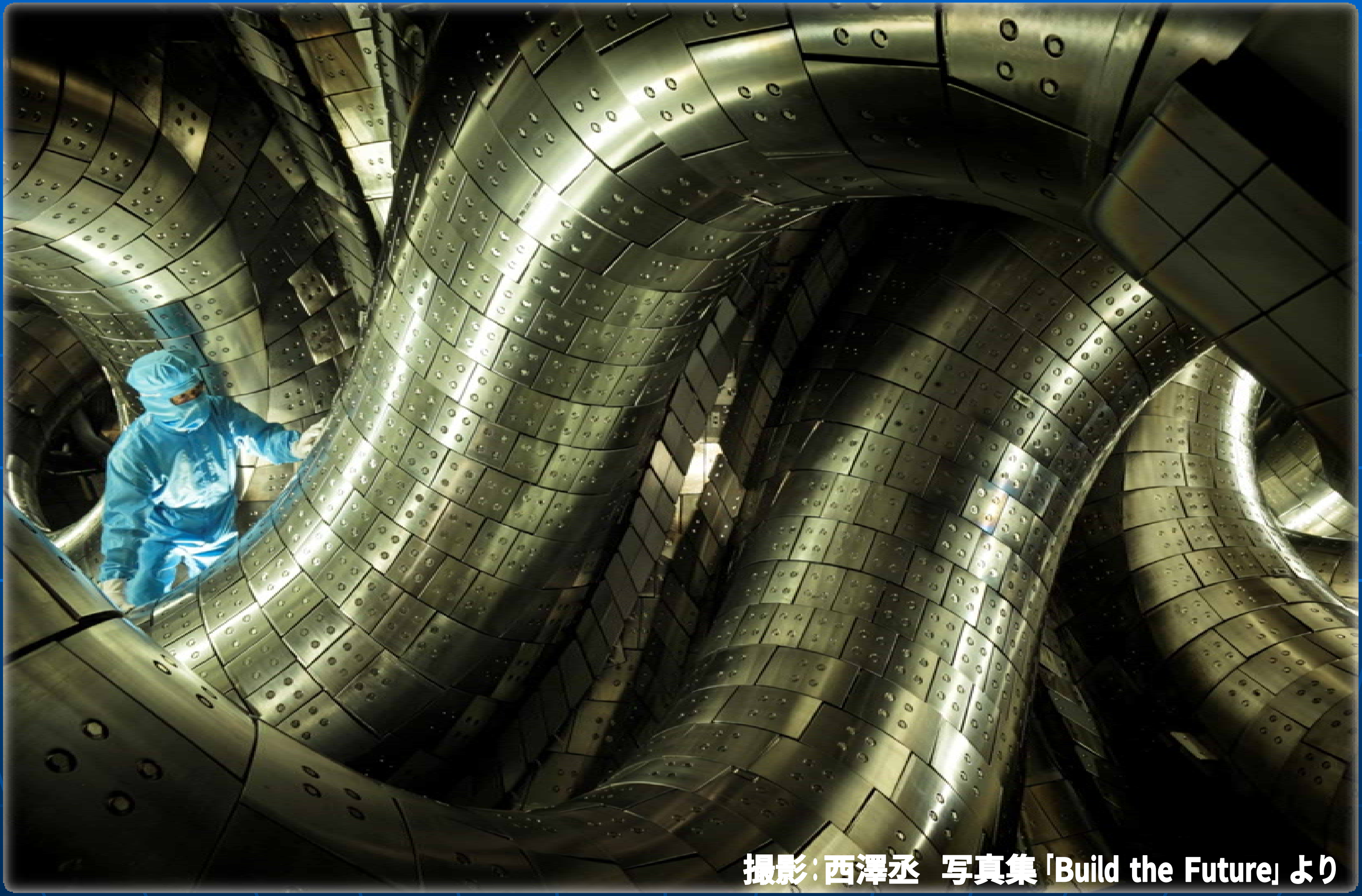
Development of Fusion Science via the Large Helical Device



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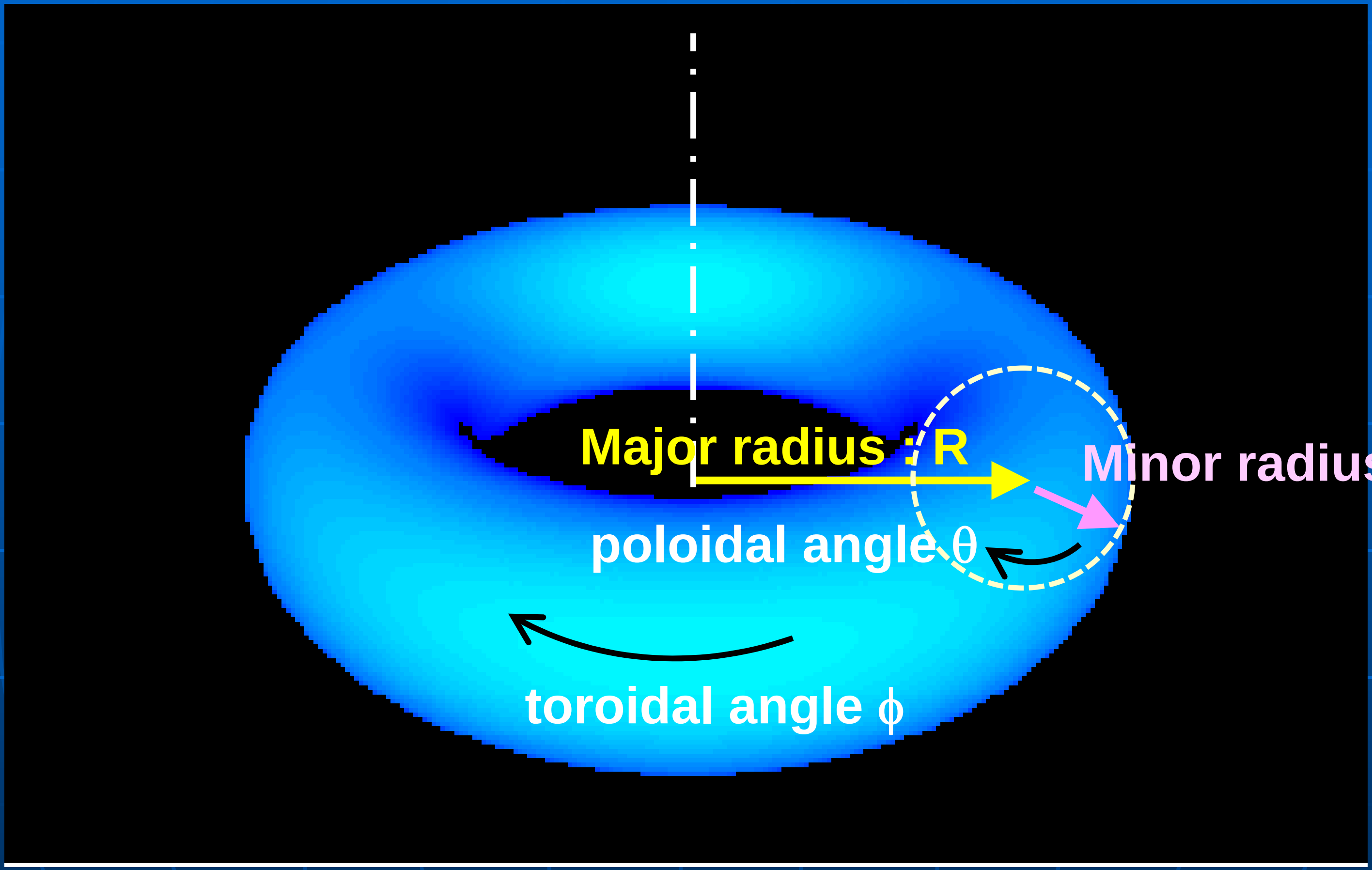
平成22年8月11日　六甲スカイヴィラ

Geometry : Torus



Winding law of helical coil: $\theta = (M/\ell)\,\phi + 0.1\sin((M/\ell)\,\phi)$

breaking of symmetry $\dfrac{\partial}{\partial \phi} \neq 0$

Summary

1. LHD with scale merit and steady-state capability provides much advantage towards comprehensive and exact fusion science.

2. A physical model with much accuracy and breadth will demonstrate its applicability to ITER as well as a helical fusion reactor.

3. Topics to validate "complementary" approaches

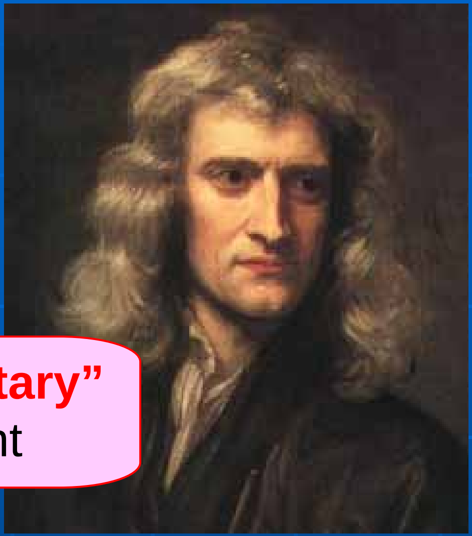
   Stability - Transport - Confinement

   Characteristic behavior of non-equilibrium open system

4. "Complementary" approaches transcend existing disciplinary horizons and enable big challenge.

“Complementary” in science
Evolution of science - compared to mechanics -

“Complementary”
is important



Quantum mechanics
The uncertainty principle

Classical mechanics
(Newtonian mechanics)

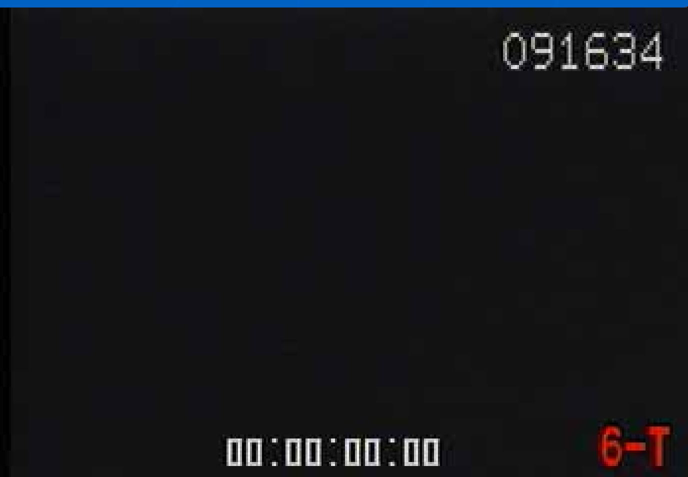
Relativity

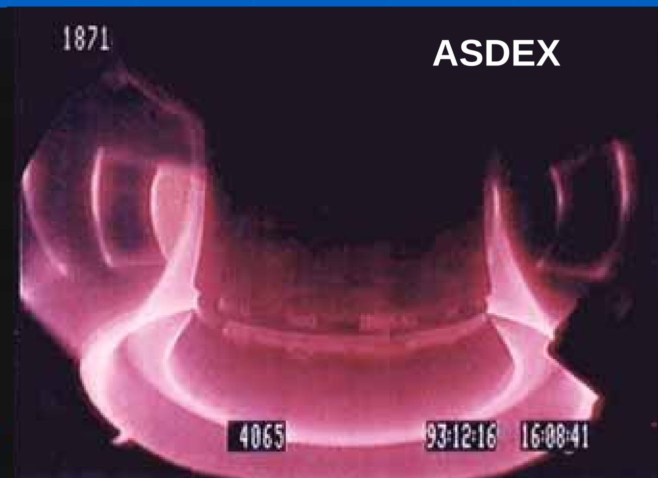
Binary opposition : Dialectic approach
Discussion on the merits and demerits is not always productive
➔ **“Complementary” approach** : *The longest way round is the shortest way*
comprehensive understanding of differences

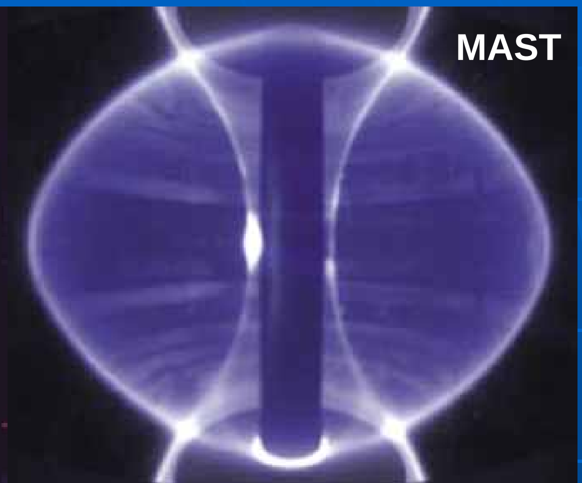
The portfolio of plasma confinement

Comprehensive understanding ⇔ Exact understanding

Externally controlled ◀ ···························





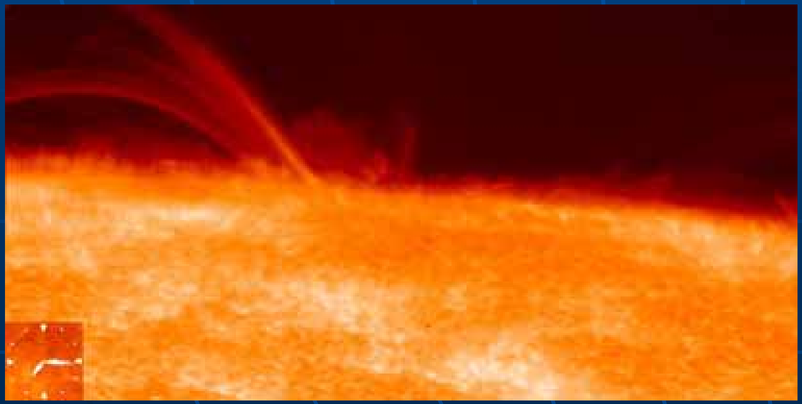


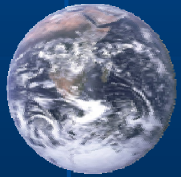
Helical system

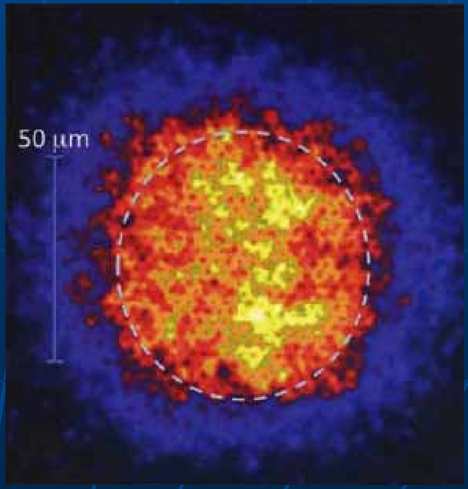
Tokamak

Spherical Torus

··························▶ **Self organized**



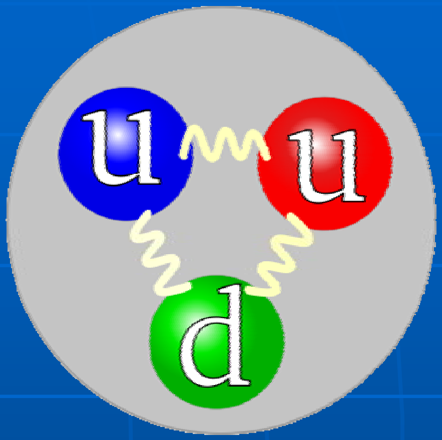




Laser Fusion

The sun (Hinode satellite JAXA/NAOJ)

What is confinement ?



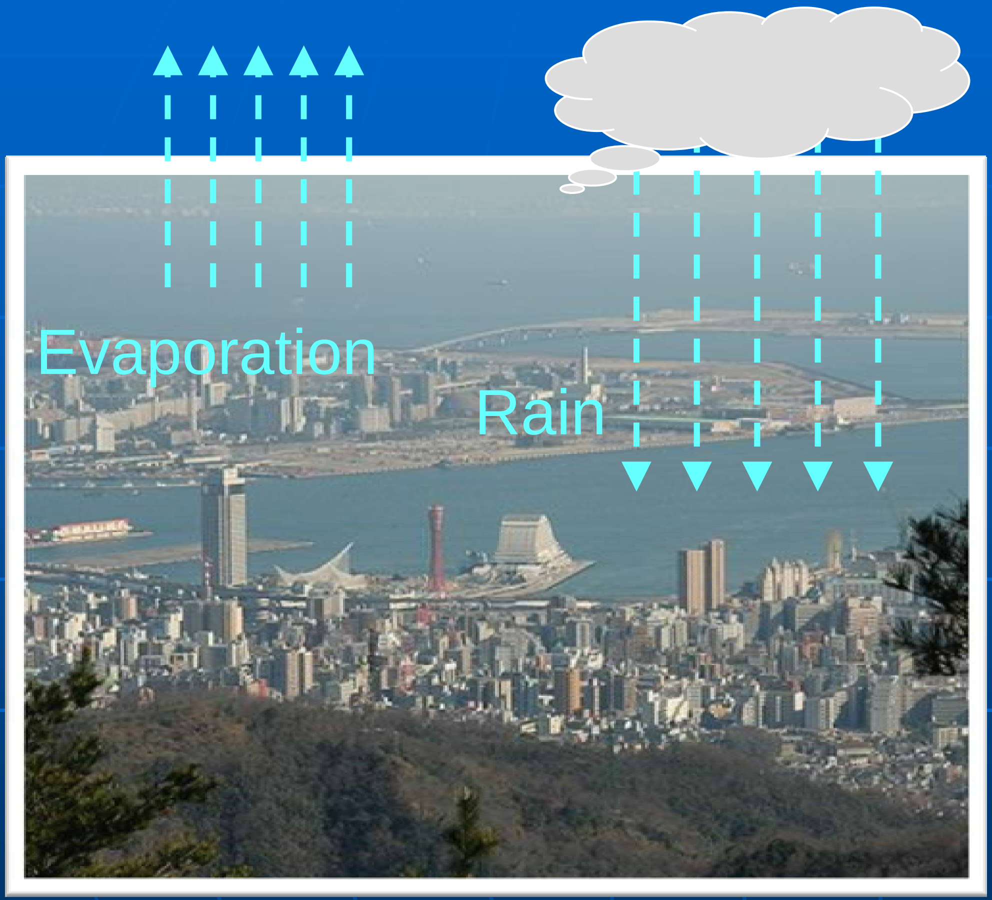
Confined in a prison

Confinement of quark in hadron
Quarks are never extracted separately

Confinement ⇔ Capability not (never!) to let objectives out

Confinement of plasma is more moderate

Outlook of state is conserved by balance between gain and loss



Helical fall in Tadachi

Panta rei
All things flow and nothing lasts
(Heraclitus, Greek philosopher in BC 500)
子在川上曰逝者如斯夫不舎晝夜
(孔子: Confucius, Chinese thinker in BC 500)

Confinement of plasmas

Heat

Neutral beam injection
Ion cyclotron resonance
Electron cyclotron resonance

Particles

Gas puff
Pellet injection

Particles and heat are replaced by every several 100 msec, however, a plasma discharge is kept stable for 1 hour

Particles

CX
Convection etc.

Heat

Conduction
Radiation etc.

