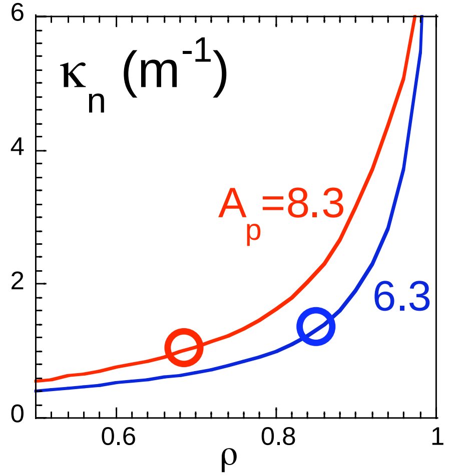
Helcal coil of LHD consists of 3 layers. By changing the curennt ratio in the 3 layers, plasma aspect ratio, mag.shear and mag. hill hight are controlled.



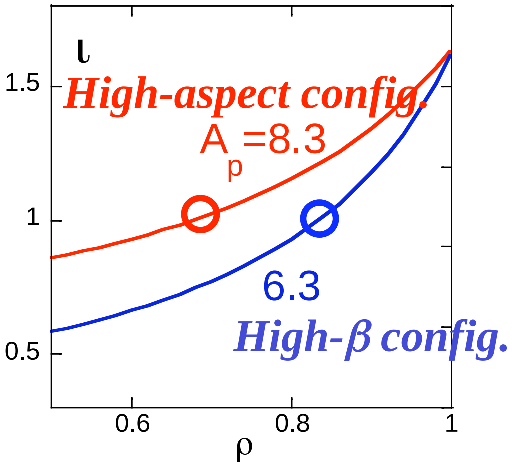
High aspect configuration (a special config.) has low magnetic shear and high magnetic hill in LHD

=> Ideal modes are more unstable

Magnetic curvature



Rotaional transform



κ_n in both aspect ratio is almost same at the m/n=1/1 rational surface.

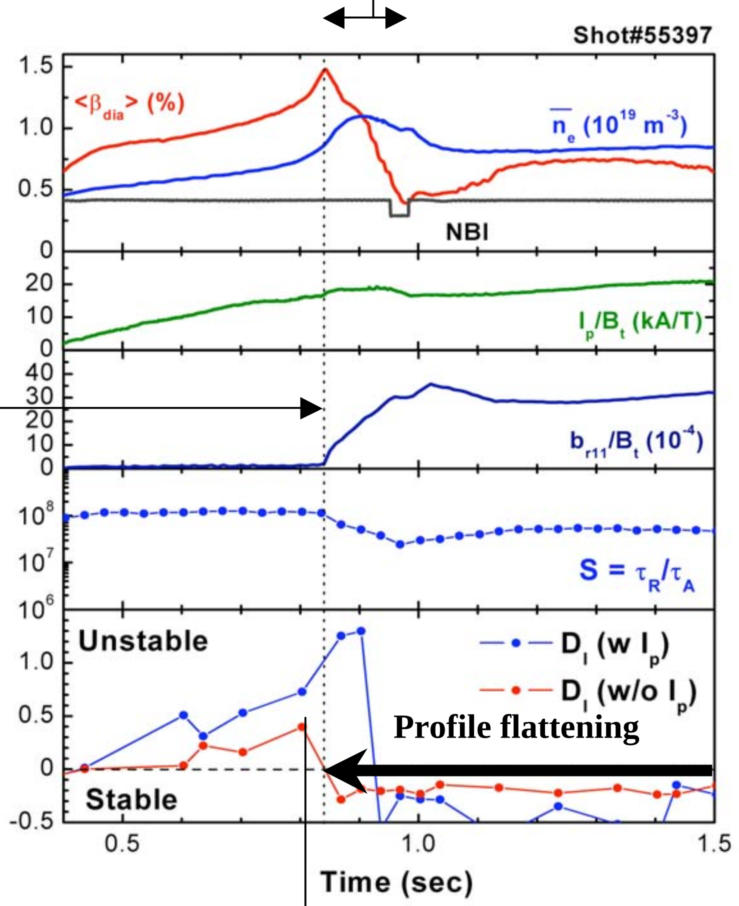
Minor collapse due to m/n = 1/1 mode in high aspect config.

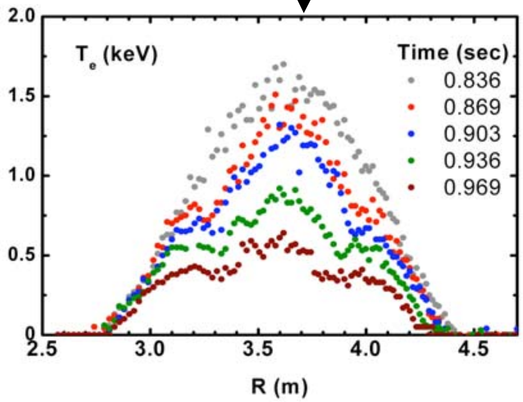
Minor collapse due to abrupt profile-fattening near m/n = 1/1 resonance

Growth of radial component of m/n = 1/1 mode (**Non-rotate**)

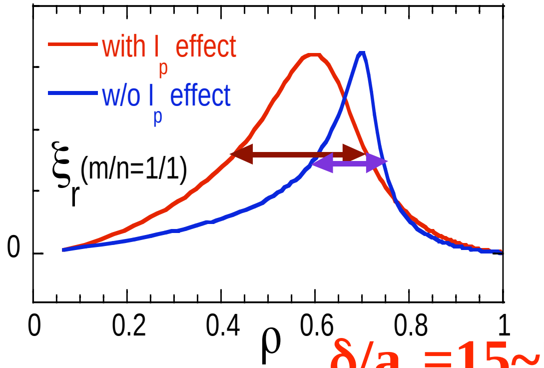
No observation of clear precursor

$D_I > 0.2$ even in currentless plasma





Predicted ideal MHD mode width before collapse



δ/a_p=15~25%

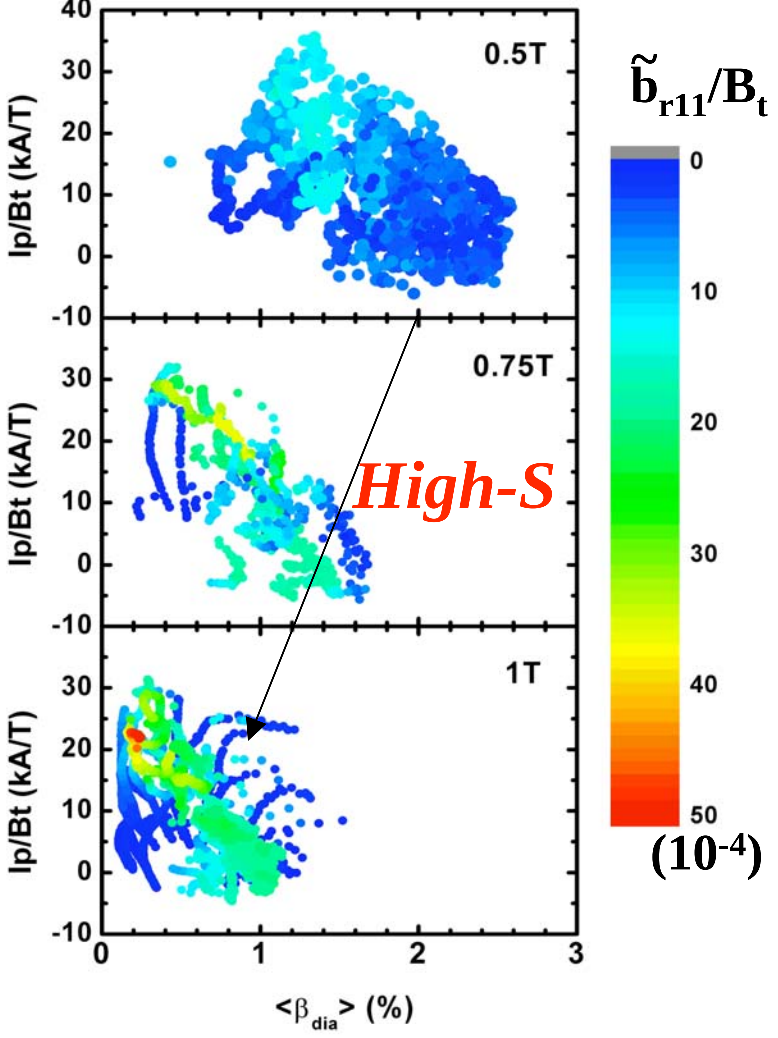
γ/ω_A=0.5~1.1x10^{-2}

A collapse occurs in a high aspect plasma with low magnetic shear and high magnetic hill. Before the collapse occurs, stability condition of **global ideal** MHD mode is **stromgly violated**. ***Mode width is much important for the effect on confinement??***

