High Beta Issues in a Helical System

- with emphasis on achievement and prospect of LHD experiments

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NINS
National Institutes of Natural Sciences

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High beta is a critical mission as well as a challenging physical issue

Fusion gain

$$P_{fusion} / P_{loss} \propto nT\tau_E \propto \beta B^2 \tau_E \propto \beta^2 B^4 V$$

High beta ➔ *Compact & Efficient* reactor

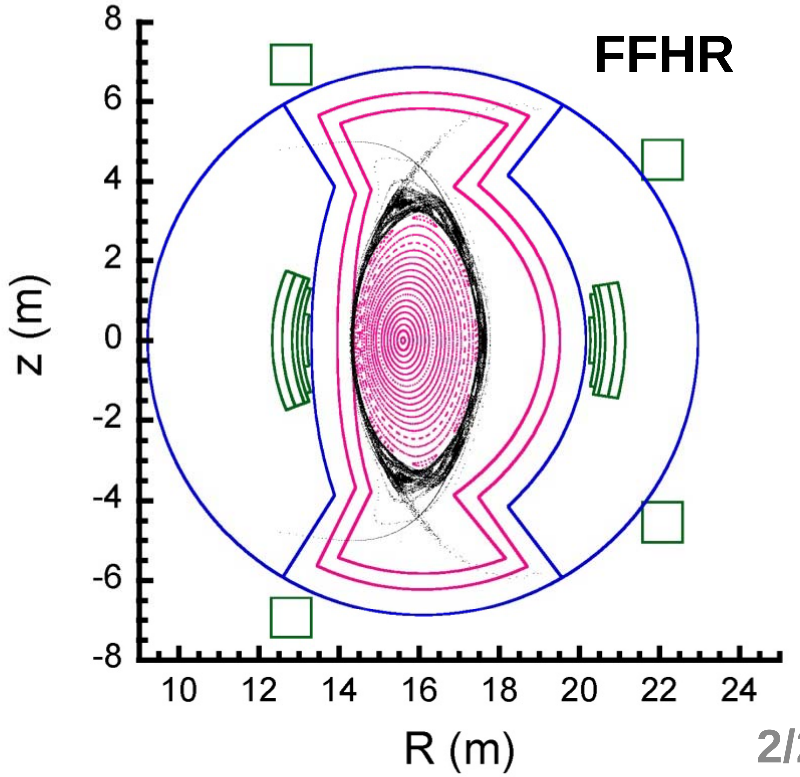
🡐 Restriction by heat and neutron loads

"High beta" is a vital issue in helical system

Reason

Critical issue in a helical reactor:
to secure sufficient space
for blanket and shield **> 1 m**

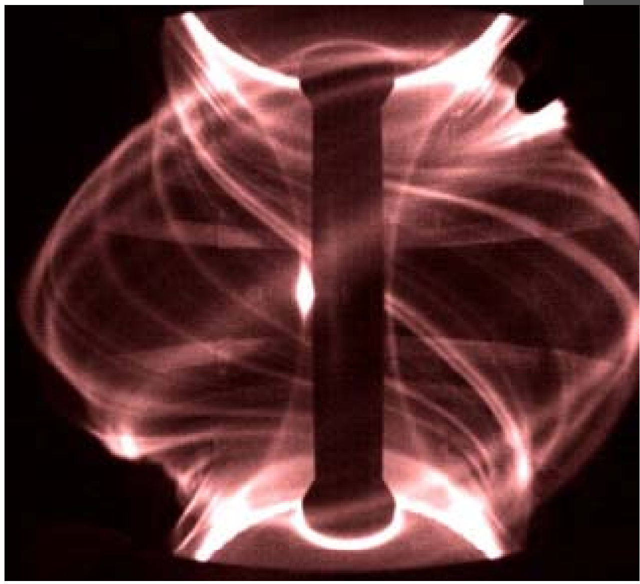
Solution 1 : Large machine
Solution 2 : **Thin magnet**
➔ **Low B** ➔ **High beta**

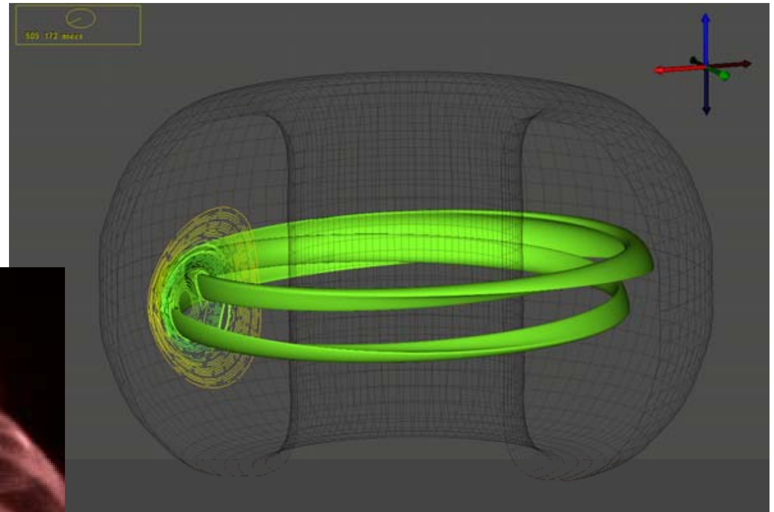


High beta is a critical mission as well as a challenging physical issue

MHD instabilities to limit beta in tokamak are inevitably 3-D
⇔ share commonalty in methodology

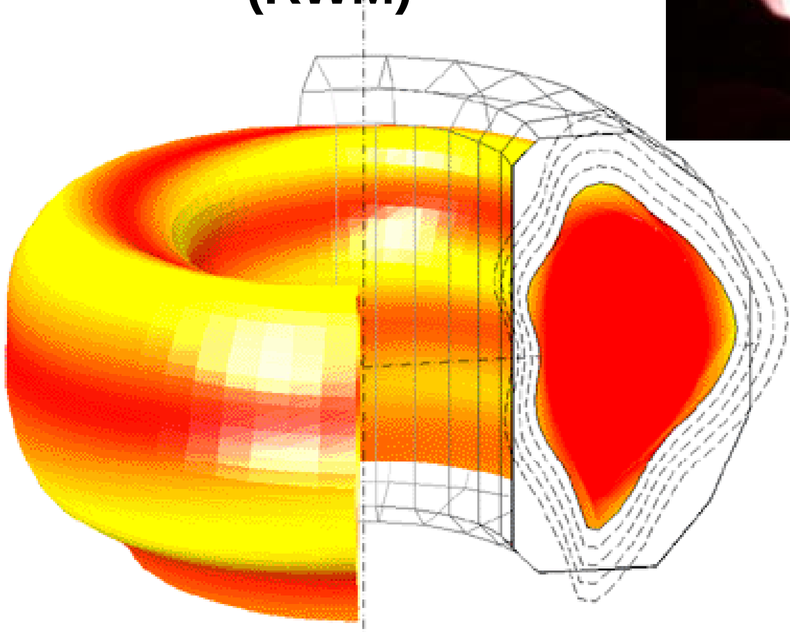
Edge Localized Mode (ELM)





Neoclassical Tearing Mode (NTM)

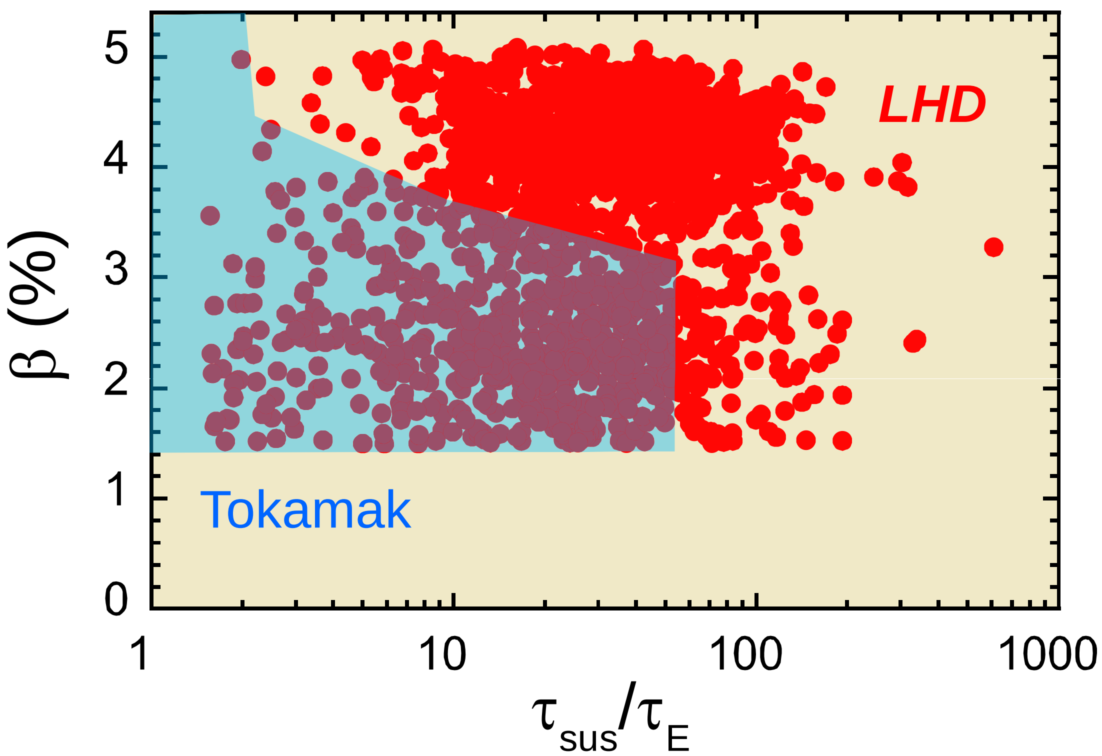
Resistive wall mode (RWM)



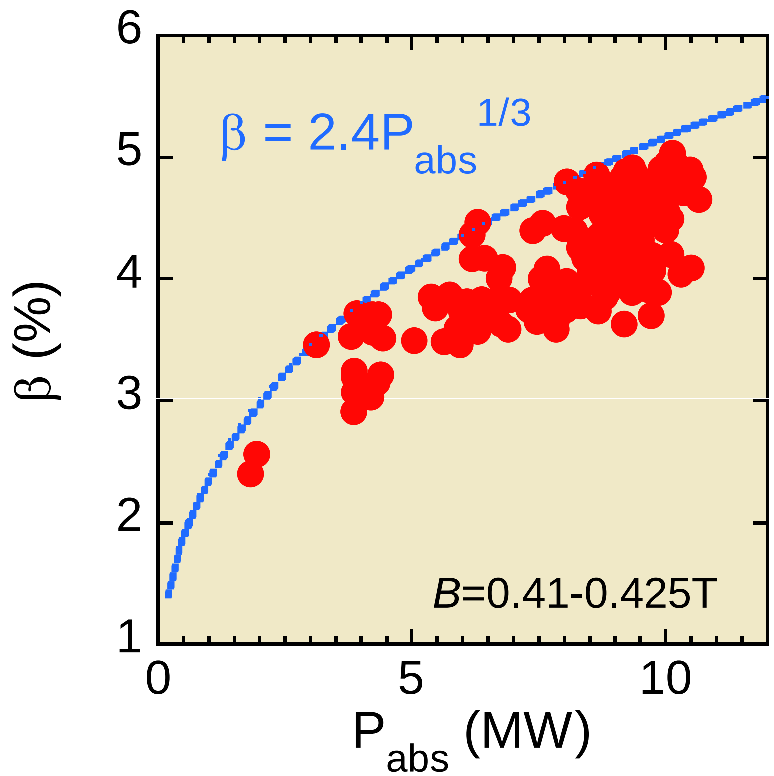
However, characteristics and effect of MHD instability are different between tokamak and helical system
← **Bias (help) by vacuum confining magnetic field is essential**
← Commonalty in physics is very challenging

Development of β in LHD experiment is very encouraging

5 % of β has been achieved without any disastrous instabilities while MHD activity is certainly seen as the theory predicts.



High β ranging 5 % is maintained in steady state for longer than 100 × τ_E



Achievable β is limited by the available heating power without a hard β-limit.

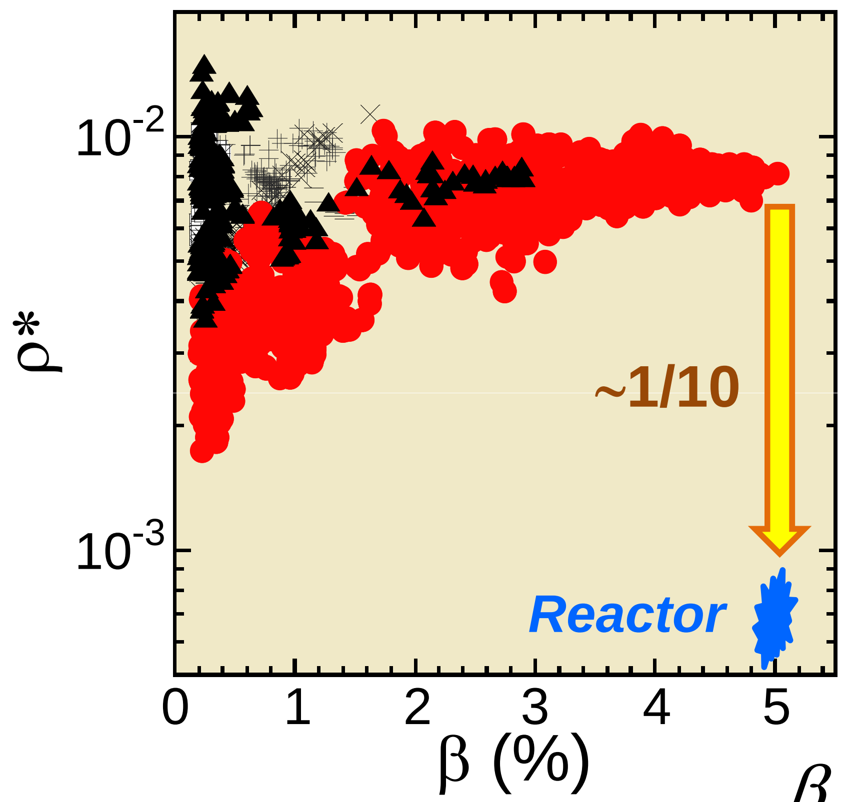
Outline

1. **Introduction**
2. **Gaps in non-dimensional parameters**
3. **Characteristics of growth of MHD instabilities**
   - ✓ Usually benign but violent under specific condition
4. **Enhancement of stochastic field and its effect**
   - ✓ 3-D effect
5. **Effect of resonant magnetic perturbation**
   - ✓ Ideal mode violated by reduction of magnetic shear
   - ✓ Resistive interchange mode
6. **Transport associated with high-β equilibrium and resistive interchange mode**
7. **Summary**

