9TH WORKSHOP ON MHD STABILITY CONTROL:
"CONTROL OF MHD STABILITY: BACK TO THE BASICS"
NOVEMBER 21-23, 2004,
PRINCETON PLASMA PHYSICS LABORATORY

Tokamak/Helical Configurations Related to LHD and CHS-qa

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Special thanks to Dr. M. Chu (GA, now in NIFS as a Guest Professor)
for helpful discussions

Outline

1. Introduction

2. Merging of Various Concepts

Tokama, Stellarator, Mirror

3. Evidence from LHD and CHS-qa

Core & Edge Mode, Island, Current

4. Optimization with Modular Coils

QA,QP,QI

5. New Concept with Simple Coils

C-Tokastar proposal

6. Final Remarks

1. Introduction

Back to the Basics

Study the Past & Find the Future

(Renaissance for Fusion)

Finding the Future

Requirements for Fusion reactor

Steady State Operation at High Beta

($>4\%$, $f_{BS}>70\%$)

=> BS current, External CD

Free from Disruptions

(< once/several years, $f_{avail}>70\%$)

=> Active Control

Divertor Solution

=> Liquid Wall, Ball Limiter

Compactness / Low Cost

=> Low Aspect Ratio

Reduction of CD power

Simple System / Easy Maintenance

=> High Aspect Ratio

<other candidates>

Stellarator

T/S Hybrid

Mirror Type

Spherical

Stellarator

Simple Coil

↓

NEW CONCEPT

Why T/S Hybrid?

No Disruption?

- Tearing Modes and their overlapping
  - ("classical" disruption, neoclassical effects)
- External Kink (High-beta disruption)
- Thermal Instability (High density disruption)
- Positional Stability (VDE)

Reduce CD power?

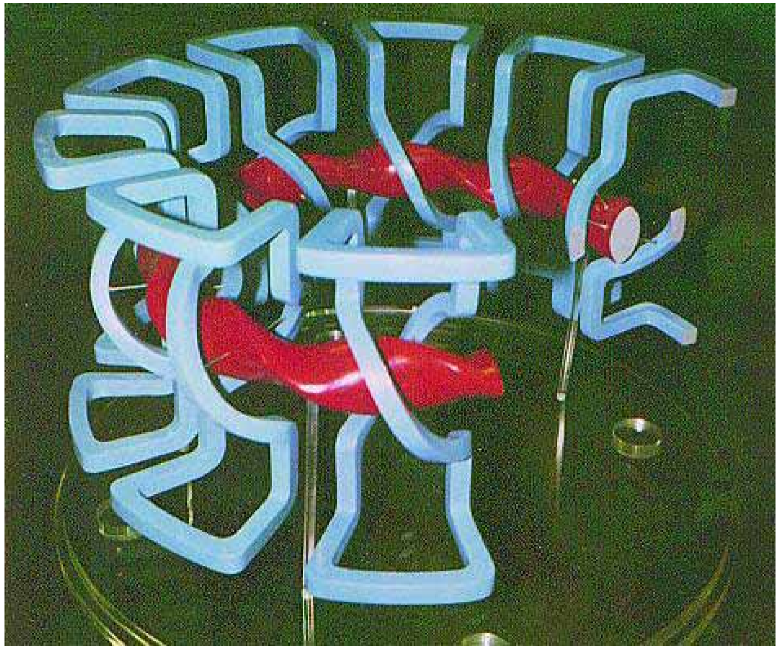
- CD Efficiency & Economical Analysis
  - (Trade-off between NBI-CD and helical shaping)

Good Core Confinement? (modular coil ?) W7X

- Quasi-Symmetry by Modular Coil
  - (Quasi-Symmetry in flux coordinates)

Simple Divertor Configuration? (continuous coil ?) LHD

- Clean Magnetic Surface by Helical Coil
  - (Quasi-Symmetry in real coordinates)

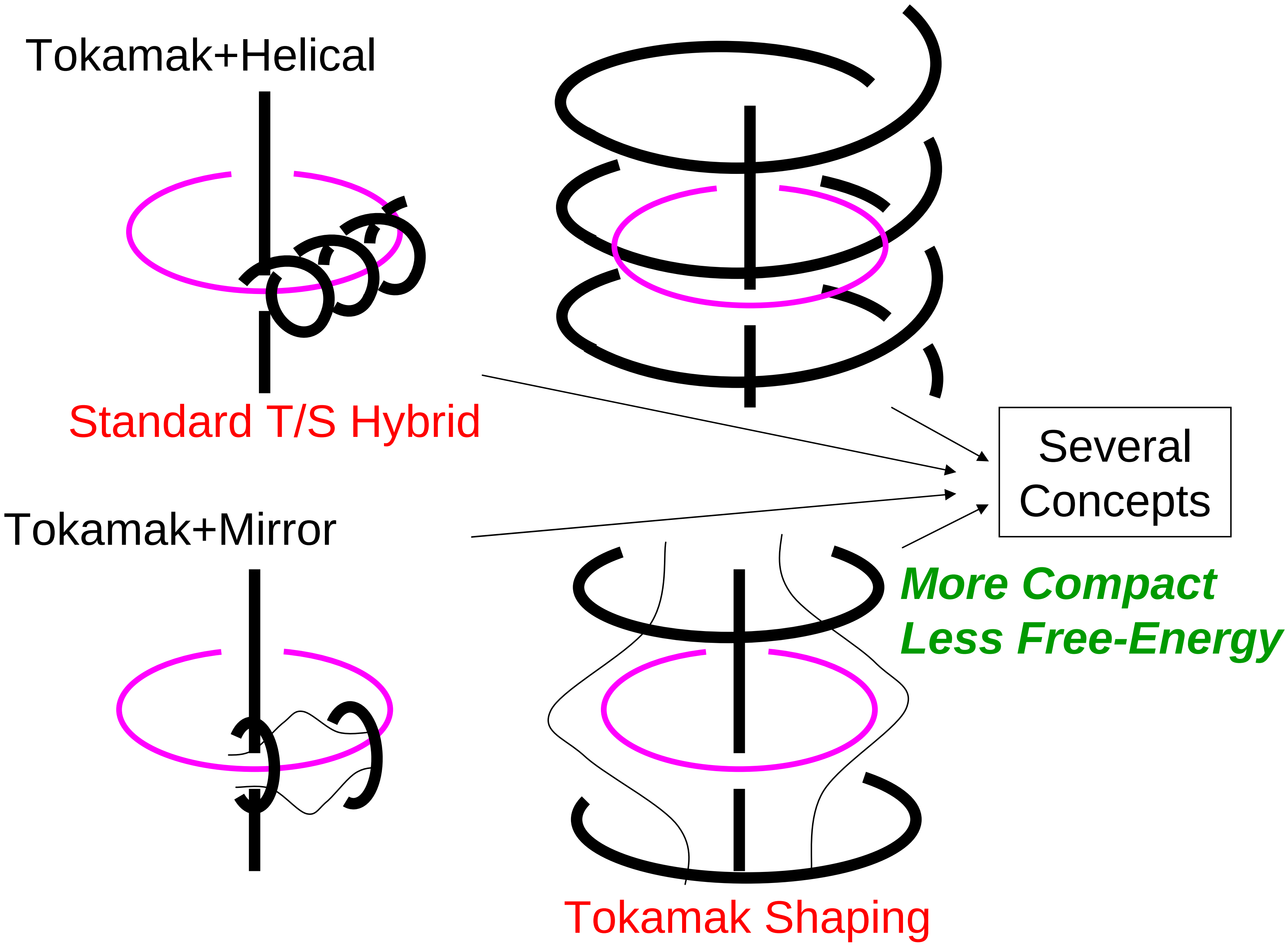


Modular Heliotron

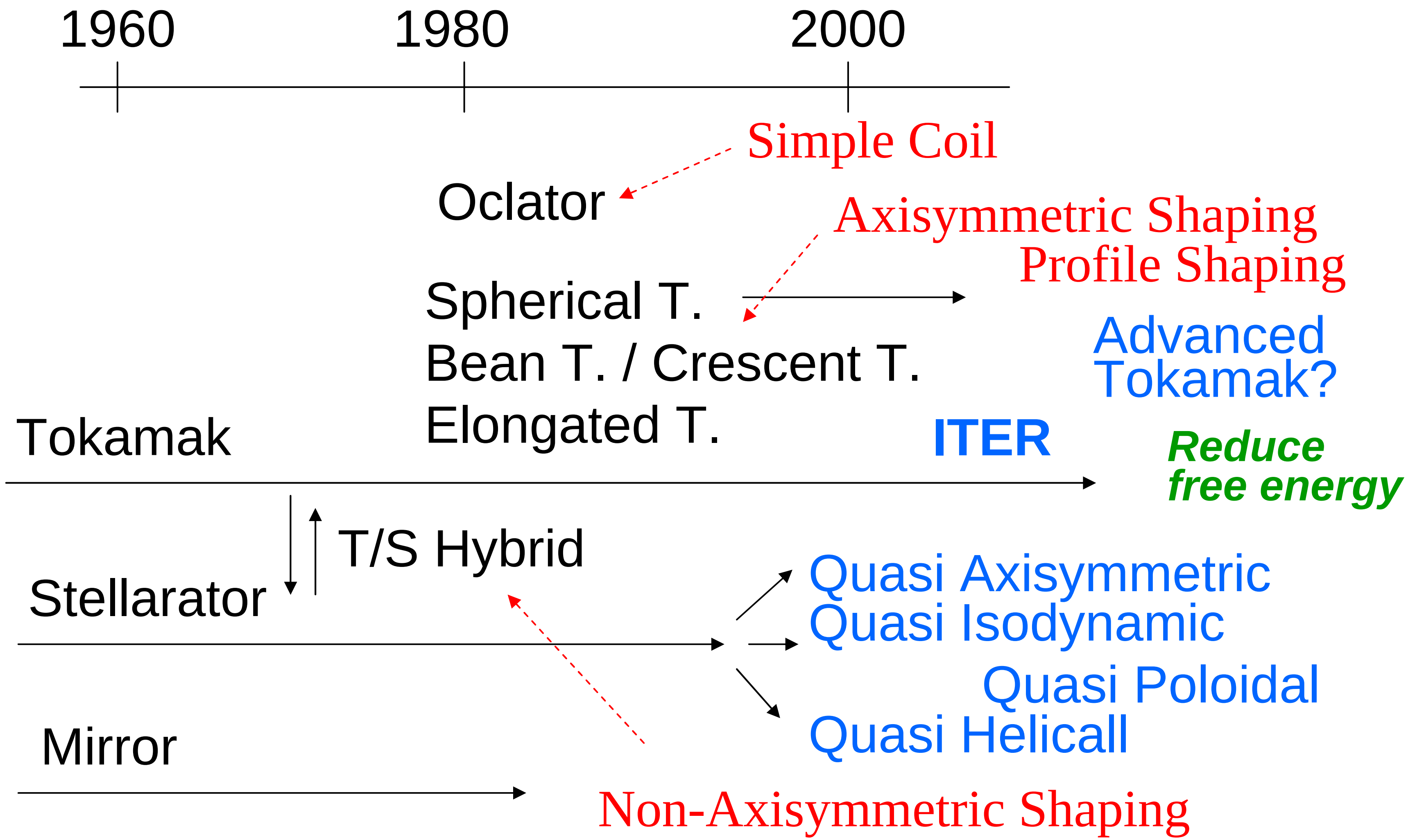
Sufficient Divertor Space
(Continuous Coil Features)
Sectored Coil System
(Modular Coil Features)