Concept of confinement time

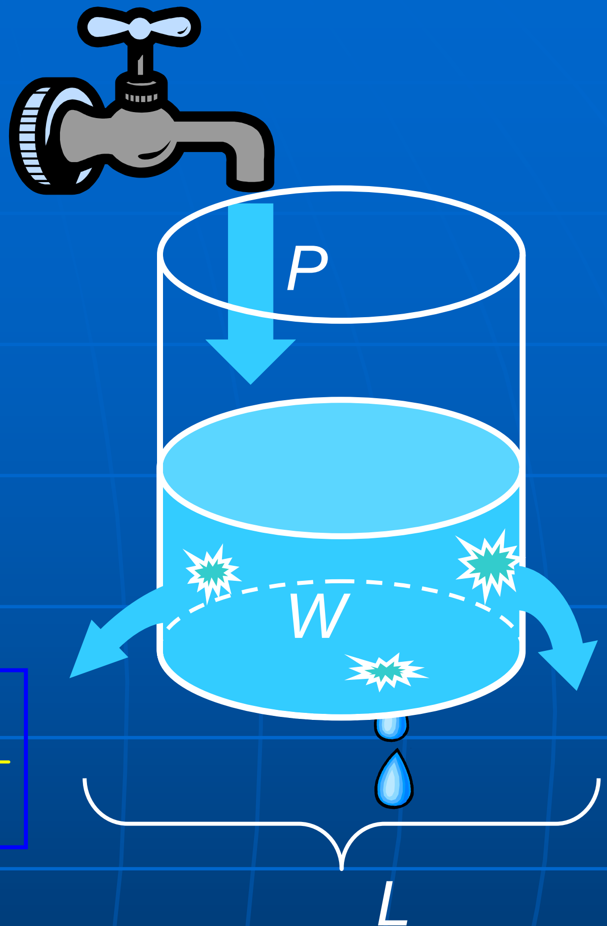
- Store water in a bucket with holes

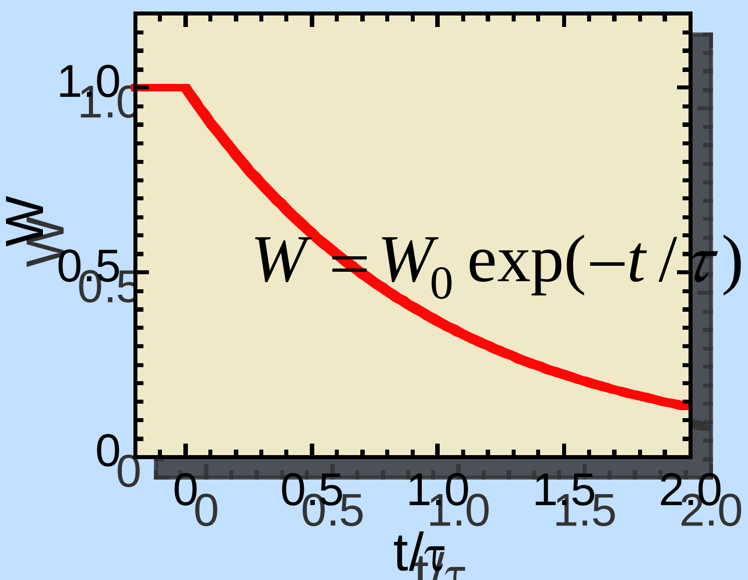
Inlet flow P m^3/s
Loss flow L m^3/s
Stored water W m^3

- Temporal change of W : $\dfrac{dW}{dt} = P - L$

L is proportional to W ➔ $L = cW = W/\tau$

$$\frac{dW}{dt} = P - \frac{W}{\tau}$$



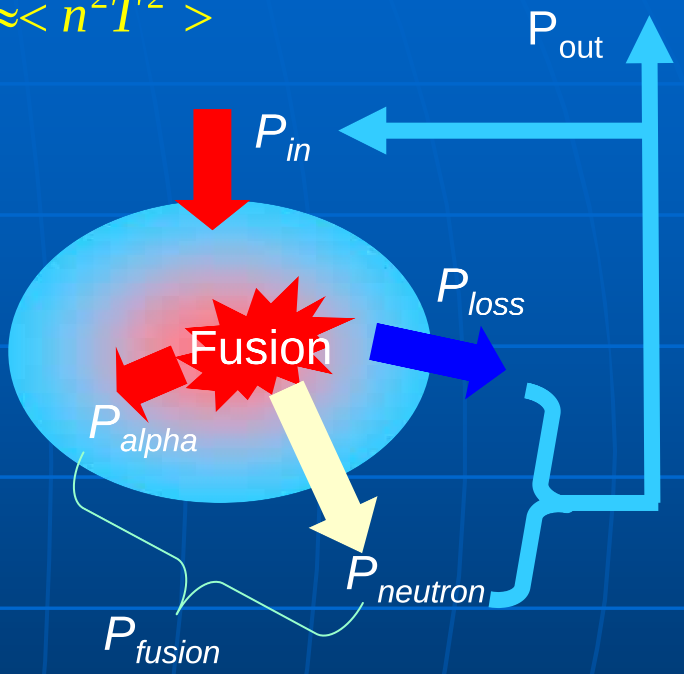


In plasma confinement
τ_E : global goodness of confinement
➔ energy confinement time
W : stored energy
P : heating power
in steady state $\tau_E = W/P$

Break-even and ignition conditions

Fusion Power for DT reaction

$$P_{fusion} = \int n_i^2 < \sigma v > (17.6\,\mathrm{eV})\,\mathrm{d}V \approx \int n_i^2 T_i^2\,\mathrm{d}V \approx < n^2 T^2 >$$



Q value : Energy breeding ratio

Ratio of fusion power to heating power

$Q = P_{fusion} / P_{in}$

Steady state; balance : input = output
heating = loss

$P_{in} = W / \tau_E = <nT> / \tau_E$

$Q = <n^2T^2> / (<nT> / \tau_E) \sim n\,T\,\tau_E$

Fusion triple product

Break-even condition : $P_{fusion} = P_{in}$ ➔ Q=1

$n\,T\,\tau_E \sim 1\times10^{21}\ \mathrm{m^{-3}\cdot keV\cdot s}$

$n \sim 10^{20}\mathrm{m}^{-3}$, $T \sim 10\mathrm{keV}$ ($\sim 10^8$ ºC), $\tau_E \sim 1\mathrm{s}$

n_i : ion density
T_i : ion temperature
V : volume

What is turbulence ?

Flow: continuous movement of a fluid, i.e. either a liquid or a gas

➔ Categorized to ***laminar*** (simple) flow and ***turbulent*** (complicated) flow

Laminar flow : moves at the *same speed* in the *same direction*

Turbulent flow : moves at *different speeds* in *different directions*

The eddying tides in Naruto

by Utagawa Hiroshige
(Ukiyo-e painter in 19th century)

Leonardo da Vinci (15-16th century)

Turbulence (1997:USA)

Confinement of toroidal plasmas

Closed surfaces formed by circum-navigating magnetic field lines

Rec

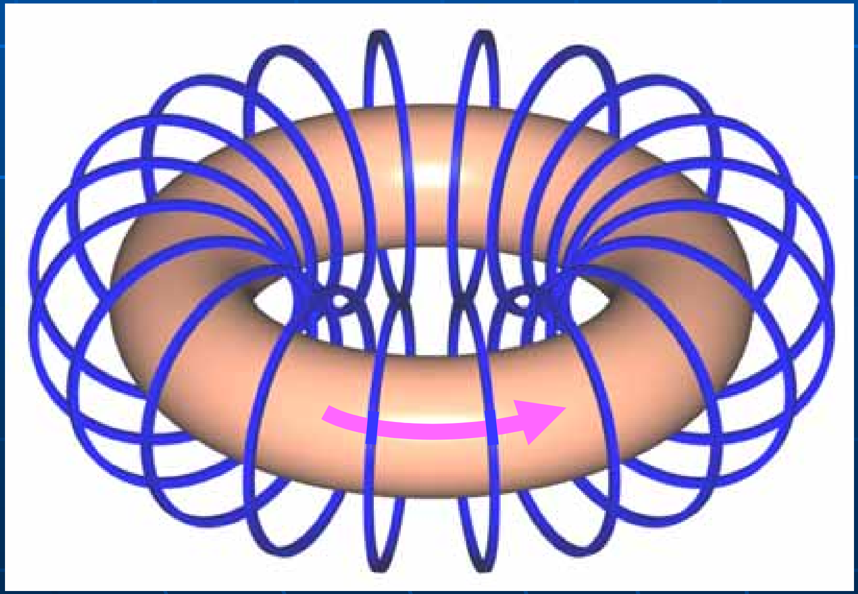
dal)

Tokamak and Helical system

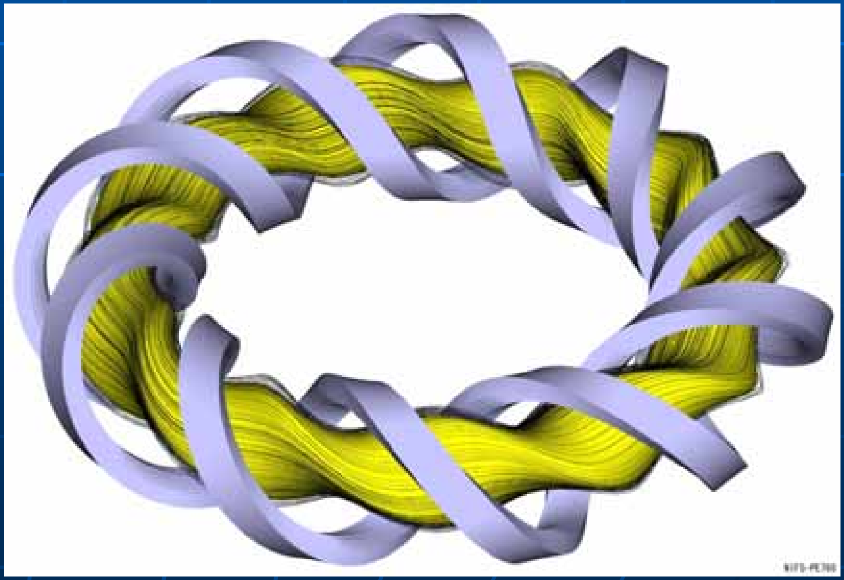
- ✓ Large commonality as toroidal system
- ✓ Difference due to existence/absence of net plasma current

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

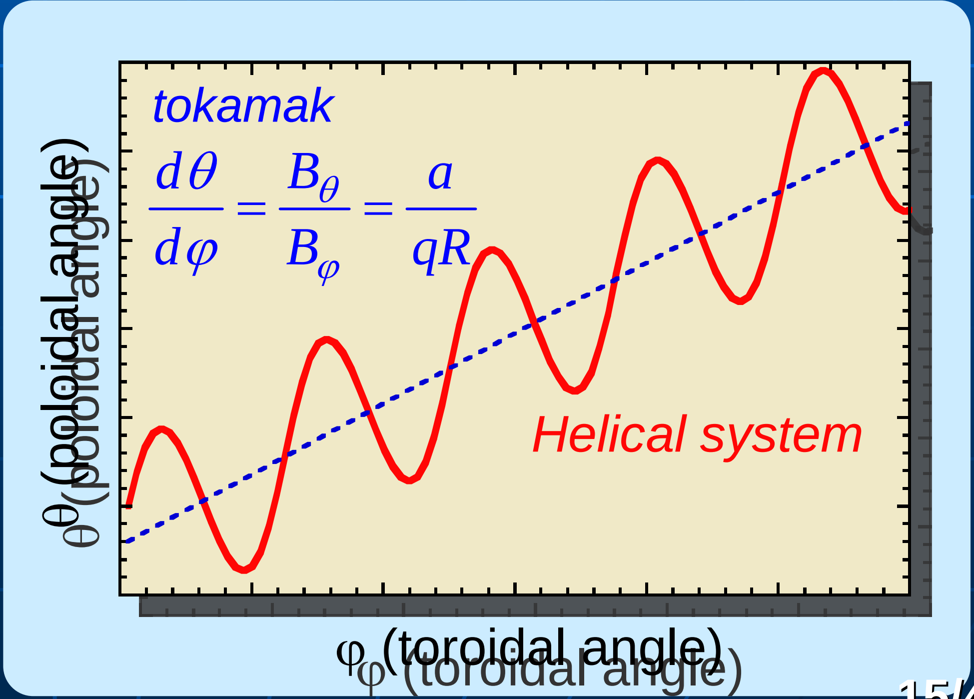
$$\int_0^{2\pi} B_\theta r d\theta = \int_0^{2\pi} \cos m\theta r d\theta = 0$$

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

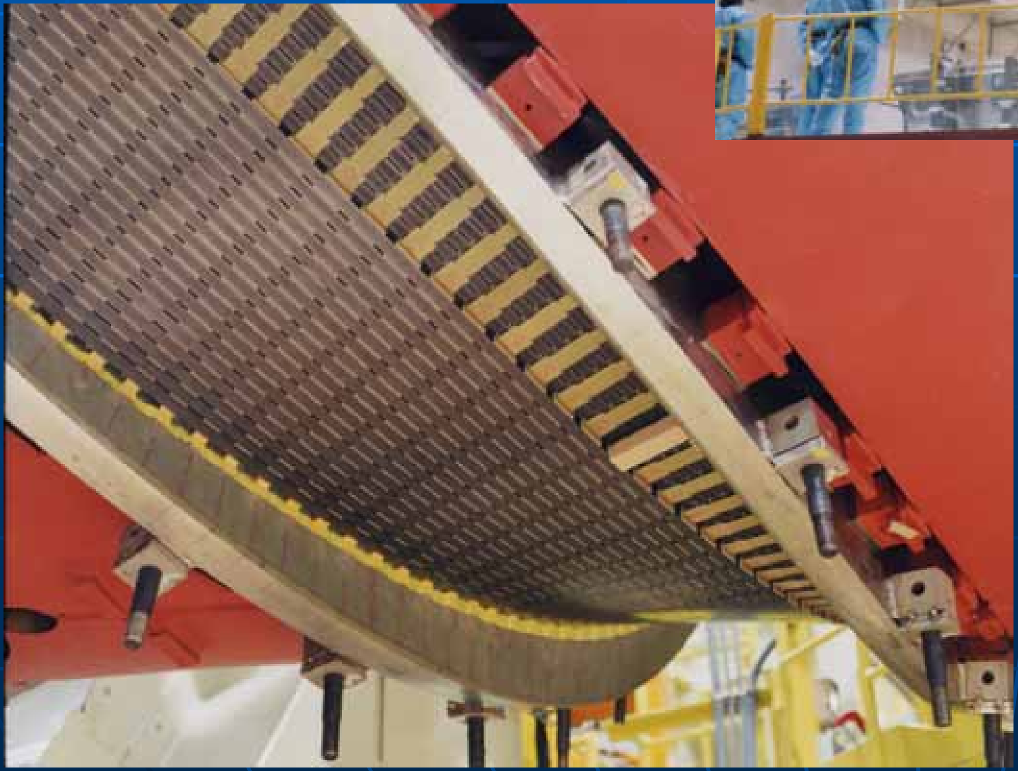
- ➔ Bumpiness in magnetic field degrades confinement
- ➔ It is true in general, however, it is not always true.
- ➔ We have a fighting chance.




Bandicam
www.gomplayer.jp

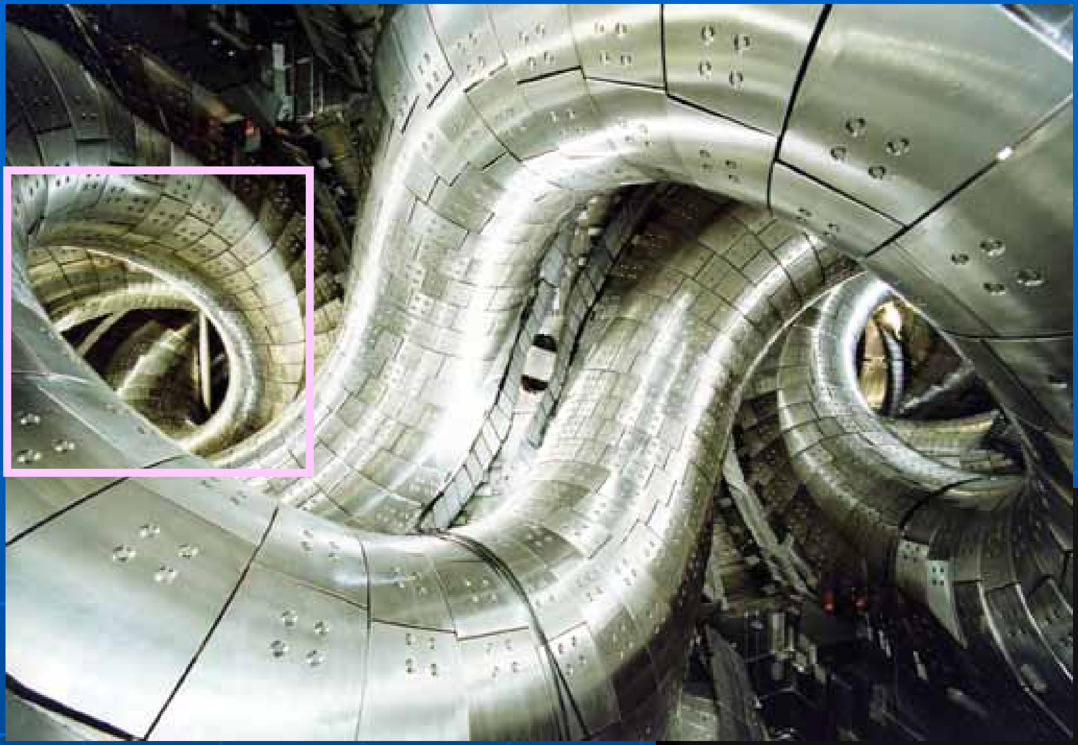
Large Helical Device (LHD) in National Institute for Fusion Science (NIFS)

Large Helical Device (LHD)



Large & Exact

Construction of LHD



$R = 3.9\ m$

$a = 0.6\ m$

$B = 3\ T$

$P_{heat} = 25\ MW$

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

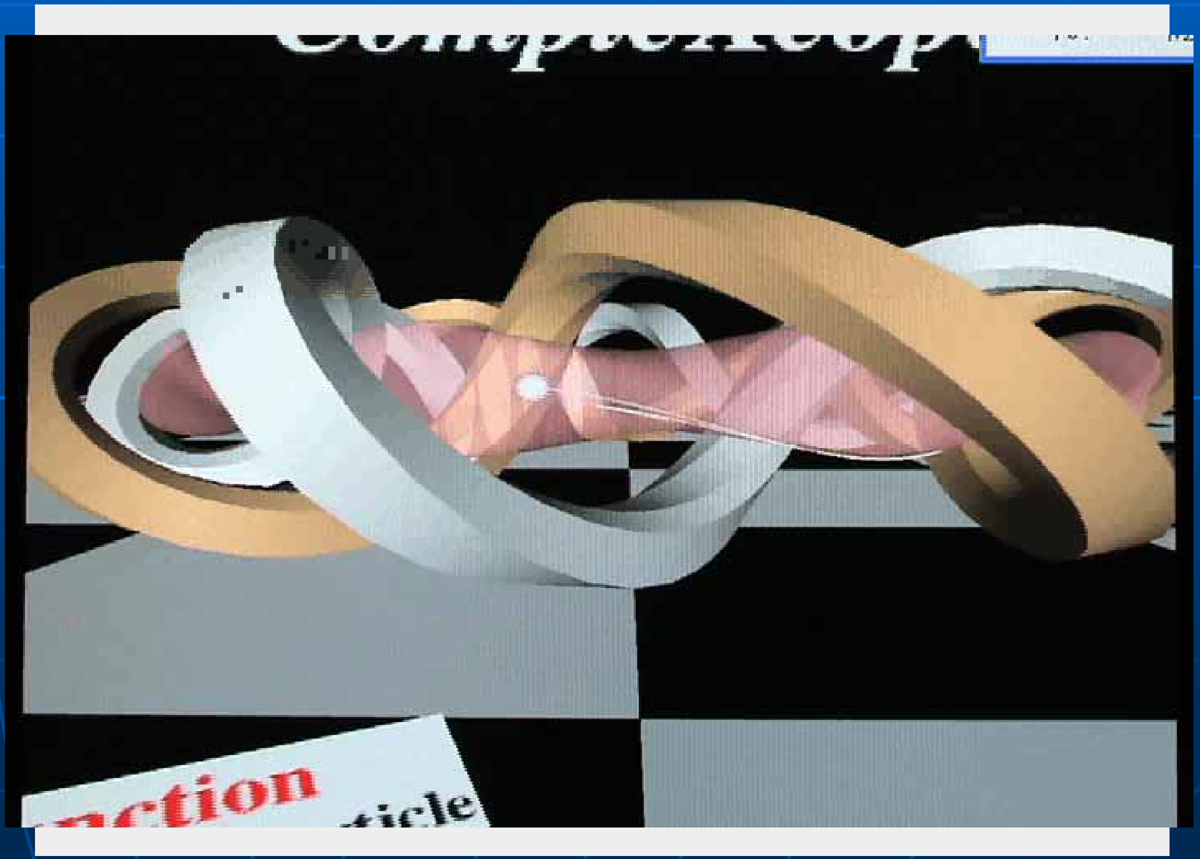
Collision changes orbit
➔ Diffusion
Neoclassical transport theory
Complicated in 3-D but solvable

