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High Performance Operational Limits of Tokamak and Helical Systems

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Outline

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3. Equilibrium Properties
4. Confinement
5. Stability Limit
6. Density Limit
7. Steady-State Operation
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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 a variety of toroidal plasma operational limits focusing on the similarities and differences between TOKAMAK and HELICAL systems.

Maximum Parameters Achieved

	TOKAMAK		HELICAL	
Electron Temperature T_e (keV)	25	(ASDEX-U, JT-60U))	10	(LHD)
Ion Temperature T_i (keV)	45	(JT-60U)	5.0	(LHD)
Confinement time t_E (s)	1.2 1.1	(JET) (JT-60U,NS)	0.36	(LHD)
Fusion Triple Product $n_i\ t_E\ T_i$ (m^{-3} •s・keV)	15×10^{20}	(JT-60U)	0.22×10^{20}	(LHD)
Stored Energy W_p (MJ)	17 11	(JET) (JT-60U,NS)	1.0	(LHD)
Beta Value b (%)	40 (toroidal) 12 (toroidal)	(START) (DIII-D)	3.0 (average)	(LHD,W7-AS)
Line-Averaged Density n_e ($10^{20}m^{-3}$)	20	(Alcator-C)	3.6	(W7-AS)
Plasma Duration t_{dur}	2 min 3 hr. 10min.	(Tore-Supra) (Triam-1M)	2 min 1 hour	(LHD) (ATF)

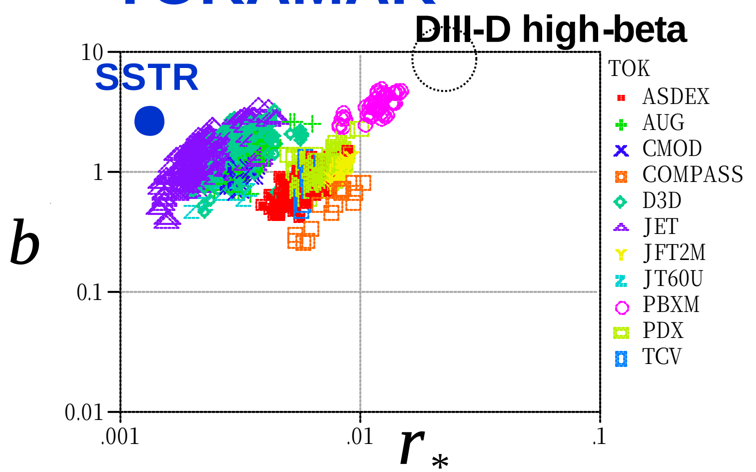
Operation Regime and Reactor Requirements

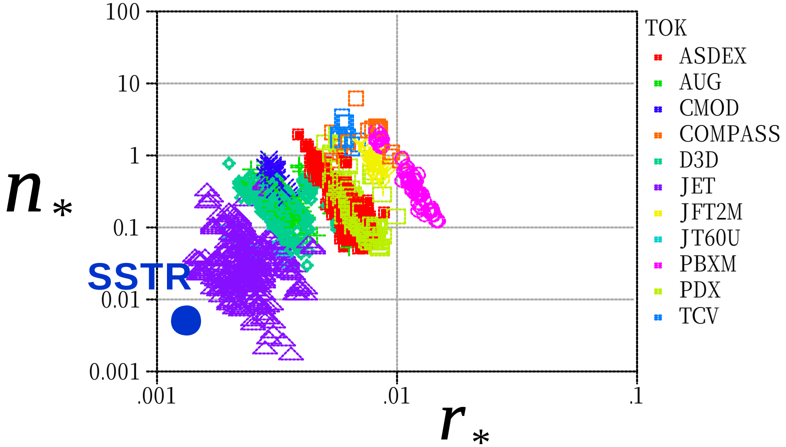
$$r_* = r_s / a \sim \sqrt{T}/(aB)$$

$$n_* = n_{ei} a / n_{th} \sim na/(e^{5/2}T^2)$$

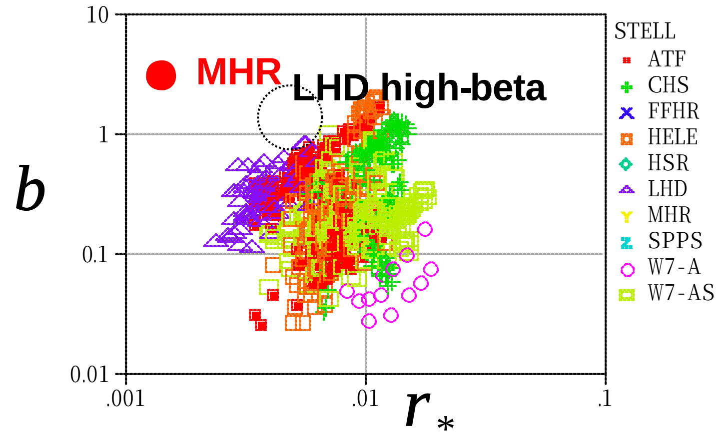
Normalized parameters $b = nkT / B^2 \sim nT / B^2$

