**INTERNATIONAL POLYTECHNIC SUMMER SCHOOL**

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# MHD properties in high beta helical plasmas - From results of the LHD -

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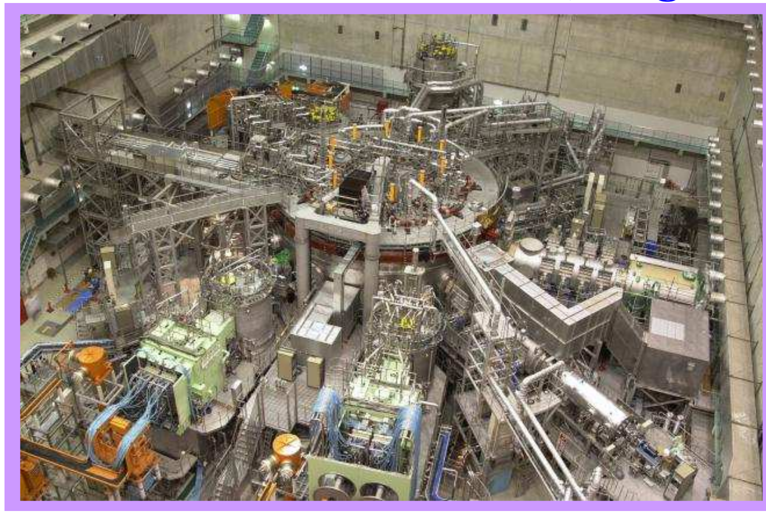
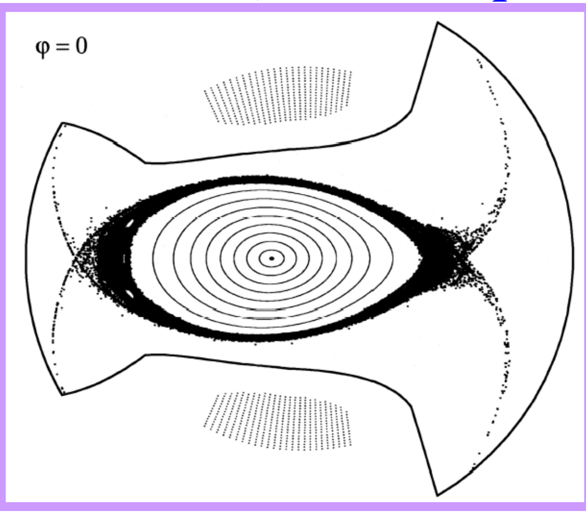
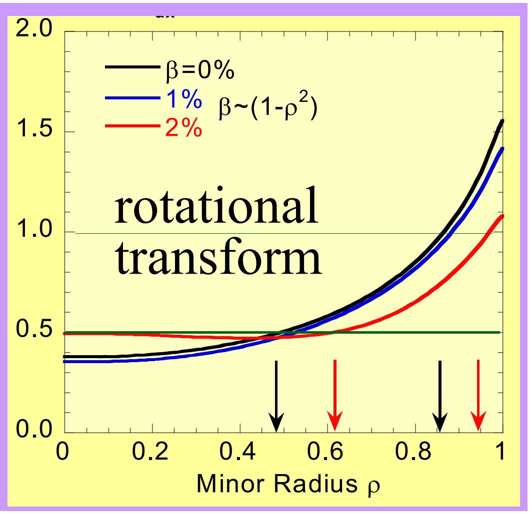
***LHD (Large Helical Device) NIFS, Japan***





# Outline of talks

# Overview of LHD

# On the MHD and transport characteristics of LHD

# Characteristics of high beta discharges of LHD

# Effect of the MHD instabilities on the confinement in LHD
--- How does the MHD instabilities affect the LHD?
--- Comparison between exp. Results and a theoretical prediction
--- On a suppression method of the MHD instability
--- Effect of the MHD instabilities on the transport

# Other topics related with the MHD instabilities in LHD
--- A collapse phenomena in the super dense discharges

# Summary and the future subjects

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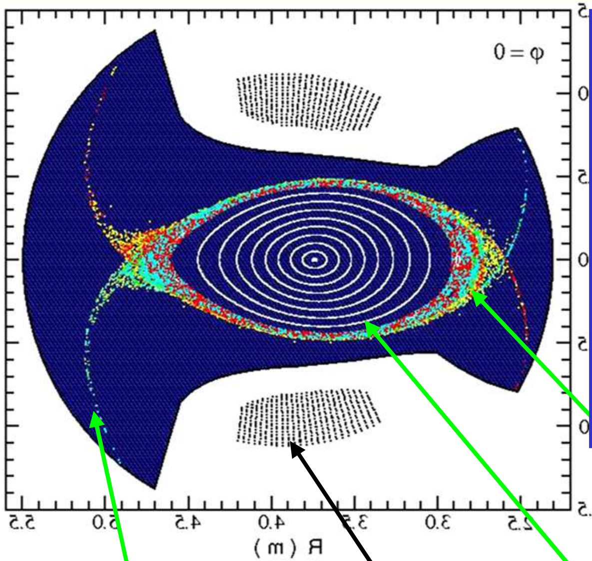
# Three main goals of LHD

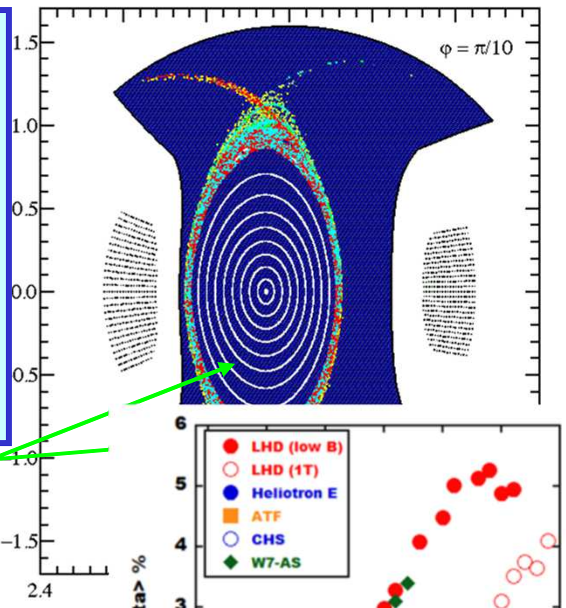
**# Volume averaged beta value 5% ($<\beta>=5\%$)**
**# Plasma temperature 10keV ($T_{i0}=T_{e0}=10$keV)**
**# Long time discharges with high performance plasma (30 min. discharge with Heating power 3MW)**

- **For construction of economical reactor, the volume averaged beta value (=plasma pressure/magnetic pressure) should be at least 5% (Before the LHD experiments, the achieved highest beta value in helical plasmas; 2.1%.)**
- **Demonstration of 10keV plasma confinement, which is a condition to react fusion because the confinement performance of helical devices was lower than that of tokamaks due to the complicated magnetic field structure.**
- **Demonstration of long time discharges to show the advantage of the currentless plasmas in helical systems and the super conductor devices.**

# Structure and plasma achievement of LHD




Continuous helical coils of
l=2/m=10 field period
All superconducting coil system
Toroidal field strength <3 T
Plasma major radius ~3.7 m
Plasma minor radius ~0.6 m
Plasma volume ~30 m$^3$
(~1/30 of ITER)

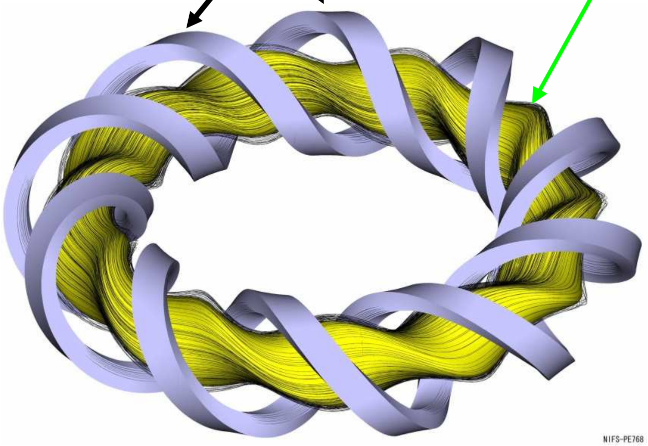



Ergodic Layer

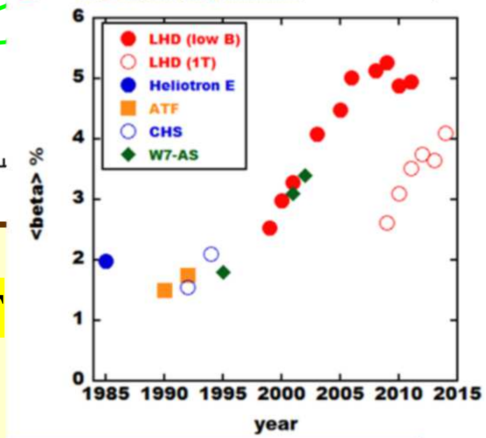
Helical Coil

Magnetic Surface

Divertor Leg



**LHD experiment started from 1998.**




High beta
$\langle\beta\rangle$ = 5.1 % at B = 0.43 T
$\langle\beta\rangle$ = 4.1 % at B = 1.0 T
High density
$n_e(0) = 1.2\times10^{21} m^{-3}$ at B = 2.5 T
High ion temperature
$T_i$ = 10 keV ($T_e$ = 8.1 keV) at $n_e = 1.3\times10^{19} m^{-3}$
High ion and electron temperature
$T_i = T_e$ = 8.7 keV at $n_e = 1.5\times10^{19} m^{-3}$
Long pulse : 1.2MW for 48min.
Fusion product; $n\,\tau_E\,T = 5\times10^{19}$ m$^{-3}$ s keV

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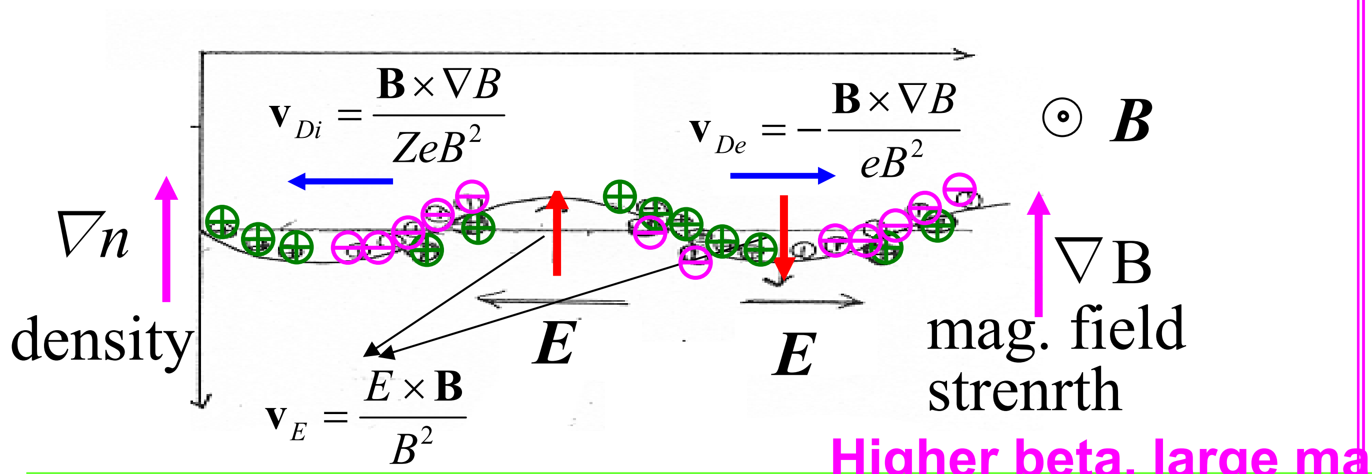
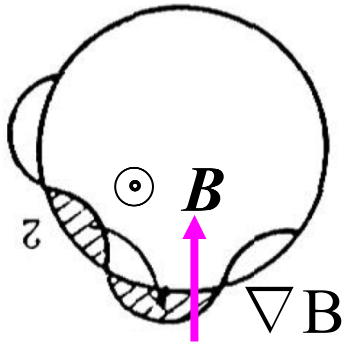
# Characteristics of pressure grad. driven MHD insta.

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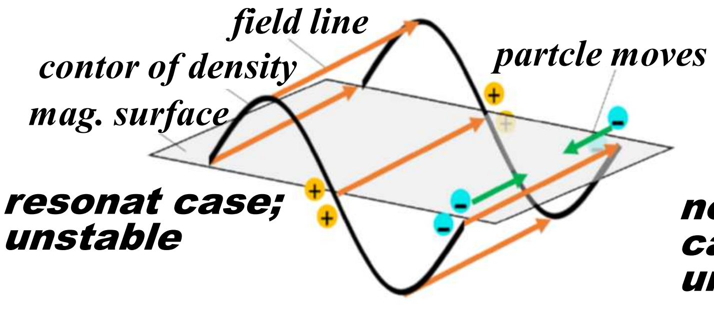
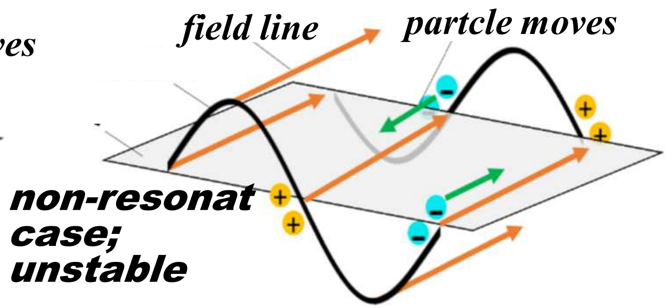
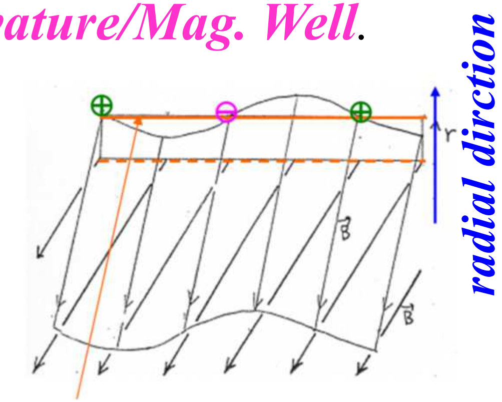
**Higher beta, large mag. hill**
**=> more unstable**

*B is smaller, $v_D$ and $v_E$ are larger.*
*Density (pressure) gradient is larger, $v_E$ are larger=> fluc. Largely grows.*
*$\nabla B$ is larger, $v_D$ is larger.*

*Direction of $\nabla B$ is same to that of $\nabla n$=> **Bad curvature/Mag. Hill**.*
*Direction of $\nabla B$ is opposite to that of $\nabla n$=> **Good curvature/Mag. Well**.*



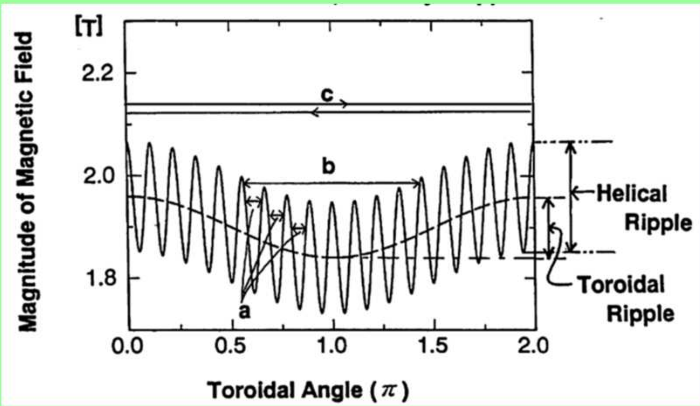




***resonant=> field line struct. coincides to perturb. struct.***
***; charge separation is maintained=> unstable***

**mag. shear**
**=> stabilizing effect**

# Particle orbit of heliotron plasmas

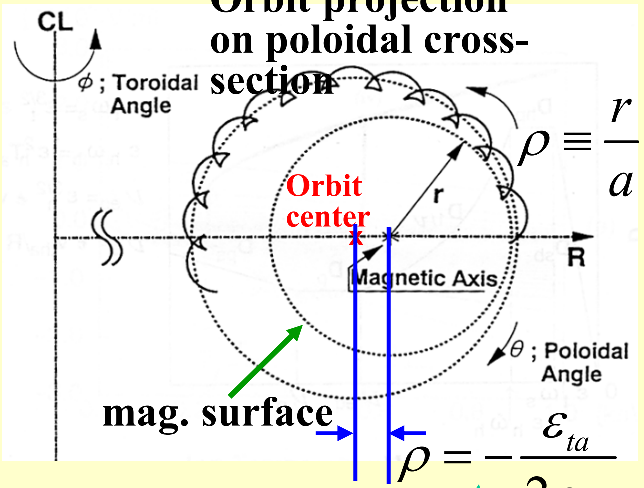


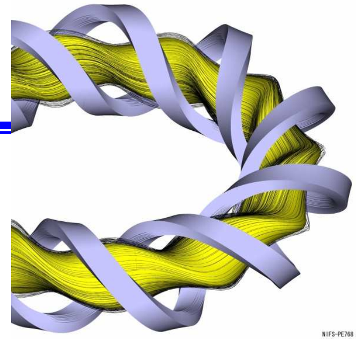

$$B(r,\theta,\phi) = B_0\left[1 - \varepsilon_t(r)\cos\theta - \varepsilon_h(r)\cos(l\theta - m\phi)\right]$$

**Model magnetic field of heliotron and the amplitude along a field line**

**c: helically trapped orbit (helical banana)**

**Orbit projection on poloidal cross-section**



**Deviation of helical banana from mag. surface is the largest.**
**=>**
**Property of helical banana is important.**

There are 3 type of orbits;
- c: circulating (passing)
- b; toroidally trapped (banana)
- c: helically trapped (helical banana)

Especially, deeply trapped particle moves along the bottom of the helical ripple of the field strength.
=> The orbit follows

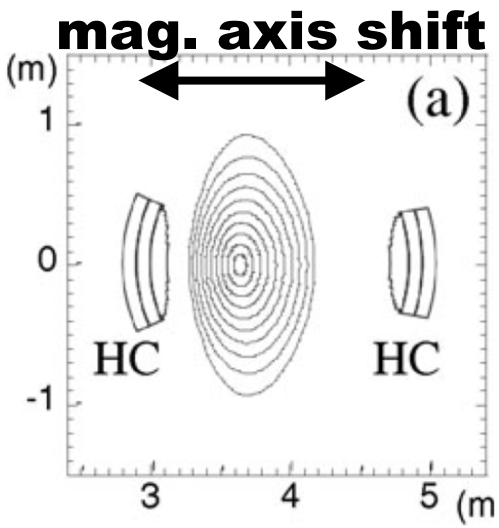
$$B(\rho,\theta,\phi_{\min}) = B_0\left[1 - \varepsilon_t(\rho)\cos\theta - \varepsilon_h(\rho)\right] = const.$$

