Workshop on Active Control of MHD Stability: Extension of Performance
November 18-20, 2002
Columbia University, New York, NY

Recent MHD-Related Experiment in LHD : Helical vs. Tokamak Comparisons

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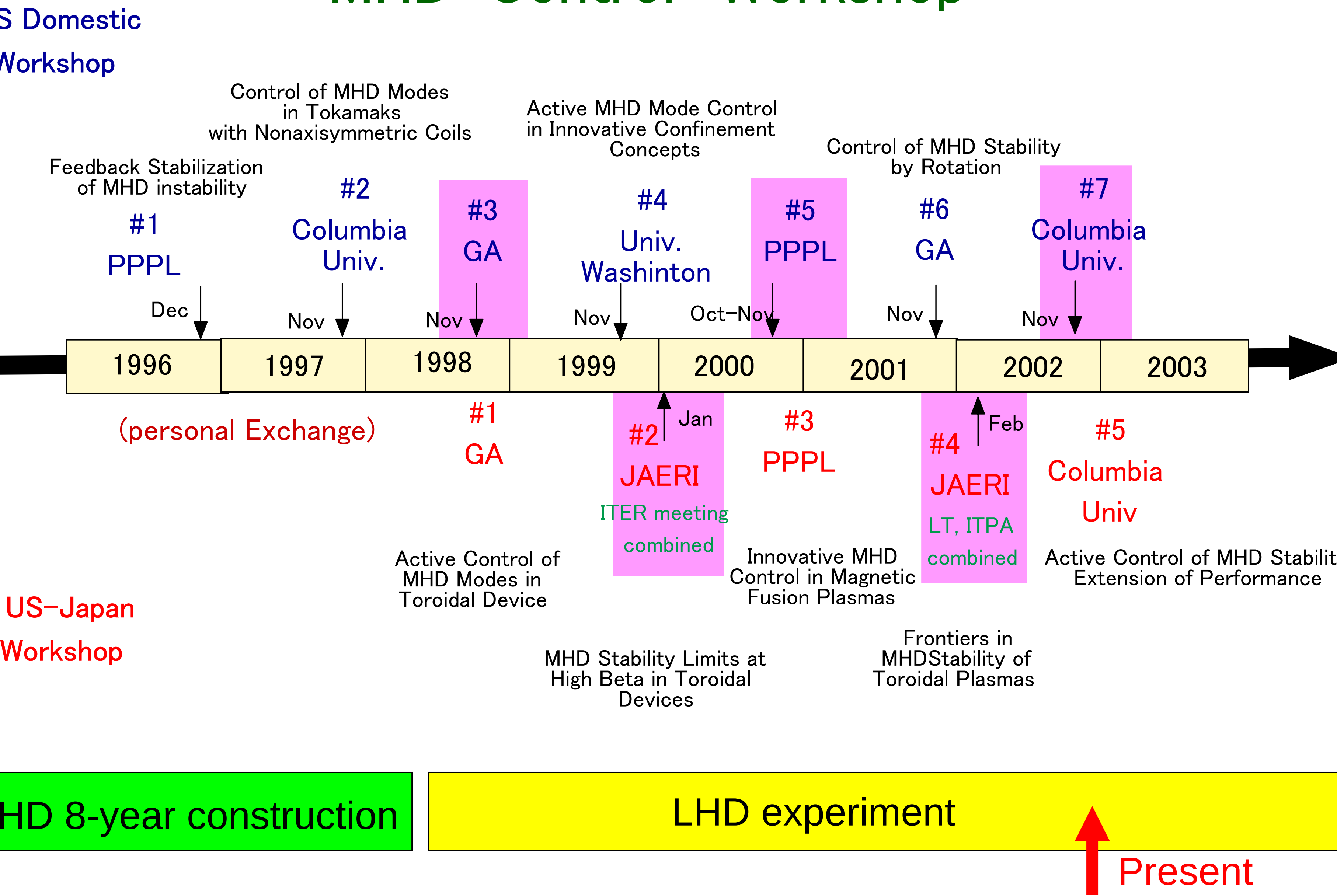
MHD Control Workshop



Domestic Research Collaboration

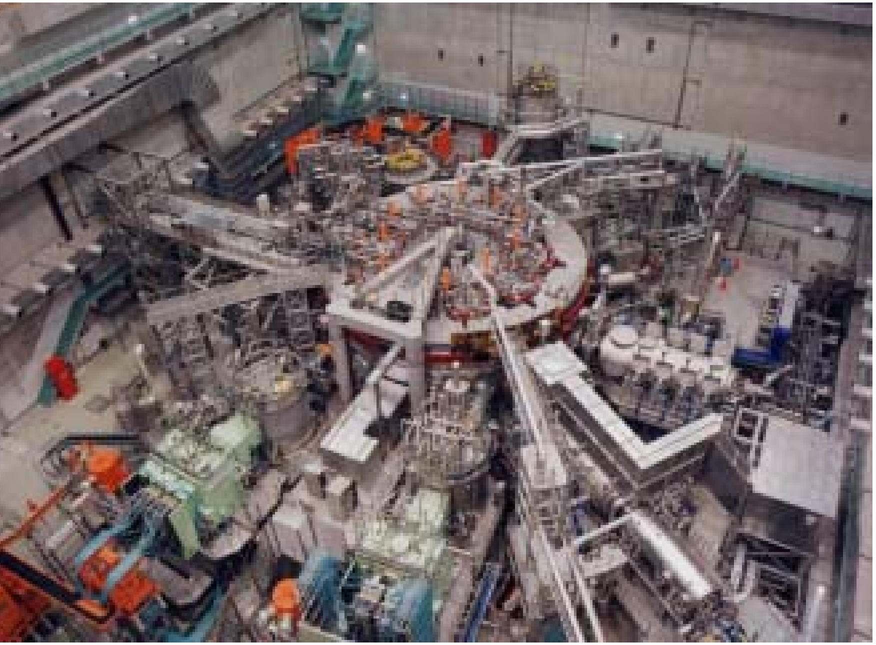
LHD → JT-60U
Sep. 2001

Feb. 2002
JT-60U → LHD

LHD & JT-60U

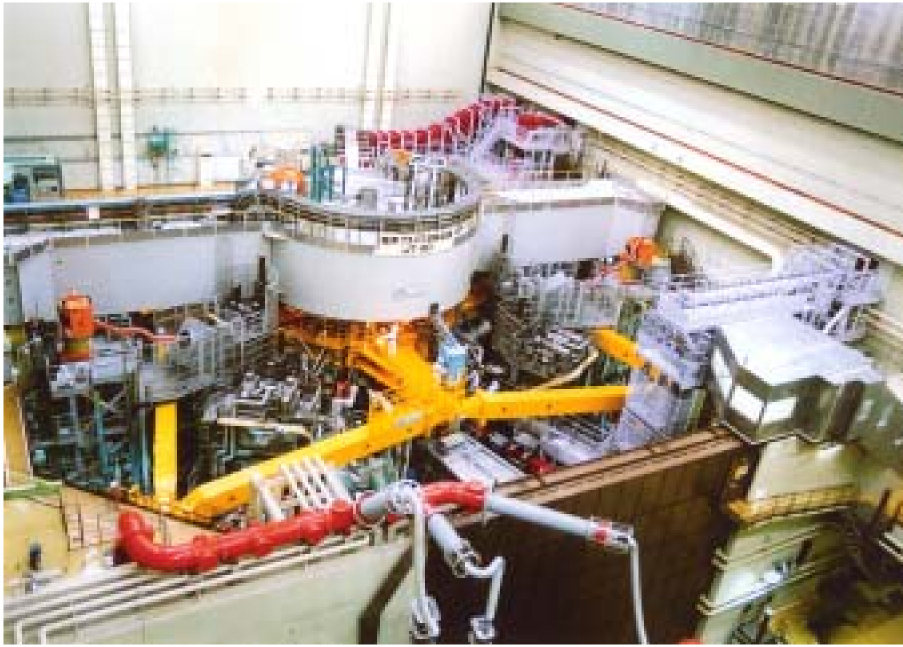
Helical

R=3.9m, a=0.6m
$V=30m^3$
B=3T (SC)
N-NBI 15MW
RF 10MW



Tokamak

R=3.4m, a=1m
$V=90m^3$
B=4T (NC), Ip=3MA
P-NBI & N-NBI 40MW
RF 15MW



Outline

1. Introduction
    - Reactor Prospect
    - Present Plasma Parameters
    - Control of LHD Plasma
2. Equilibrium Properties
3. Stability and Confinement
4. Density Limit and Disruption
5. Steady-State Operation
6. Summary

INTRODUCTION

For the realization of attractive fusion reactors, plasma operational boundaries should be clarified, and be extended to the higher performance limit.

There are several plasma operational limits:

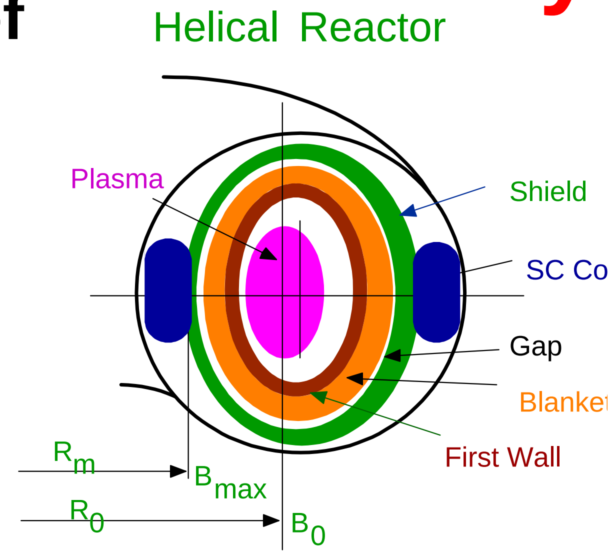
(1) confinement Limit ,
(2) stability Limit,
(3) density limit, and
(4) pulse-length limit.

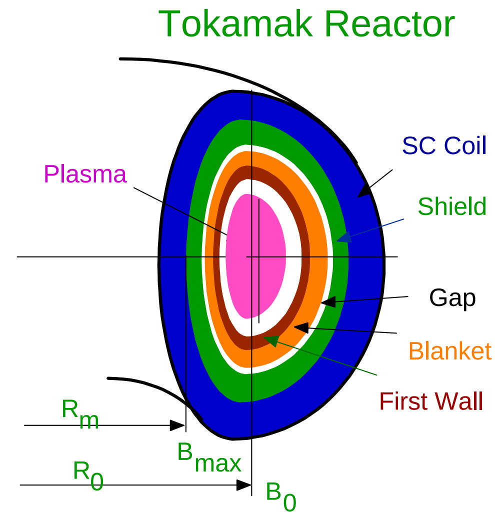
Here we would like to discuss on the similarities and differences between TOKAMAK and HELICAL systems.

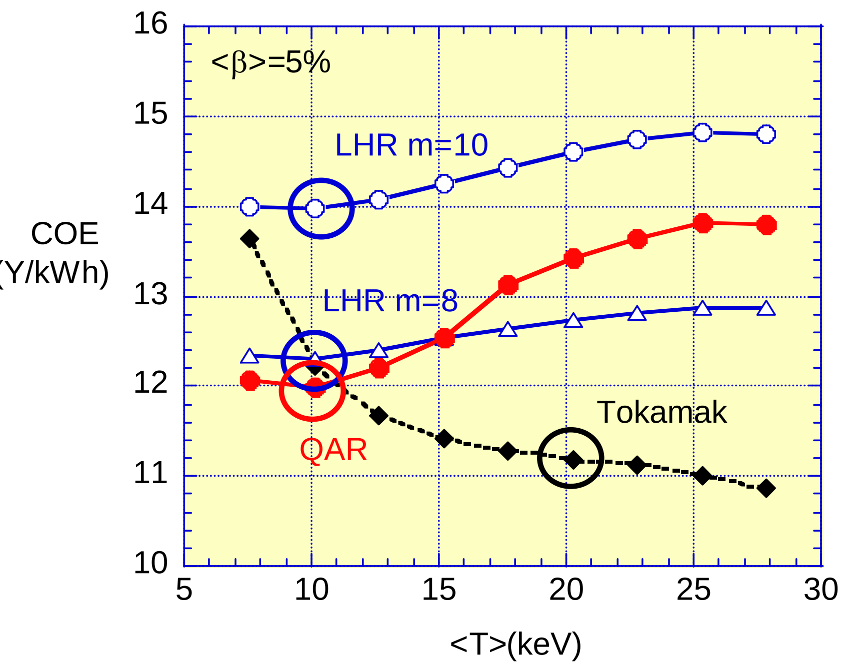
Clarify the Target!