In reality

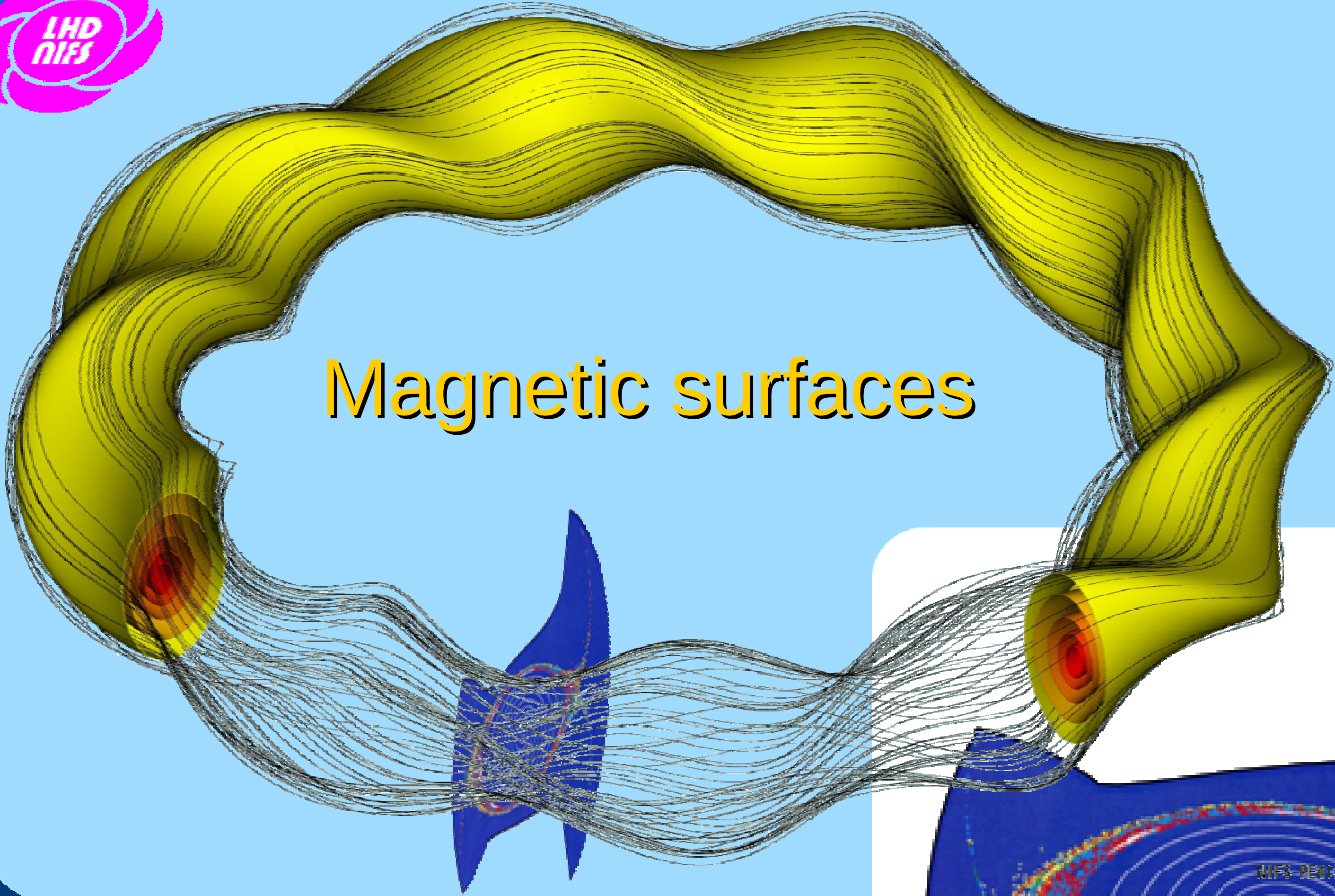
Particles and heats are lost more rapidly than the neoclassical theory
Anomalous transport
not clarified yet,
driven by turbulence

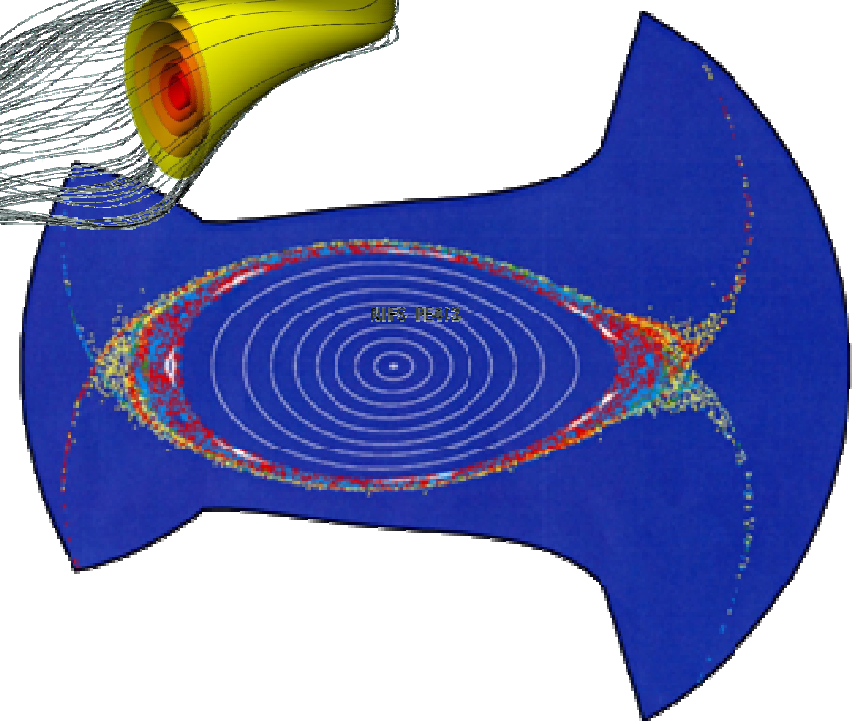
Trapped particle

Circulating particle

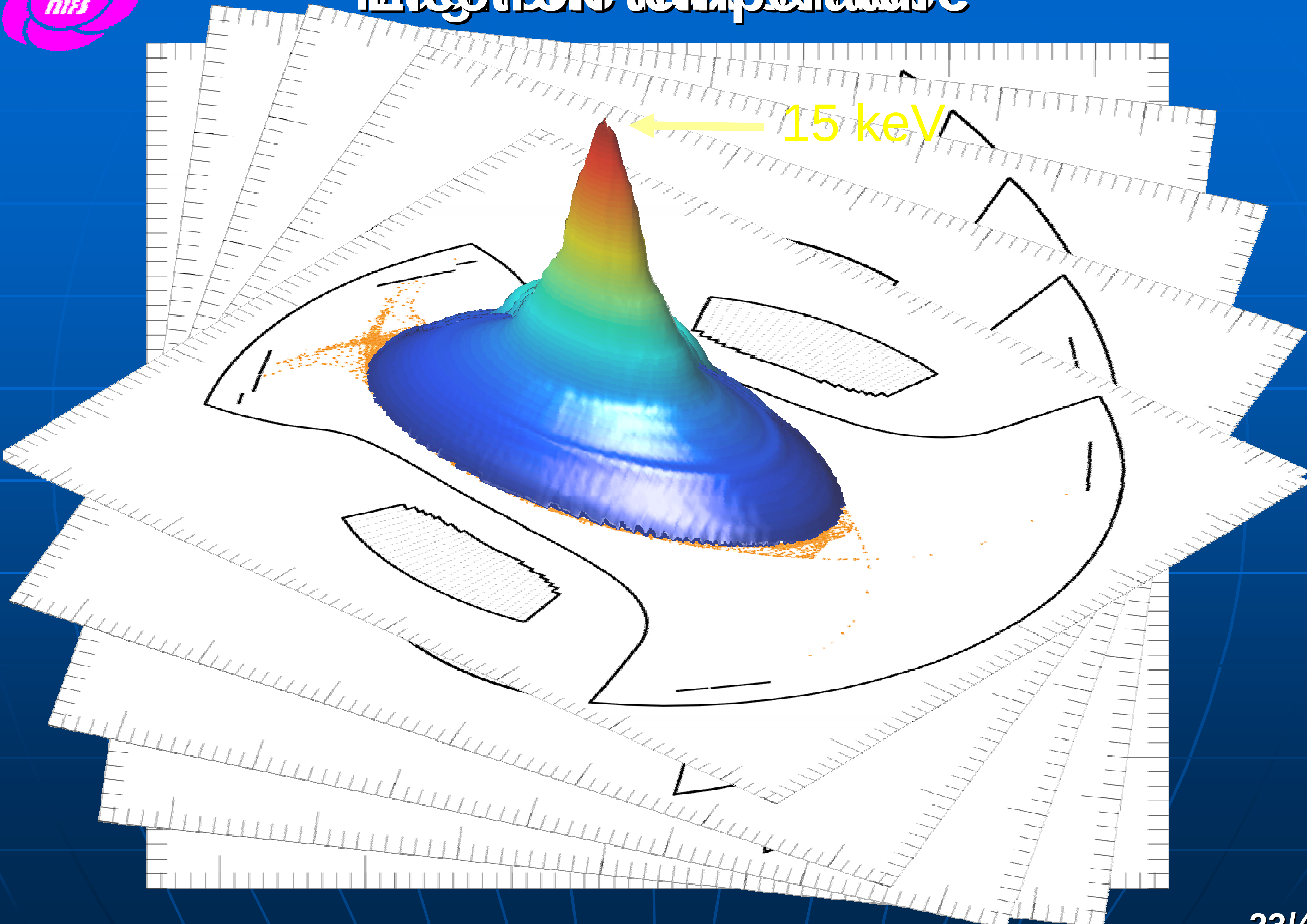


Magnetic surfaces

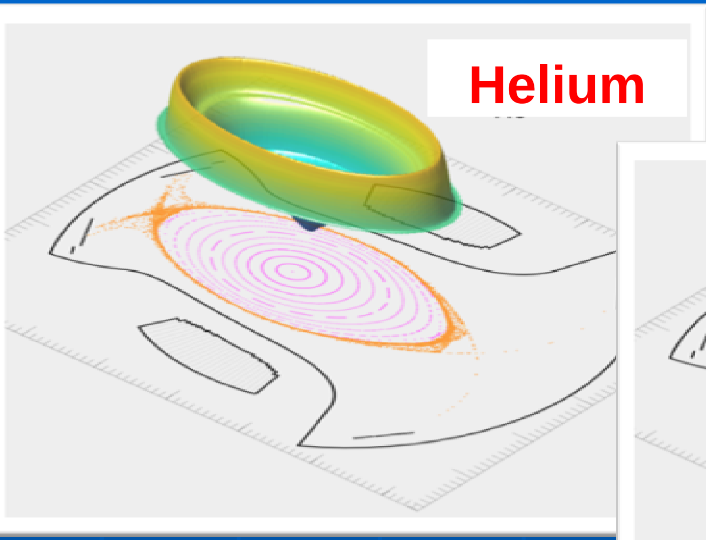


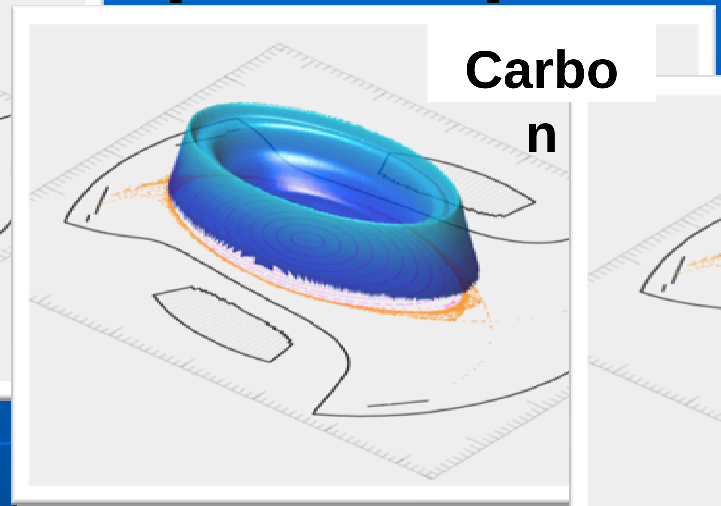


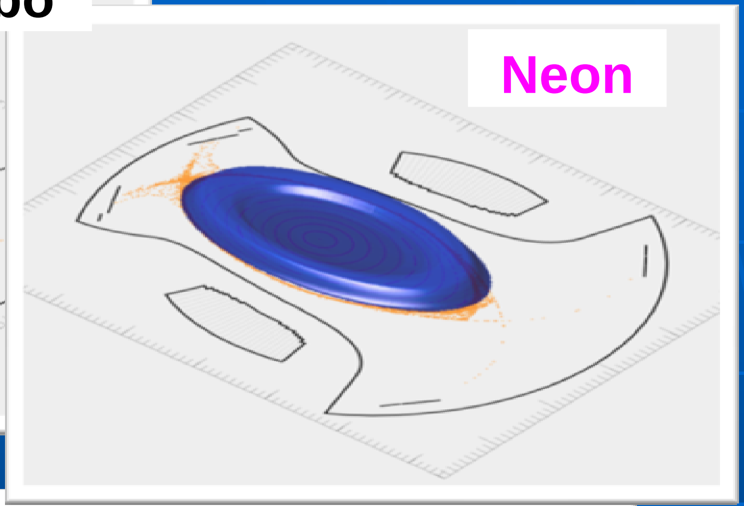
Electron temperature

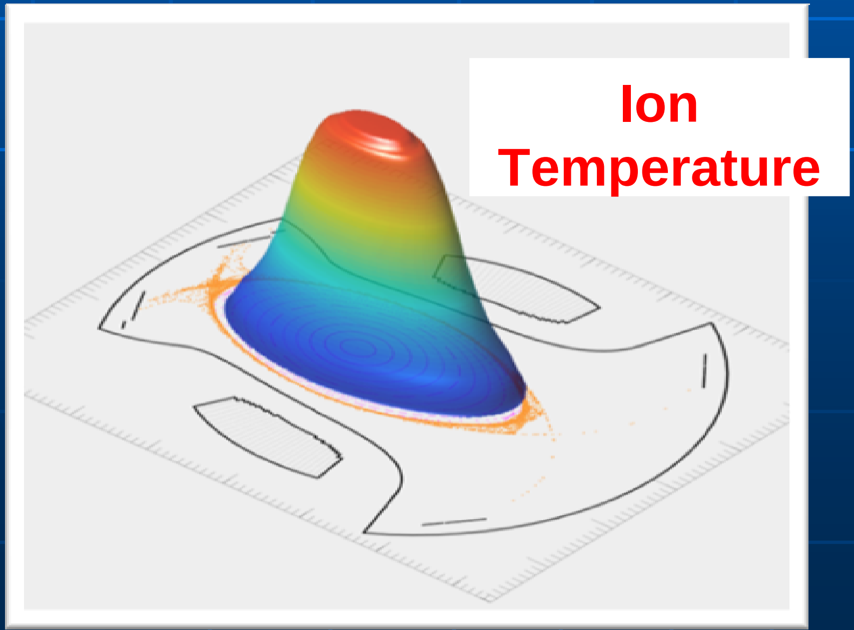


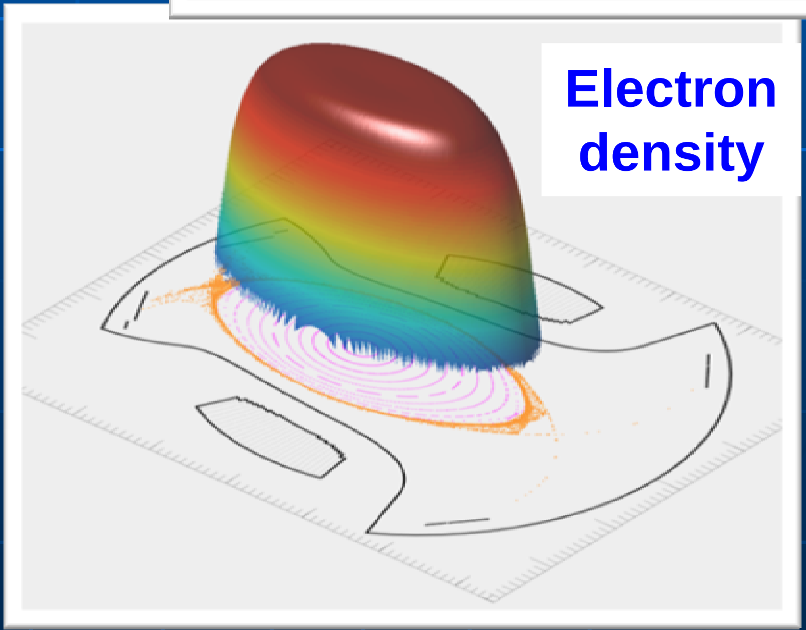
Detailed profiles of plasma parameters





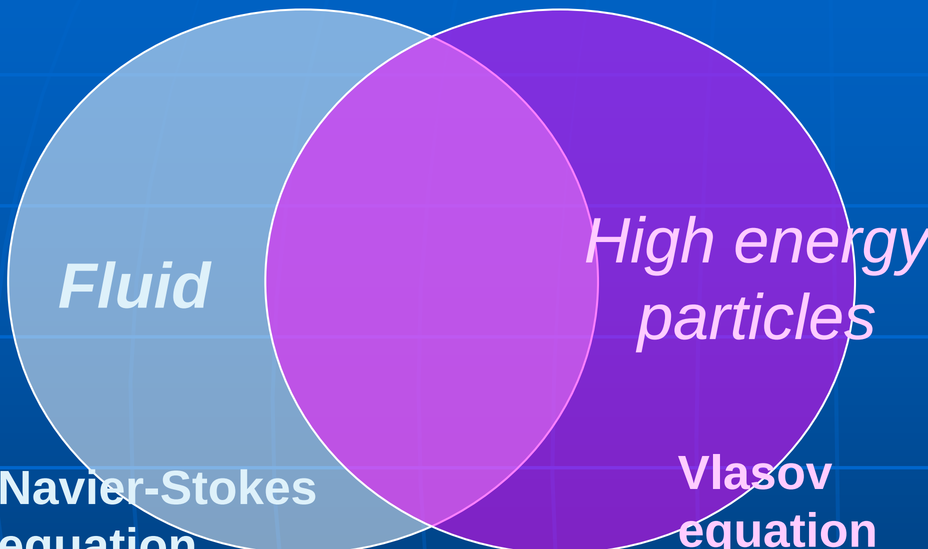






Confinement of plasma is a primary issue in fusion Research

Plasma has a pair of contrasting characteristics

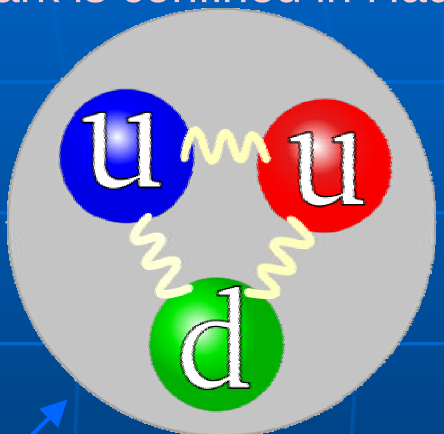


Navier-Stokes equation

Vlasov equation

What is confinement ?

Quark is confined in Hadron



These two problems are appointed *Millenium Problems* by the Clay Mathematics Institute

Furthermore

- Plasmas are accompanied by and generate electro-magnetic field
- Plasmas replace themselves with interaction with the outside

➔ Much more complicated than neutral fluid and particles

Navier-Stokes equation cannot be solved analytically but tells us nature of turbulence

$$\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V}\cdot\nabla)\mathbf{V} = \nu\Delta\mathbf{V} - \frac{1}{\rho}\nabla p + \mathbf{g}$$

Reynolds number R: $\frac{(\mathbf{V}\cdot\nabla)\mathbf{V}}{\nu\Delta\mathbf{V}}$

Large R : $$\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V}\cdot\nabla)\mathbf{V} = -\frac{1}{\rho}\nabla p + \mathbf{g}$$

➔ Equation of motion
➔ Turbulence easily develops

Small R : $$\frac{\partial \mathbf{V}}{\partial t} = \nu\Delta\mathbf{V}$$

➔ Diffusion Equation
➔ Turbulence is suppressed

Centrifugal force V•∇V ⇔ Depletion of pressure ∇p
➔ thermal force by gradient (ununiformity) bends the field (generates eddies)

Fluid model of plasmas ; MHD : Ohm-Navier-Stokes system

$$\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V}\cdot\nabla)\mathbf{V} = \nu\Delta\mathbf{V} + \frac{1}{\rho}\left[\frac{(\nabla\times\mathbf{B})\times\mathbf{B}}{\mu_0} - \nabla p\right]$$

Electro-magnetic force

Ohms law $\mathbf{E} = \eta\mathbf{j} - \mathbf{V}\times\mathbf{B}$

Electric field and flow are two side of the same coin

Maxwell equations $\nabla\times\mathbf{B} = \mu_0\mathbf{j}$ $\quad \frac{\partial \mathbf{B}}{\partial t} = -\nabla\times\mathbf{E}$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla\times(\mathbf{V}\times\mathbf{B}) = \left(\frac{\eta}{\mu_0}\right)\Delta\mathbf{B}$$

