Complementary Study

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NINS
National Institutes of Natural Sciences

LHD NIFS

2nd International ITER Summer School
Fukuoka, 22-25 July, 2008

Outline

1. **"Complementary"**
2. **Introduction of helical system**
3. **Importance (Raisons d'être) and role of helical system**
   - ✓ exact estimate ⇔ comprehensive understanding
   - ✓ complementary approach

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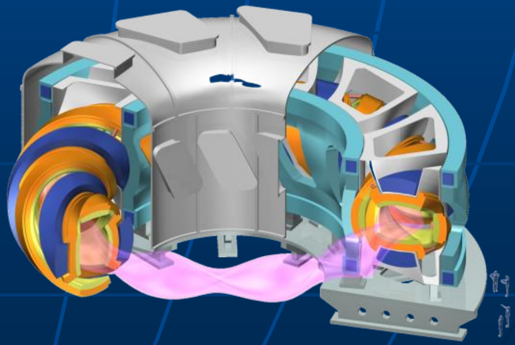
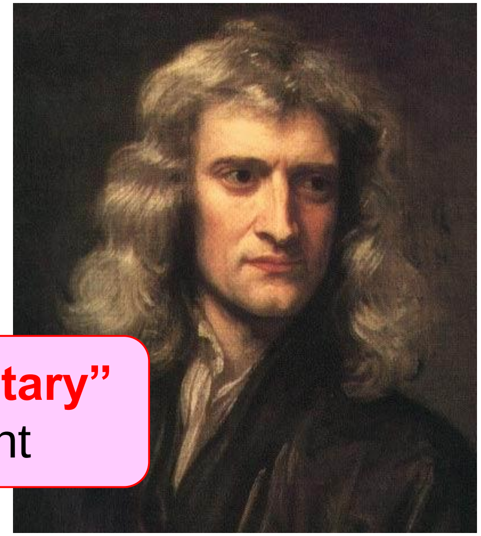
4. **Topics to validate "complementary" portfolio approach**
   - ✓ 3-D Equilibrium
   - ✓ MHD - interchange mode -
   - ✓ control of radial electric field & structure formation
   - ✓ dynamics of magnetic island
   - ✓ density limit
   - ✓ edge plasma



5. **Summary**

What is "complementary"
Evolution of science - compared to mechanics -



Quantum mechanics
The uncertainly principle
abandonment of classical "law of causality"

Classical mechanics (Newtonian mechanics)

Relativity
Space and time are not uniform

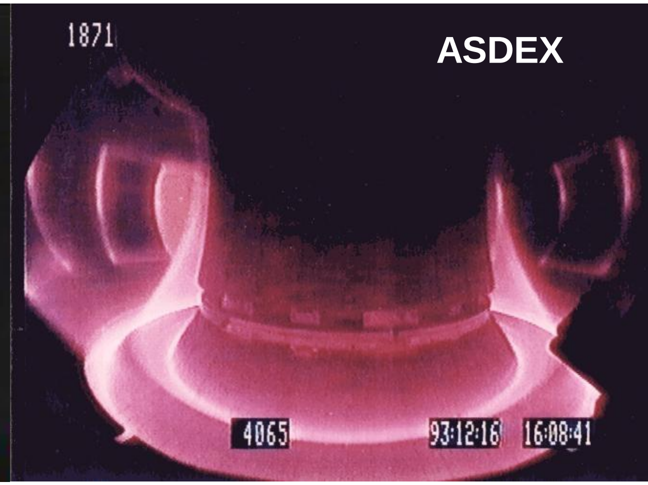
Binary opposition : Dialectic approach
Discussion on the merits and demerits is not always productive
➔ **"Complementary" approach** : *The longest way round is the shortest way*
comprehensive understanding of differences ➔ portfolio approach

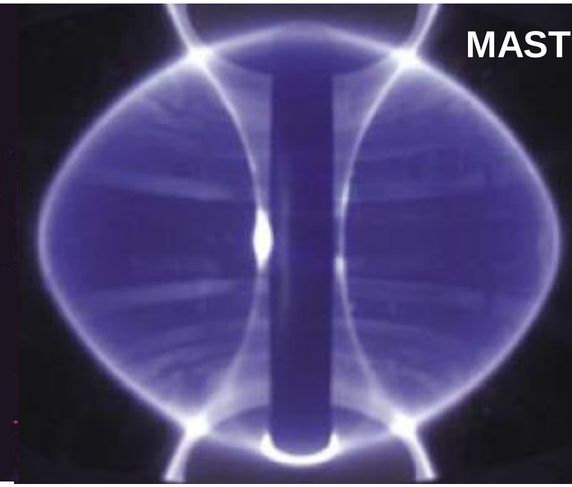
➔ Challenge to Theory of Everything (>> Great Unification Theory)
& identification of big bang

The portfolio of plasma confinement

Comprehensive understanding ⇔ Exact understanding

Externally controlled ◀‑‑‑‑‑‑‑‑‑‑‑‑‑‑‑‑‑‑‑‑



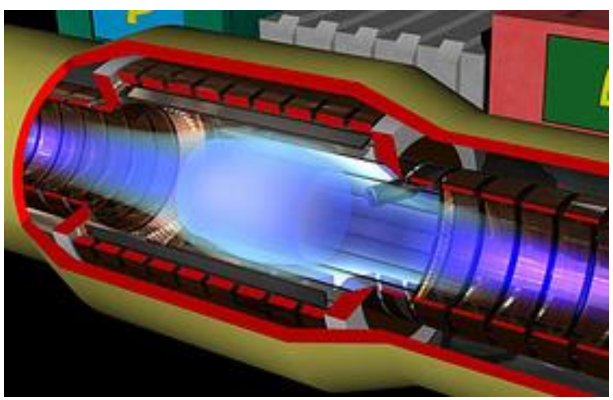


Helical system

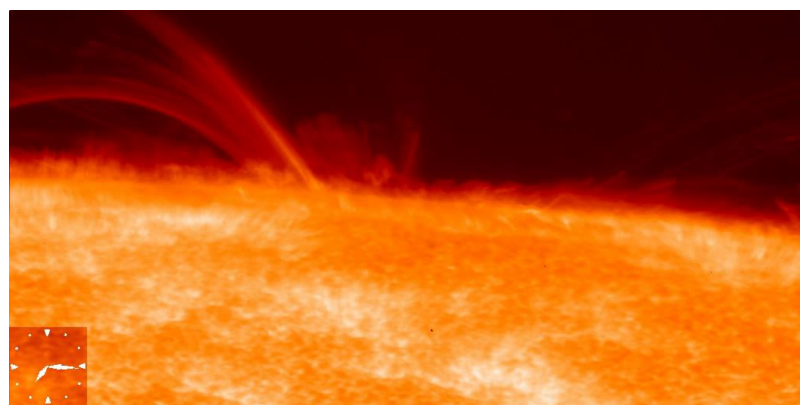
Tokamak

Spherical Torus

‑‑‑‑‑‑‑‑‑‑‑‑‑‑‑‑‑‑‑‑▶ **Self organized**



FRC (Field Reversed Configuration)

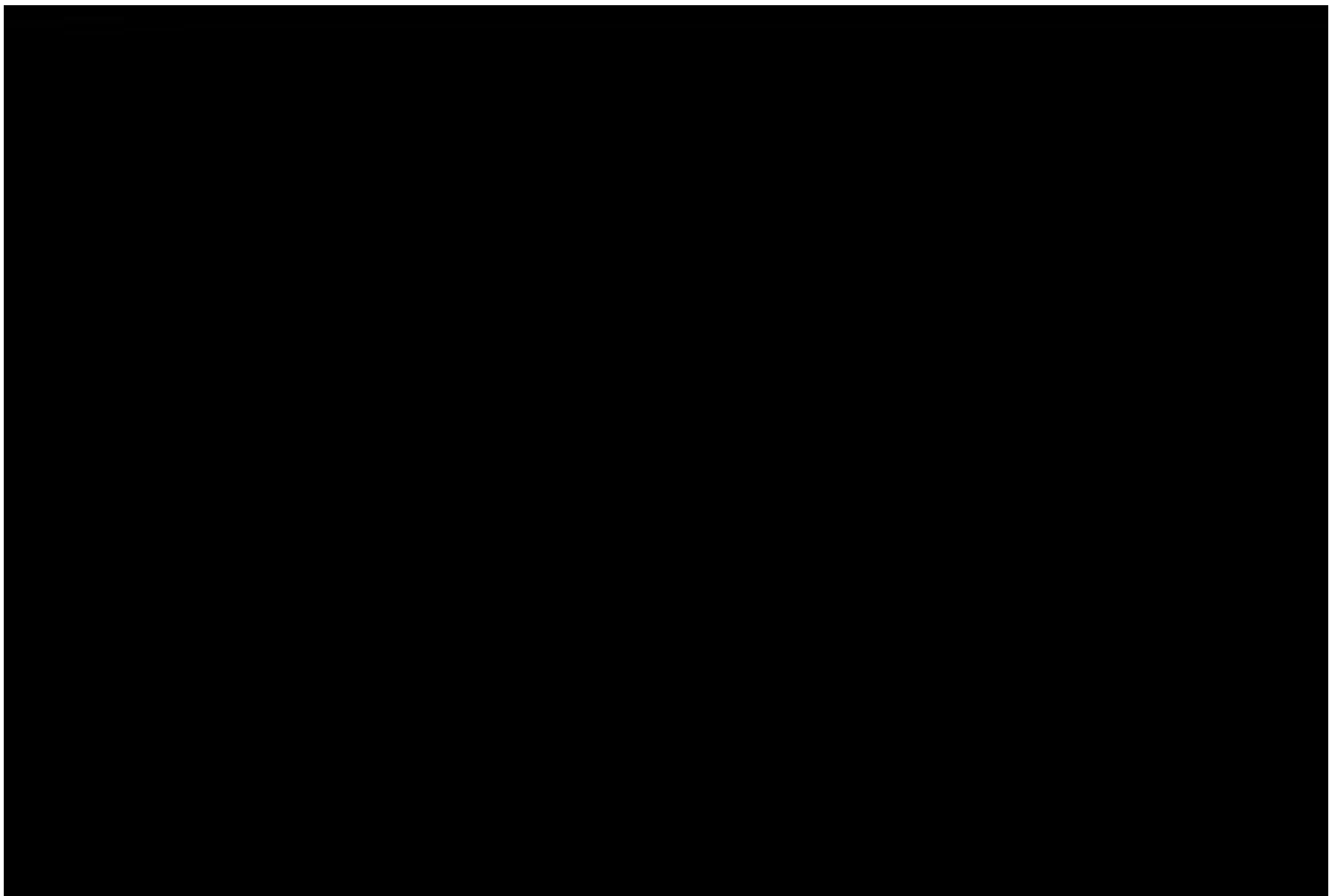


The sun (Hinode satellite JAXA/NAOJ)

Confinement of plasma by magnetic field

Common basis

1) Lamor motion of charged particles
2) Circumnavigating field lines without end (torus)
3) Rotational transform to compensate curvature drift & charge separation



Confinement of toroidal plasmas

Closed surfaces formed by circum-navigating magnetic field lines

Re

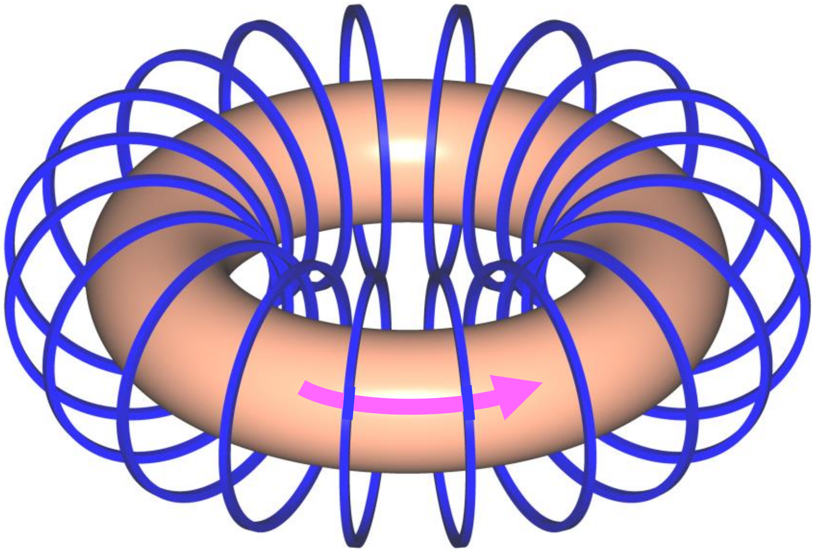
idal)

Tokamak and Helical system

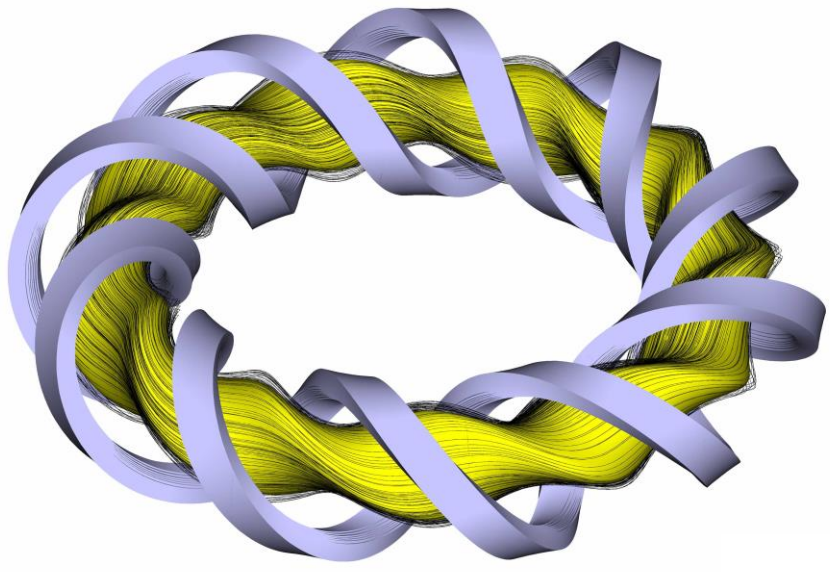
- ✓ Large commonality as toroidal system
- ✓ Difference due to existence/absence of net plasma current

Helical system : no requirement of current drive,
no current driven instability (disruptions)

➔ mitigates engineering demands for a fusion reactor



Tokamak (approximately 2-D)



Helical system (intrinsically 3-D)

How the rotational transform is generated without net plasma currents?

$$\nabla \times \mathbf{B} = 0$$

There is no rotation around the magnetic axis ?