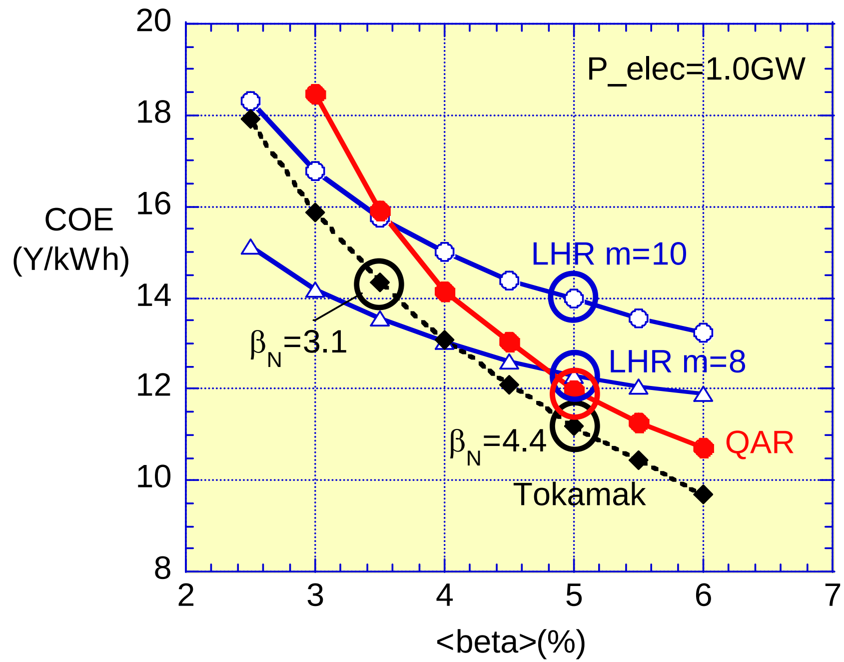
System Assessment of Helical Reactors in Comparison with Tokamaks

K.Yamazaki et al.,
IAEA-Lyon FT/P1-20









Requirement of MHD properties derived from Reactor System Assessment

High Bootstrap Current Fraction (>70%)

➔ Reduction of Current Drive Power

High Beta (>4%) Steady-State

➔ Compactness

Without Disruption (< once/several years)

➔ High Availability (>70%)

Helical/Tokamak Achieved Maximum Parameters

	TOKAMAK		HELICAL	
Electron Temperature T_e (keV)	26	(JT-60U)	10	(LHD)
Ion Temperature T_i (keV)	45	(JT-60U)	5	(LHD)
Confinement time τ_E (s)	1.2 1.1	(JET) (JT-60U,NS)	0.36	(LHD)
Fusion Triple Product $n_i \tau_E T_i$ ($m^{-3} \cdot s \cdot keV$)	15×10^{20}	(JT-60U)	0.22×10^{20}	(LHD)
Stored Energy W_p (MJ)	17 11	(JET) (JT-60U,NS)	1	(LHD)
Beta Value β (%)	40 (toroidal) 12 (toroidal)	(START) (DIII-D)	3.2 (average)	(LHD,W7-AS)
Line-Averaged Density n_e ($10^{20} m^{-3}$)	20	(Alcator-C)	3.6	(W7-AS)
Plasma Duration τ_{dur}	2 min 3 hr. 10min.	(Tore-Supra) (Triam-1M)	2 min 1 hour	(LHD) (ATF)

Control of LHD Plasma

- Shape Control
  inward shift ,elongation, triangularity, etc.
  (3-pair **PF Current** Control)
  minor radius (3-block **HF Current** Control)
  helical axis (1-pair **HF Current** Control)
  local island (10-pair **Additional Coils**)
- Current Control
  V_{loop} feed-back control (3-pair **PF Current** F.B.Control)
  N-NBI & ECH current drive
  BS current control (power and profile control)
- Density and Heating Power Control
  Gas Puffing and **Pellet** fueling
- Profile Control
  ITB & good confinement with **localized ECH**
  good confinement with **Pellet**
- Wall & Divertor Control
  Boronization & LID(local Island Control)

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2. **Equilibrium Properties**
3. Stability and Confinement
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Equilibrium: Similarities and Differences between Tokamak and Helical Systems

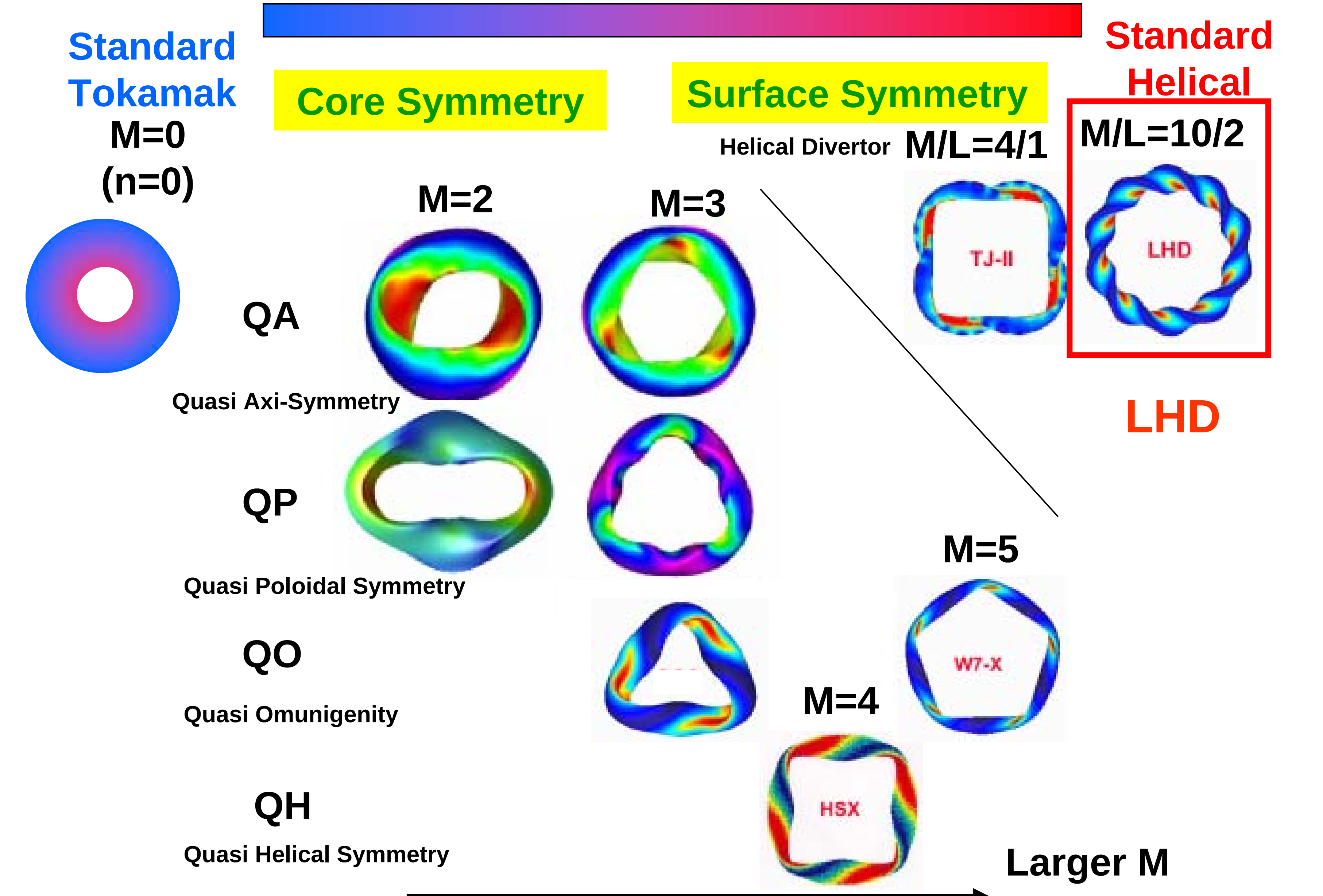
quilibrium

	STANDARD TOKAMAK	STANDARD HELICAL
Plasma Boundary Shape	2D	3D
Magnetic Field Components	Toroidal (m,n)=(1,0)	Toroidal (1,0) +Helical (L,M)+ Bumpy (0,M) Ripples
Plasma Currents	External + BS Currents	No net toroidal current or BS Current
q-profile	Normal or Reversed shear profile	Flat or Reversed shear profile
Divertor	Poloidal divertor 2D	Helical or island divertor 3D

Physics Properties

	STANDARD TOKAMAK	STANDARD HELICAL
Magnetic shear	Substantial Shear or Shearless in the core	Substantial Shear
Magnetic Well	Well in whole region	Hill near edge
Radial Electric Field	driven by toroidal rotation & grad-p	driven by non ambipolar loss (Helical Ripple)
Toroidal Viscosity	Small	Large (Helical Ripple)
grad-j, grad-p	grad-j driven grad-p driven	grad-p dominant
Island, Ergodicity	near separatrix	Edge Ergodic Layer

Advanced Plasma Shapes



Magnetic Shear / Well

Tokamak:

Shear is changed by current profile.

Magnetic well.

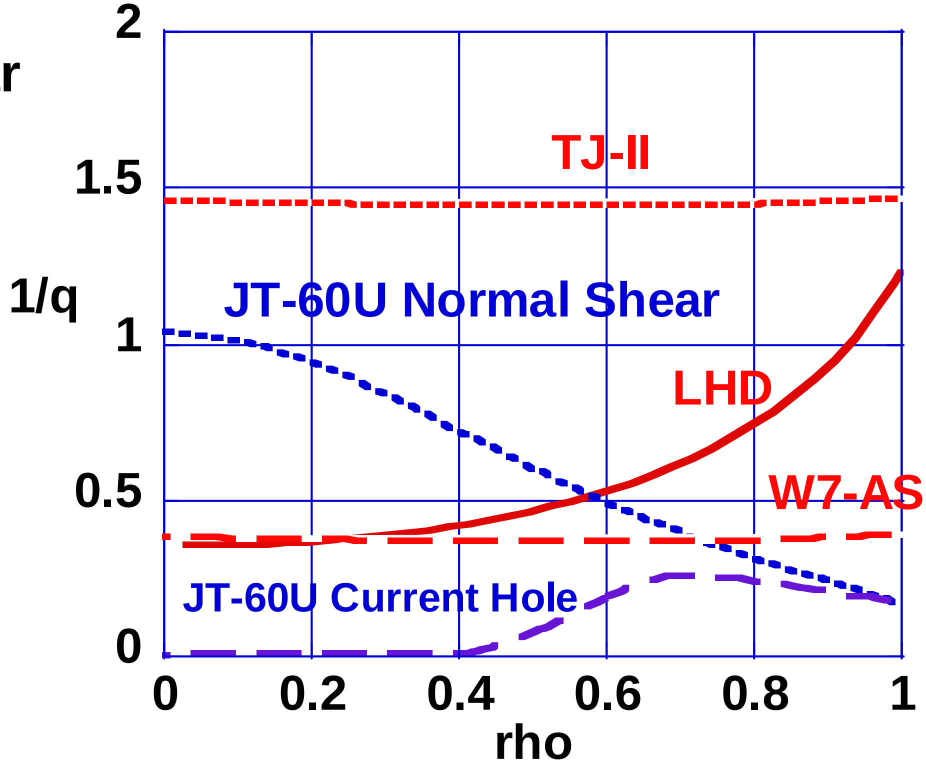
Helical:

A variety of shears by helical coil.