$\varepsilon_t \sim \varepsilon_{ta}{}^*\rho$, $\varepsilon_h \sim \varepsilon_{ha}{}^*\rho^2$ (in the LHD)

$$C = 1 - \varepsilon_{ta}\rho\cos\theta - \varepsilon_{ha}\rho^2$$

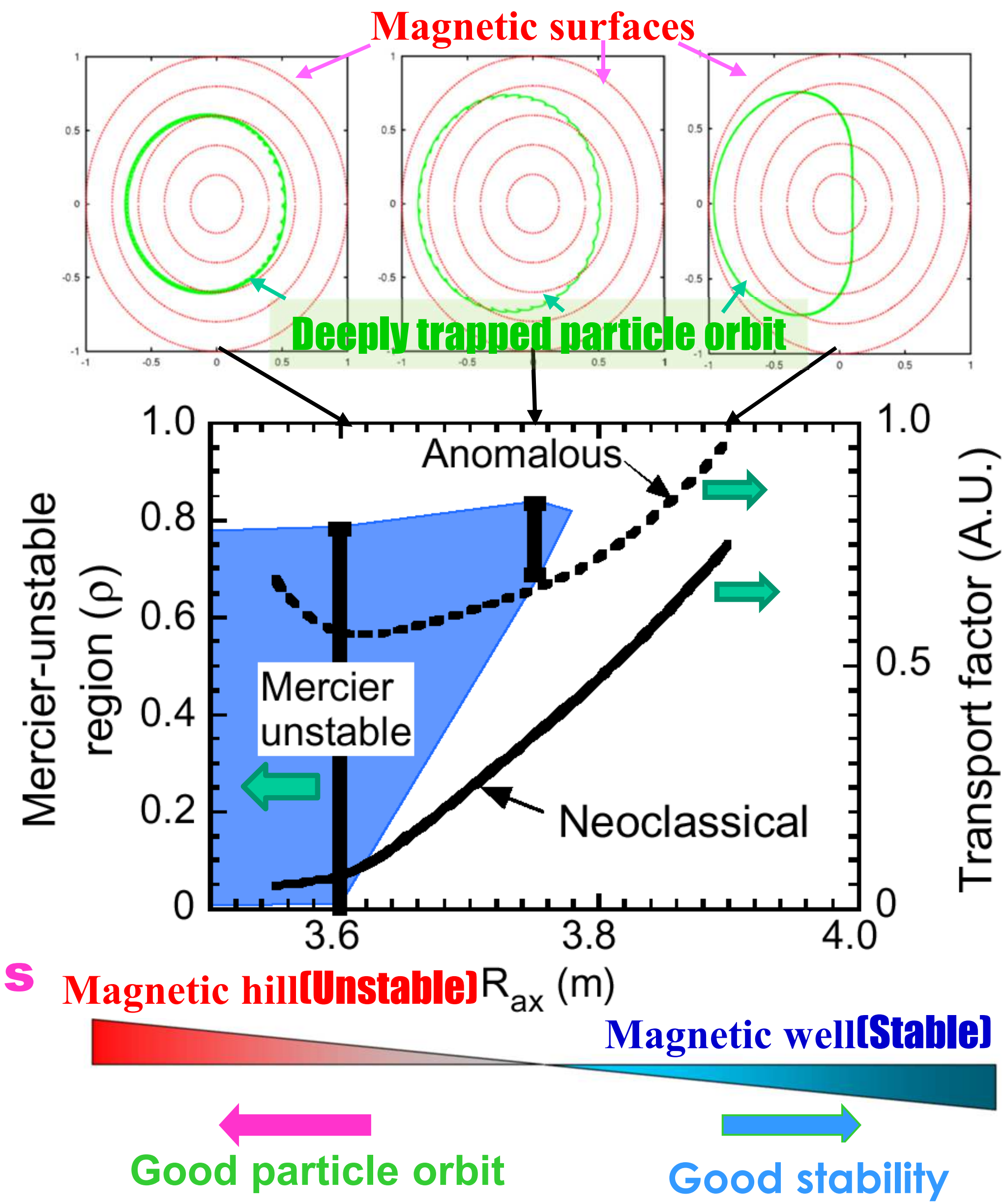
$\Rightarrow$ Orbit center does not coincide with the mag. axis.
Distance between Orbit center and mag. Axis
is $\rho = -\frac{\varepsilon_{ta}}{2\varepsilon_{ha}}$.

# Plasma performance strongly depends on $R_{ax}$

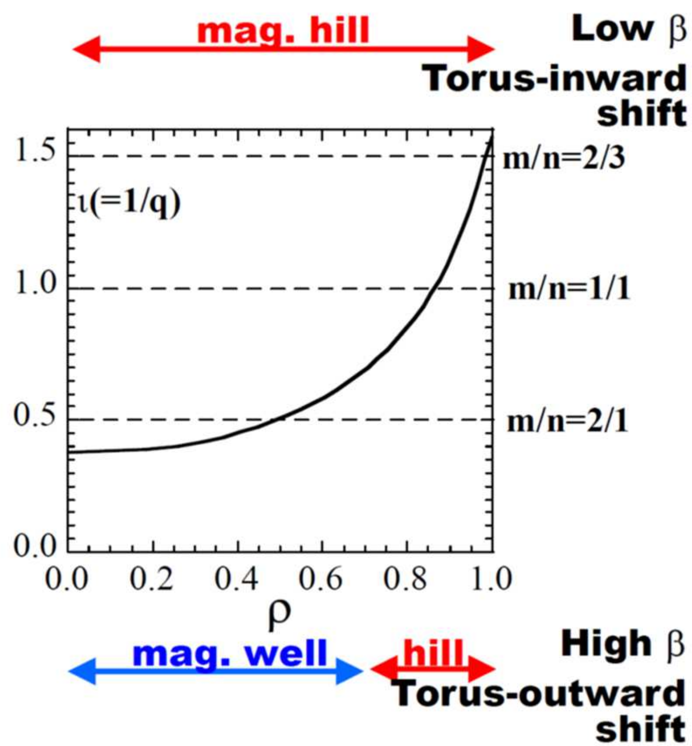


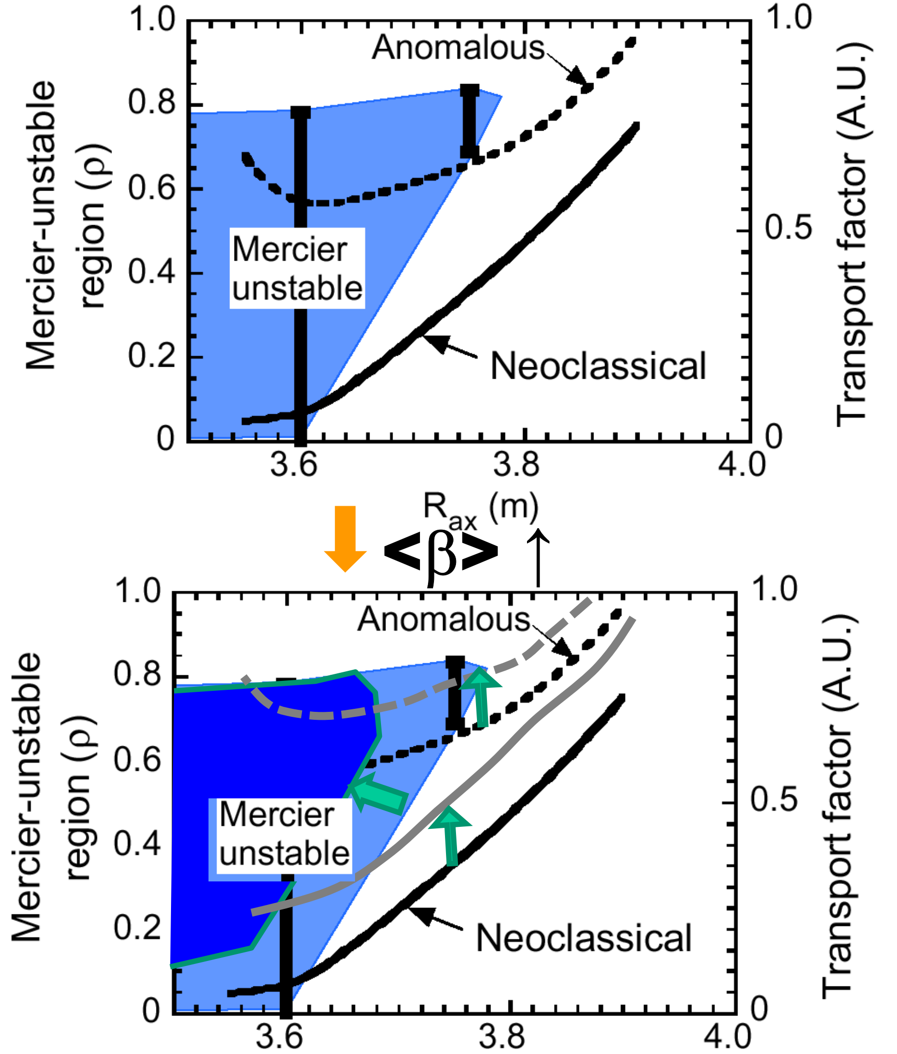

**Theoretical prediction;**
**in the torus-inward shifted mag. axis config. transport properties are good, but stability properties are bad.**

**Compatibility between stability and confinement is a main subject to obtain the high beta plasmas.**



# With increase of beta, stability property is improved




With increase of beta, $R_{ax}$ tours-outwardly shifts and well region expands in core.
=> stability property is improved, but transport property becomes worse.

**# Optimization of mag. axis location and mag. field strength leads to the achievement of <β>~5%.**

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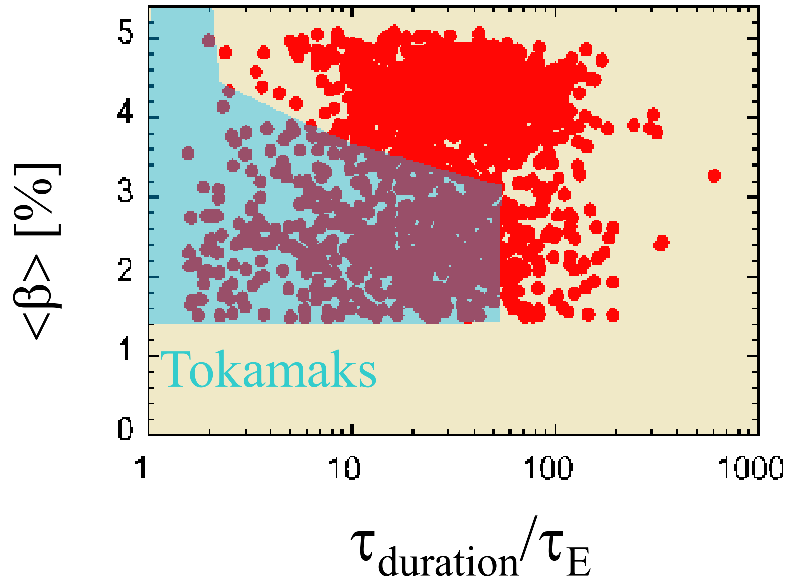
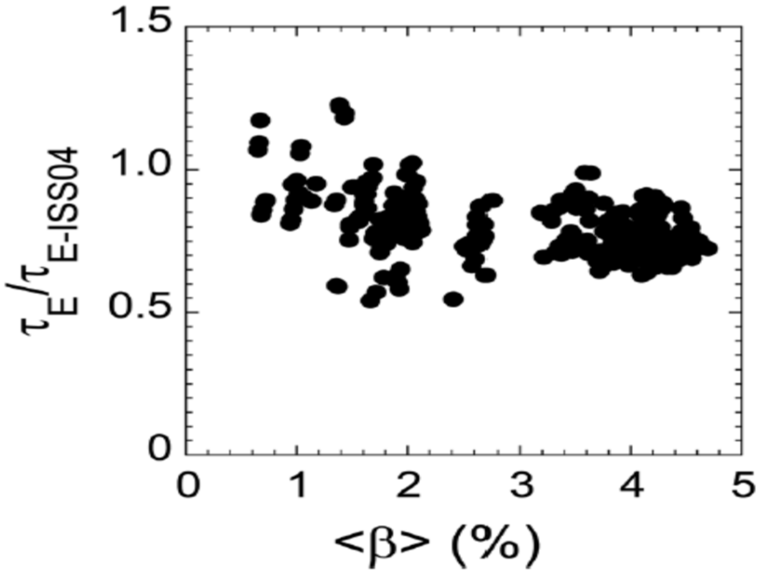
# Characteristics of high beta discharges of LHD

**Duration time; much longer than energy confinement time, $\tau_E$**




**Normalized $\tau_E$ by ISS04 empirical scaling decreases with $\beta$.**




[K.Y.Watanabe et al., PoP 2011]

**# The high beta discharges are maintained till the heating power stop.**

**# Performance of global energy conf. time degrades with beta.**

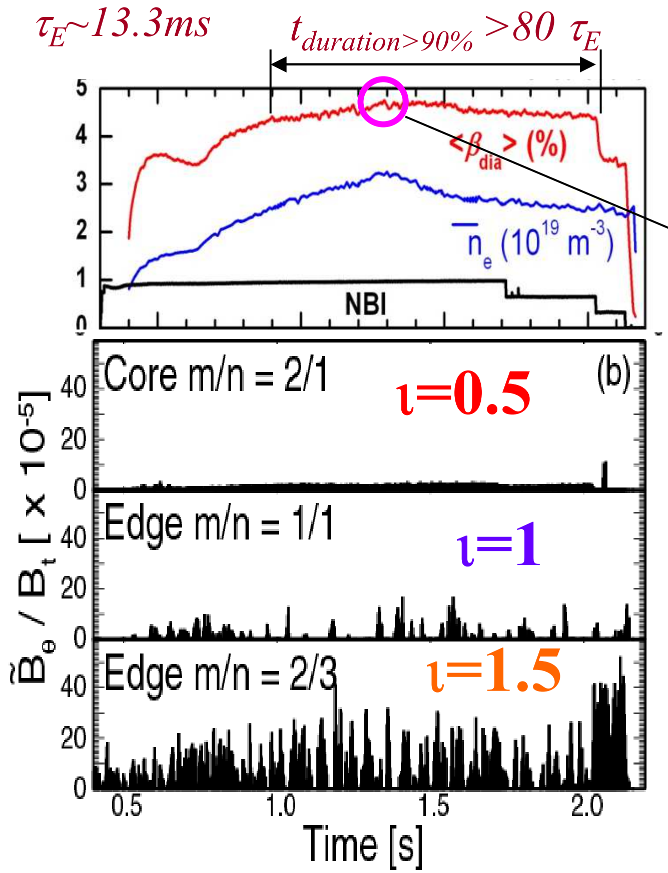
$$\chi \sim \frac{T_e}{eB}\frac{\rho_s}{a} \sim T^{1.5}B^{-2}a^{-1}$$

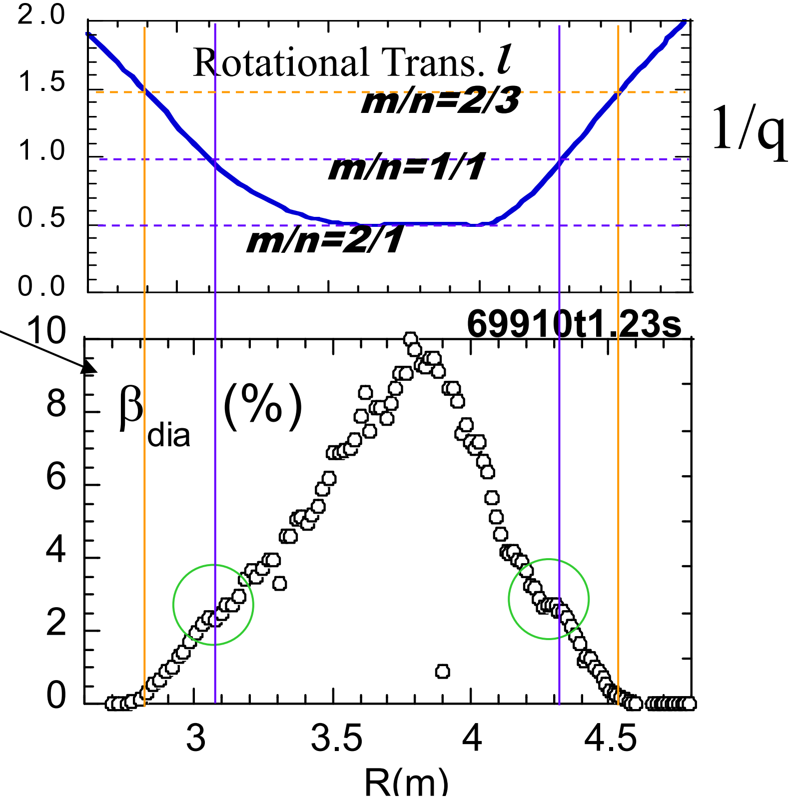
**ISS04;** $\tau_E \propto a^{2.28}R^{0.64}n_e^{0.54}P^{-0.61}B^{0.84}q^{-0.41}$

**A energy confinement scaling similar with gyro-Bhom.**

[H.Yamada et al., 2005 NF]

# Detail of Reactor relevant high-β discharge in LHD




# No disruptive high beta plasma is maintained during more than $80\tau_E$

# Low-n,m MHD activities

- No observation of core resonant modes.
- Only resonating mode with peripheral surf. (m/n = 2/3 and 1/1) appear

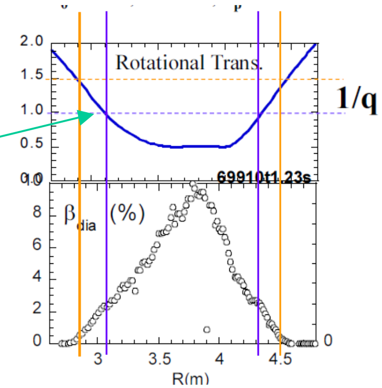
**Fine flattening and asymmetric structure on rational surf.**