Establishment of integrated physics model is required to bridge over the gap

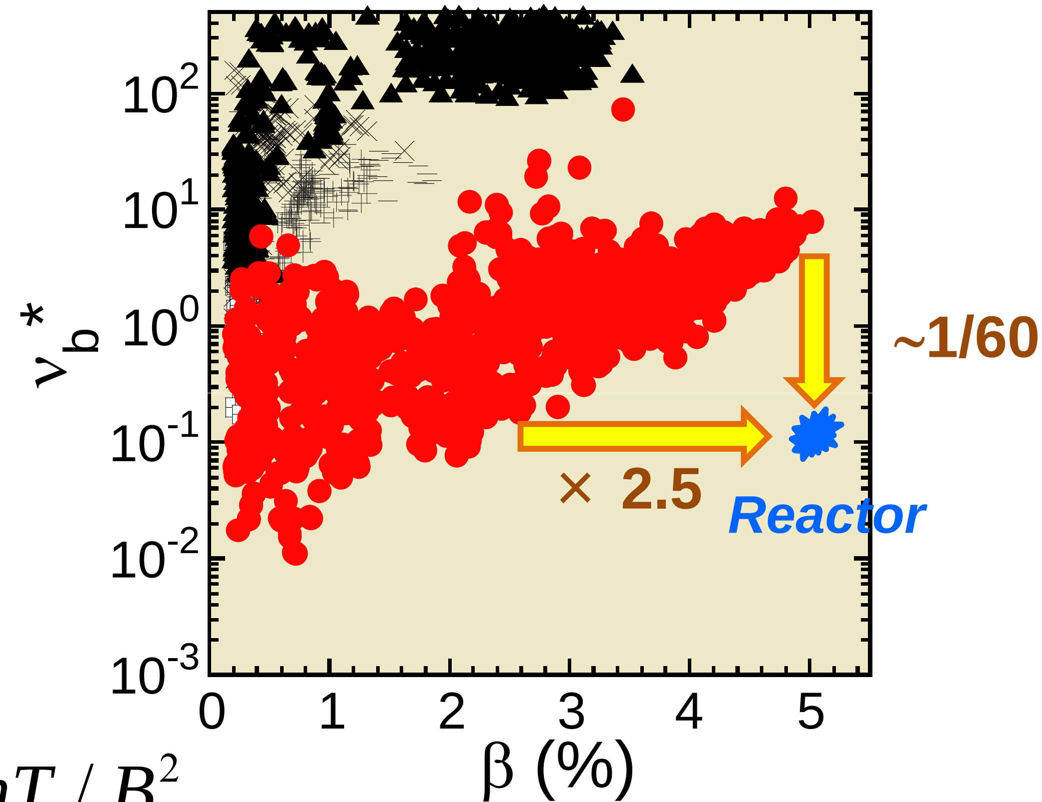
Normalized gyro radius

$$\rho^* \propto T^{1/2} / aB$$



Collisionality

$$\nu_b^* \propto n / T^2$$



$$\beta \propto nT / B^2$$

Gyro-Bohm nature in confinement is preferable

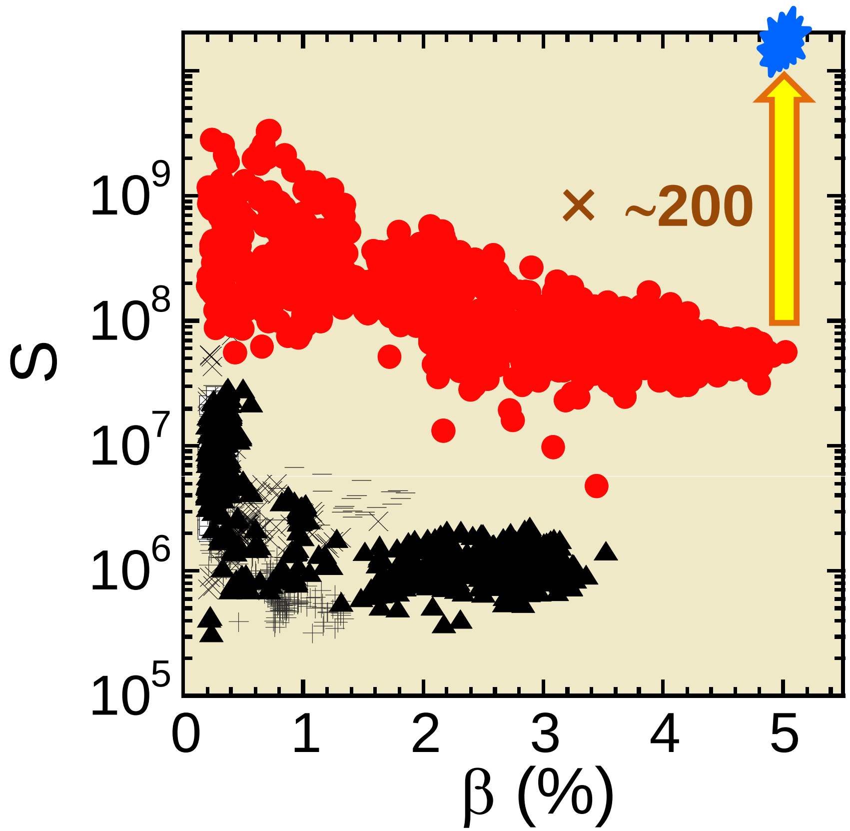
$$\chi \propto \rho^*$$

Collisionless (Long mean free path) high β is an important issue

ex. effect of stochasiticity

Establishment of integrated physics model is required to bridge over the gap

Magnetic Reynolds Number : *S*



$$S = \tau_R / \tau_A \propto \frac{aBT_e^{3/2}}{ZA^{1/2} n_i^{1/2}} \propto \frac{\beta^{1/2}}{\nu_b * \rho *^2}$$

Role of resistivity

➔ Resistive interchange mode

Growth rate of resistive mode

(B.Coppi, NF (1966))

$$\gamma \propto S^{-1/3}$$

Pay careful attention to extrapolation

γ is reduced by 1/6 ?

Note: LHD cannot realize a plasma with full dimensional similarity

➔ ***Integrated physics model with reliable predictability which bridges over the gap of non-dimensional parameters***

Revision of physical picture of MHD instability
- development of new horizon -

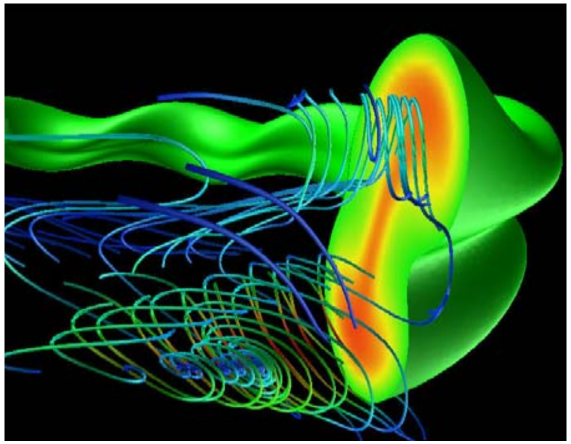
1950' magnetic hill ➔ unstable against interchange mode

"Minimum B" or "Averaged minimum B"

Ioffe bar, Baseball coil, Astron-Spherator, Ohkawa torus ➔ **tokamak**

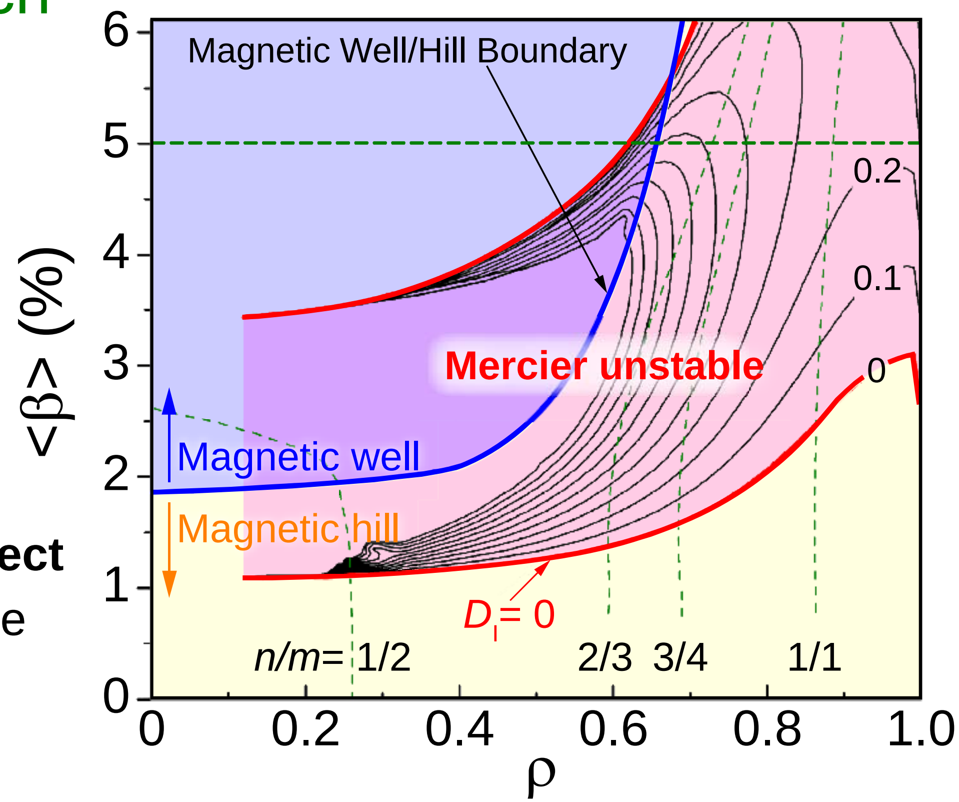
Standard paradigm in fusion research
beneficial, but causes constraints

2000- LHD experiment
discovered that interchange
instability in magnetic hill is benign
: **New paradigm**



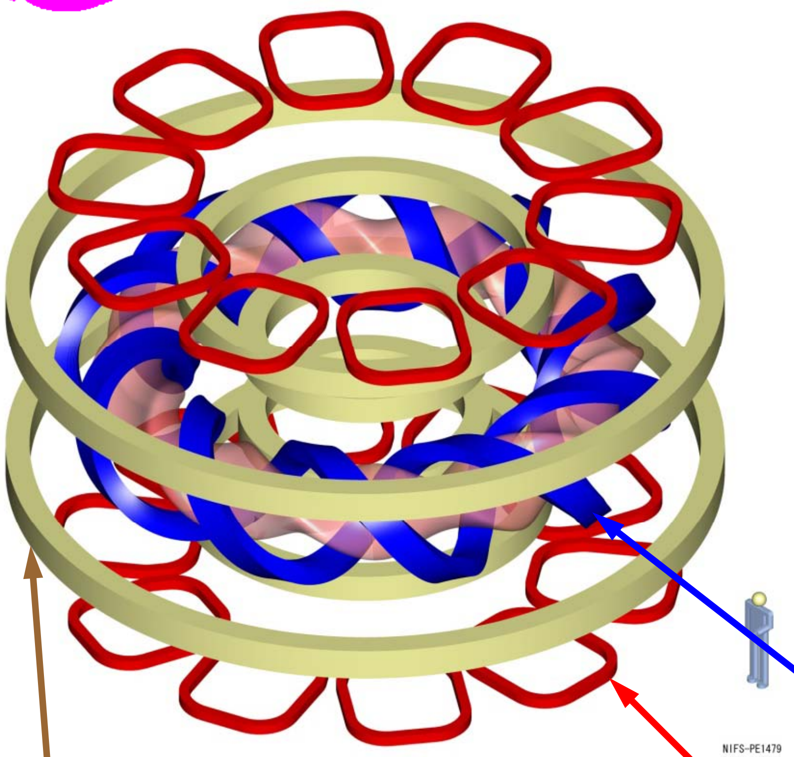
Possible mitigation effect
new elements should be considered

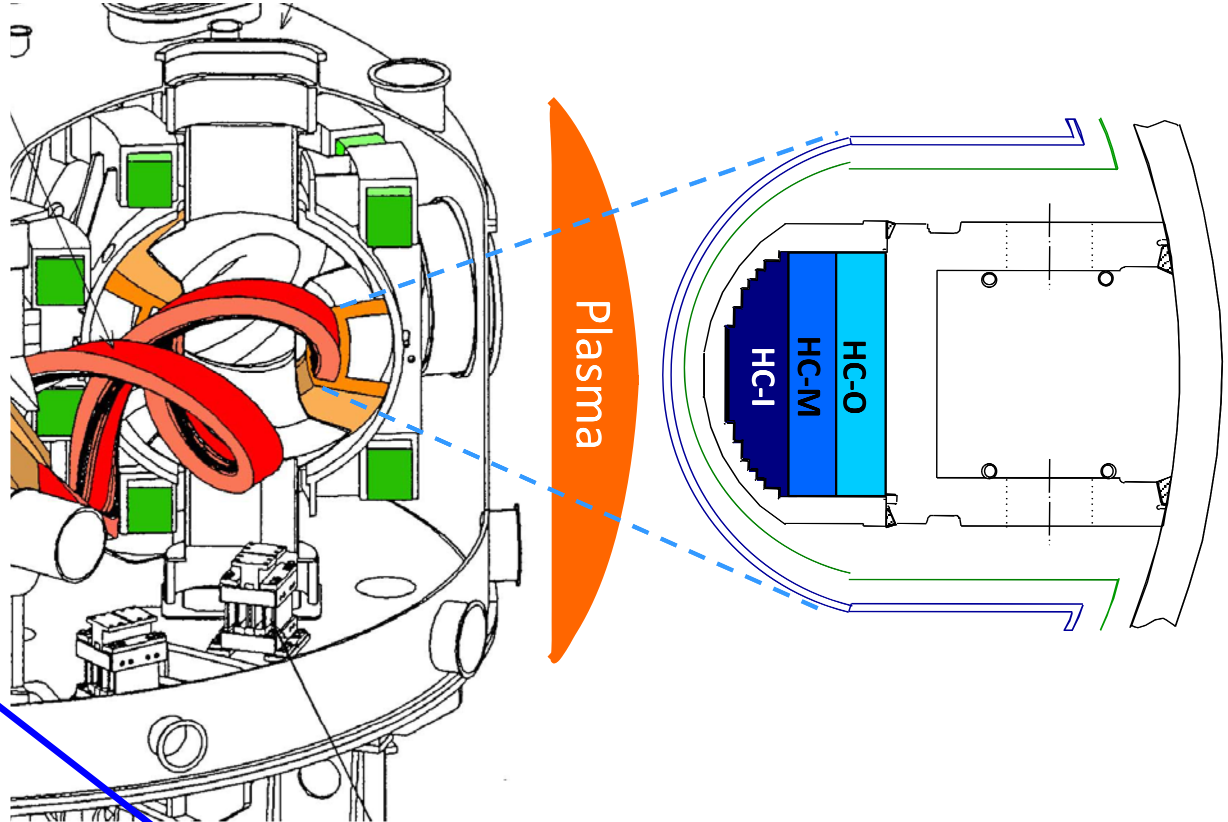
- ✓ 3-D free boundary
- ✓ Compressibility
- ✓ Flow along field lines
- ✓ Thermal diffusion etc…



M.Sato, P03-11 on Thu.