2. Merging of Various Concepts

Tokama, Stellarator, Mirror


Tokamak+Helical
Standard T/S Hybrid
Several Concepts
Tokamak+Mirror
More Compact
Less Free-Energy
Tokamak Shaping

Studying the Past



Disruption

TOKAMAK

Tearing Mode

Classical Disruption

Non-Linear Overlapping?

NTM

External Kink Mode

High beta disruption, RWM

High current disruption

Thermal Instability

High density disruption

Positional Instability

VDE

HELICAL

Experimental evidence:
no disruption at iota_ex>0.14

Current reduction

(Δ' analysis)

Weak Resonant Helical

Island healing

Shaping effects

(Terpshicore,
CAS3D)

Ergodic layer

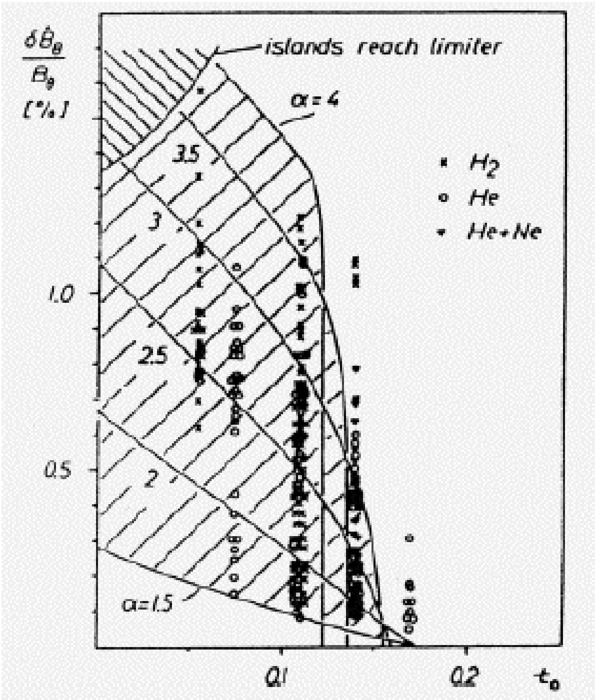
Strong focusing

no clear theories exit => needs exp.

Disruption-Free in Helical System

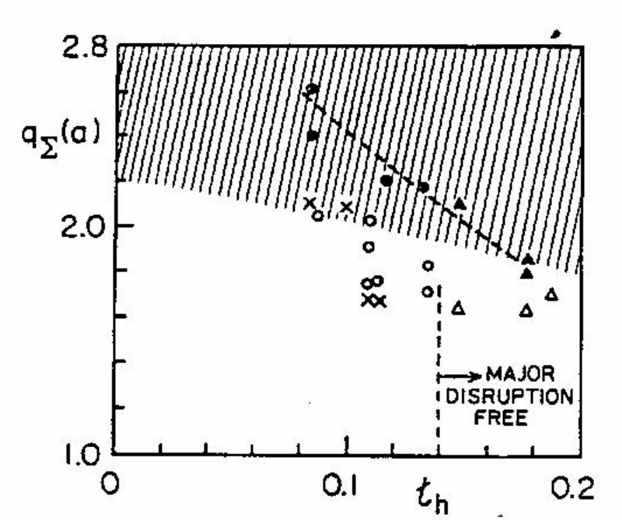
(Current Carrying Stellarator)

W7-A



WVII- A Team,
Nucl. Fusion 20 (1980) 1093.

JIPP T-II



Fujita et al.,
IEEE Transaction on
Plasma Science
PS-9 (1981) 180.

3. Evidence from LHD & CHS-qa Researches

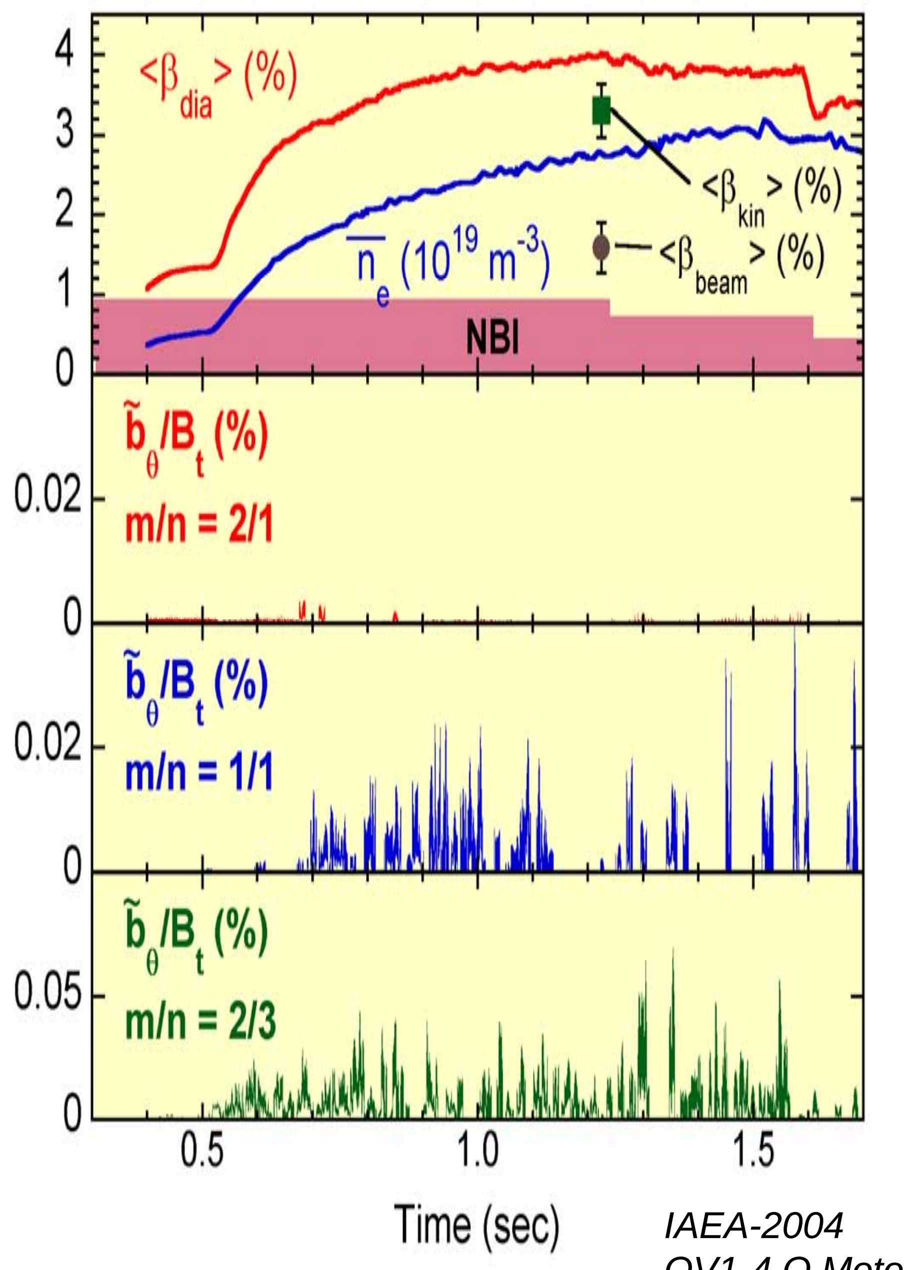
Core & Edge Modes
Mode Localization
Island Healing
BS Effects