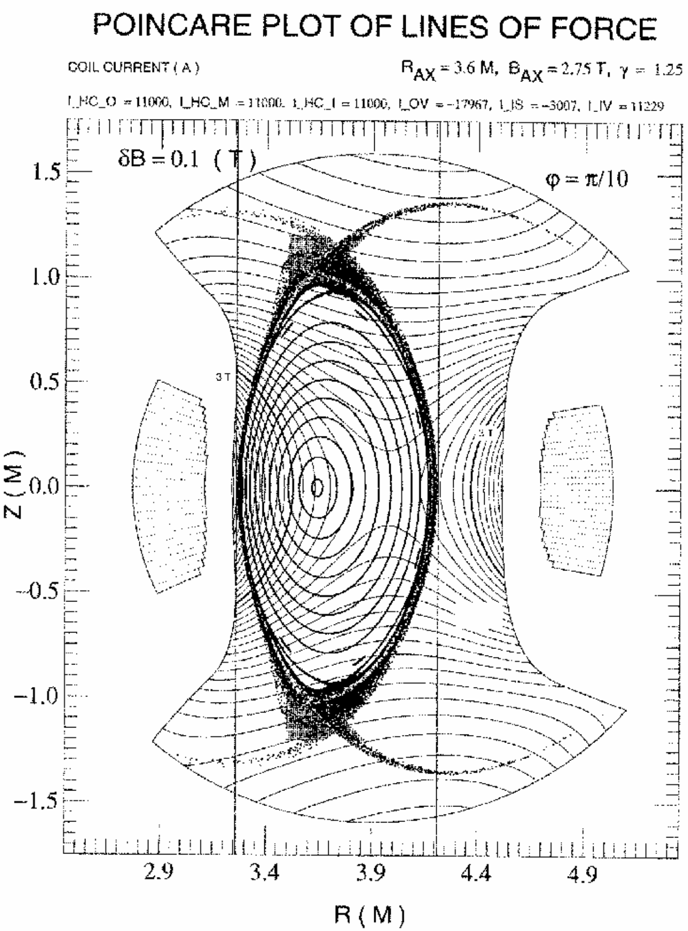
Magnetic hill near edge.

Normal or Reversed Shear

Flat or Reversed Shear



LHD Experimental Set-Up



LHD plasma is surrounded by ergodic field layer.

- **Experimental Conditions:**

  H & He Plasmas , R_{ax}=3.6 m B_t=2.8 T ~ 0.5 T, co & ctr-NBIs: $P_{abs}\leq$ 6MW, E$\leq$ 150 keV

- **Main diagnostics:**

  Magnetic probe arrays, SX-detector arrays, Hα-arrays, Tangential viewing high speed SX-camera, Thomson scattering, FIR-interferometer, ECE, micro-wave reflectometer and so on

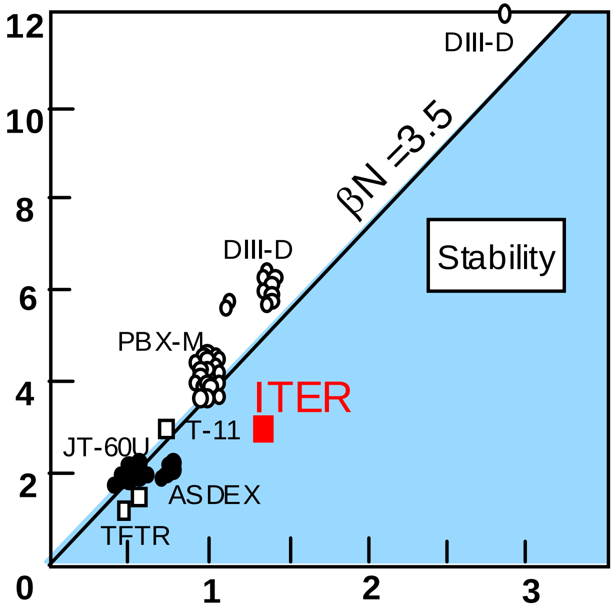
Stability Limits

j (grad-j) dominant or grad-p dominant ?

Tokamak

Ideal beta agrees with Ideal MHD

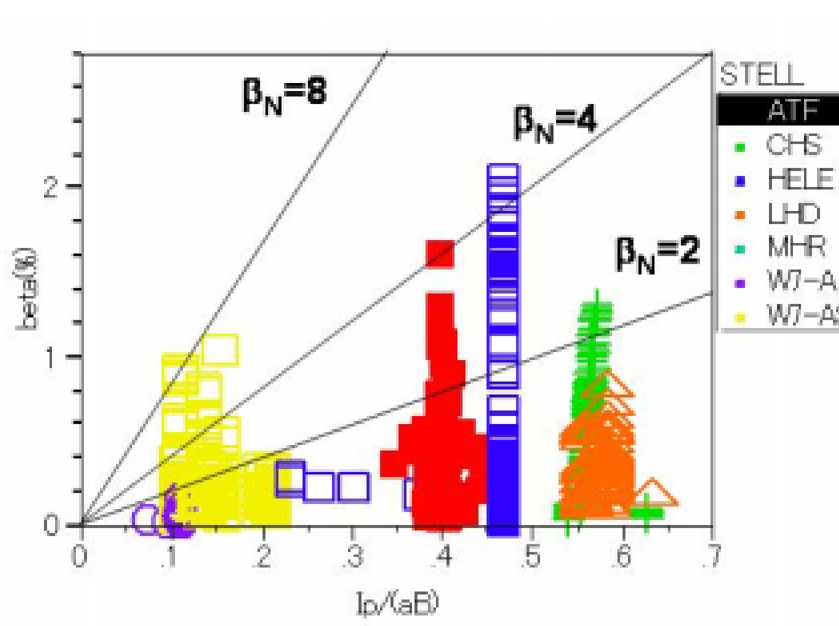
Resistive beta agrees with NTM & TM, RWM theories



Helical

Beta obtained beyond Mercier mode

Global mode is still marginal.

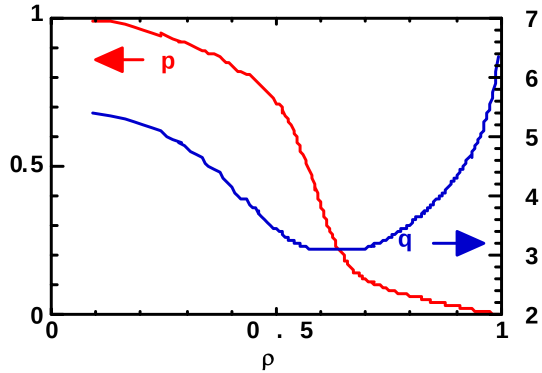


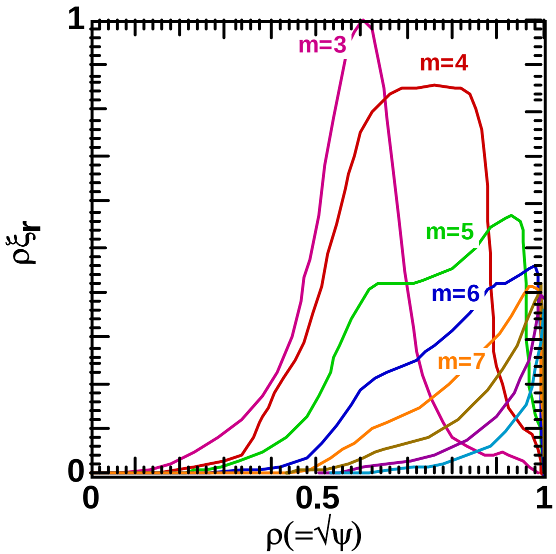
Mode structure

TOKAMAK

(JT-60U, Takeji)
ERATO-J code

Global mode driven by j

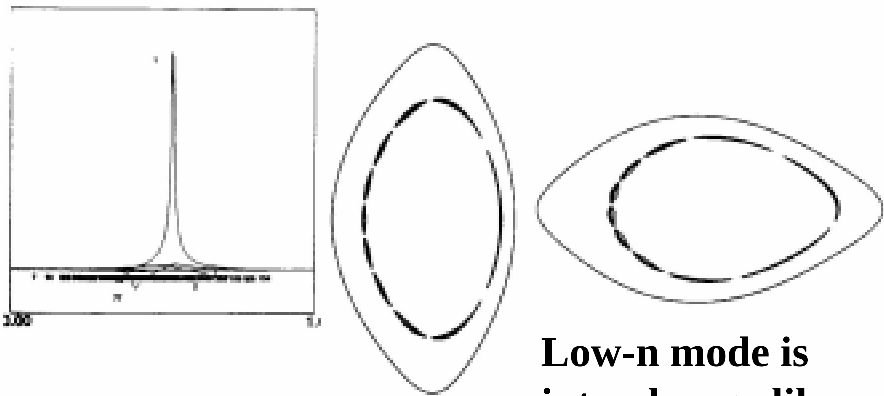




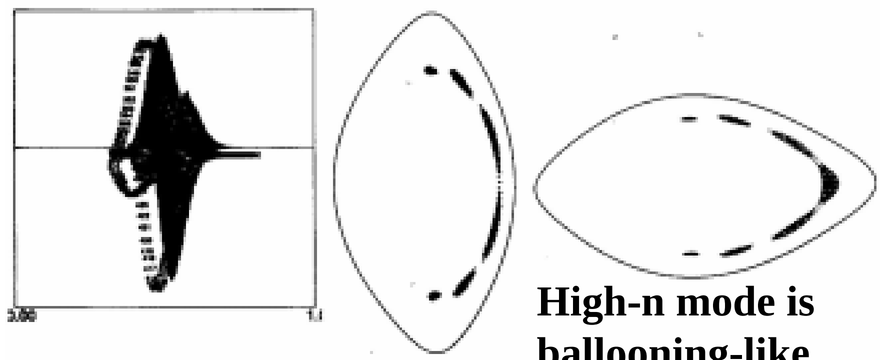
HELICAL

(LHD, Nakajima)
CAS3D code

Localized mode driven by grad-p



Low-n mode is interchange-like.

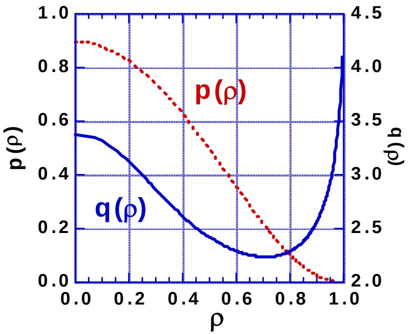


High-n mode is ballooning-like.

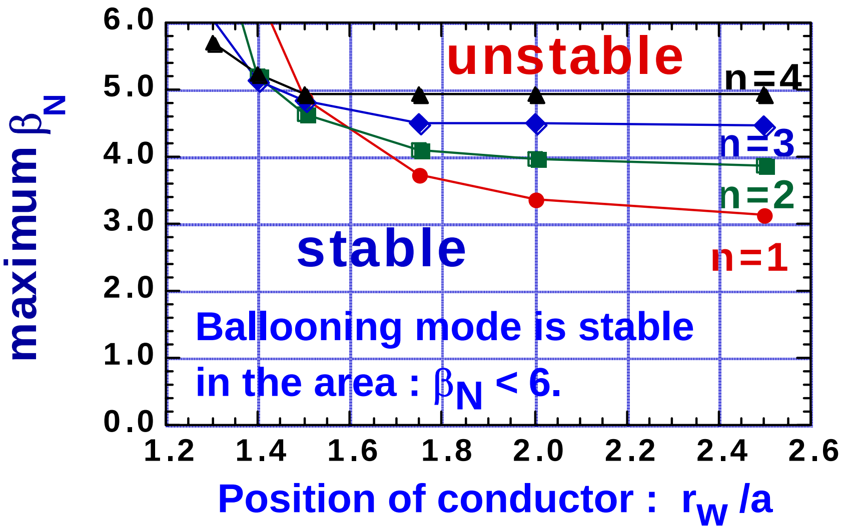
Effects of Wall

Tokamak

Kink-ballooning modes driven by j & grad-p can be easily stabilized by the fitted wall.