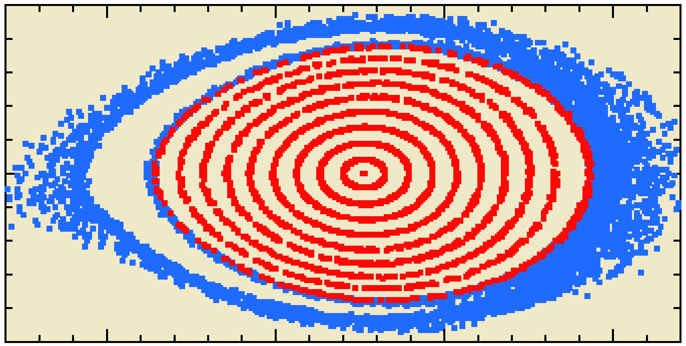
LHD has large flexibility of magnetic configuration





Poloidal field coil

- ➔ Position of magnetic axis
- ➔ Elongation



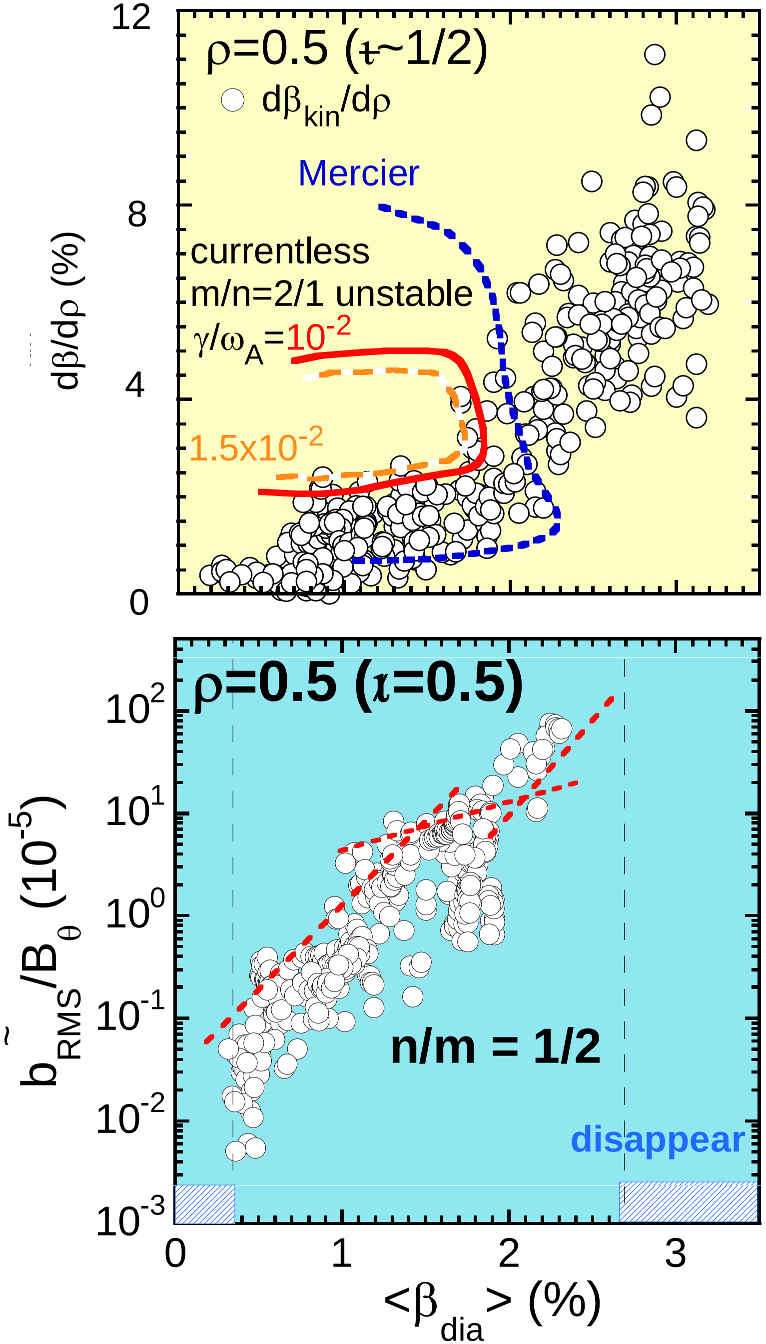
Control of current center of helical coil

- ➔ Aspect ratio
  - ➔ Rotational transform

Local Island Divertor coil

- ➔ Generates m/n=1/1 Resonant Magnetic Perturbation (RMP)
  - ➔ Magnetic island

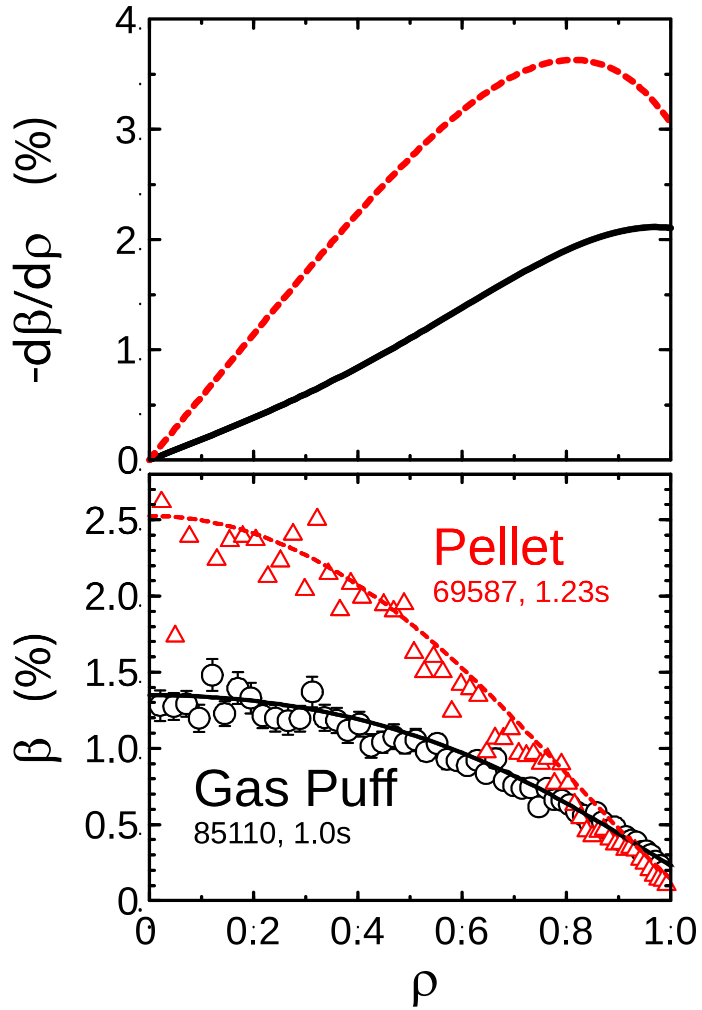
Mercier criterion can be violated and quantification of low-m mode stability is an issue

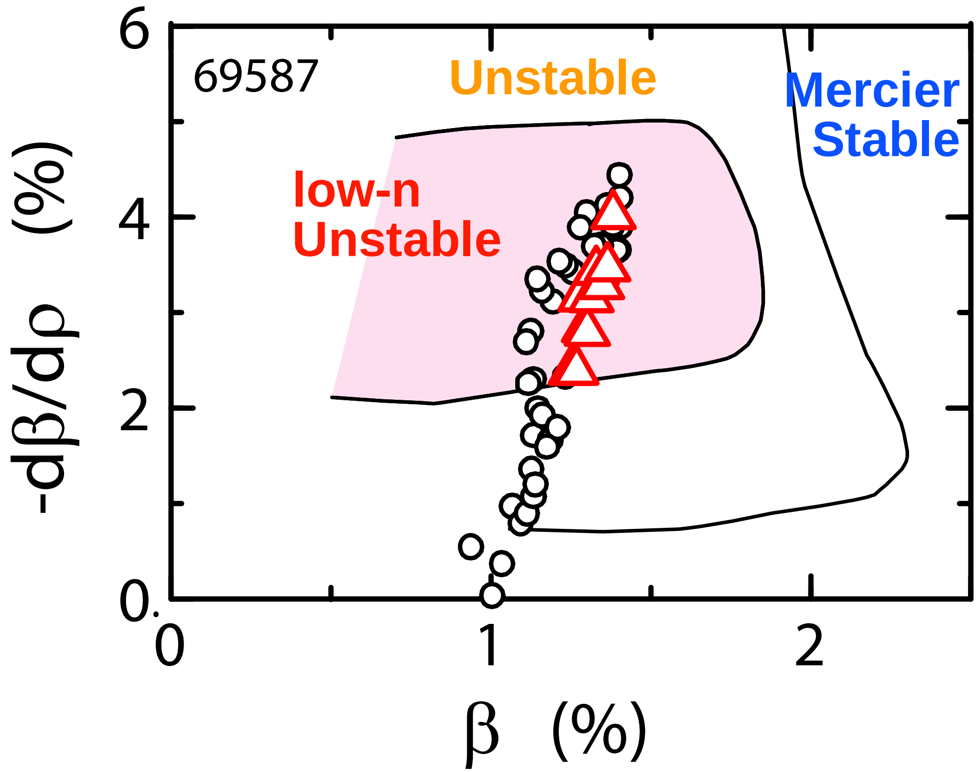


R_{ax}=3.6m : inward shifted

- ✓ Mercier unstable region does not inhibit access to higher β and no destructing event is observed.
  - ➔ unlikely in tokamaks
- ✓ Low-*n* interchange mode unstable region looks prohibited
  - ➔ inhibits access to higher-β regime in the case with further inward shift of R_{ax} (<3.6m), where stability is violated seriously.
- ✓ Excitation and disappearance of MHD modes corresponds to prediction by Mercier criterion
- ✓ These MHD modes usually saturate at harmless level

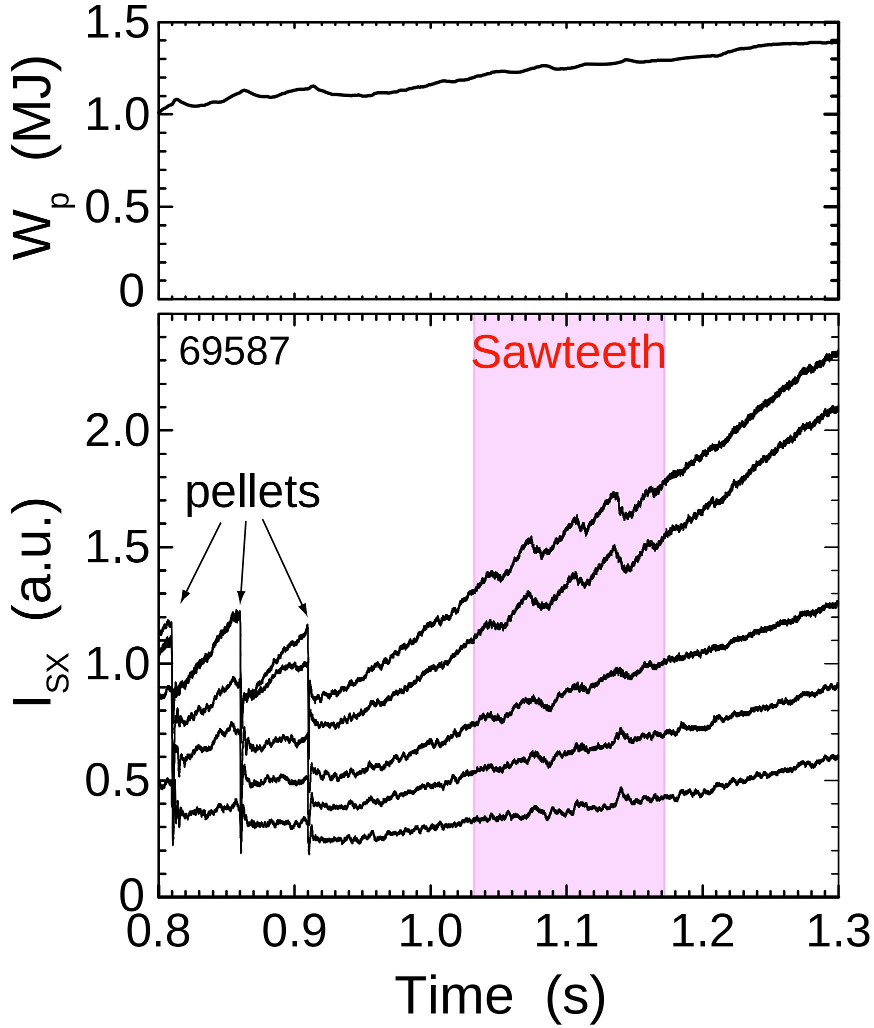
Sawtooth-like activity is repeated in unstable regime for ideal interchange mode

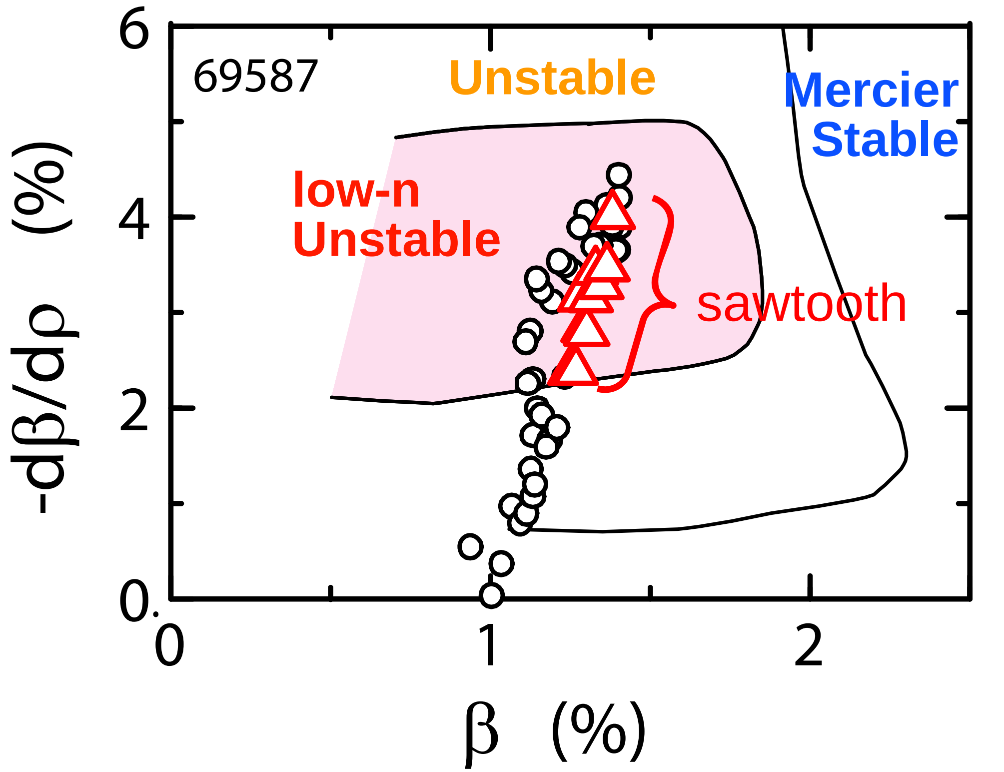




- ✓ With pellet injection, pressure profile is peaked compared with gas-puff-fueled plasma.
- ✓ When the pressure gradient exceeds the low-*n* unstable condition, sawtooth-like MHD activities are destabilized, but pressure gradient continues to evolve.