High beta discharge at B=0.45T

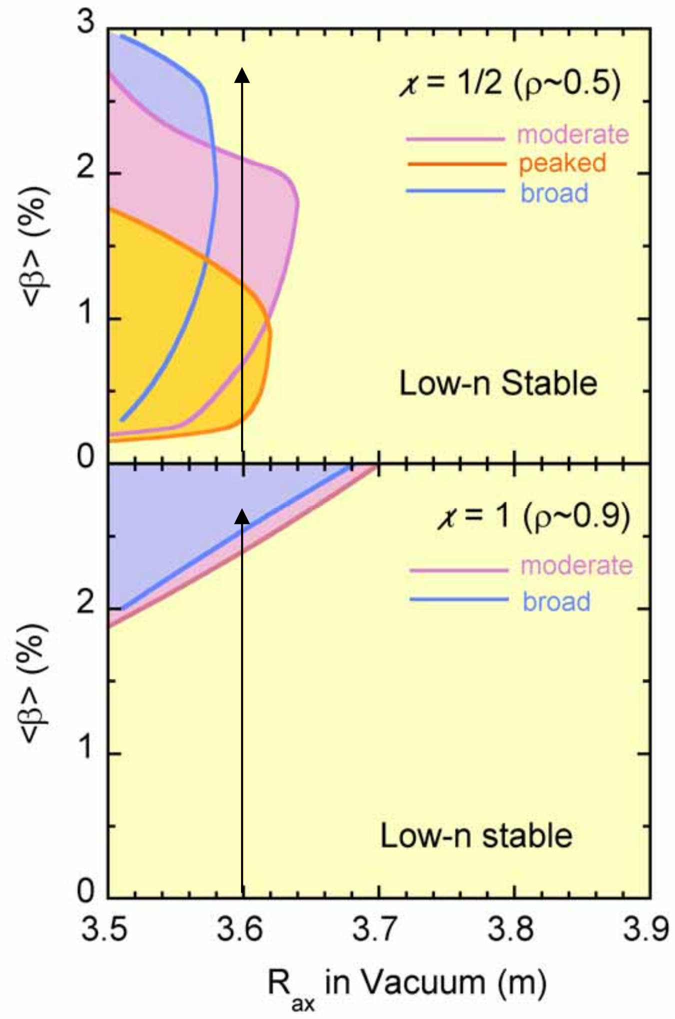
LHD

* The core fluctuation (ex.*n*/*m*=1/2) disappears because of spontaneous generation of magnetic well

* Even edge fluctuation (*n*/*m*=1/1) is mitigated because of flattening of pressure gradient



IAEA-2004
OV1-4 O.Motojima



- Core mode in the marginal region on low-n stability affects plasma profile and is stabilized by magnetic well formation.

  S. Sakakibara, *et al*, *Nucl. Fusion* 9 (2001)1177

  PPCF 44 (2002) A217 etc.

- Moderate plasma current is valid for an avoidance of core instability.

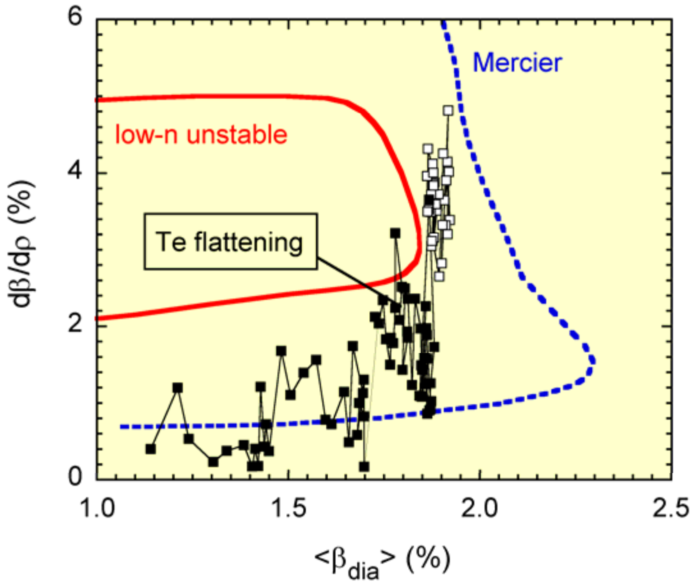
  S. Sakakibara *et al*, proc. ICPP (2002) etc.

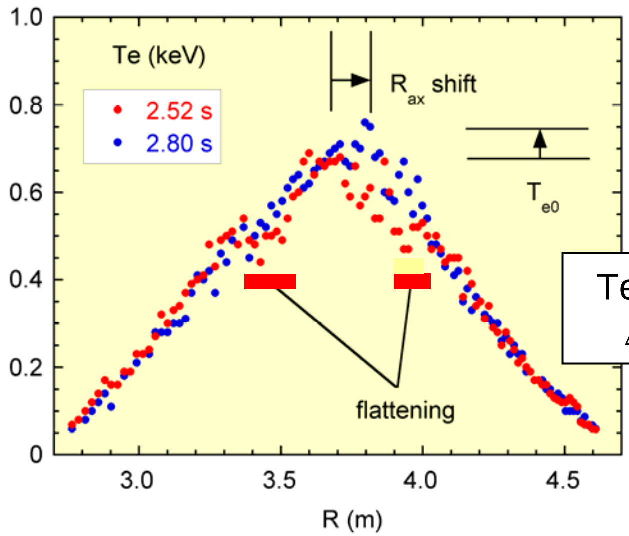
- MHD modes in periphery with magnetic hill are unstable in high-β range. Amplitudes of modes increase with β.

  K. Toi *et al*, *Nucl. Fusion* 44 (2004) 217. etc.

Peripheral MHD activities are crucial in higher-β range.

m/n = 2/1 mode activity in low-n marginal region

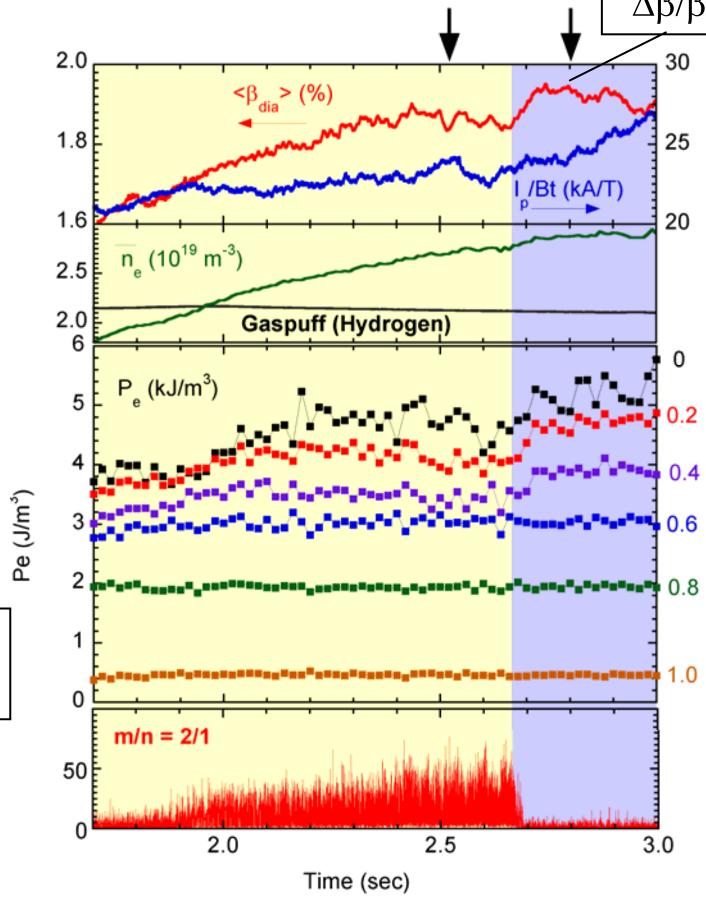




Te flattening
Δ/a ~ 0.2

– The m/n = 2/1 mode affects the plasma profile in low-n marginal region

– Degradation of core pressure with growth of the mode



S.Sakakibara

Changes of Dominant Modes as a function of β
from the core to the edge

Suppression of $\iota/2\pi < 1$ modes → $\beta\uparrow$ → Suppression of $\iota/2\pi \leq 1$ modes → $\beta\uparrow$ → Suppression of $\iota/2\pi \leq 2$ modes