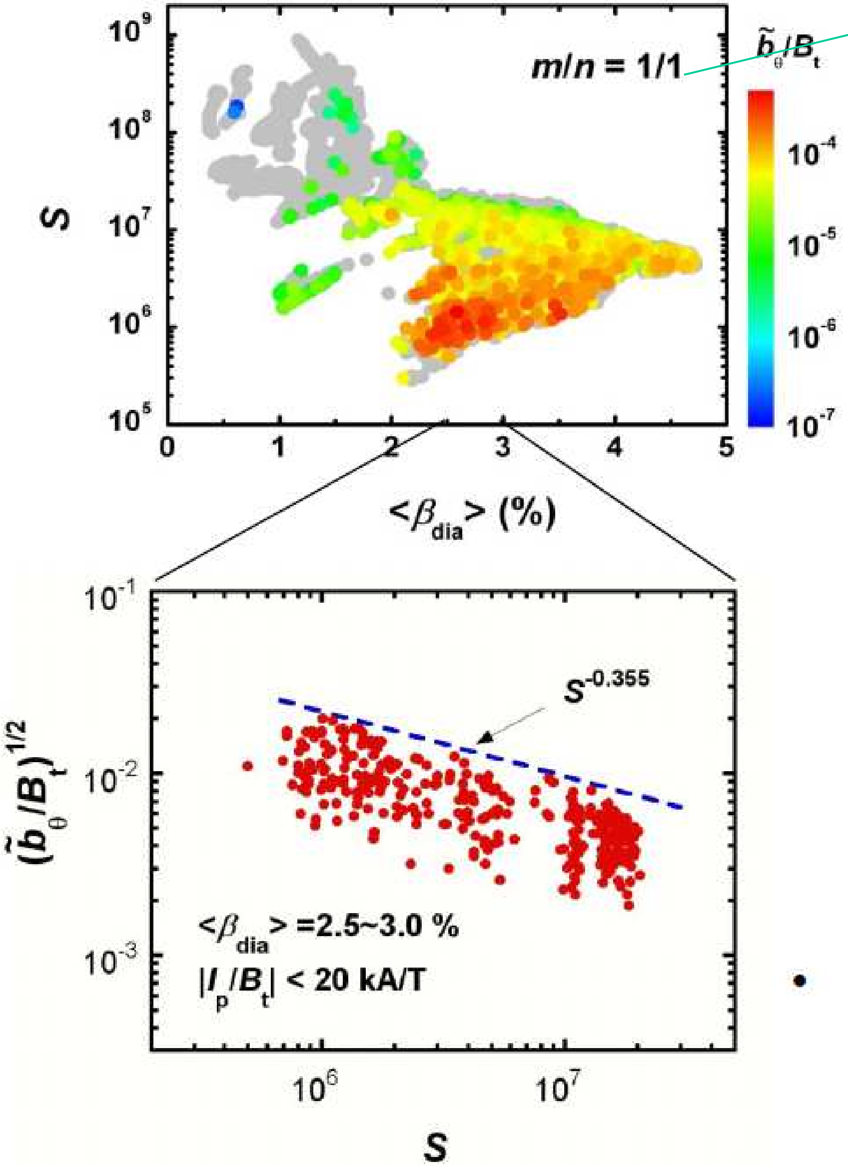
**=>**

**How does MHD instabilities affect confinement?**

# Instability in high-β discharges

**$b^{\sim}$ (mag. fluc) dependence on $\beta$ and $S$ (mag. Reynold #)**




[S.Sakakibara et al., 2010 Fusion Sci. Tech.]

**Magnetic island size due to $b^{\sim}$ is proportional to $\sqrt{b^{\sim}}$.**
**Saturation level of $b^{\sim}$ would be larger as the predicted linear growth rate.**
**($W \propto S^{-1/3}$, $\gamma \propto S^{-1/3}$)**

=>

**$S$ dependence of $b^{\sim}$ is close to the linear mode width and growth rate predicted by resistive interchange mode.**

$$S = \tau_R/\tau_A \quad \textbf{(mag. Reynold \#)}$$
$$\propto B_t T_e^{3/2}/n_e^{1/2}$$

***Growth rate and mode width of resist. Interchange***

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

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

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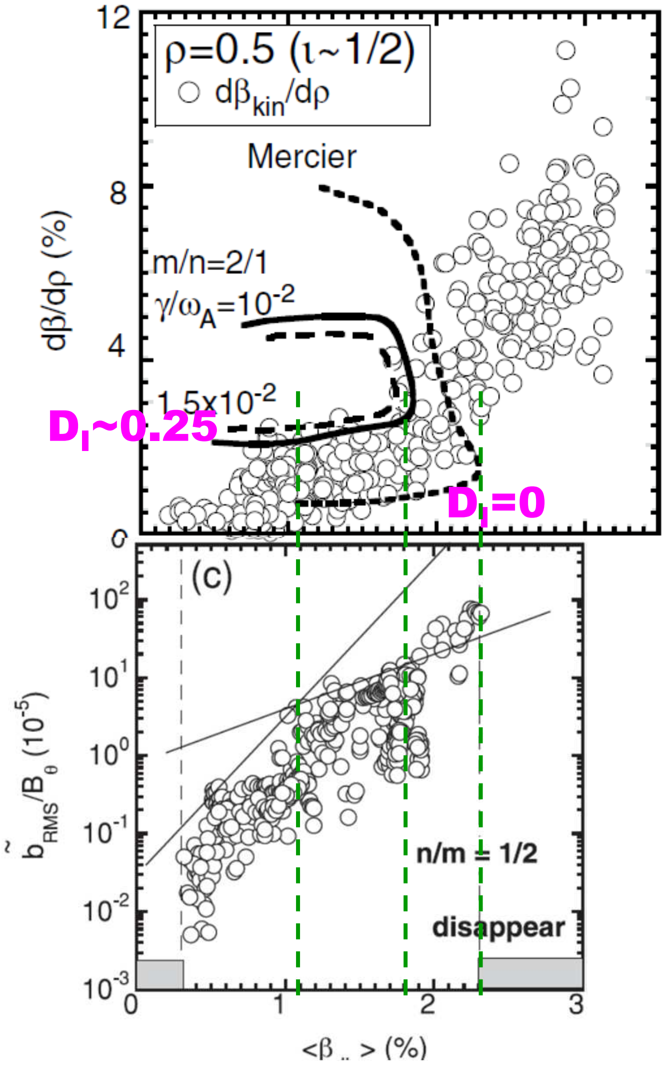
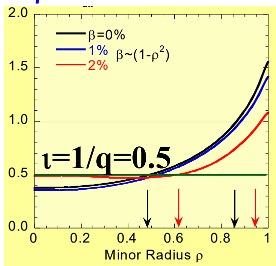
# Effect of interchange instability on the core

Relationship between stationary achieved pressure gradients and predicted ideal instability

Gradients are evaluated from averaged prof. for $\Delta\rho=0.1$




**$D_I$ ; Mercier parameter**
**A index of ideal interchange insta.**
**$D_I>0$; sufficient condition to be unstable for the localized mode**

**$\gamma$; linear growth rate of m/n=1/1 global ideal mode**
**$\gamma/\omega_A$~0.01=> growing time = 0.1~1ms**

*Linear growth rate analysis is a little more realistic than Mercier one from the viewpoint of theory.*

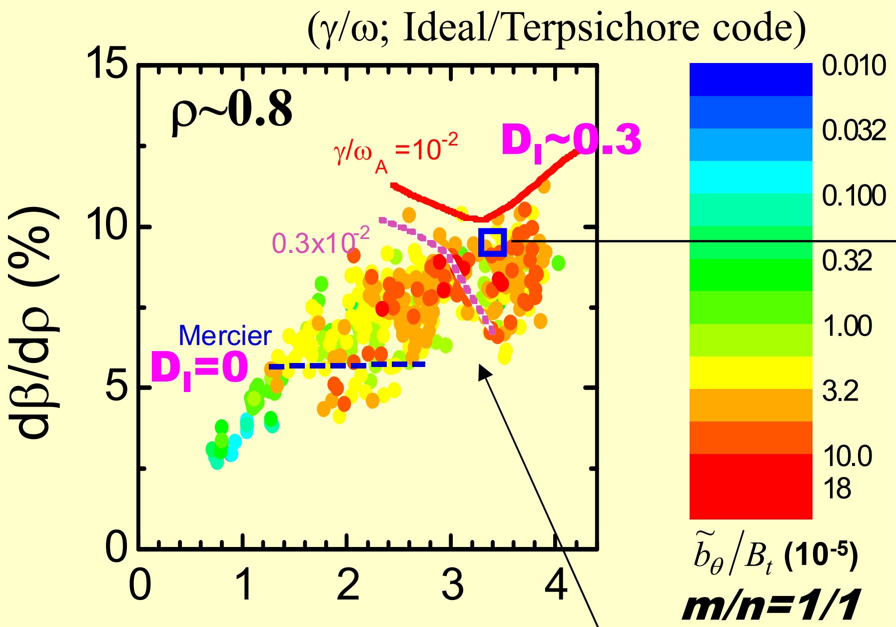
**Stationary achieved pressure gradients seem to avoid low-n ideal interchange unstable condition ($\gamma$ is calculated by Terpsichore code)** W.A.Cooper (CRPP/ Switzerland)

**However, even if low-n ideal mode is predicted to be a little unstable, the pressure gradients are not affected by the "linear mode".**

**When the beta reaches a value where the predicted growth rate is larger than a value, the increment of mag. fluc. decreases.**
**When the beta is above a value(there growth rate is smaller than a value), the increment of mag. fluc. increases.**

[K.Y.Watanabe et al., 2005 NF]

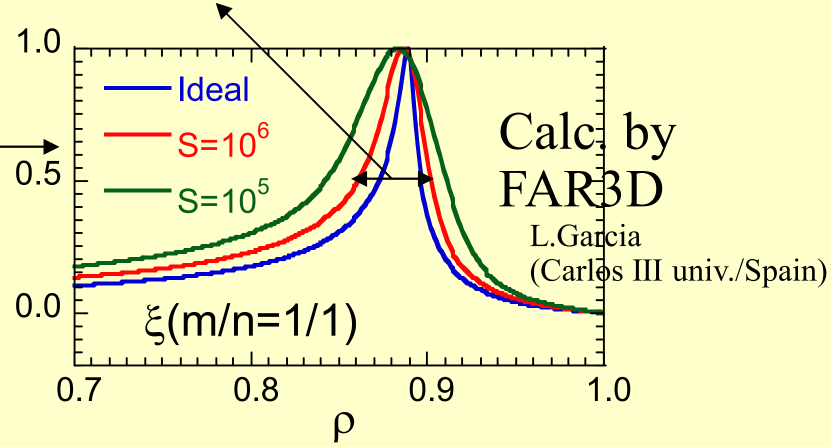
# Effect of interchange instability on the peripheral



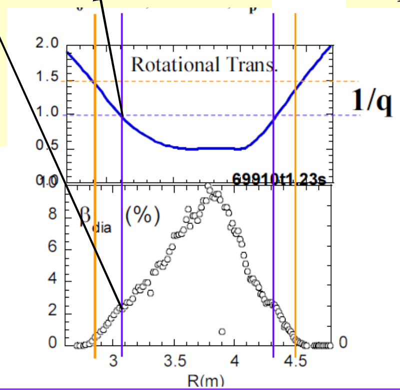

Observed beta gradients and resonant mag. fluc.

**$\Delta/a_p$~3% (Ideal)**

**~5%(S=10^6) consistent with exp.**




Radial structure of low-n ideal and resistive MHD mode



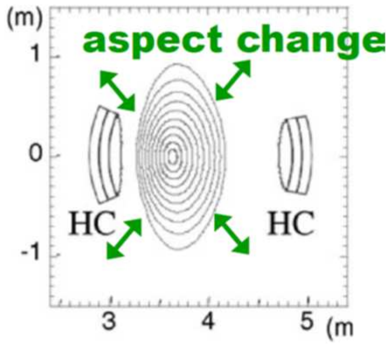

**For the b~/B$_0$~10$^{-4}$ with S=10$^6$, predicted $\Delta/a_p$ ~ 5%**
**=> consistent with the preliminary experimental mode width.**

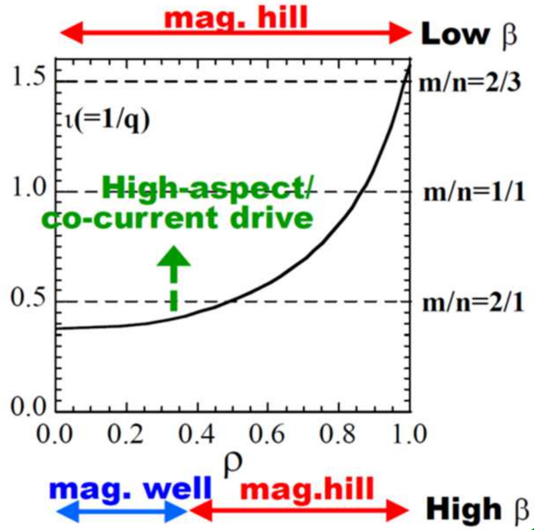
## *A speculation*

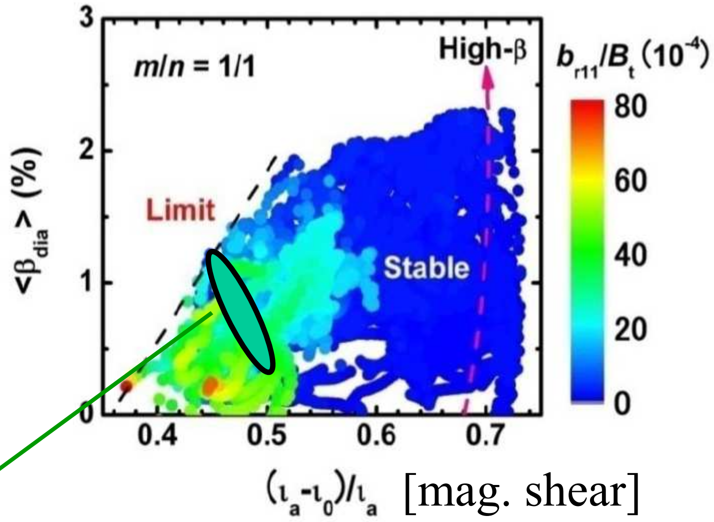
**Even in the mode is expected linearly unstable, when the mode width is narrow, the effect on the confinement is quite small**

[K.Y.Watanabe et al., 2005 NF]

# How about much unstable cases on interchange insta.

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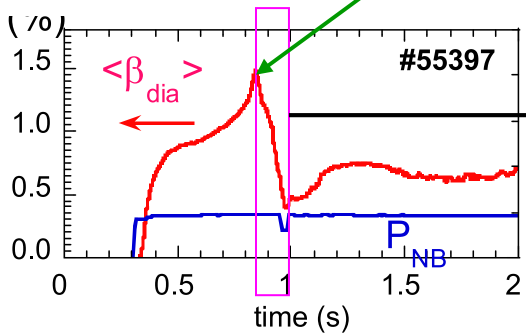
**aspect-ratio /co-current increases**

**In low shear and high hill conf. due to high aspect and co-current**

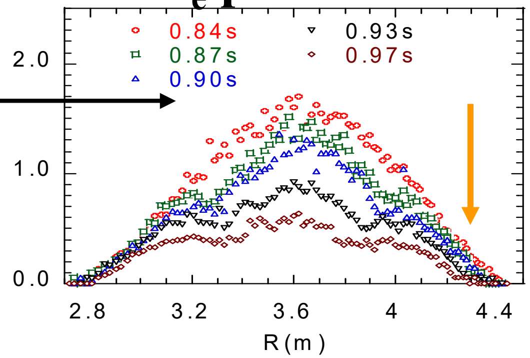
**=>**

**Unfavorable for ideal interchange instabilities**

**Magnetic fluctuation increases, and a minor collapse happens, the achieved beta is reduced.**



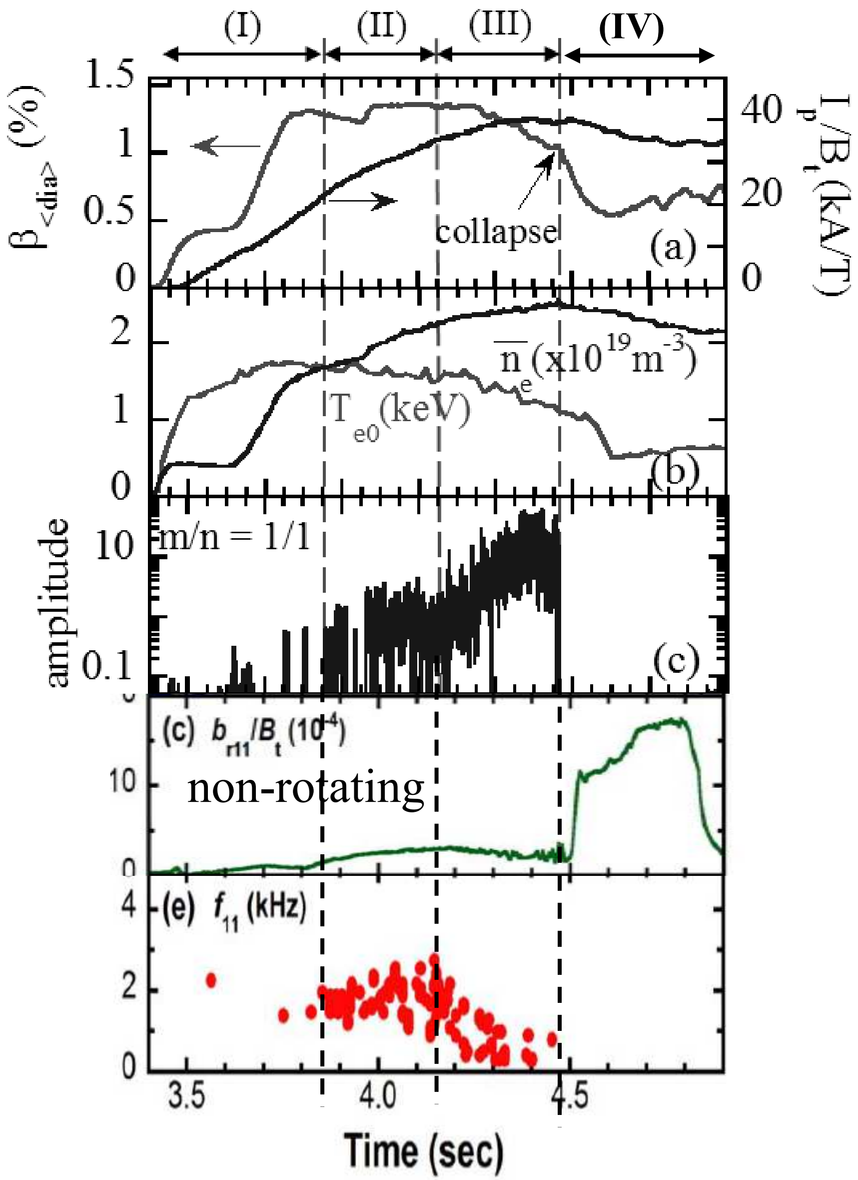

**$T_e$ profile**




**Minor collapse; >50% of beta decreases.**

# Detail of plasma behavior in high-aspect/co-current discharges

**$R_{ax}$ = 3.6 m, Bt = −1.2663 T**




## Behavior of β, the amp. and freq. of *b*˜.

**Phase (I);**

Amp. of m/n =1/1 mode hardly appears and Mercier criterion at ι/2π=1 surface is stable.