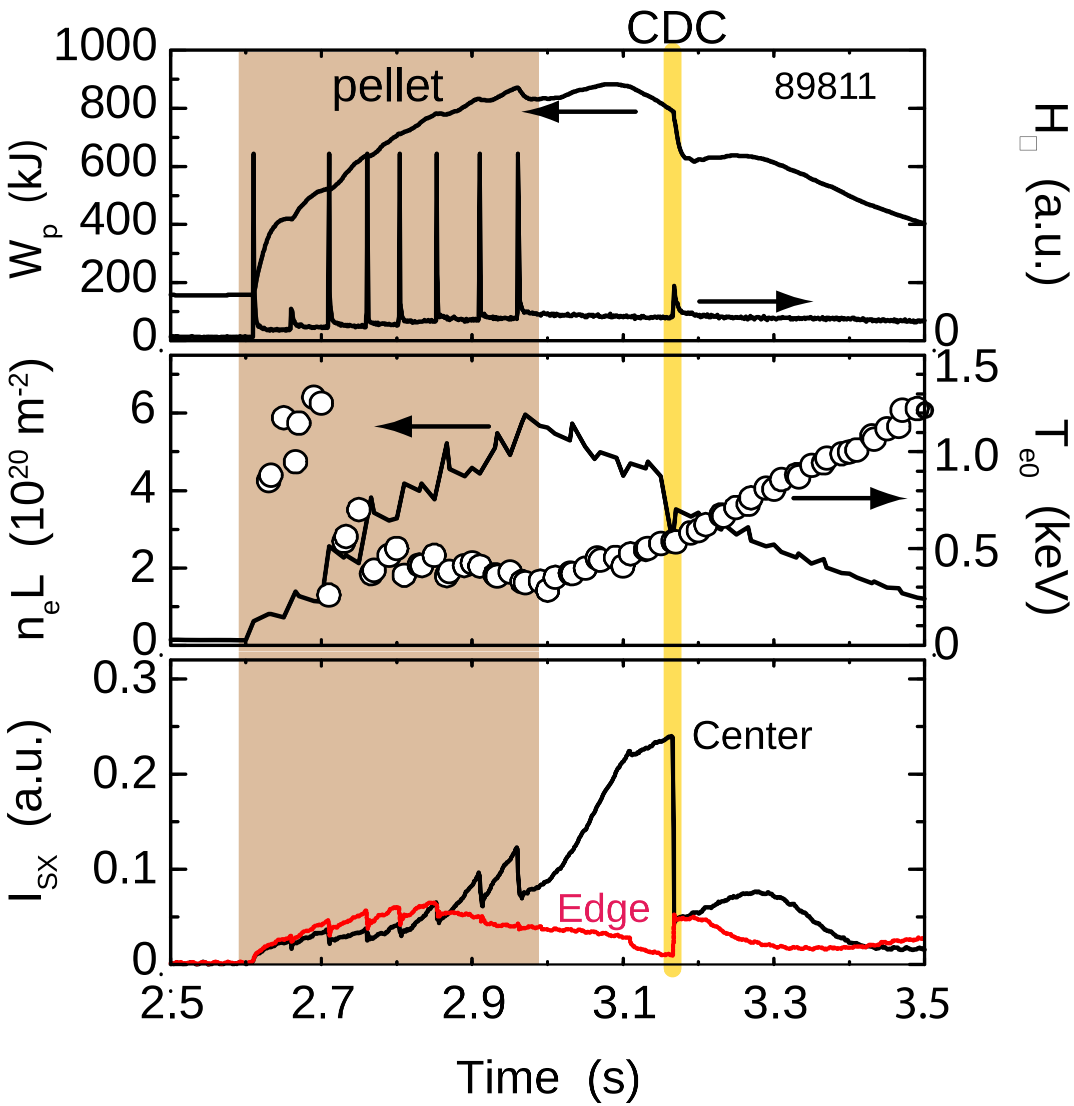
Sawtooth-like activity is repeated in unstable regime for ideal interchange mode

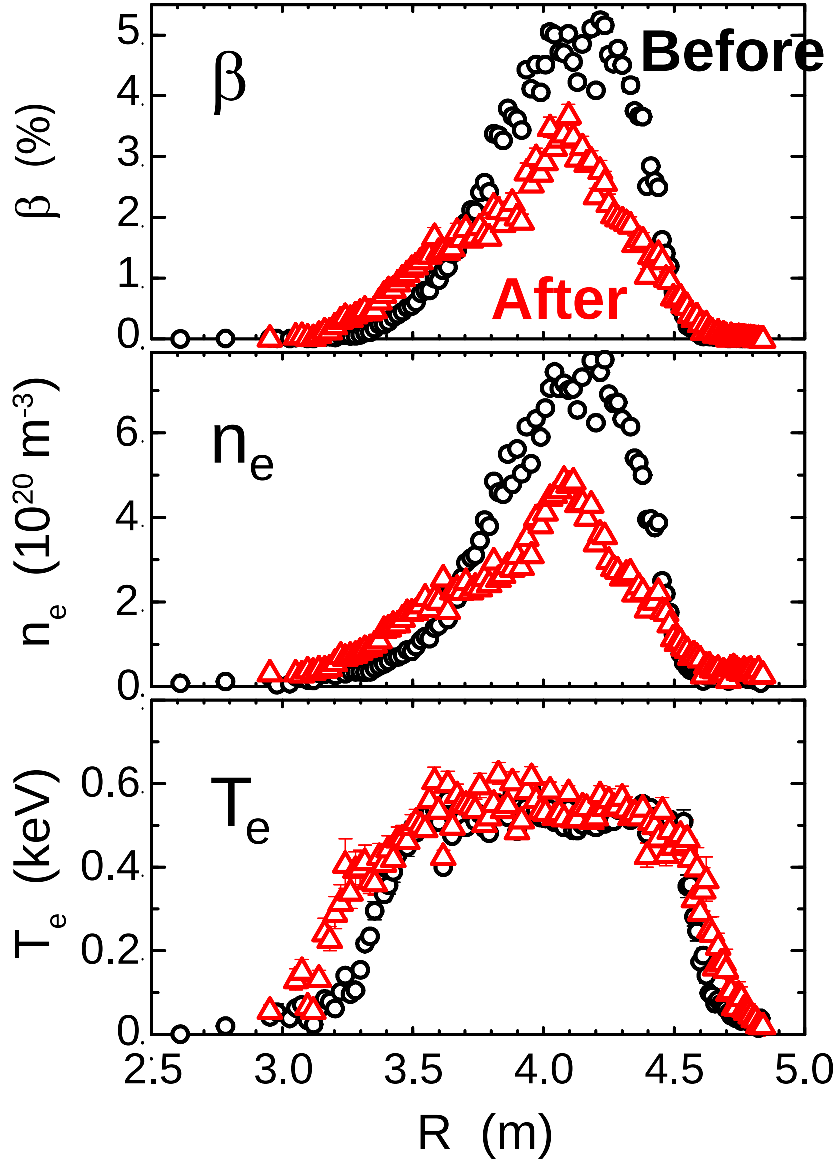




- ✓ After pellet injection, pressure profile is peaked compared with gas-puff-fueled plasma.
- ✓ When the pressure gradient exceeds the low-n unstable condition, sawtooth-like MHD activities are destabilized, but pressure gradient continues to evolve.

Core Density Collapse limits the central beta





- ✓ IDB/SDC plasmas, peaking of the plasma is limited by so-called CDC
- ✓ Half of particles are expelled from the high density core in sub ms.

S.Ohdachi, I.06 on Mon.

3-D MHD equilibrium without assumption of nested flux surfaces

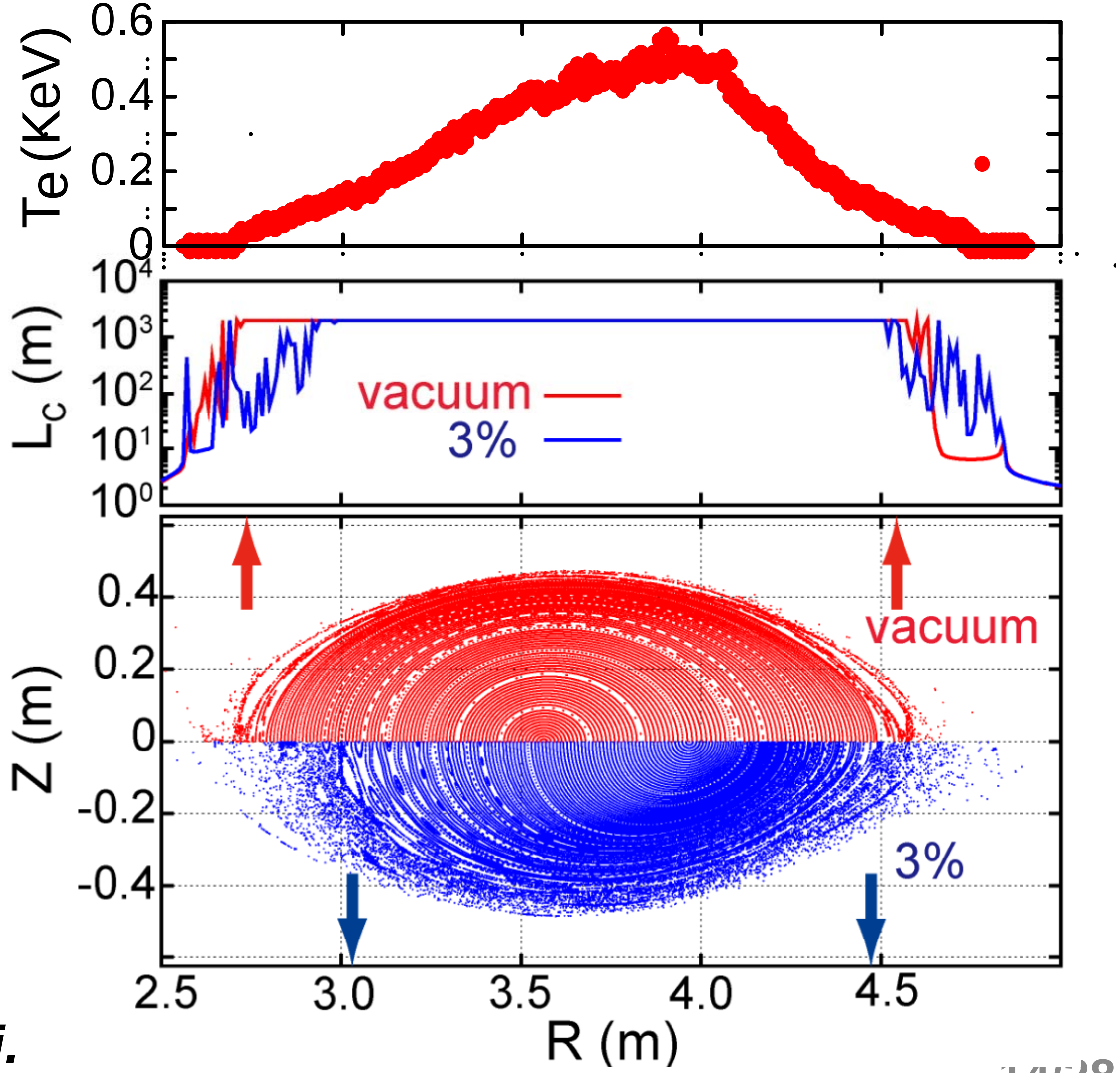
MHD equilibrium axi-symmetry $\partial/\partial\phi=0$ — Grad-Shafranov eq. → nested flux surface

Distinguished feature of 3-D equilibrium : magnetic island, stochastic field

HINT code can cope with 3-D equilibrium without assumption of nested flux surfaces.

Peripheral region becomes stochastic as β increases because of induced islands due to Pfirsch-Schlüter current

→ Significant T_e gradient exists in the edge stochastic area



Y.Suzuki, I.34 on Fri.

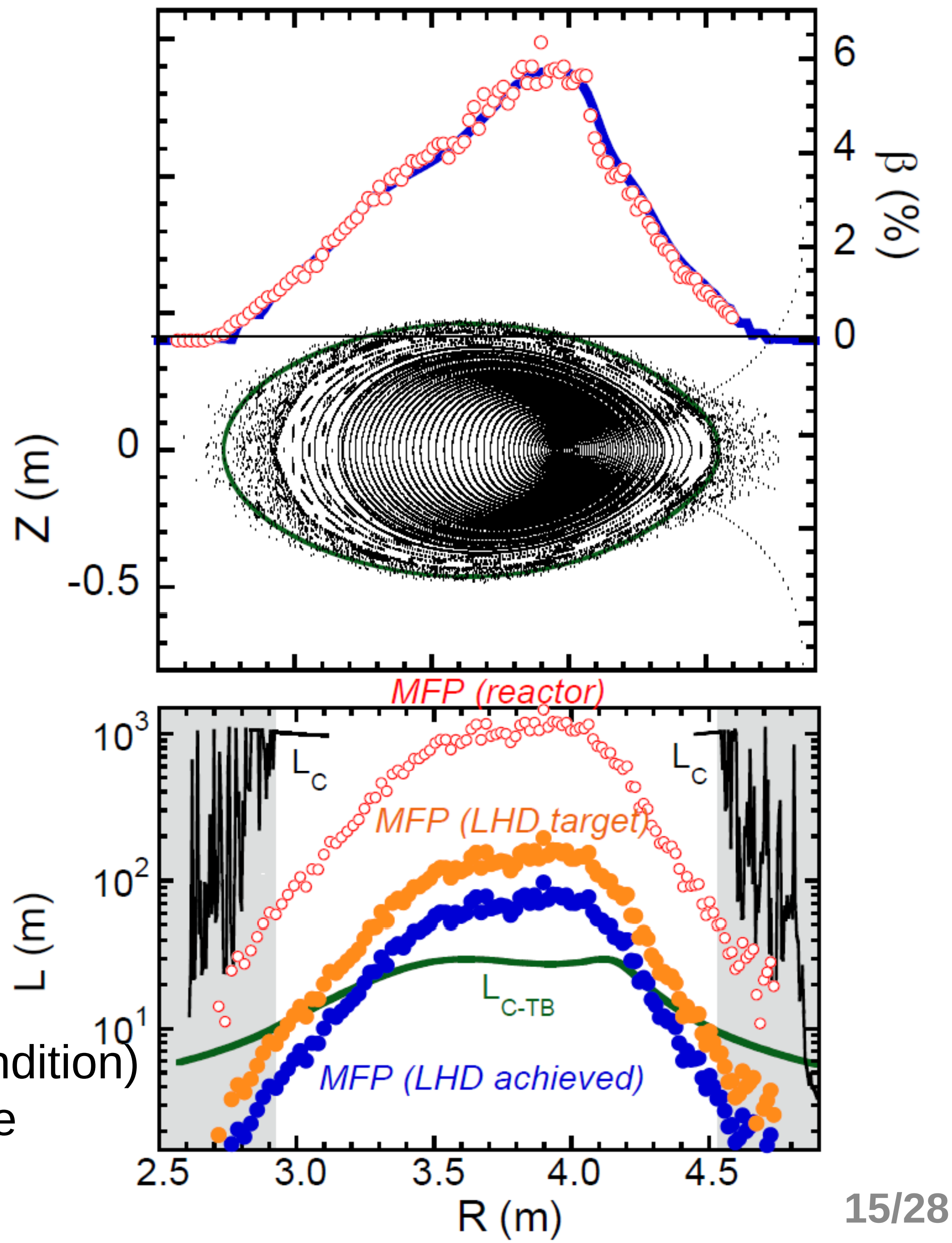
Results from HINT well describes deformation of magnetic surfaces

3-D equilibrium consistent with experimental observation, i.e., Shafranov shift, pressure profile, etc.