$\langle\beta_{dia}\rangle$, n_e

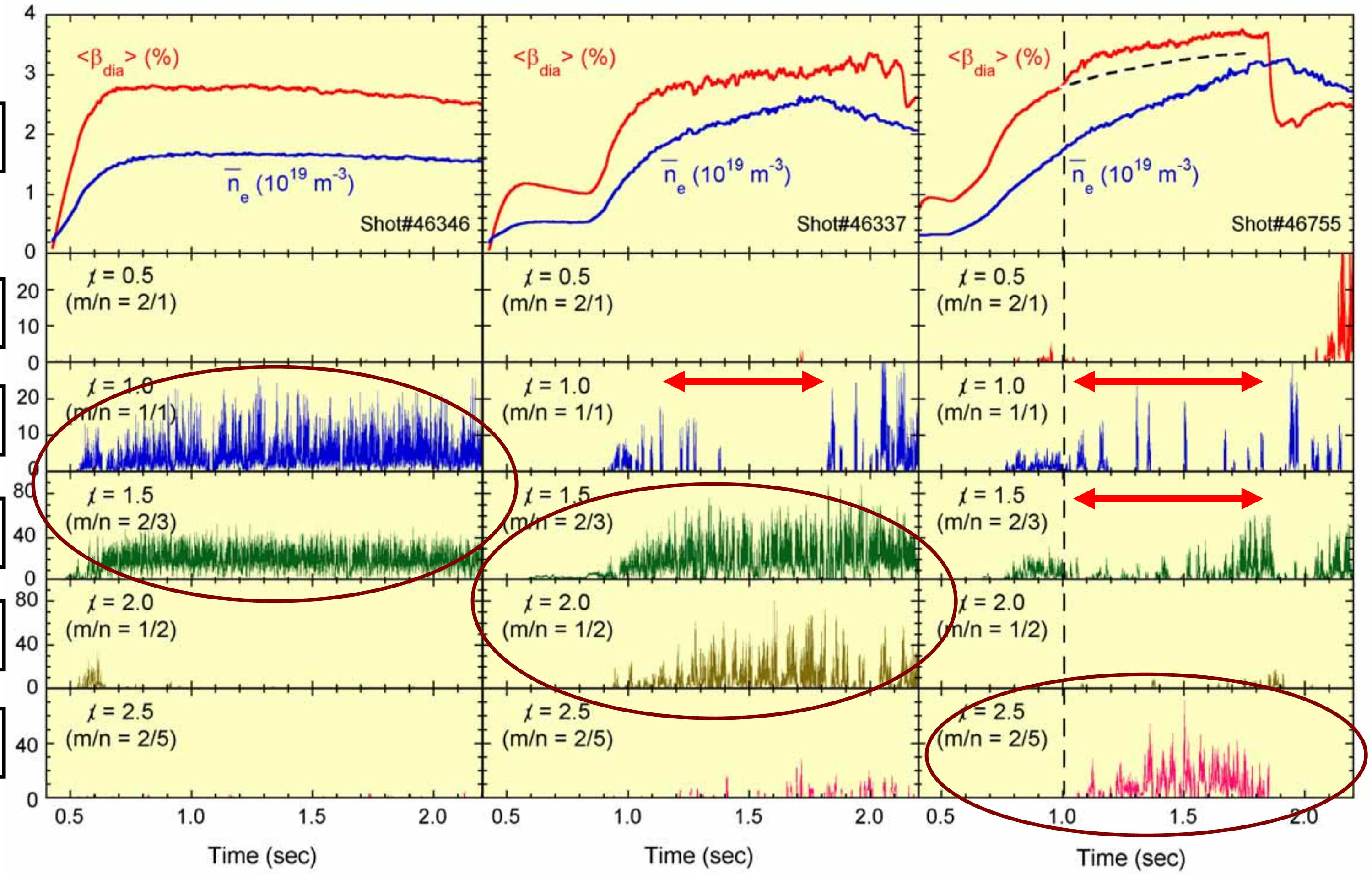
$\iota/2\pi = 0.5$

$\iota/2\pi = 1.0$

$\iota/2\pi = 1.5$

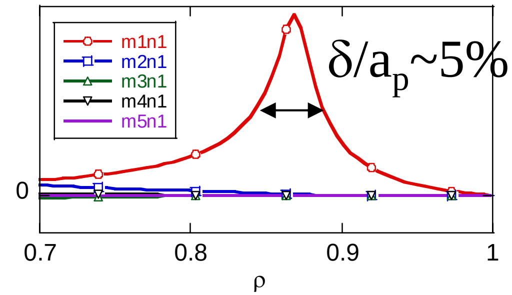
$\iota/2\pi = 2.0$

$\iota/2\pi = 2.5$



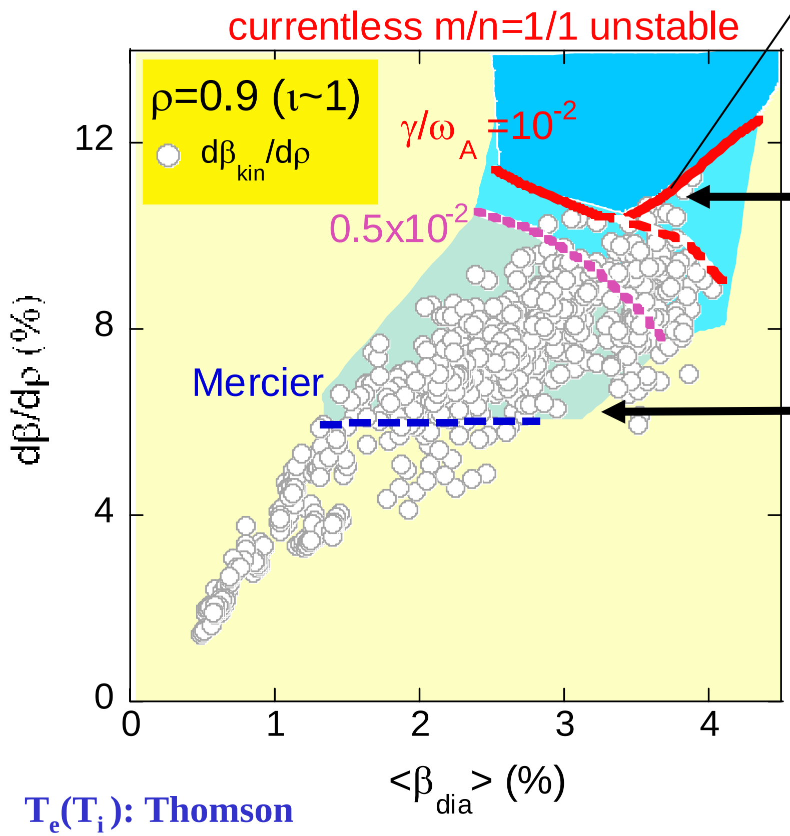
S.Sakakibara

High beta stability near the edge in LHD



Terpsichore

Radial structure of ideal MHD mode



Achieved beta is close to the m/n=1/1 ideal mode limit

No wall effect due to pressure-driven mode

Achieved beta significantly exceeds the Mercier limit

γ=1.22

($\gamma=\kappa\varepsilon=2na_c/R$)