Analogous to Navier-Stokes equation

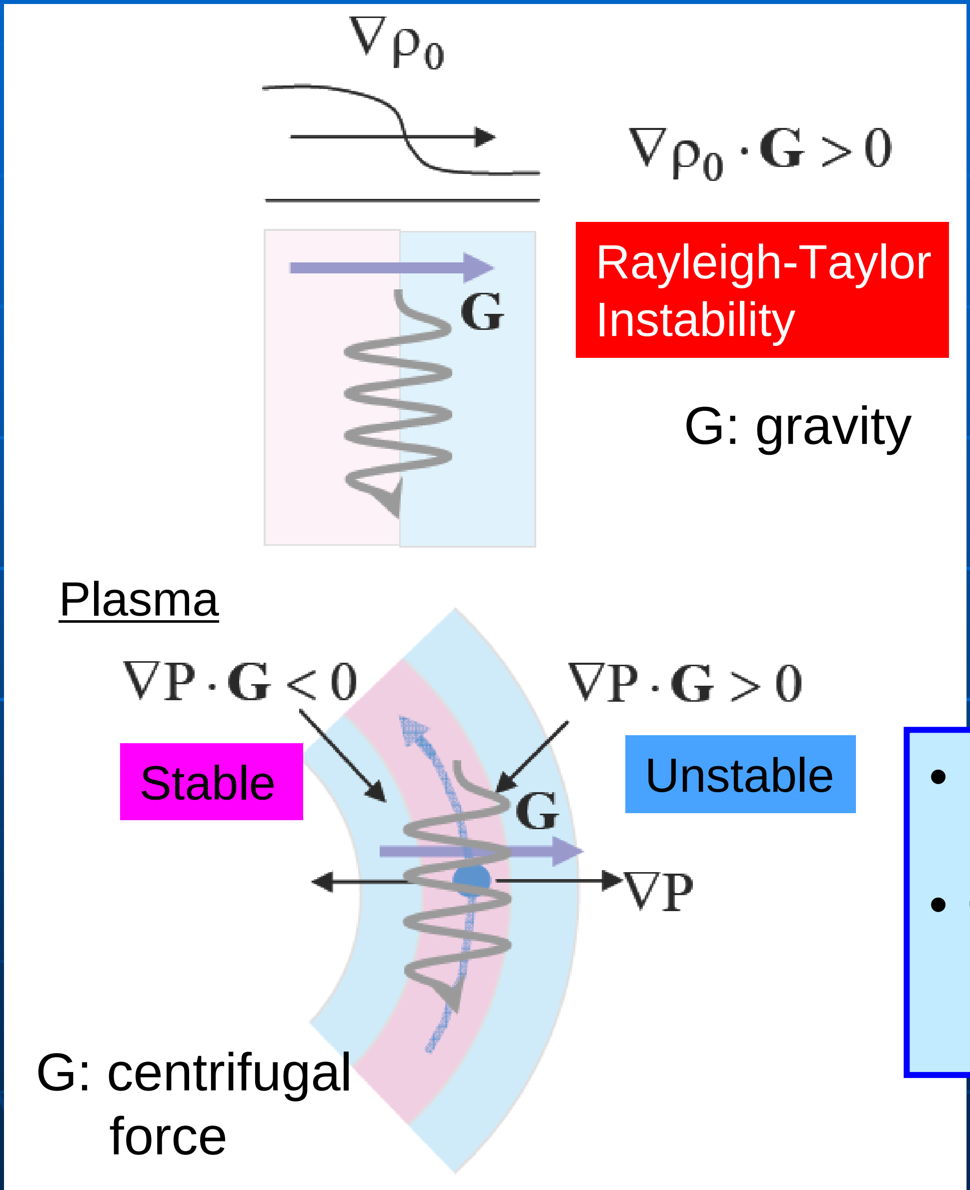
$$\frac{\text{Non-linear term}}{\text{Dissipation term}} = \frac{\nabla\times(\mathbf{V}\times\mathbf{B})}{\left(\frac{\eta}{\mu_0}\right)\Delta\mathbf{B}}$$

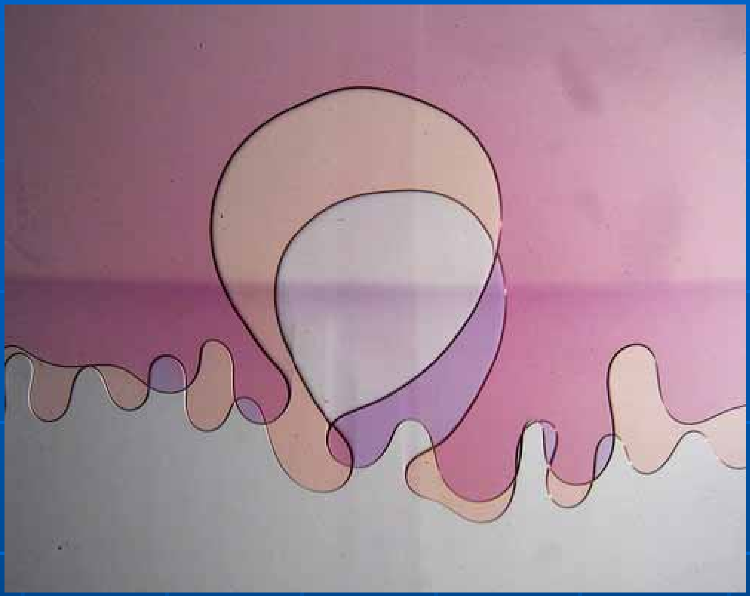
: **Magnetic Reynolds number *S***
(Lundquist number)

Large *S* : **magnetic field is frozen in fluids**

➔ much more complicated than neutral fluids

Origin of turbulent transport : kinetic gradient and force





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

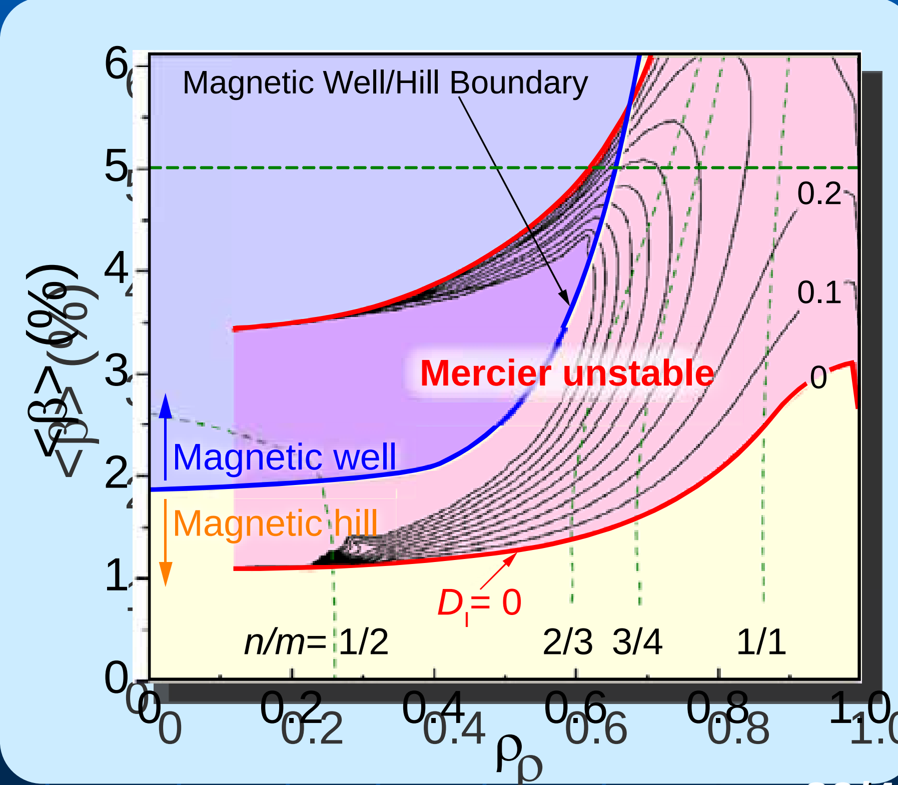
Revision of physical picture of MHD instability - development of new horizon -

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

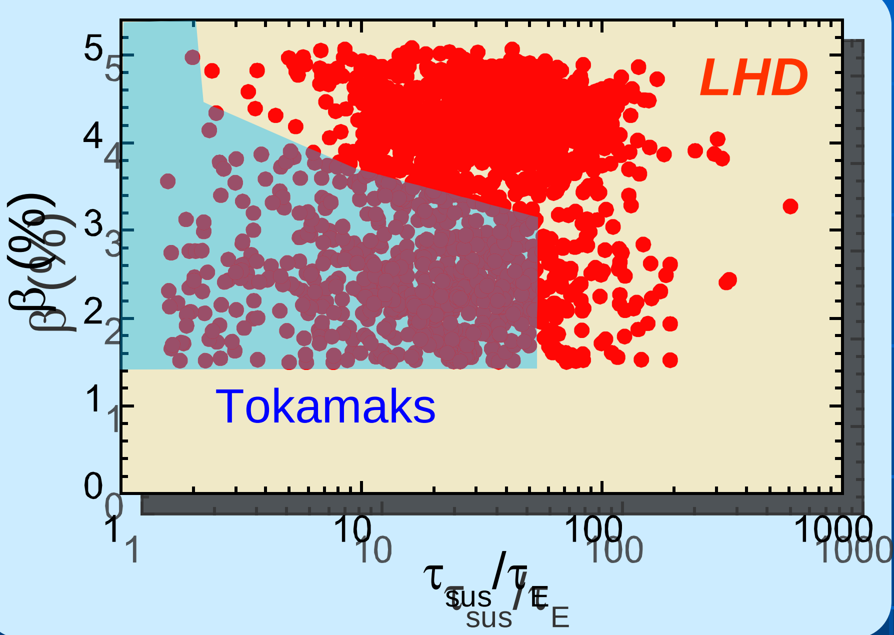


LHD experiment

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



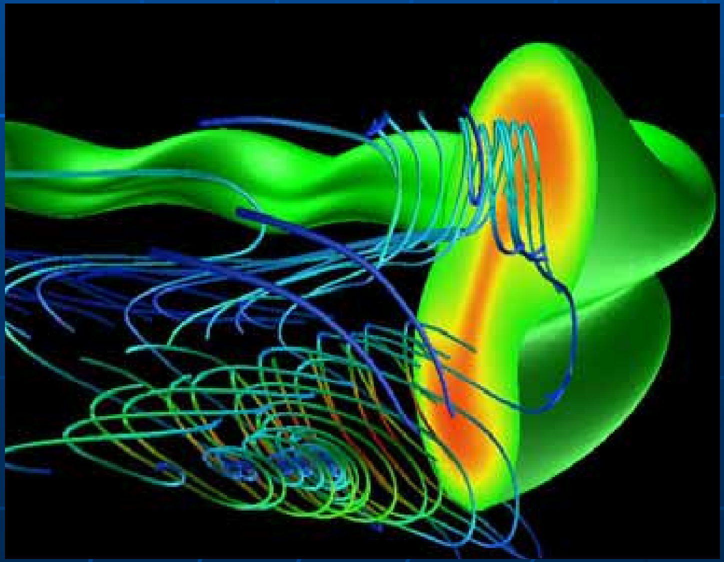
Possible mitigation effect

new elements should be considered

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

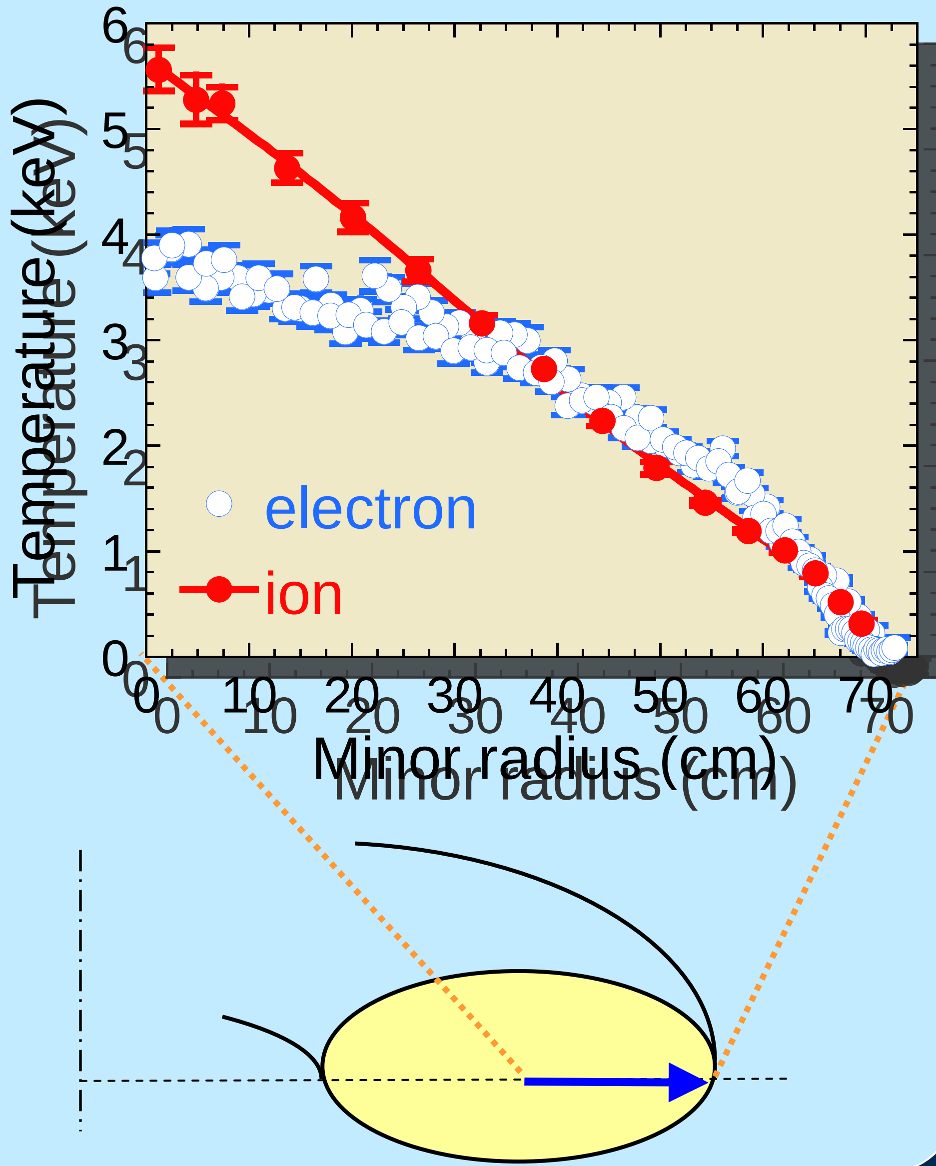
etc…

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

Good thermal shield generates large gradient



- Central ion temperature
  5.6 keV = 65 million℃
- Radius 65 cm

Themal shield capability = 1 million℃/cm

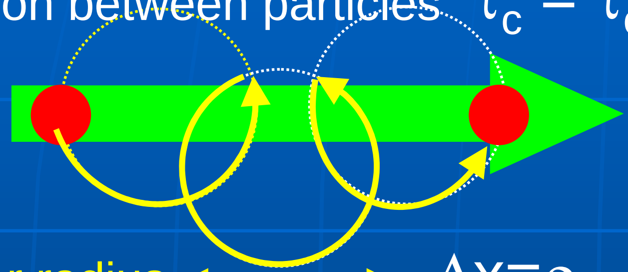
A gradient of physical quantity generates convection and consequent turbulence

Diffusion coefficient

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

<u>Collisional diffusive transport</u>
(Neoclassical transport)

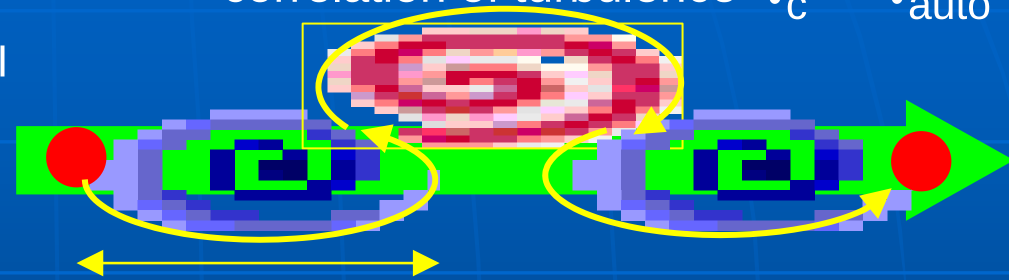
collision between particles $\tau_c = \tau_{coll}$



Larmor radius ⟷ $\Delta x = \rho_i$

<u>Turbulent transport</u>

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

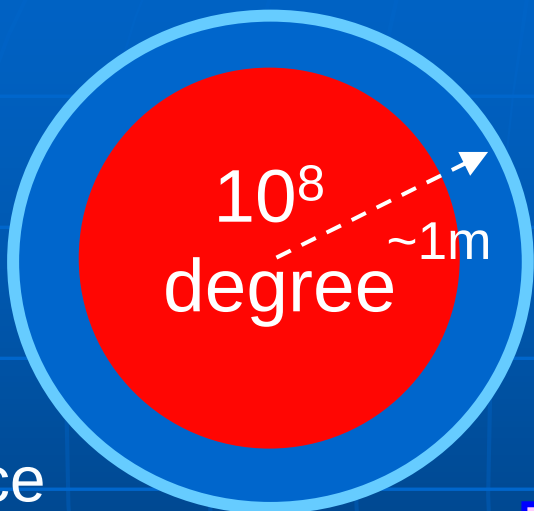
$$D \propto \frac{n}{B^2 T^{1/2}} \qquad\qquad D \propto \frac{T}{B}$$

- 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)

Plasma Confinement

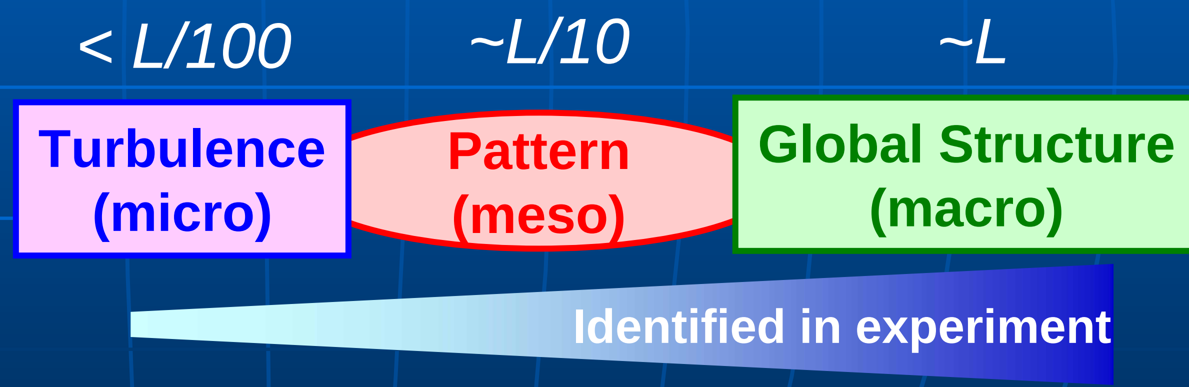
Challenging requirement:
Extreme thermal insulation