Significant pressure (T_e) gradient exists in the edge stochastic area

Hypothesis

1) Plasma heals flux surfaces
2) Profile is consistent with characteristics of stochastic field
3) Somewhere between 1) & 2)



$L_{C\text{-}TB}$: connection length between the torus-top and - bottom

✓ L_C >> $L_{C\text{-}TB}$

➔ Pfirsch-Schlüter current is effective

➔ Secure MHD equilibrium

✓ L_C >> MFP (even under a reactor condition)

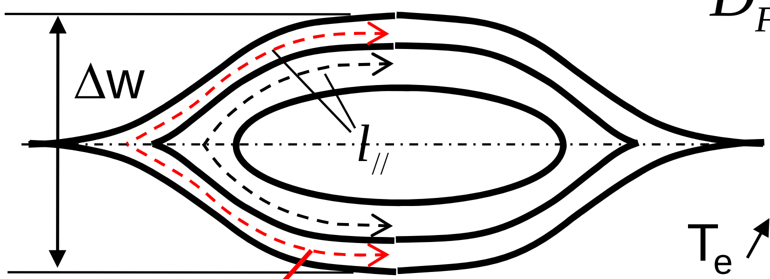
➔ Plasma is collisional enough to secure isotropic pressure

Electron temperature profiles in stochastic region at high beta operation

3D edge transport simulation (EMC3-EIRENE)

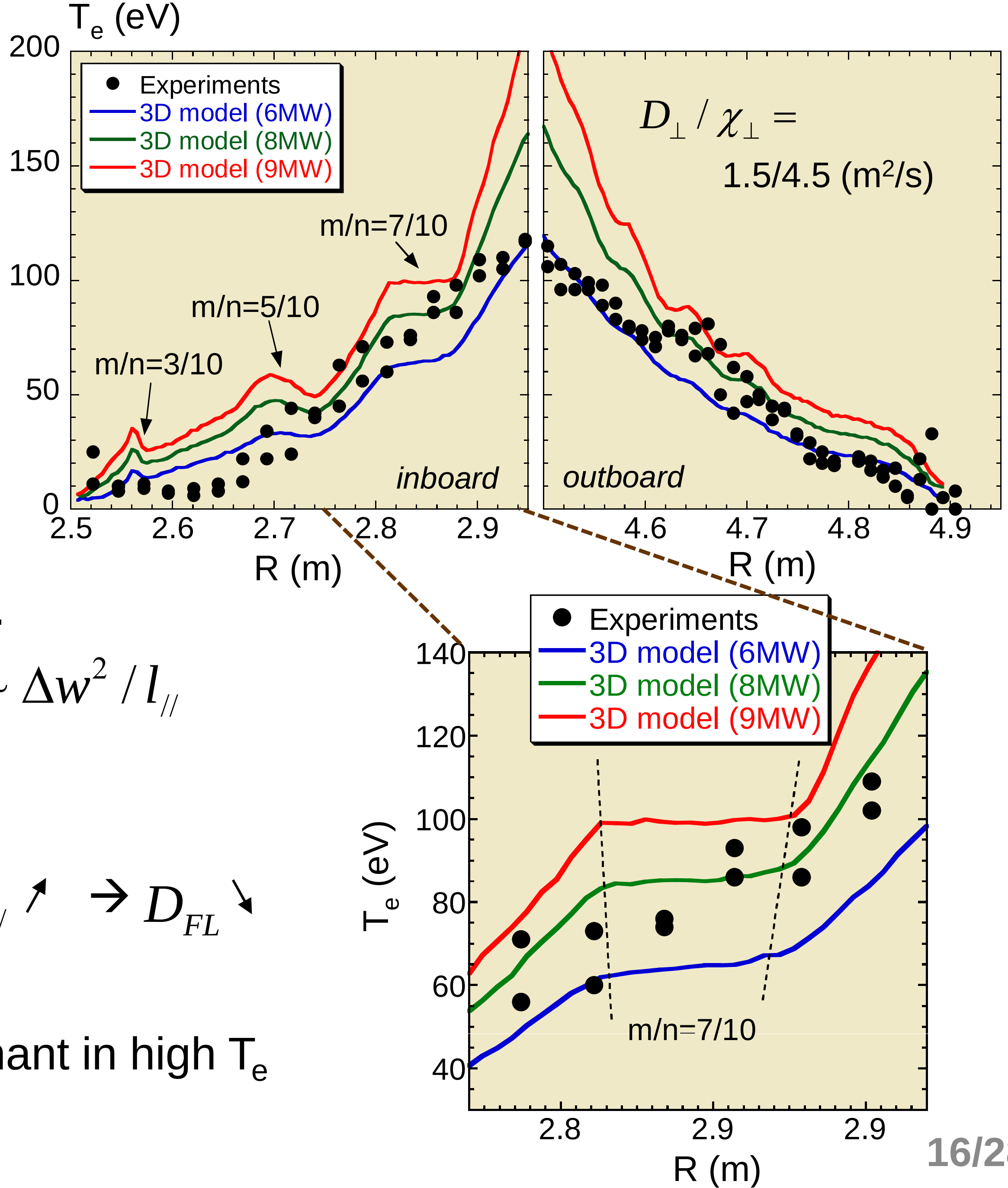
- ✓ T_e profiles are sustained even at higher input power.
- ✓ Rechester-Rosenbruth model predicts larger radial transport at high T_e. $\chi_{\perp eff} \propto D_{FL} T_e^{0.5\sim2.5}$
- ✓ The 3D modelling indicates high T_e plasma sees different D_{FL}.

$$D_{FL} \sim \Delta w^2 / l_{//}$$



$T_e \nearrow \quad l_{//} \nearrow \quad \rightarrow D_{FL} \searrow$

The parallel path becomes predominant in high T_e



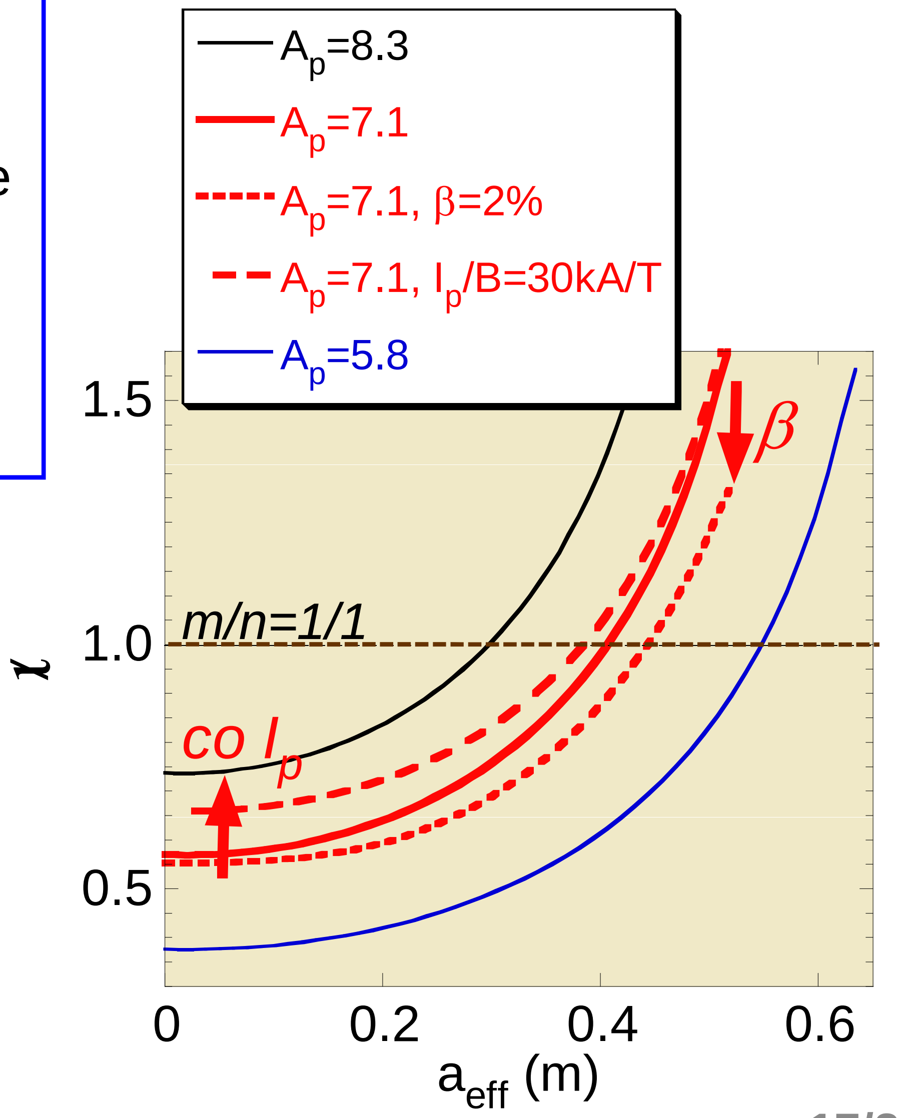
m/n=1/1 mode is excited in case of high β, enhanced magnetic hill and loss of magnetic shear

Large aspect ratio

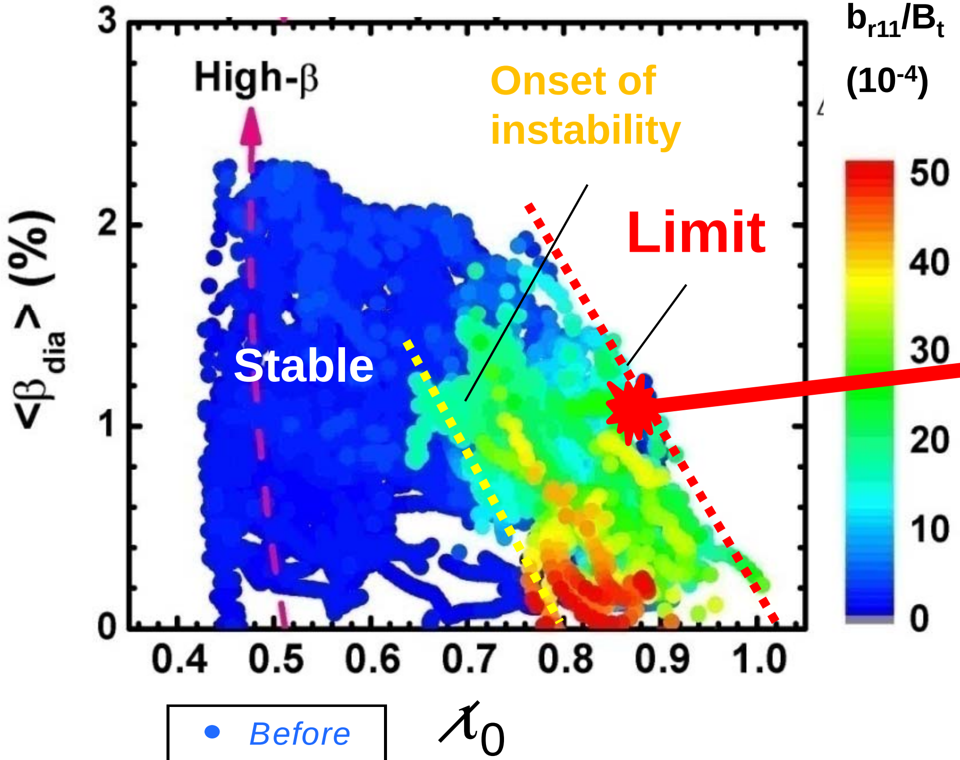
- ✓ Disadvantage
  - Enhanced magnetic hill
  - Reduced magnetic shear
  - ➔ less stable against interchange mode
- ✓ Advantage
  - High equilibrium-β limit
  - ⇔ Reduced Shafranov shift
  - Good confinement and heating efficiency

- ✓ Finite β effect
  - ➔ decreases edge ƚ
  - ➔ reduces magnetic shear
- ✓ Co- plasma current
  - ➔ increases central ƚ
  - ➔ reduces magnetic shear

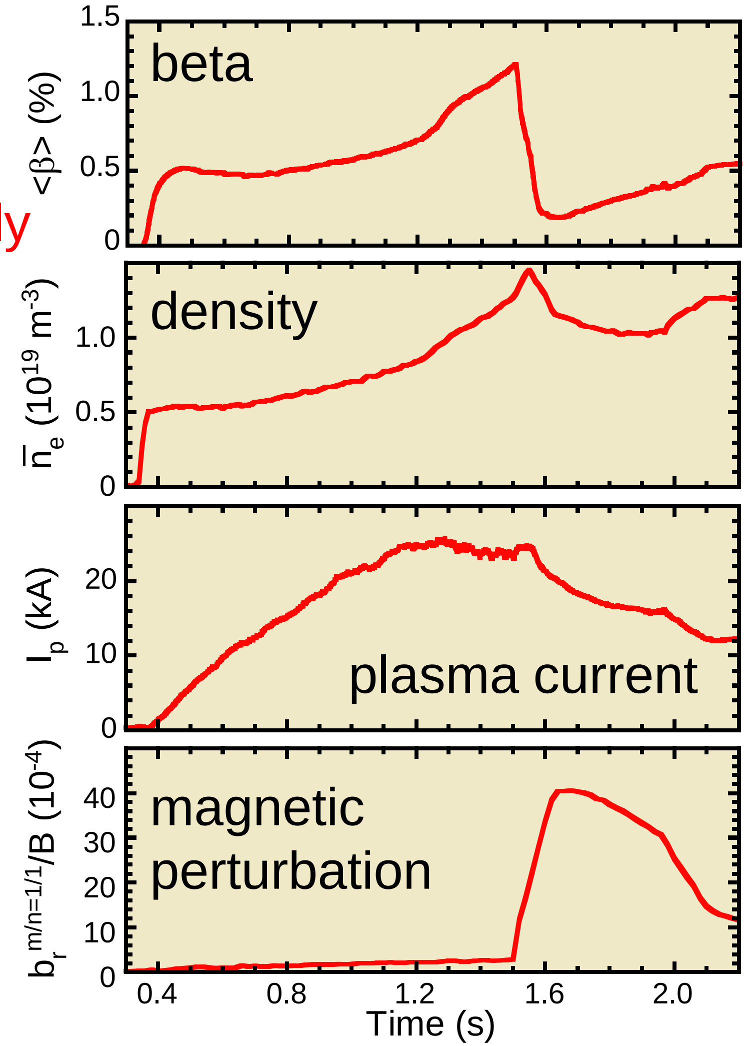
➔ **Violation of stability**

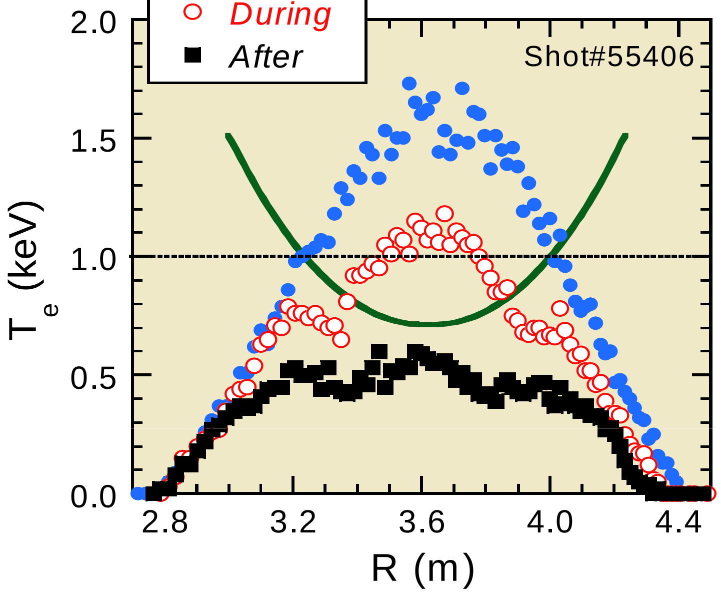


Large scale MHD event is triggered in case of high β, enhanced magnetic hill and loss of magnetic shear



Stability is violated significantly D_l>>0.