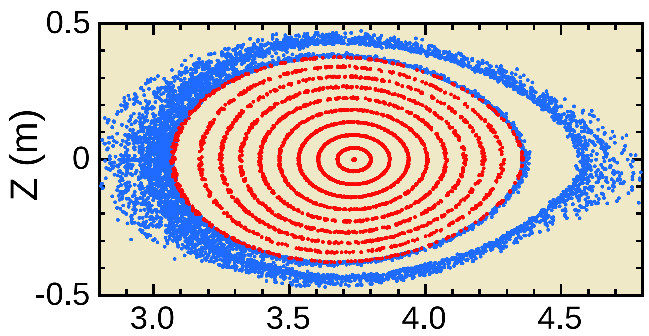
T_e(T_i): Thomson

n_e:FIR

IAEA-2004

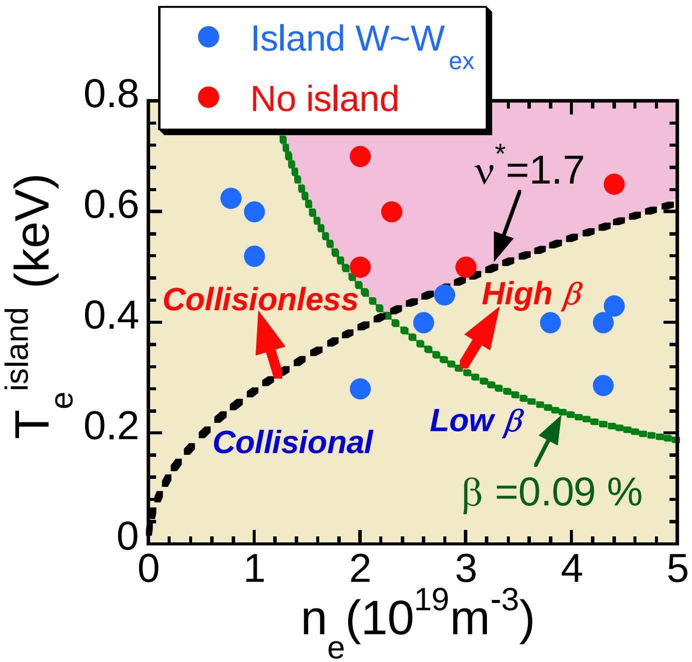
EX/3-3 K.Watanabe

Tearing mode, even NCTM, can be stabilized in helical system （LHD）



m/n=1/1
W_{ex}/a=0.085

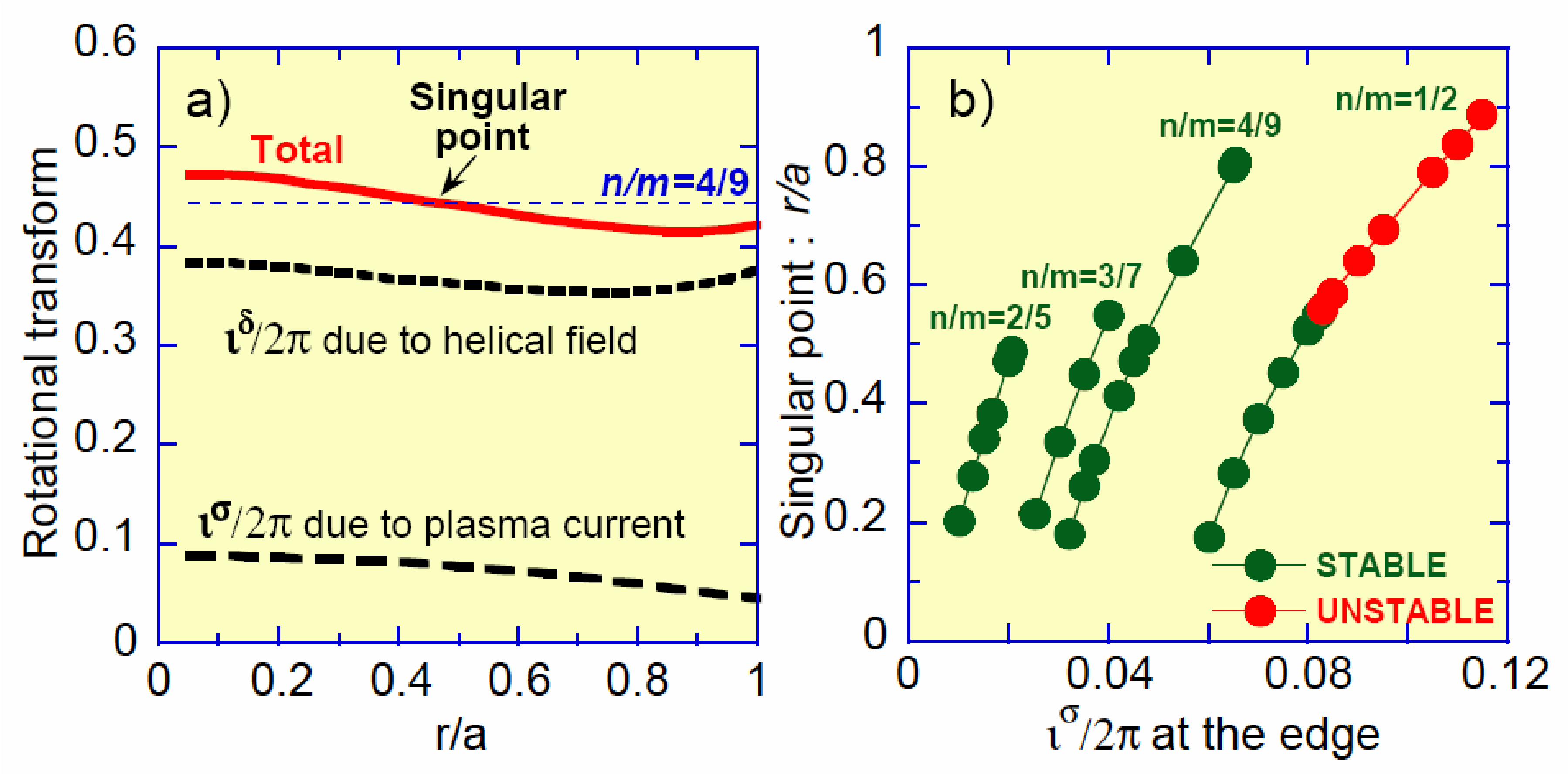
Island healing



N.Ohyabu

Tearing Mode Analysis in CHS-qa

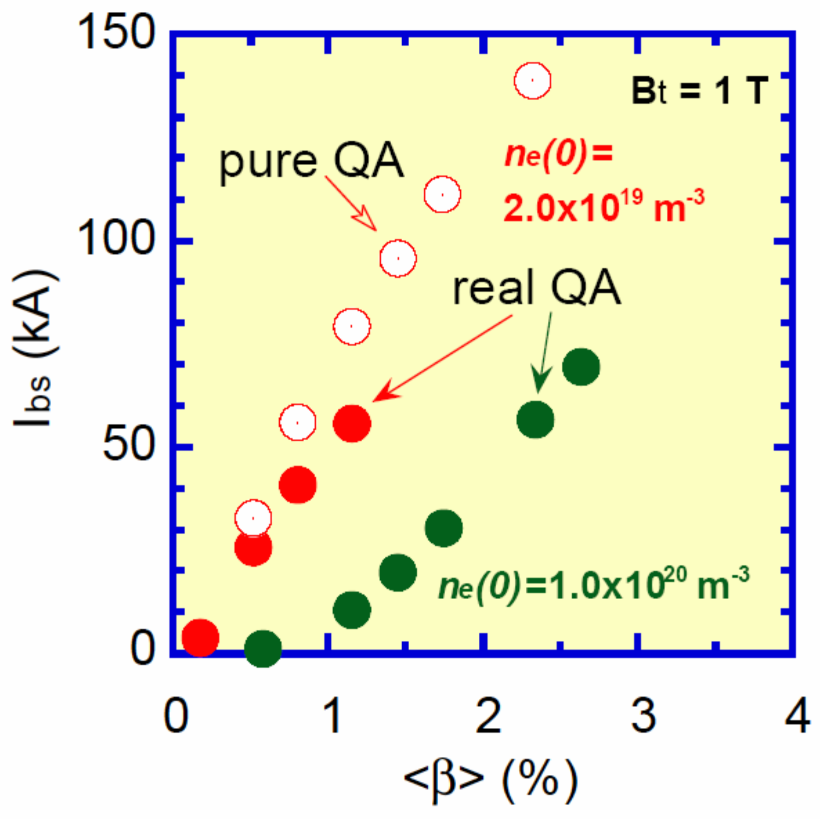