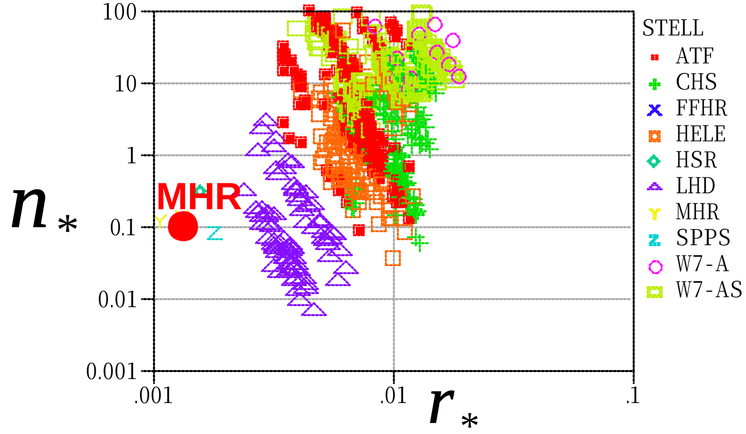
TOKAMAK





HELICAL





Similarities and Differences between Tokamak and Helical Systems

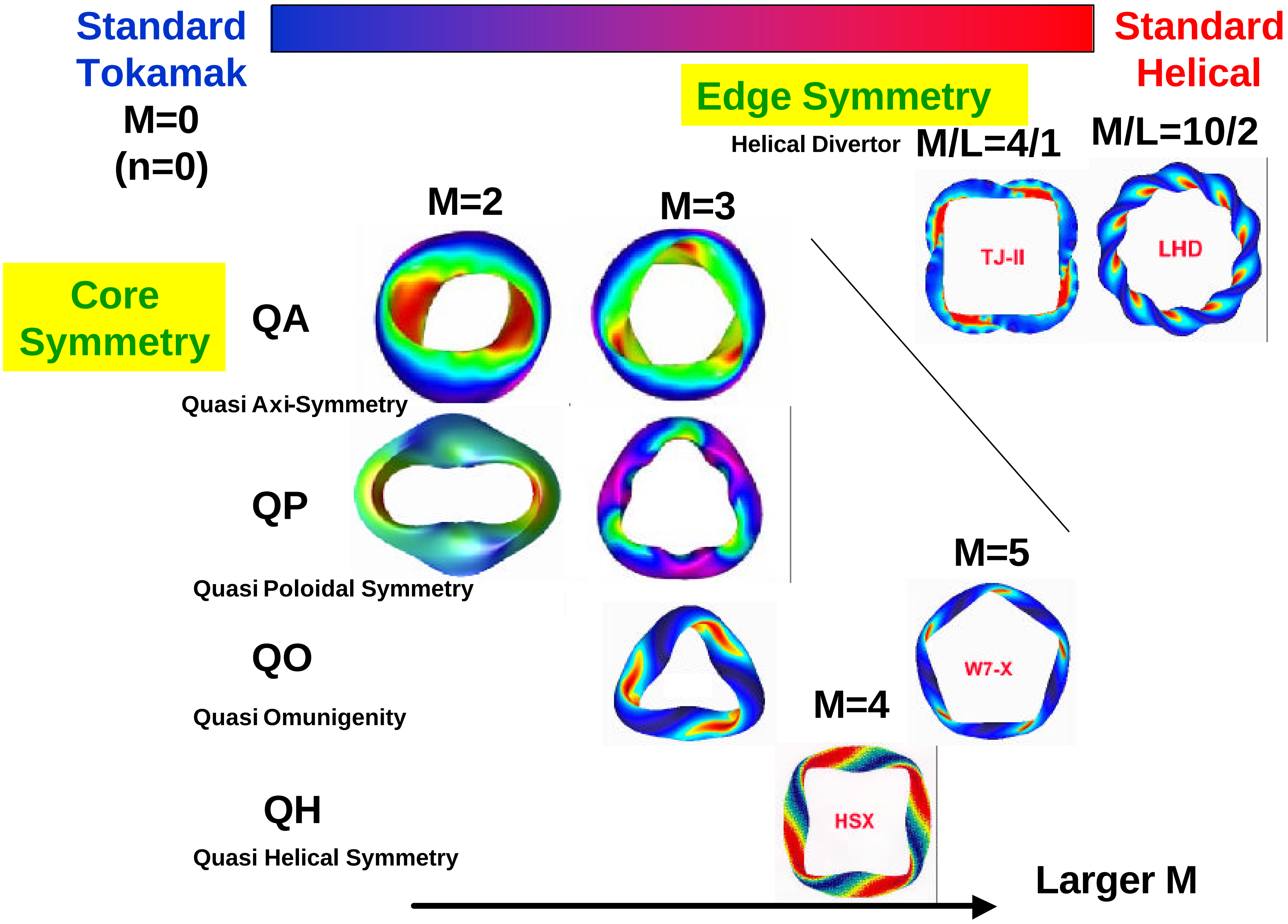
Equilibrium

	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.

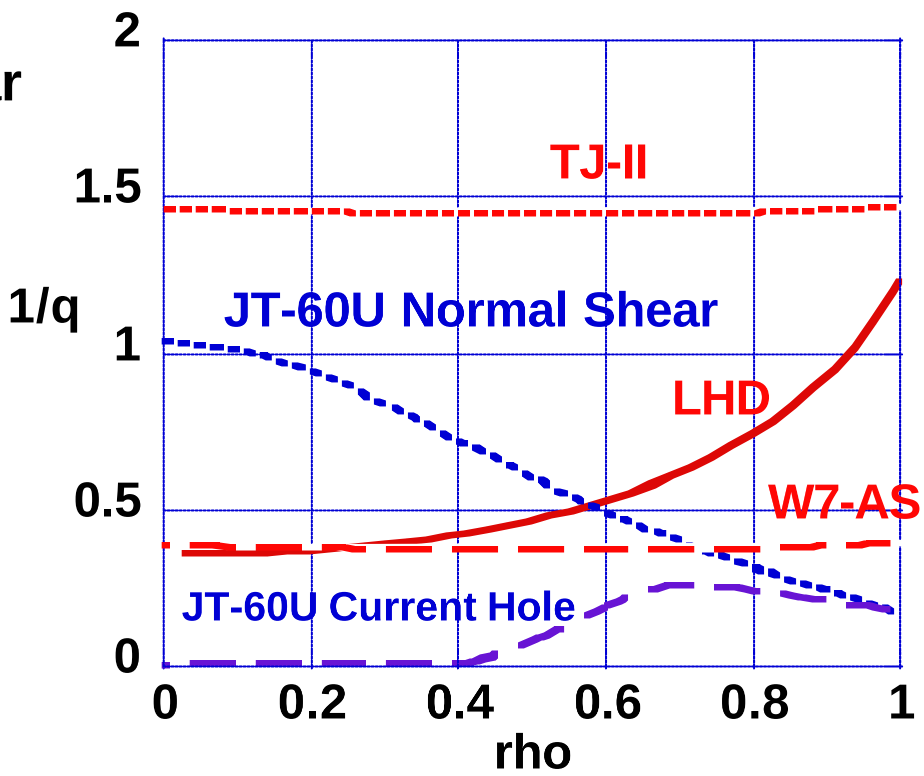
Normal or Reversed Shear

Helical:

A variety of shears by helical coil.

Magnetic hill near edge.

Flat or Reversed Shear

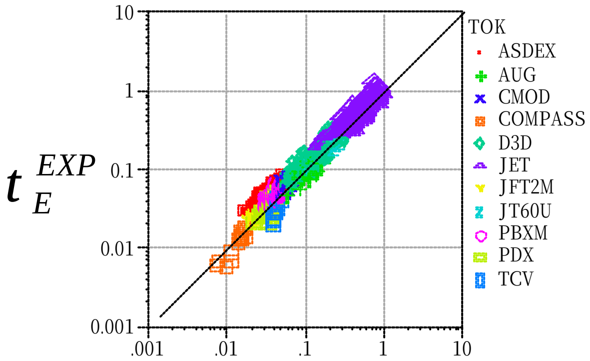


Confinement Scaling Laws

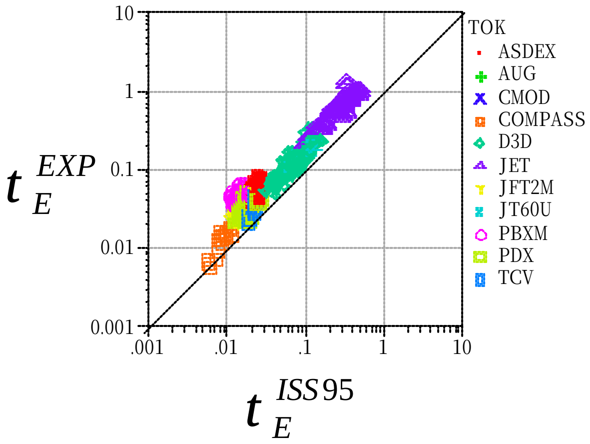
Comparing between ITER ELMy-H Database and stellarator Database adding LHD data