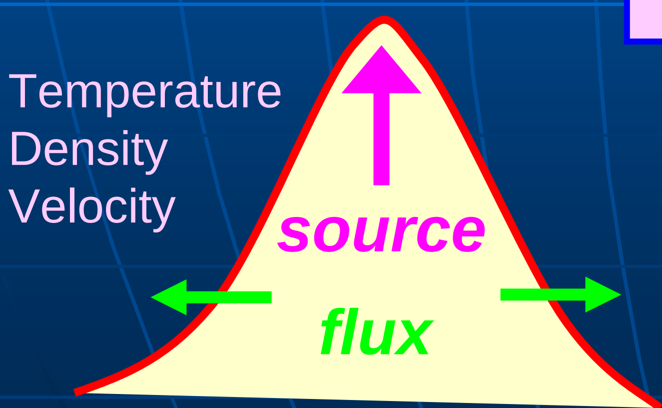
1 M ºC/cm



Device
at room temperature

Steep gradient causes turbulence
Temperature ∇T, Density ∇n



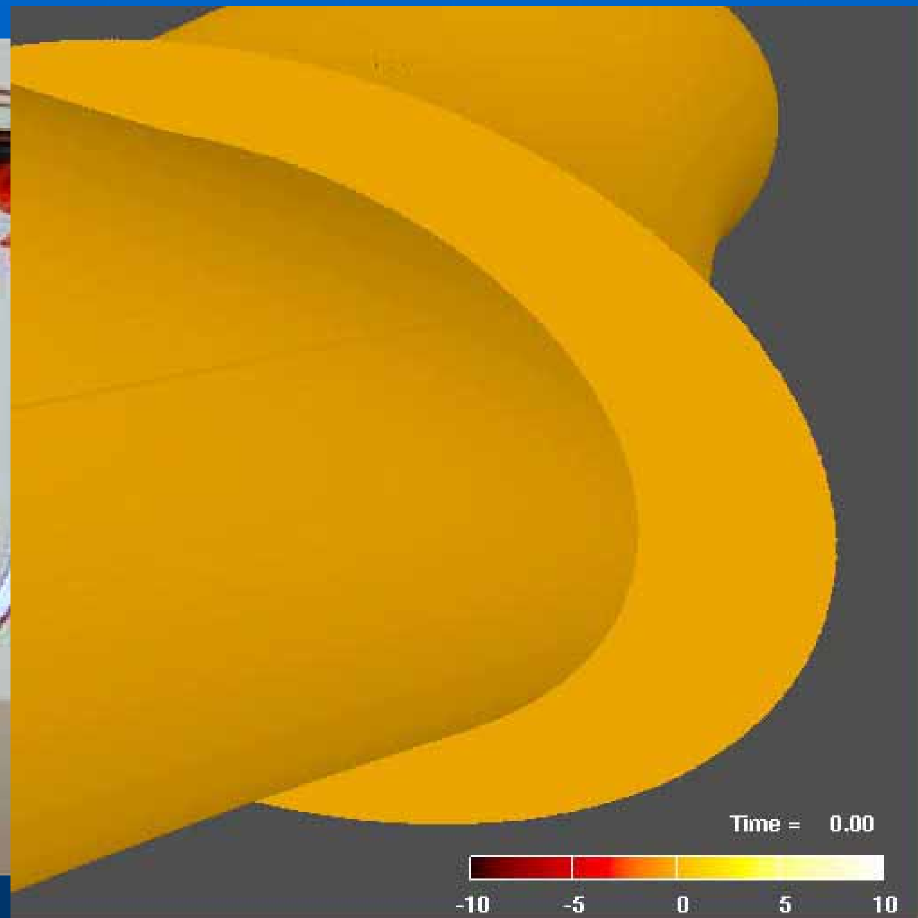


Radial profile

Radial profile : Structure

← formed and maintained by characteristics of non-linear, non-equilibrium system

Development of turbulence



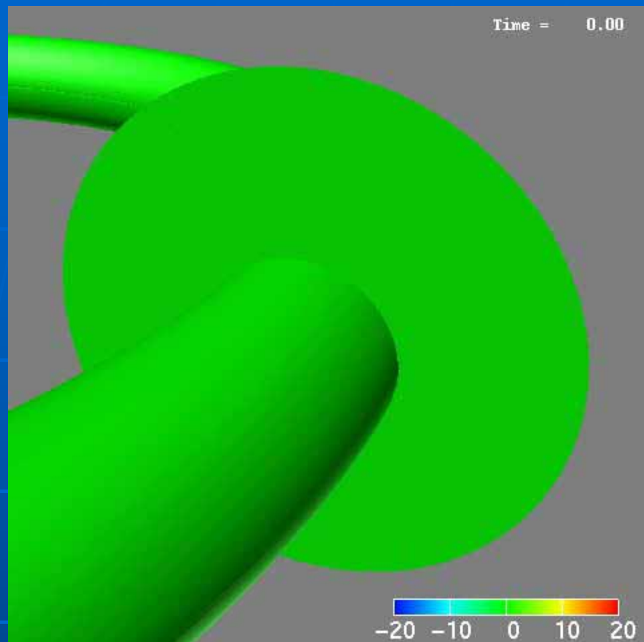
Courtesy of T.H.Watanabe

Heavier media replaces lighter media

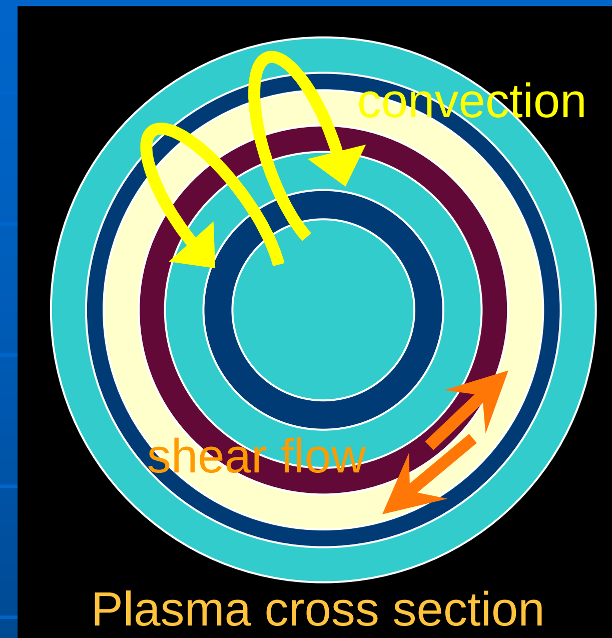
Cooler media replaces hotter media

➔ directed to uniform distribution

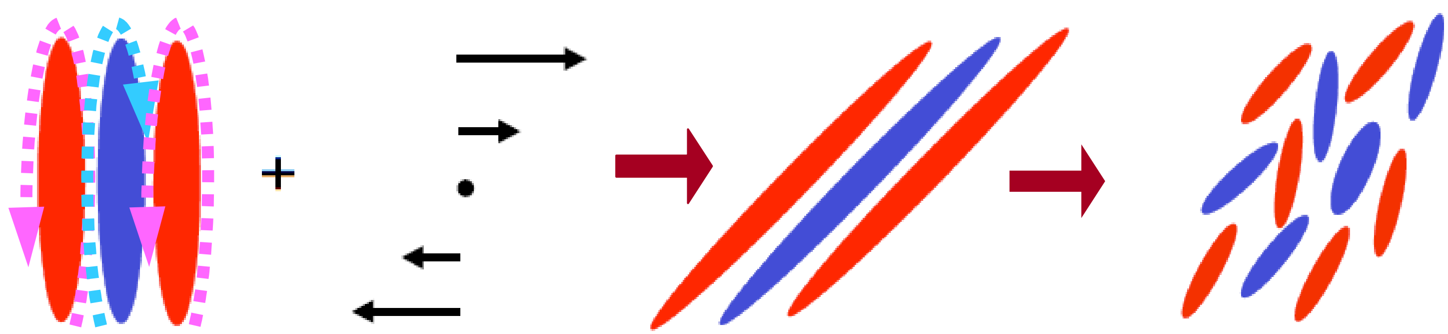
Turbulence drives zonal flow and regulates itself



Courtesy of T.H.Watanabe



outside



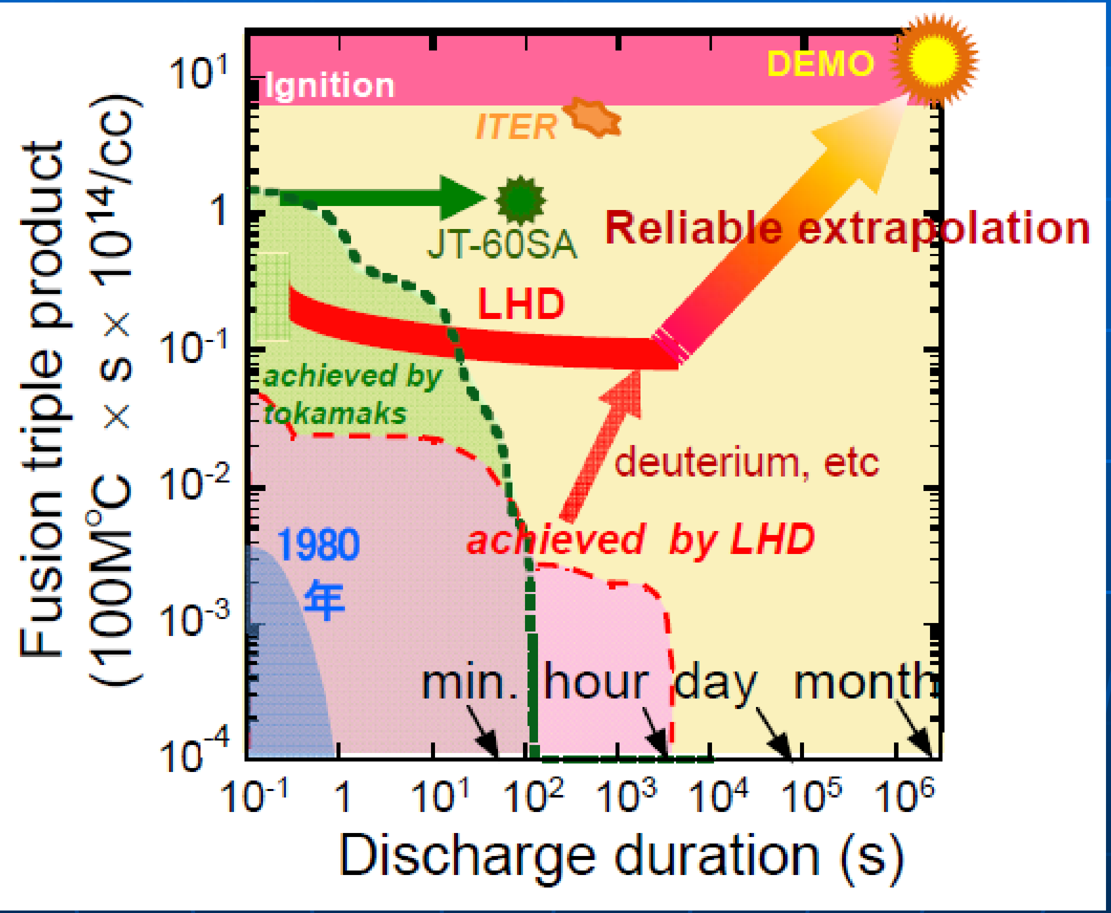
inside

Zonal shear flow reduces the size of eddy, consequently suppresses transport

Where are we now ?

Fusion condition > 100 M℃ × 1 s × 10^{14}/cc

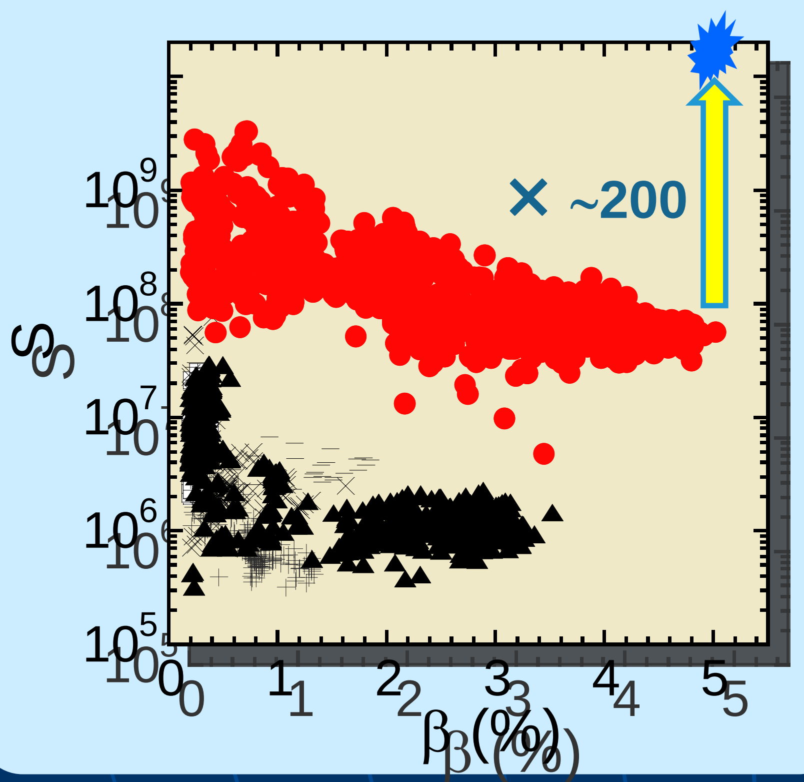
Difficulty to ignite plasma



Difficulty to sustain plasma

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 ?

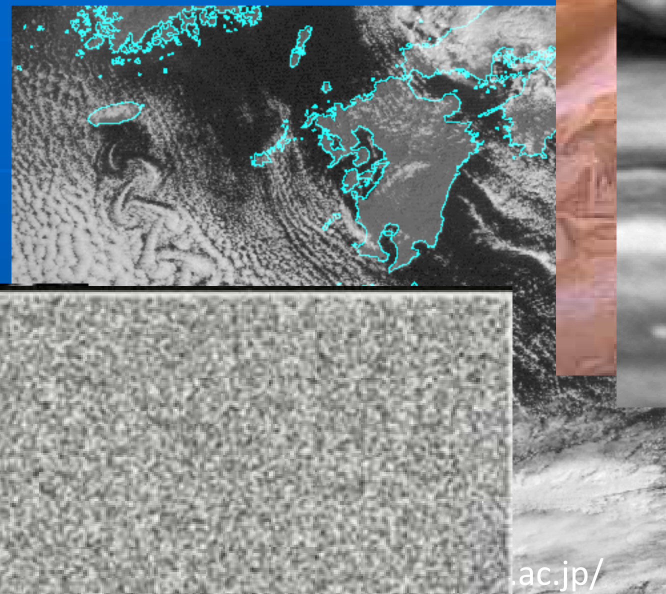
Note: LHD cannot realize a plasma with full dimensional similarity

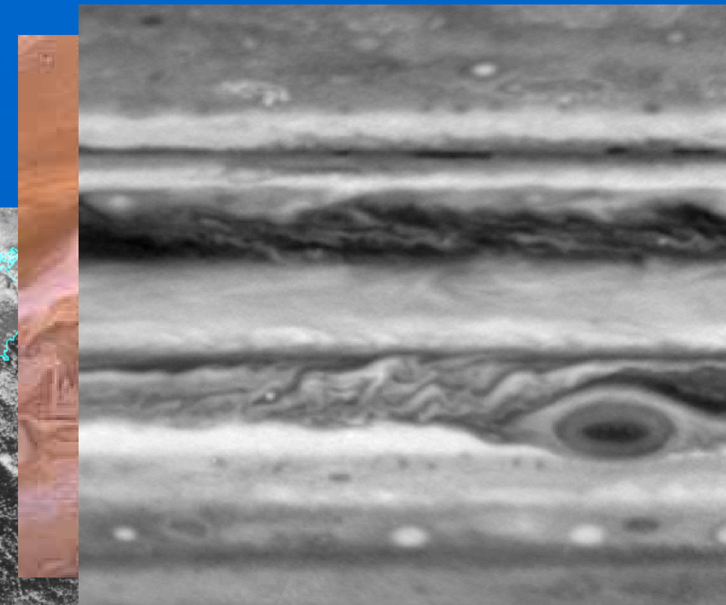
➔ ***Integrated physics model with reliable predictability which bridges over the gap of non-dimensional parameters***

Dimensionless similarity

Karman vortex street

Downstream clouds
behind the Jeju island





Great red spot on Jupiter

Flow behind a cylinder

Design →

Prediction of large scale from small scale

Dimensional Analysis

Vlasov equation
(Collisionless Boltzman equation)

$$\frac{\partial f_j}{\partial t} + \mathbf{v}\cdot\frac{\partial f_j}{\partial \mathbf{x}} + \frac{e_j}{m_j}(\mathbf{E}+\mathbf{v}\times\mathbf{B})\cdot\frac{\partial f_j}{\partial \mathbf{v}} = 0$$

Condition of electric charge neutrality

$$\sum_j e_j \int f_j \, d^3 v = 0$$

This set of equations are invariant to the following 3 scale transformations

1) $f_j \rightarrow a f_j$
2) $v \rightarrow b v$, $t \rightarrow b^{-1} t$, $E \rightarrow b^2 E$, $B \rightarrow bB$
3) $t \rightarrow g t$, $x \rightarrow gx$, $E \rightarrow g^{-1}E$, $B \rightarrow g^{-1}B$

Assume the dependence of energy confinement time

$$\tau_E \propto n^p B^q T^r a^s \qquad n = \int f \, d^3 v \qquad nT = \frac{1}{3} m \int v^2 f \, d^3 v$$

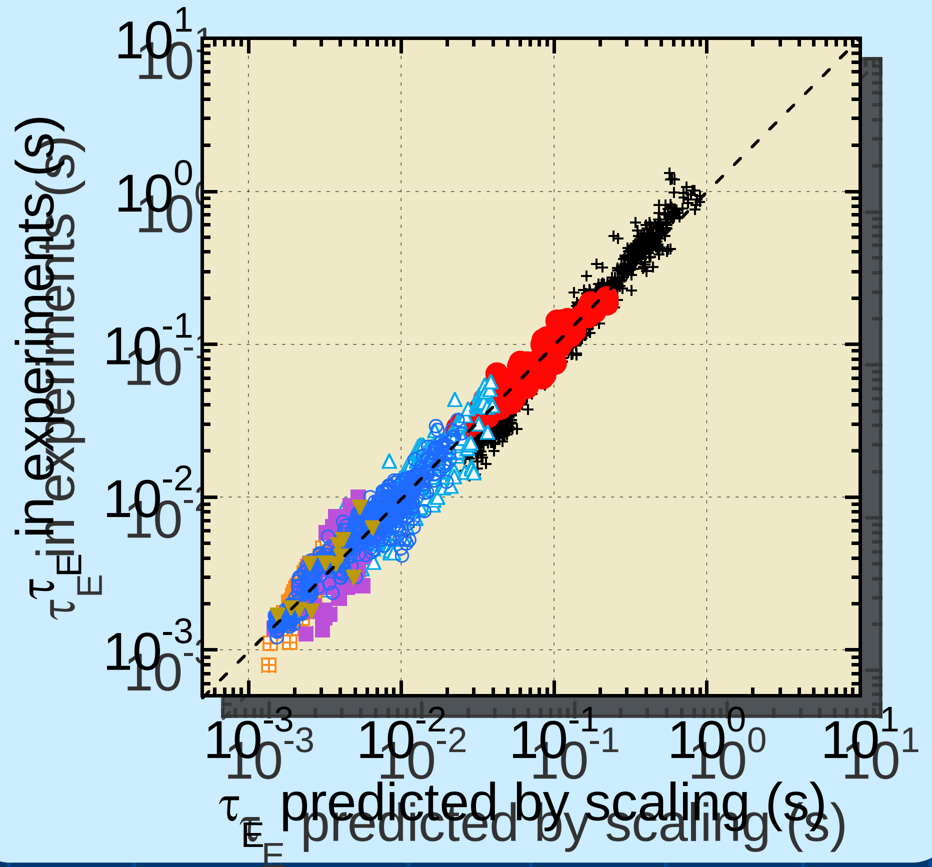
The invariant condition gives **dimensional constraint** : p=0, q+2r=-1, s-q=1

$$\tau_E \propto \frac{1}{B}\left(\frac{T}{a^2B^2}\right)^r F(....)$$

Three major important non-dimensional parameters :

1. normalized gyro radius $\rho^* = \rho/a$ ρ: Larmor radius
2. beta $\beta = p/(B^2/2\mu_0)$
3. collisionality $\nu^* = \nu_{ei}/\nu_b$

Scaling law



Expression by operational parameters

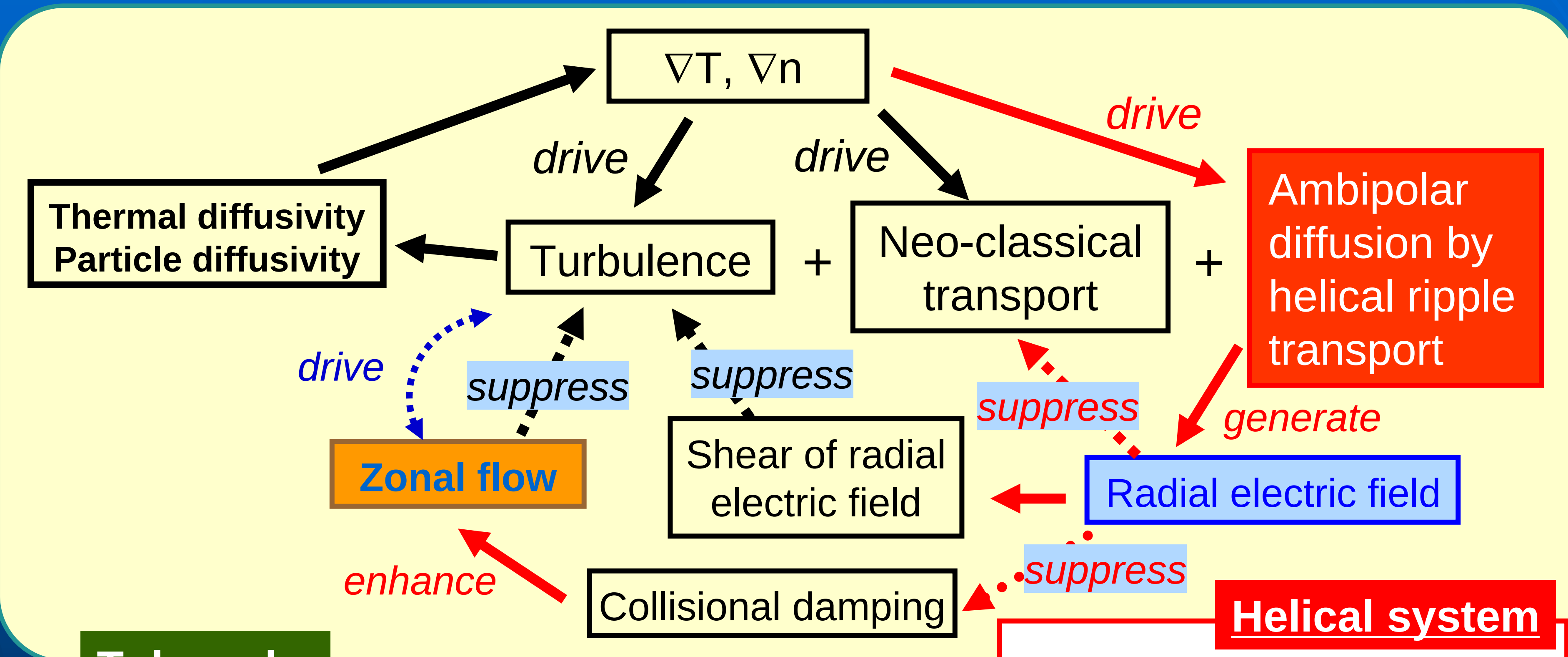
a: minor radius
R: major radius
P: heating power
n: density
B: magnetic field
ι : rotational transform
etc.