Δ' Analysis

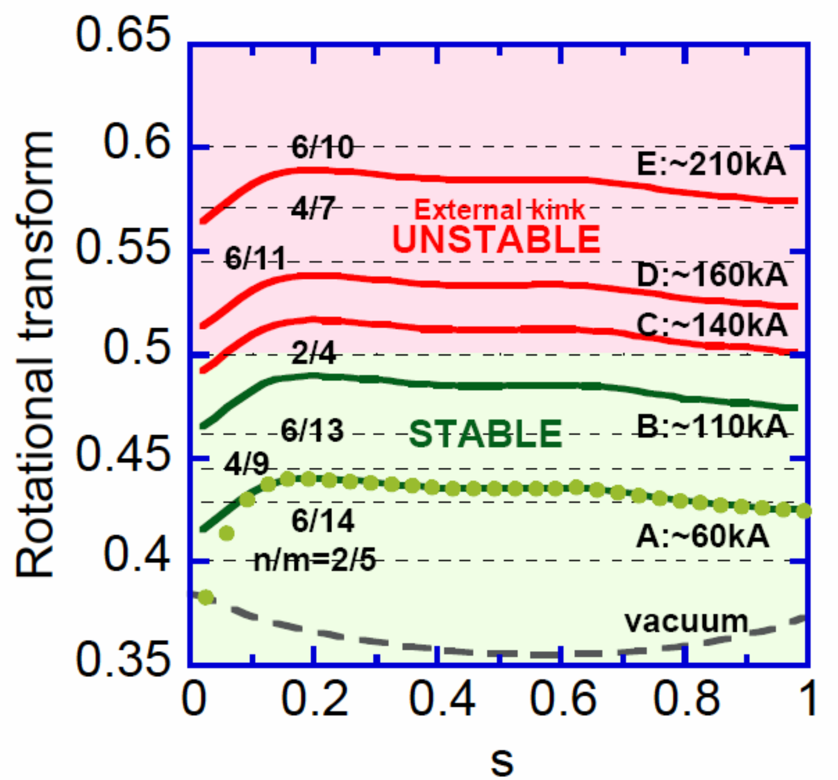


M.Isobe

External Kink Mode Analysis in CHS-qa

CAS3D Analysis



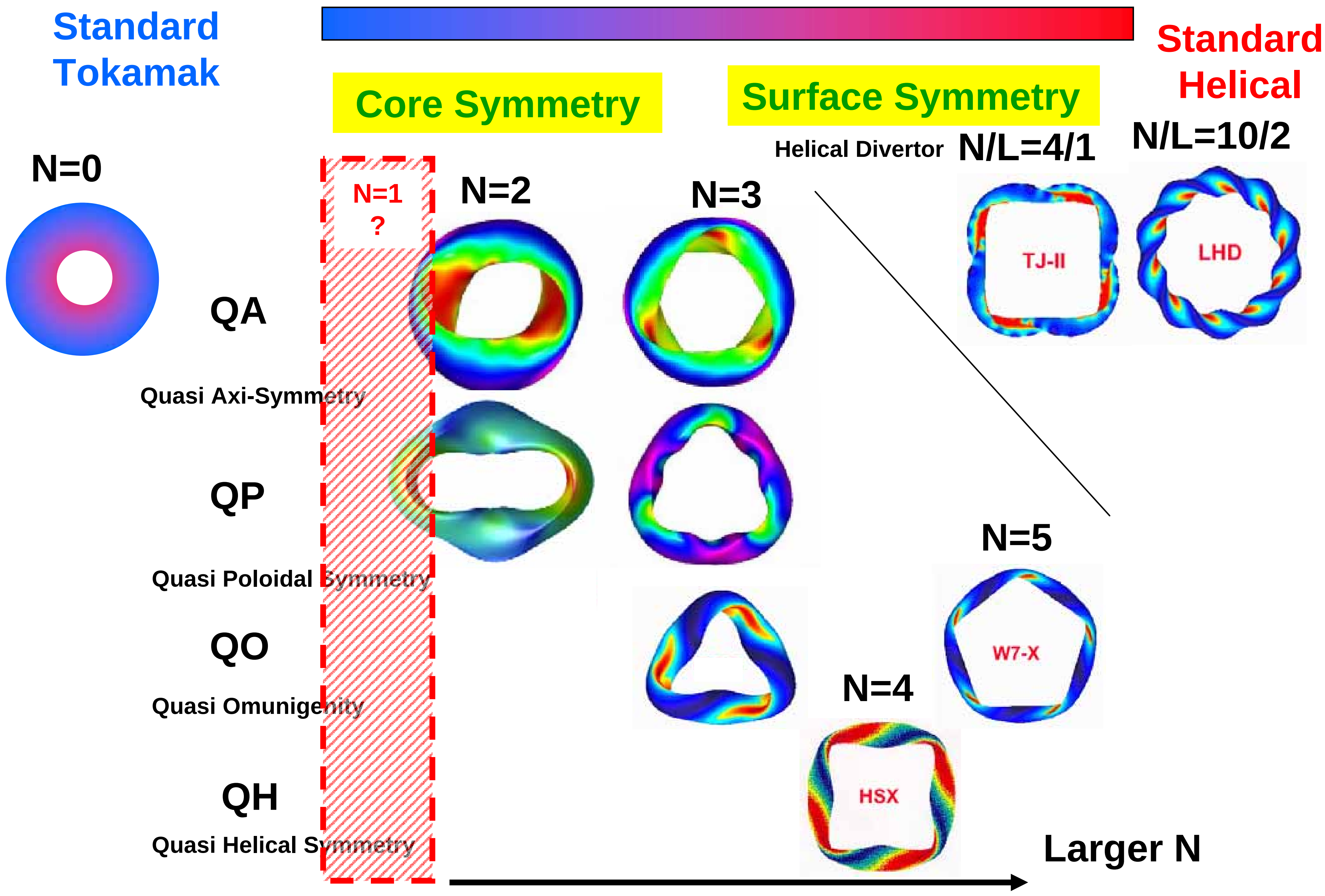


M.Isobe

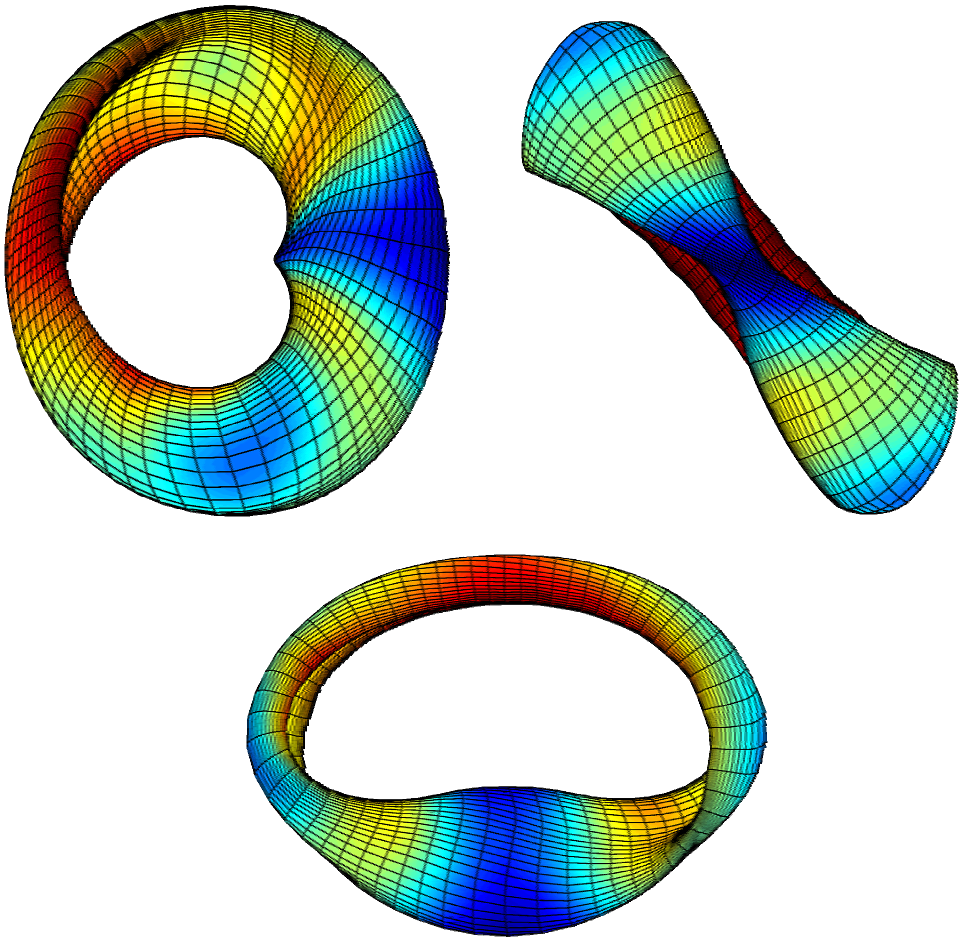
4. Optimization with Modular Coils

QA,QP,QI

Advanced Plasma Shapes

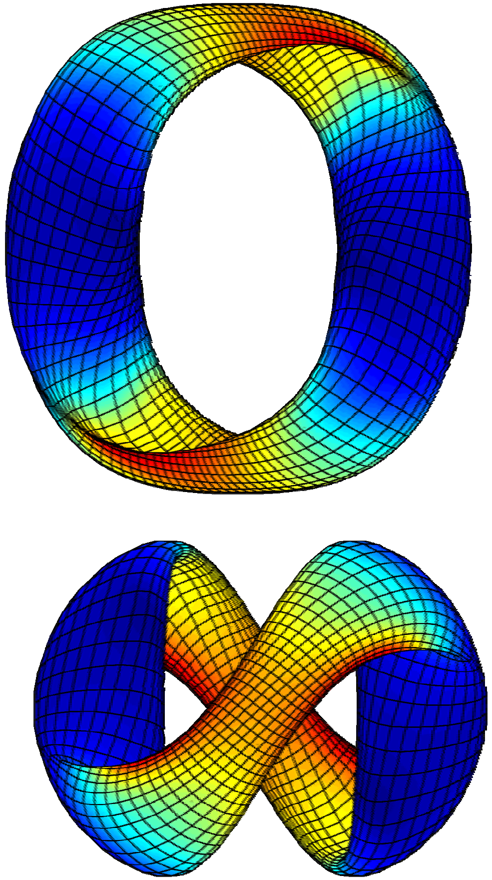


New Configuration !



N=1 QI (QO)