Periodic modulation of magnetic field along the field line

Poloidal field $B_\theta = \cos m\theta$

Toroidal field $B_\varphi = 1 - \varepsilon \cos m\theta$

$$\int_0^{2\pi} B_\theta r d\theta = \int_0^{2\pi} \cos m\theta r d\theta = 0$$

Eq. of field line

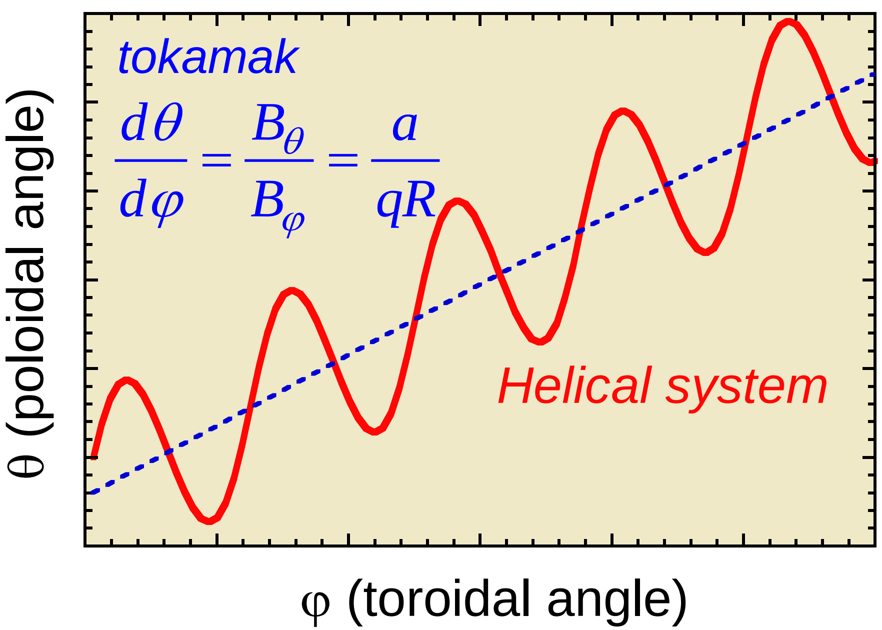
$$\frac{d\theta}{d\varphi} = \frac{B_\theta}{B_\varphi} = \frac{\cos m\theta}{1 - \varepsilon \cos m\theta}$$

Resonance of modulated toroidal and poloidal field generates rotational transform with keeping ∇×B=0

➔ Bumpiness in magnetic field degrades confinement

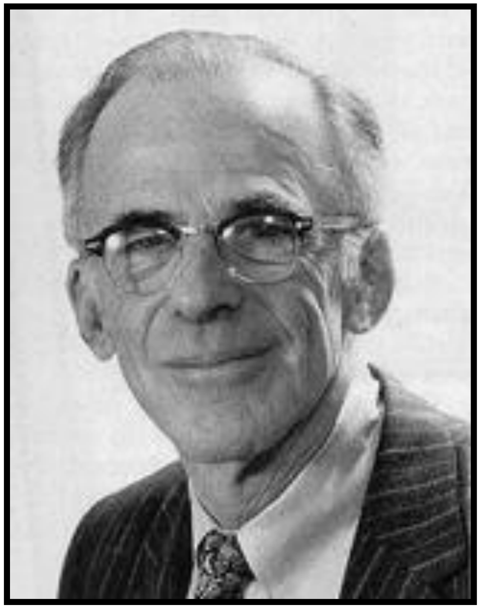
➔ It is true in general, however, it is not always true.

➔ We have a fighting chance.

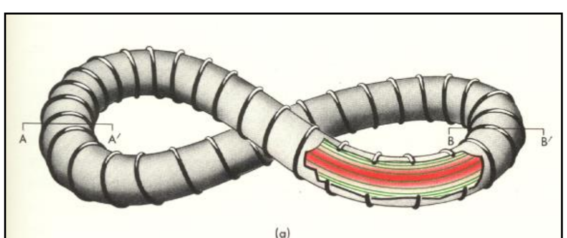


Origin and developments of helical systems

1951 (Princeton)

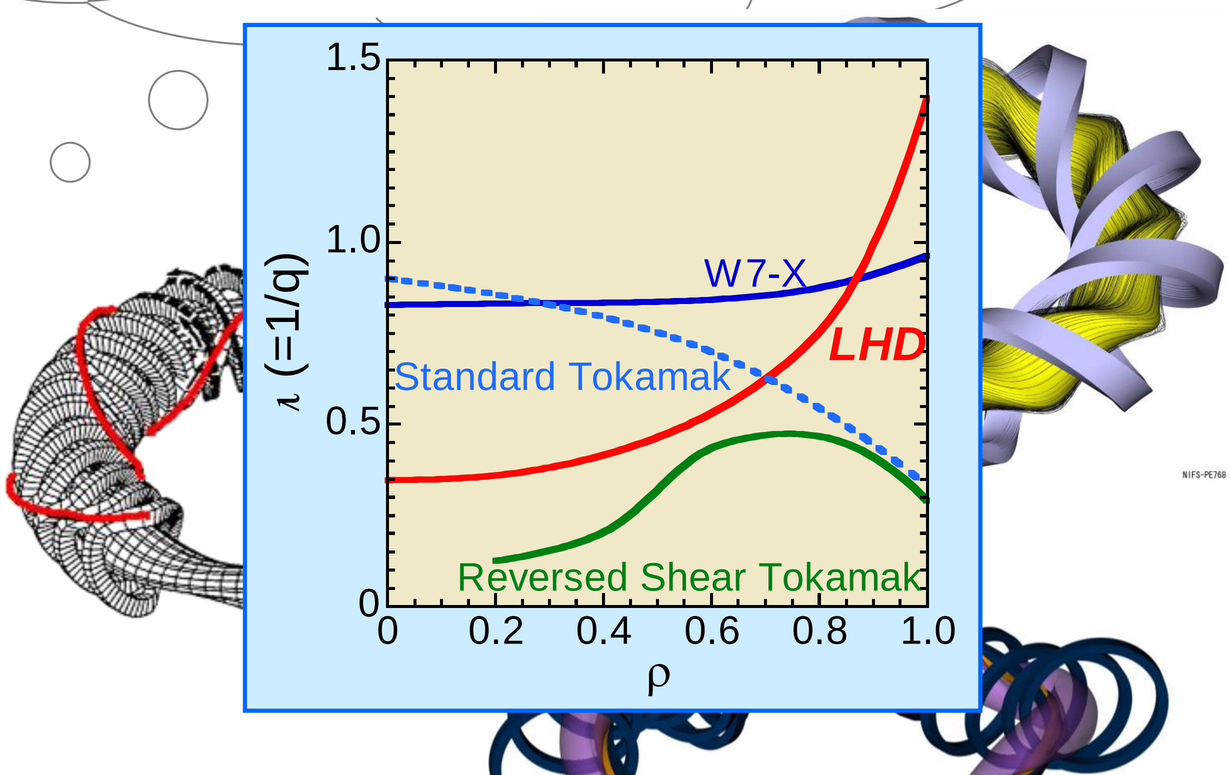


Lyman Spitzer Jr.



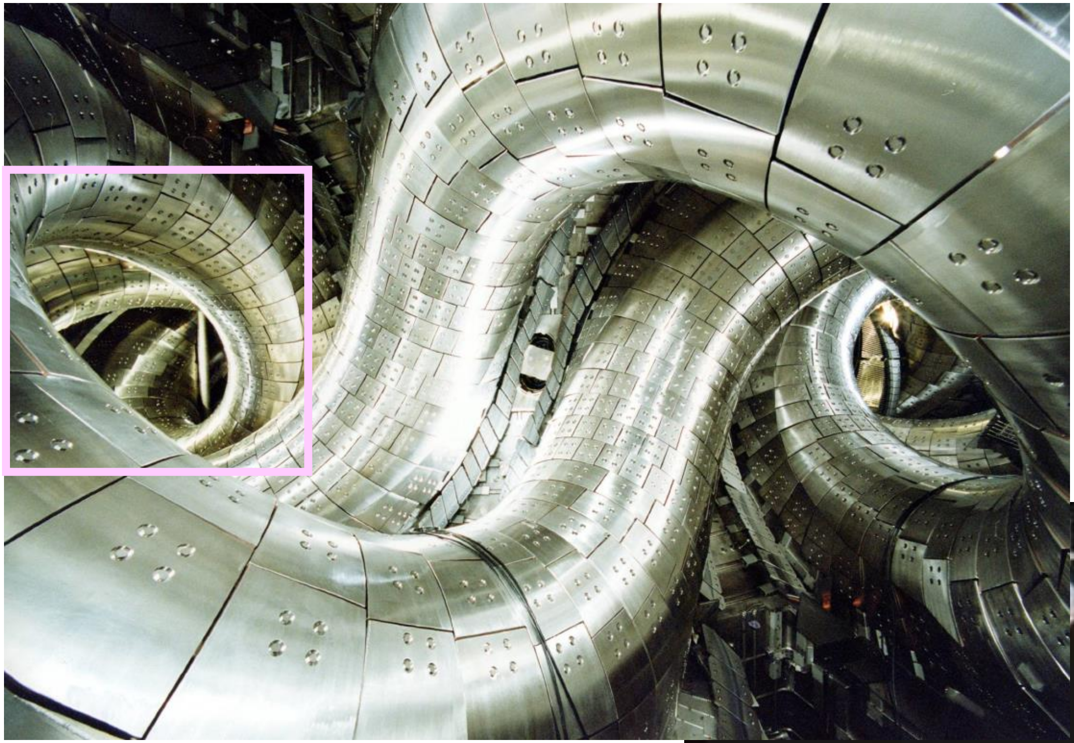
Confinement of toroidal plasma by external coil

Design of the shape of coil and resultant rotational transform ?



➔ Large flexibility & Optimization is necessary

Large Helical Device (LHD) in National Institute for Fusion Science (NIFS)



LHD

R = 3.9 m

a = 0.6 m

B = 3 T

P_{heat} = 20 MW

Superconducting coils with magnetic energy of 0.9GJ

Fundamental process to induce loss

Collisions between charges particles

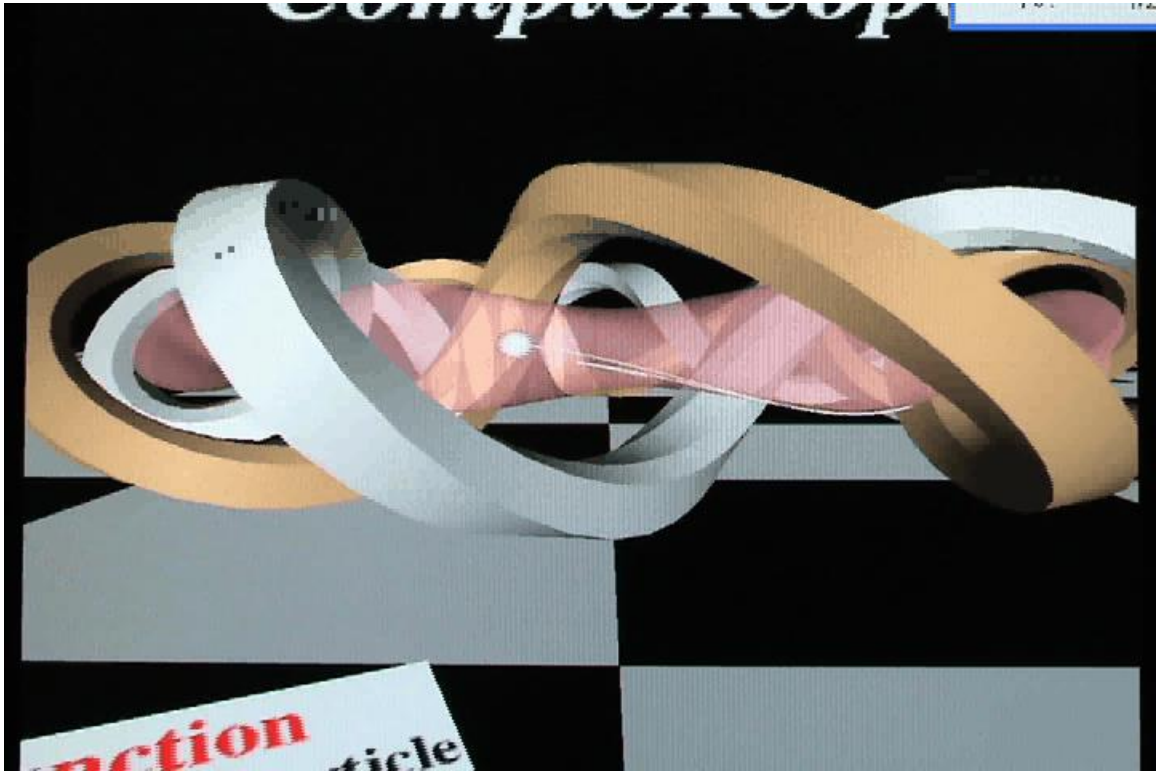
Orbit of a single charged particle
restricted by magnetic field
➔ Complicated but solvable

Collision changes orbit
➔ Diffusion
➔ **Neoclassical transport theory**
Complicated in 3-D but solvable

In reality

Particles and heats are lost more rapidly than the neoclassical theory
➔ **Anomalous transport**
not clarified yet, driven by turbulence

Trapped particle
Circulating particle



Courtesy of N.Mizuguchi

Definition of Broader Approach

Joint Report of EU/JA Expert Group Meeting (Culham, April 2004) on A Broader Approach to Fusion Power

Basic Activities and Functions in a Broader Approach

1. Primarily ITER oriented : Joint implementation of ITER

2. ITER/DEMO oriented

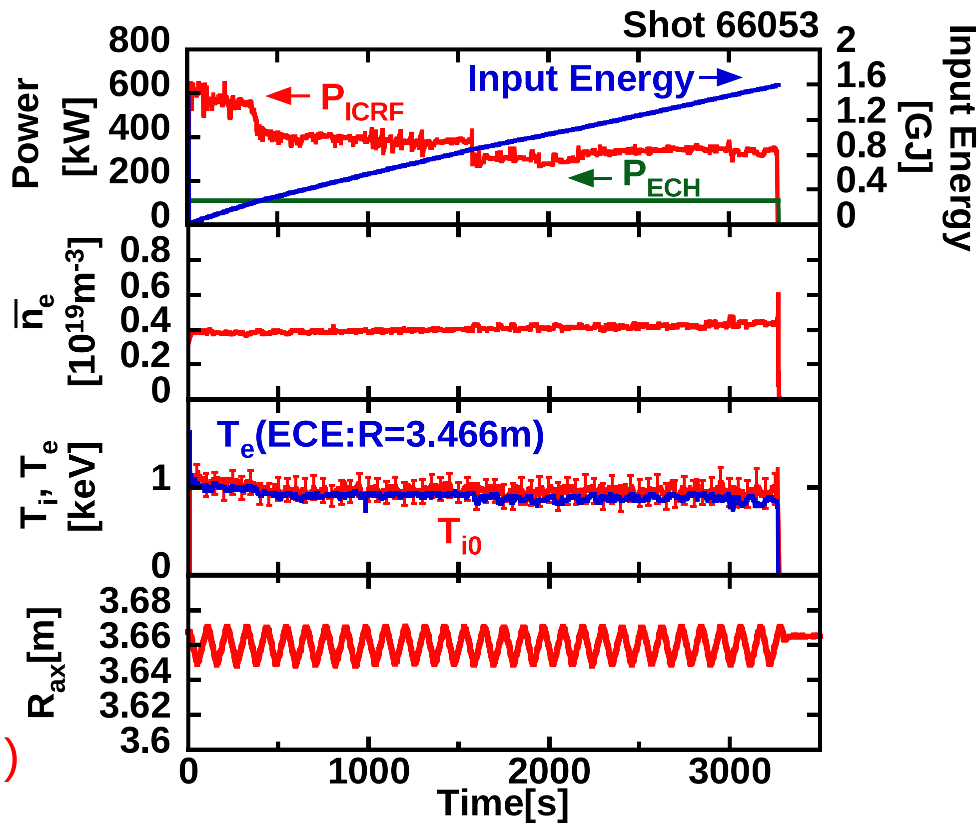
Satellite tokamak – ITER/DEMO physics support function