Convenient in quantification of the performance in existing experiments and predicting that in future machines

$$\tau_E^{\mathrm{ISS04}}(\mathrm{s}) = 0.134 \times \mathrm{a}^{2.28}\,\mathrm{R}^{0.64}\,\mathrm{P}^{-0.61}\,\mathrm{n}^{0.54}\,\mathrm{B}^{0.84}\,\iota^{0.41}$$
$$\propto \rho^{*-0.79}\,\beta^{-0.18}\,\nu^{*0.00}\,\iota_*^{1.06}\,\epsilon^{-0.08}$$

Reliability of extrapolation much depends on clarification of underlying physics

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

Transport matrix for plasma

	Flux		Diffusion coefficient	Thermo-dynamical force : gradient	
particle	Γ		$D \quad - \quad - \quad -$	∇n_e	→ Non-Diffusive
toroidal momentum	P_f	= -	$- \quad \mu_f n m_i \quad - \quad -$	∇V_f	→ Non-Diffusive
ion heat	$Q_{i,}$		$- \quad - \quad n\chi_{i,} \quad -$	∇T_i	→ Diffusive
electron heat	$Q_{e,}$		$- \quad - \quad - \quad n\chi_e$	∇T_e	→ Diffusive

$$\begin{pmatrix} \Gamma \\ P_f \\ Q_{i} \\ Q_{e} \end{pmatrix} = - \begin{pmatrix} D & - & - & - \\ - & \mu_f n m_i & - & - \\ - & - & n\chi_i & - \\ - & - & - & n\chi_e \end{pmatrix} \begin{pmatrix} \nabla n_e \\ \nabla V_f \\ \nabla T_i \\ \nabla T_e \end{pmatrix}$$

4 radial fluxes are expressed by 4 x 4 transport matrix

4 diagonal coefficients are determined by turbulence

$\Gamma = -D\nabla n_e$ $\qquad Q_e/n_e = -\chi_e \nabla T_e$

$P_f/(m_i n_i) = -\mu_f \nabla V_f$ $\qquad Q_i/n_i = -\chi_i \nabla T_i$

Diffusive nature :

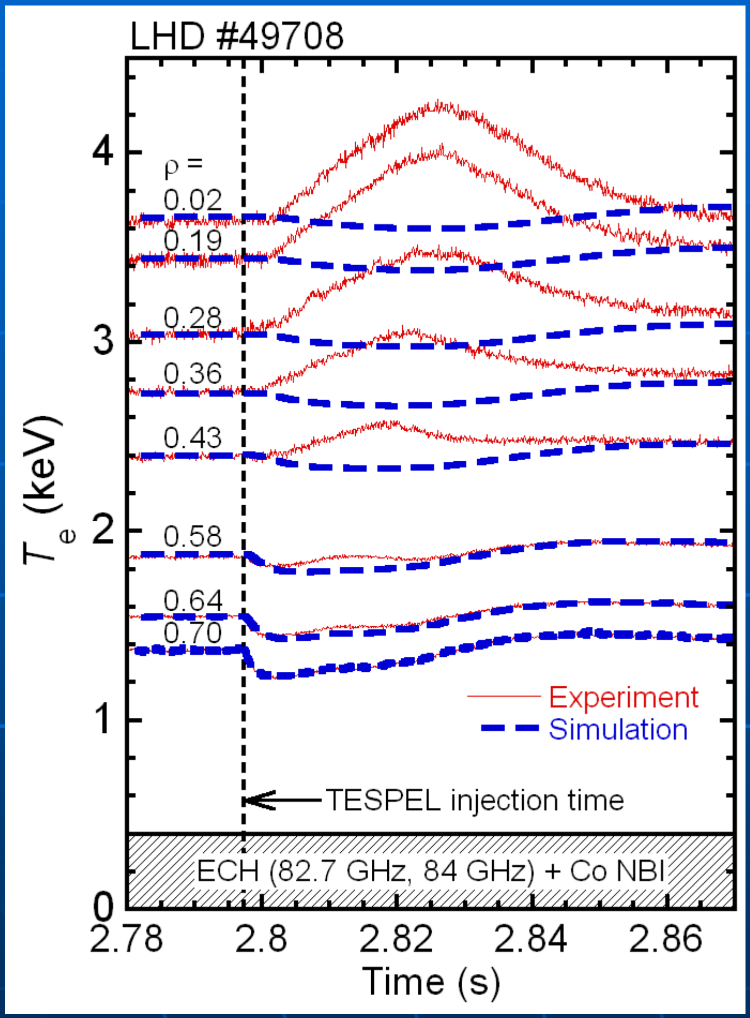
Curie's principle : linear relation between flow and thermo-dynamical force

In plasmas, off-diagonal terms play essential roles :

← difficulty in finding **orthogonal** basis

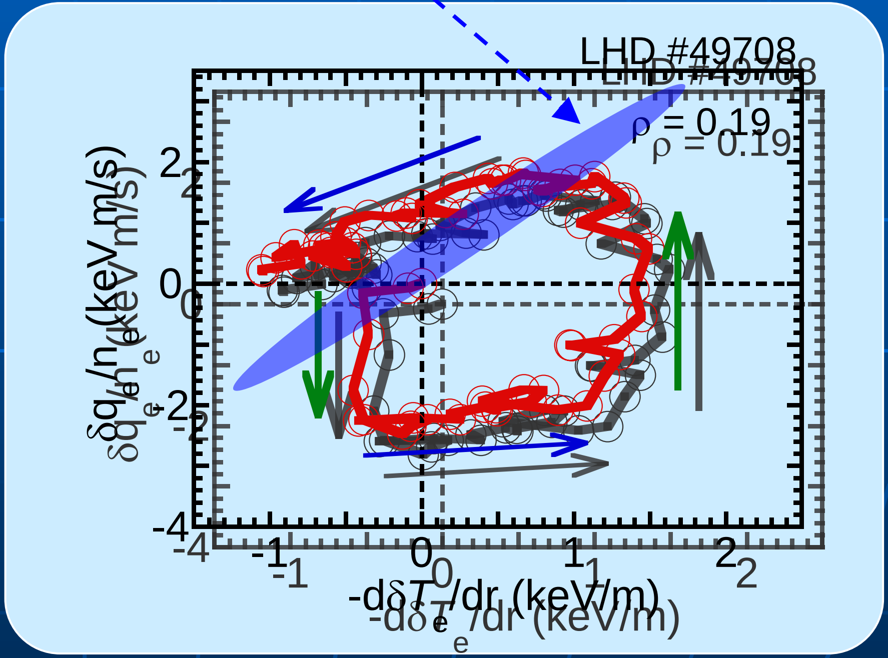
Loss of spatial symmetry → formation of structure

Non-local phenomena : transient response



Heat flux $\delta q_e(r,t) = -\frac{1}{r}\int_0^r \frac{3}{2} n_e \frac{\partial \delta T_e(r,t)}{\partial t} \rho d\rho$

Diffusive term	Additional term
Q = - c (T,▽T) ▽T	+ ∫ f(▽T, , ,) dr +



→ Non-local transport can be expressed as additional flux contributed by the ▽T at different radii

N.Tamura,, Nucl. Fusion 47, (2007) 4495

Particle, momentum and heat transports : 3N's : Non-linear, Non-orthogonal, Non-local

simplified — *unrealistic ?*

1 Linear + diffusive + local transport model (simple!)

$\Gamma = - D\nabla n$ $P/(n_i m_i) = - \mu \nabla V$ $Q/n = - \chi \nabla T$

2 Add Non-linearity

$\Gamma = -D(n,\nabla n) \nabla n$ $Q/n = - \chi(T,\nabla T) \nabla T$

Non-liner dependence → stiffness

3 Add Non-diffusivity (inter-linkage between flux)

$\Gamma = - D(n,\nabla n)\nabla n + D^N(n/T) \nabla T +$

Non-diffusive term → particle inward/outward pinch

$P_f/(n_i m_i) = - \mu_f(\nabla E)\nabla V_f + \mu^N(V_{th}/T) \nabla T +$

Non-diffusive term → spontaneous rotation

4 Add Non-locality (inter-linkage in space)

$\Gamma = - D (n,\nabla n) \nabla n + D^N(n/T)\nabla T + \int f(n,\nabla n,\nabla T, \;,\;,)dr +$

Non-local term

complicated — *realistic ?*

Déconstruction

3-D MHD equilibrium without assumption of nested flux surfaces

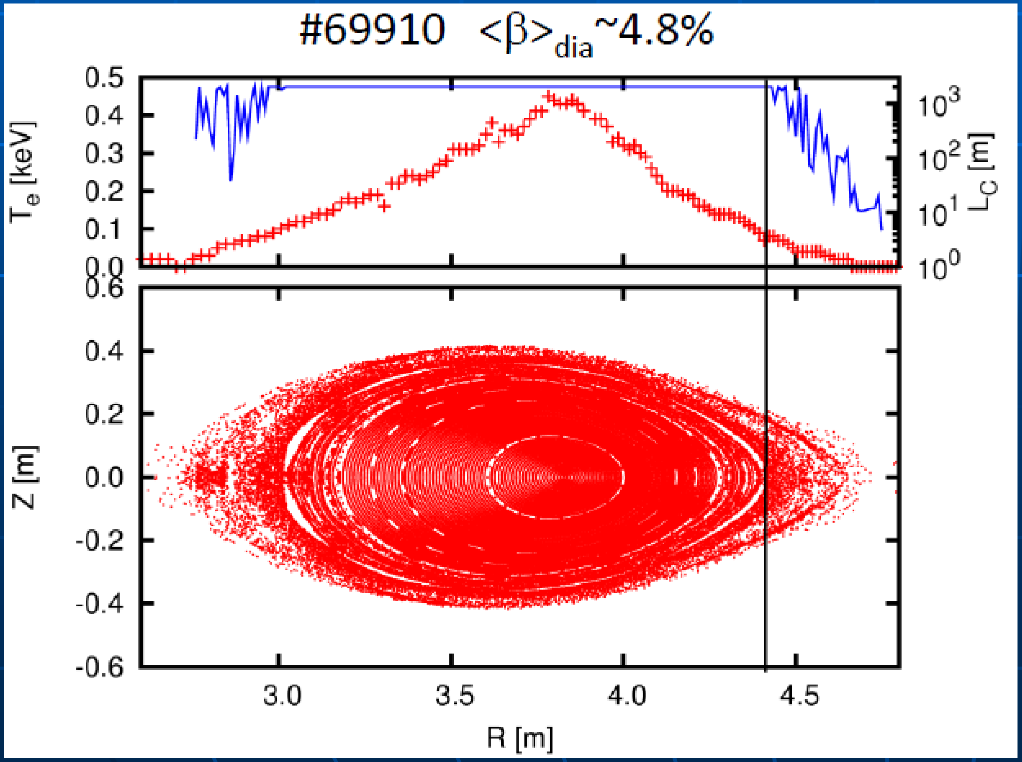
MHD equilibrium

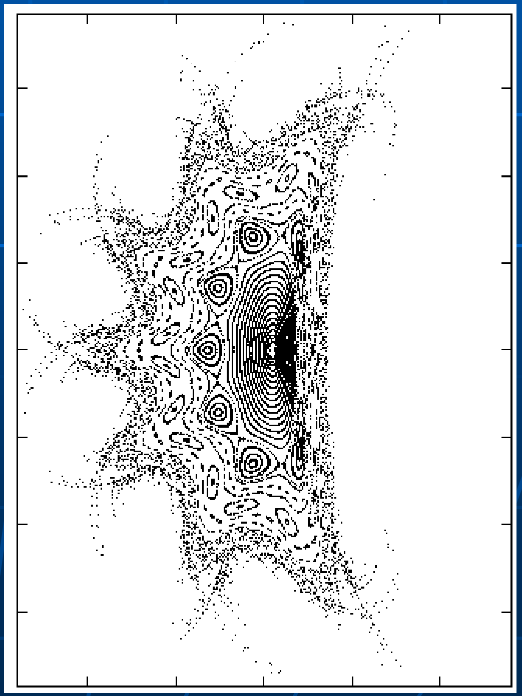
$$\left.\begin{array}{l}\mathbf{J}\times\mathbf{B}=\nabla p\\ \nabla\times\mathbf{B}=\mu_0\mathbf{J}\\ \nabla\cdot\mathbf{B}=0\end{array}\right\}$$

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



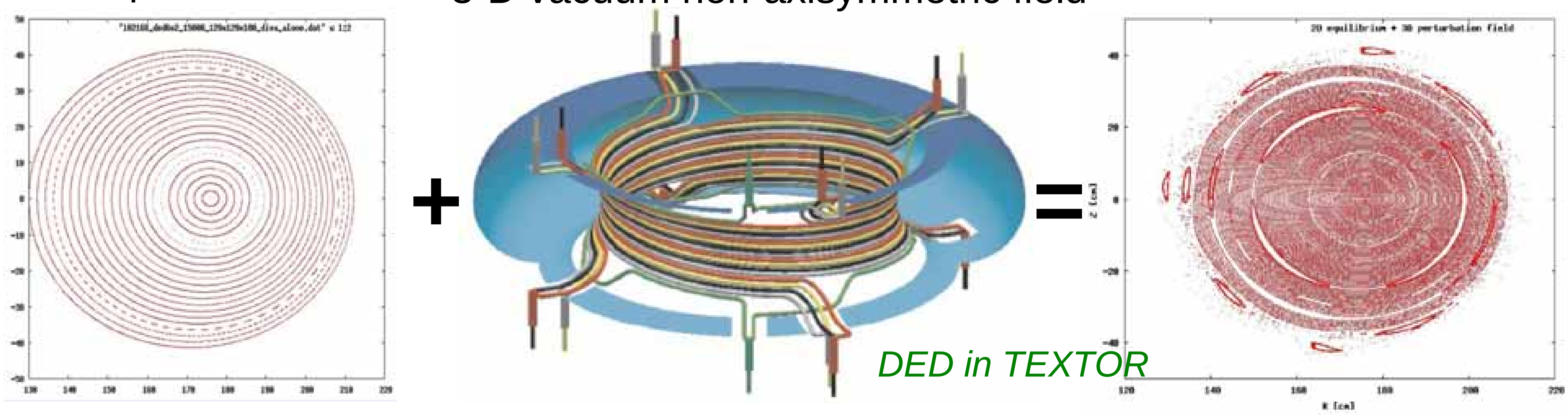


Courtesy of Y.Suzuki

Application of HINT to Resonant Magnetic Perturbation experiment

RMP : control of **ELM** under consideration in ITER

2-D equilibrium field 3-D vacuum non-axisymmetric field Resultant field ?



Crude Ansatz for treat of perturbations: Vaccuum approximation

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

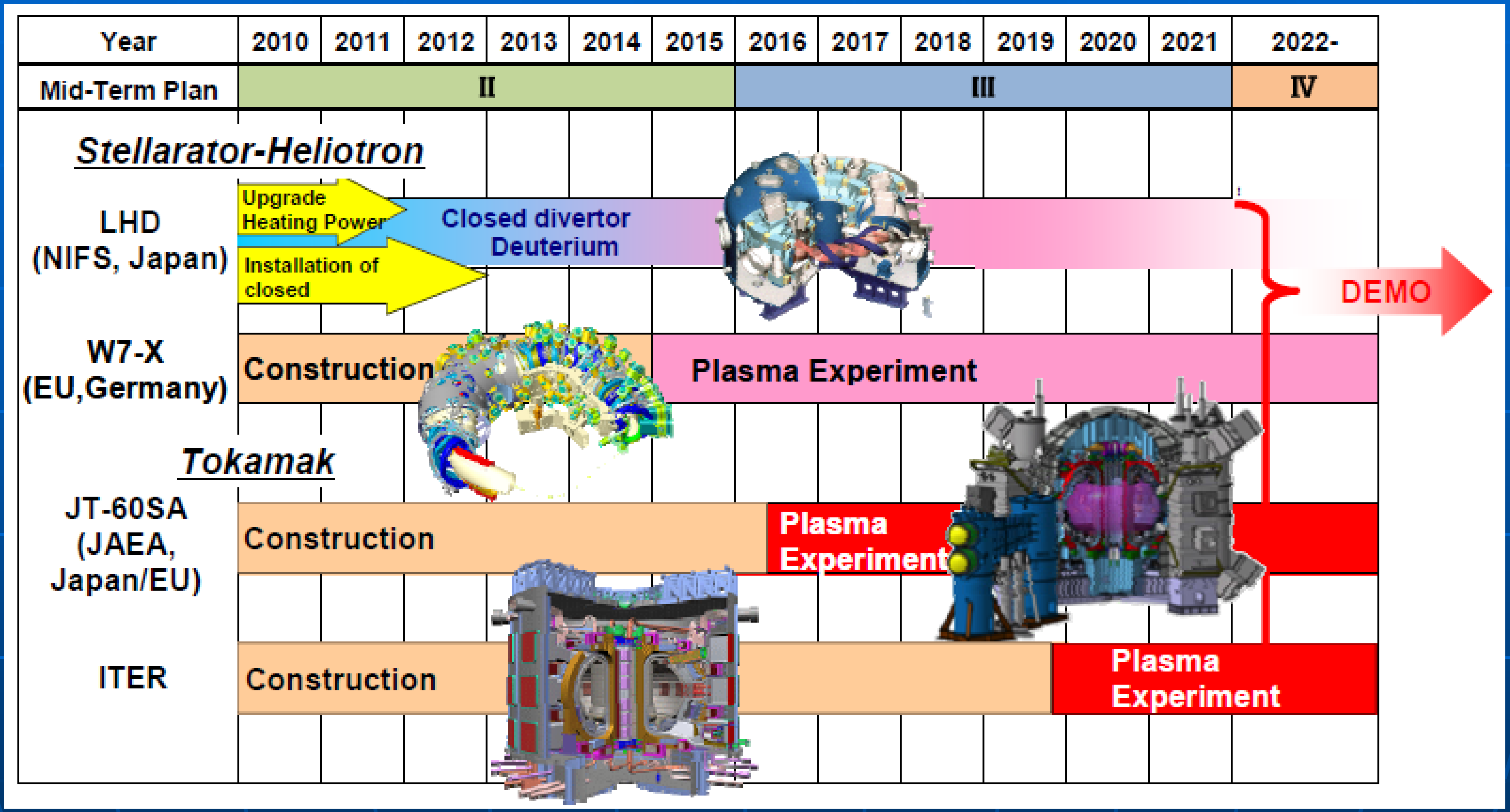
- Acceptable for small perturbations, but "What is small?"

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

- Where is the limit?