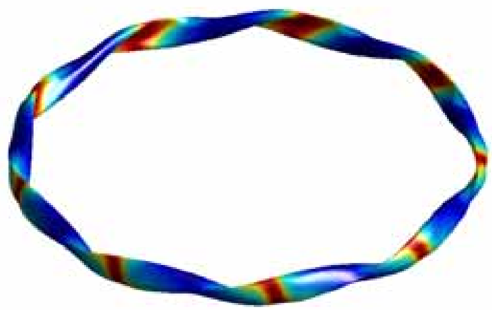
K.Yamazaki,M.Mikhailov,M.Samitov



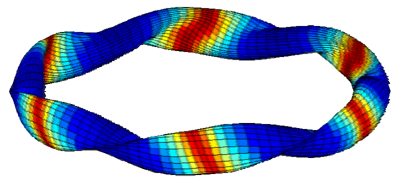
N=2 QI

Beta Limit of QI Configurations

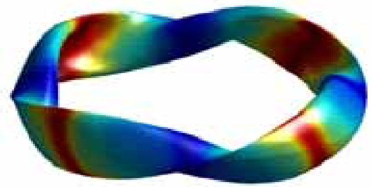
M.Mikhailov,M.Samitov



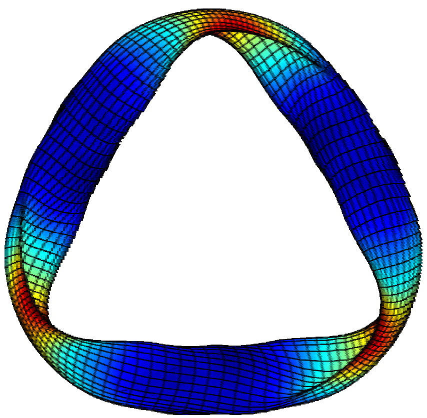
N=9, A~22
$\langle\beta\rangle$=10~ 15%



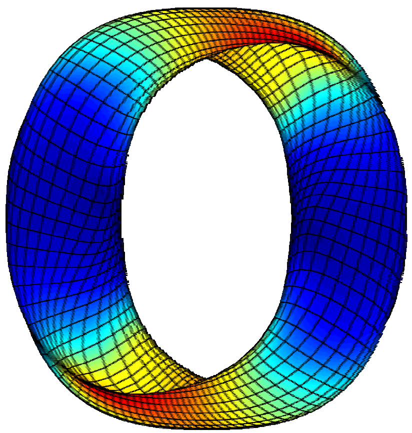
N=6, A~12
$\langle\beta\rangle$=5~8.8%



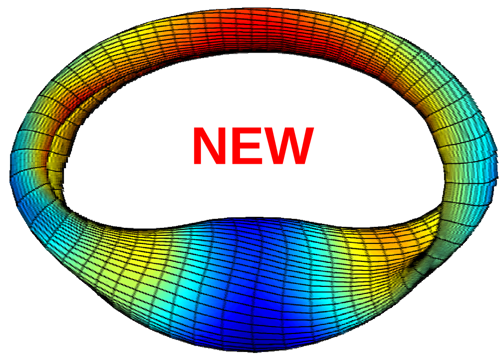
N=4, A~9
$\langle\beta\rangle$=5%



N=3, A~6.8,
$\langle\beta\rangle$=3.9%

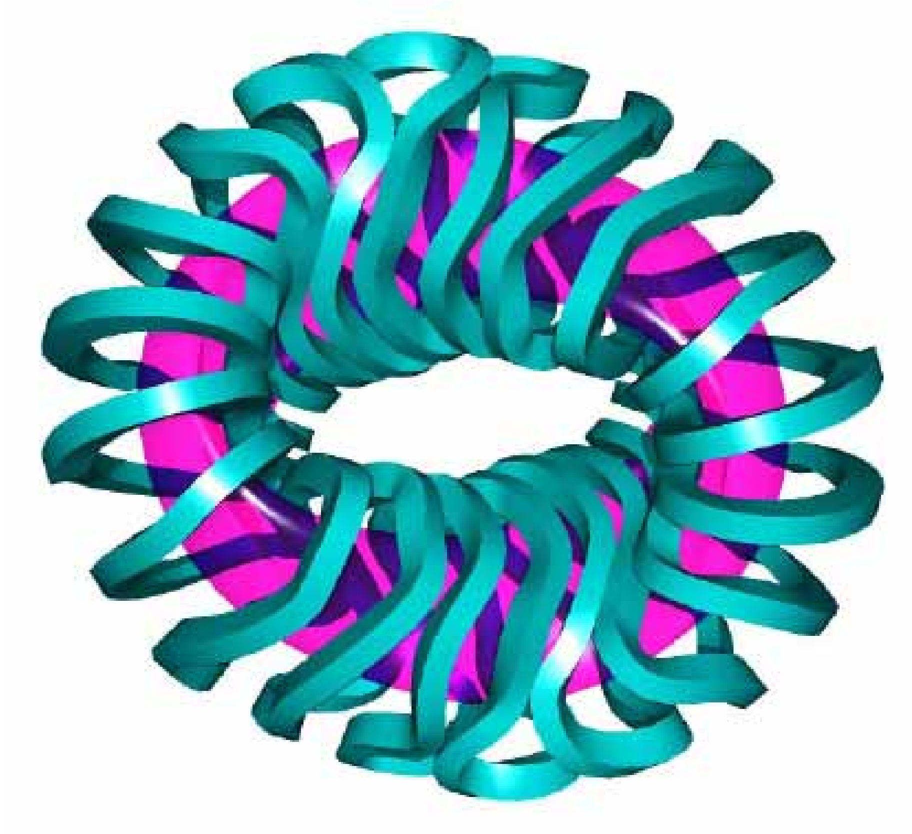


N=2, A~3.9,
$\langle\beta\rangle$=2.4%

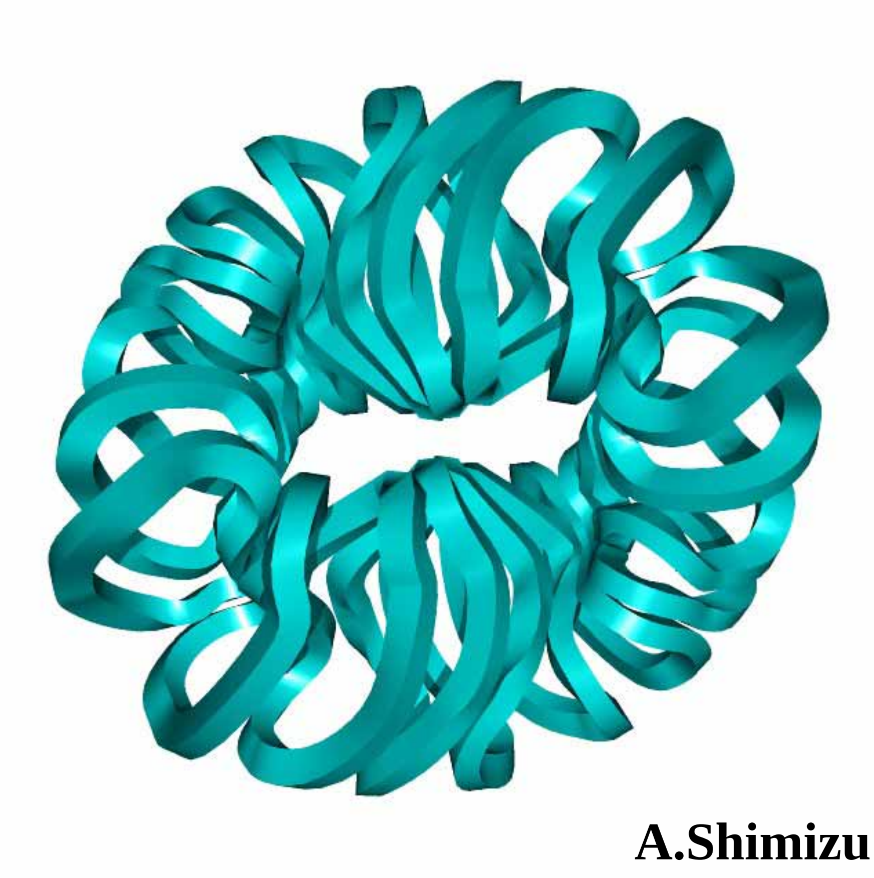


N=1, A~4,
$\langle\beta\rangle$=1.5%

By adding plasma current
We may get higher beta.



N=2 QA
(CHS-qa)



N=2 QI
(not optimized yet)

N=1 QI coil system is
now under investigation

5. New Concept with Simple Coils

C-Tokastar

Why plasma surface symmetry?

Core quasi-symmetry

=> X complicated coil system

=> X lack of divertor space

core confinement optimization

Starting from real coil

=> quasi-symmetry of plasma surface

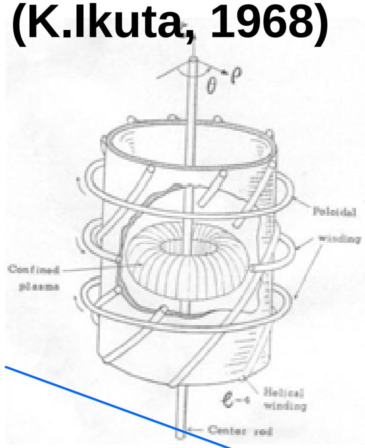
=> O rather simple coil

=> O appropriate divertor space

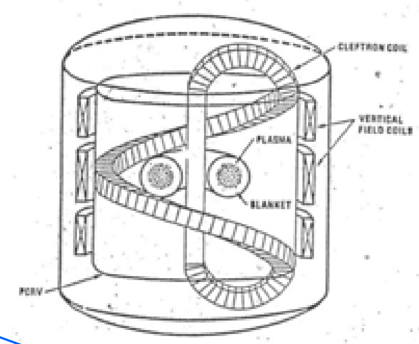
coil and divertor system optimization

Non-Axisymmetric Shaping

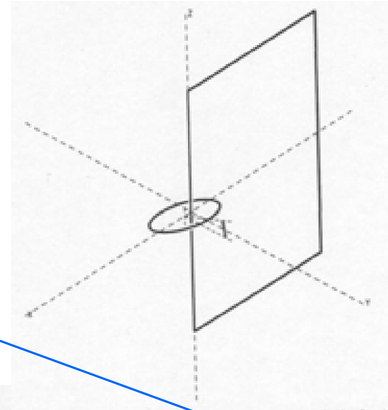
Ikuta Torus
(K.Ikuta, 1968)



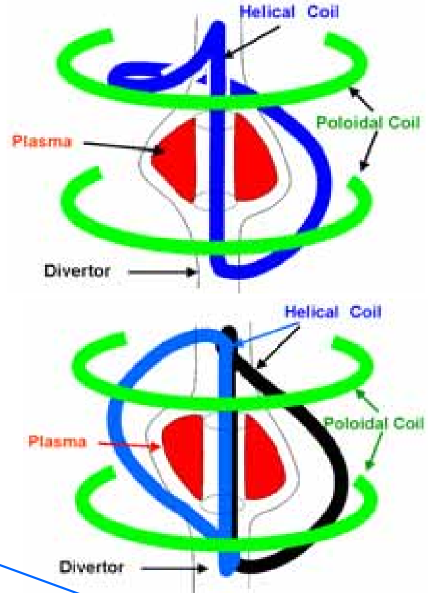
Cleftron
(T.Ohkawa, 1981)

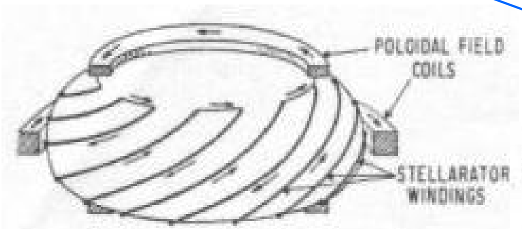


Ultra Simple Stellarator
(T.Todd,1990)

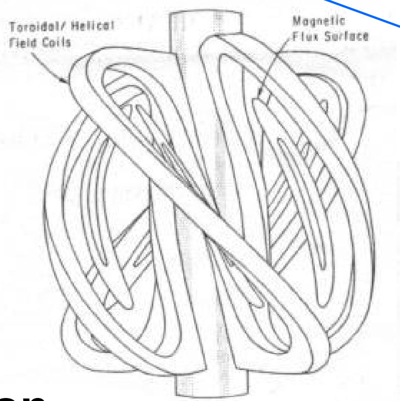


C-Tokastar
(K.Yamazaki,2004)

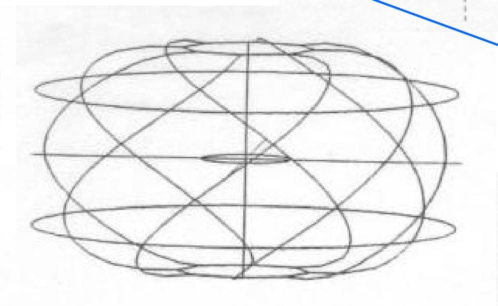




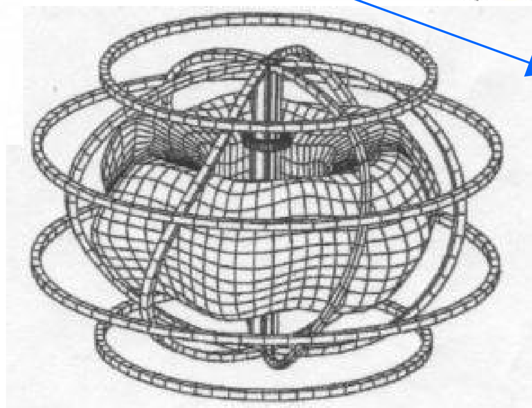
Strong Negative V''
(H.P.Furth et al., 1968)



Tokatron
(H.P.Furth et al., 1981)