3. Primarily DEMO oriented

DEMO concept definition,

Design and coordination of R&D,

IFMIF



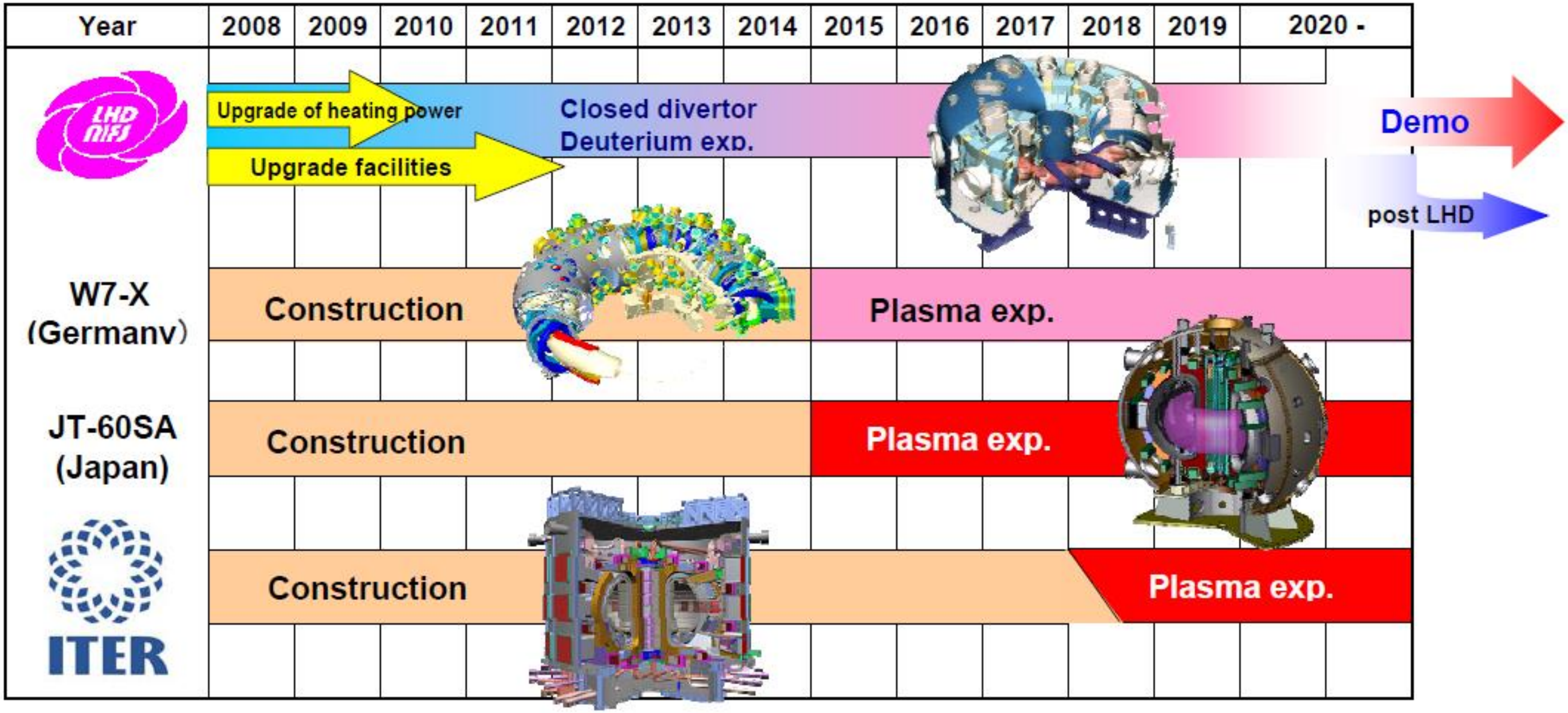
ITER/DEMO oriented

The main functions in support to DEMO will be to explore operational regimes and issues *complementary* to those being addressed in ITER

- ✓ Steady state operation
- ✓ Advanced plasma regime (high β)
- ✓ Control of power fluxes to walls (PWI)

➔ **Addressed major issues in LHD**

Effective use of facility for bidirectional benefits
- Strategy in this decade -



1. Two time scales; in these 10 years & next decade
2. Provision against risks and alternative plan (Portfolio)
3. Enhancement of collaboration, Human resource development
4. NIFS offers collaboration for public subscription

Outline

ITER needs much more accurate and efficient methodology than the existing.

4. Topics to validate "complementary" portfolio approach
    1) 3-D Equilibrium
    2) MHD - interchange mode -
    3) control of radial electric field & structure formation
    4) dynamics of magnetic island
    5) density limit
    6) edge plasma

5. Summary

3-D MHD equilibrium without assumption of nested flux surfaces

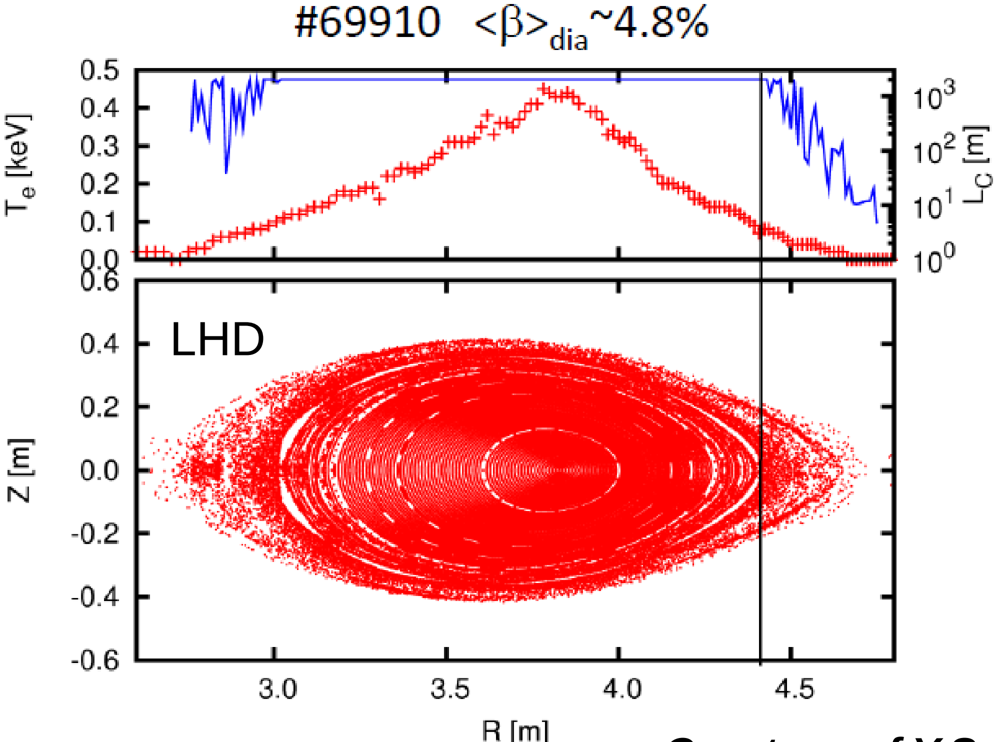
MHD equilibrium

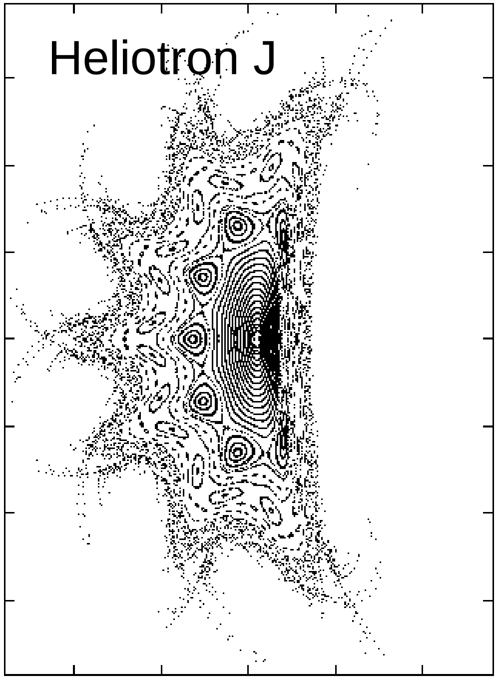
$$\left.\begin{aligned} \mathbf{J} \times \mathbf{B} &= \nabla p \\ \nabla \times \mathbf{B} &= \mu_0 \mathbf{J} \\ \nabla \cdot \mathbf{B} &= 0 \end{aligned}\right\}$$

axi-symmetry $\partial/\partial\phi=0$ → Grad-Shafranov eq.

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

HINT code : calculate 3-D MHD equilibrium with time-dependent relaxation scheme



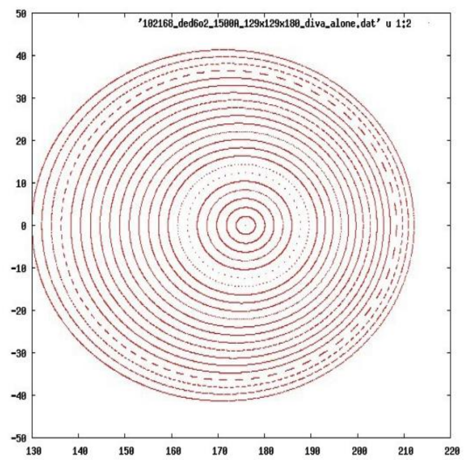


Courtesy of Y.Suzuki

Application of HINT to Resonant Magnetic Perturbation experiment

RMP : control of **ELM** and **RWM**, under consideration in ITER

2-D equilibrium field



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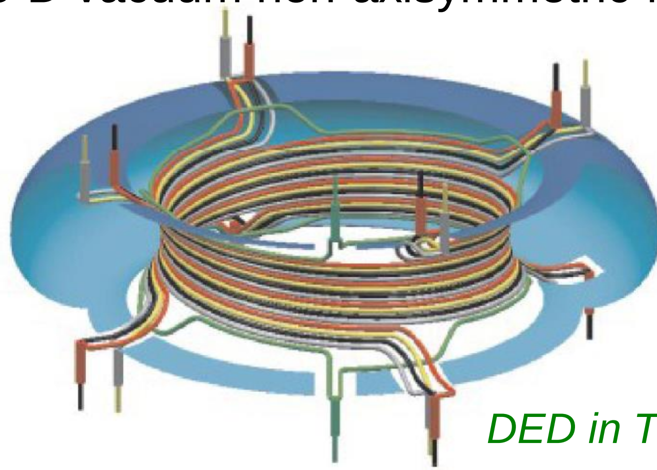
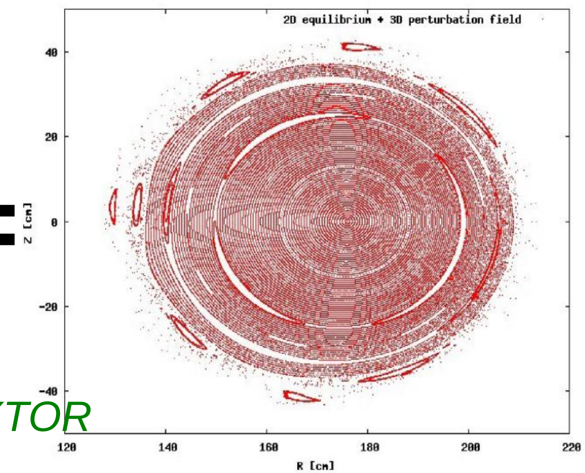
3-D vacuum non-axisymmetric field



DED in TEXTOR

=

Resultant field ?



Usual Ansatz for treat of pertubations: Vaccuum approximation

Neglects feedback of plasma to the changes in flux surface geometry (modified current distributions!): => neglects 3-D effect!

- Acceptable for small perturbations, but "What is small?"

$$\nabla p_{2Dequi} \approx \mathbf{J}_{2Dequi} \times (\mathbf{B}_{2Dequi} + \mathbf{B}_{3Dpert})$$

- Where is the limit?

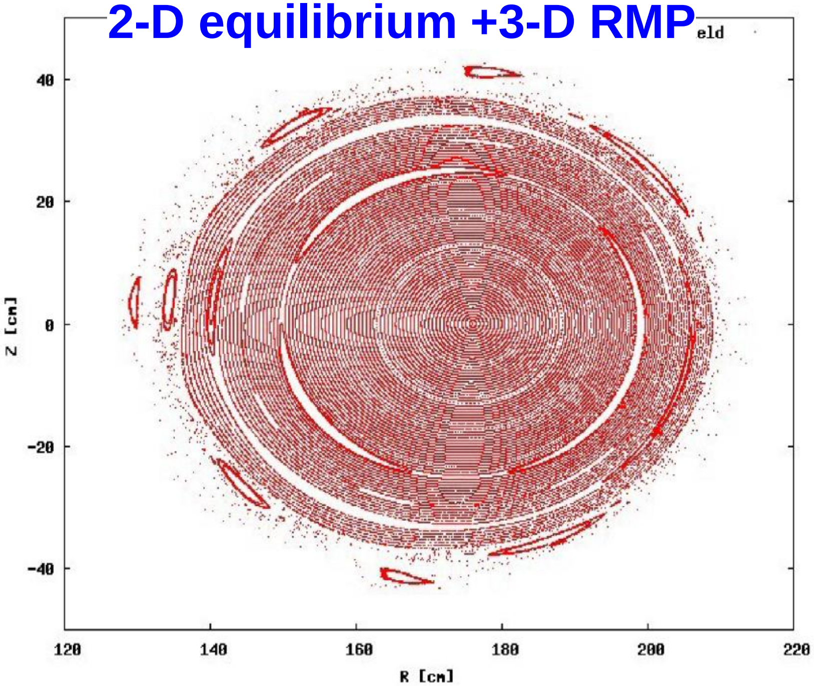
Courtesy of Y.Suzuki&C.Wiegmann

Application of HINT to TEXTOR-tokamak

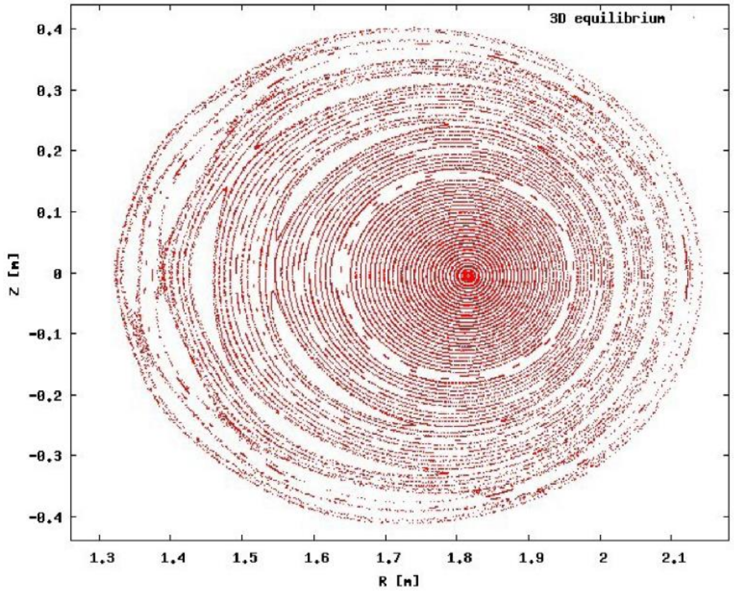
First (preliminary) results for:

- 2D-equilibrium: B_{tor}=1.3T, I_{pl}=245kA
- 3D-pertubation field (6o2 mode of DED, I_{DED}=1.5kA)

2-D equilibrium +3-D RMP



3-D equilibrium by HINT



Notes:

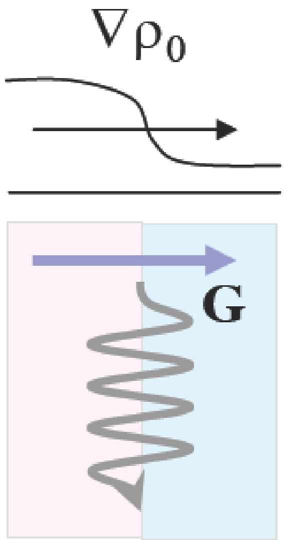
Growing island sizes

Less ergodicity at boundary in HINT2-calc.even at higher β .