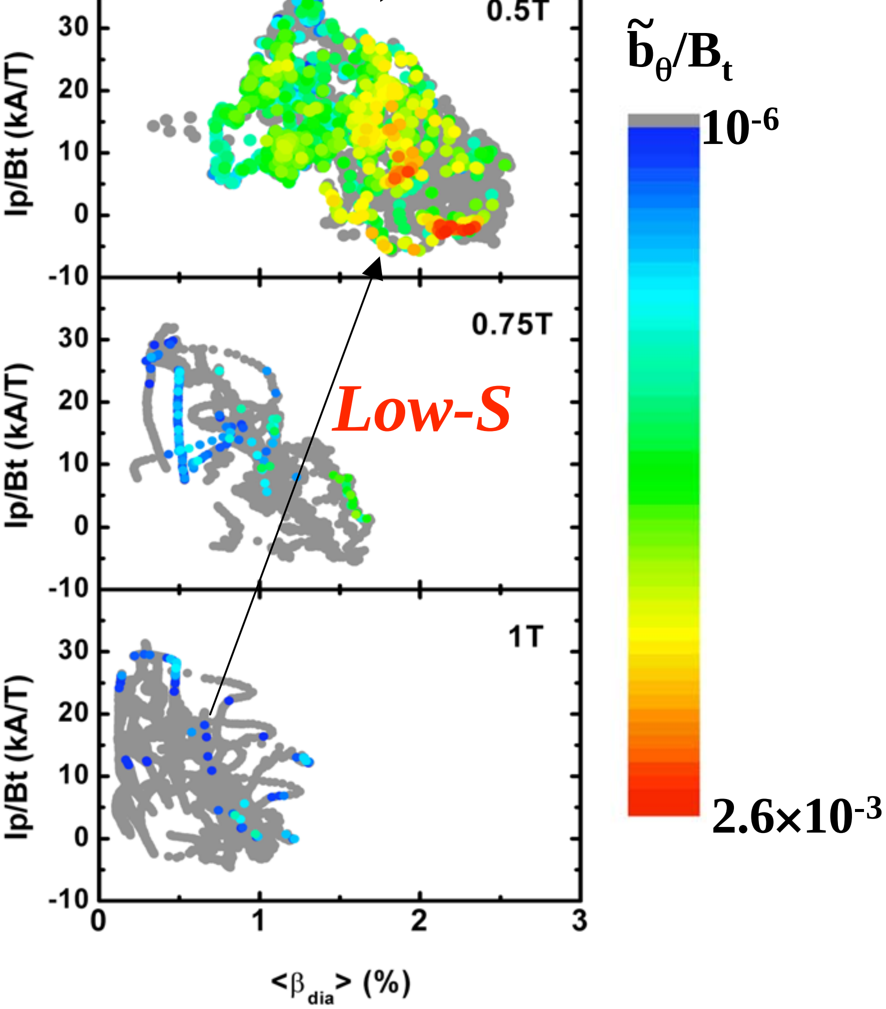
Bt dependence of “Non-rotating” mode

$A_p = 8.3$

Non-rotating mode



Common mode with rotation (f ≥ 0.1 kHz)



Non-rotating modes are often observed high S operation.

Before the collapse occurs, **global ideal** MHD mode is **stromgly unstable**.