**Phase (II);**

The precursor-mode clearly appears. Sometimes it is not clearly observed.

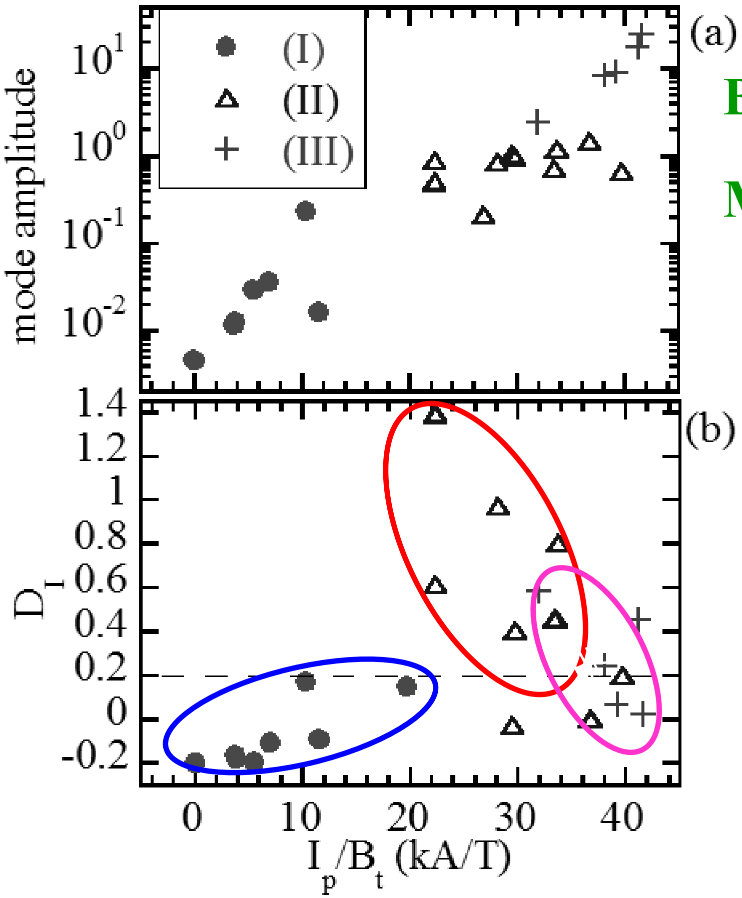
**Phase (III);**

The mode amplitude increases gradually, and the mode rotation speed decreases, the central electron temperature $T_{e0}$ and $\langle\beta\rangle$ gradually decrease.

**Phase (IV);**

The mode rotation is stopped , and non-rotating mag. fluctuation increases, $T_{e0}$ and $\langle\beta\rangle$ rapidly decrease.

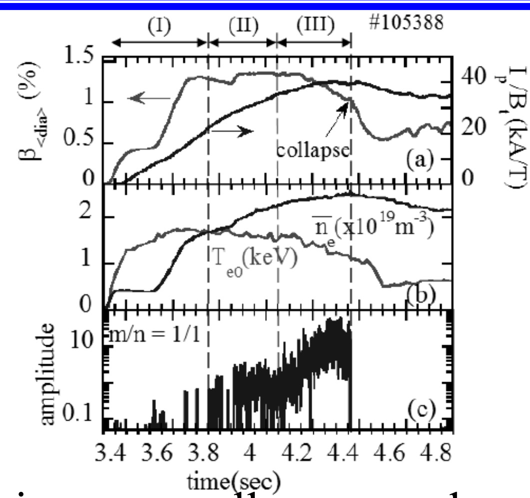
# On insta. in high-aspect/co-current discharges




∝ **Time**

For the accurate estimation of $D_I$, the identification of toroidal current profile is crucial. Here, MSE diagnostic is applied. And data of some similar discharges are imposed.

**Behavior of amp. of $\tilde{b}$ and Mericer parameter $D_I$.**




### In Phase (I);

Mag. fluc. amplitude is very small compared with other periods. Mercier criterion is stable.

### In Phase (II);

Mag. fluc. is clearly observed and the amplitude is almost constant. Value of $D_I$ becomes very large at the initial phase of period (II), then it decreases with the increase of $I_p$. **Even if $D_I$ becomes much large, the collapse does not occur immediately**.

### In Phase (III);

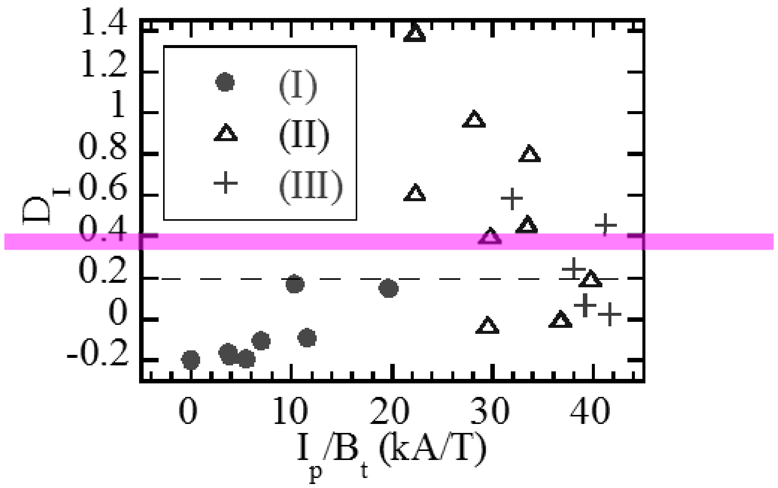
Fluc. amp. increases with the increase of $I_p$. On the other hand, $D_I$ decreases until the collapse because of the $T_e$ flattening.

=> **Linear analysis is not available.**

*Non-linear analysis is needed(Later discussed).*

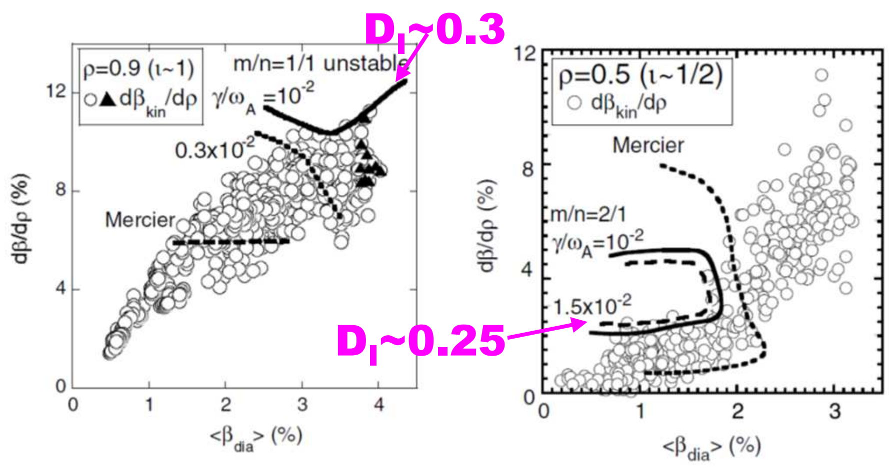
# On insta. in high-aspect/co-current discharges II

**Discussion;**
**relationship**
**between the on-set condition of the minor collapse in LHD and $D_I$ (Mercier parameter).**




**# The threshold value for minor collapse is $D_I$>>0.3 at the beginning phase of the precursor leading to the phenomena.**

**# It is consistent with the observation that the stationary achieved pressure gradient does not access the region of $D_I$ >0.3.**




**Relationship between operational regime and $D_I$ on quasi-steady discharges**

[M.Okamoto et al., 2020 NF]

# Outline of talks

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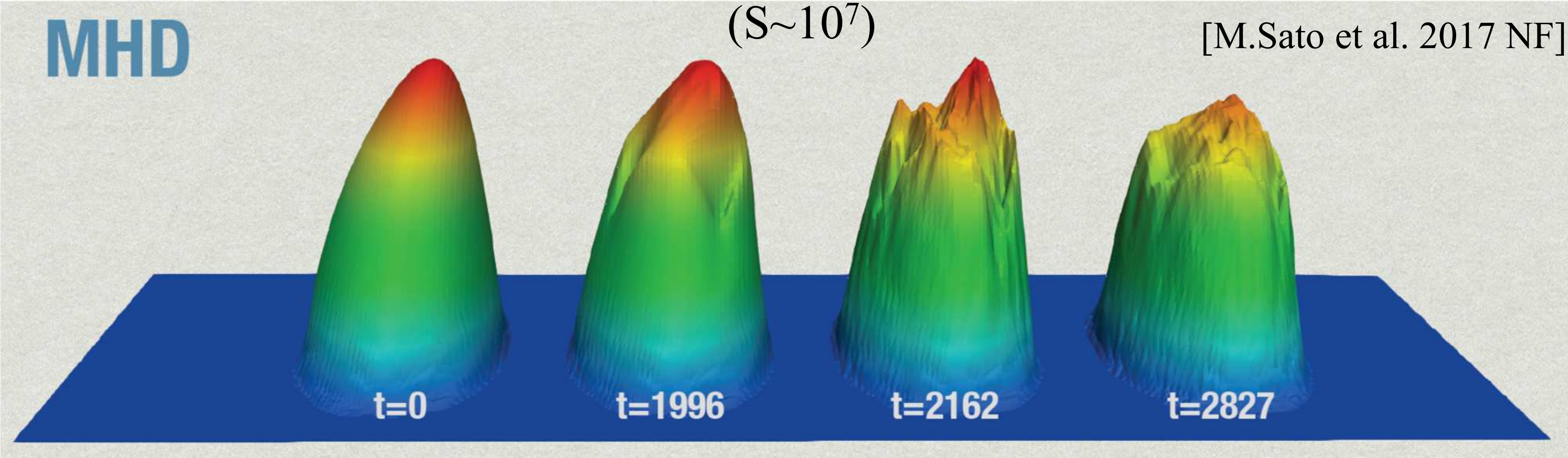
# Summary and the future subjects

# Theoretical prediction of MHD instability on reactor relevant high-β LHD discharge

Results of the non-linear time evolution of pressure profile based on MHD model

($S \sim 10^7$)

[M.Sato et al. 2017 NF]



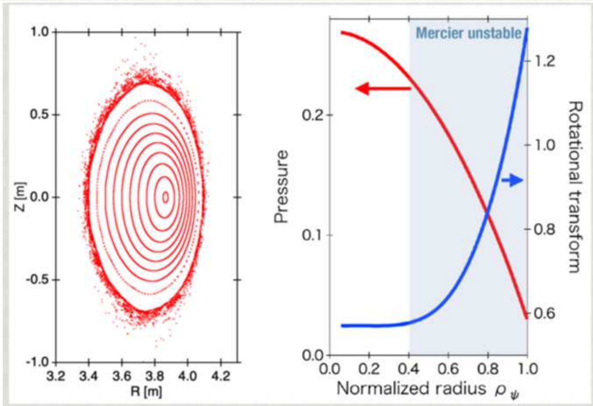

According to prediction based on full-MHD model, after a resistive ballooning instability grows in the plasma peripheral region, the pressure perturbation extend to the core regime, the pressure gradients in the core are strongly reduced.

=>

Inconsistent with the experimental results!!

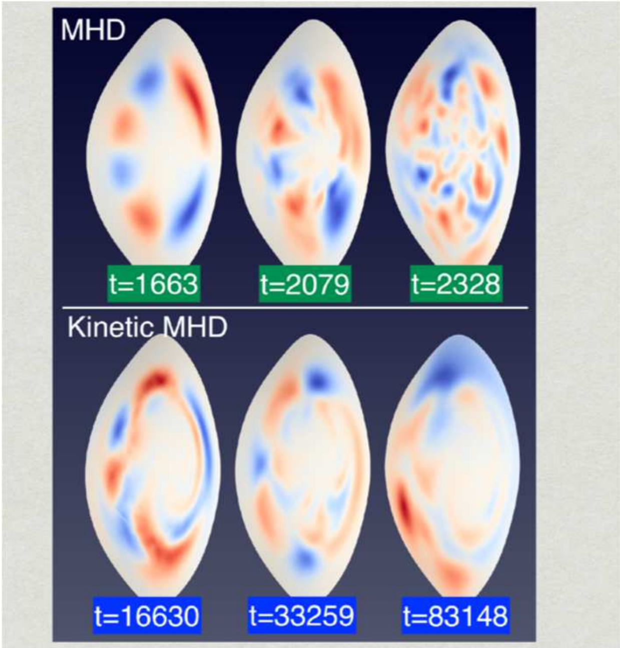
Some effects would stabilize the MHD instability!!

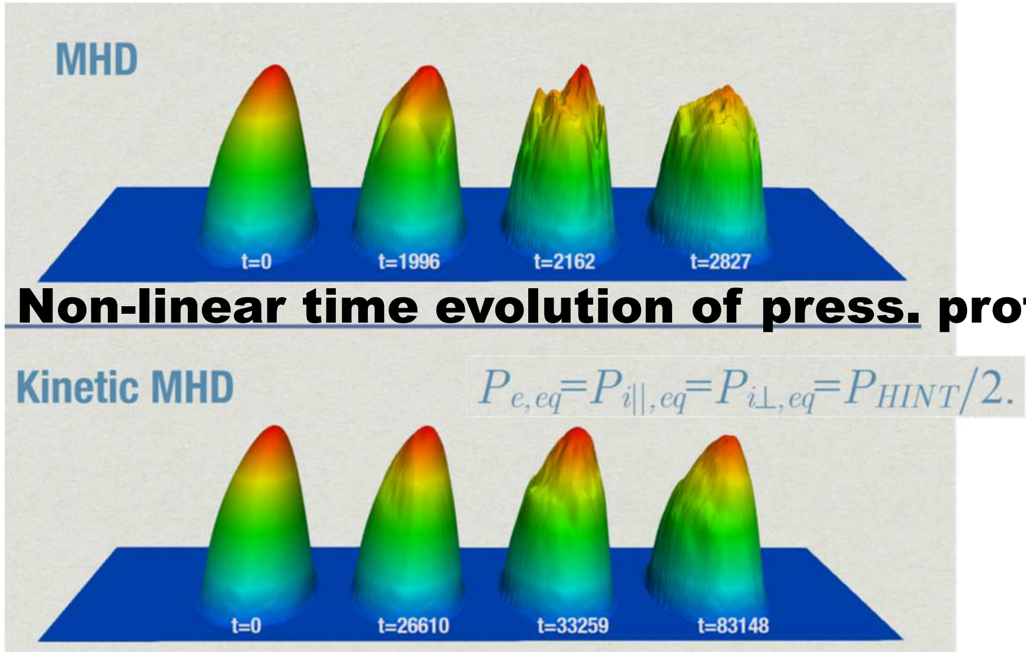
**A candidate;**
**kinetic effects like thermal ion orbit?!**




**Initial condition of non-linear full-MHD calculation (similar with high-β discharge <β>~5%)**

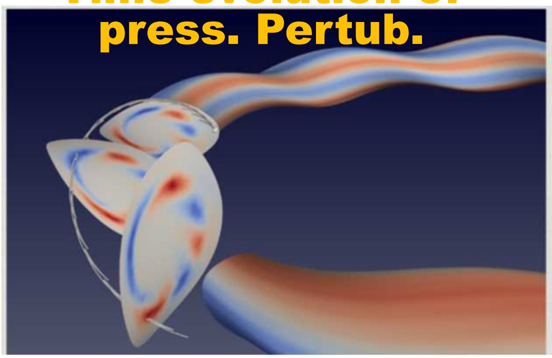
# Finite orbit effect of thermal ions on MHD instabilities

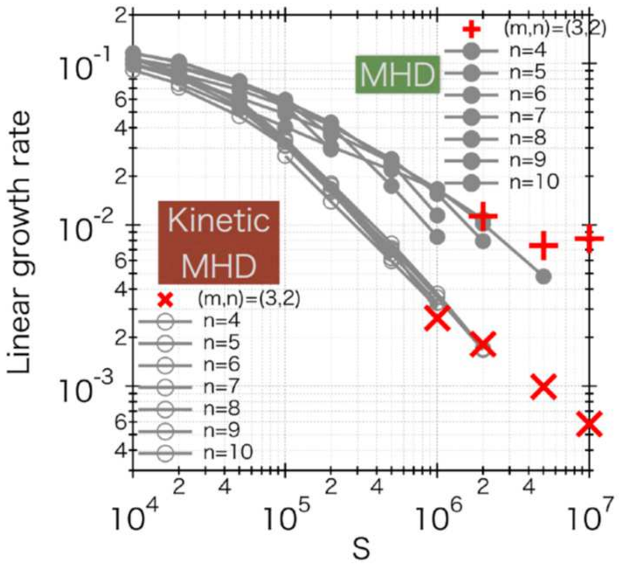



**Non-linear time evolution of press. prof.**

**Time evolution of press. Pertub.**






**Kinetic MHD model taking thermal ions' orbit effects into account reduces the growth rates in the wide m/n ranges, which leads to the maintenance of the pressure gradients in the high-$\beta$ regime.**

[M.Sato et al. 2020 J. Plasma Phys, 2020 Annual meeting of Jpn. Soc. plasma and fusion]