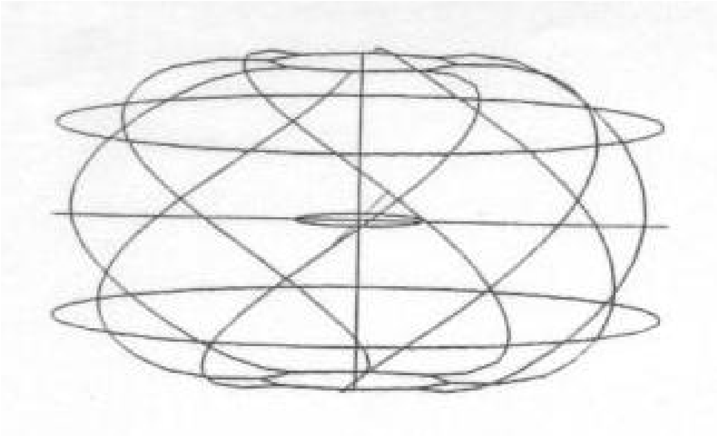


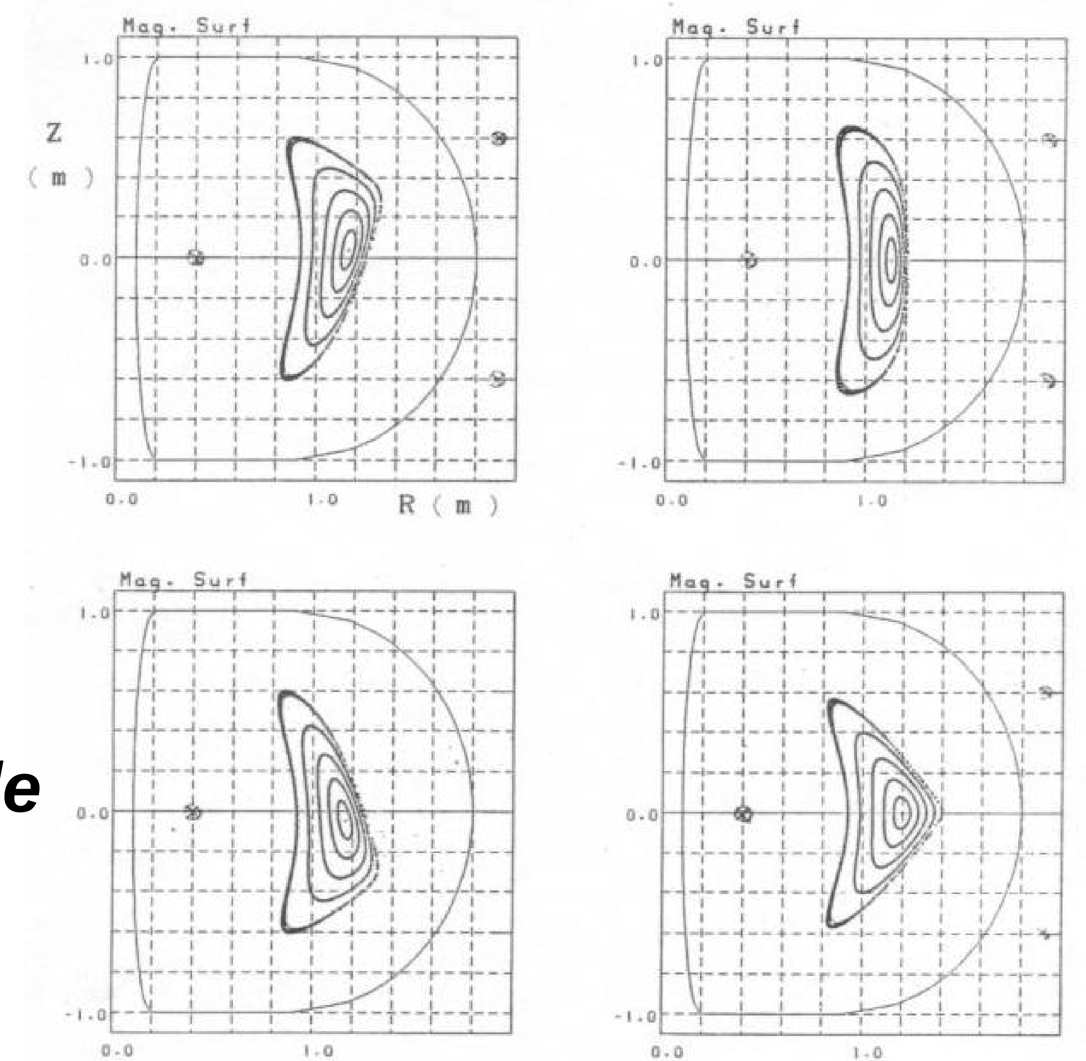
Tokastar
(K.Yamazaki, 1985)



Spherical Stellarator
(P.E.Moroz, 1996)

TOKASTAR (1985)





N=4
Pure Stellarator Mode

Sufficient Divertor Space is required in the Reactor.
==> reduce coil number and install mirror-type divertor
==> new configuration (C-TOKASTAR(2004))

New Concept for Advanced Torus
C-TOKASTAR
(Compact Tokamak-Stellarator Hybrid)

Steady-State: External rotational transform

to avoid disruption

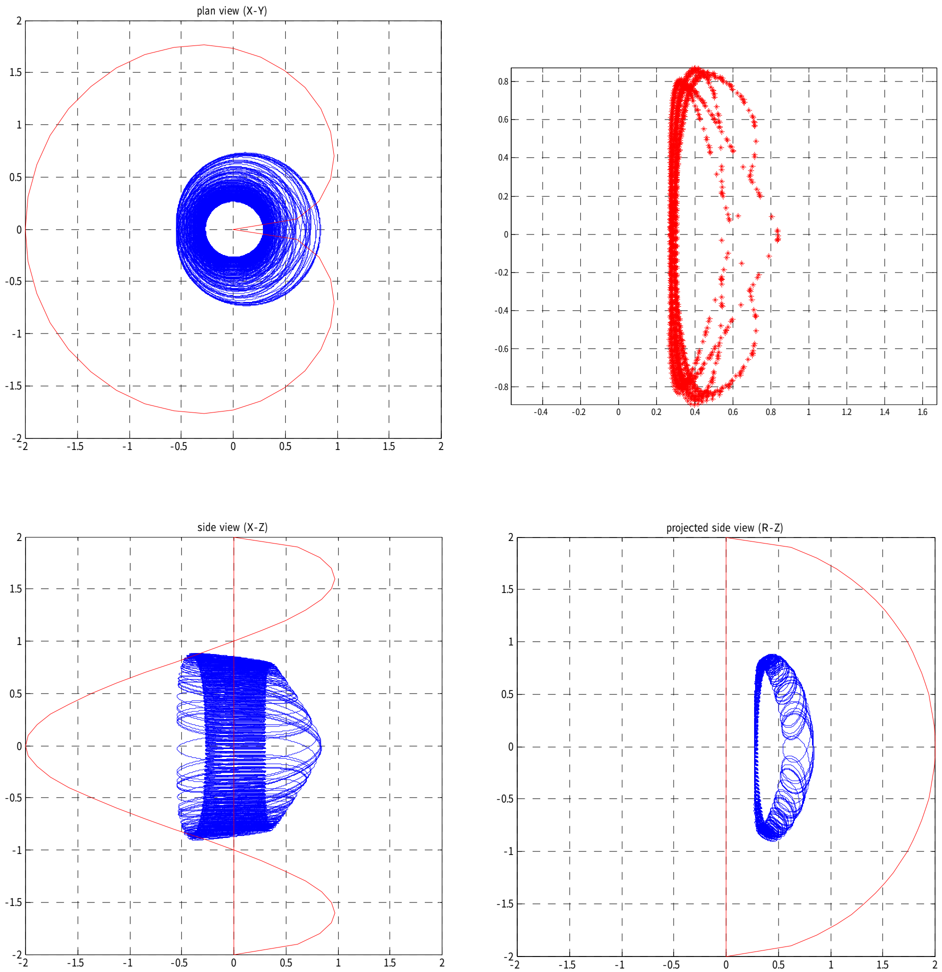
High beta: Deep magnetic well

Divertor: Mirror type configuration

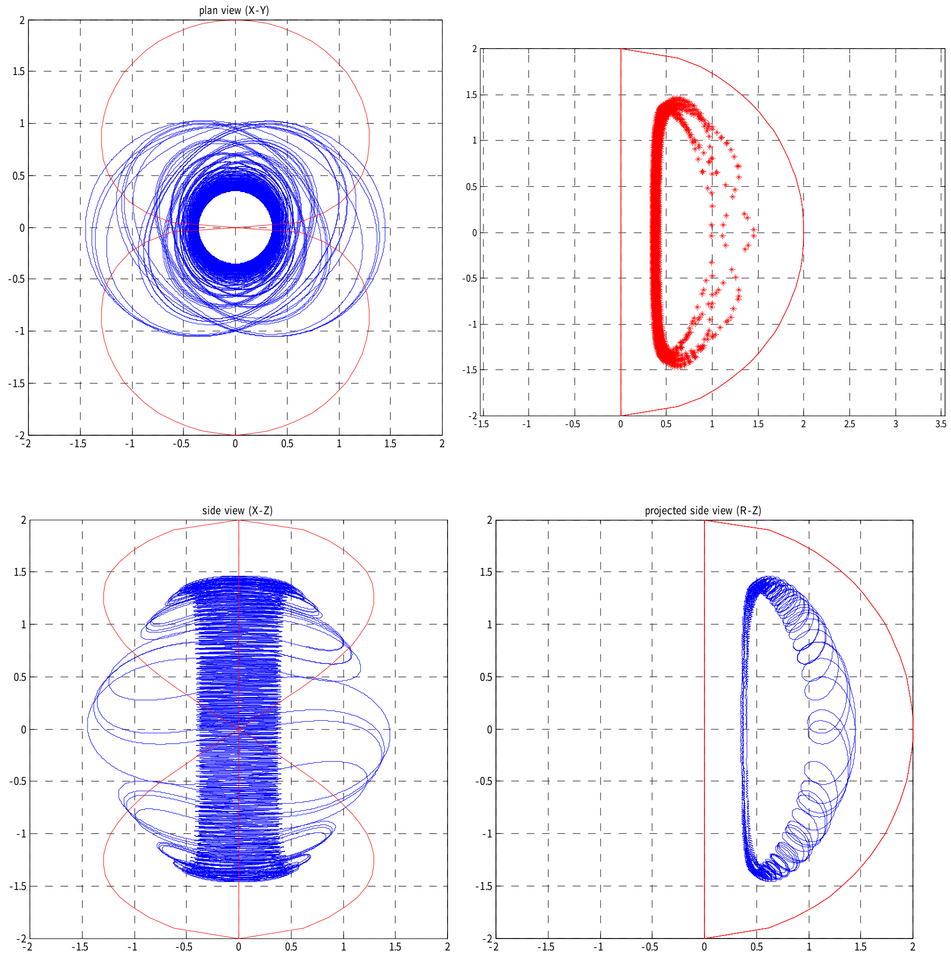
to keep sufficient divertor space

Compactness: Single or Double HF coil

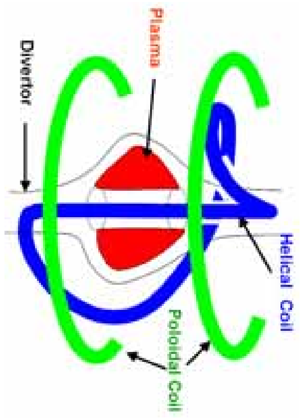
Particle confinement should be improved

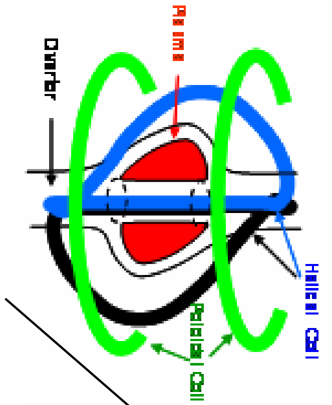


N=1 C-Tokastar



N=2 C-Tokastar





"pocket plasma production" experiment for C-TOKASTAR

Rp~10cm
B<0.1kG

Y.Kubota, K.Yamazaki

6. Final Remarks

For returning “Back to the Basics”,
“Fusion Science Renaissance” might be required
for the promotion of a wide variety of
confinement researches (tokamak, stellarator, others)
to search for a final optimized MHD configuration,
in addition to the strong promotion of ITER project.