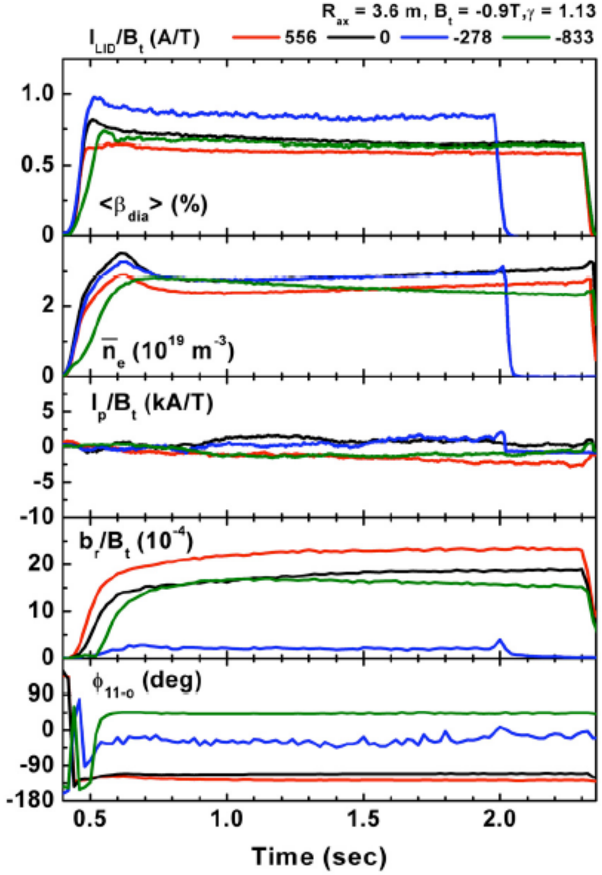
=> **Ideal mode!?**

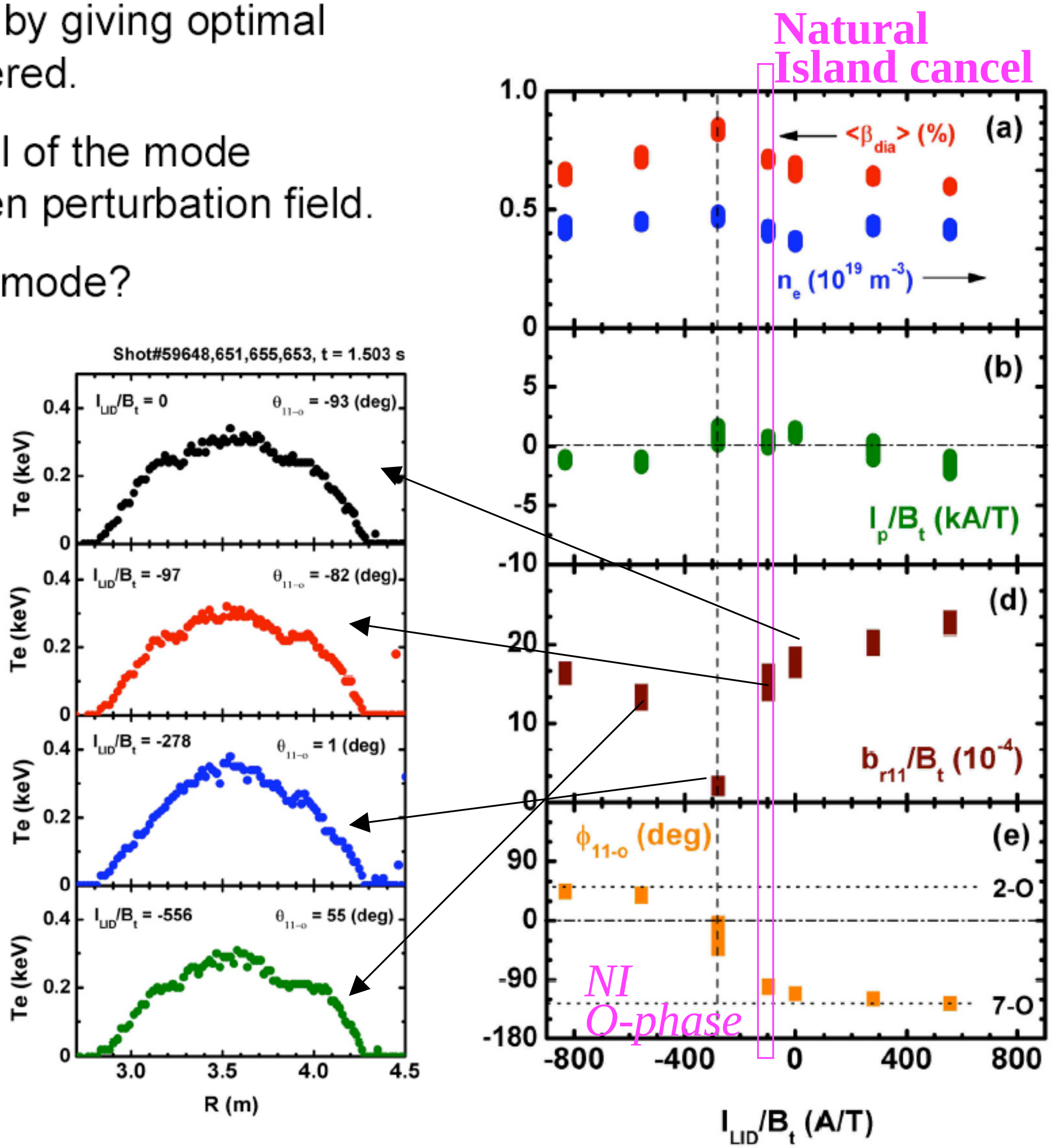
Suppression of m/n=1/1 Mode

- The mode could be suppressed by giving optimal perturbation field, and $\langle\beta\rangle$ recovered.

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

- Non-linear instability like locked mode?





Characteristics of m/n = 1/1 mode in LHD

Several differences of characteristics of the mode in different configurations.

Experiments	**"non-rotating" mode** *(High-A_p, and/or large I_p)*	**"rotating" mode** *(high-β)*
radial location	$\rho \sim 0.7$ (currentless)	$\rho \sim 0.9$
configuration	**weak shear**, magnetic hill (D_R>0)	magnetic hill (D_R>0)
Prediction	Ideal unstable **with large mode width**	Ideal stable, or unstable **with narrow mode width**
frequency	DC ~ several Hz	several kHz
spatial location	ϕ~ -120 deg (near natural error field)	rotating
S dependence	Low-S => not appears(?!)	**Low-S => large signal**
Interaction with static 1/1 island	**Suppression or growth**	Reduction of rotation, suppression
	"Ideal" mode	**"Resistive" mode**

Summary

1. Disruptive phenomena have not been observed in high beta operation with $<\beta_{dia}>$ =4.5% in LHD.
2. In high beta plasmas, peripheral MHD modes excited in the magnetic hill are dominantly observed. The plasmas with $<\beta_{dia}>$ >3% is predicted that an ideal interchange type MHD modes are unstable for a low-m mode, whose radial width and linear growth rate are δ/a_p~5% and $\gamma/\omega_A=10^{-2}$ at $<\beta_{dia}>$ ~4%. According to local transport analysis at a peripheral low-m,n resonant surface, no abrupt degradation of transport has not been observed up to $<\beta_{dia}>$ ~4.5% though the gradual degradation of normalized electron thermal conductivities observed with β in more than 1%.
3. The observed dependence of the amplitudes of their modes on S(magnetic Reynolds #) is close to square of the mode width of linear resistive interchange mode. The above facts suggest that the observed modes in high beta operation is the resistive interchange mode.

Summary (Cont.)

4. In higher aspect config. with lower magnetic shear and higher magnetic hill compared with high-β config., a minor collapse occurs. Before the collapse occurs, stability condition of ideal global MHD mode is strongly violated. The predicted mode width and growth rate are δ/a_p=15~25% and γ/ω_A~0.5~1x10^{-2}. The observed magnetic fluctuation is not rotating. It is observed more easily as S is larger. The above facts suggest that the observed modes in the collapse is the ideal interchange mode.
5. From Aabove results suggest a possibility that the ideal low-m,n MHD instability with large mode width affects the large effect of on the confinement in heliotron devices.
6. Both the observed modes in high beta plasmas and in a minor collapse can be suppressed by using the external resonant field. However, the mechanism has not been clear. The non-linear calculation of the MHD instability in wide range of S is necessary taking static error fields into account.

Ref.

[1] K.Y.Watanabe et al., Nucl. Fusion, 45, 1247-1254 (2005).

[2] S.Sakakibara et al., ISW15, Madrid, Oct., 2005.

[3] S.Sakakibara et al., 33th EPS, Rome, Jun. 2006.

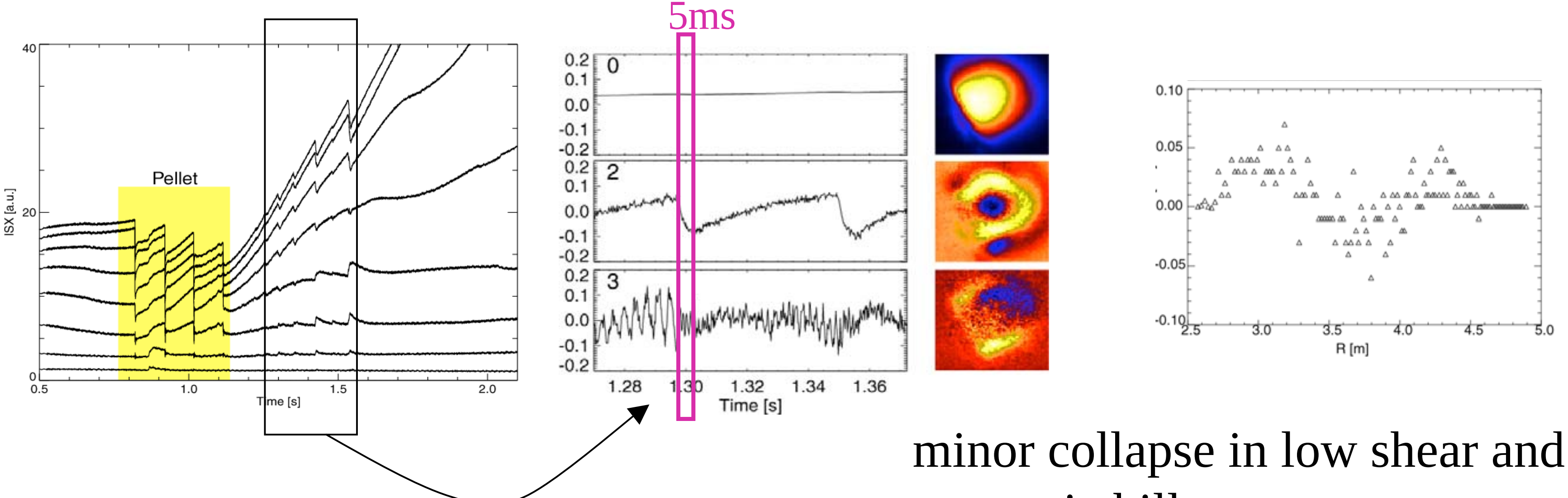
[4] K.Y.Watanabe et al., ICPP2006, Kiev, May, 2006.

[5] S.Sakakibara et al., Ex/7-5 in 21th IAEA, Chengdu, Oct. 2006.