# Stabilizing mechanism due to helically trapped ions

$$p_{i,eq} = \left(p_{i//,eq} + 2p_{i\perp,eq}\right)/3$$

$$p_{i1} = \left(p_{i//1} + 2p_{i\perp 1}\right)/3$$

**MHD model**; ion & electron=> $p_{e1}=p_{i1}=p_1/2$

**Vortex eq. (reduced-MHD)**

$$\rho_0 \frac{\partial}{\partial t}\nabla_\perp{}^2 U = -(\mathbf{B}_0\cdot\nabla)\nabla_\perp{}^2\psi_1 - \nabla\psi_1\times\mathbf{e}_\phi\cdot\nabla j_{\phi 0} + \boxed{\mathbf{e}_\phi\times\boldsymbol{\kappa}_r\cdot\nabla p_1} \longrightarrow \boxed{\frac{k_\theta}{\omega}\frac{dp_0}{dr}\mathbf{e}_\varphi\times\boldsymbol{\kappa}_r\cdot\nabla U}$$

$$\frac{\partial}{\partial t}p_1 + \nabla U\times\mathbf{e}_\phi\cdot\nabla p_0 = 0 \longrightarrow p_1 = \frac{k_\theta}{\omega}U\frac{dp_0}{dr}$$

**kinetic MHD model**; $p_{e1}=p_{i1//}$, $p_{i1\perp}<0.1*p_{e1}$@$S>10^6$

$$p_{e,eq} = p_{i//,eq} = p_{i\perp,eq} = p_0/2$$

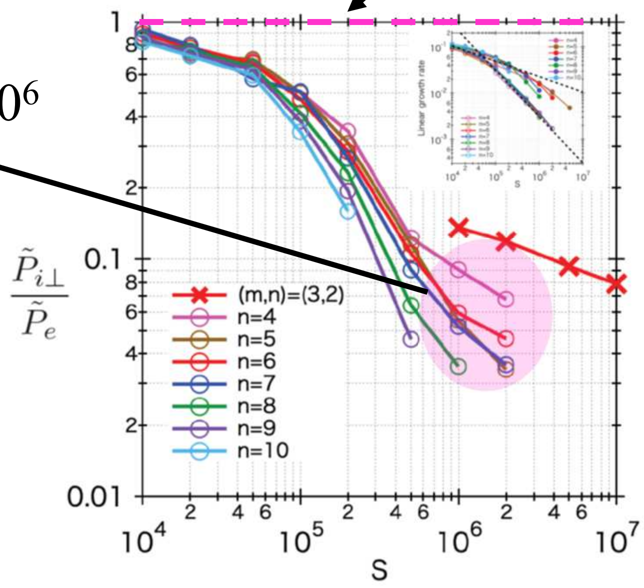
$$\rho_0 \frac{\partial}{\partial t}\nabla_\perp{}^2 U = -(\mathbf{B}_0\cdot\nabla)\nabla_\perp{}^2\psi_1 - \nabla\psi_1\times\mathbf{e}_\varphi\cdot\nabla j_{\varphi 0} + \boxed{\mathbf{e}_\varphi\times\boldsymbol{\kappa}_r\cdot\nabla\left(p_{e1} + p_{i1}\right)}$$

$$\frac{\partial}{\partial t}p_{e1} + \nabla U\times\mathbf{e}_\varphi\cdot\nabla p_{e,eq} = 0$$

$$\frac{\partial}{\partial t}p_{i1} + \nabla U\times\mathbf{e}_\varphi\cdot\nabla p_{i,eq} \neq 0$$

$$\boxed{\sim 0.4\frac{k_\theta}{\omega}\frac{dp_0}{dr}\mathbf{e}_\varphi\times\boldsymbol{\kappa}_r\cdot\nabla U}$$

MHD model




**Precession motion of the helically trapped particles reduces the perpendicular perturbation of ion.**
**=>**
**Reduction of the growth rate of the interchange instability.**

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# Suppression of instability
## -- Background --

**Previous researches on active control methods of instability**

**Tokamak**

Major MHD instabilities ( Edge Localized Mode (ELM) / Resistive Wall Mode (RWM) )

→ ▪Degradation of plasma confinement performance (β-value)
▪Plasma termination

specially on tokamaks, serious effect

Solution methods ① Plasma rotation ② Pellet injection ③ Applying Resonant Magnetic Perturbation (RMP)

↓ They are effective.

**In helical type, few researches about active control of instability have been done.**

**Our research target**

**Helical**

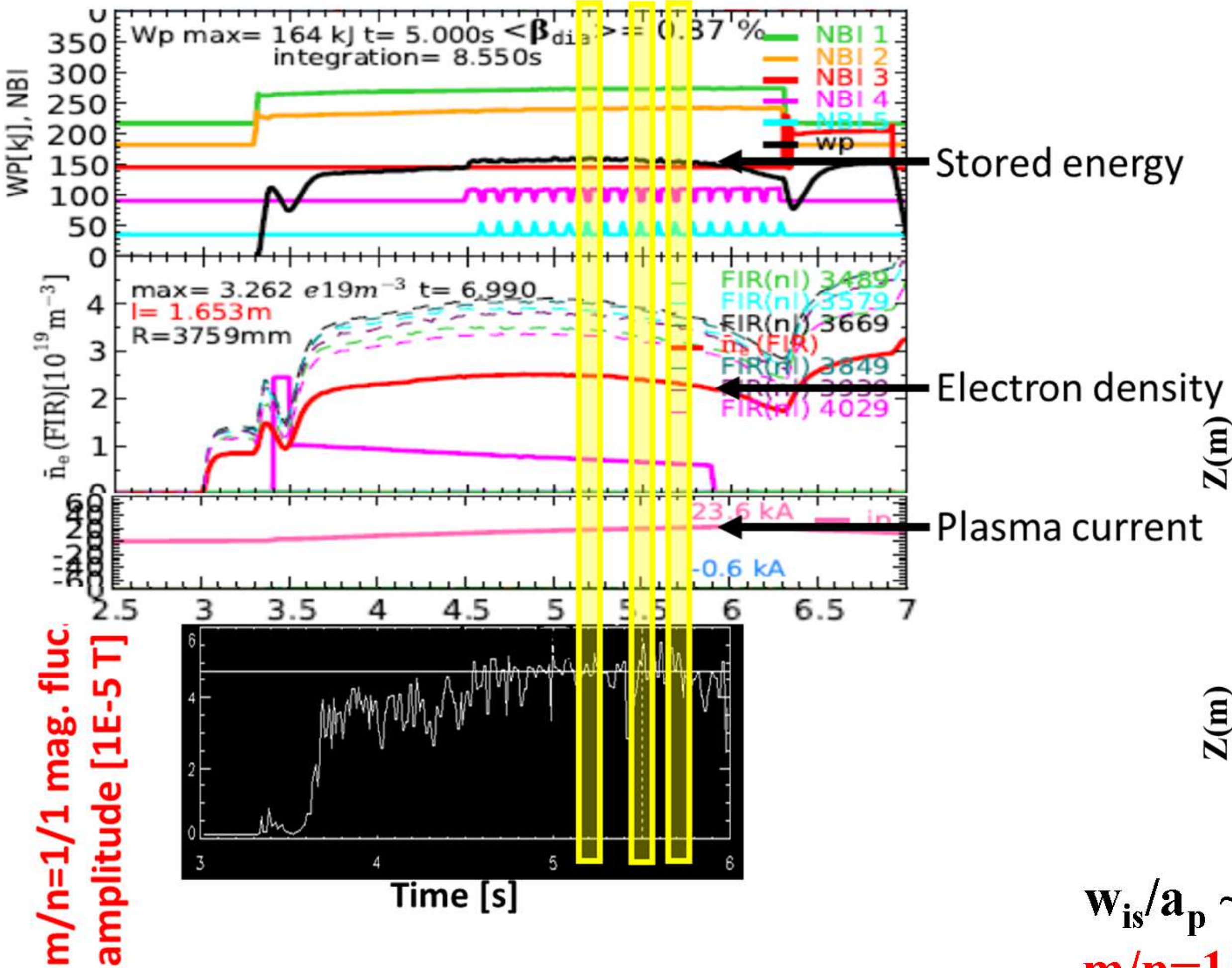
Major MHD instability ( **Interchange instability** )

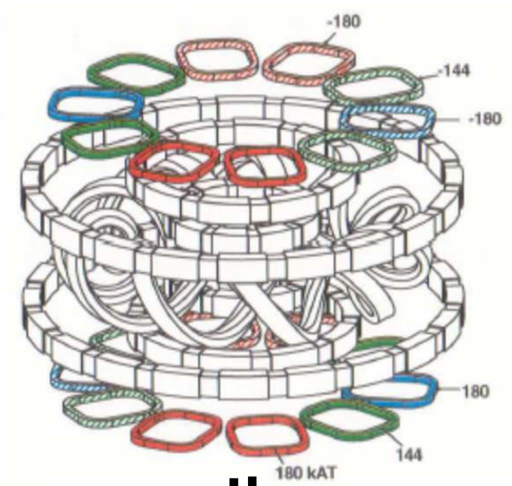
→ Degradation of plasma confinement performance (β-value)

develop the methods to avoid or suppress

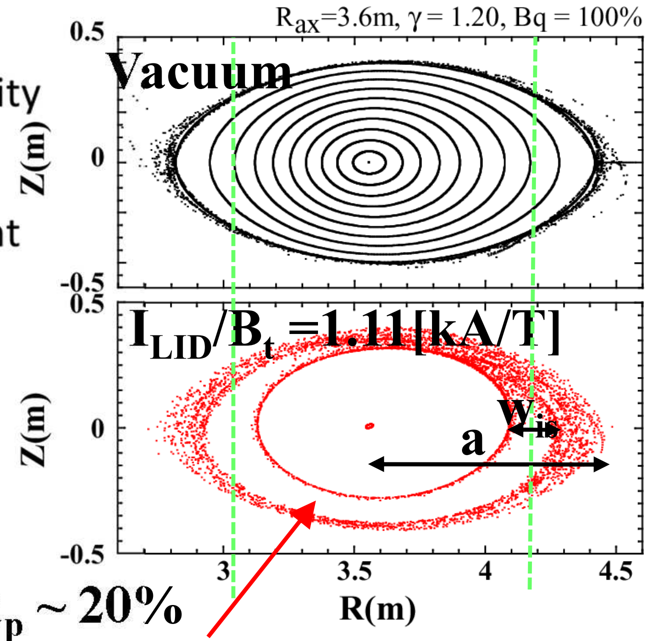
# Suppression of instability
## -- Experiment set-up --

**Typical waveform of discharges with interchange instability**




RMP coils




$w_{is}/a_p \sim 20\%$

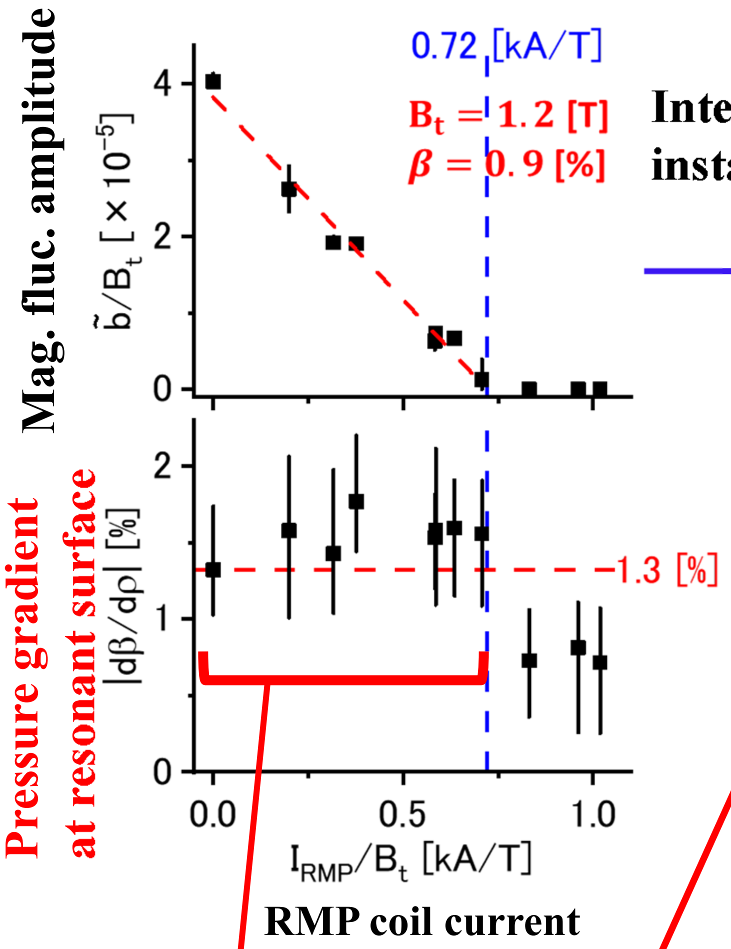
m/n=1/1 static island

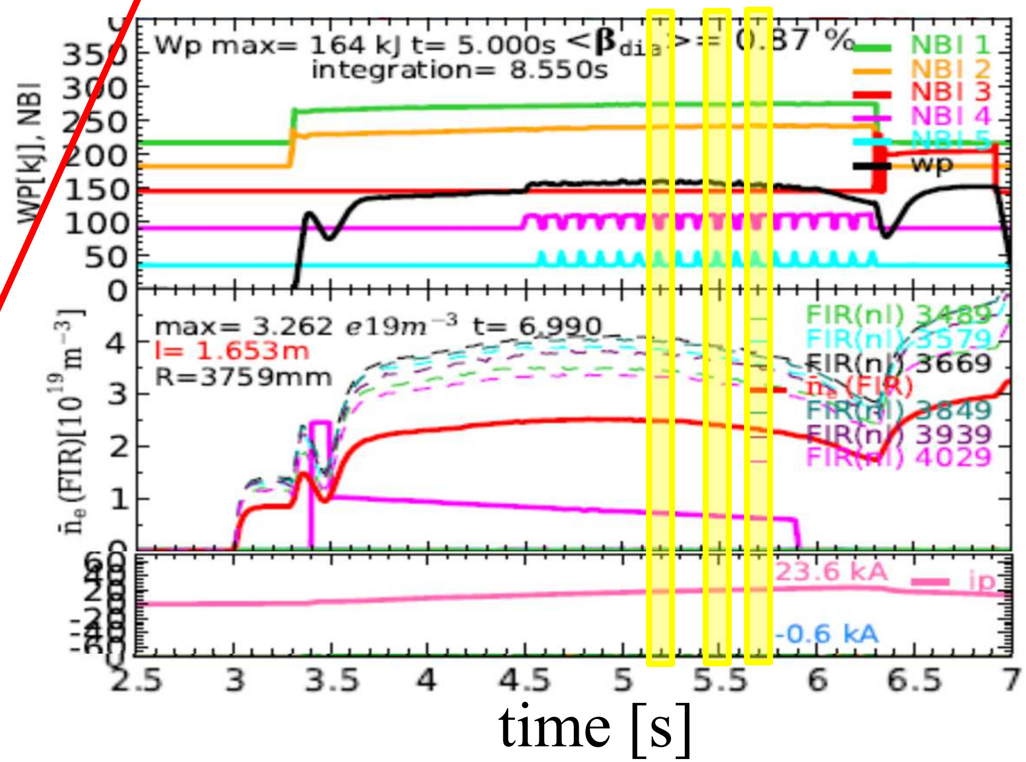
# Suppression of instability
## -- Response of interchange instability due to external RMP I --

Red : Destabilizing effects
Blue : Stabilizing effects

**Interchange instability** ←
- ① High pressure gradient
- ② Magnetic shear
- ③ Magnetic well・hill

← β-value, Plasma current



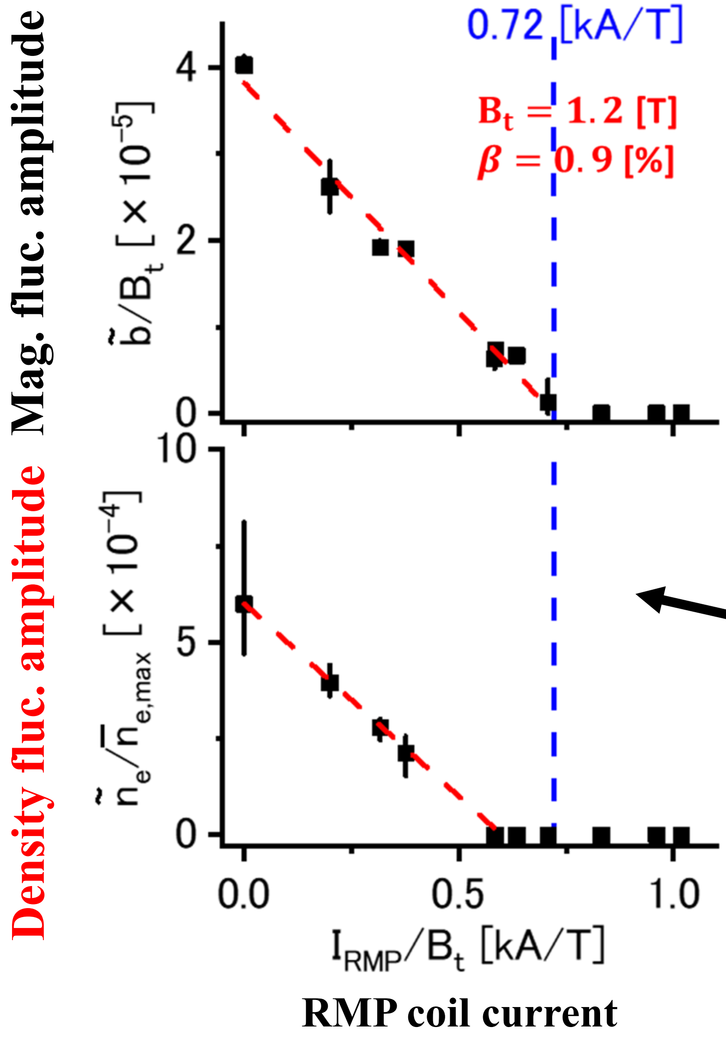

When external RMP increases,
**pressure gradient does not decrease** but
**magnetic fluctuation amplitude decreases.**

Conditions of ② and ③ are constant.