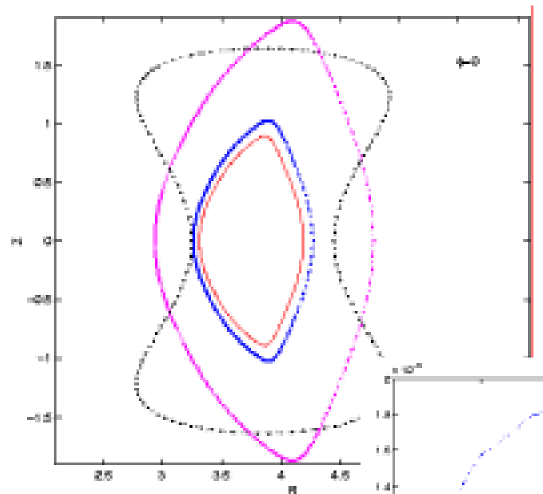


(JT-60SC, Kurita)

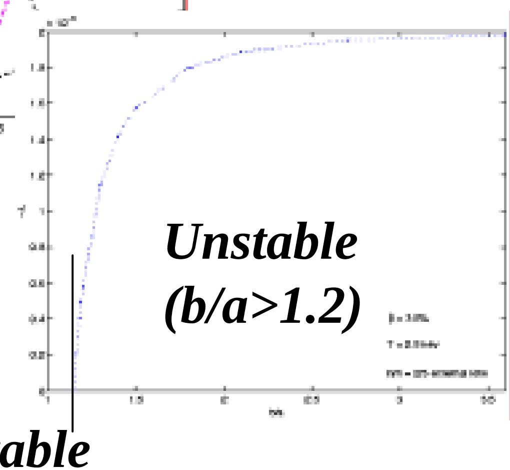


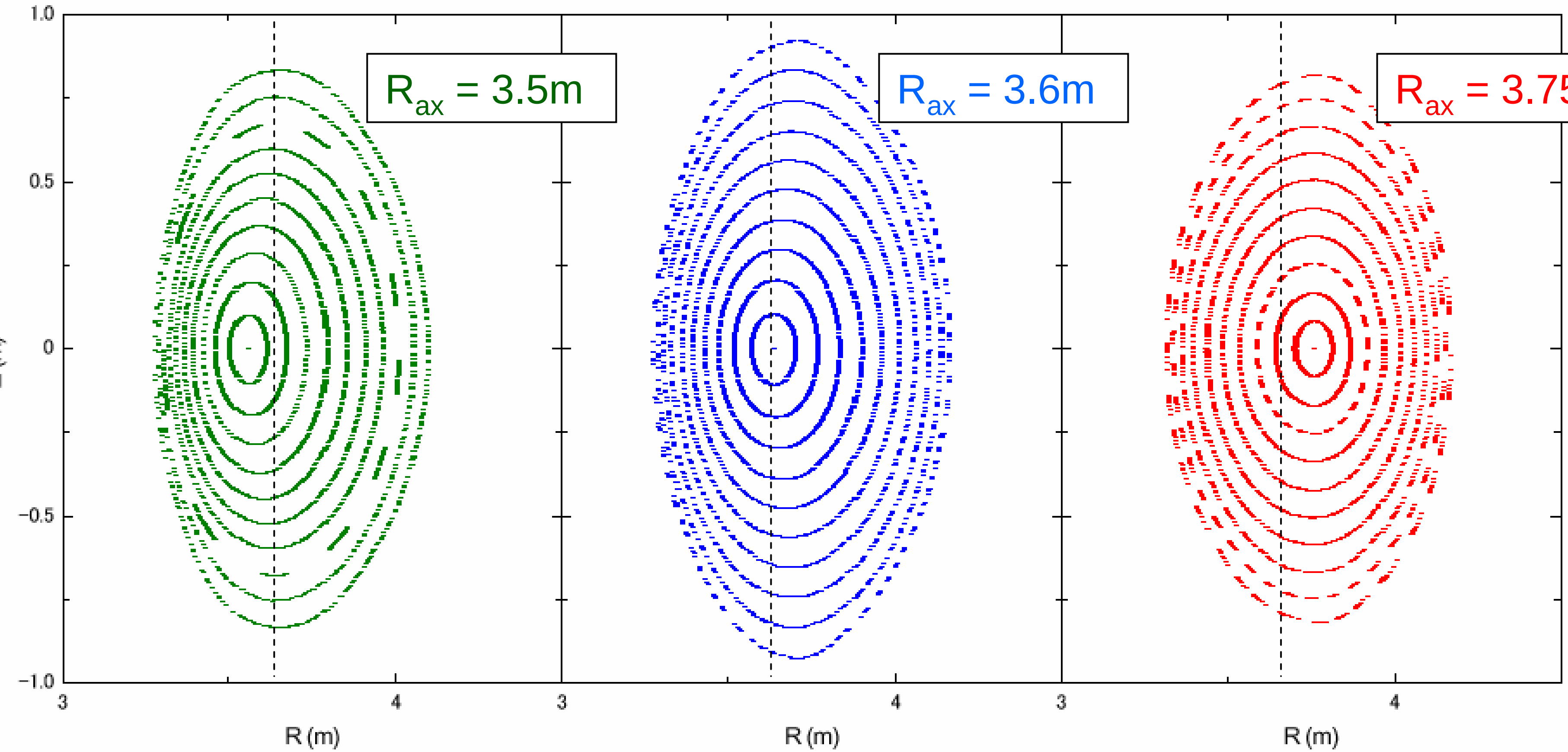
Helical

Mode is localized and there is no strong wall effect on pressure-driven mode, but substantial effects on BS current-driven external mode.



(LHD, Cooper) Terpsichore



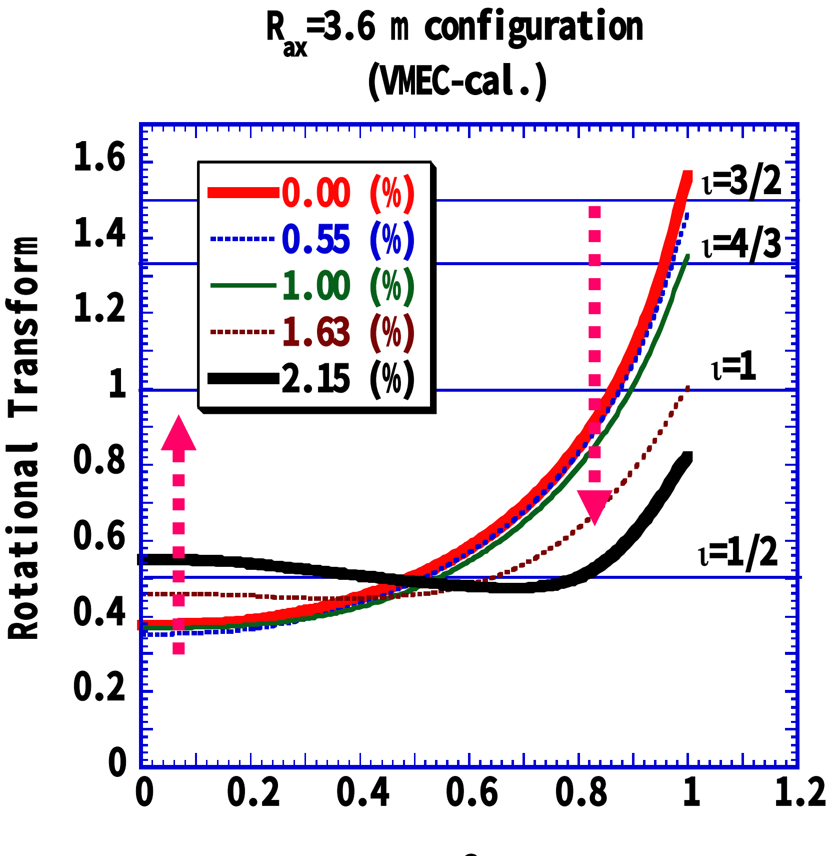


Prediction	**better**	← **Particle Confinement** →	**worse**
	worse	← **MHD Stability** →	**better**
Experiment	**better**	← **Energy Confinement** →	**wors**

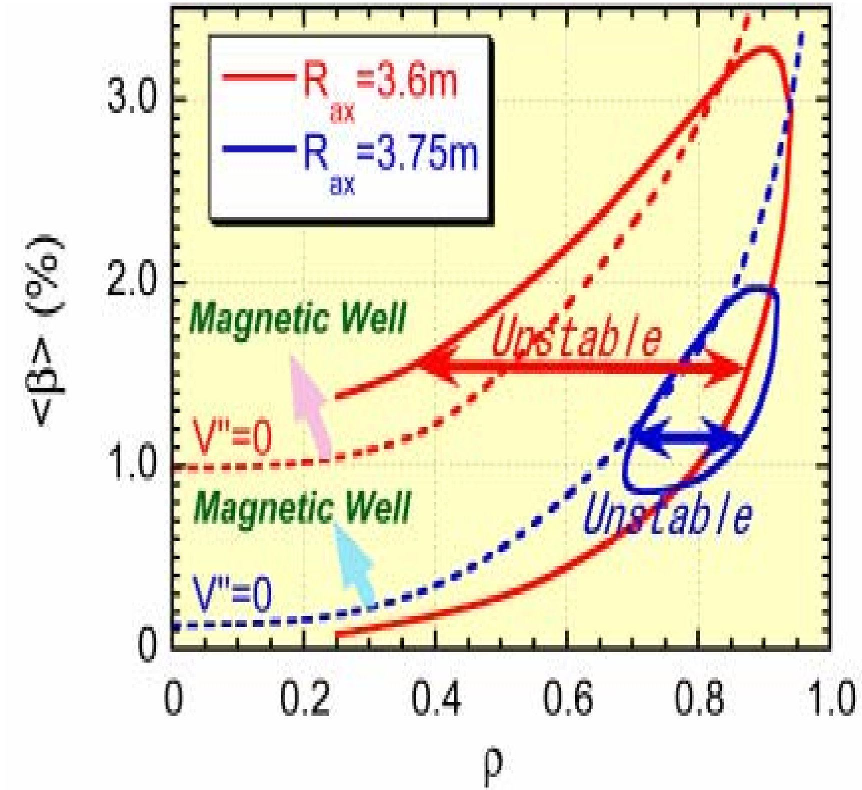
Characteristics of Magnetic Configuration

◆ LHD: *l*=2/N=10 Heliotron , R~3.6 m, <a>~0.6m, B_t<3 T

◆ Rotational transform: increasing function against ρ



◆ Magnetic Configuration with magnetic hill & well

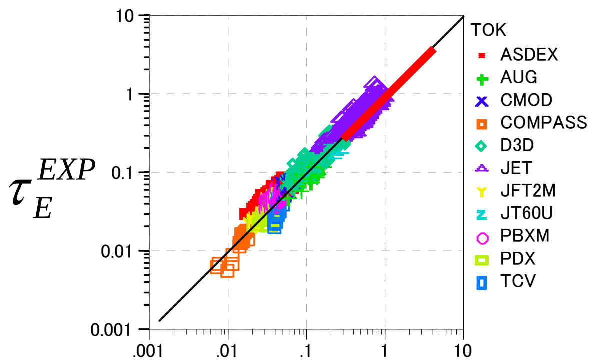


Confinement Scaling Laws

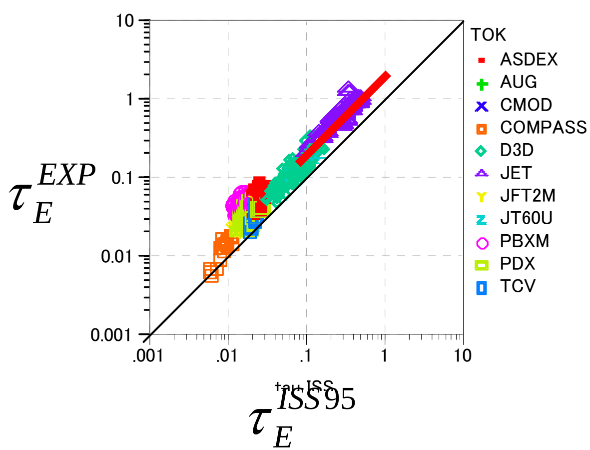
Comparing between ITER ELMy-H Database and Stellarator Database adding New LHD data