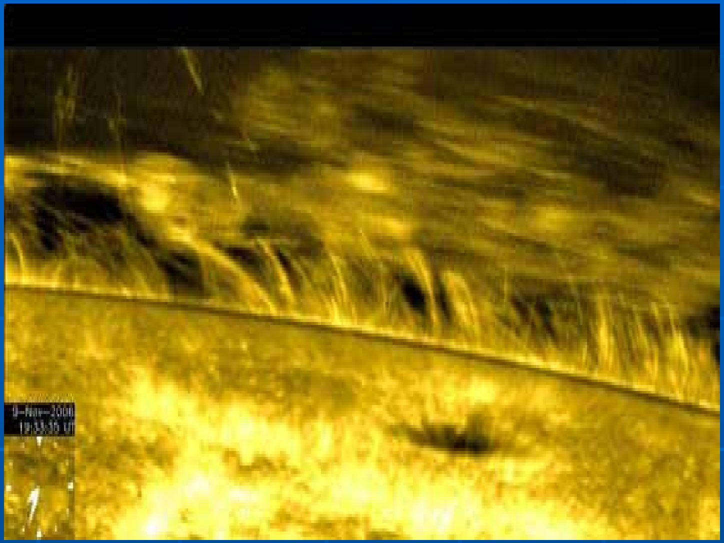
Courtesy of Y.Suzuki&C.Wiegmann

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
   ➔ Complementary portfolio
3. Enhancement of collaboration, Human resource development
4. NIFS offers collaboration through public subscription

Plasma connects fusion's in space and on the earth

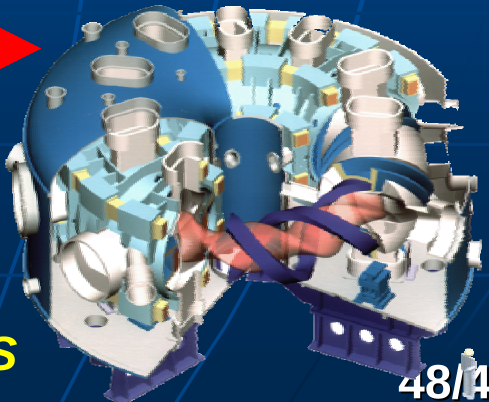


LHD

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

Collaboration for understanding of non-equilibrium plasmas

Solar coronal heating



Hinode/NAOJ

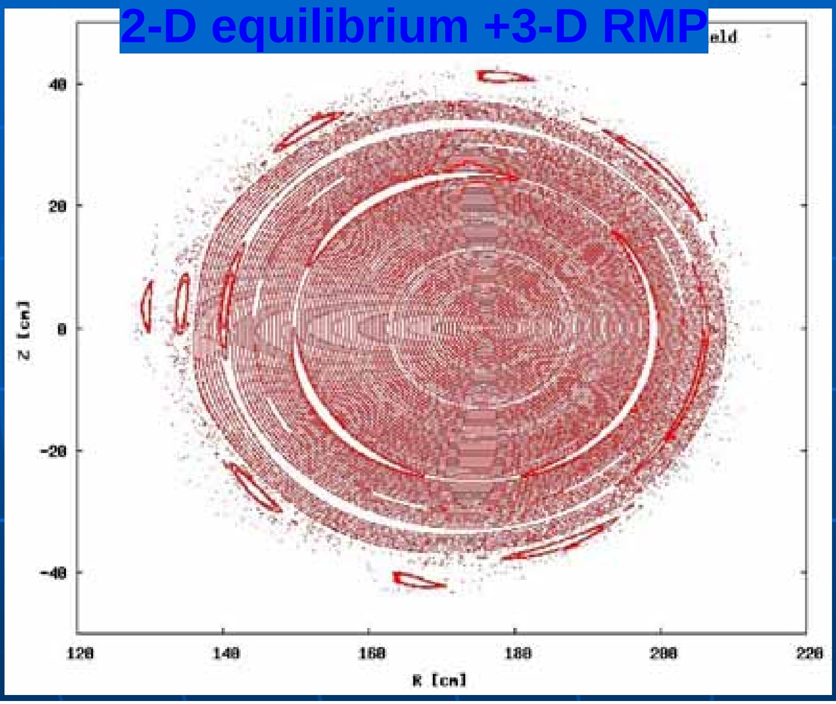
LHD/NIFS

Application of HINT to TEXTOR-tokamak

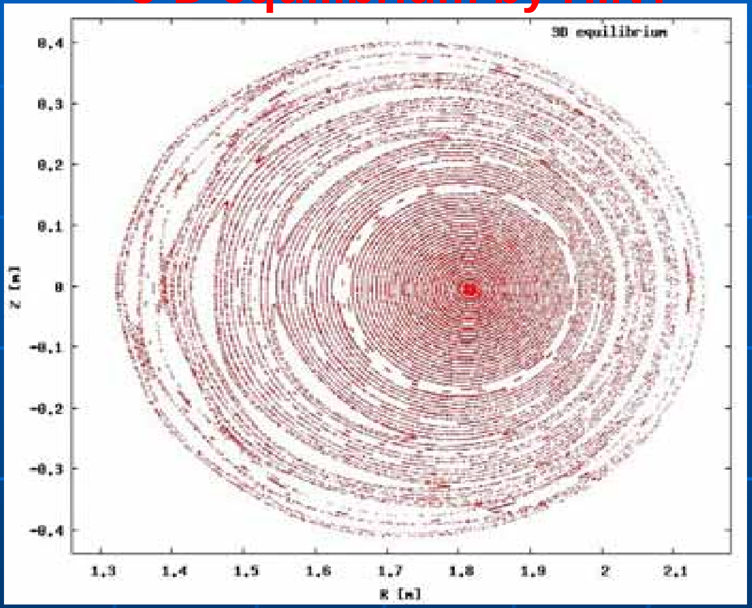
First (preliminary) results for:

- 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

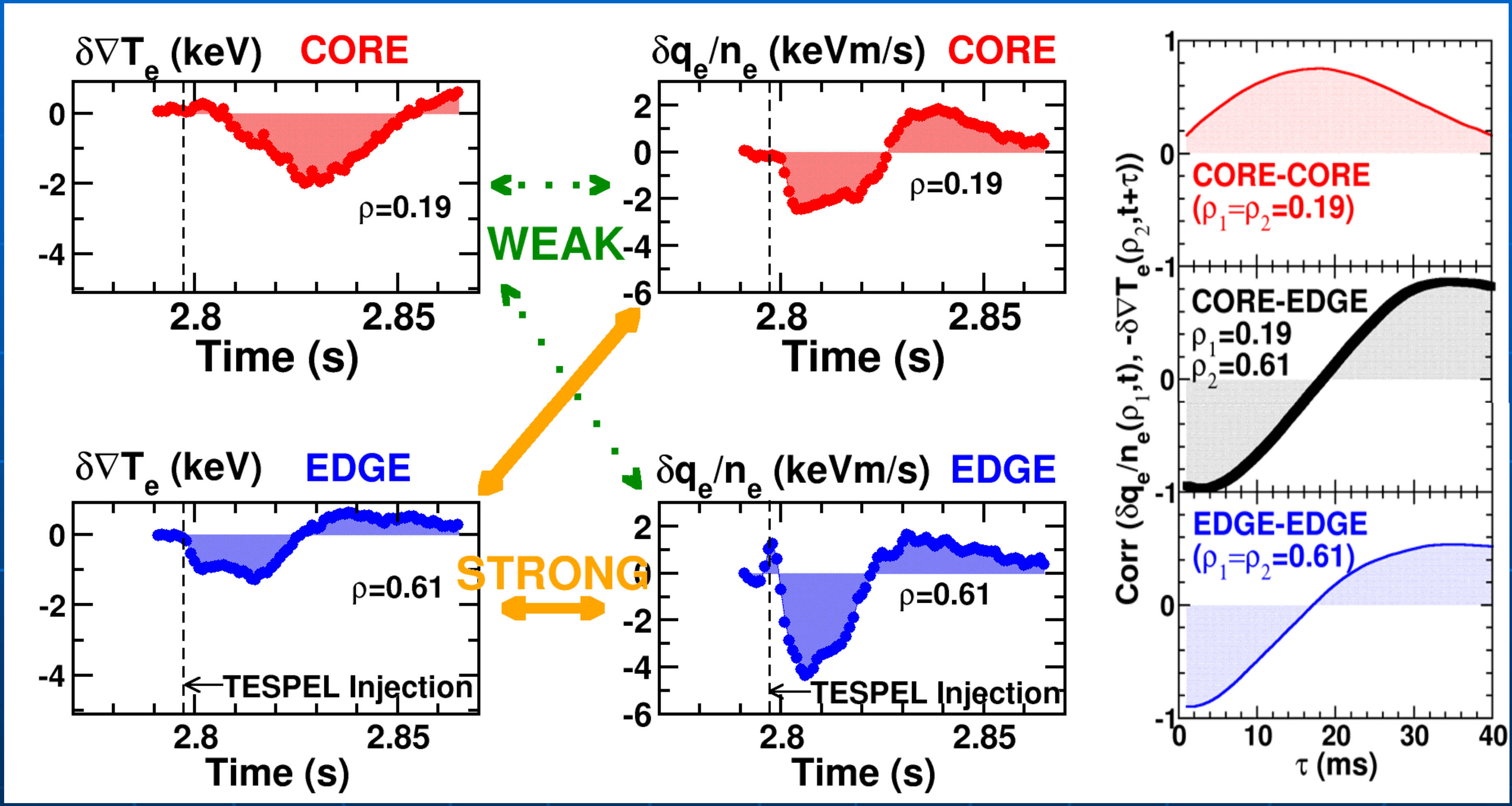


Notes:
Growing island sizes
Less ergodicity at boundary in HINT2-calc.even at higher b .

Preliminary! Checking of calculations is still under way!

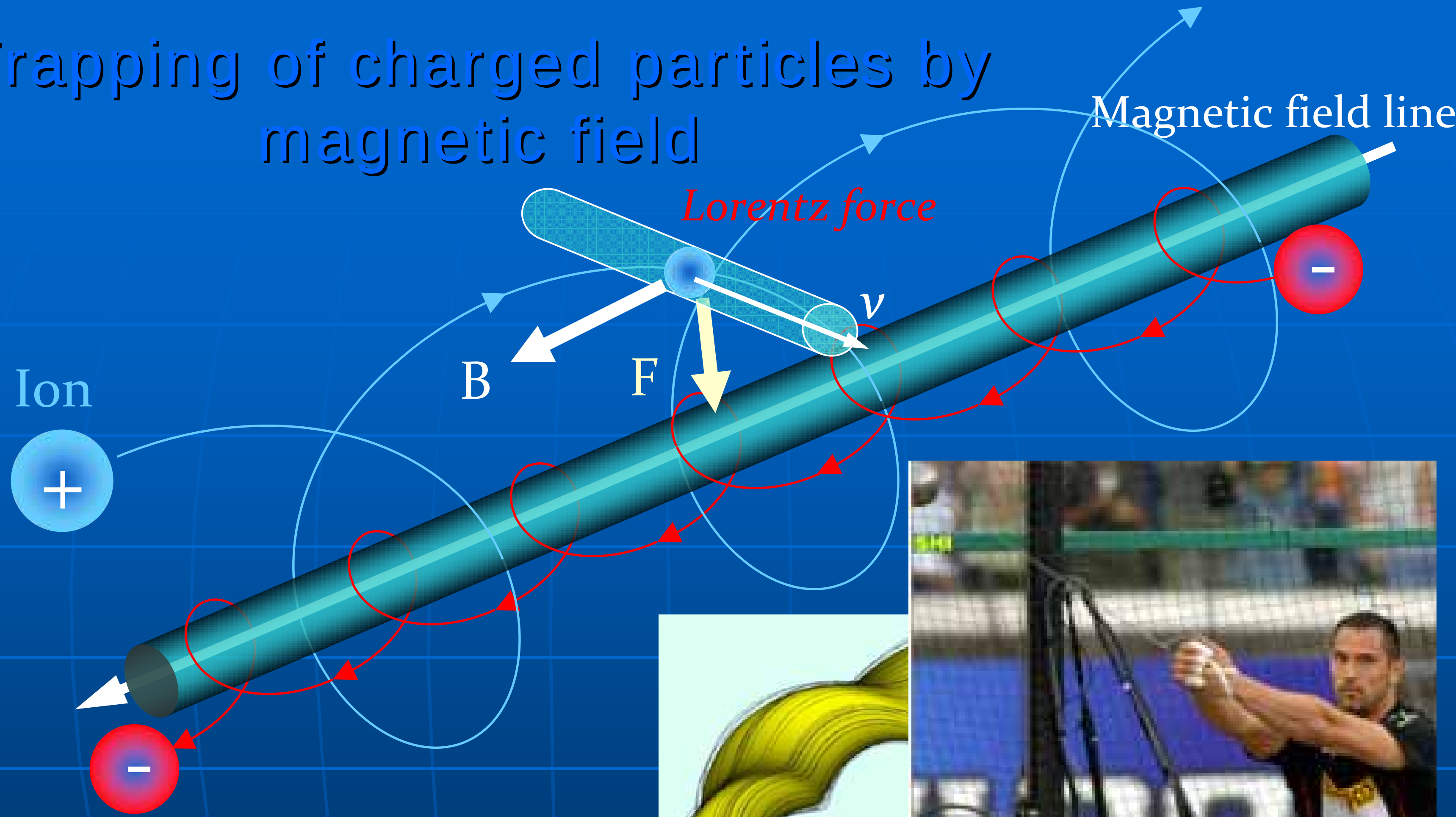
Courtesy of Y.Suzuki&O.Wiegmann

Transient response analysis suggests strong coupling between the core and the edge

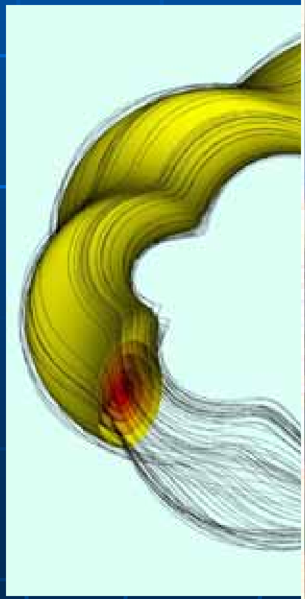


→ Suggest strong coupling of turbulence through meso-scale flow between two separated locations

Trapping of charged particles by magnetic field



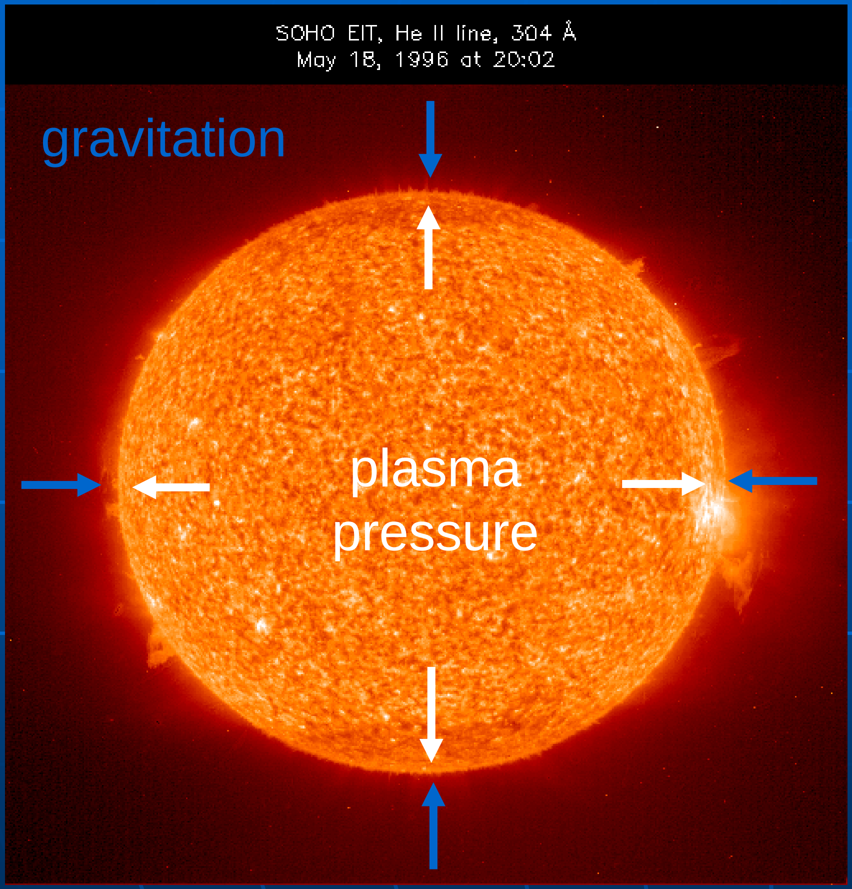
$$F = q\mathbf{v} \times \mathbf{B}$$



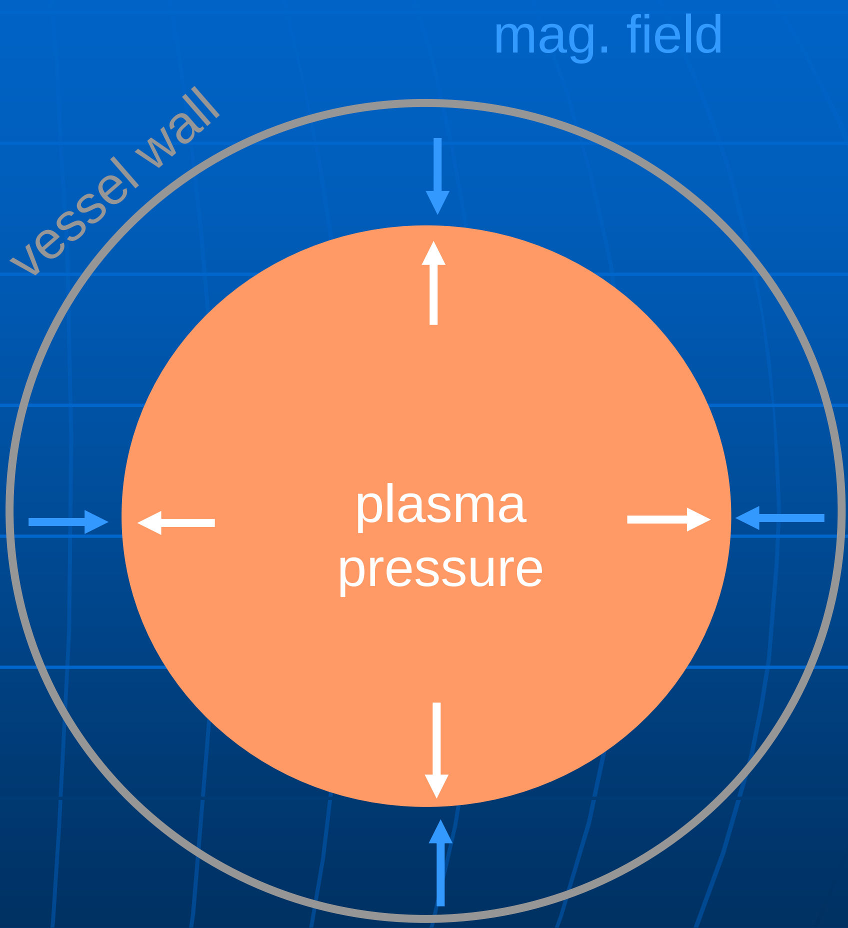
Circlin

Courtesy of Prof.T.Klinger

Pressure equilibrium : confinement



equilibrium in the sun



plasma on earth

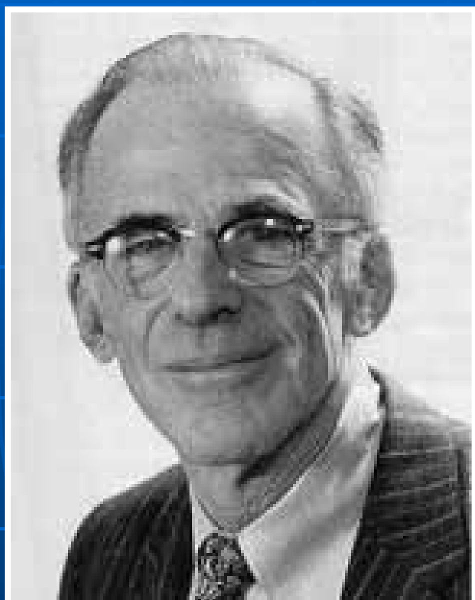
much, much smaller & tiny mass!

Origin and developments of helical systems

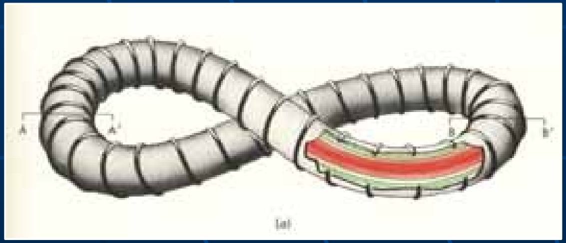
1951 (Princeton)

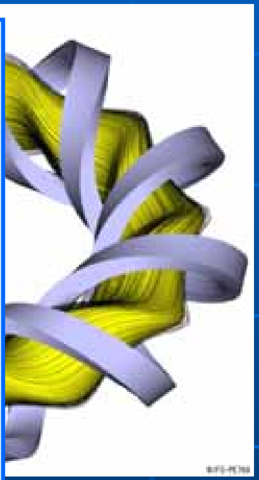
Confinement of toroidal plasma by external coil

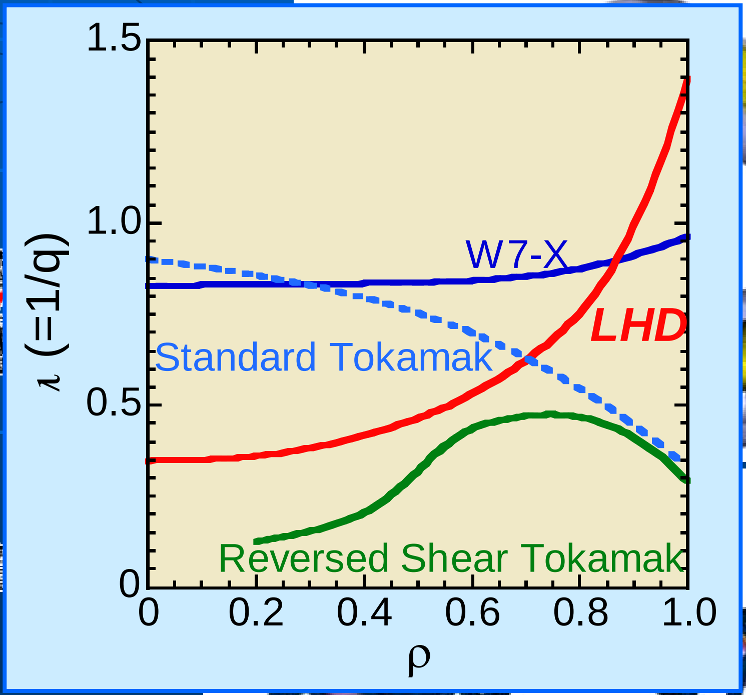
Design of the shape of coil and resultant rotational transform ?

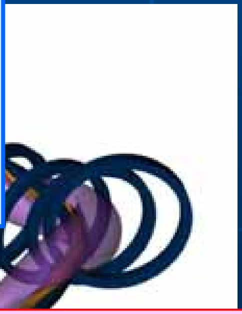


Lyman Spitzer Jr.