Preliminary! Checking of calculations is still under way!

Courtesy of Y.Suzuki&C.Wiegmann

Origin of instabilities
kinetic gradient and force



$\nabla \rho_0 \cdot \mathbf{G} > 0$

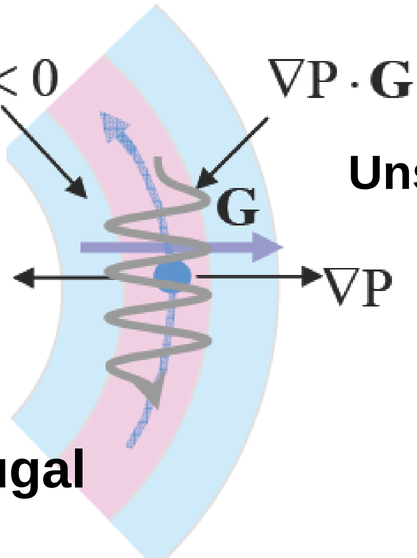
Rayleigh-Taylor Instability

G: gravity

Plasma

$\nabla P \cdot \mathbf{G} < 0$ $\nabla P \cdot \mathbf{G} > 0$

Stable **Unstable**



G: centrifugal force

- Pressure gradient and curvature induces convection : **interchange mode**
- Curvature **G** :
  gradient of magnetic pressure
  centrifugal force

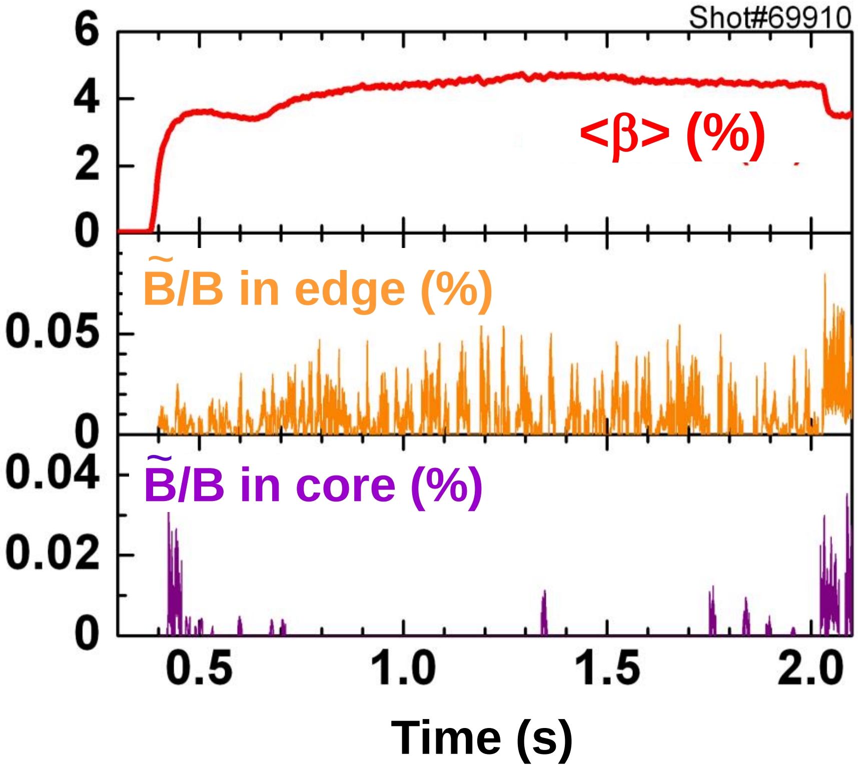
Fluctuation glows or shrinks ?
- unstable or unstable -

Stable:
good curvature
magnetic well

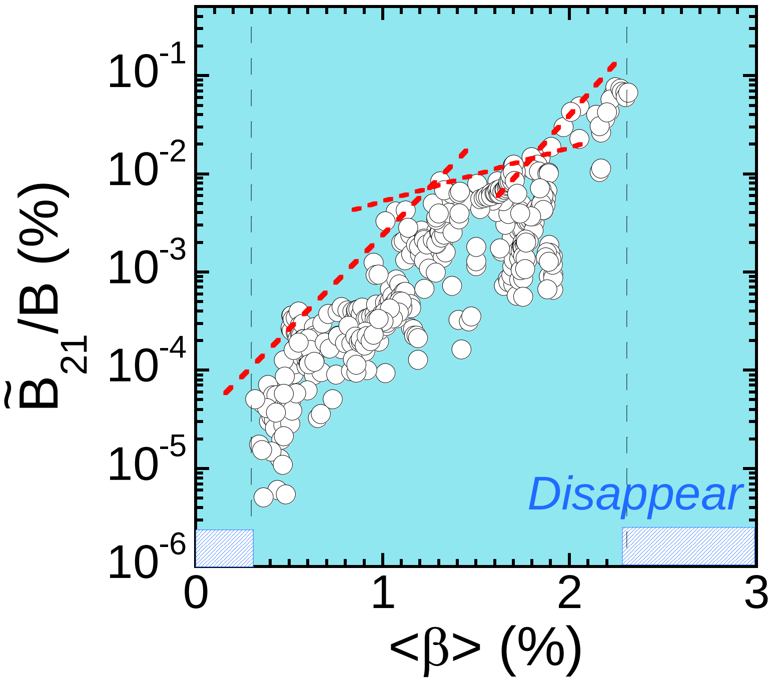
Unstable:
bad curvature
magnetic hill

Magnetic well is necessary condition for good confinement. Absolutely ??

β (plasma pressure/magnetic pressure) reaches 5 % in LHD



Magnetic fluctuation in plasma core



- ✓ Fluctuation does not grow to serious level
- ✓ Instability is generated but does not destruct confinement
  - ➔ Pressure driven instability is harmless
- ✓ Instability in the core is self-stabilized due to spontaneous generation of magnetic well

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

1950' magnetic hill ➔ unstable against interchange mode

"Minimum B" or "Averaged minimum B"

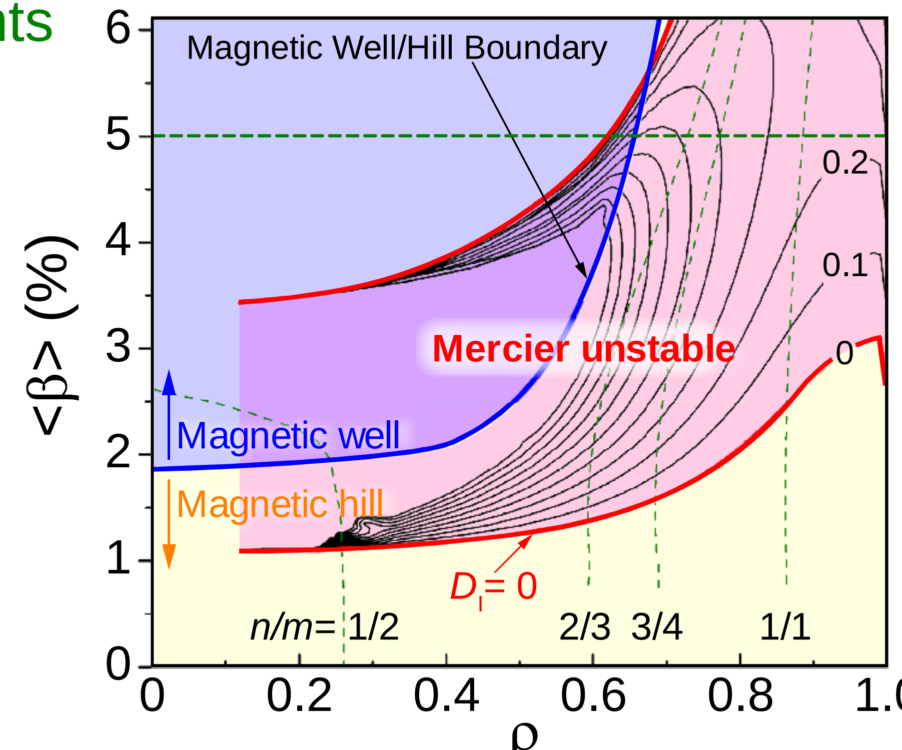
Ioffe bar, Baseball coil, Astron-Spherator, Ohkawa torus ➔ **tokamak**

Standard paradigm in fusion research
beneficial, but provides constraints

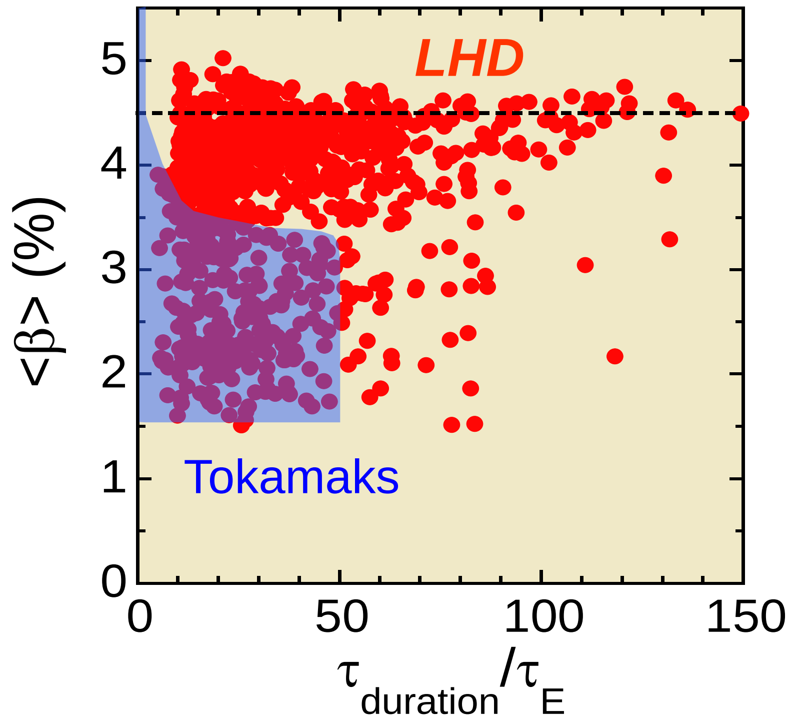
2000- LHD experiment

discovered that interchange instability in magnetic hill is benign
: **New paradigm**

➔ enables optimization of both transport and stability



High-beta state is maintained for 100 τ_E
Arousing new advanced MHD theory



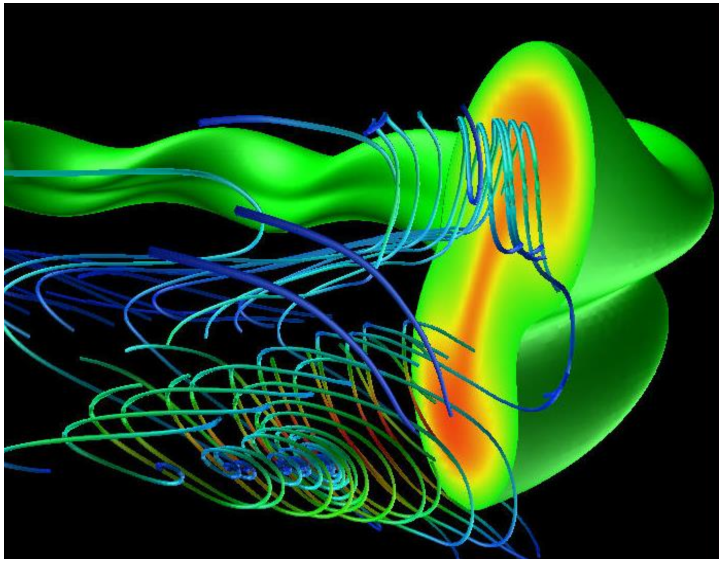
Possible mitigation effect

new elements should be considered

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

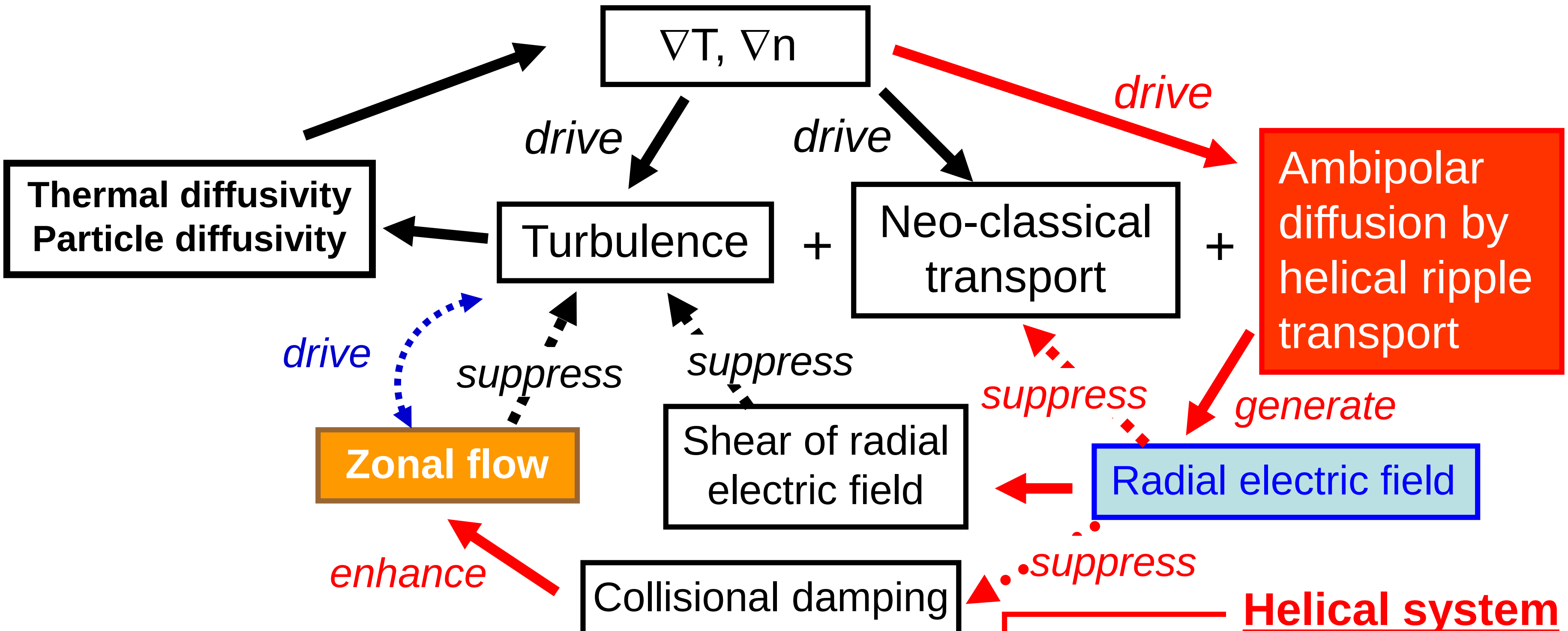
etc…

New advanced physical picture on MHD instability provides more accuracy and will demonstrate its ability in reliable prediction of high performance tokamak discharges as well.