TOKAMAK

$$\tau_E^{ELMY} \propto \tau_B\, \rho^{*-0.83}\, \beta^{-0.50} \nu^{*-0.10}$$

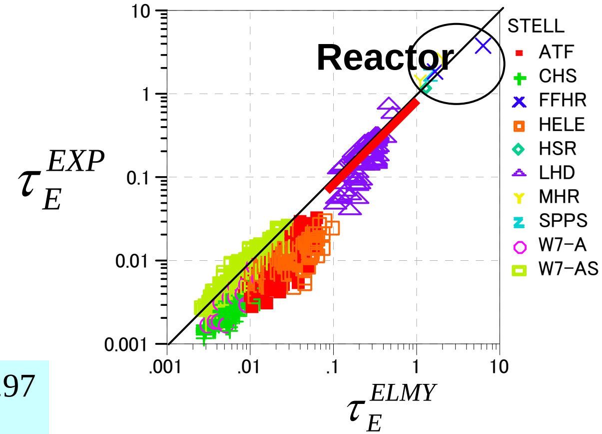


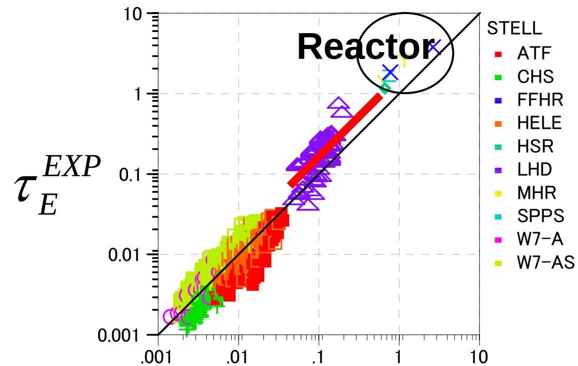
$$\tau_E^{ELMY} = 0.0365 R^{1.93} P^{-0.63} \overline{n}_e^{0.41} B^{0.08} \varepsilon^{0.23} I^{0.97}$$



HELICAL

$$\tau_E^{ISS95} \propto \tau_B\, \rho^{*-0.71}\, \beta^{-0.16} \nu^{*-0.04}$$

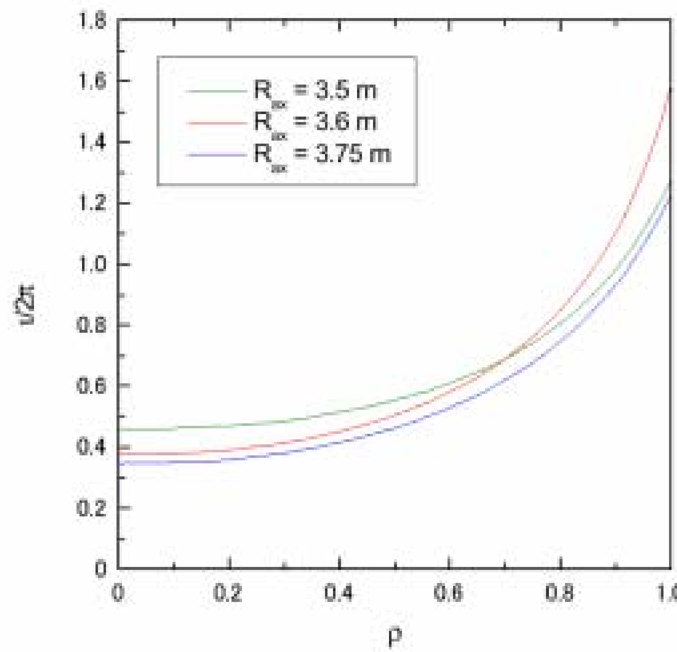




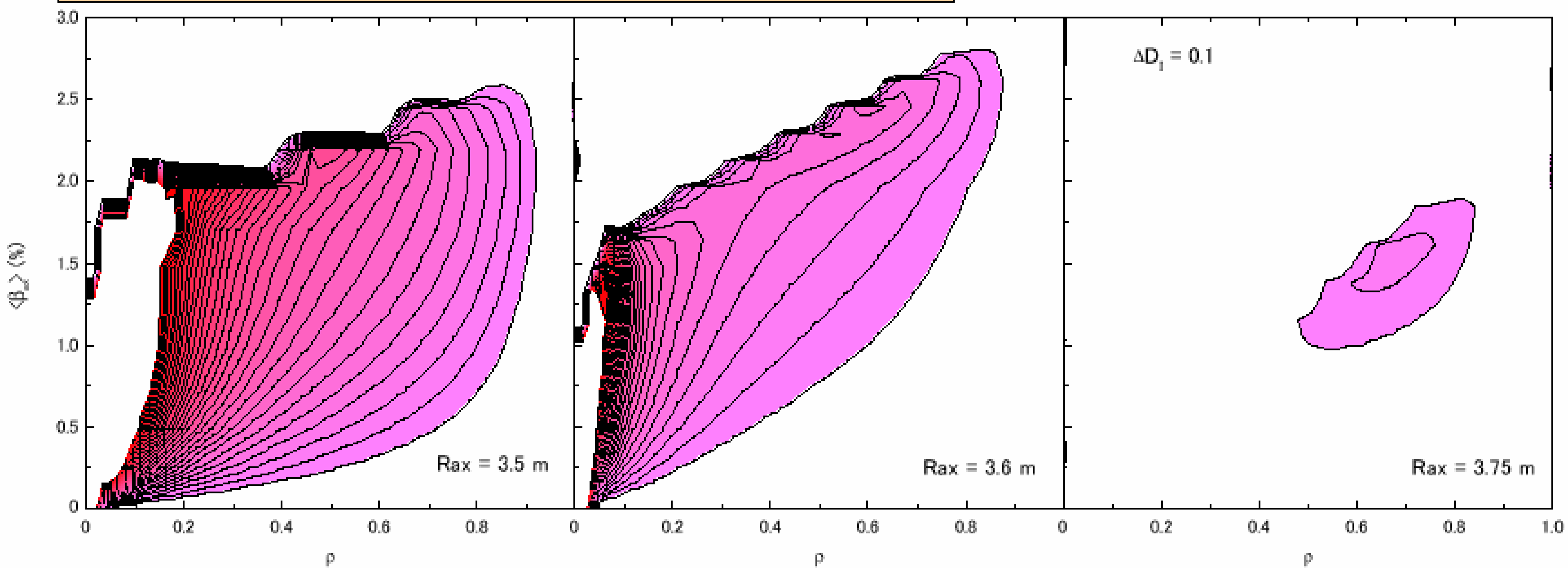
$$\tau_E^{ISS95} = 0.08 a^{2.21} R^{0.65} P^{-0.59} \overline{n}_e^{0.51} B^{0.80} \iota_{2/3}^{0.40}$$

Mercier Mode Stability

- Magnetic hill formation due to R_{ax} inward shift
  → Expansion of Mercier unstable region
- magnetic shear destabilizes core- MHD mode
- Shafranov shift → Second stability



Achieved <β> R_{ax} = 3.5 m ⇒ 2.8 %
R_{ax} = 3.6 m ⇒ 3.2 %
R_{ax} = 3.75 m ⇒ 1.5 %



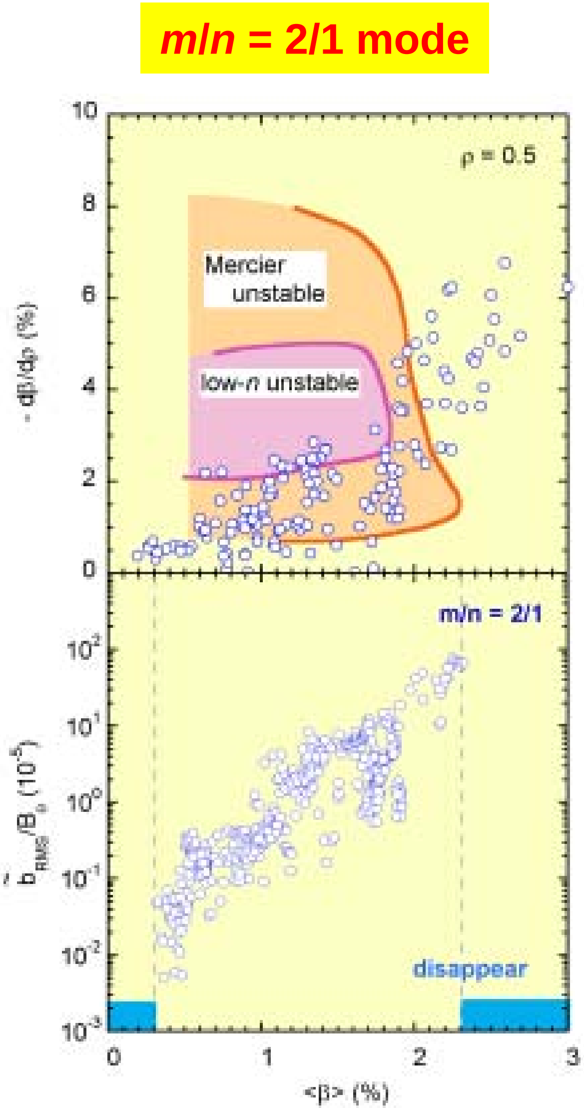
MHD Activities in R_{ax} = 3.6 m Configuration

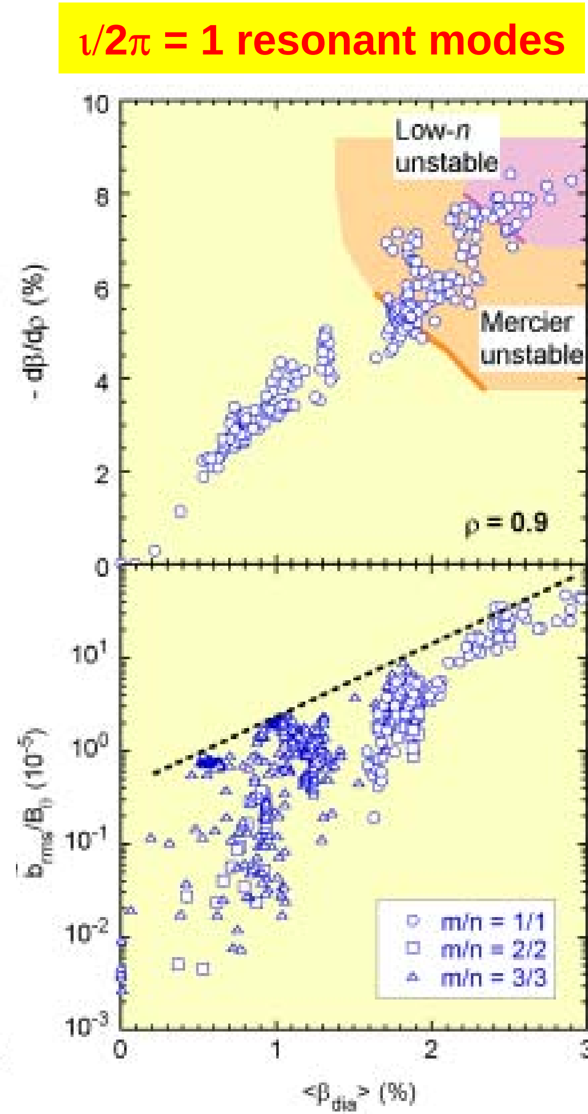
***m*/*n* = 2/1 mode**

- The present operational region is located in marginal against the low-*n* ideal instability
- Mercier mode is unstable when $<\beta_{dia}>$ < 2.3 %
- The *m/n* = 2/1 mode has been observed in Mericier *unstable* region

$\iota/2\pi$ = 1 resonant modes

- In high-β reigon, ideal mode in the peripheral region is unstable because of reduction of magnetic shear.
- Amplitudes of the $\iota/2\pi$ = 1 resonant modes increases with the pressure gradient.