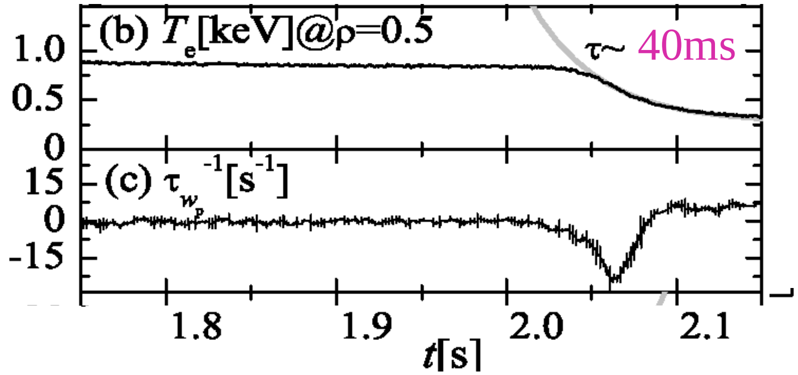
Options

Examples of minor collapses driven by MHD events in LHD

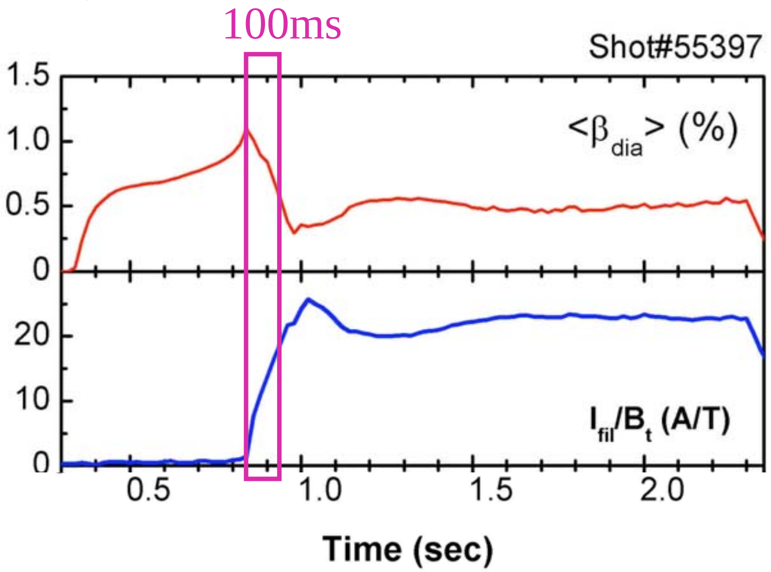
Sawtooth



minor collapse in carrying large toroidal current



minor collapse in low shear and magnetic hill



Difference of decay time in minor collapses in between Tokamak and Helical

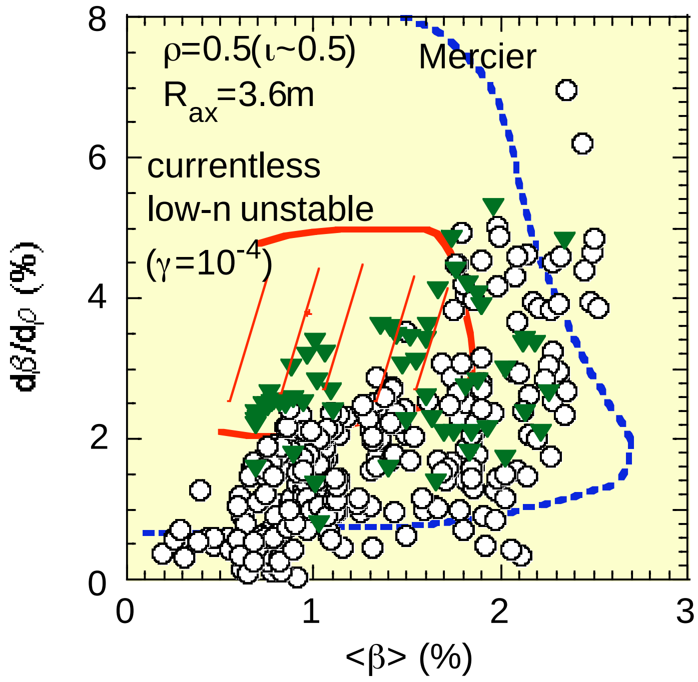
	Exp. Cond./Cause	decay time	Influence on confinement	measurement	n_e, T_e
Tokamk (JT60)	sawtooth	<1ms	$\delta T_e/T_e\sim0.2$	ECE	Example, T_{e0}=4~5keV
	beta collapse	~0.1ms	$\delta T_e/T_e\sim0.3$	ECE	$T_{e0}\sim4$keV
	negative mag. shear	1-2ms	plasma disrupt	ECE	Example, T_{e0}=4~5keV
Helical (LHD)	sawtooth	2~3ms	$\delta T_e/T_e$ ~0.05	SX	$n_{e0}\sim6\text{x}10^{19}\text{m}^{-3}$ $T_{e0}\sim1$keV
	large positive I_p	30~40ms	$\delta T_e/T_e\sim0.5$	ECE、saddle loop	$n_{e0}\sim5\text{x}10^{18}\text{m}^{-3}$ $T_{e0}\sim1.2$keV
	low mag. shear/mag.hill	~100ms	$\delta T_e/T_e\sim0.5$	saddle loop	$n_{e0}\sim2\text{x}10^{19}\text{m}^{-3}$ $T_{e0}\sim1.$keV

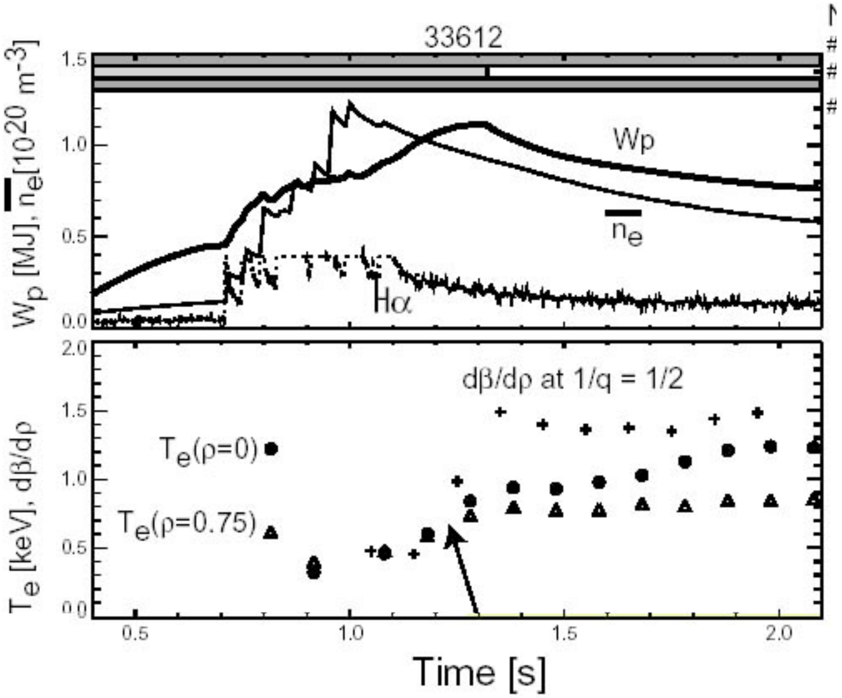
The study of the reason why the decay time is too different (the decay time in helical is much longer than that in tokamak) is an important issue.

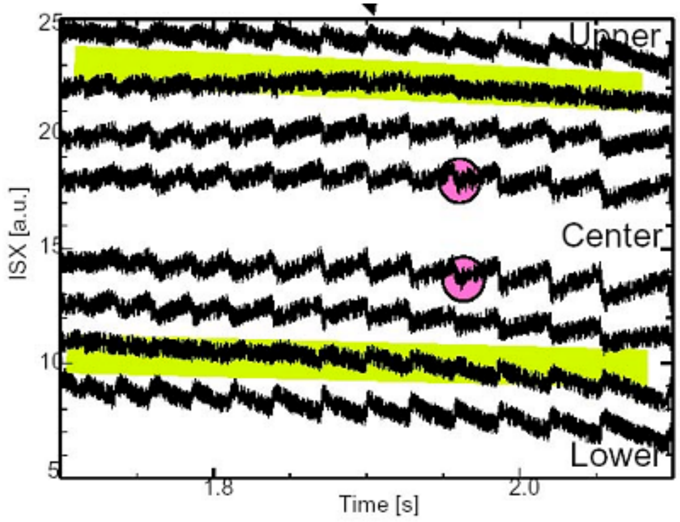
Reason/Cause (candidate)
 # Deference of influence on MHD equilibrium ?,
 # Deference of mechanism driven by mechanism ?