TOKAMAK

$$t_E^{ELMY} \propto t_B\, r^{*-0.83}\, b^{-0.50}\, n^{*-0.10}$$

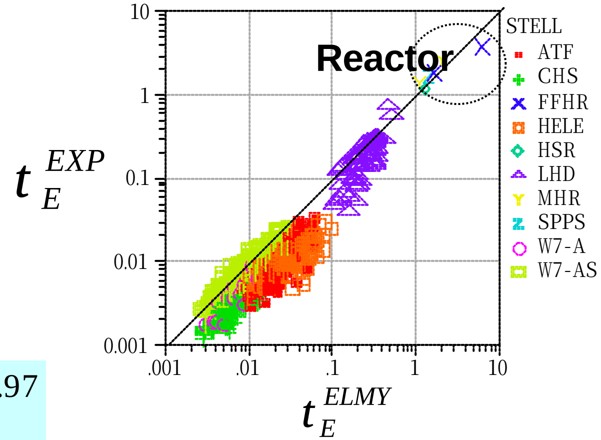


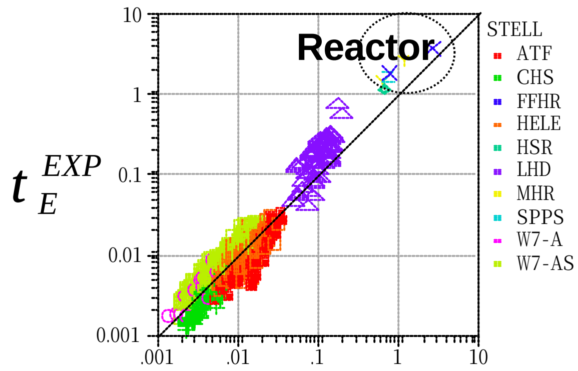
$$t_E^{ELMY} = 0.0365 R^{1.93} P^{-0.63} \bar{n}_e^{0.41} B^{0.08} e^{0.23} I^{0.97}$$



HELICAL

$$t_E^{ISS95} \propto t_B\, r^{*-0.71}\, b^{-0.16}\, n^{*-0.04}$$



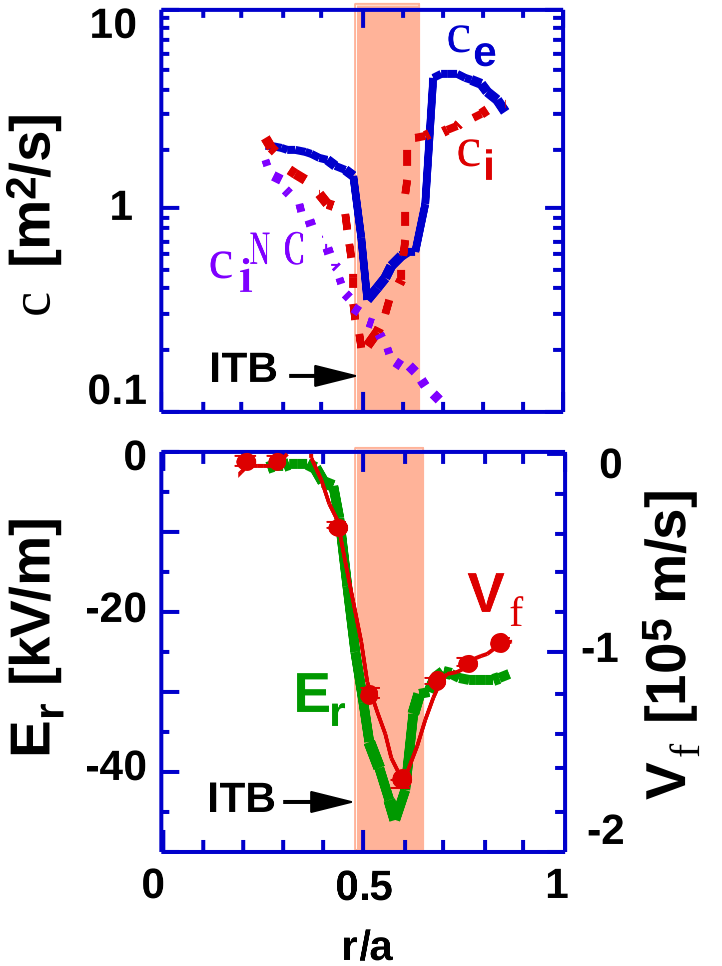


$$t_E^{ISS95} = 0.08 a^{2.21} R^{0.65} P^{-0.59} \bar{n}_e^{0.51} B^{0.80} \iota_{2/3}^{0.40}$$

Radial Electric Field & ITB

TOKAMAK

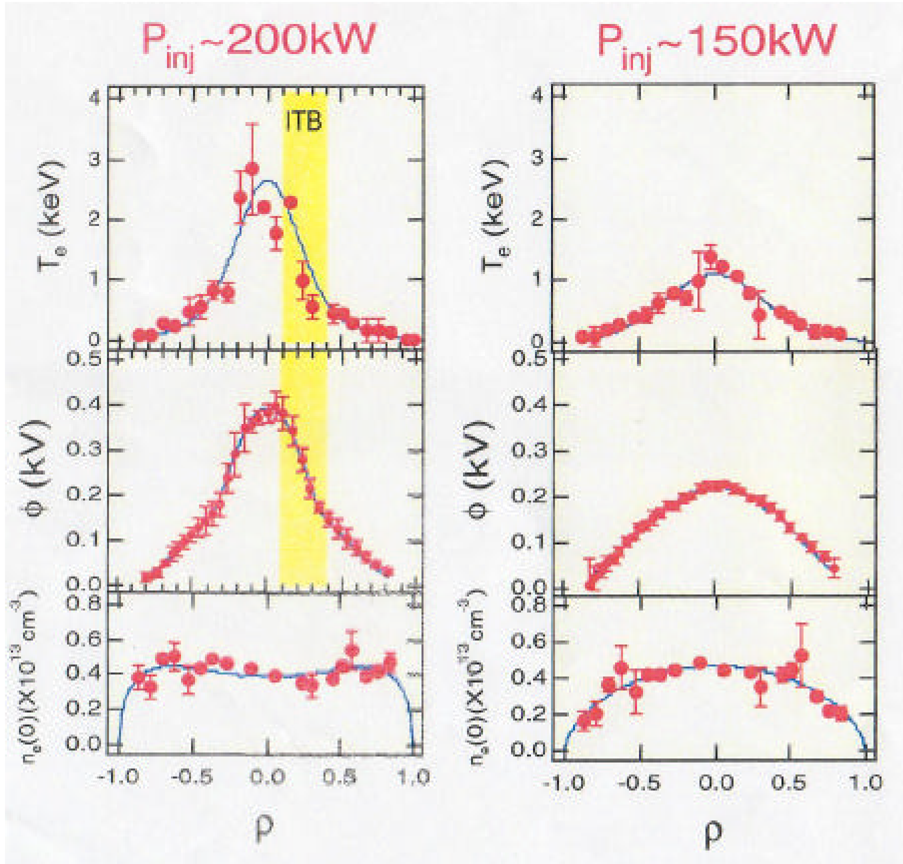
Er shear driven by toroidal rotaion and grad-p (JT-60U,Shirai)