→ **We watch the change of ①**

# Suppression of instability

## -- Response of interchange instability due to external RMP II --




**Index how unstable is instability**

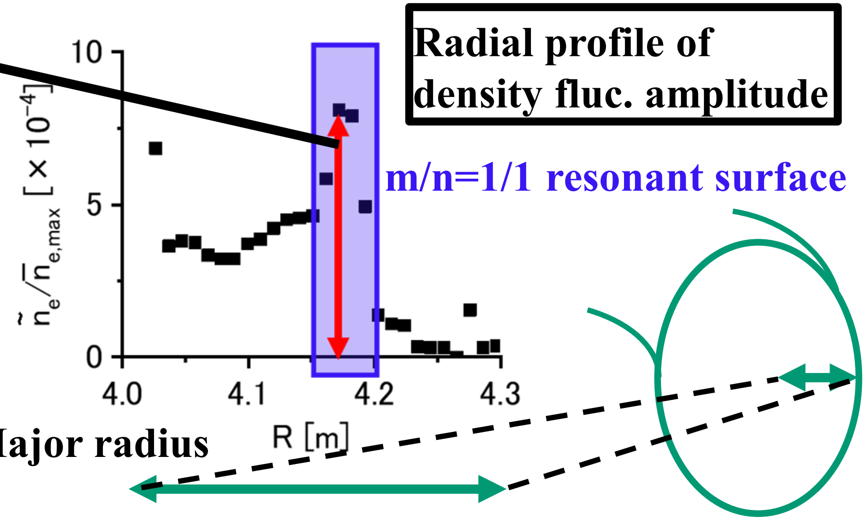
① Mag. fluc. amplitude ← outside plasma

\+

② Density fluc. amplitude ← inside plasma

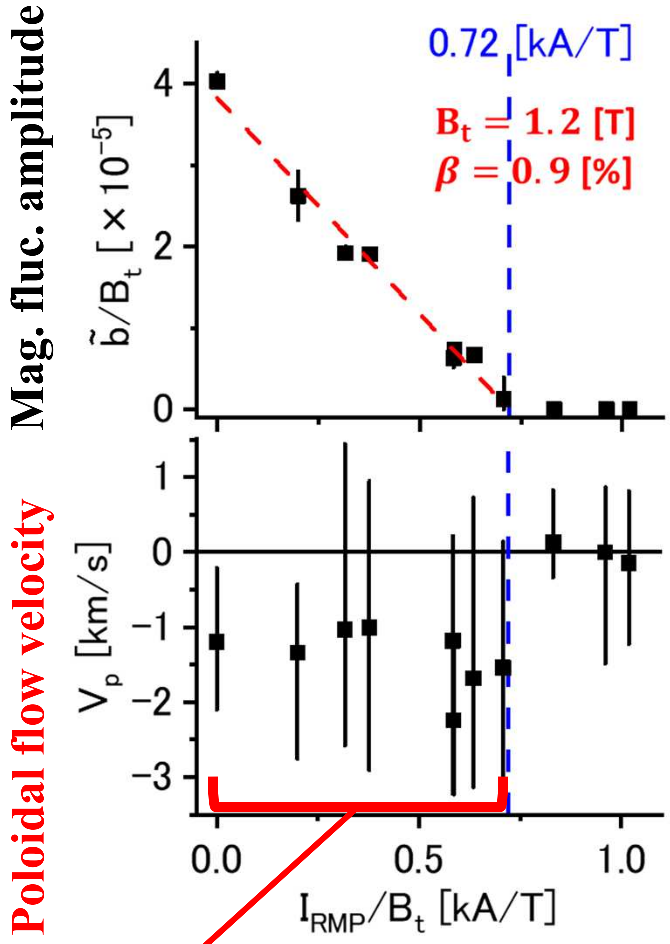
Density × Temperature = Pressure

- corresponds to amplitude of pressure fluctuation
- affects confinement performance




When external RMP increases,
both magnetic and density fluctuation amplitude decreases monotonically.

# Suppression of instability
## -- Response of poloidal flow velocity to external RMP --




**RMP coil current**

**Mechanism of interchange instability suppression by external RMP**

**① Effect of external RMP on plasma boundary**

There is only vacuum between RMP coils and plasma surface without vacuum chamber.

So, external RMP is sure to reach at plasma boundary.

Change of the boundary condition of RMP would suppress the interchange instability.

We need to verify this effect by numerical simulation. (future plans)

**② Effect of plasma flow**

**It is theoretically predicted that plasma flow affects MHD instabilities.**

**As external RMP increases, amplitude of poloidal flow velocity increases a little.**

**➡This is relative to instability suppression？**

[S.Ito et al. 2020 Annual meeting of Jpn. Soc. plasma and fusion]

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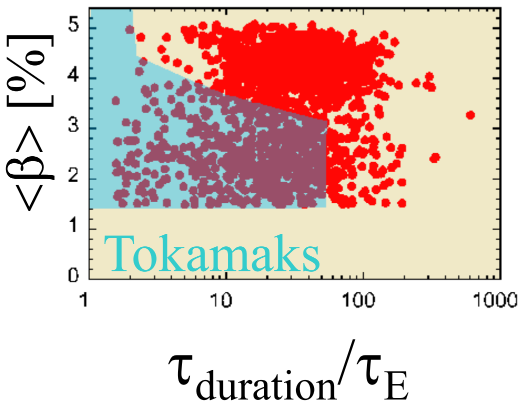
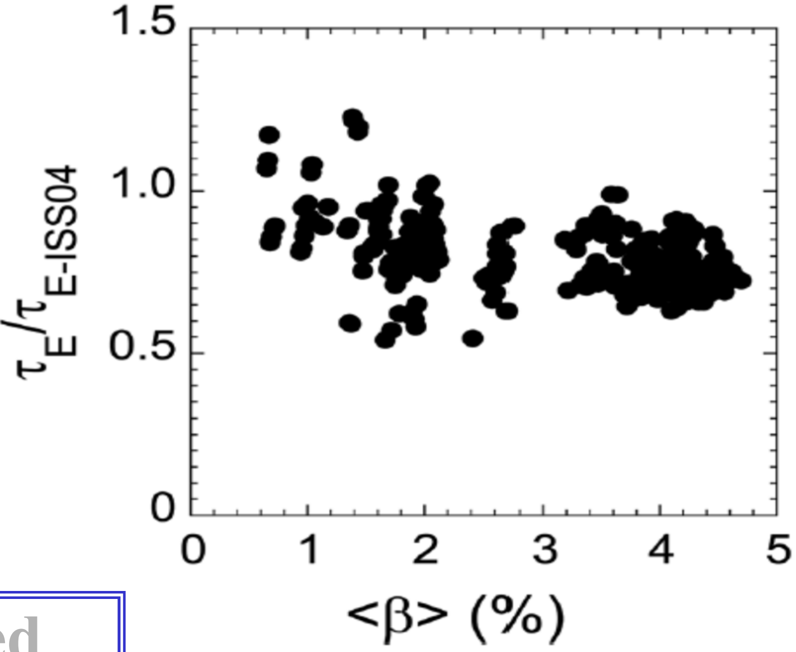
# Summary and the future subjects

# Effect of press. driven MHD turb. on confinement




**Normalized $\tau_E$ by ISS04 empirical scaling decreases with $\beta$.**



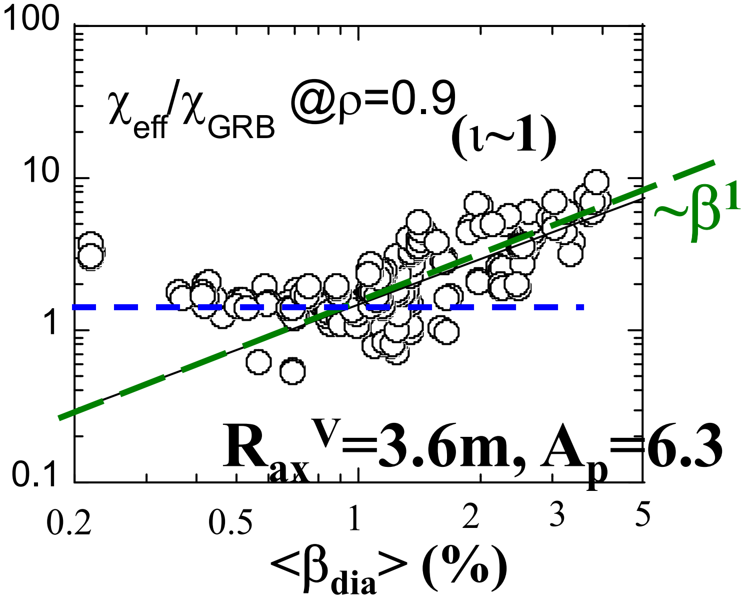

**# The high beta is maintained till the heating power stop.**

**# Performance of global energy conf. time degrades with beta.**

**Reason why?**

# Peripheral thermal transport in high $\beta$ regime

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




**Normalized thermal conductivity by GB (Gyro-reduced Bohm) model (Global property of GB is quite similar with ISS04)**

**$\chi/\chi^{GRB}$ in peripheral region increases with $\beta$ in more than 1%.**

**# $\chi$ dependence on $\beta$ is similar with a prediction based on MHD (resistive interchange mode) driven turbulence.**

$$\boxed{\chi_{GMTe} \propto \beta^1 \nu_{p*}{}^{0.67} \rho_*{}^{0.33} \chi_B}$$

**proposed by Carreras et al. (PoF B1 (1989))**

**# Resistive interchange (g-) mode is always unstable in the peripheral region of LHD finite beta.**

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

# Effect of g-mode on peripheral transport

Thermal conductivity based on g-mode (resistive interchange 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)

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

*Present Model*

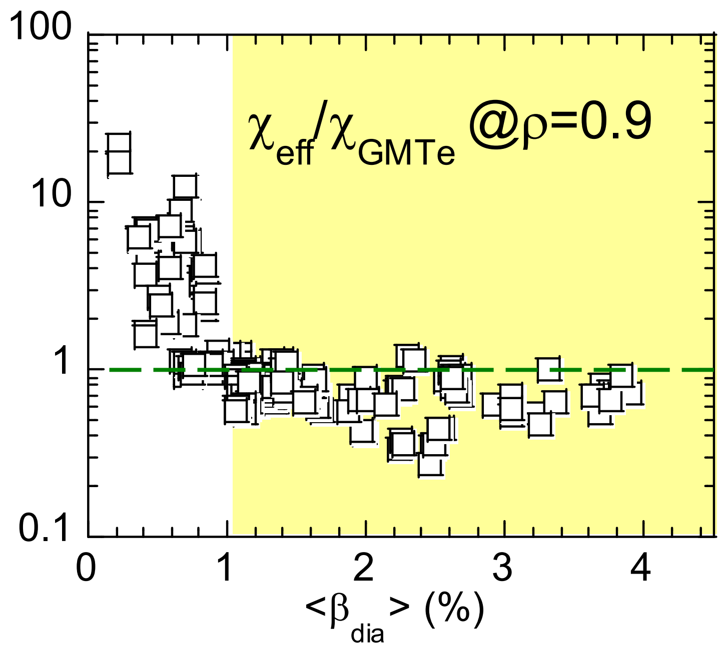
***Renormalization factor***

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

***Linear growth rate and mode width of g-mode***

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

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




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

**Depend. on geometric param.**

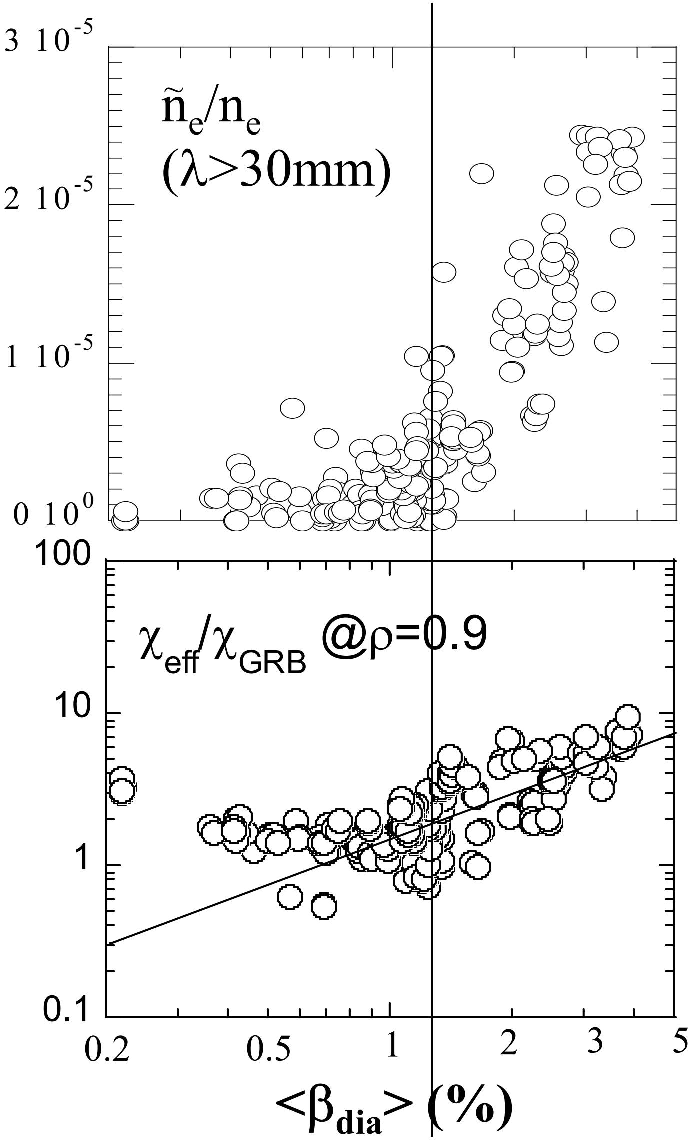
$$\chi \propto \boxed{\left(\frac{q}{\hat{s}}\right)^{\frac{7}{3}}\left(\kappa_n R_0\right)^{\frac{4}{3}}\frac{a_{eff}}{R_0}}\ \boxed{\left(\frac{\beta R_0}{L_p}\right)^{\frac{4}{3}} S^{-\frac{2}{3}}\, v_{Te} a_{eff}} \propto G_{GMTe}\,\beta^1 \nu_{p*}^{\ 0.67}\rho_*^{\ 0.33}\chi_{Bohm}$$

**Depend. on plasma param.**

[H. Funaba al., 2007 Fusion Sci. Tech.]

*Another collateral evidence*

# Density fluctuation amplitude with relatively long wavelength increases with β




**Beta dependence of the density fluctuation amplitude with relatively long wavelength, λ>~30mm(m[poloidal mode #]<100)**

**# Sight line passes the relatively peripheral region**

**# Inflection point of normalized thermal conductivity looks synchronized with that of the density fluctuation amplitude.**

[K.Y.Watanabe et al., 2011 PoP]

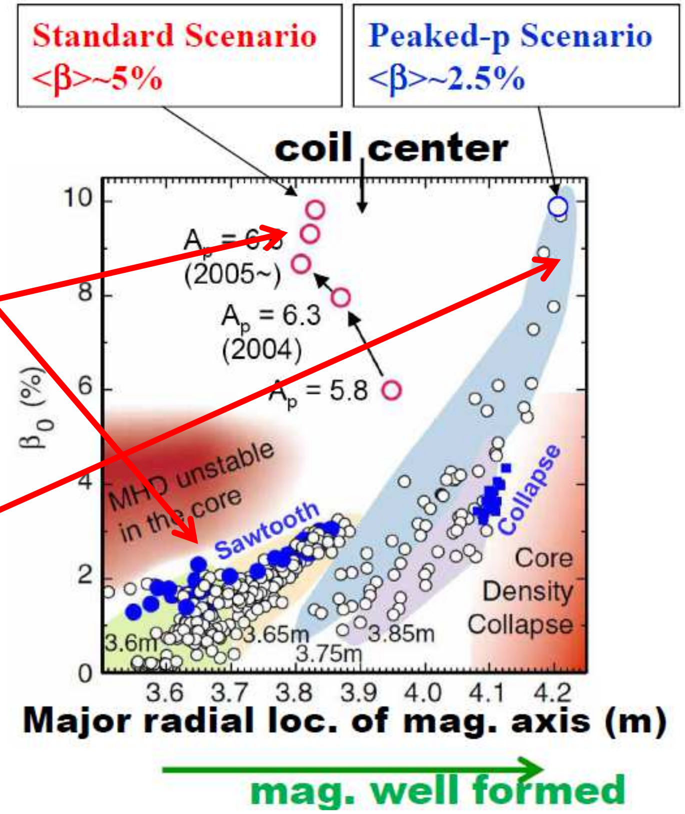
# Summary of MHD instabilities in the LHD

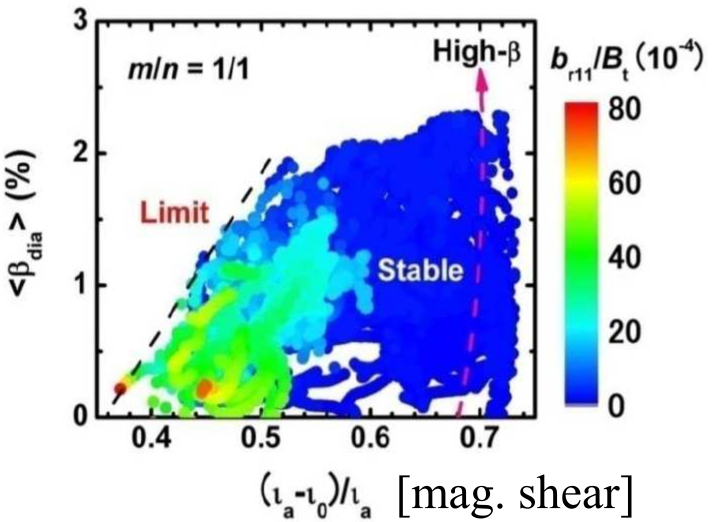
**1) In low beta and/or $R_{ax}$ torus-inward shifted plasma,**
**=> Interchange insta. in core**

**2) In high beta with standard pressure profile,**
**=> Interchange insta. in edge**

***2) 3) limit high-β operation.***

**3) In high beta with peaked pressure profile with large $R_{ax}$,**
**=> Ballooning type insta.**




**aspect-ratio/co-current decrease**

**4) In high-aspect and/or high co-current plasmas**
**=> Minor collapse and Locked-mode like phenomena**

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# Insta. in high beta with peaked pressure profile

## Achievements of high-n and high-p in *Internal Diffusion* Barrier (IDB) plasmas

\# Super high density with peaked prof. is obtained just after the multi-pellet injection.

Maximum $n_e(0)$ exceeds $1 \times 10^{21}$ $m^{-3}$

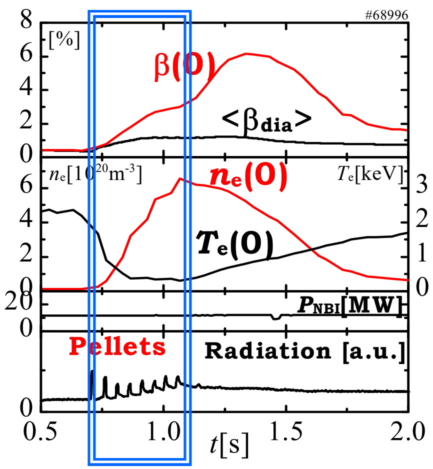
\# High central pressure is obtained during the density decay phase.