MHD Activity in Ideal Interchange Unstable Region (LHD)

▲ Pressure gradient just after pel. inj (0.75, 2.8T)







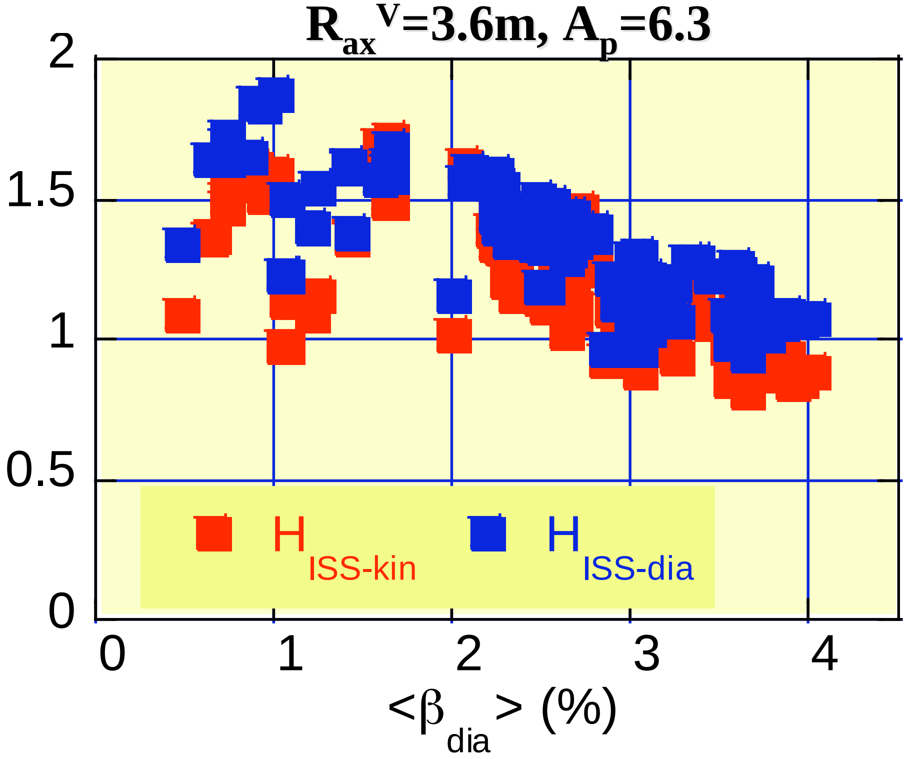
Achievement of pressure gradients in the region predicted as ideal MHD unstable

==> *observation of saw-tooth oscillation as fluctuation signal*

=> Achievement as Transitional State

=> Possibility of Achievement in Stationary ???? => Future Subjects

τ_E normalized by ISS95 scaling



$$\tau_{ISS95} \propto a^{2.21} R^{0.65} P^{-0.59} n_e^{0.51} B^{0.53} \iota_{2/3}^{0.4}$$

A disruptive degradation has not been observed up to $<\beta_{dia}>$ ~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 MHD effects?!

Effect of resistive interchange mode on peripheral transport

Thermal conductivity based on resistive interchange (g) mode turbulence (induced through the magnetic field diffusion)

refs. B.A.Carrers et al. Phys.Fluids 30, 1388 (1987)
B.A.Carrers et al. Phys.Fluids B1, 1011 (1989)

$$\chi_e = \sqrt{\frac{\pi}{4}}\frac{\hat{S}}{R_0 q} V_T \frac{\mu_0}{\eta}\gamma^{(0)}_{\langle m\rangle}\left(W^{(0)}_{\langle m\rangle}\right)^4 \Lambda^{4/3}.$$

Today's Model

Renormalization factor

$$\Lambda = \frac{2}{3\pi}\ln\left[\frac{256 S^2 L_p}{\beta R_0^2 \kappa_n}\left(\frac{\hat{S}}{r k_\theta q}\right)^4\right] - \frac{2}{\pi}\ln\Lambda.$$

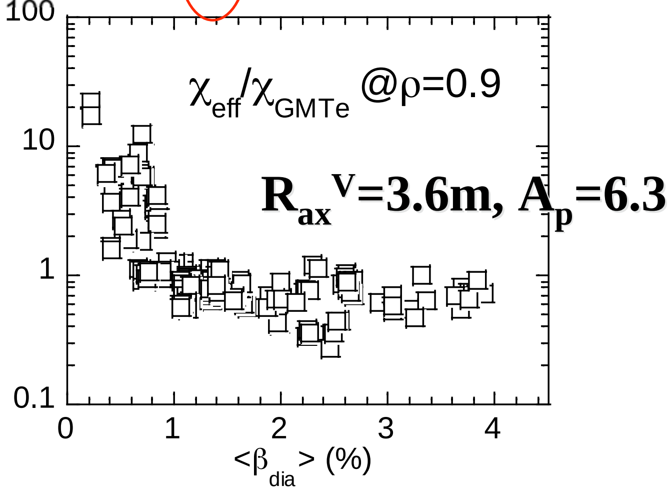
Linear growth rate and mode width of g-mode

$$\gamma^{(0)}_{\langle m\rangle} = \frac{1}{S^{1/3}}\left(\frac{\beta}{2}\frac{r}{L_p}R_0^2\kappa_n k_\theta\frac{q}{\hat{S}}\right)^{2/3}\tau_{hp}^{-1}.$$

$$W^{(0)}_{m} = \left(\frac{q^2}{S\hat{S}^2 k_\theta r}\right)^{1/3}\left(\frac{\beta}{2}\frac{R_0^2\kappa_n}{L_p}\right)^{1/6} r.$$

$$\chi_{GMTe} \propto \left(\frac{q}{\hat{s}}\right)^{\frac{7}{3}} (\kappa_n R_0)^{\frac{4}{3}}\; a_{eff}^{\;2} \left(\frac{\beta R_0}{L_p}\right)^{\frac{4}{3}} S^{-\frac{2}{3}}\frac{v_{Te}}{R_0}$$

$$\propto G_{GMTe}\,\beta^1 \nu_*^{0.67}\rho_*^{0.33}\chi_B$$



Normalized thermal conductivity by g-mode turbulence model is constant in a high beta regime with β >1%.

Depend. on geometric param.

$$\chi \propto \frac{q}{\hat{s}}\,(\kappa_n R_0)^{\frac{4}{3}}\; a_{eff}^{\;2}\left(\frac{\beta R_0}{L_p}\right)^{\frac{4}{3}} S^{-\frac{2}{3}}\frac{v_{Te}}{R_0}$$

Depend. on plasma param.

[ref] H.Funaba et al, Fusion Sci. Tech. to be publised in 2006, Proc. in 15th Int. Stell. WS in Madrid (2005).

Why is the predicted χ_{GMTe} (χ induced by g-mode turbulence) of a high aspect (A_p=8.3) plasma much large??

G_{GMTe}

$$\chi \propto \frac{q}{\hat{s}}\left(\kappa_n R_0\right)^{\frac{4}{3}} a_{eff}^{\,2}\left(\frac{\beta R_0}{L_p}\right)^{\frac{4}{3}} S^{-\frac{2}{3}} \frac{v_{Te}}{R_0}$$

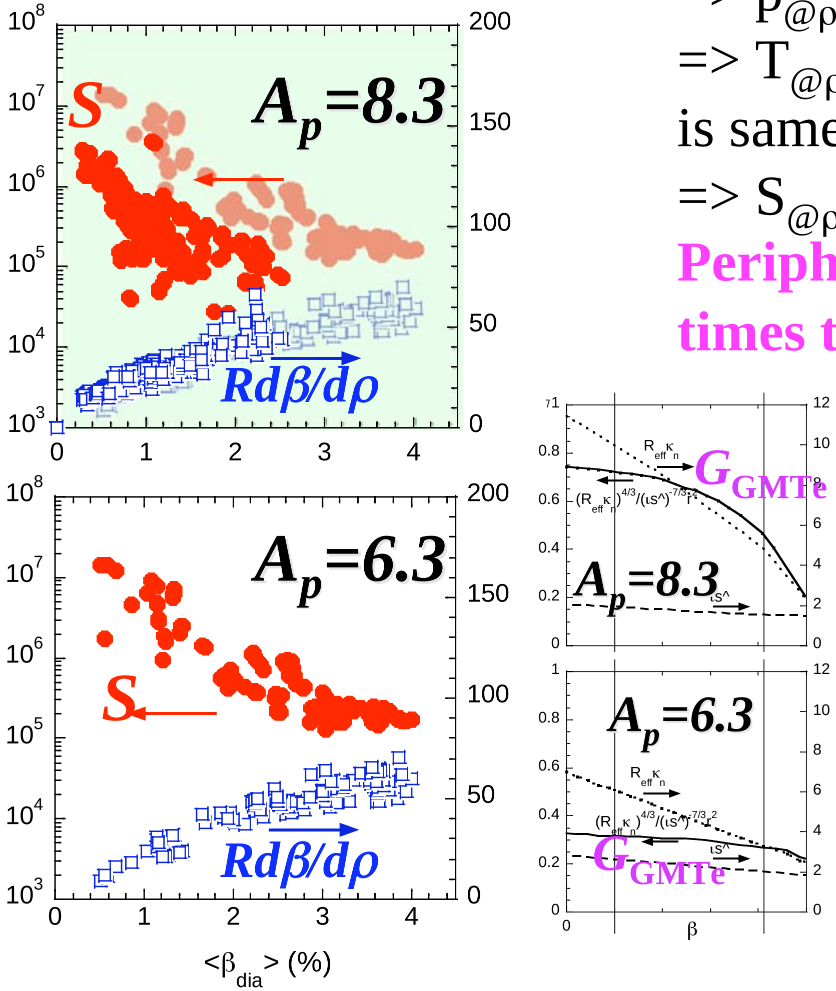
Peripheral Rdβ/dρ both in A_p=8.3 and 6.3 are almost same.