HELICAL

Positive electric field driven by ripple loss in low density regime predicted by Neo-Classical Theory

NC-ITB (CHS, Minami & Fujisawa)

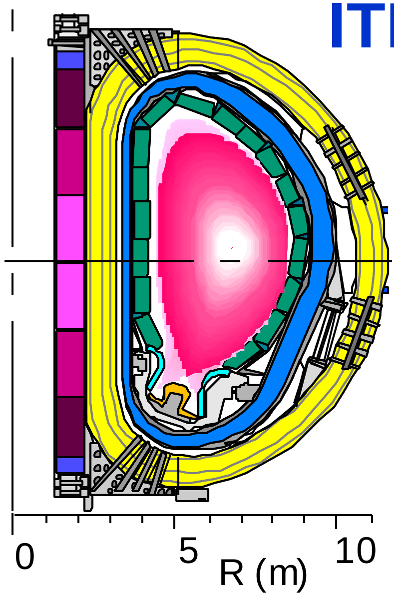


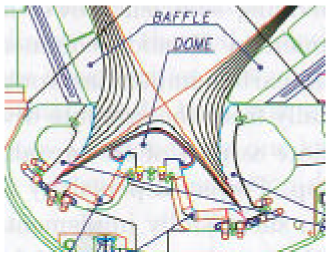
Island, Ergodicity and Divertor

TOKAMAK

Poloidal Divertor

ITER



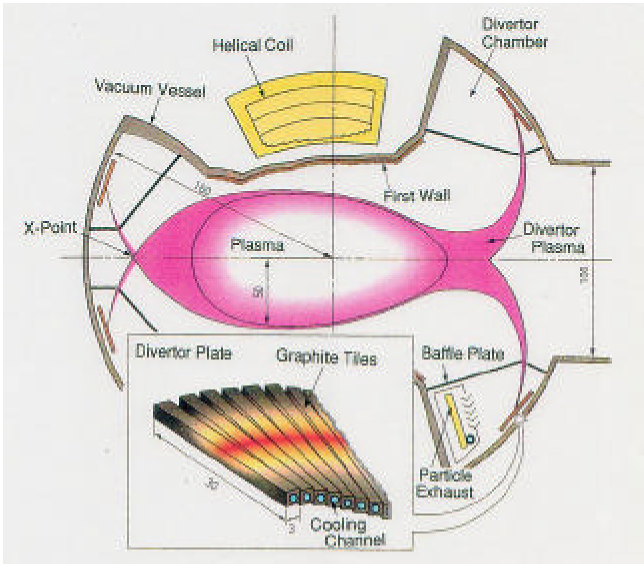


Remote radiation

HELICAL

Helical Divertor

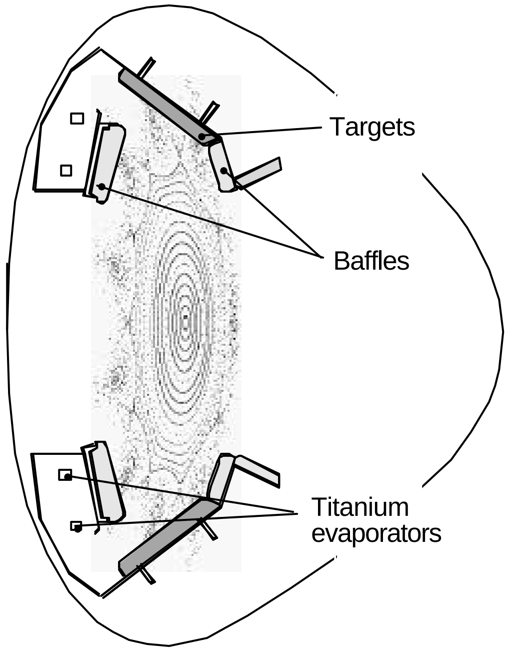
LHD



Short connection length
Rather clean separatrix

Island Divertor

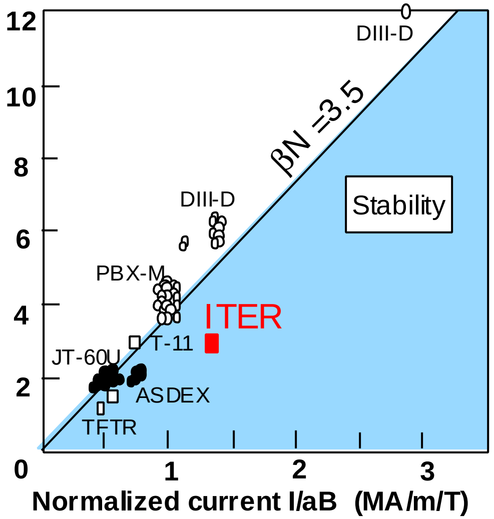
W7-AS, LHD



Stability Limits

grad-j dominant or grad-p dominant ?