Courtesy of H.Miura

Linkage of physical mechanisms to determine transport in toroidal plasmas



Tokamaks

Radial distribution of T&n is determined by self-consistent turbulence with
1) ∇T and ∇n
2) dE_r/dr
3) Zonal flow

Commonality
Contrast

Elevate understanding from correlation to causality

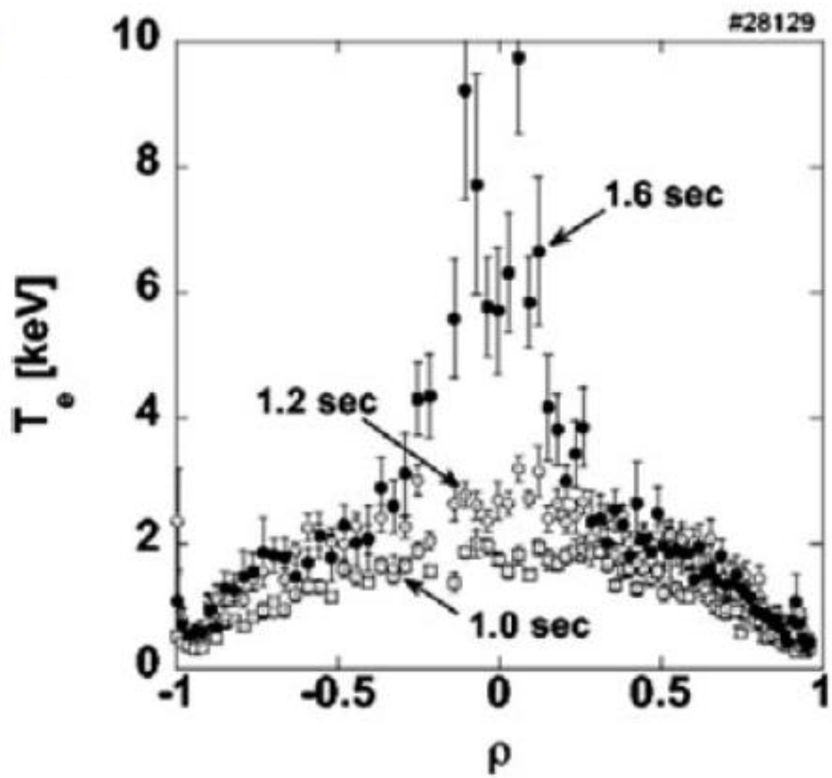
Helical system

E_r due to helical ripple diffusion can control
1) dE_r/dr
2) Zonal flow via collisional damping
3) Neoclassical transport

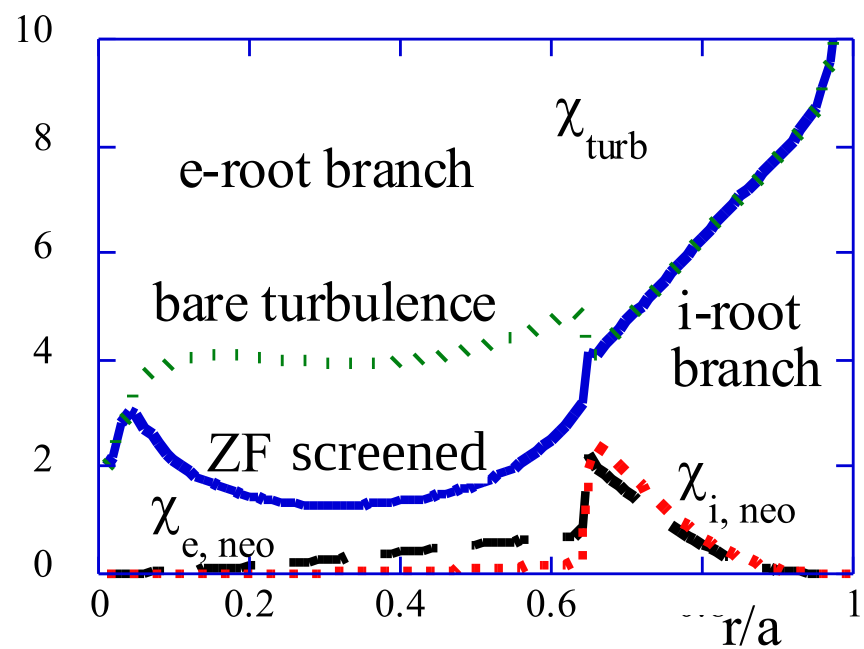
➔ a new knob for ∇T and ∇n

Formation of Internal Transport Barrier

1. Neoclassical ambipolar diffusion generates strong positive Er
2. Collisional damping of zonal flows is suppressed
3. Anomalous transport is suppressed
4. ITB is formed



K.Ida et al., PRL 2003



S.Toda,K.Itoh et al., Nucl. Fusion 2007

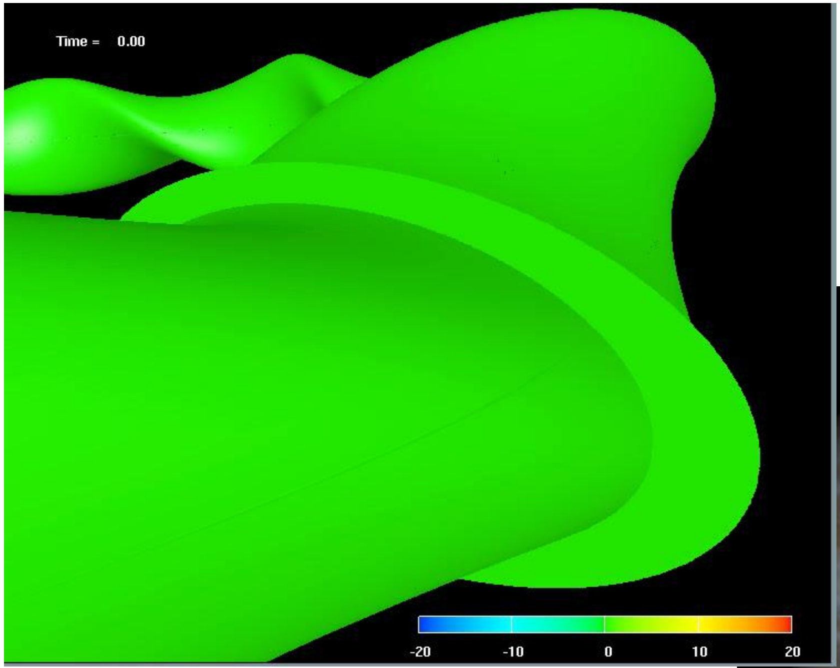
Large-scale simulation of micro turbulence in 3-D

Gyro-kinetic computation by GKV code
Fine structure in distribution function ⬄ Turbulence • Zonal flow
⬄ Evaluation of anomalous transport

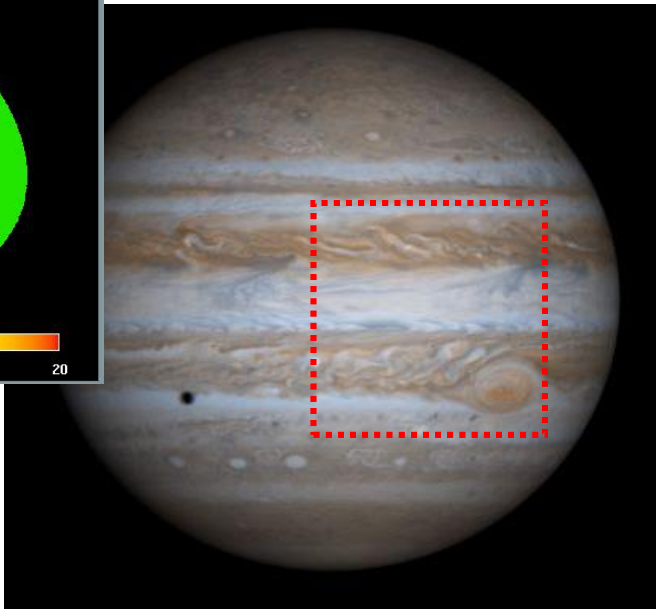
Precise analysis of distribution function & Pursuit of complex particle motion

Flow and electric field due to helical field ➔ Control of transport

Large-scale simulation
Frontier of simulation science



Cooperation in extended field of natural science

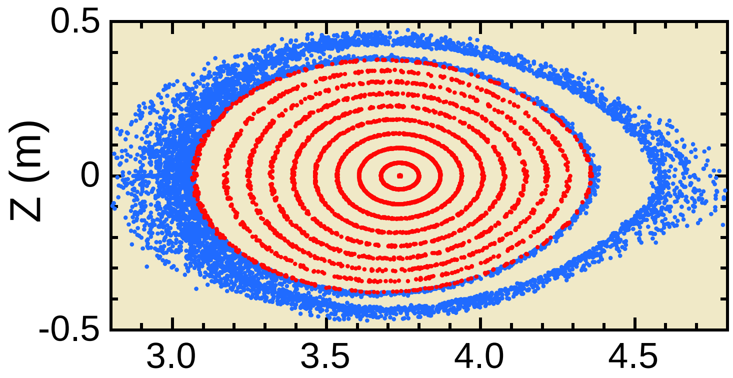


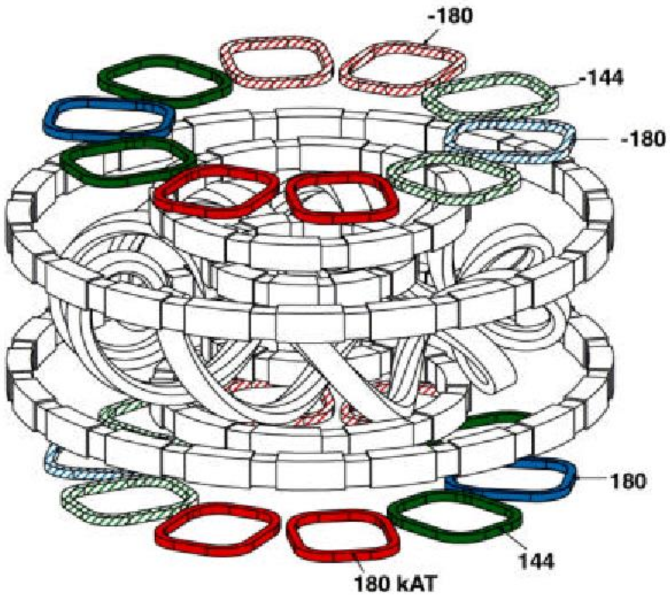
Cassini, NASA

Challenge to dynamical system with infinite freedom in 5-D phase space

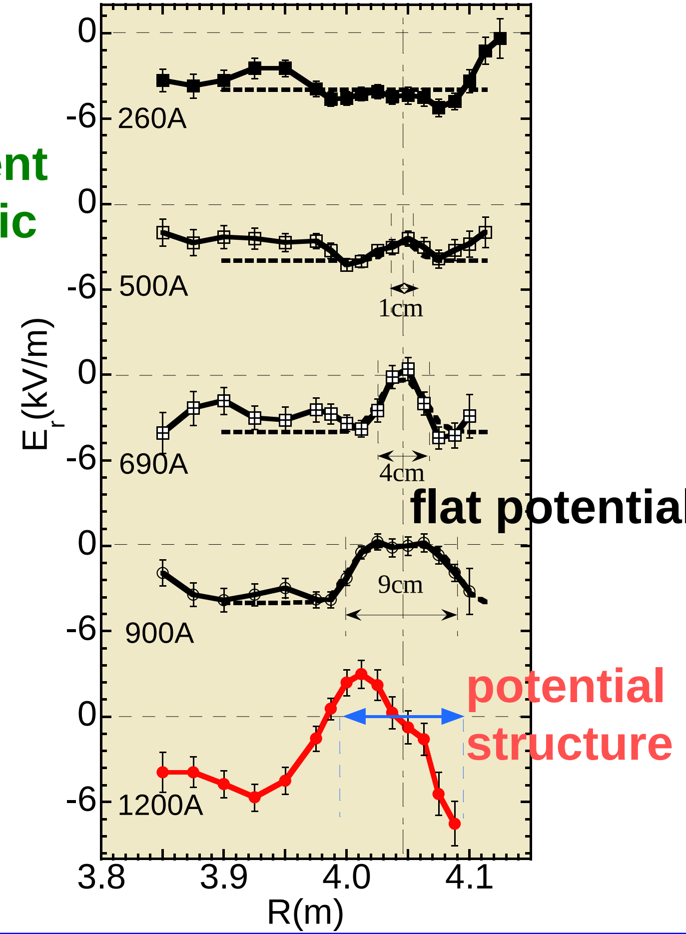
Courtesy of T.-H. Watanabe, NIFS

Observation of spontaneous changes related to magnetic island





Enlargement of magnetic island

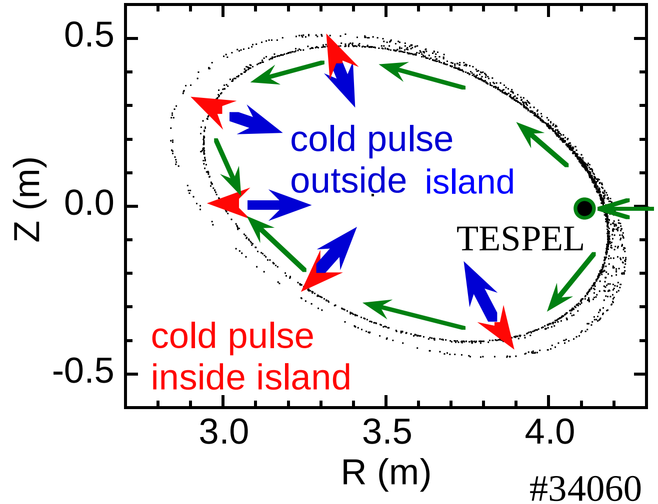


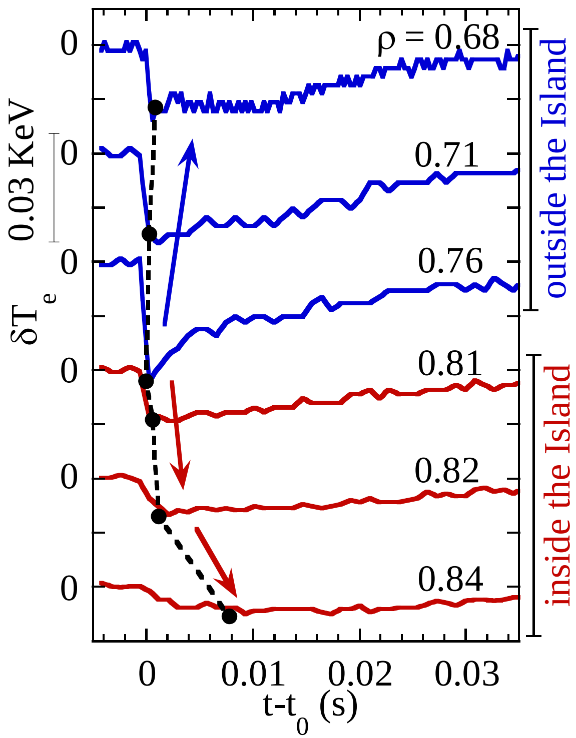
- Change of topology generates an interface
- Emergence of flow in magnetic island ➔ formation of E_r shear