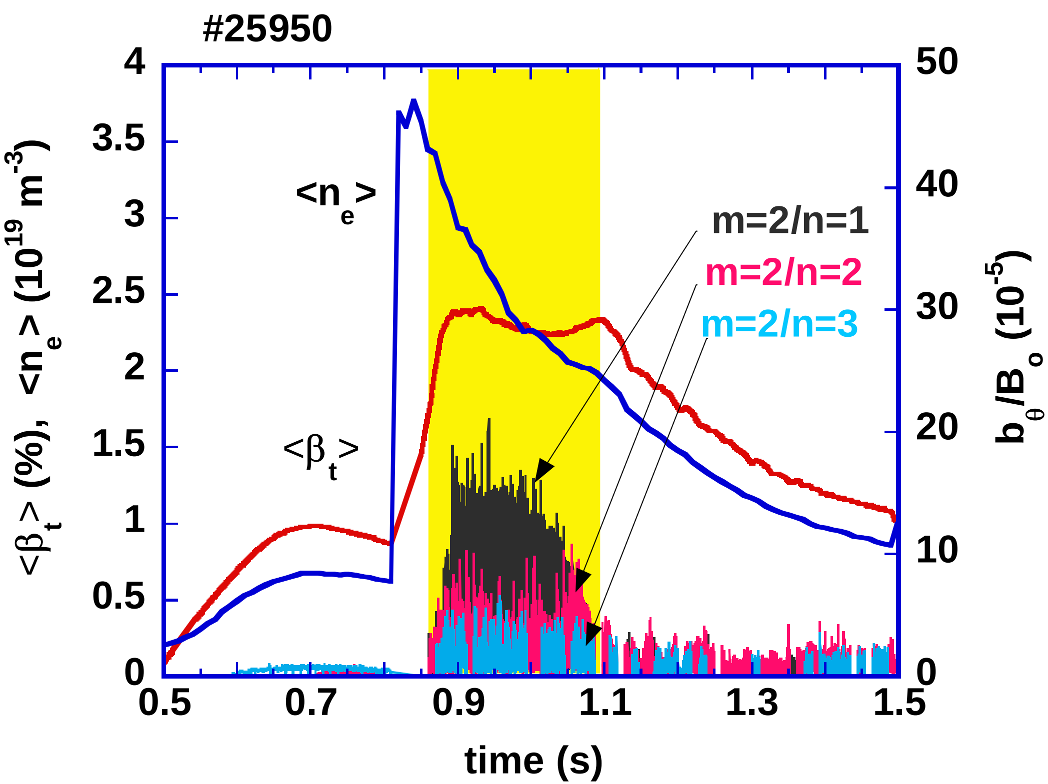


Effects of m=2/n=1 mode on plasma confinement

K.Toi et al., IAEA-Lyon (2002) EX/S3-2

- **NBI heated plasma with ice pellet injection at B_t=0.6T**
- **m=2/n=1 mode is strongly destabilized when $\langle\beta_t\rangle$ exceeds ~2.2%, together with m=2/n=2 mode.**

(S. Sakakibara et al, NF2001&PPCF2002)



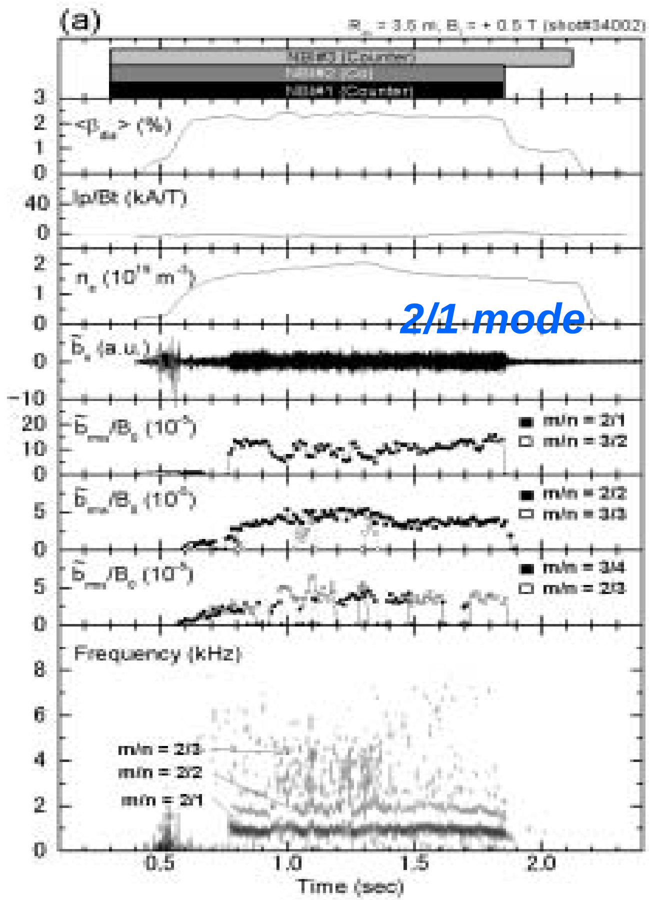
In the case that ∇P is transiently enhanced by ice pellet injection, m=2/n=1 interchange mode often induces sawtooth crash even in low beta plasmas. (*S. Ohdachi et al., Int. Stellarater W/S 2002*)

Effect of Plasma Current on High-β Discharges in R_{ax} = 3.5 m Configuration

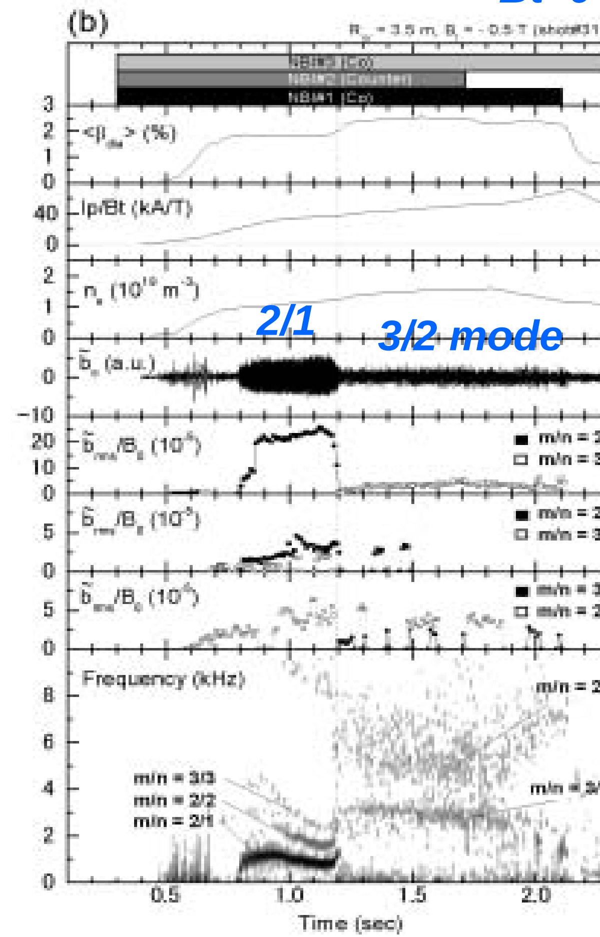
(a) **$|I_p/B_t| \leq$ 5 kA/T**
Ohkawa Current (Counter) + Bootstrap Current (Co) ~ 0
- *m/n* = 2/1 and 2/2 modes are observed to the end of discharge
- Amplitude of m/n = 2/2 mode increases and decreases with n_e
→ pressure gradient depends on n_e

(b) **$|Ip/Bt| \leq$ 70 kA/T**
Ohkawa Current (Co) + Bootstrap Current (Co)
- *m/n* = 2/1 mode abruptly appears and disappears
→ Disappearance of the resonant surface
- $<\beta_{dia}>$ increases after the disappearance of the mode
- *m/n* = 3/2 mode appears after the event
→ the decrease in magnetic shear
- *ι/2π = 1 resonant modes disappear with the m/n = 2/1*

$|I_p/B_t| \leq$ 5 kA/T *Bt>0*



$|I_p/B_t| \leq$ 70 kA/T *Bt<0*



0.5T/6.1MW

S.Sakakibara et al. ICPP-Sydney (200

Disappearance of MHD Activity

S.Sakakibara et al.
ICPP-Sydney (2002)

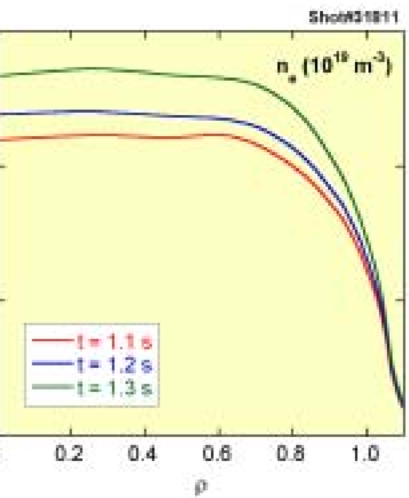
- Amplitude of the m/n = 2/1 mode starts to decrease, core pressure increases, and the peripheral pressure also increases after the mode disappears .

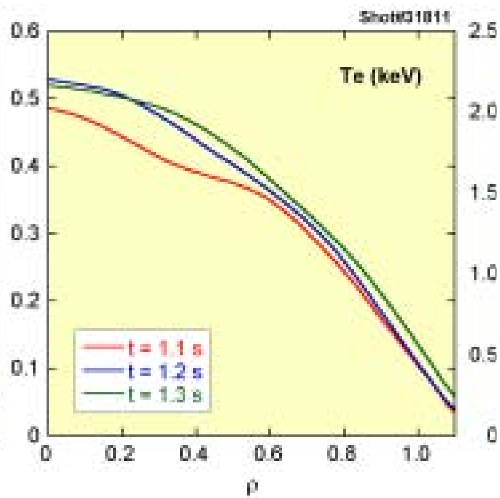
- T_e at $\rho \leq 0.6$ at t = 1.2 s is higher than that at t = 1.1 s, and the profile at t = 1.3 s is almost the same as that at t = 1.2 s

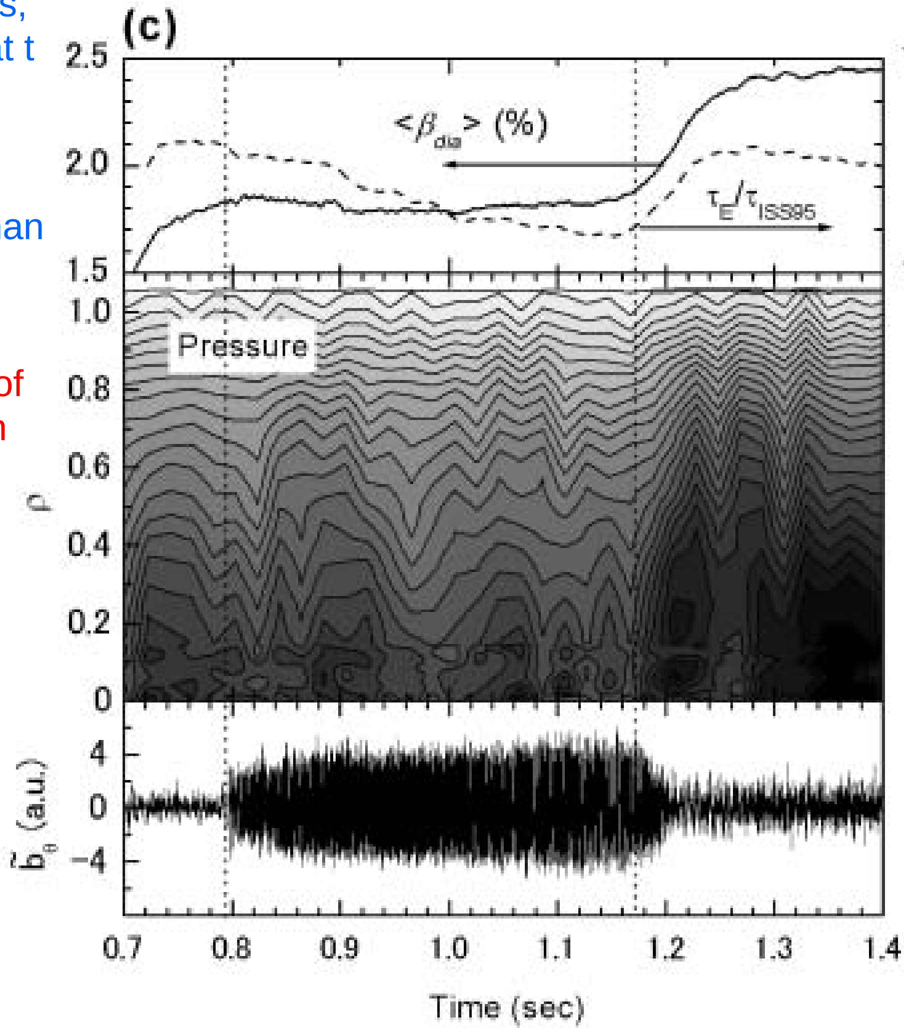
- The n_e increases with keeping the same profile.

The ramp-up rate of n_e from 1.1 s to 1.2 s is higher than that from 1.2 to 1.3 s, although the gas puff fueling is constant.

- The increase with $<\beta_{dia}>$ is caused by the increment of n_e in the peripheral region in addition to the increase in core - T_e.