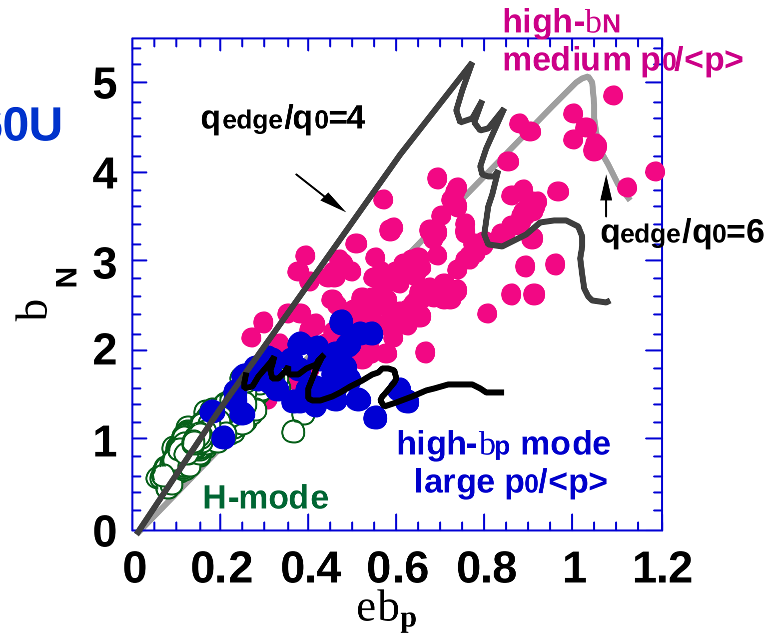
Tokamak



Ideal beta agrees with Ideal MHD

Resistive beta agrees with NTM & TM, RWM theories

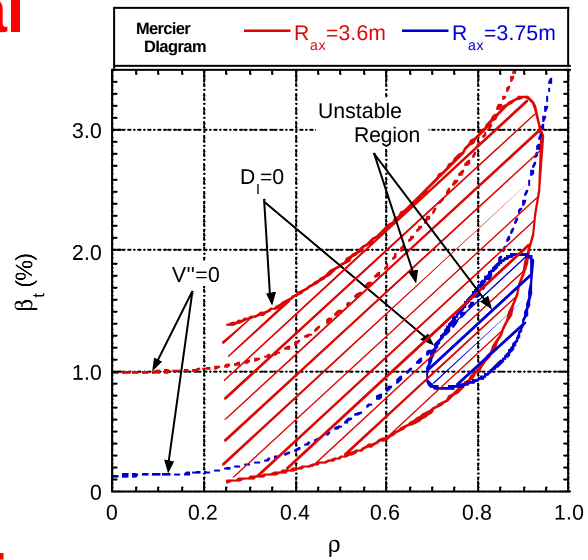
JT-60U



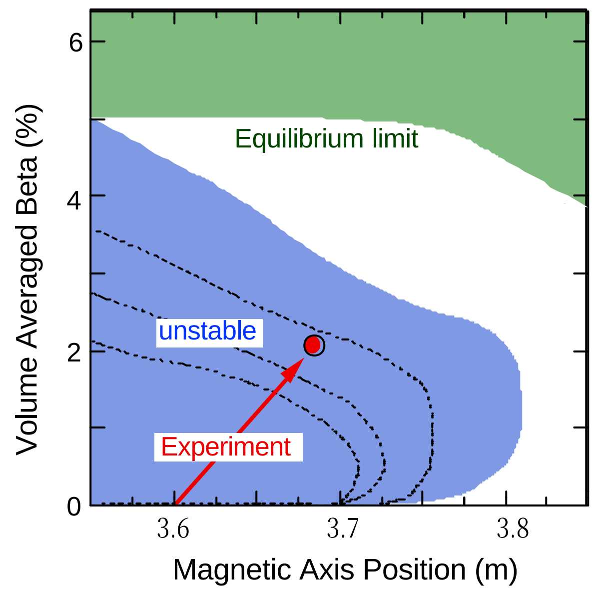
Helical

Beta obtained beyond Mercier mode

Global mode is still marginal.



LHD

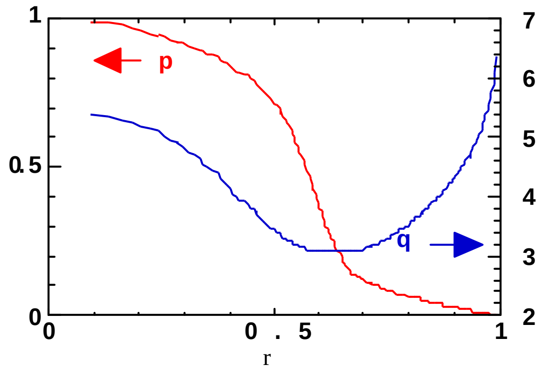


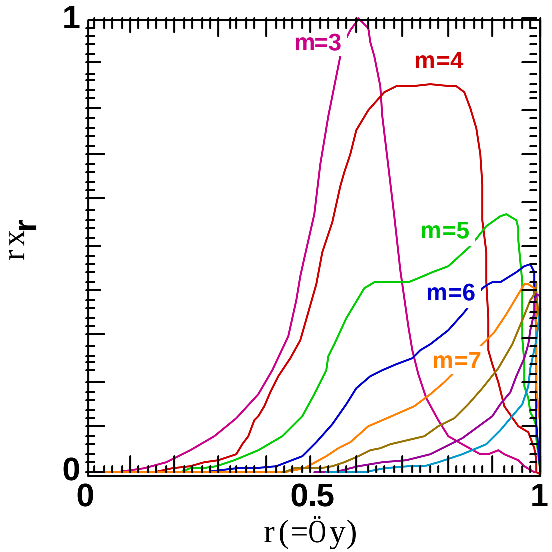
Mode structure

TOKAMAK

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

Global mode driven by grad-j

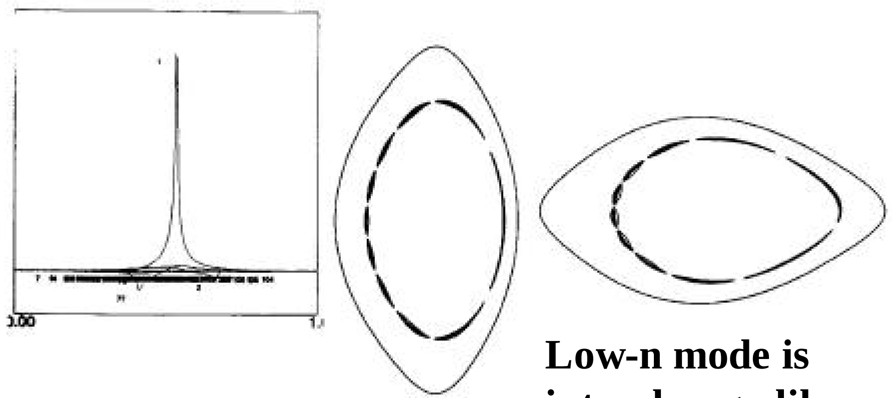




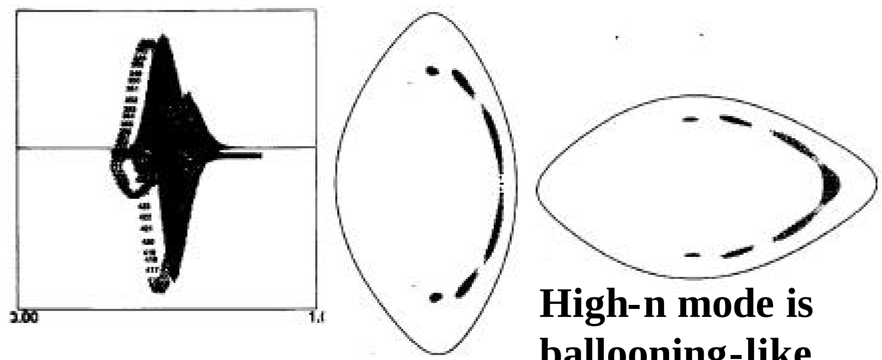
HELICAL

(LHD, Nakajima)
CAS3D code

Localized mode driven by grad-p



Low-n mode is interchange-like.

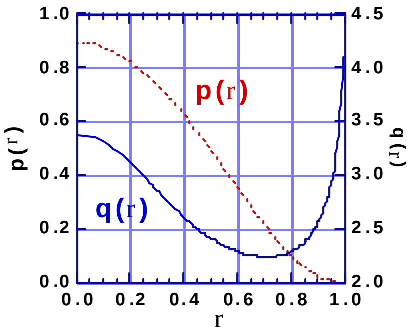


High-n mode is ballooning-like.