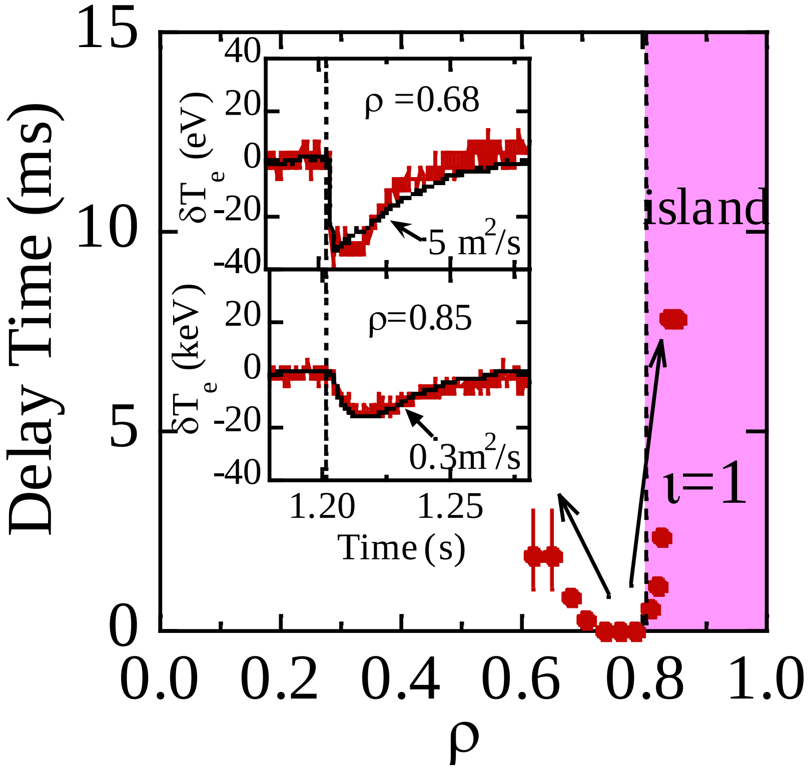
➔ Comprehensive and precise understanding of Neoclassical Tearing Mode (NTM)

K.Ida et al. PRL 2002

Transport inside magnetic island







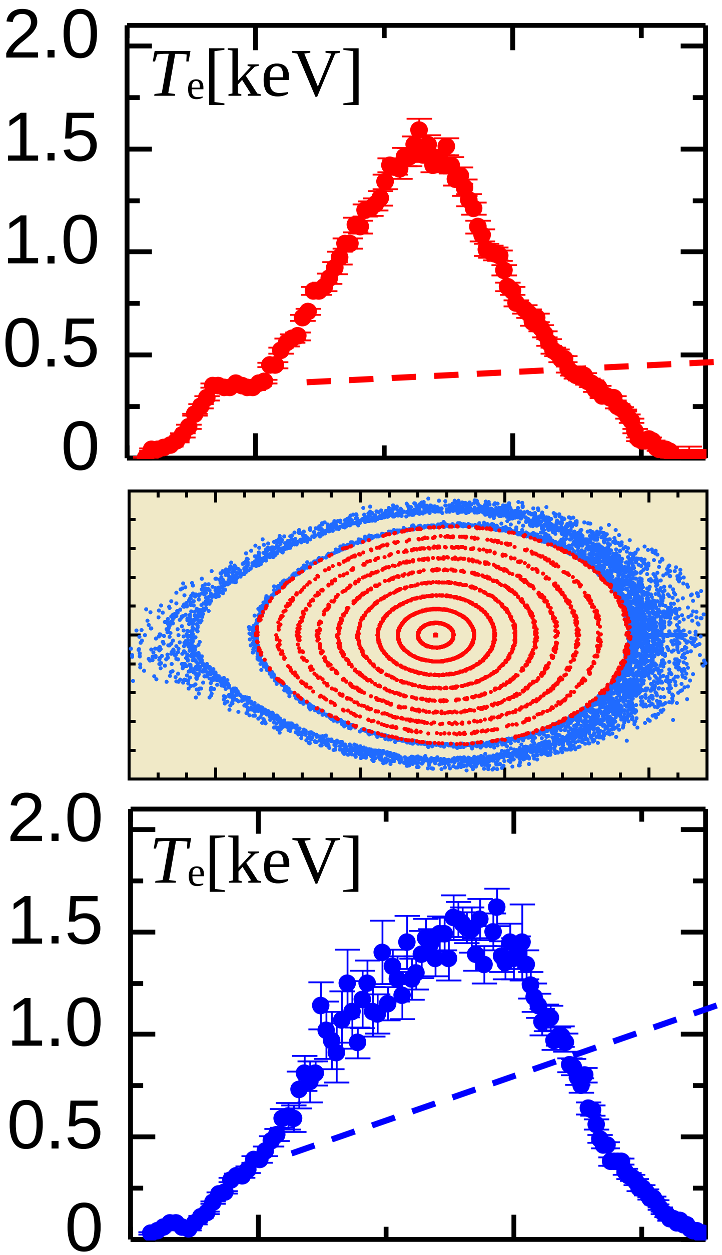
Inside magnetic island : χ = 0.3 m^2/s

Outside magnetic island : χ = 5 m^2/s

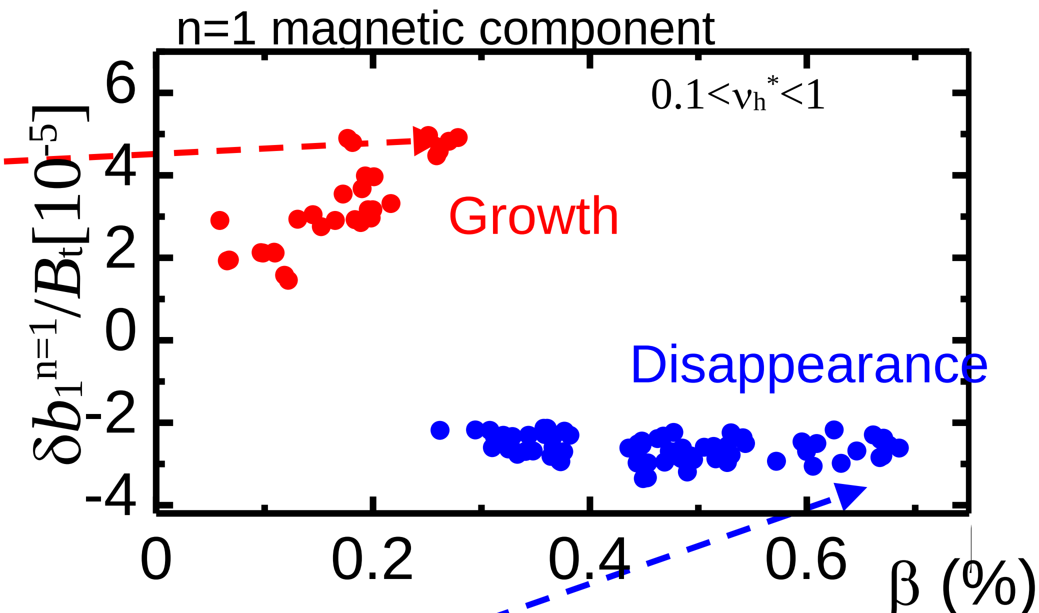
Significant reduction of transport is observed inside the magnetic island

S.Inagaki et al. PRL 2004

Dynamics of magnetic island



Interaction of static island due to external perturbation and plasma



Complementary approach to understanding of magnetic island

Note: Magnetic shear is opposite

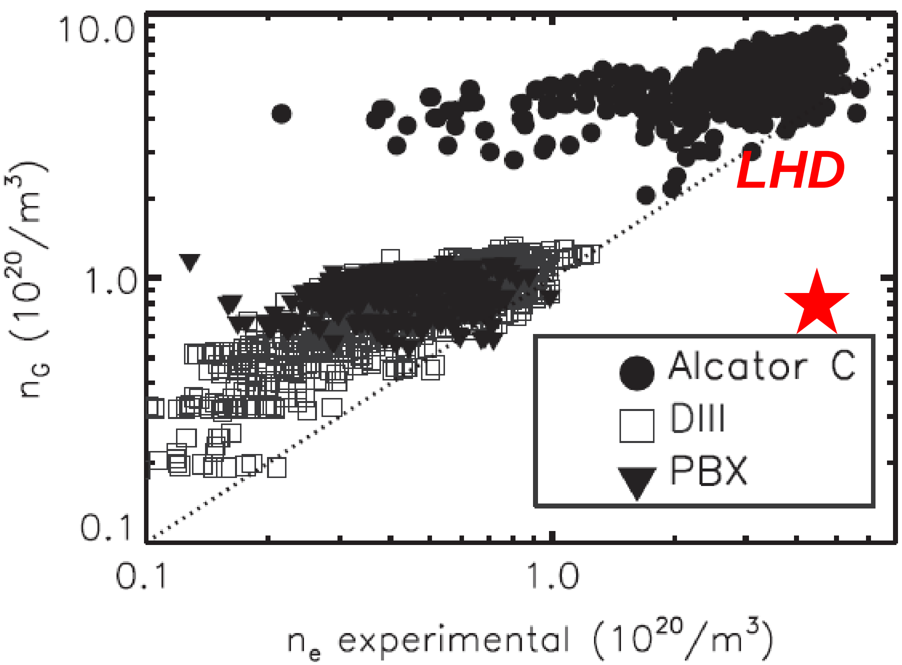
➔ Control of NTM

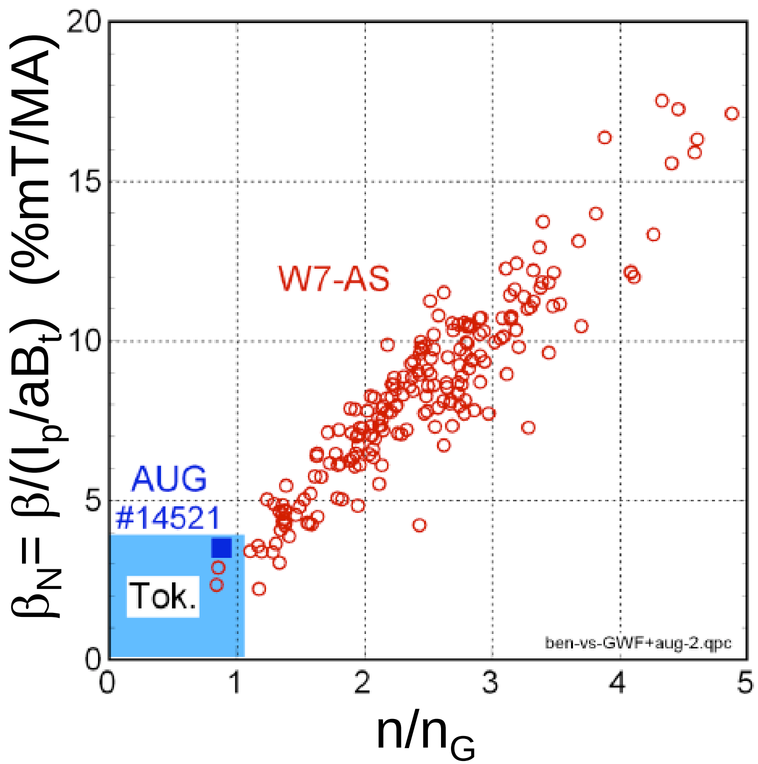
Y.Narushima et al. Nucl.Fusion 2008

Helical systems can be operated in much higher density regime than tokamaks

Greenwald density limit $n_G = \kappa J = I_p / \pi a^2$

$$I_p = 5 \frac{a^2 B}{R} \cdot \frac{1+\kappa^2}{2} \iota_a$$





M.Greenwald, PPCF 2002

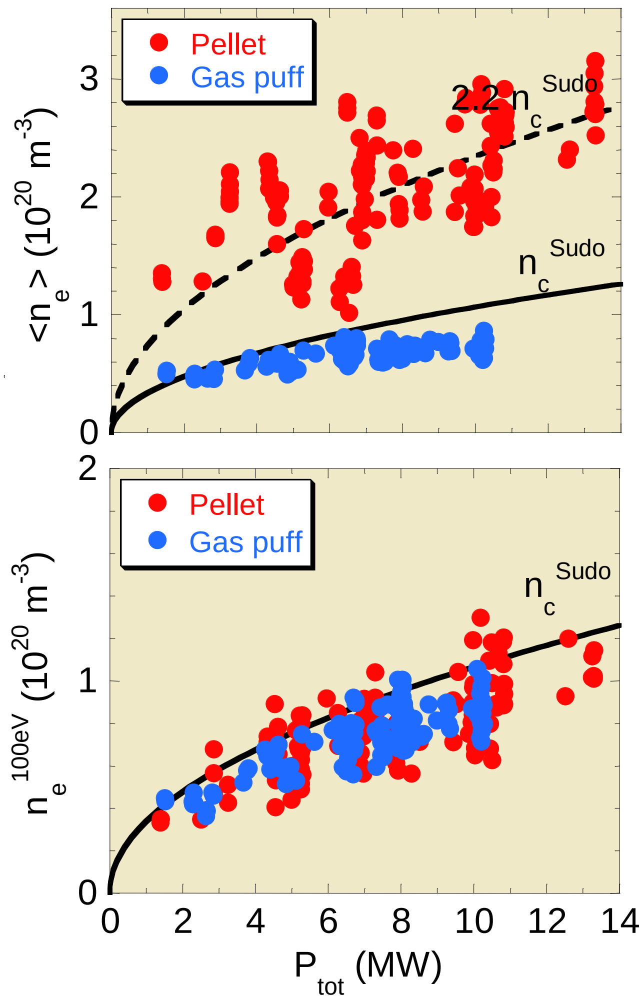
Courtesy of A.Weller

Clarification of underlying physics of density limit

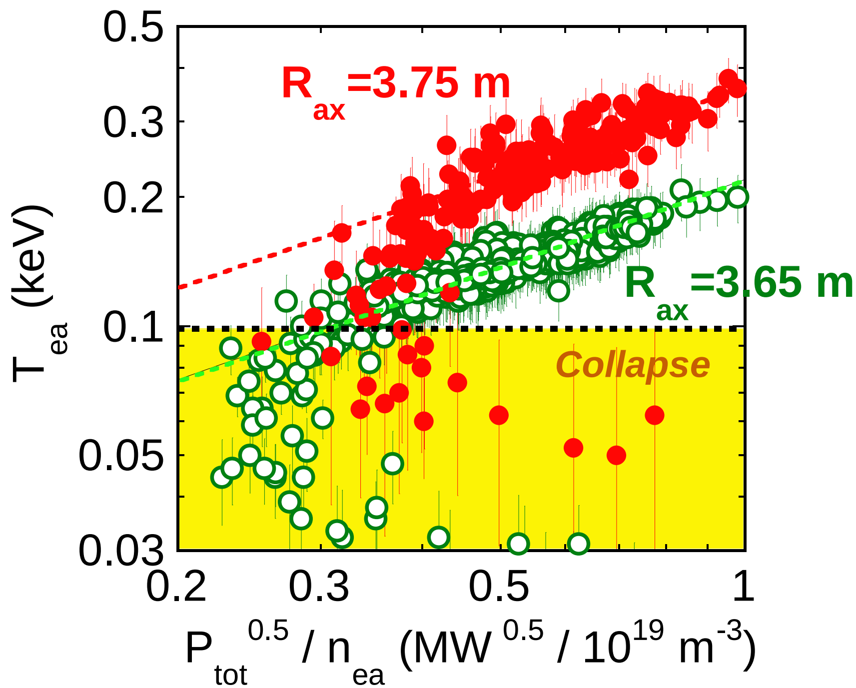
Density limit in helical systems is determined by radiation collapse, i.e., power balance