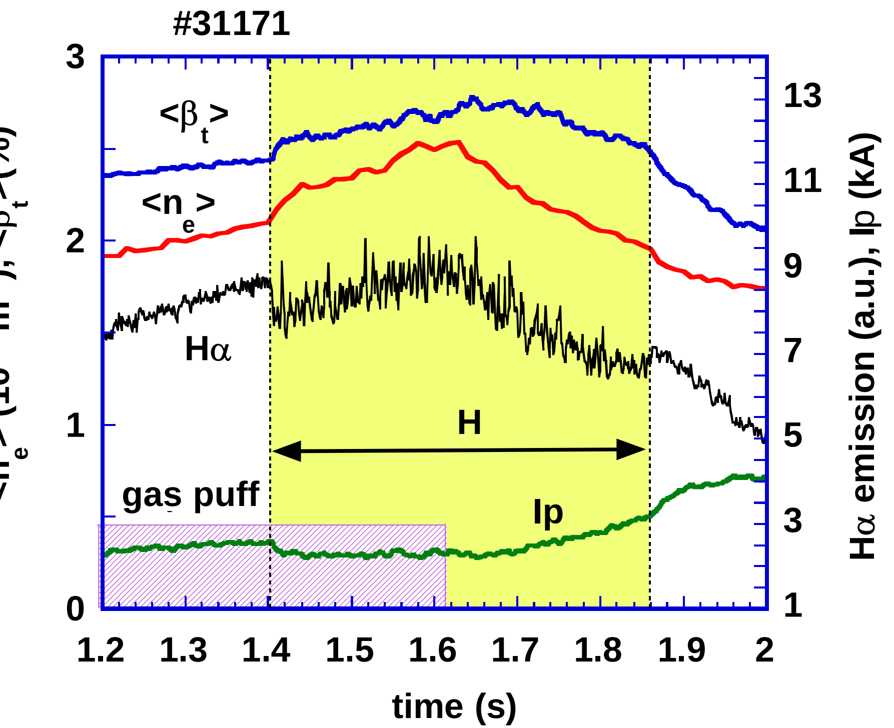


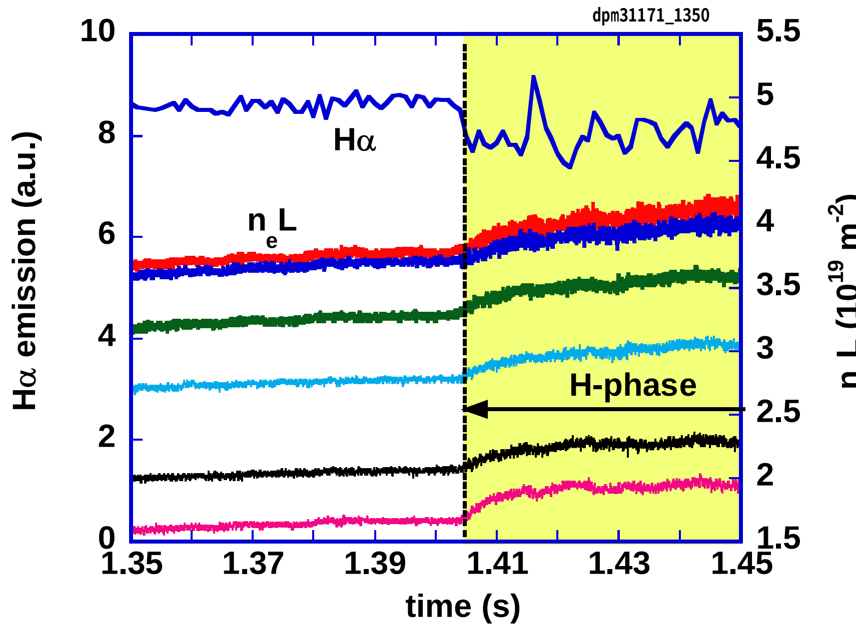


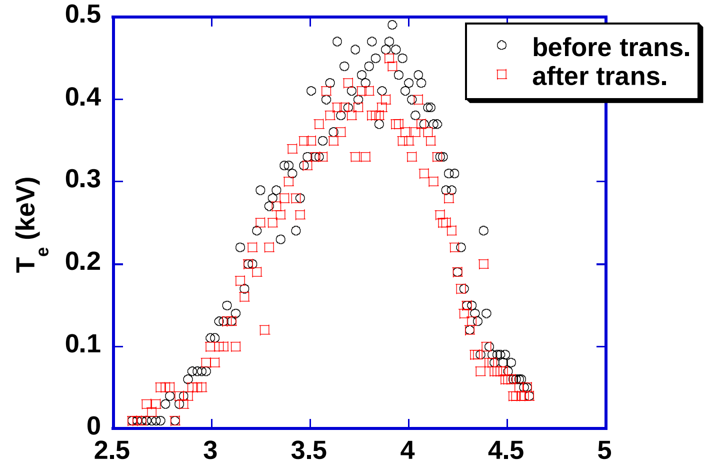


L-H Transition in magnetic hill region of high beta plasmas

K.Toi et al., IAEA-Lyon (2002) EX/S3-2

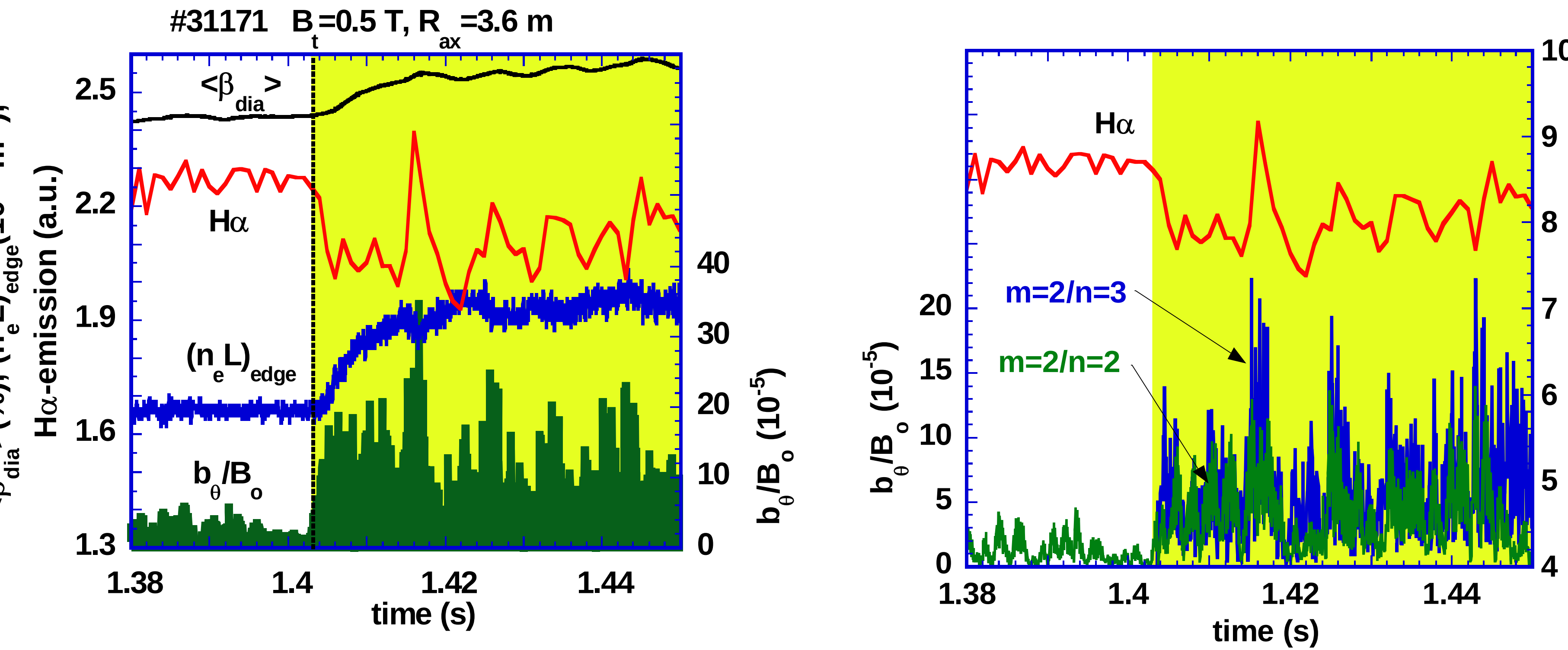






- NBI heated plasma with L-H transition at B_t=0.5T & P_{abs}~6MW.
- At the transition, ne-profile becomes further broad, while Te-profile remains unchanged.

L-H Transition in magnetic hill region of high beta plasmas

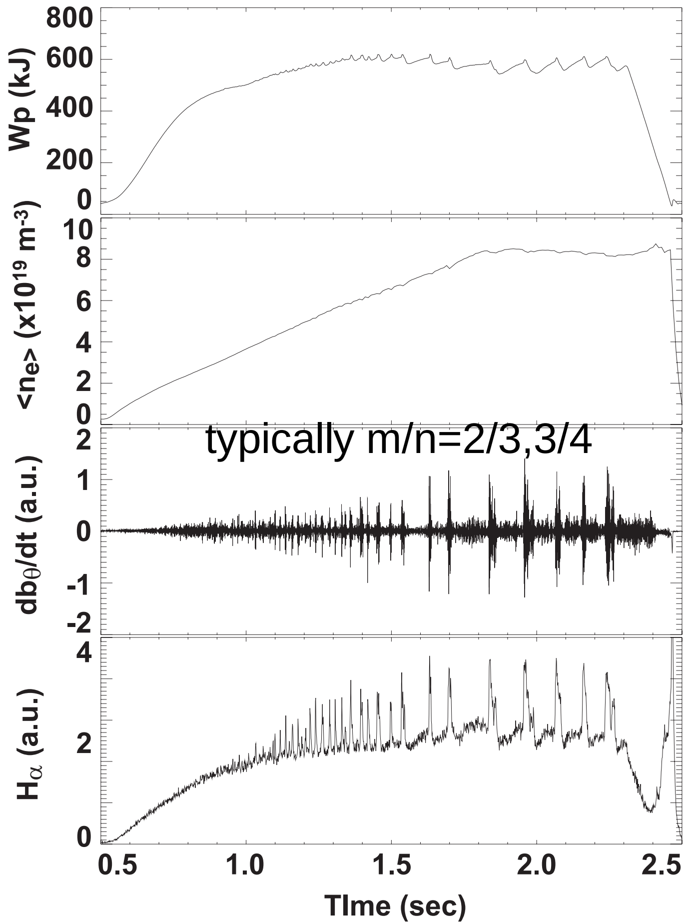


◆ **m=2/n=3 and m=2/n=2 modes are promptly destabilized at the L-H transition that takes place in the plasma edge region of magnetic hill. The excitation of these modes leads to beta-saturation.**

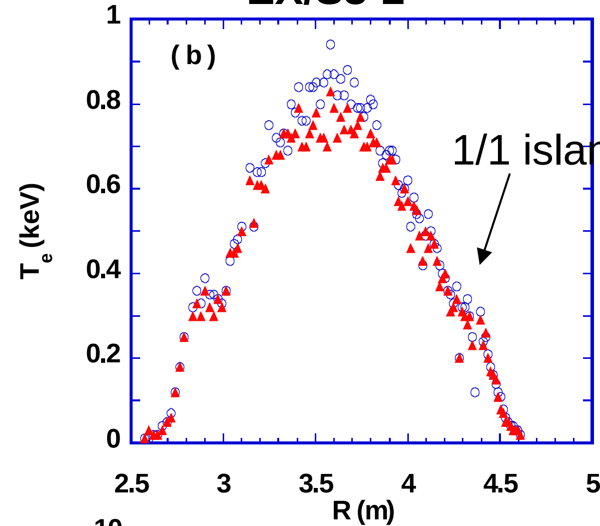
K.Toi et al., IAEA-Lyon (2002) EX/S3-

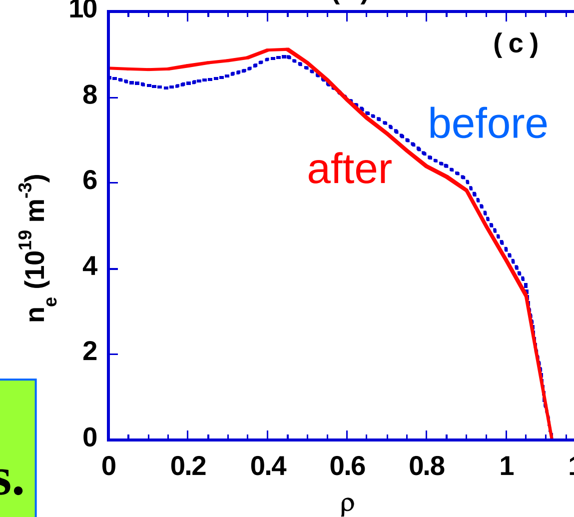
Edge harmonic modes in a plasma with steep pressure gradient near the edge

- EHMs are often excited in high performance plasma with steep edge ∇P even in low beta (< 1%), and become bursting at a certain $(\nabla P)_{crit}$.
- Bursting EHM →10% drop of Wp (ne-drop rather than Te in the edge)



K.Toi et al., IAEA-Lyon (2002 EX/S3-2





- Bursting character of EHM can be suppressed by removing m=1/n=1 magnetic island using LID fields.