=> $p_{@\rho=0.9}$ in A_p=8.3 < $p_{@\rho=0.9}$ in A_p=6.3

=> $T_{@\rho=0.9}$ in A_p=8.3 < $T_{@\rho=0.9}$ in A_p=6.3 if n_e is same.(Reason not clear)

=> $S_{@\rho=0.9}$ in A_p=8.3 > $S_{@\rho=0.9}$ in A_p=6.3

Peripheral S in A_p=8.3 is smaller by ~10 times than A_p=6.3.



Beta dependence of plasma parameter and geometric facter determining χ_{GMTe}

Geometric factor of g-mode turbulence model (G_{GMTe});

G_{GMTe} in A_p=8.3 is larger by 2~2.5 times than A_p=6.3.

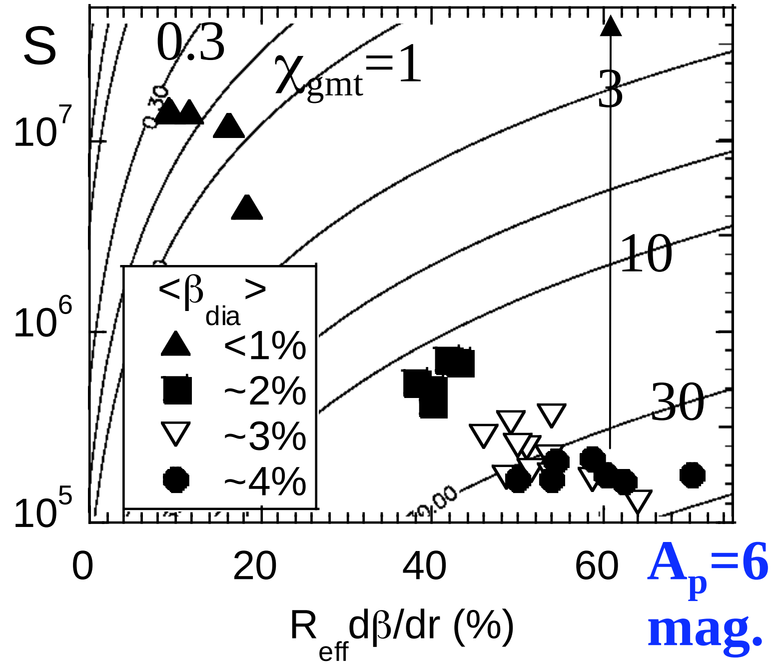
G_{GMTe}; 2~2.5=> χ_{GMTe}; 2~2.5

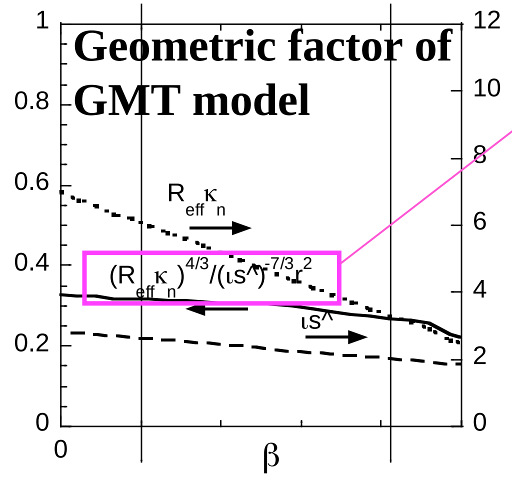
S; ~1/10=> χ_{GMTe}; ~4.5

=> χ_{GMTe}; ~10 times larger

Plasma parameter dependence of thermal conductivity induced by g- mode turbulence

$$S \propto \frac{T_e^{3/2}}{n_e^{1/2}} B_0 \frac{a_{eff}^{\ 2}}{R_0} \rho^2 = \frac{\beta^{3/2}}{n_e^{\ 2}} B_0^{\ 4} \frac{a_{eff}^{\ 2}}{R_0} \rho^2$$





A$_p$=6.3 config. (lower mag. hill), ρ=0.9

Geometric factor of GMT model in A$_p$=6.3(lower mag. hill) config. is not sensitive to beta.

$$n_{ec} \propto P^{0.5} B_0^{\ 0.5} a_{eff}^{\ -1} R_0^{\ -0.5}$$

$$S \propto \frac{\beta^{3/2} B_0^{\ 3} a_{eff}^{\ 4}}{P}$$

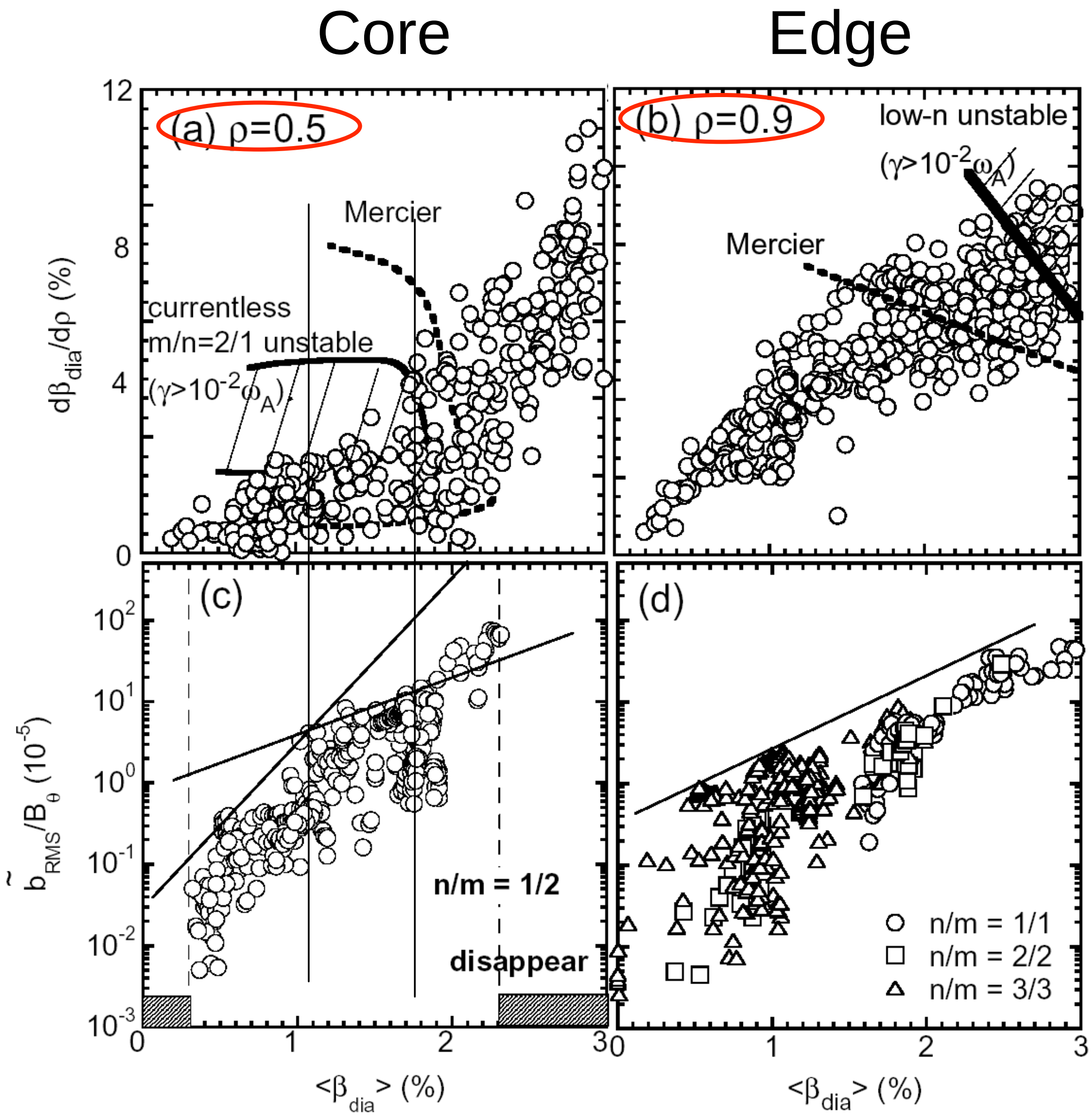
In order to increase S by 100 times than in present LHD, the high beta operation under 4 times larger B_0 is necessary.
(B_0=2T/β~4%, W_p~2MJ)
4 times large power is neccesary.