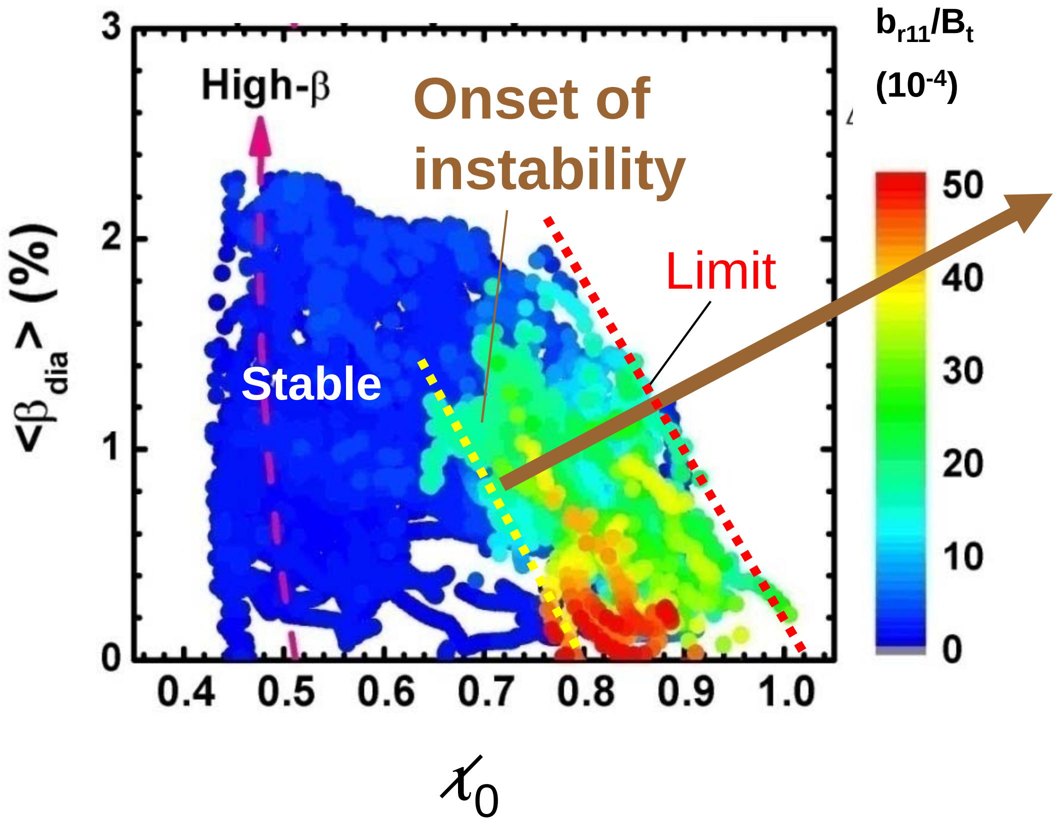


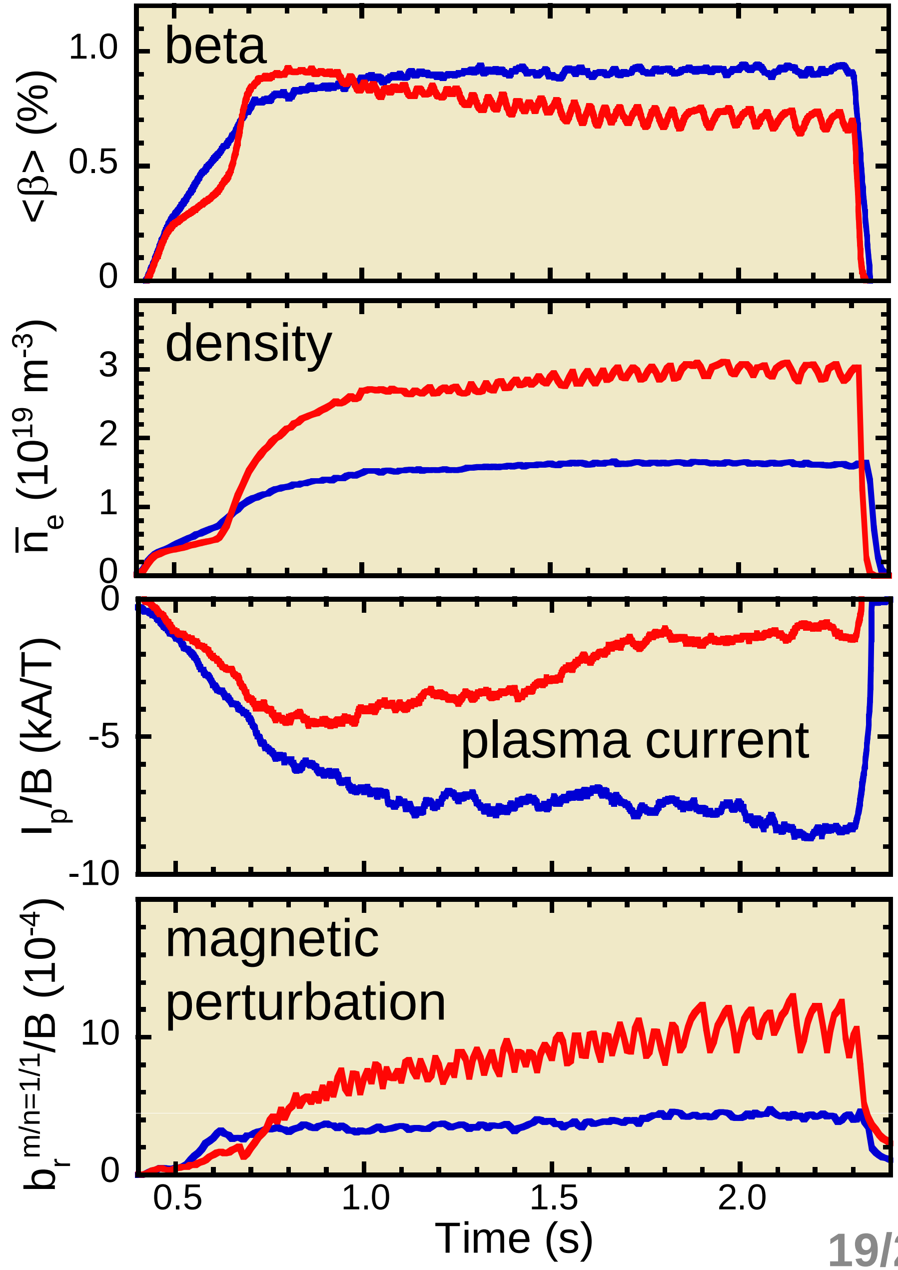


- ✓ Instability causes T_e profile-flattening in the vicinity of a resonant surface
- ✓ Plasma current to reduce magnetic shear enhances MHD activity.

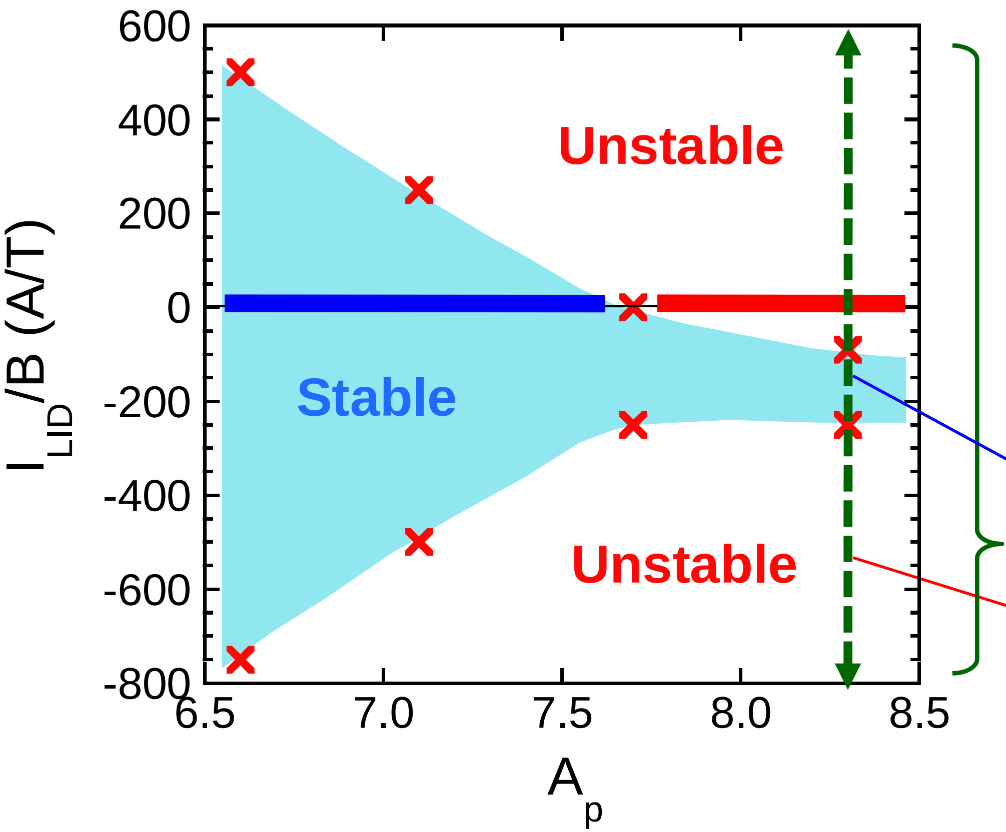
Large scale MHD event is triggered in case of high β, enhanced magnetic hill and loss of magnetic shear

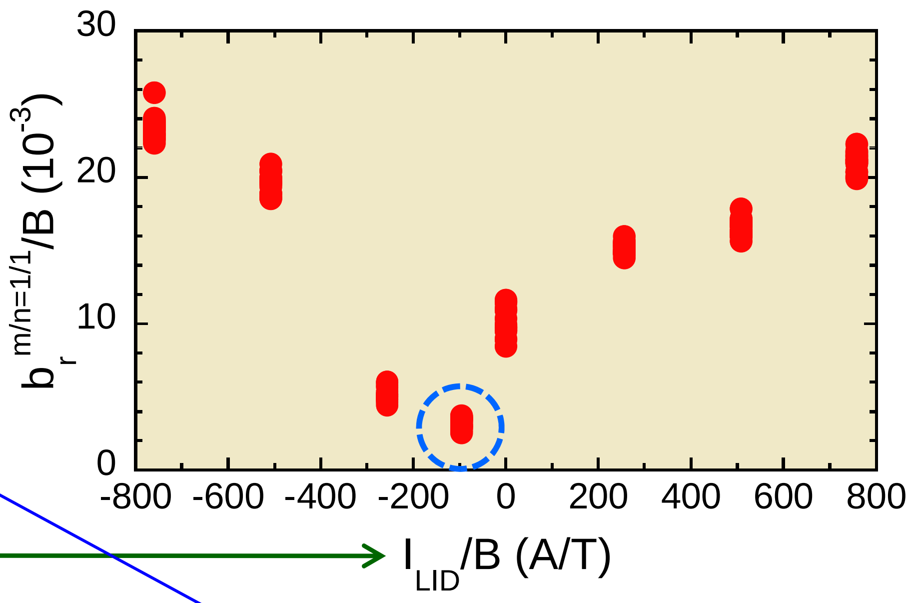
- ✓ Sawtooth-like amplitude correlates with plasma current
- ✓ Ctr-current stabilizes instability.

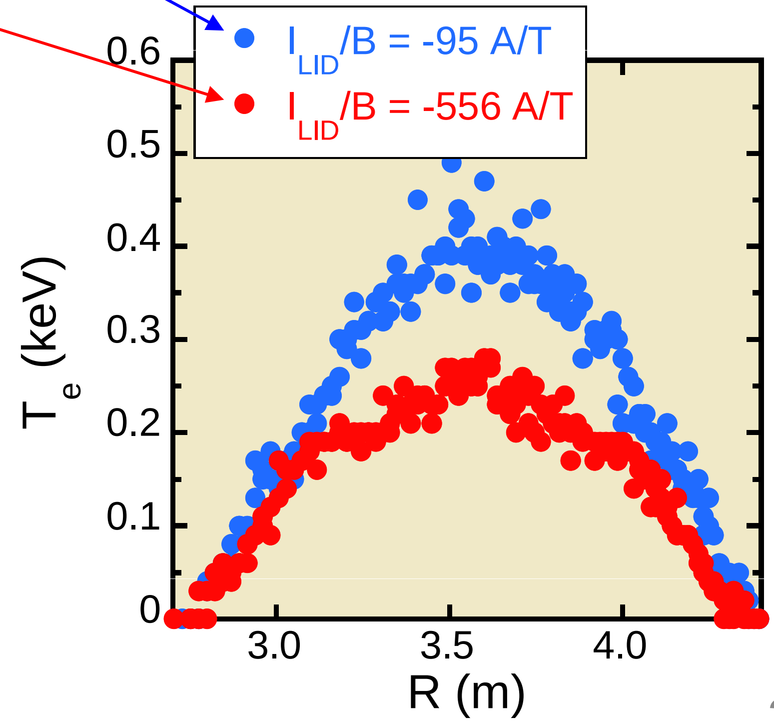




Unstable mode can be stabilized by RMP





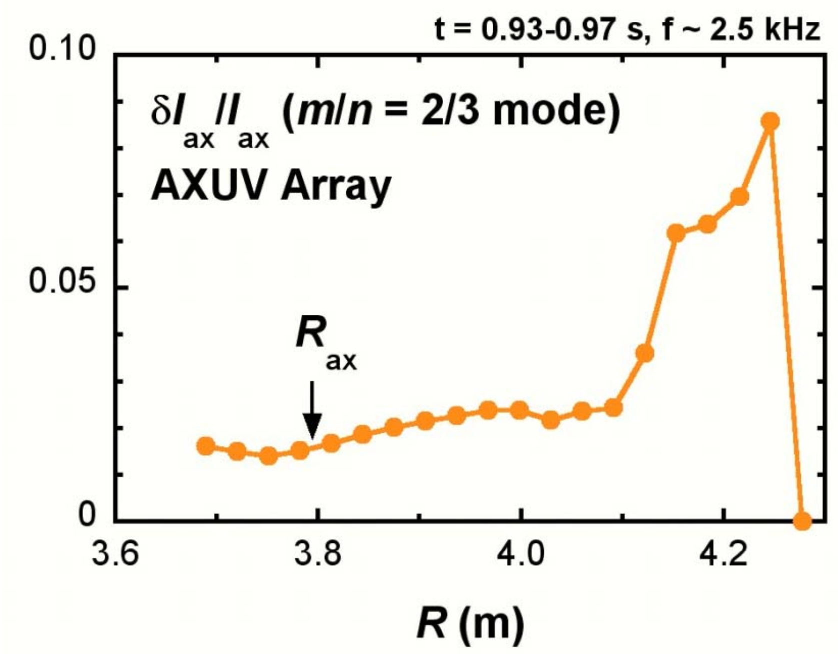


- ✓ Elimination of the seed seems to mitigate the onset of *m*/*n*=1/1 instability in an enhanced magnetic hill.
- ✓ Island healing is linked with this mechanism

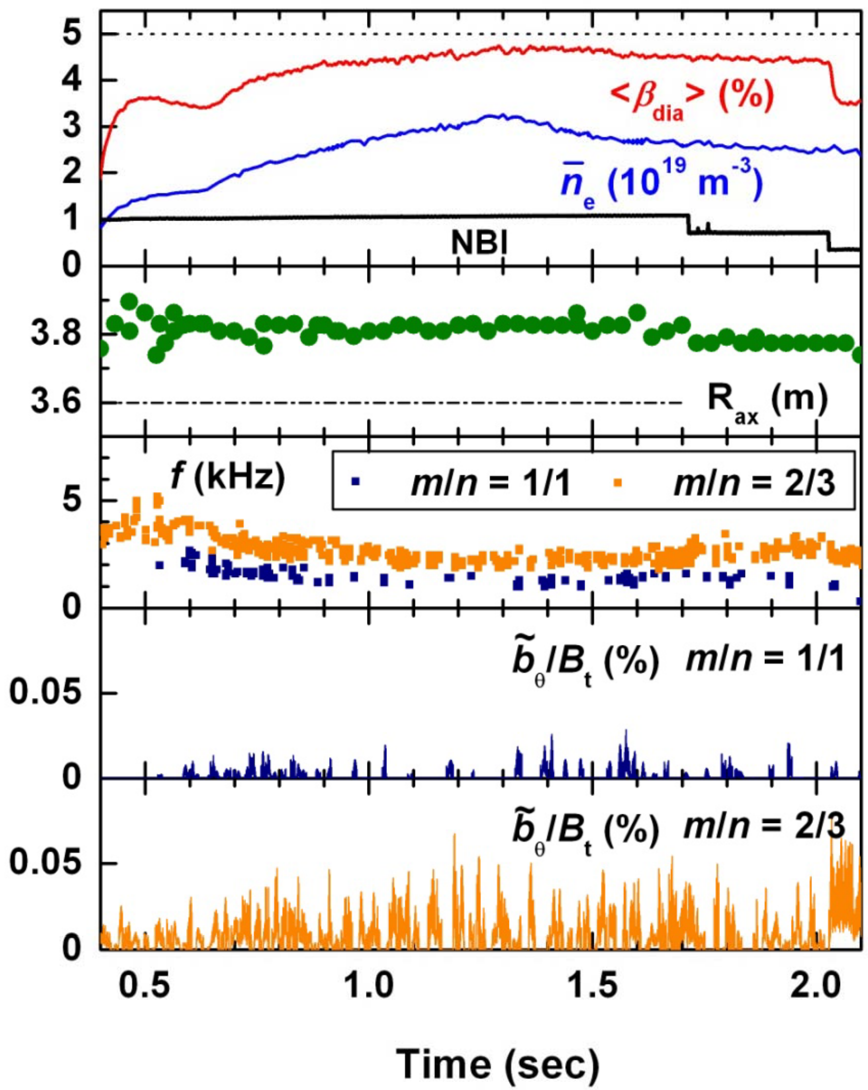
Y.Narushima, I.10 on Tue.