Density limit in helical systems: **Sudo limit**

$$n_e^{Sudo} = 0.25(PB/(a^2R))^{0.5}$$



Scale merit of LHD clarifies that this is a constraint on edge condition



Common feature under a variety of conditions

➔ Edge temperature ~ 100 eV is critical condition for radiation collapse

➔ $n_e^{100\ eV}$ is an important factor

J.Miyazawa et al. Nucl.Fusion 2008

Peaked high density profile is enhanced by IDB

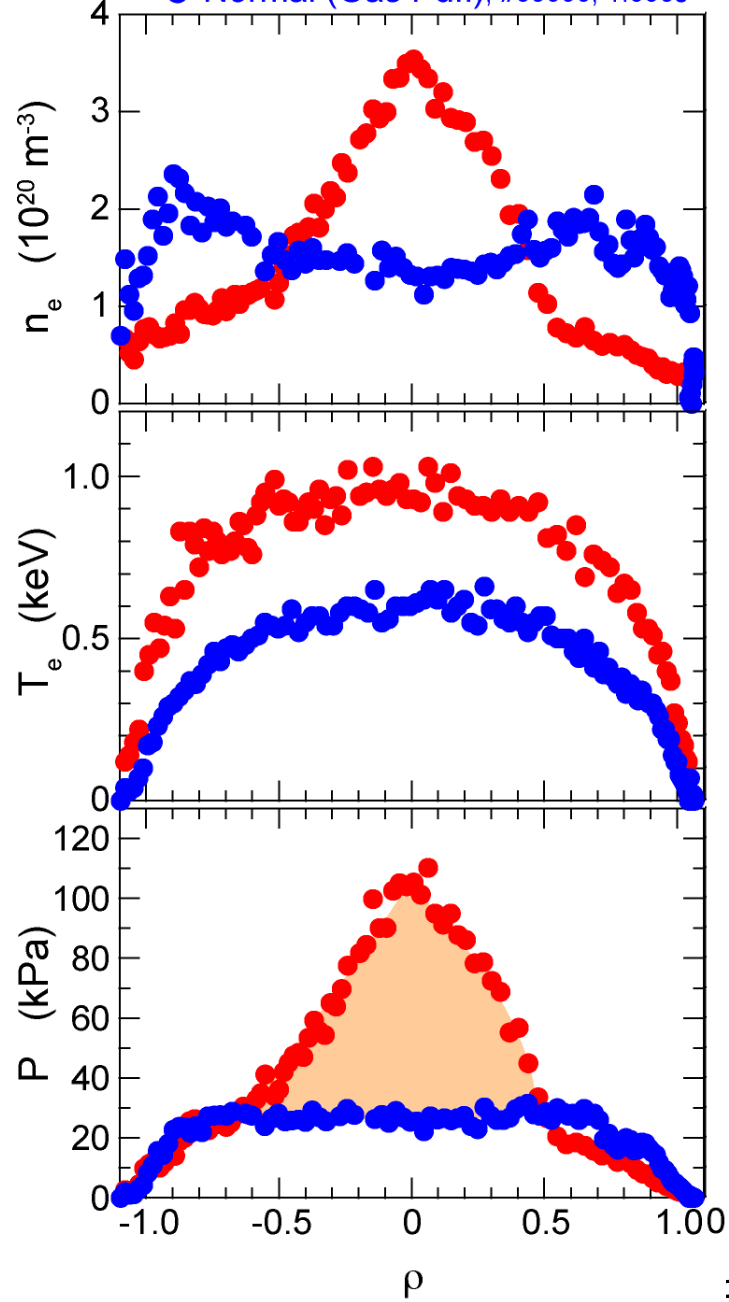
- ✓ Gas-fueled discharge :
  hollow density profile
- ✓ Density profile in the plasma with an IDB :
  highly peaked density profile
- ✓ Large Shafranov shift reaching a half the radius

Much higher density than a usual gas-fueled plasmas with the higher temperature

➔ Confinement improvement pronounced in the core leads to higher central pressure

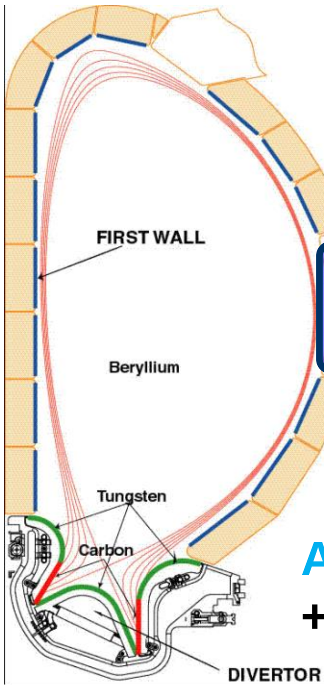
Central density reaches $1.1\times10^{21}m^{-3}$ at 2.5 T

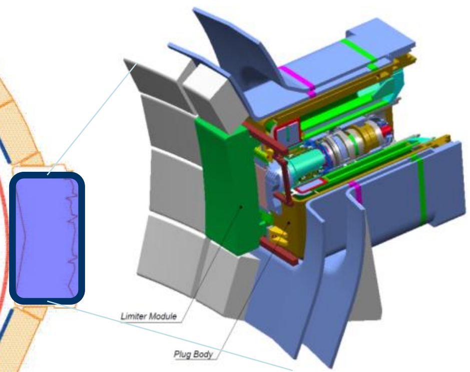
Note: Intermediate state between these two contrasting state does not exist



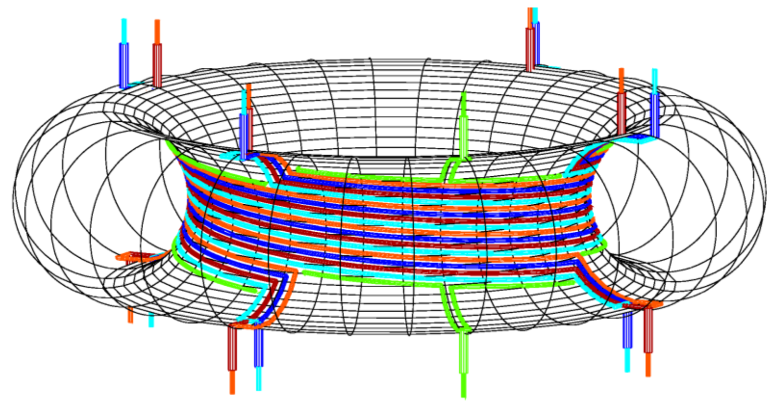
Edge plasma is essentially non-axi-symmetric even in tokamaks

Start-up with limiters in ITER



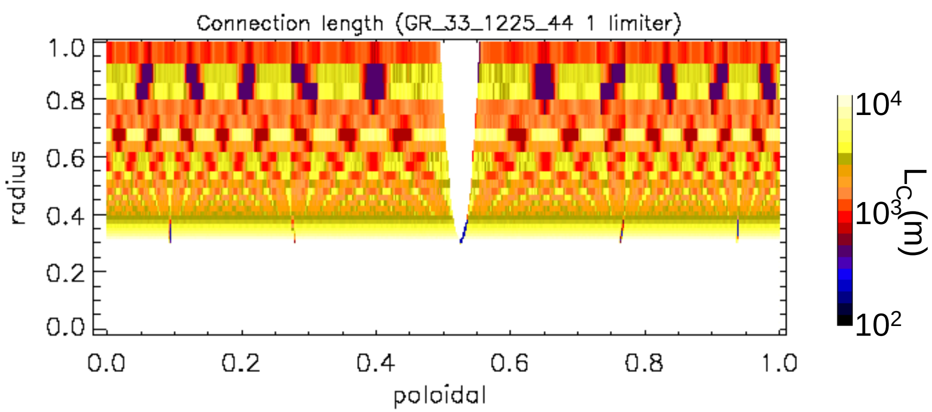


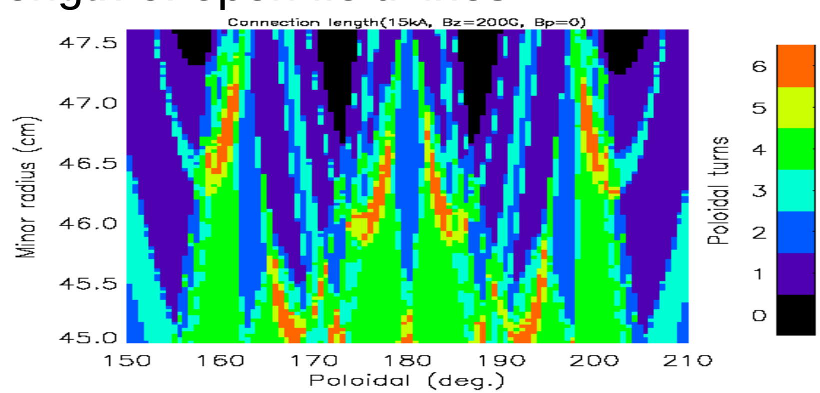
Resonant Magnetic Perturbation to control of ELM&RWM



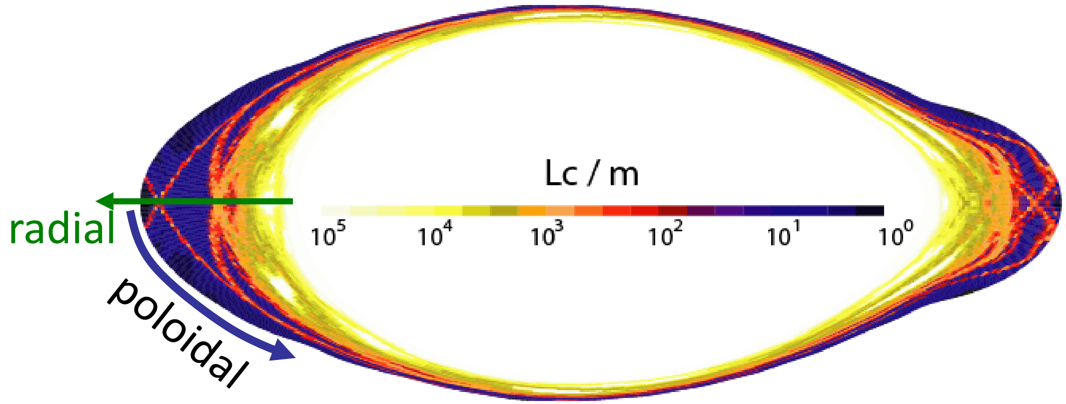
Axisymmetric field + Non-axisymmetric wall ⟷ **Non-axisymmetric field + Axisymmetric wall**

Distribution of connection length of open field lines



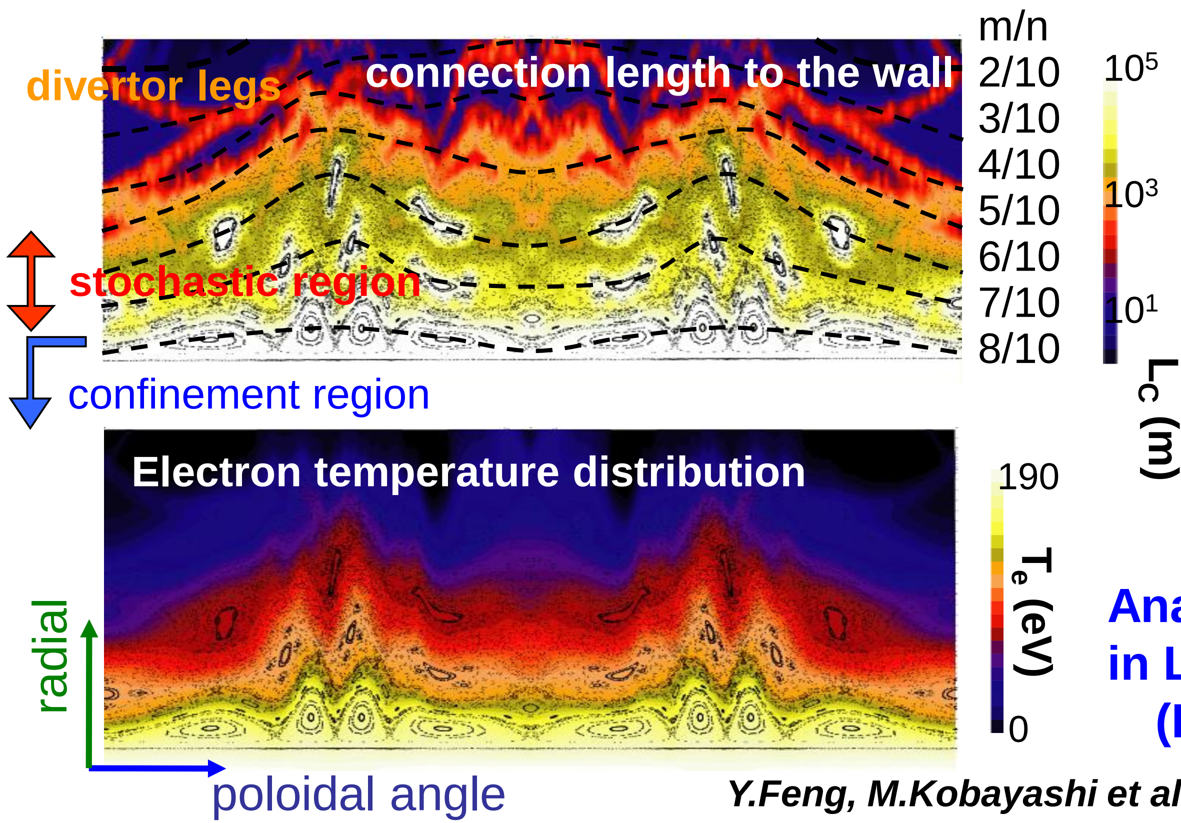


Research (Experience) in helical systems complements an idea and a scheme



Non-axisymmetric field
+ Non-axisymmetric wall

Property of transport:
1-D trans.⇔ 2,3-D trans.