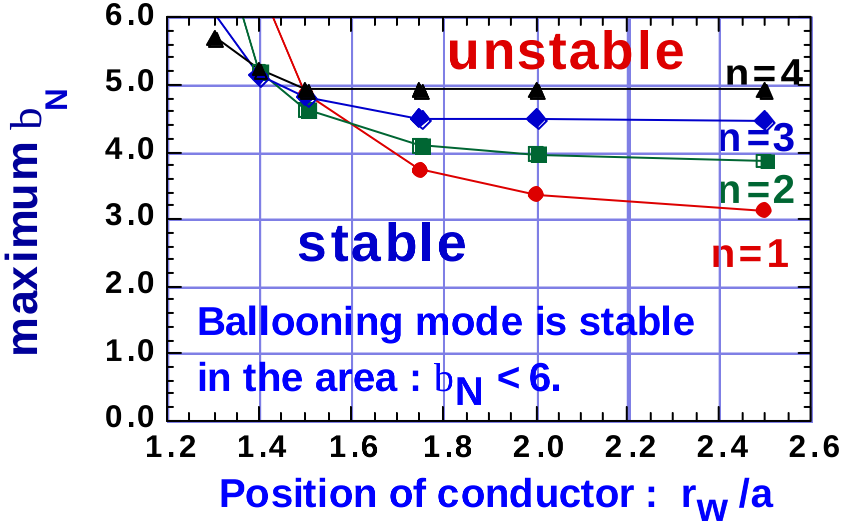
Effects of Wall

Tokamak

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

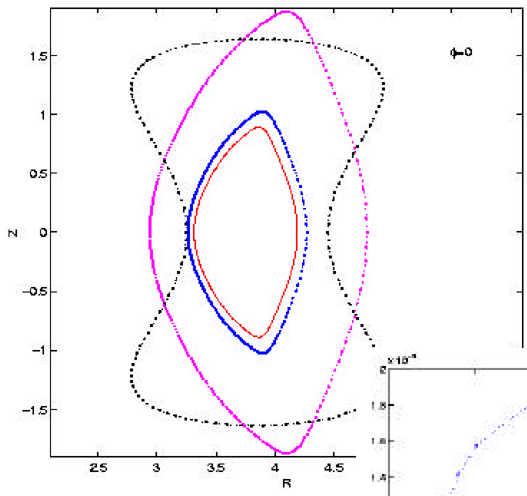


(JT-60SC, Kurita)