Fluctuation localized at the edge is predominant in regular high-β plasma

- ✓ $\beta \sim 4.8$ %, $\beta_0 \sim 9.6$ %, $H_{ISS95} \sim 1.1$
- ✓ Plasma was maintained for $\sim 100\tau_E$
- ✓ Shafranov shift $\Delta/a_{eff} \sim 0.25$
- ✓ Edge MHD modes are dominantly observed.



R_{ax} = 3.6 m, B_t = -0.425 T



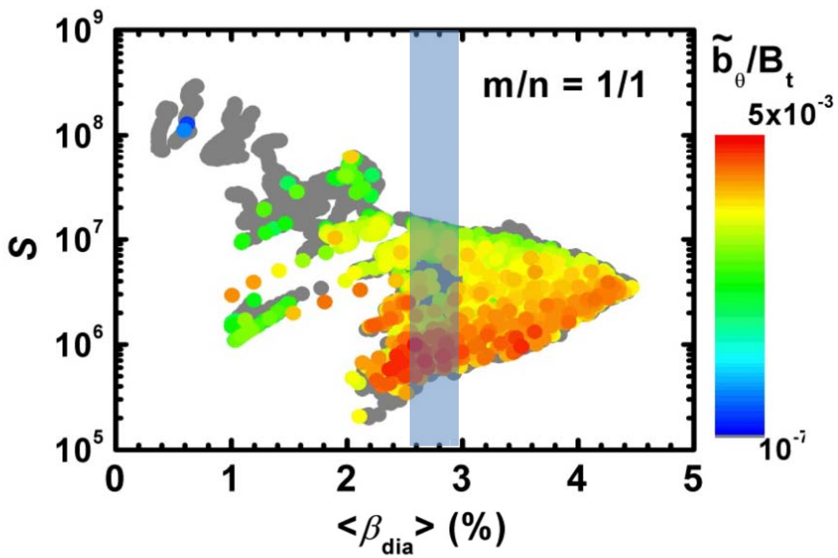
Edge region is a magnetic hill but MHD stability is secured by magnetic shear ➔ Ideal mode is stable ➔ resistive mode

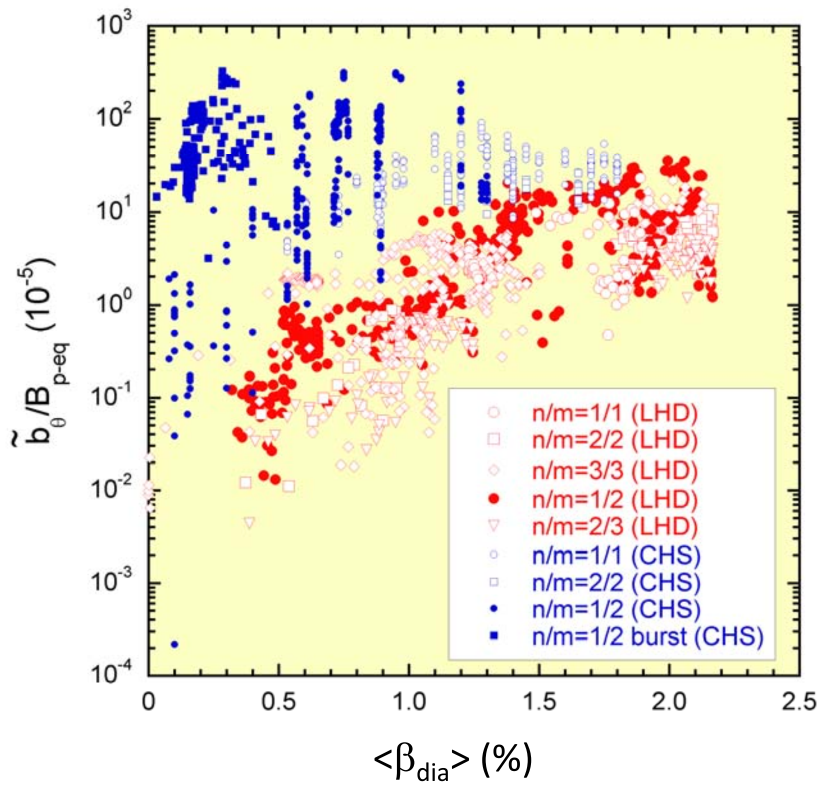
F.Watanbe, P03-09 on Thu.

Reynolds number dependence agree with resistive interchange mode

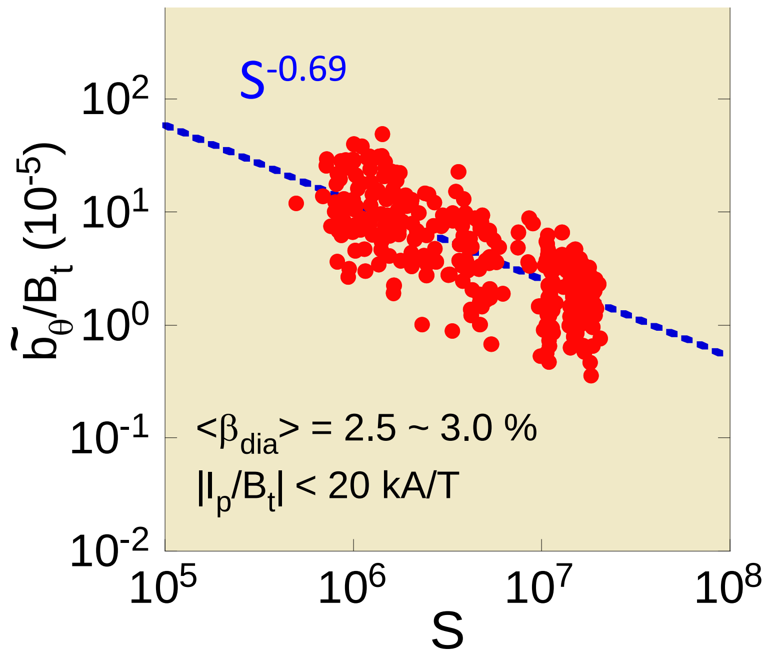
Magnetic Reynolds number is related with growth of resistive mode ($\gamma \propto \beta^{2/3} S^{-1/3}$), the change of topology (reconnection)

CHS: $S=10^3 \sim 10^5$ LHD: $S=10^6 \sim 10^8$





Comparison of MHD activities in between LHD and CHS



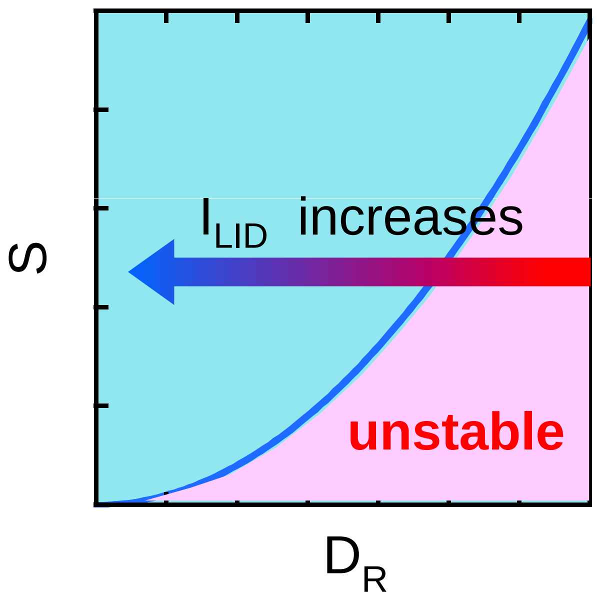
Saturation of peripheral MHD mode depends on S parameter.

Interaction of resistive mode with static RMP

✓ Pressure gradient near ɫ = 1 surface gradually decreases with I_{LID}.

✓ Amplitude of the mode decreases with reduction of the gradient, and the mode disappears while finite gradient still remains.

➔ below threshold of excitation



$\gamma \propto D_R^{2/3} S^{-1/3}$

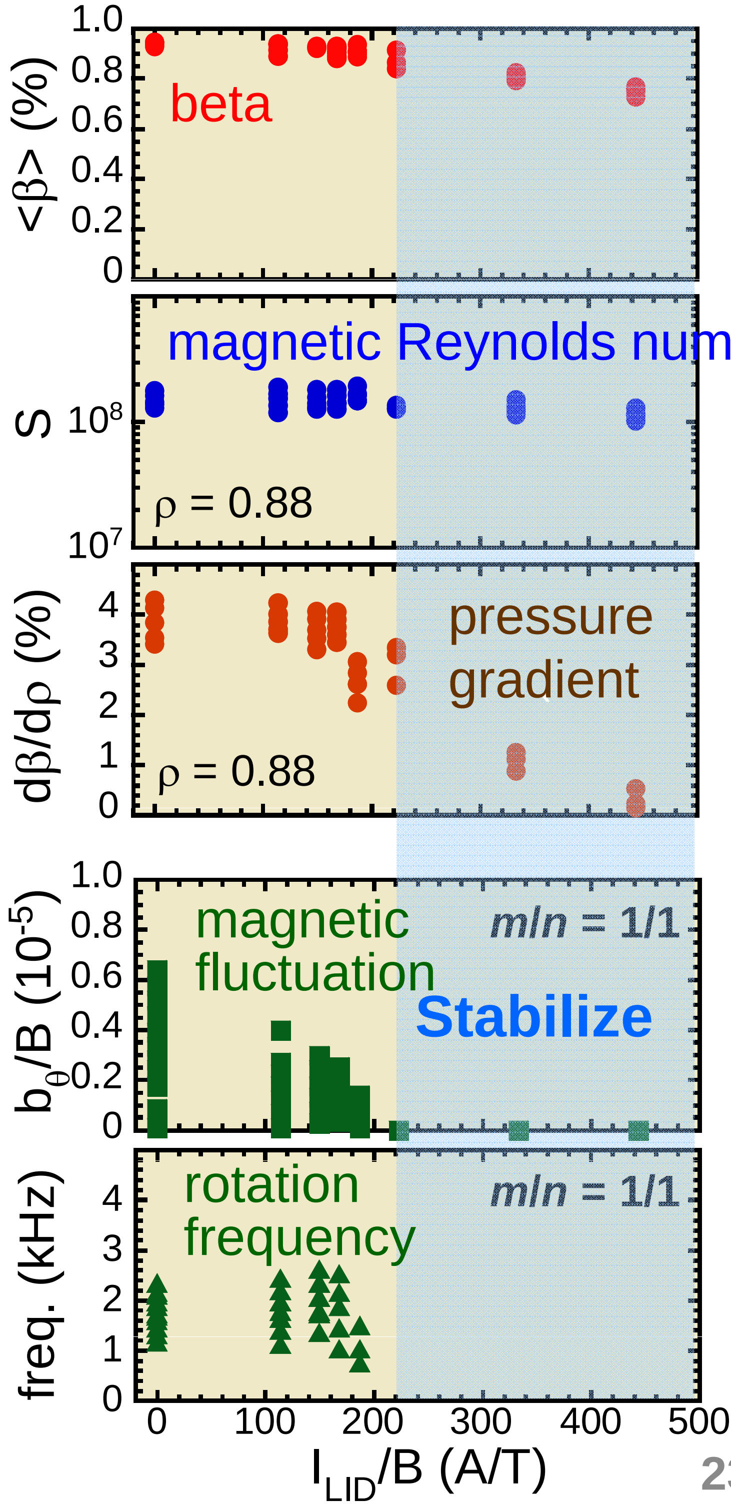
I_{LID} ↑

➔ $\nabla\beta$ ↓

➔ D_R ↓

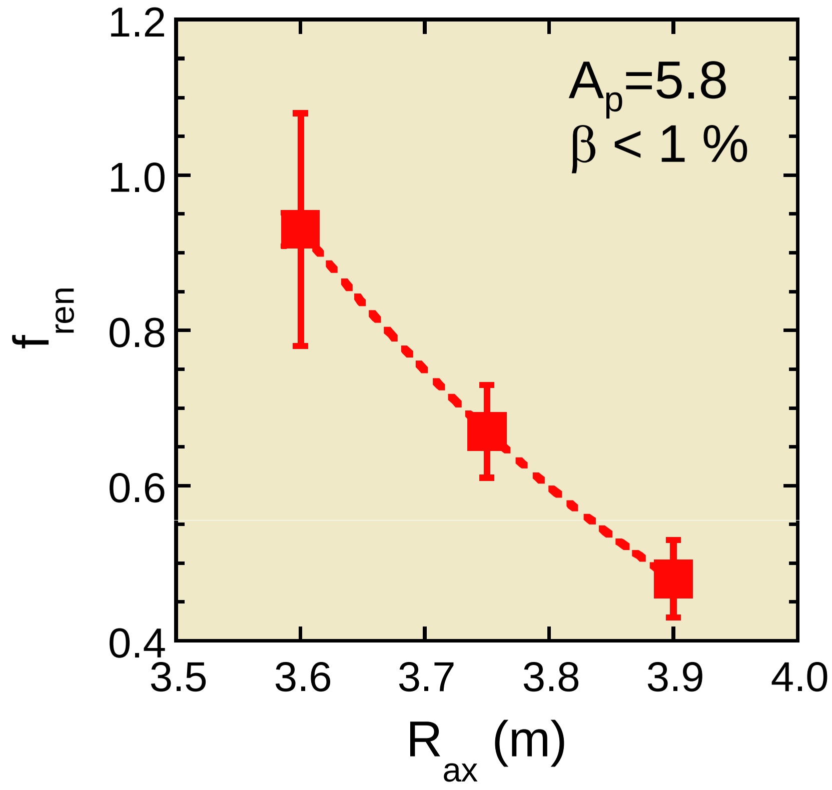
*✓ **Stabilization is due to reduction of D_R or other mechanism?***