LHD high beta plasmas are obtained under low mag. field operations. Then S is reduced as beta increases.
=> The prediction of large value of χ in high beta regimes.

In a reactor, B_0 and n_e are larger by 10 times, and a_{eff} is by 3~4 times than LHD high beta operations.
=> S would be larger by 300-400 times.
=> χ~1m^2/s (Not negligible but not large)

The confirmation is necessary in experiments with wide parameter range of S and β.

Observed Magnetic Fluctuation and Ideal MHD Analysis



Core region

\# β -gradients;

Saturated with β (1%<β<1.8%)

Increases as β (1.8%<β)

\# Magnetic Fluctuation;

In Mercier stable region, resonant fluctuation (low-n) mode is *not observed*.

Amplitude increases as β gradients

Edge region

\# β -gradients;

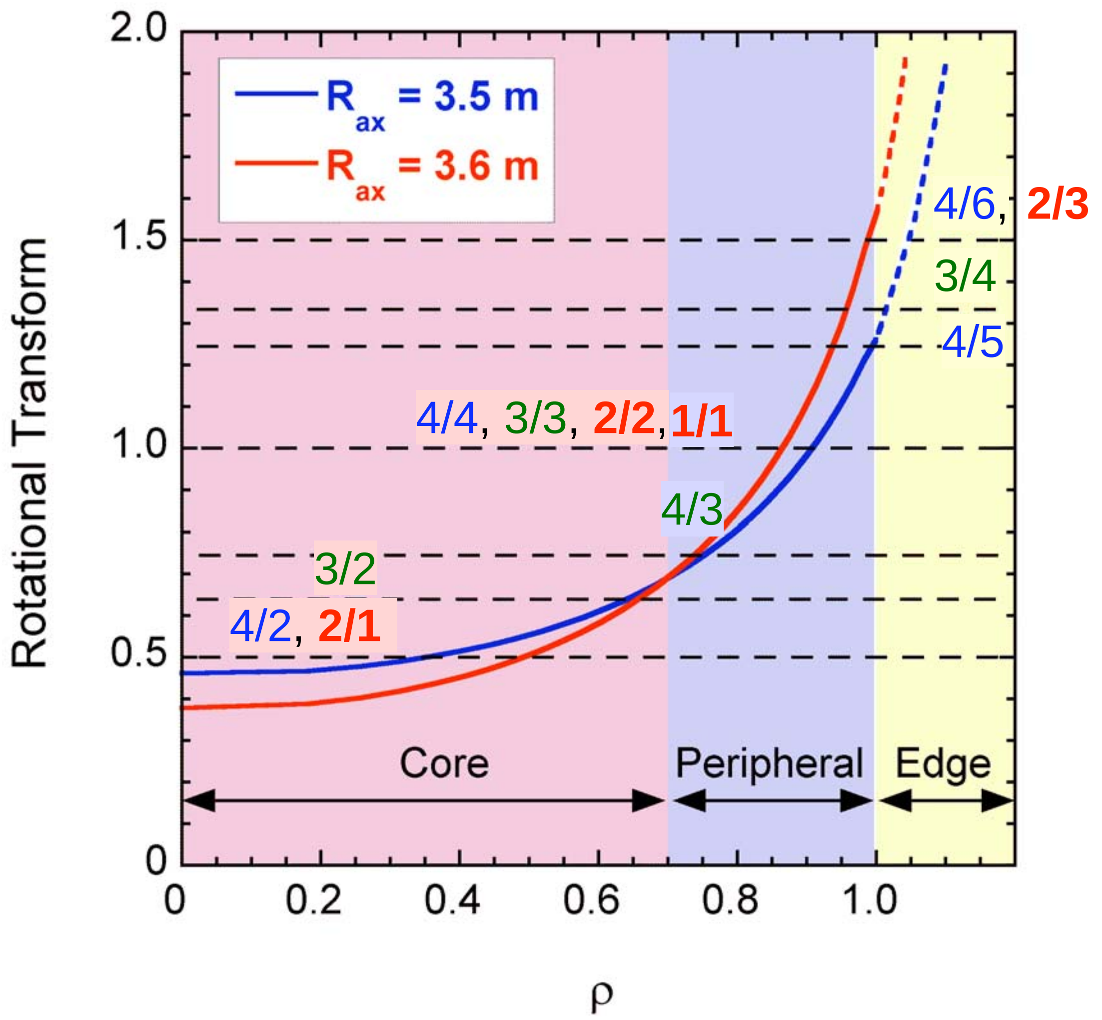
Increases as β

\# Magnetic Fluctuation;

Even in Mercier stable region, resonant fluctuation (low-n) mode is *observed*.

Amplitude increases as β and β -gradients

How large m number is effective on the global confinement?



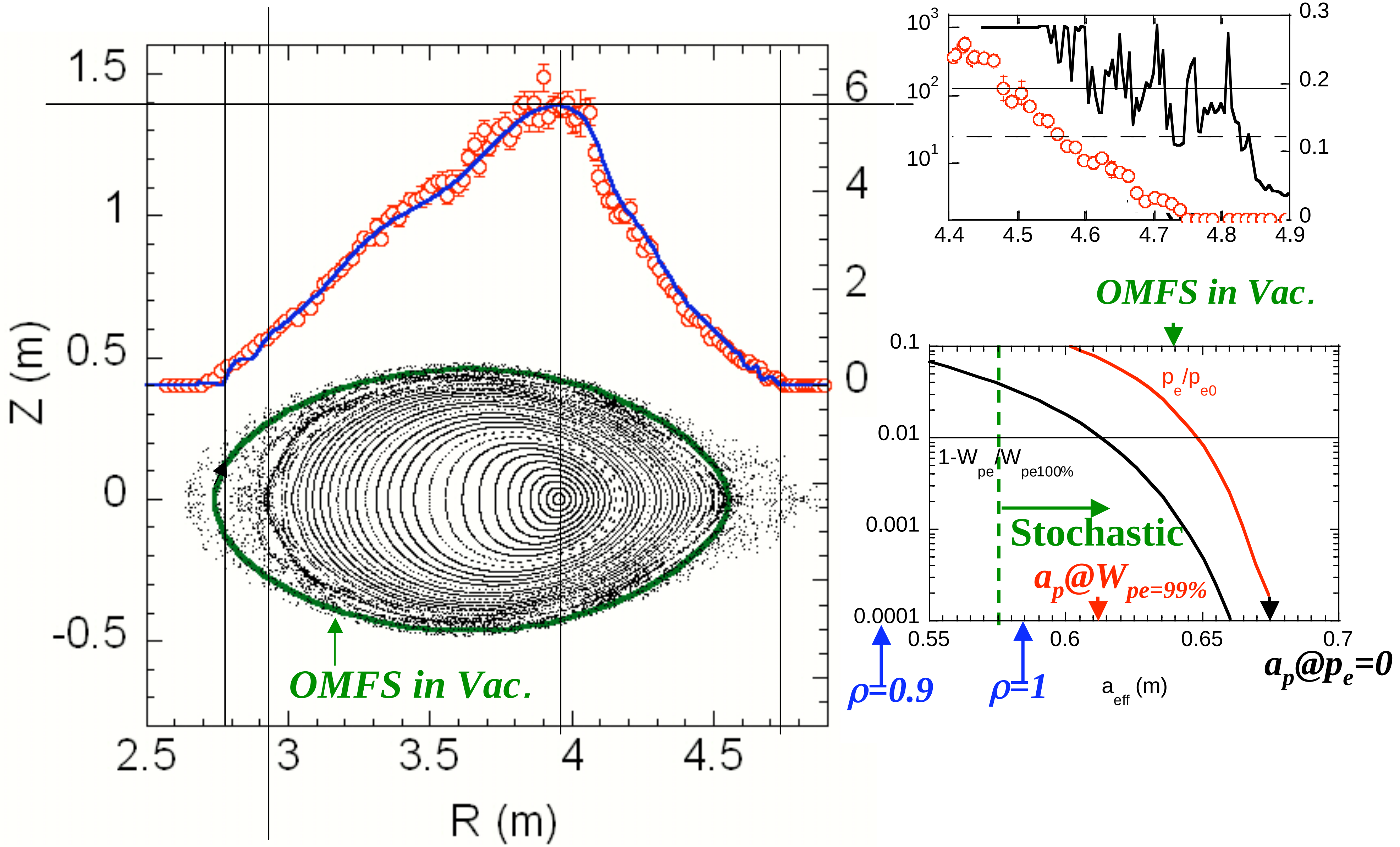
m=1,2 => Effective!!