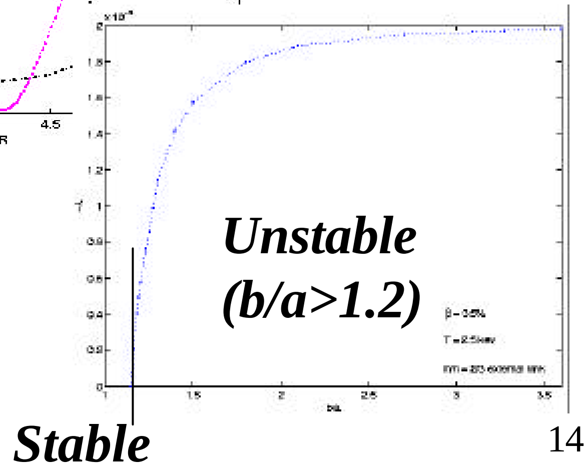


Helical

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



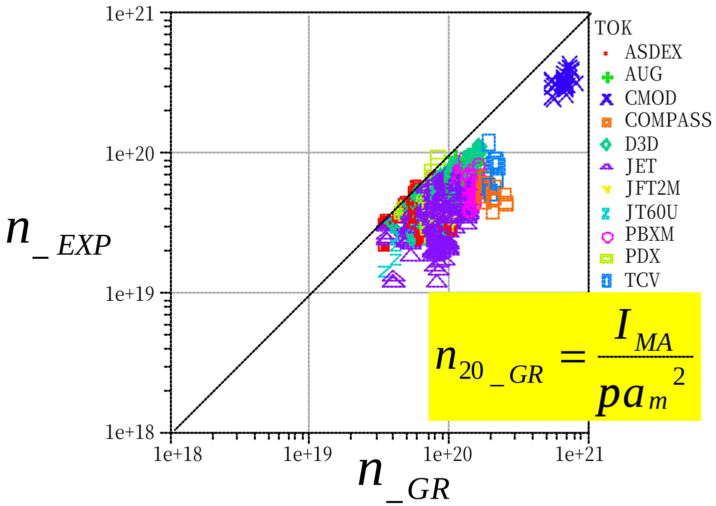
(LHD, Cooper) Terpsichore



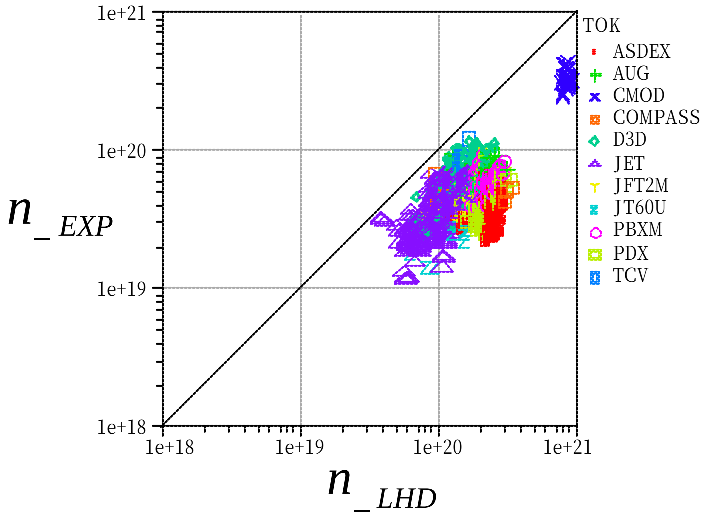
Operational Density Regime

Tokamak

radiation collapse
leading to current disruption

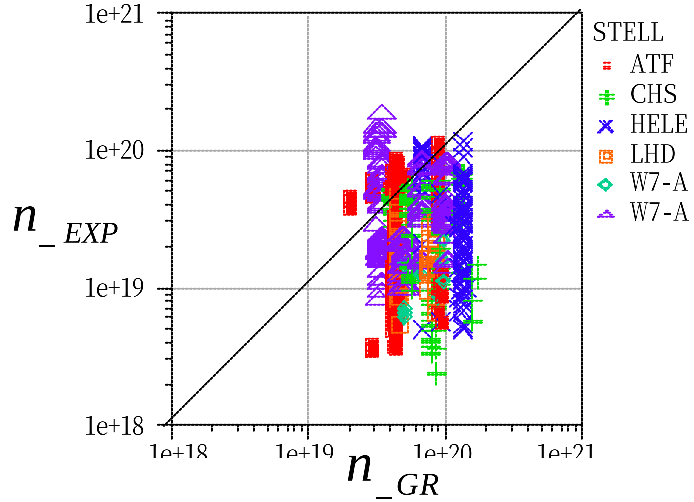


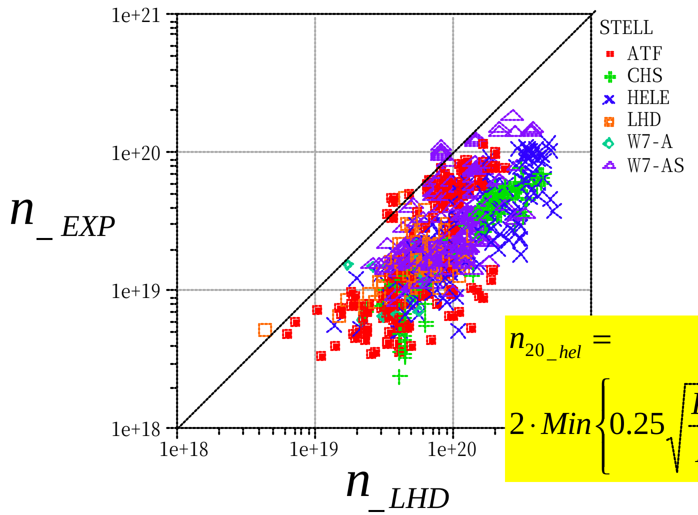
$$n_{20\_GR} = \frac{I_{MA}}{\pi a_m^{2}}$$



Helical

radiation collapse
slow plasma decay



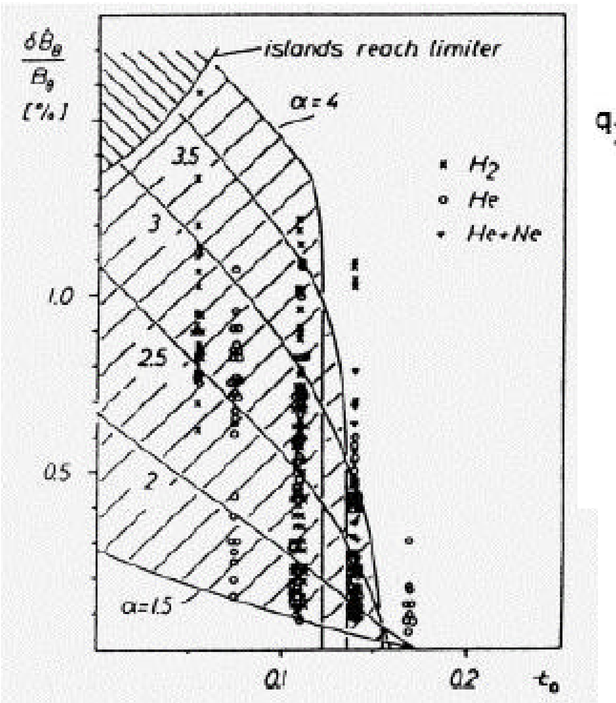


$$n_{20\_hel} = 2\cdot Min\left\{0.25\sqrt{\frac{P_{MW}B_T}{R_m a_m^{2}}}, 0.35\frac{P_{MW}}{R_m a_m}\sqrt{B_T}\right\}$$

Disruption-Free in Helical System ?

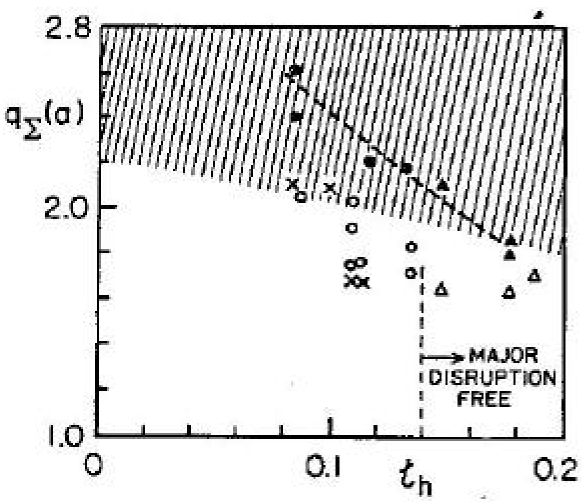
Tokamak - Helical Hybrid
(Current Carrying Stellarator)

W7-A



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

JIPP T-II

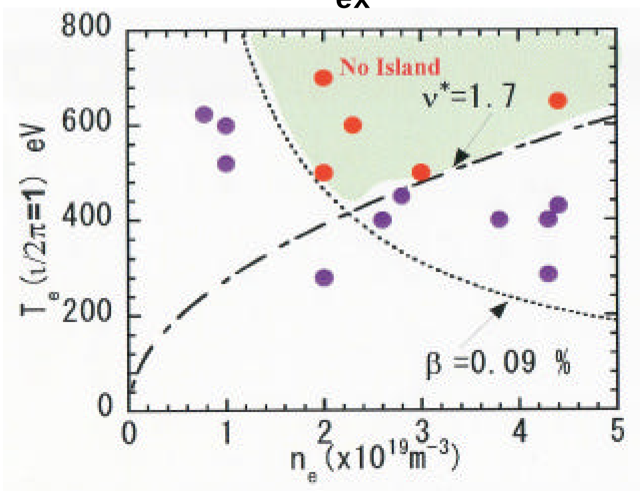


Fujita et al.,
IEEE Transaction on
Plasma Science
PS-9 (1981) 180.

Tearing mode, even NCTM, can be stabilized in helical system?