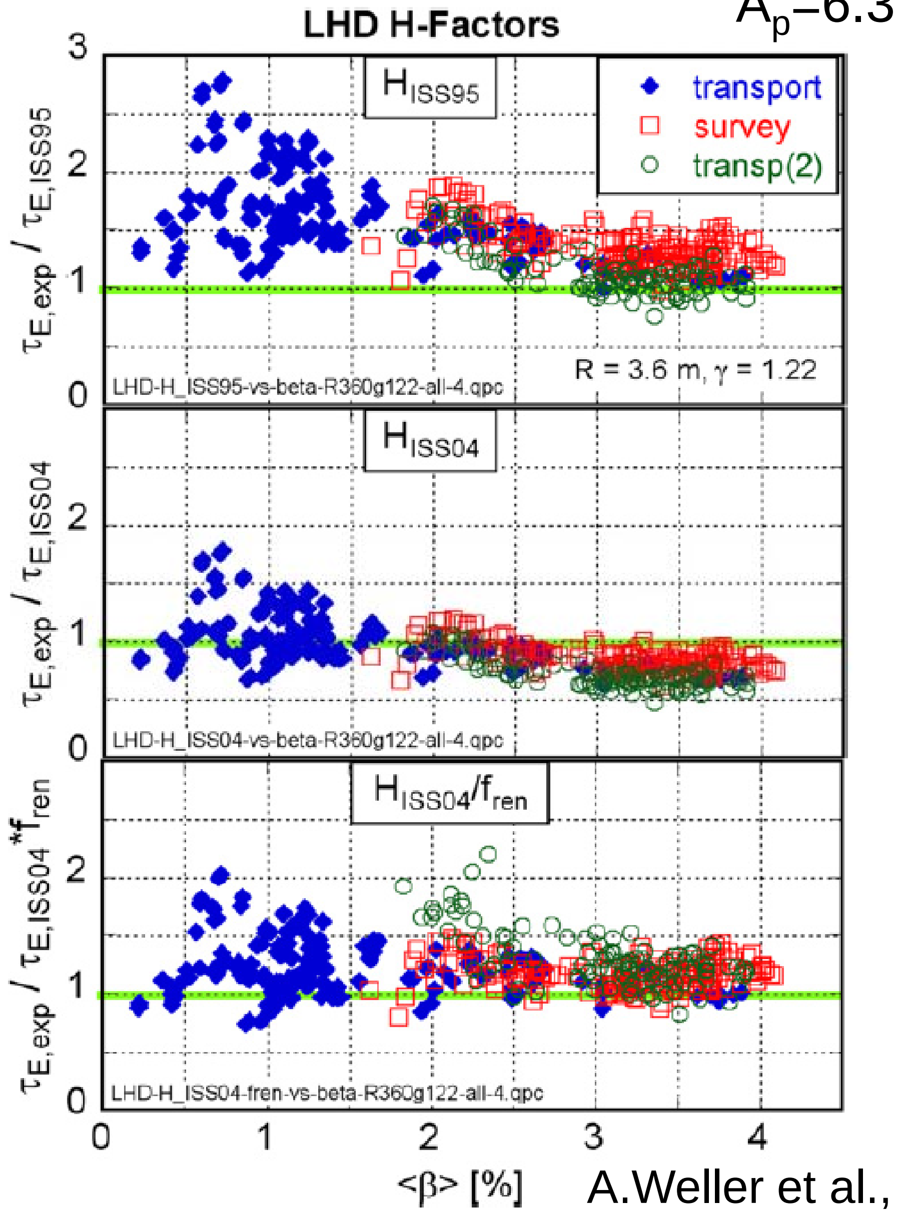
✓ Mode frequency slows down with decrease of the amplitude.



Energy confinement degrades moderately with increase of β

Confinement dependence on R_{ax} in low β





A.Weller et al., NF (2009)

Reconsideration of the normalization factor f_{ren} corresponding to the position of magnetic axis shifted due to β

➔ Degradation is mitigated

➔ But looks still remained

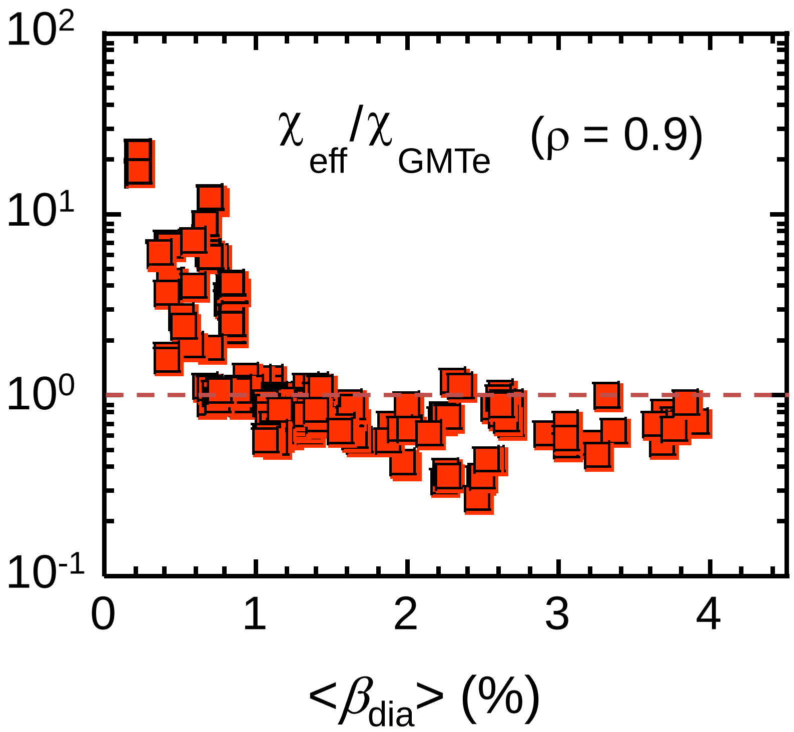
S.Sakakibara, H.Funaba, P03-07 on Thu.

Transport and density fluctuation increases with β

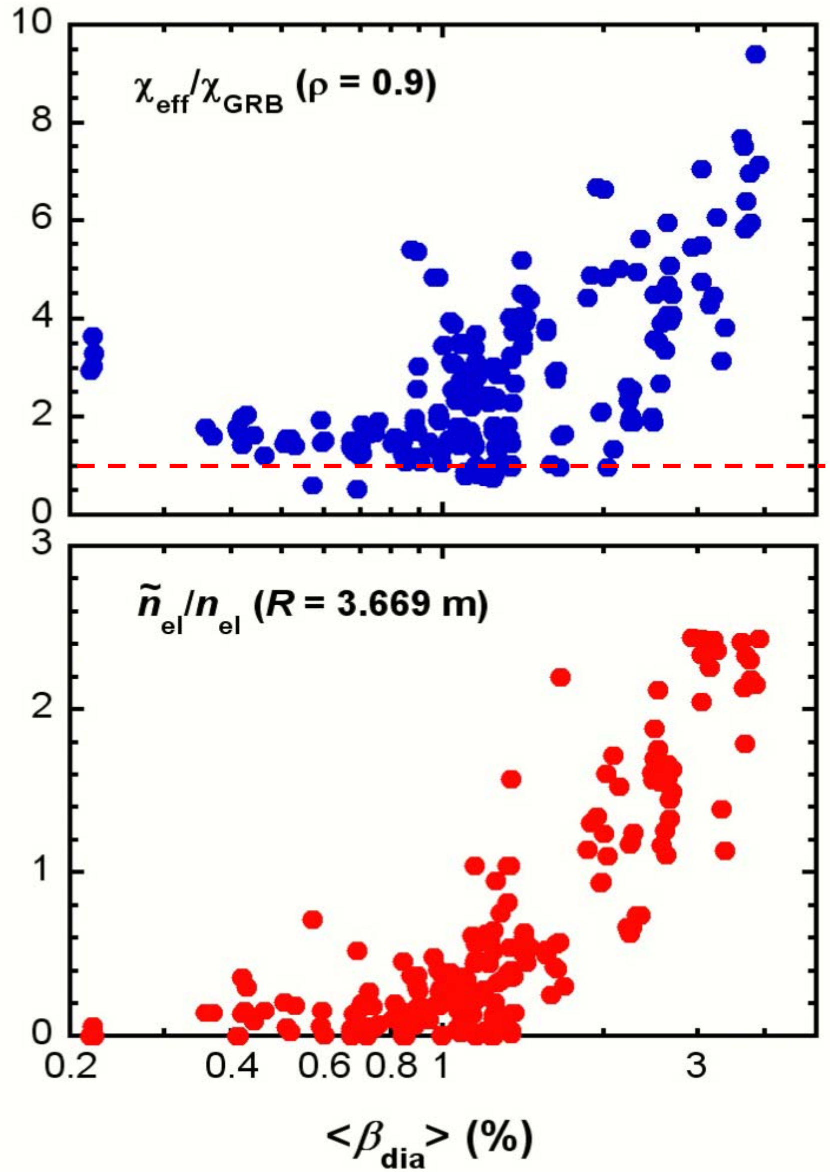
Interpretation of local transport by resistive-g mode model

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

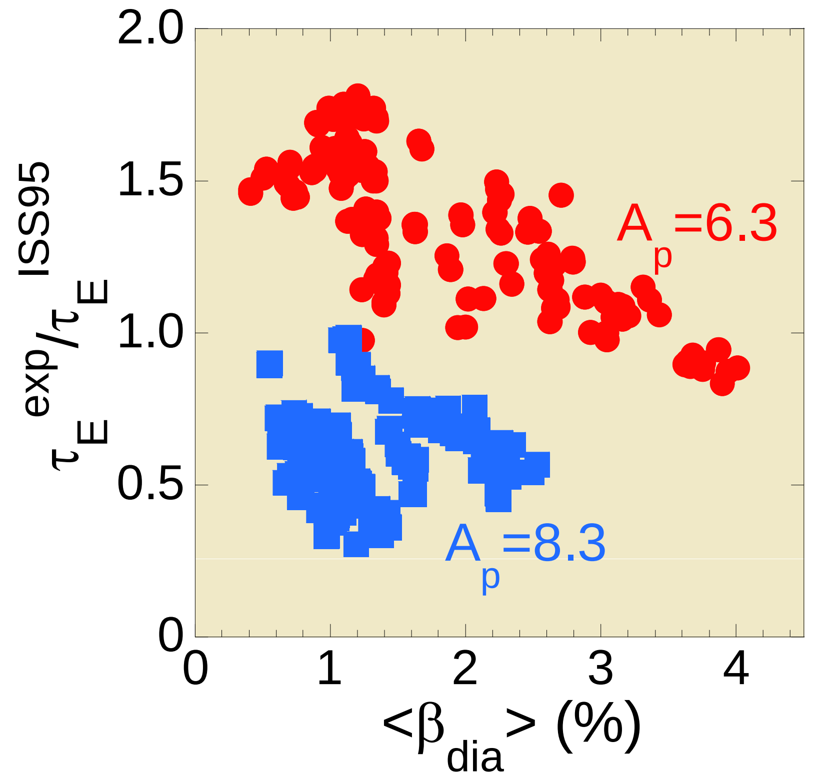
Carreras B A *et al* 1989 *Phys.Fluids* B1, 1011

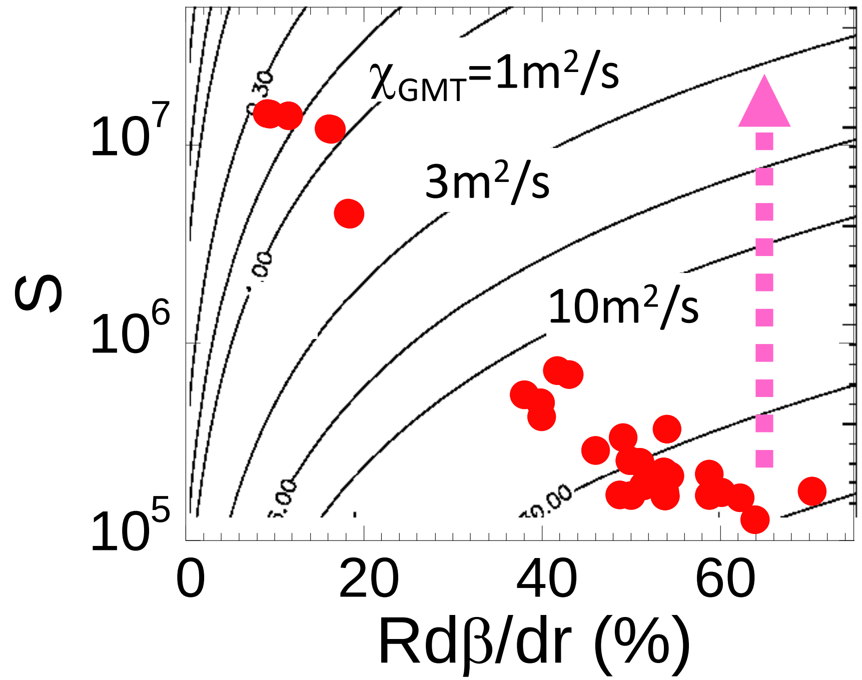


✓ Thermal diffusivity χ and density fluctuation show a coincidental increases with β



Confinement/transport gradually degrades in high-β regime





Degradation becomes large with enhancement of magnetic hill (large A_p).

Resistive g-mode turbulence

$$\chi_{GMT} \propto \beta^{4/3} S^{-4/3}$$

Confinement is anticipated to be improved in higher temperature operation

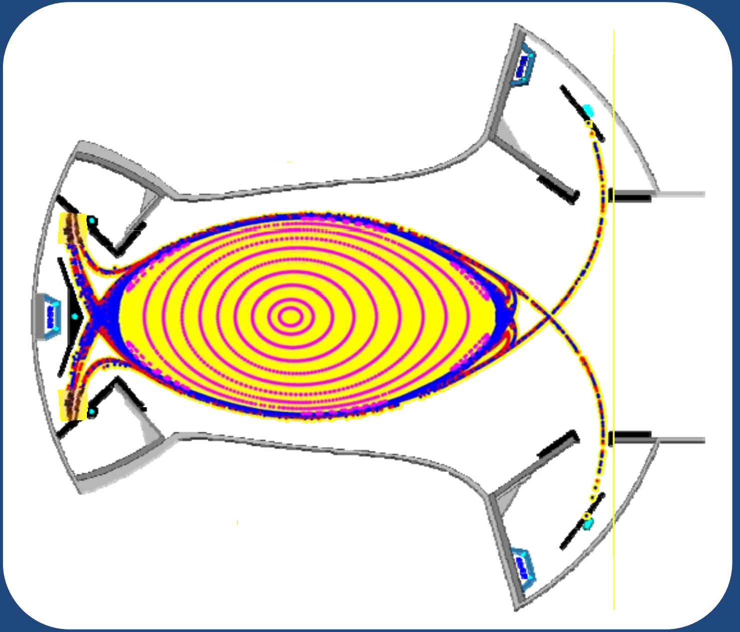
Summary

1. Achievement of high b of a reactor relevant 5 % in LHD is encouraging, however, integrated physics model is required to bridge over the gap to a reactor. Predictability should range over 10 for ρ*, 60 for ν_b* and 200 for *S*.
2. Documentation of saturation of the unstable mode is required to assess how much benign the interchange mode is.
3. Mechanism of Core Density Collapse is an open question.
4. Advanced theory/model to describe MHD stability in 3-D field, in particular, with magnetic islands and/or RMP, and stochastic field is demanding but necessary.
5. Confinement improvement is expected in large *S* regime.
6. Confinement of α particles on the way to high β and their driving instabilities (*K.Toi, PL04, on Fri.*)
7. Discussed high beta issues are not specific to LHD/heliotron. Significant contribution is expected from smaller devices together with theory and simulation.

On-going and Nearest Future Plan
- for collisionless high-β plasmas -

1. Optimization of dynamic B_v control
   (S.Sakakibara, P03-08 on Wed.)

2. Upgrade in 2010
   ✓ NBI 5th beam line 7 MW, 60 keV
   ➔ 30 MW in total
   ✓ Partial modification for closed divertor
   ➔ 2/10 inboard section, proto-type



3. Closed helical divertor *(S.Masuzaki, I.20 on Wed.)*

4. Deuterium
   ✓ Identification and documentation of isotope effect
   ✓ Upgrade of NBI (32 MW in total)

5. Reactor design study
   FFHR : Force-Free Helical Reactor *(T.Goto,C.13 on Wed.)*