1. Introduction
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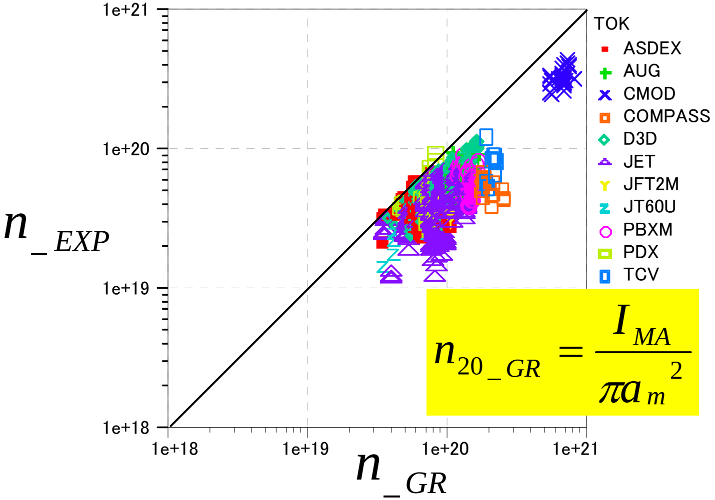
4. **Density Limit and Disruption**
5. Steady-State Operation
6. Summary

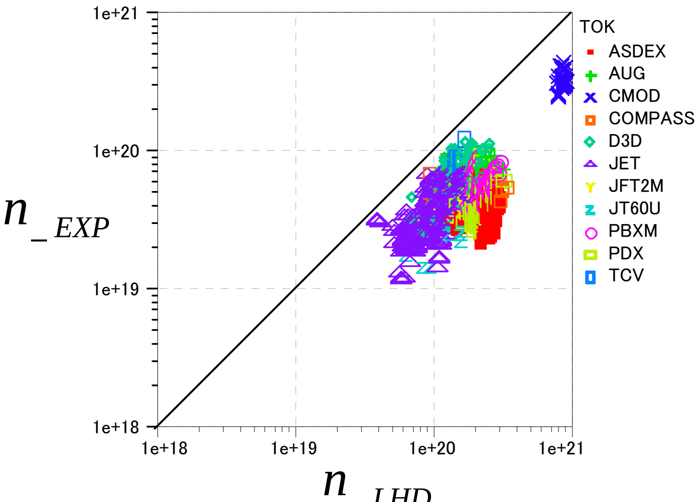
Operational Density Regime

Tokamak

radiation & MHD collapse
leading to current disruption

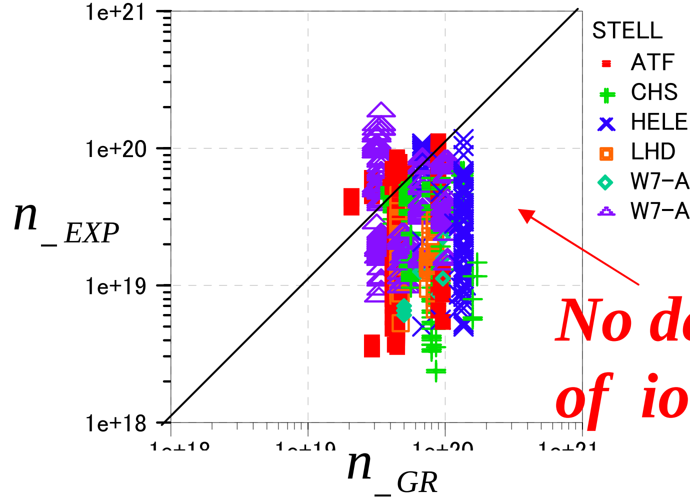


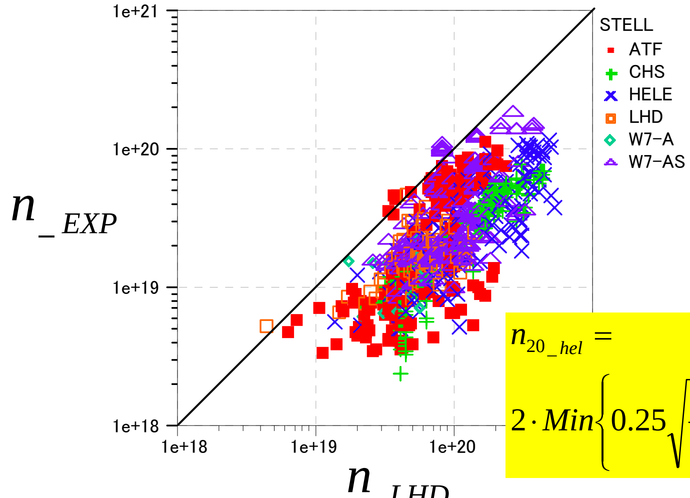
$$n_{20\_GR} = \frac{I_{MA}}{\pi a_m^{\,2}}$$



Helical

radiation collapse
slow plasma decay





$$n_{20\_hel} = 2 \cdot Min\left\{0.25\sqrt{\frac{P_{MW} B_T}{R_m a_m^{\,2}}}, 0.35\frac{P_{MW}}{R_m a_m}\sqrt{\ldots}\right.$$

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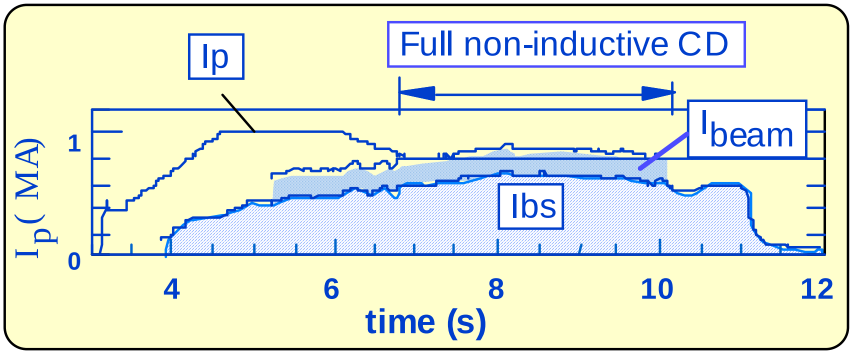
Steady-state Operation

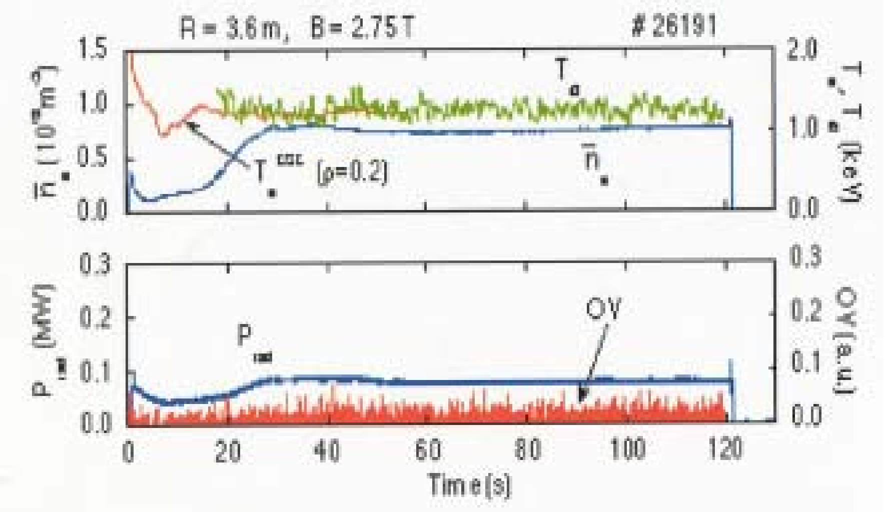
Tokamak

NB Current Drive
in JT-60U RS Elmy H-mode
(80% bootstrap current fraction)

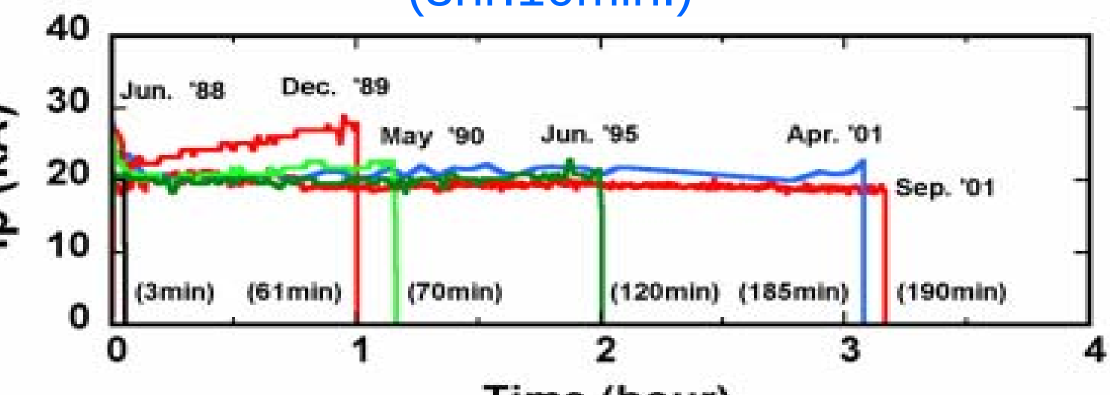


Helical

~1 keV long pulse operation
In LHD (ICRF 0.8MW)



LH Current Drive in Triam-1M
(3hr.10min.)



(Triam-1M,
M. Sakamoto,
ITC-12)

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Operational Limits (General Summary)

	STANDARD TOKAMAK	STANDARD HELICAL
Confinement	Gyro-Bohm	Gyro-Bohm (Global) Helical Ripple Effect (Local)
Beta Limit	Kink-Ballooning Mode Resistive Wall Mode Neoclassical Tearing Mode	Low-n Pressure-Driven Mode
Density Limit	Radiation & MHD Collapses	Radiation Collapse
Pulse-Length Limit	Recycling Control Resistive Wall Mode Neoclassical Tearing Mode	Recycling Control Resistive mode (?)

Beyond limit	Thermal collapse Current quench	Thermal collapse

Summary on Recent MHD-related LHD Experiment

●A volume averaged beta value of ~3 % was achieved in NBI plasmas without disruptive phenomena.

●The m/n = 2/1 mode excited in the core region is dominant, and the plasma current decreasing magnetic shear enhances the mode activity.

●The plasma current exceeding a certain value (I_p/B_t ~40kA/T) leads to the disappearance of the 2/1 mode, and improves the plasma confinement by ~20 %.

●L-H transition in magnetic hill region of high beta (>2%) plasmas and the beta saturation after this transition were observed.

●Bursting Edge Harmonic Modes (EHMs) excited in a plasma with steep (∇P)edge even in low beta regime (< 1%). ELM-like events reduce ~10% of the stored energy. Suppression of bursting EHMs can be done by control of static island.

Near-term Experimental Plan

Helical: LHD

6th Experimental Campaign:

- From Oct.1, 2002 to Feb.6,2003.
- Negative-NBI 12 MW upgraded
- LID (Local Island Divertor) installed
- Target of this campaign
  - Te = 10keV
  - Ti = 7keV
  - Wp = 1.3MJ
  - beta = 4%
  - duration = 30 min.

Tokamak: JT-60U

Next year:

- Advanced Tokamak Experiment
  - Current Hole
  - Full CD with Negative-NBI
- ITPA Physics R&D
- University Collaborations