LHD

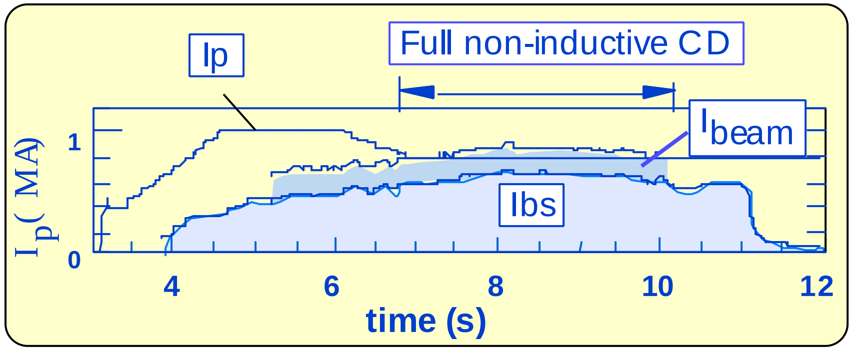
m/n=1/1
W_{ex}/a=0.085



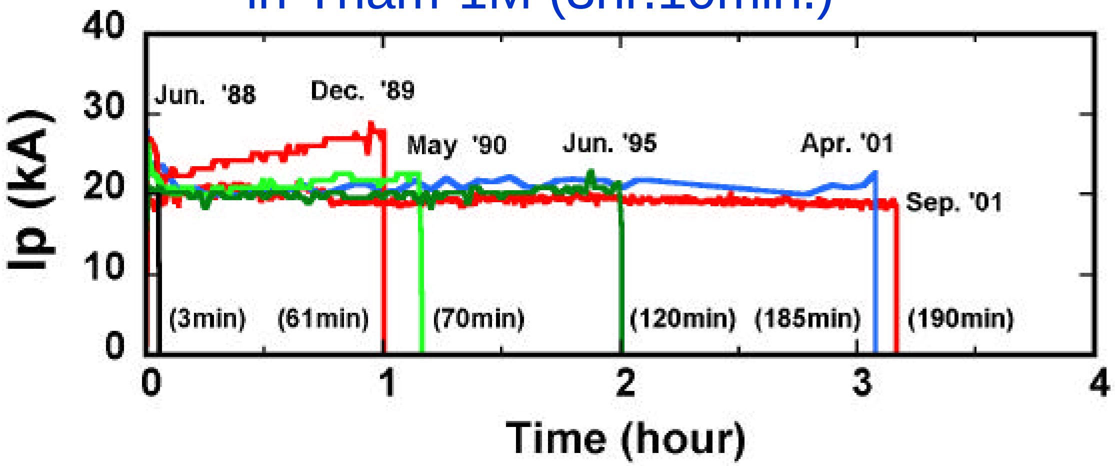
Steady-state Operation

Tokamak

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

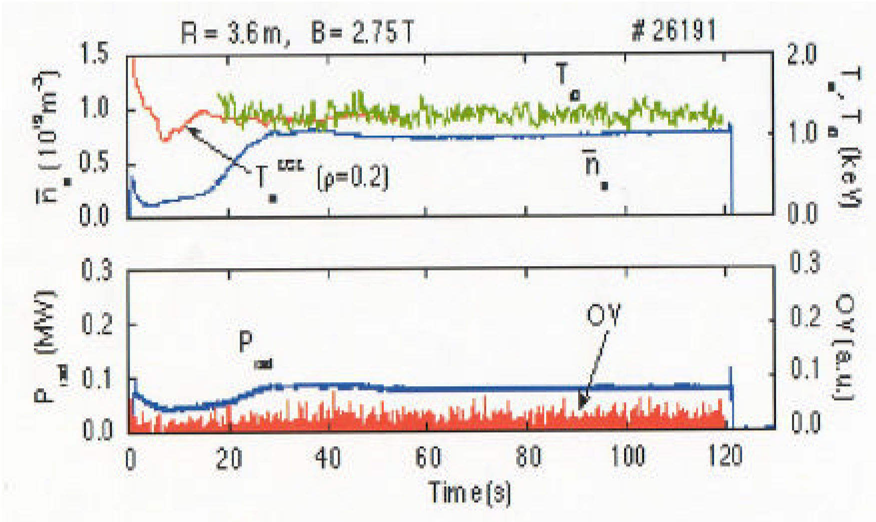


LH Current Drive
in Triam-1M (3hr.10min.)



Helical

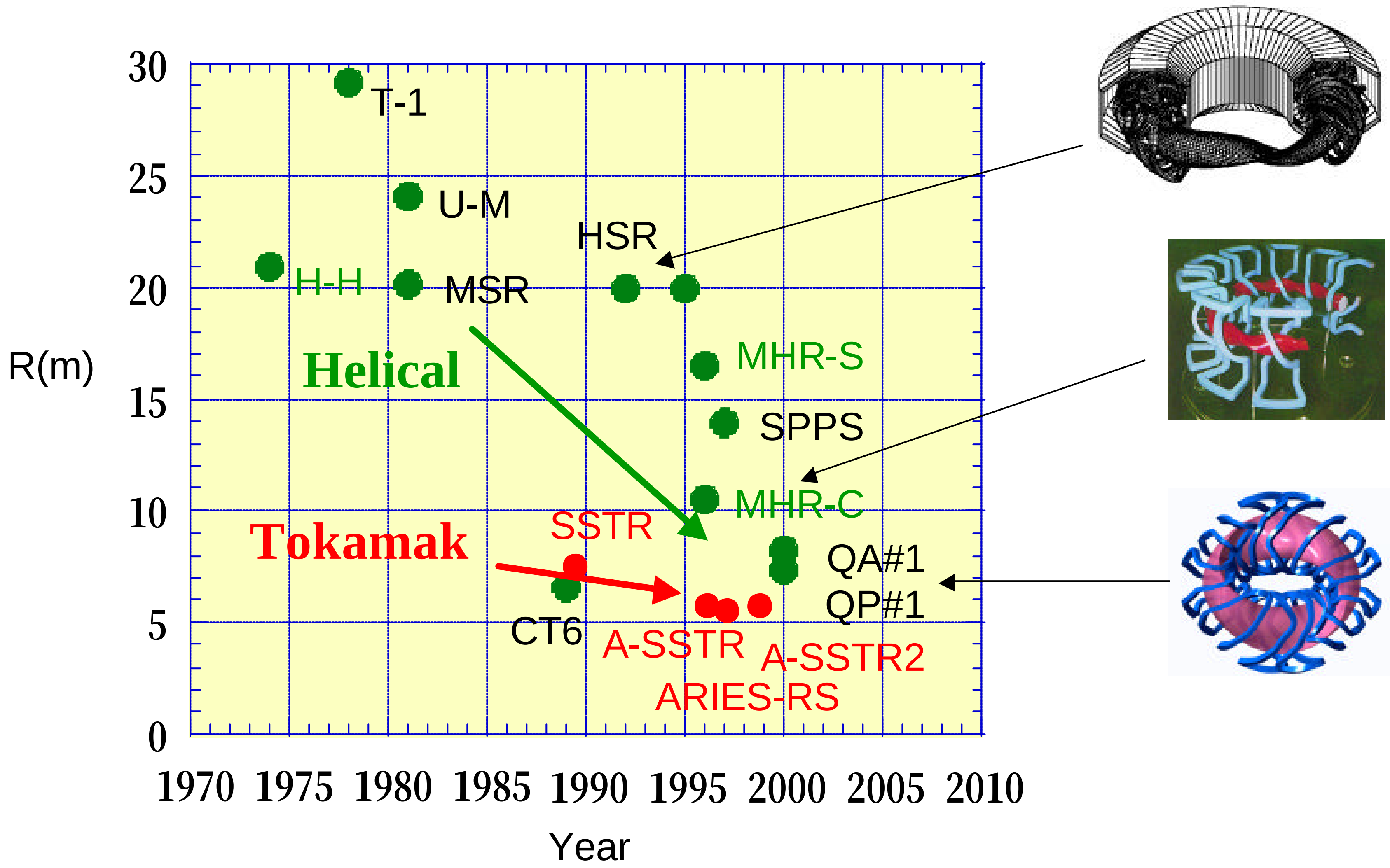
~1keV long pulse operation
In LHD (ICRF 0.8MW)



(Triam-1M,
Sakamoto,
this conference)

Progress on Reactor Designs

Lower-aspect designs are explored.



Operational Limits

	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

● **For realization of attractive fusion reactors, better confinement and longer-pulsed operations should be achieved in addition to burning plasma physics clarification.**

● **In tokamak systems, critical issue is to avoid disruption and to demonstrate steady-state operation.**

● **In helical systems, high performance discharges should be demonstrated with reliable divertor, and compact design concepts should be developed.**

● **Each magnetic concepts should be developed complementally focusing on above critical issues keeping their own merits, for realization of attractive reactors and for clarification of common toroidal plasma confinement physics.**