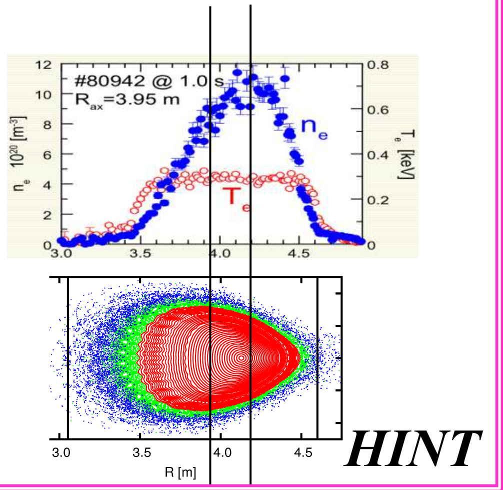
Maximum P(0) ~150 kPa

Large Shafranov shift;

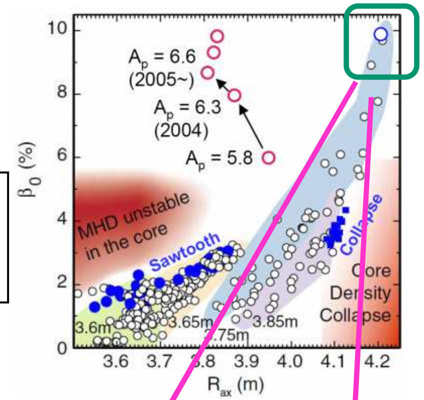
reaches to half the radius

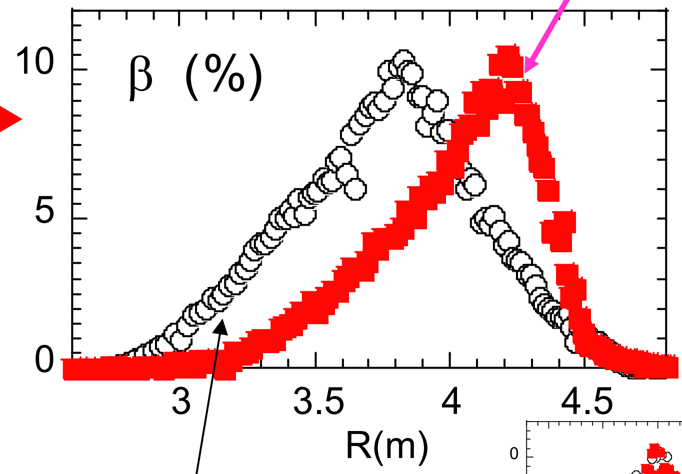
predicts large stochastic region.



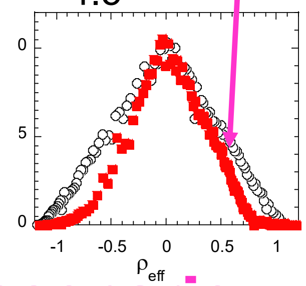




**Peaked-p Scenario**
**<β>~2.5%**



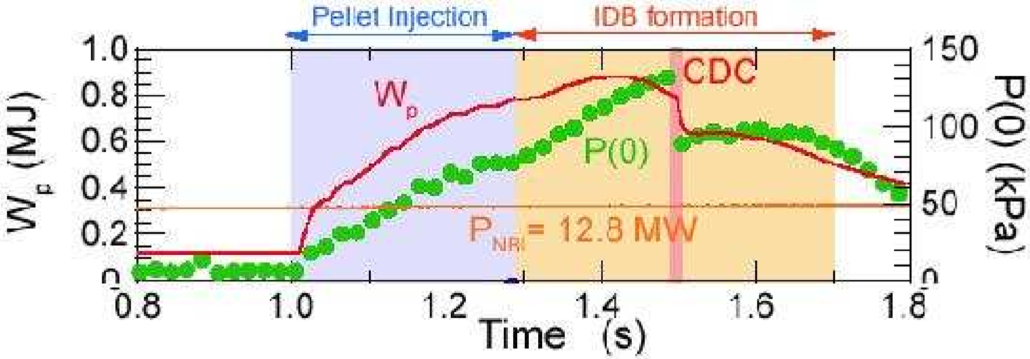




**Standard Scenario**
**<β>~5%**




**Peaked pressure scenario;**
**Large Shafranov shift**
**and high central beta value.**

# Insta. in high beta with peaked  pressure profile II



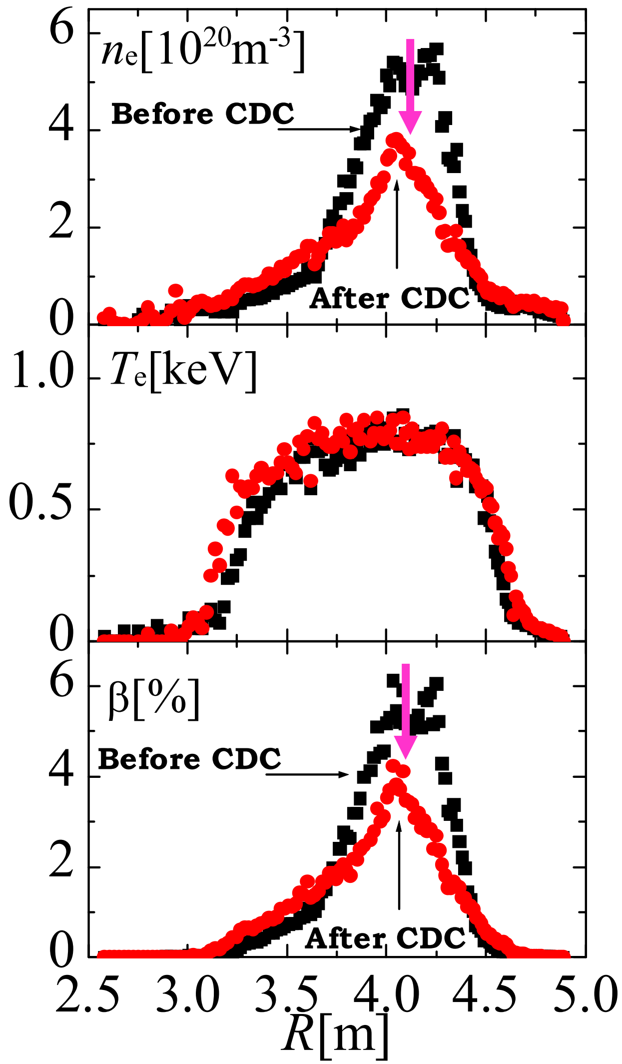

# Core density and the pressure abruptly decrease during the high central pressure phase within 1ms.

**Core Density Collapse (CDC)**

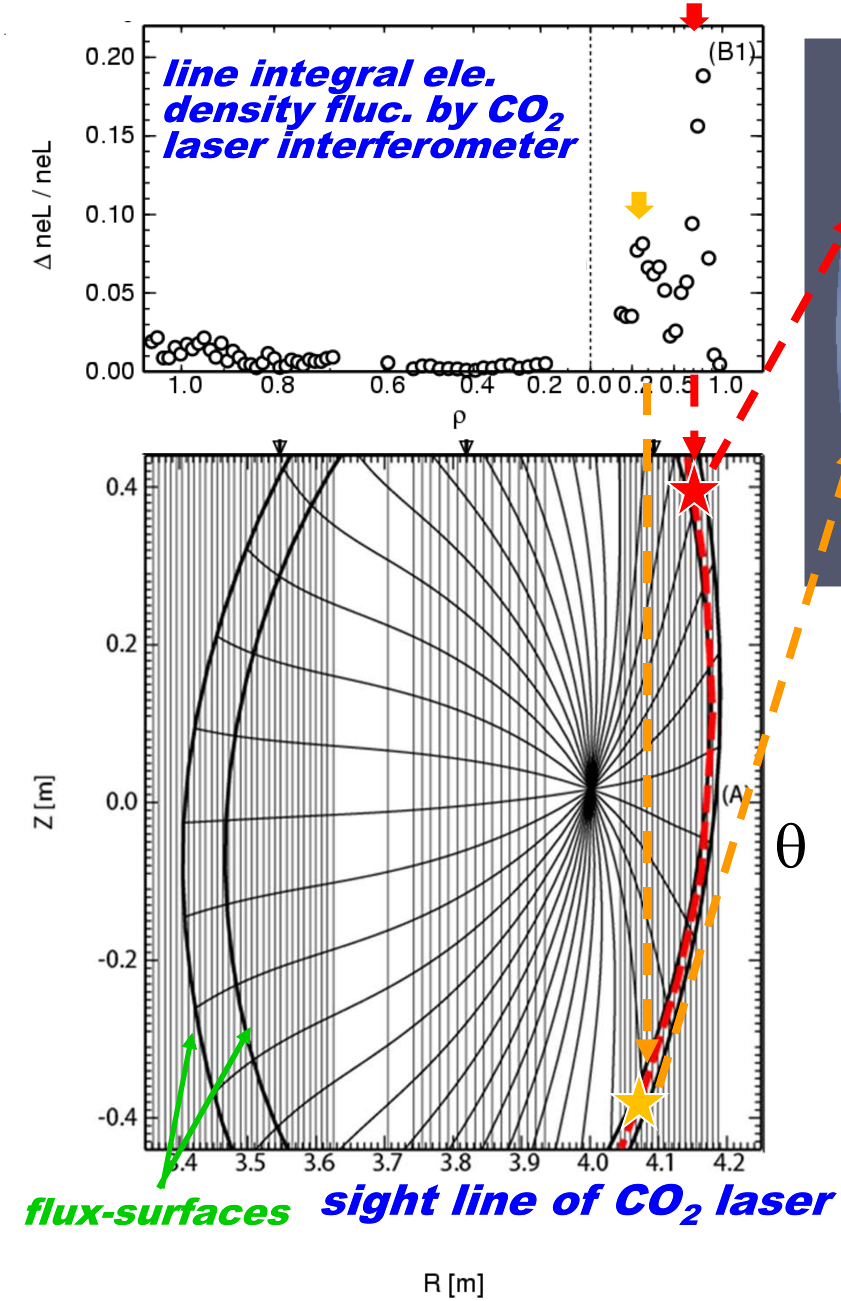
***Core density is expelled => Limitation of central pressure***

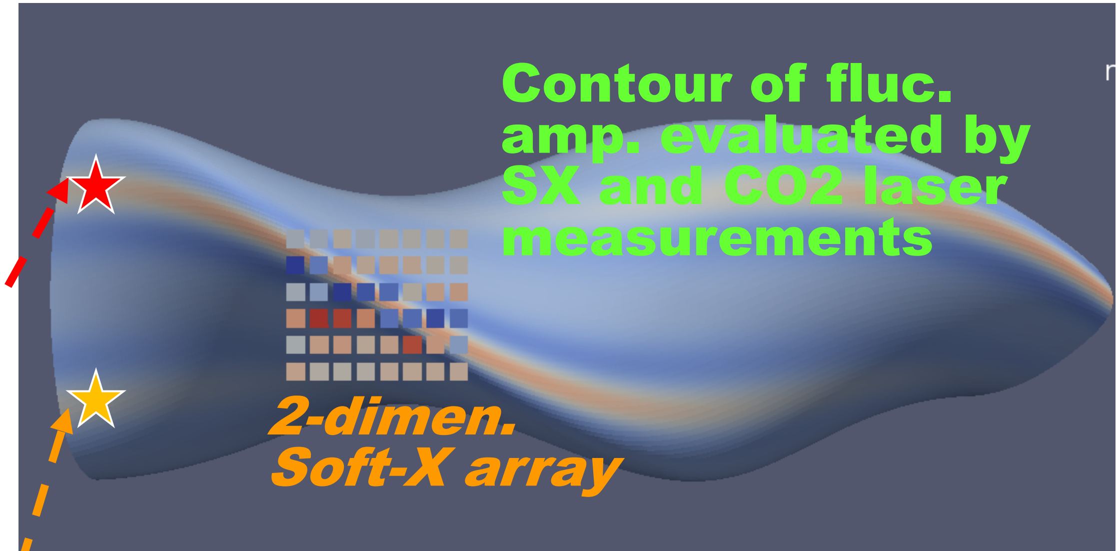
# Sometimes MHD events are observed around CDC.

**What is driving mechanism?**



# Pre-cursor observation / Mode structure




**2-dimen. Soft-X ray profile**
=> fluc. is localized along the mag. field lines which go through the torus-outboard equator in the horizontally elongated cross-section

**Line integral density fluc. by $CO_2$ laser**
=> fluc. is localized around bad curvature region (in torus-outboard) and is also in a minor radius location ρ=0.85~0.95.

**# Mode structure is evaluated as shown in the above color contour**

**# Region with large fluc. amp. coincides to the bad curvature region**

**=> Fluctuation driving the collapse is identified as ballooning instability**

[S. Ohdachi et al., NF 2017]

# Unstable condition for ballooning instability

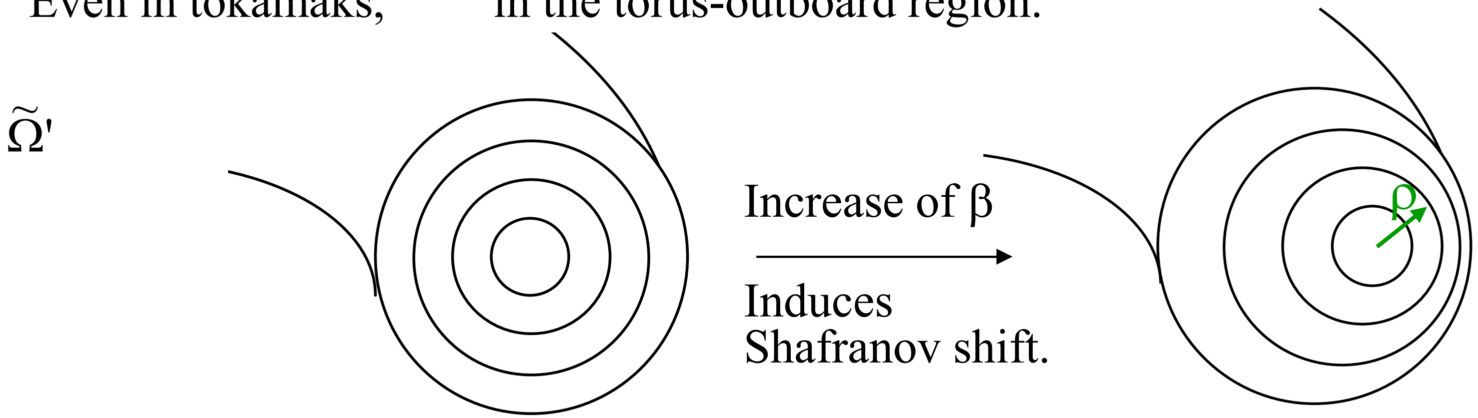
In principle, the unstable condition is similar with the interchange insta. Difference is that the condition should be considered locally around the bad curvature region.

***Suydum criterion***

$$-\frac{\beta'\Omega'}{(\varepsilon\rho\iota')^2} > \frac{1}{4} \quad \left( \;' = \frac{d}{d\rho} \right) \Rightarrow \quad -\frac{\beta'\tilde{\Omega}'}{(\varepsilon\iota)^2} > \frac{1}{4}\tilde{s}^2 \quad \left( \tilde{s} \equiv \frac{\rho}{q}\tilde{q}' = -\frac{\rho}{\iota}\tilde{\iota}' \right)$$

Here, ~ corresponds to the value at the bad curvature region.

Even in tokamaks, in the torus-outboard region.




Shafranov shift induces the compression of the magnetic field lines in the bad curvature region (the torus out-board region).

=> Increase of poloidal magnetic field, $B_p$, in the bad curvature region.

=> As the magnetic field lines are denser, the increment of is larger. (Distance between magnetic surfaces is shorter as the more peripheral region.)

=> $d\Delta B_p/d\rho > 0$.

# Unstable condition for ballooning instability II

Change of magnetic shear in the bad curvature region due to Shafranov shift is shown as the following;

$$\tilde{s} \equiv \frac{r}{q} q' + (\Delta q)' \qquad (\Delta q)' = \frac{d}{dr}\left(\frac{r}{\Delta B_p}\frac{B_t}{R}\right) \sim \frac{rB_t}{R}\frac{d}{dr}\left(\frac{1}{\Delta B_p}\right) < 0$$

**Global shear(mag. surface averaged)**

Here, $-\alpha \equiv (\Delta q)'$ => $\tilde{s} \equiv s - \alpha$

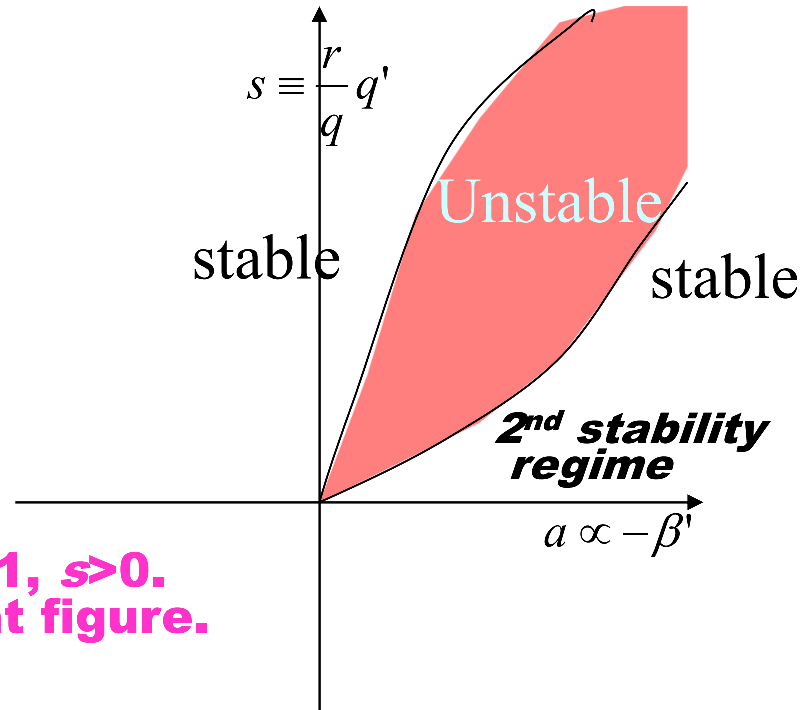
**Local shear**

From $-q^2 \beta' \tilde{\Omega}' > \frac{1}{4}\tilde{s}^2$ ,

$$(s-\alpha)^2 < k\alpha \Rightarrow s^2 - 2\alpha s + \alpha^2 - k\alpha < 0$$

$$\Rightarrow \alpha - \sqrt{k\alpha} < s < \alpha + \sqrt{k\alpha}$$

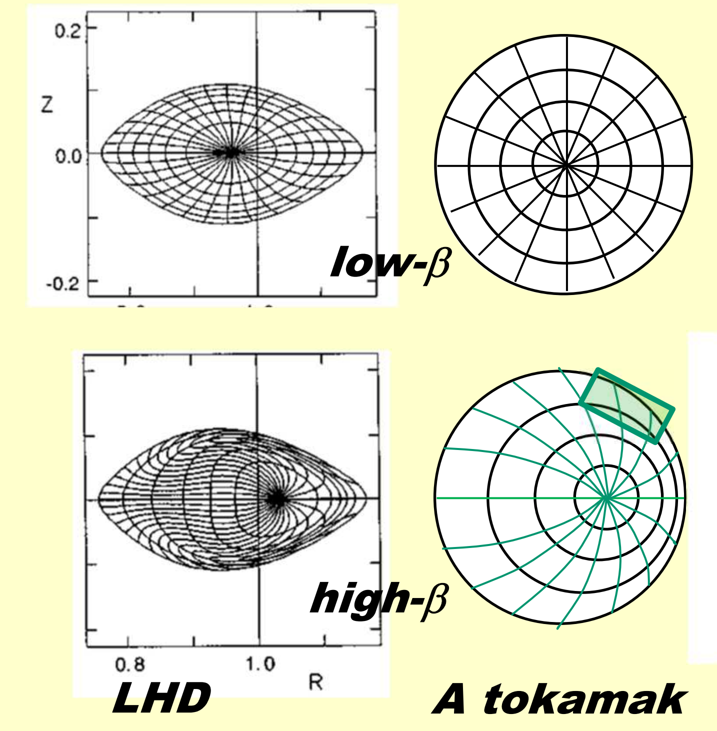
where $-\beta' \equiv a$, because a increases as the increment of $-\beta'$.