m=3,4 ???
m>4 => Not effective??

high m => Not effective!!
β gradients not care Mercier.

To make clear
A final goal of LHD
high beta experiments

If only unstable modes with m=1,2 are effective, pressure profile locally flattened near limited resonant surfaces might lead to high beta discharges with around β~5%.

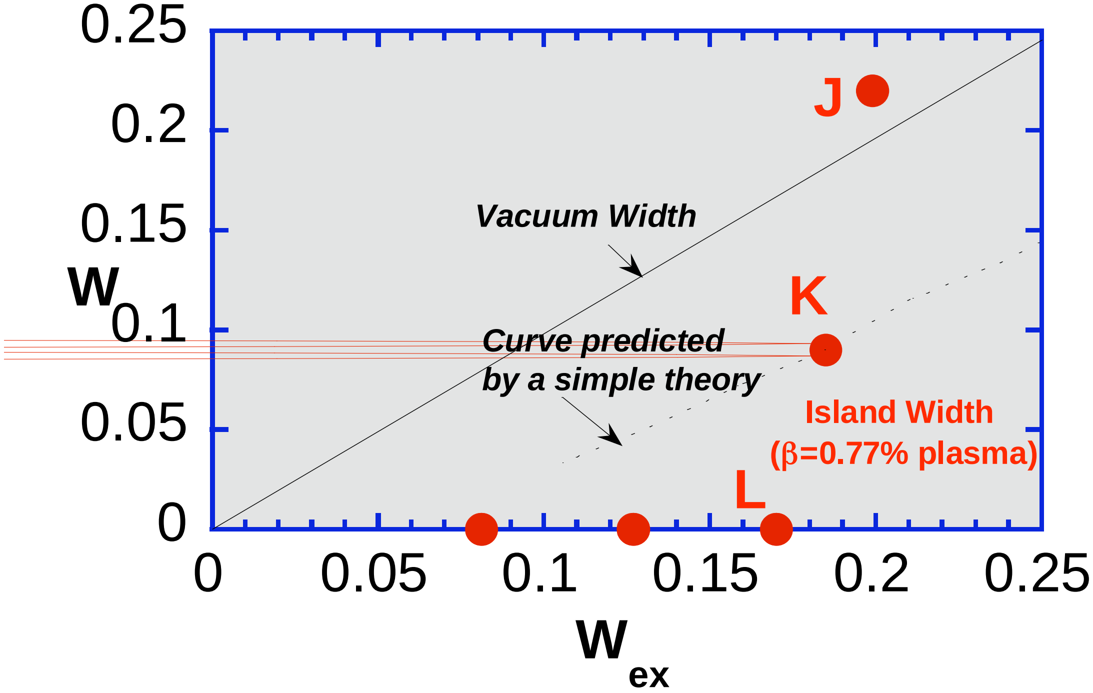


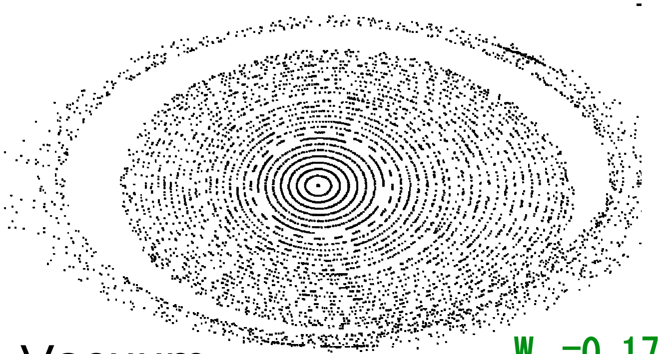
Predicted magnetic field structure by HINT and observed pressure profile in a high beta LHD discharge with R_{ax}^{V}=3.6m, B_0=0.5T and $<\beta_{dia}>$~2.9%.

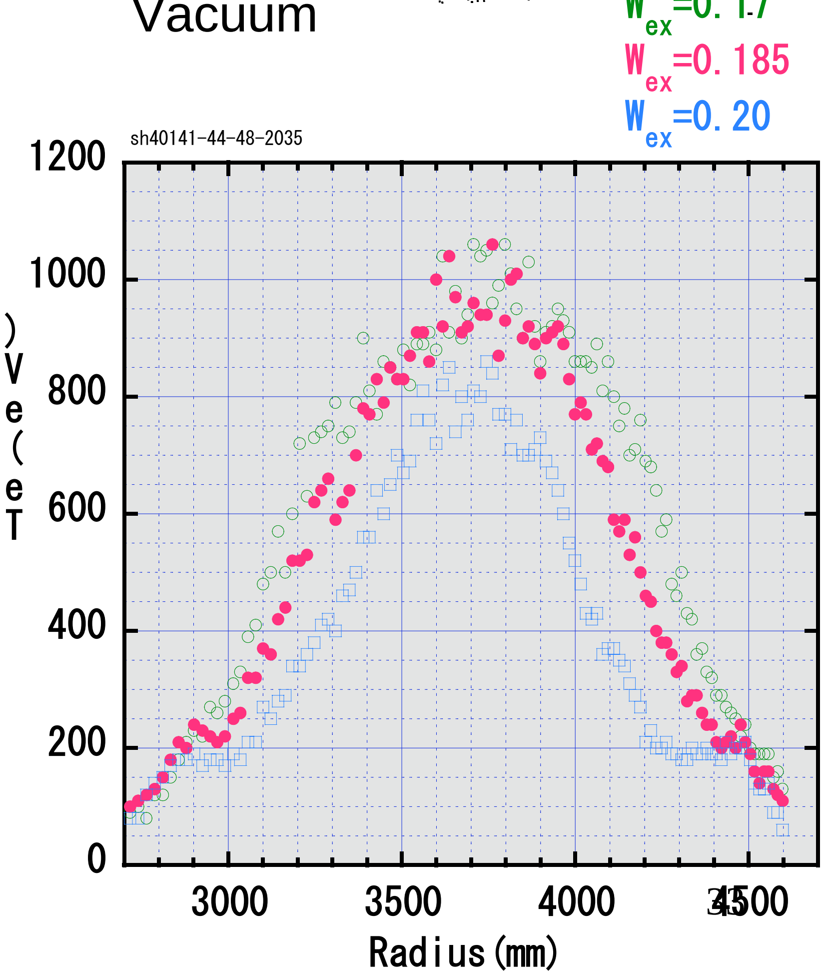
N.Ohyabu

Plasma heals magnetic island structure

Plasma dynamics against magnetic island,
which generated by external resonant field




Vacuum



- Island structure is put out by plasma
- This kind of mechanism may heal magnetic island in edge in high-β regime.

➔ Consequently, plasma boundary may not be destructed unlike the prediction of static MHD equilibrium