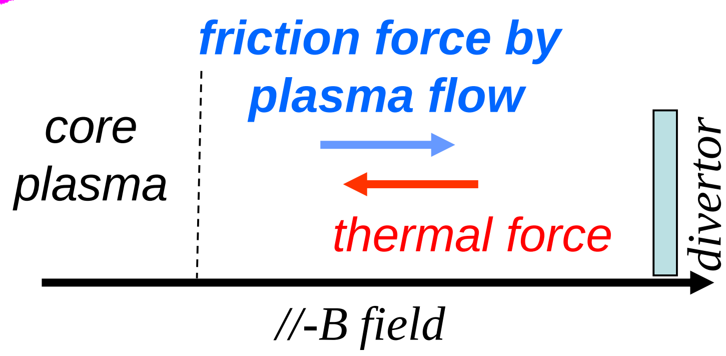
Stretch and fold due to magnetic shear and overlap of magnetic islands

- ✓ fine structure of field line (generation of long open field line)
- ✓ enhancement of role of perpendicular transport
- ✓ role of neutral particles

Analysis of edge ergodic layer in LHD (EMC3/EIRENE code)

Y.Feng, M.Kobayashi et al. Nucl.Fusion 2008

Friction force by plasma flow screens impurity influx



//-impurity velocity

$$V_{Z//} = V_{i//} + 2.2\frac{\tau_{Zi}}{m_Z} Z^2 \nabla_{//} T_i$$

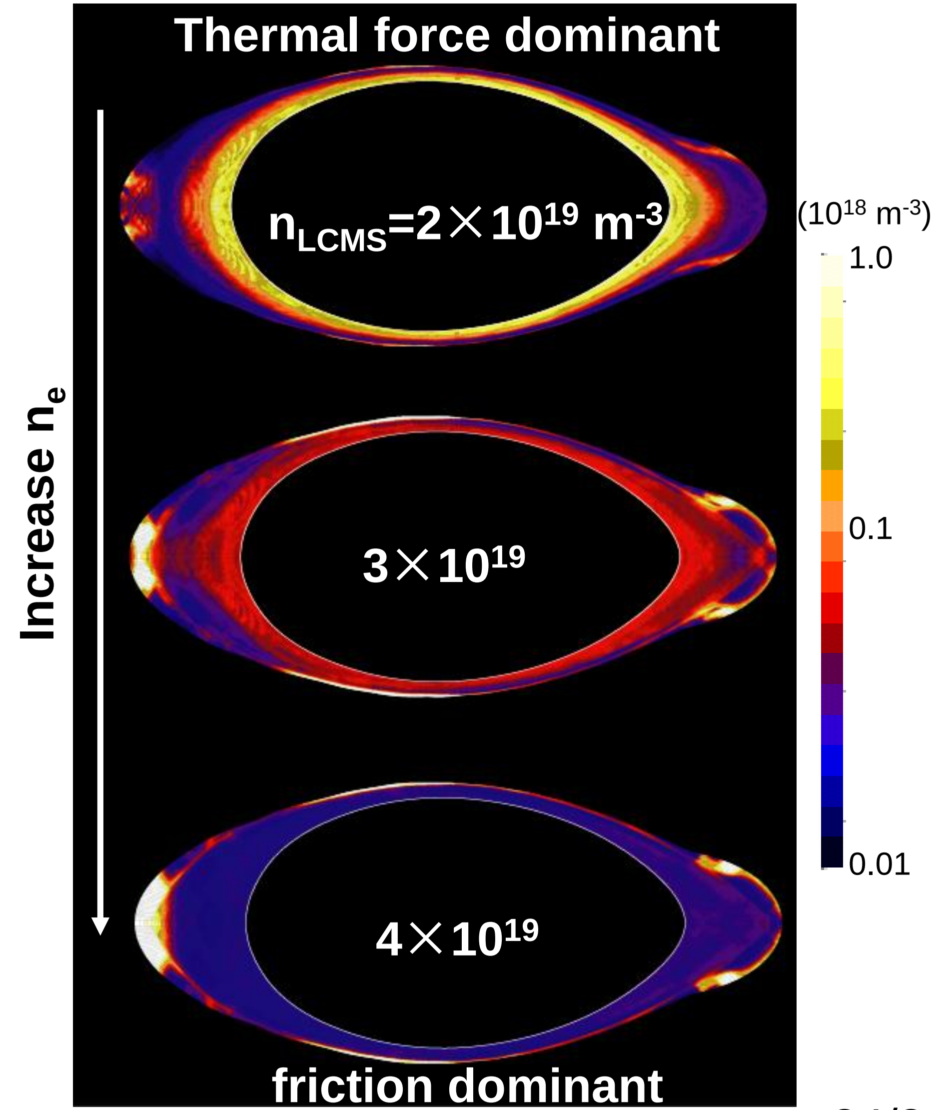
friction force by plasma flow — thermal force

Condition for impurity retention

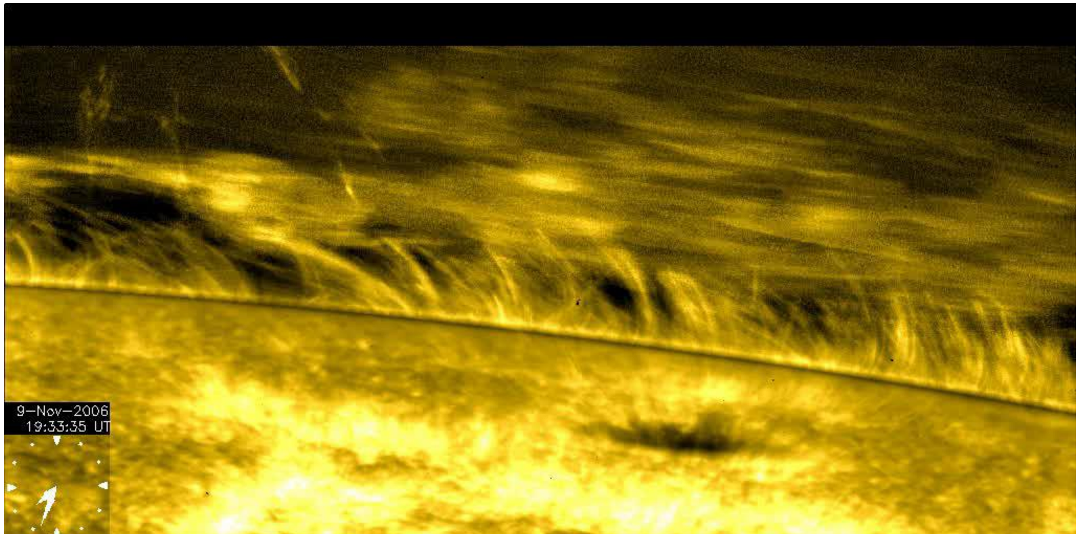
$$\frac{friction\ force}{thermal\ force} \sim \frac{5/2 n_i T_i V_{i//}}{\kappa_0^i T_i^{2.5} \nabla_{//} T_i} > 1 \rightarrow V_{z//} > 0$$

The more collisional,
the more effective retention
in an ergodic layer

Carbon density distribution (EMC3-EIRENE)



Plasma connects fusion's in space and on the earth



Hinode (NAOJ, JAXA)
http://hinode.nao.ac.jp/news/071207PressRelease/

LHD

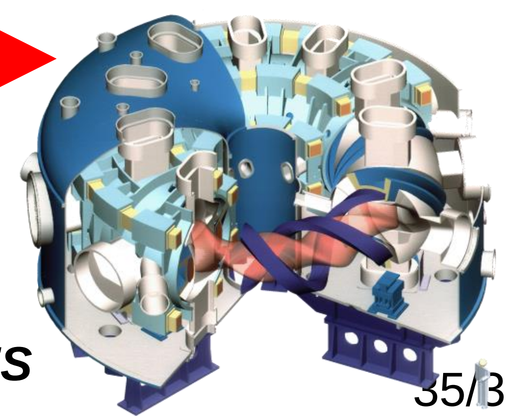
Collaboration for understanding of non-equilibrium plasmas

Solar coronal heating

Hinode/NAOJ

NINS
National Institutes of Natural Sciences

LHD/NIFS

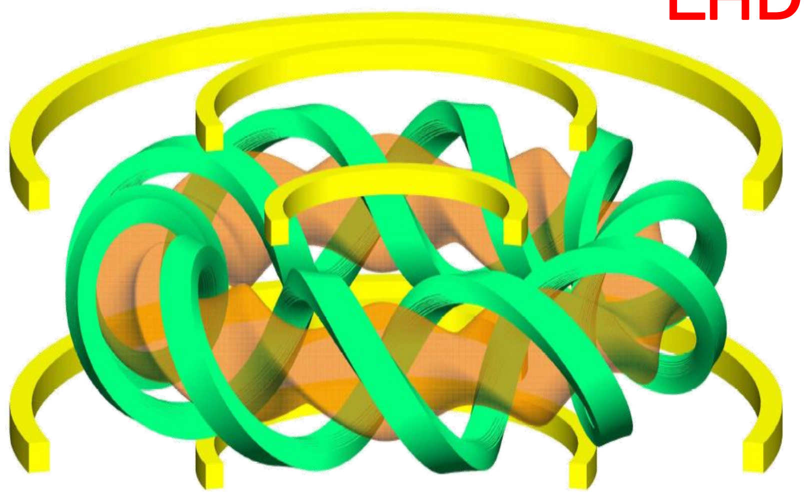


Summary

1. The exact science to manage a 3-D geometry has been being developed in helical systems. A physical model with much accuracy and breadth will demonstrate its applicability to ITER.
2. Topics to validate “complementary” approaches
   - ✓ 3-D Equilibrium
   - ✓ MHD - interchange mode -
   - ✓ control of radial electric field & structure formation
   - ✓ dynamics of magnetic island
   - ✓ density limit
   - ✓ edge plasma
3. “Complementary” is not “Supplementary”. ITER is complementary to development of a helical fusion reactor as well.
4. “Complementary” approaches transcend existing disciplinary horizons and enable big challenge.

Helical system and tokamak

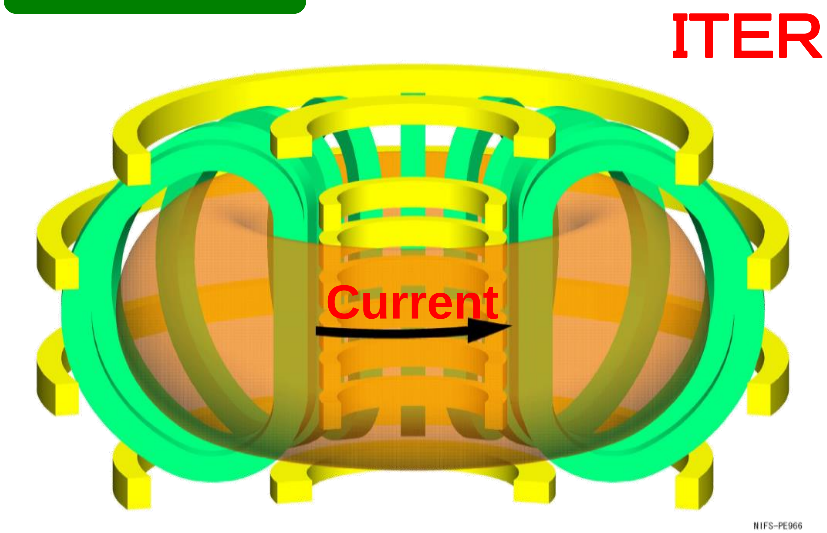
Helical system



- Confine plasmas by magnetic field by helical (contortive) coils.
- Due to magnetic field produced only by external coils, plasma current in plasma is not necessary.
  ➔ Advantage for steady state operation

LHD (NIFS since 1998)
W7-X (IPP, Germany from 2014)

Tokamak



- Most popular and leading concept
- Currents induced in plasma forms confining magnetic field together with toroidal field
- Break-even condition has been achieved ➔ Ignition in ITER

JT-60U, JT-60SA (JAEA)
JET (EU), DIII-D (USA)
EAST (China), KSTAR(Korea)

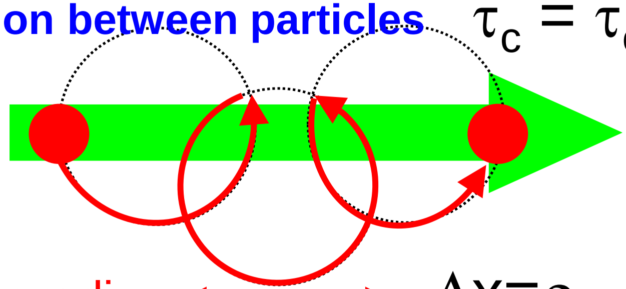
Diffusion coefficient

$$D = \frac{\Delta x^2}{\tau_c} \qquad \tau_c = 1/\nu_c$$

Collisional diffusive transport

(Neoclassical transport)

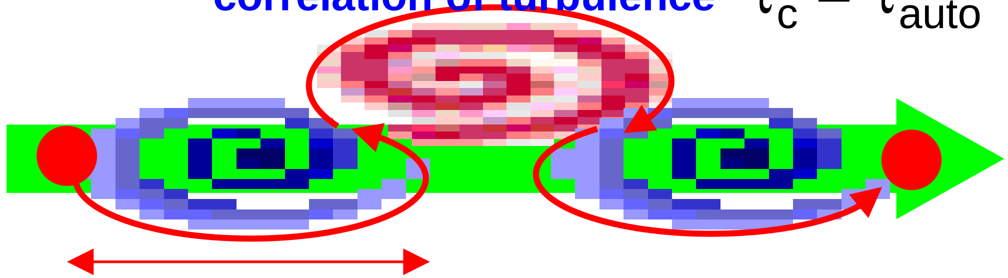
collision between particles $\tau_c = \tau_{coll}$



Larmor radius ↔ $\Delta x = \rho_i$

Turbulent transport

correlation of turbulence $\tau_c = \tau_{auto}$



Wave length of turbulence

Typical diameter of eddies

$\Delta x = \Delta r$

Interaction between particles in ***given*** magnetic (electric) field	⟺	Interaction between particle in ***self-generated*** electromagnetic field
$D \propto \frac{n}{B^2 T^{1/2}}$		$D \propto \frac{T}{B}$

- **D.Bohm** proposed a worst-case thermal diffusion model : **Bohm diffusion**

  ← Eddies are system-scale : Δx = a (ITER 2 m)
- Standard "gyro-Bohm" model of ion-scale drift-wave turbulence

  ← Eddies are ion gyro radius : $\Delta x = \rho_i$ (ITER 10 keV, 5 T → 3mm for deuterium)