**In the conventional tokamaks, 0<*k*<1, *s*>0.**
**Unstable region is shown in the right figure.**

***Rough estimation of Unstable condition of ballooning insta.***

# Characteristics of ballooning instability in LHD

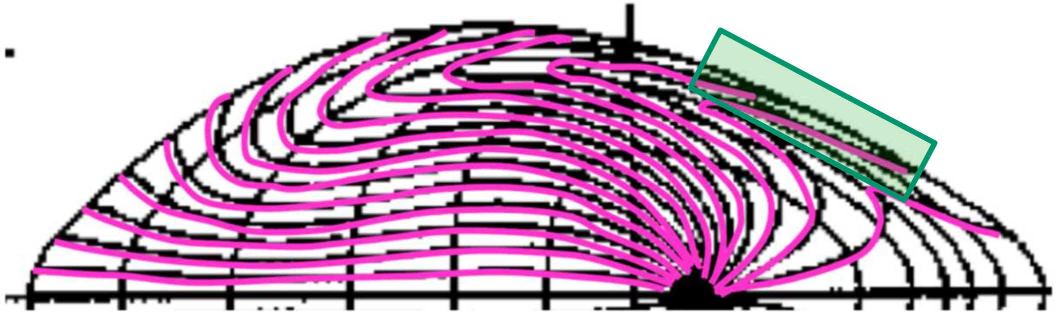



*Local mag. shear in tokamaks*

$$\tilde{s} \approx s - \alpha$$

$$s = \frac{r}{q}\frac{\mathrm{d}q}{\mathrm{d}r}, \quad q = \frac{1}{\iota}, \quad \bar{\alpha} \equiv -\Delta' > 0$$

**With the increment of β, The sign of magnetic shear changes, and the absolute value increases.**



*Local mag. shear in LHD (heliotron plasmas)*

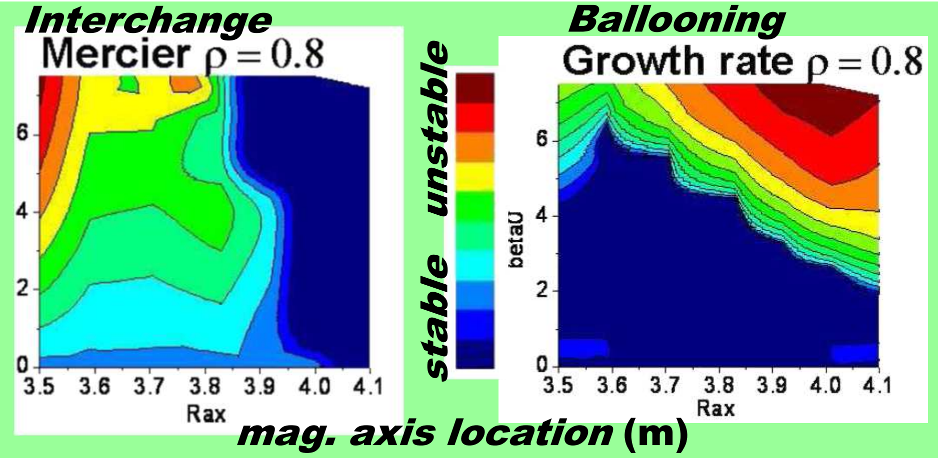
$$\tilde{s} \approx s - \alpha\left(\underbrace{\frac{1}{4} + \frac{3}{4}s}_{>0} + \underbrace{\frac{\rho\beta''}{\beta'}}_{>0 \text{ or } <0}\right)$$

**>0 or <0**

**When <0, even if β increases, absolute value of the local shear does not increase.**
**=> Unstable**

Especially, region shown by [green box] of the above fig. corresponds to ()<0 region.
These region appears in torus outward config and peripheral region because Bp by helical coil is much larger than $\Delta B_p$ by Shafranov shift.

**Rax dependence of instability**




[J. Varela et al., Plasma Fusion Res. 2011].

[N.Nakajima, PoP. 1996].

# Outline of talks

\# Overview of LHD

\# On the MHD and transport characteristics of LHD

\# Characteristics of high beta discharges of LHD

\# Effect of the MHD instabilities on the confinement in LHD
--- How does the MHD instabilities affect the LHD?
--- Comparison between exp. Results and a theoretical prediction
--- On a suppression method of the MHD instability
--- Effect of the MHD instabilities on the transport

\# Other topics related with the MHD instabilities in LHD
--- A collapse phenomena in the super dense discharges
--- Slowing-down of the frequency of the modes before collapse phenomena

\# Summary and the future subjects

# Effort of extension of operation range in high β

## Previous achievement of high-$\beta$ operation

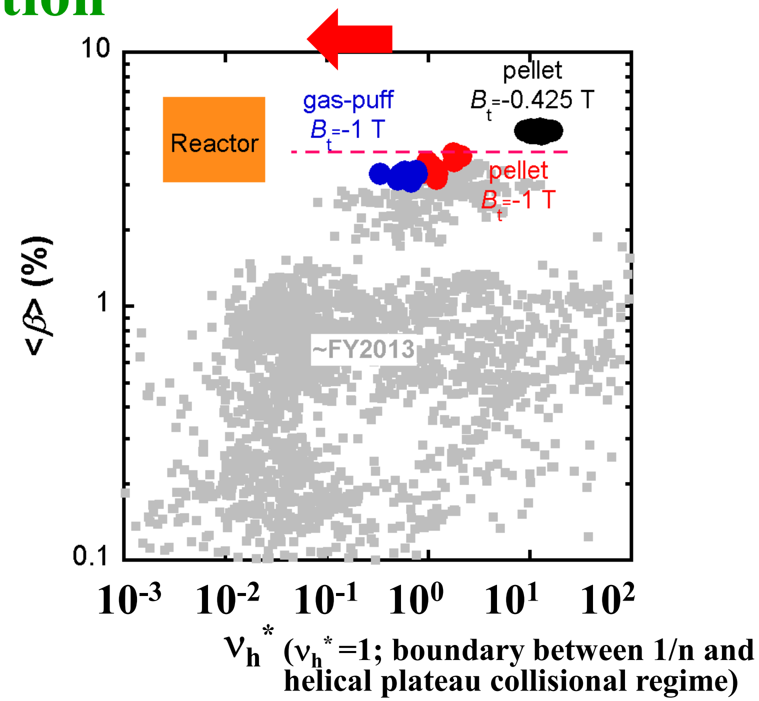
- 5.1 % at $\nu^*$ ~ 1000 (S ~ $3.9 \times 10^6$)

**0.43T**

## Extension to high-$\beta$ operation with low $\nu^*$ (high-$S$) regime

- 4.1 % at $\nu^*$ ~ 100 (S ~ $1.3 \times 10^7$)
- 3.4 % at $\nu^*$ ~ 20 (S ~ $1.6 \times 10^7$)

**1.0T**




**Subjects to be clarified:**

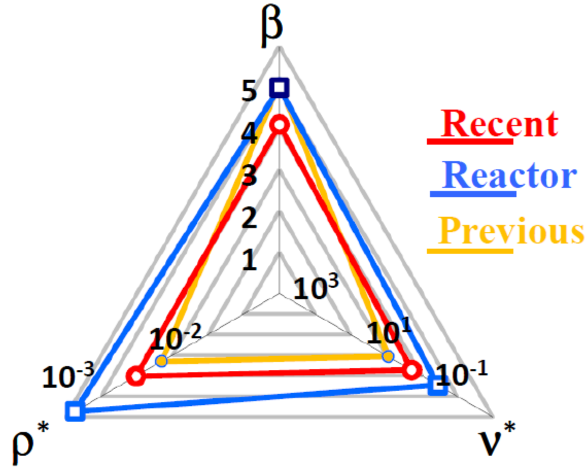
- **high-S**

=> reduction of growth rate of interchange mode and suppression of resistive-g turbulence

=> recovery of plasma confinement

- **Low-ν***

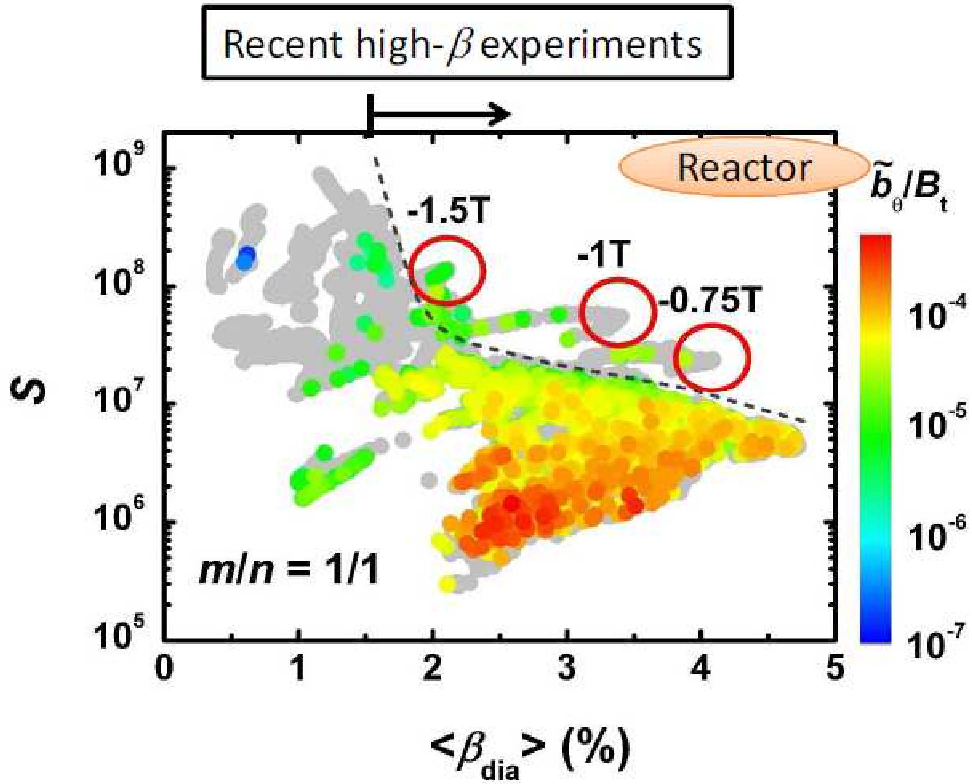
=> Change of transport and magnetic topology



# Suppression of interchange mode due to increase of *S*

Amplitudes of observed modes decrease with the increase in magnetic Reynolds number, *S*, which is consistent with previous results.

Stabilization in reactor-plasma is expected if ideal mode is stable

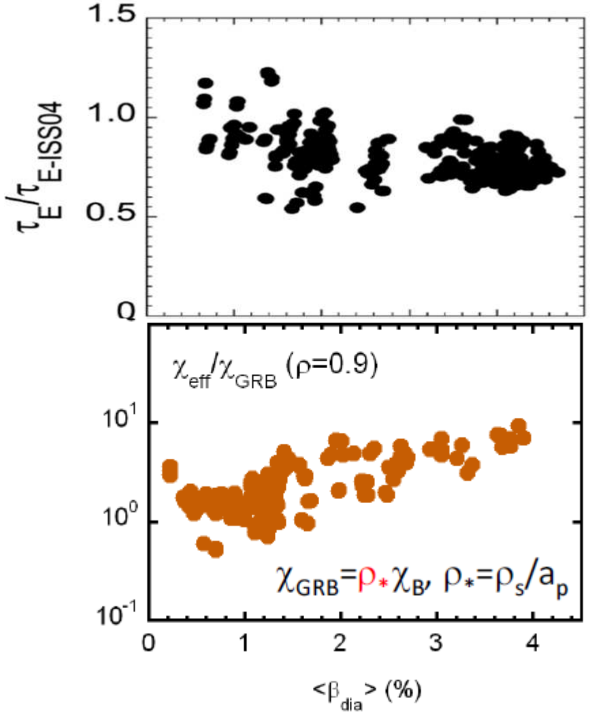



$$S = \tau_R/\tau_A \propto B_t T_e^{3/2}/n_e^{1/2}$$

# Is turbulence thermal transport reduced in high-S ?

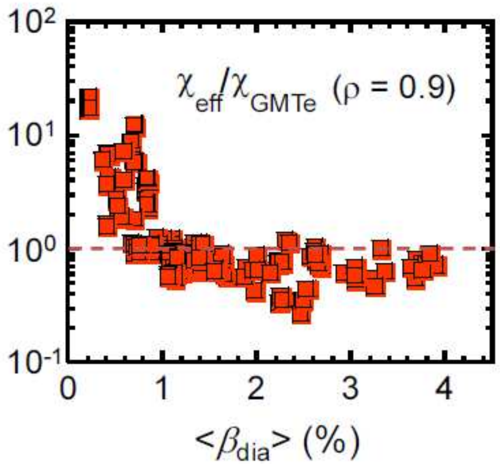
The energy confinement property normalized by ISS04 emp. scaling degrades with the increment of β.

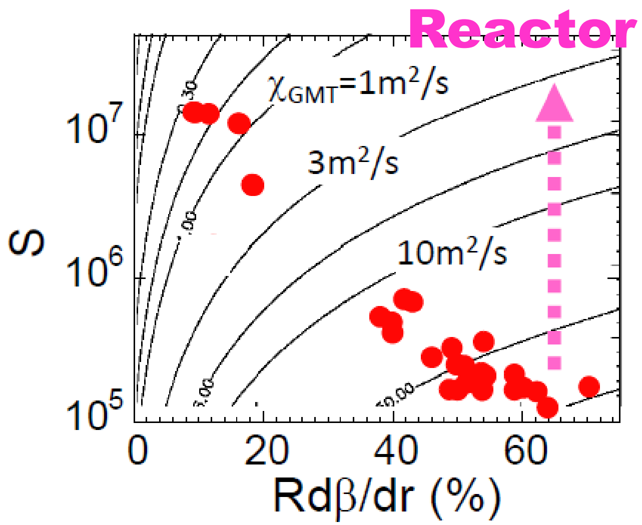
The most probable candidate of the cause is g-mode (resistive interchange instability) driven turbulence, which is predicted to improve confinement in high-S.




$$\chi_{GMTe} \propto \underbrace{\frac{q}{\hat{s}}(\kappa_n R_0)^{\frac{4}{3}}\frac{a_{eff}}{R_0}}_{\text{geometry}} \underbrace{\left(\frac{\beta R_0}{L_p}\right)^{\frac{4}{3}} S^{-\frac{2}{3}} v_{T_e} a_{eff}}_{\text{plasma}}$$

Carreras B A *et al* 1989 *Phys.Fluids* B1, 101




**Important issue is the conformation of the S dependence of g-mode turbulence, which expects the suppression due to the increment of S.**

***Accuracy of the extrapolation of the S dependence in reactor relevant plasma parameters??***

# Summary

# The LHD has achieved the volume averaged beta 5%, without any major collapse phenomena and apparent degradation of confinement, with finite fluctuation. The typically observed mag. fluctuation is identified as the resistive interchange instability.

# By comparative analysis between the achieved pressure gradients and a linear MHD stability analysis, the quasi-stationary pressure gradients seems to avoid a low-n ideal interchange unstable condition.

# By comparative analysis between the qusi-stationary maintained discharges and the discharges with collapse, an index when the collapse happen is found, Mercier parameter is larger than 0.3. However, even if the above index is temporary satisfied, the collapse does not occurs immediately.
# The comparison between the non-linear MHD simulation and the achieved high-beta plasma in the LHD suggests that the stabilization effects by the helically trapped ions the maintenance of the high beta discharges in the LHD.

# In order to suppress the MHD instability, we apply an external resonant magnetic perturbation (RMP). As the amplitude of mag. Fluctuation decreases with the increment of RMP. The mechanism od the stabilization is under investigation.

# Summary II

# Effects of the MHD instabilities on the thermal transport is investigated. As the beta increases, a degradation is observed. It is shown that the cause of the degradation is due to the resistive interchange instability driven turbulence.

# The driving mechanism of the collapse even in the high-density operation (CDC; core density collapse) is investigated. From the observation of the mode structure of the precursor leading to the collapse, It is shown that the ballooning instability would induce the collapse event.

# Finally, the future subjects on the MHD and the high-beta discharges are shown.  On the stabilization of the instability and the reduction of the transport, the conformation of the S dependence is important in the high-mag. Reynold number relevant to a reactor.