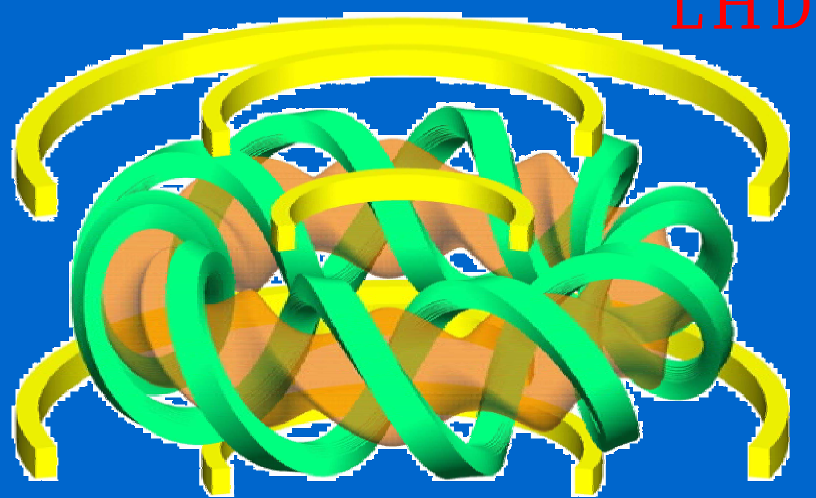




➔ Large flexibility & Optimization is necessary

Helical system and tokamak

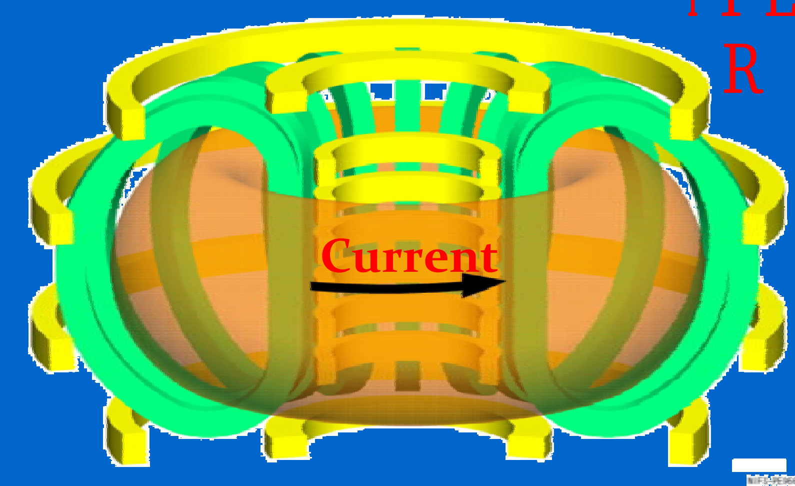
Helical system



- 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)

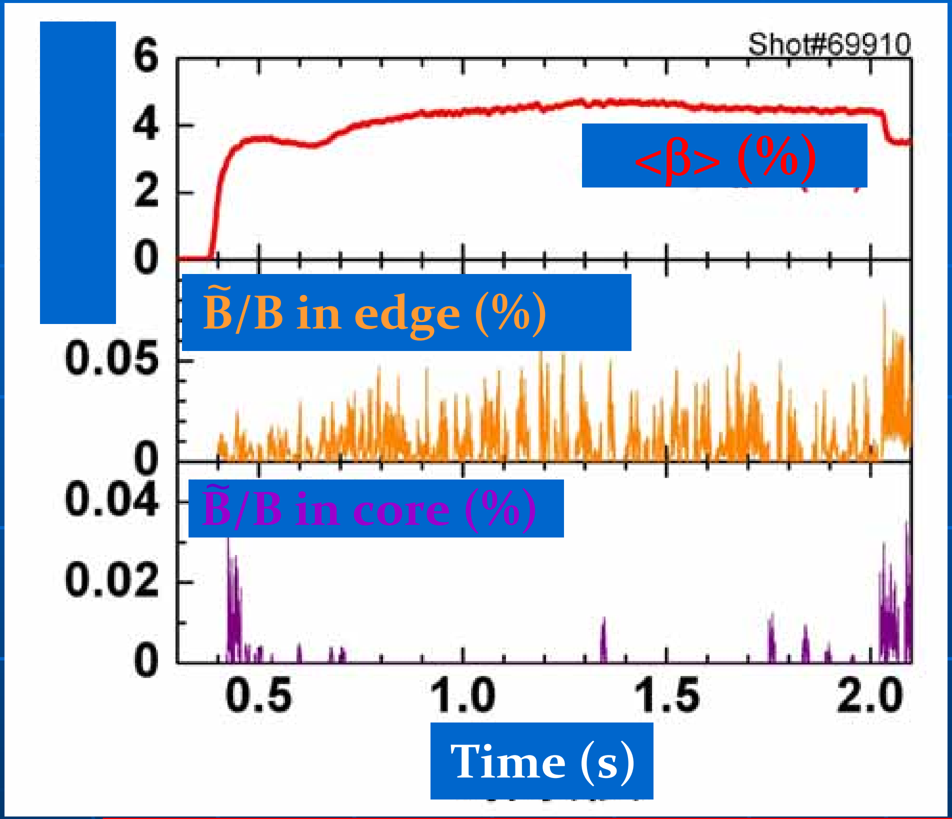
Tokamak



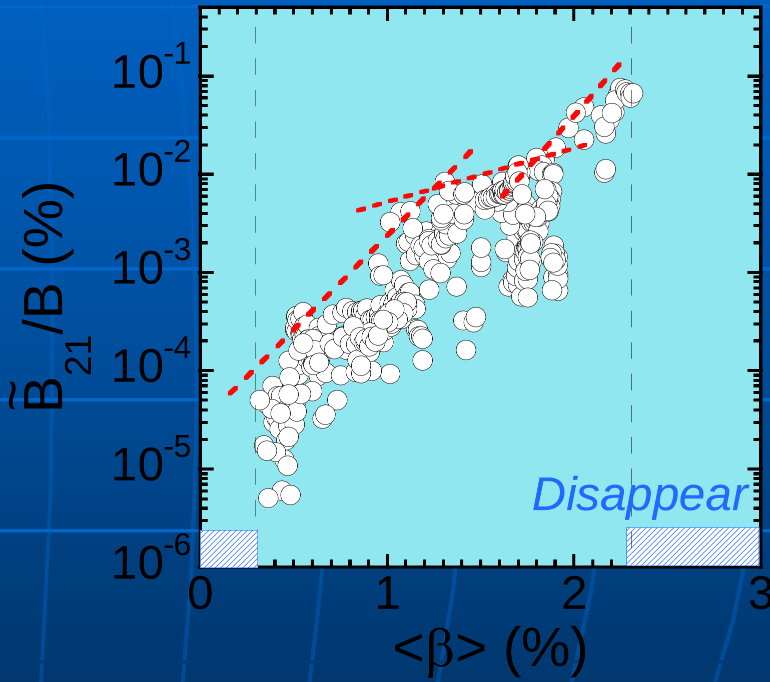
- Most popular and leading concept
- Currents induced in plasma forms confining magnetic field together with toroidal field
- Break-even condition has been achieved ➔ Ignition in ITER

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

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



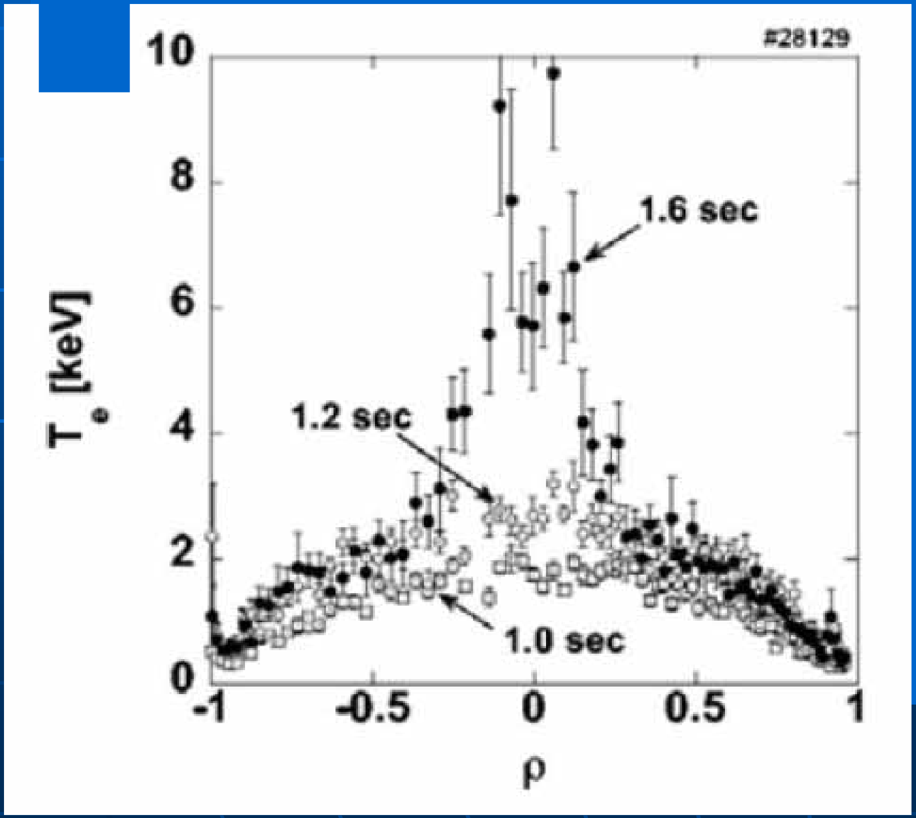
Magnetic fluctuation in plasma core



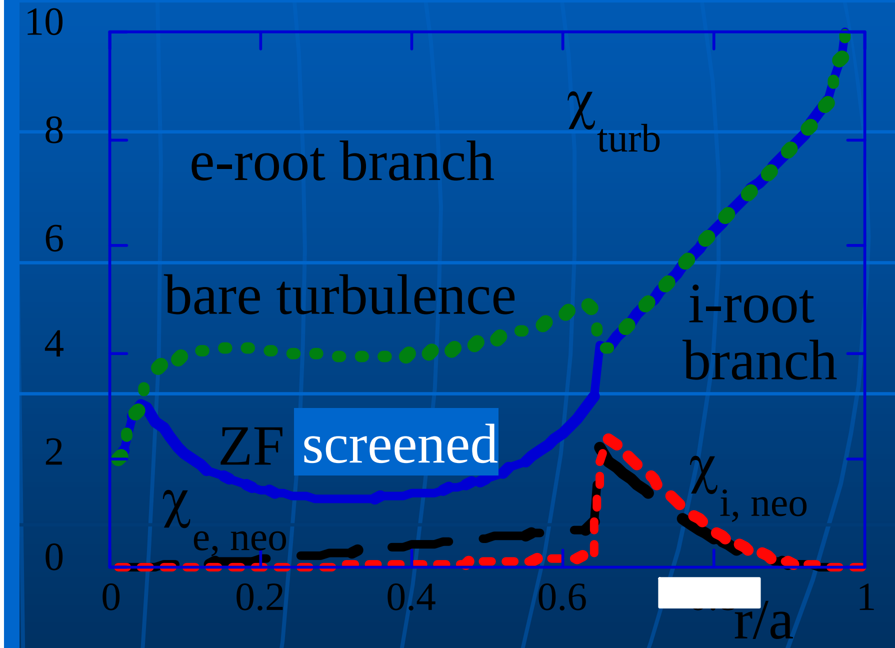
- ✓ Fluctuation does not grow to serious level
- ✓ Instability is generated but does not destruct confinement
  - ➔ Pressure driven instability is harmless
- ✓ Instability in the core is self-stabilized due to spontaneous generation of magnetic well

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

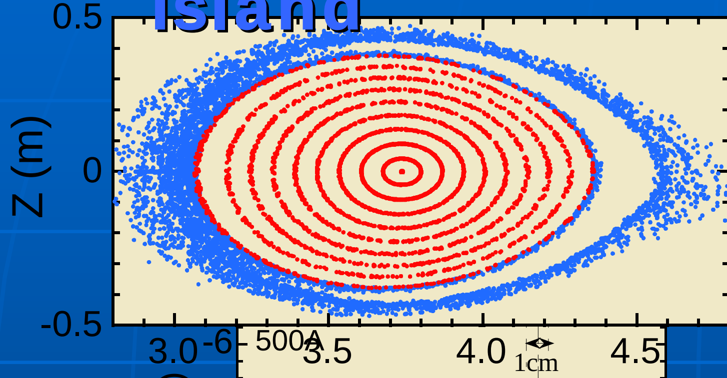


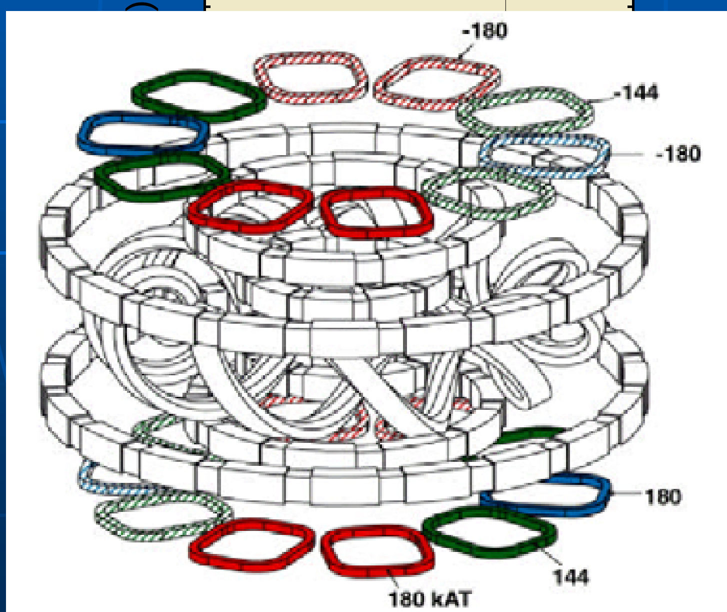
K.Ida et al., PRL 2003



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

Observation of spontaneous changes related to magnetic island





Enlargement of magnetic island

flat potential

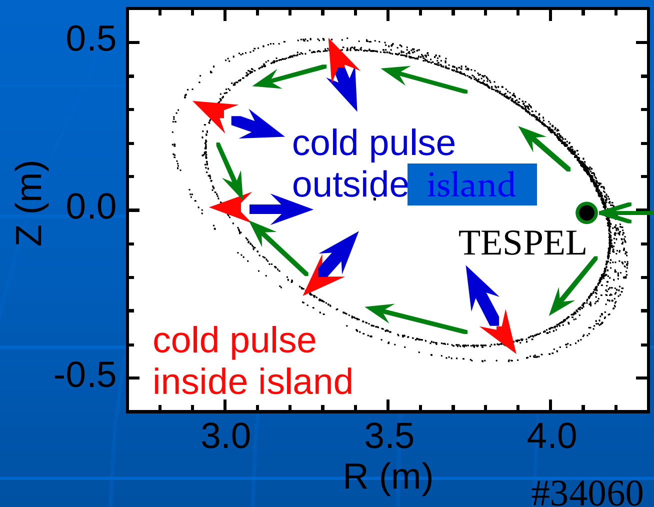
potential structure

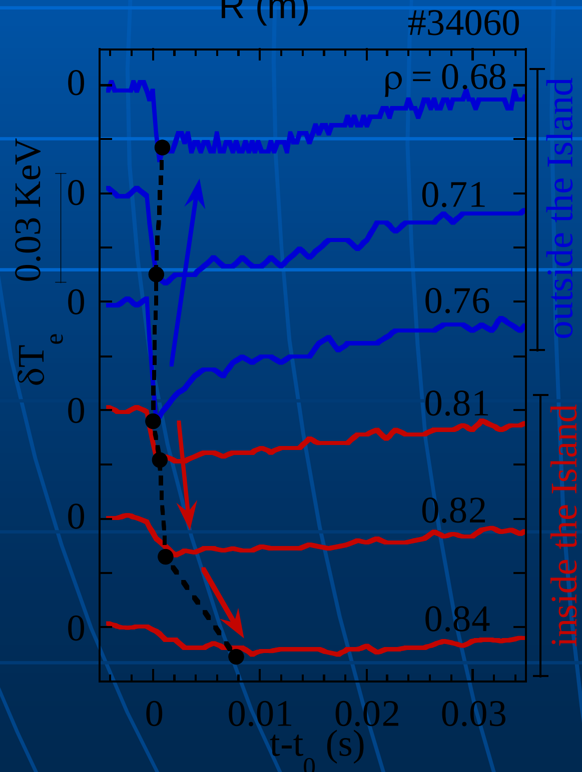
- Change of topology generates an interface
- Emergence of flow in magnetic island ➔ formation of E_r shear

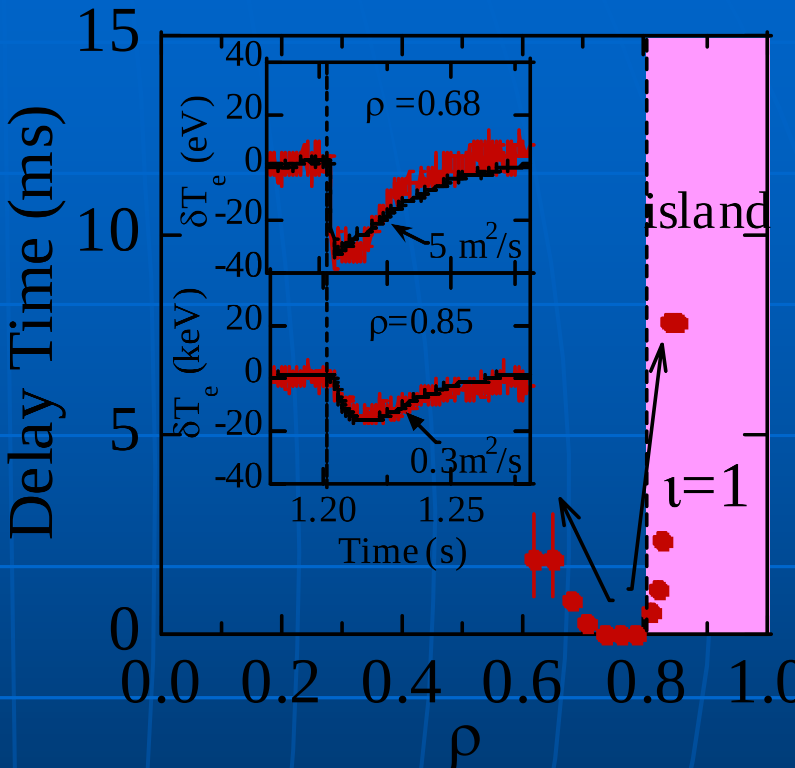
➔ Comprehensive and precise understanding of Neoclassical Tearing Mode (NTM)

K.Ida et al. PRL 2002

Transport inside magnetic island







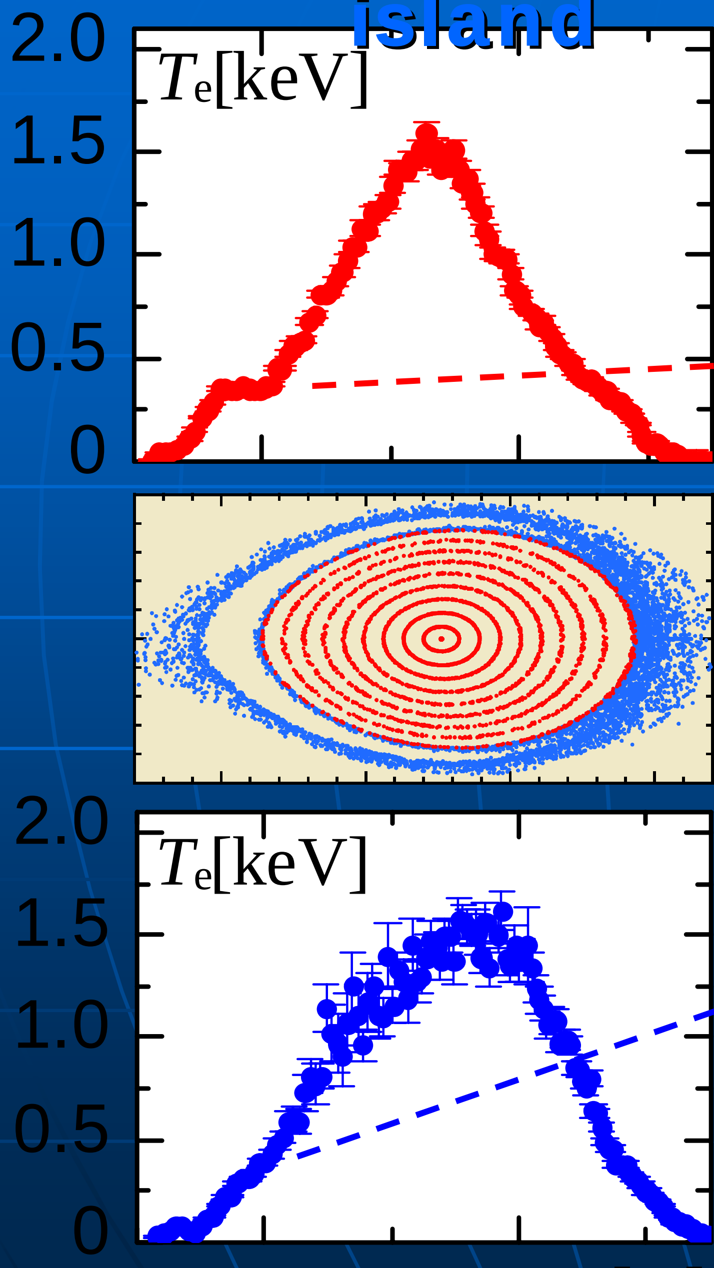
Inside magnetic island : $\chi = 0.3\ m^2/s$

Outside magnetic island : $\chi = 5\ m^2/s$

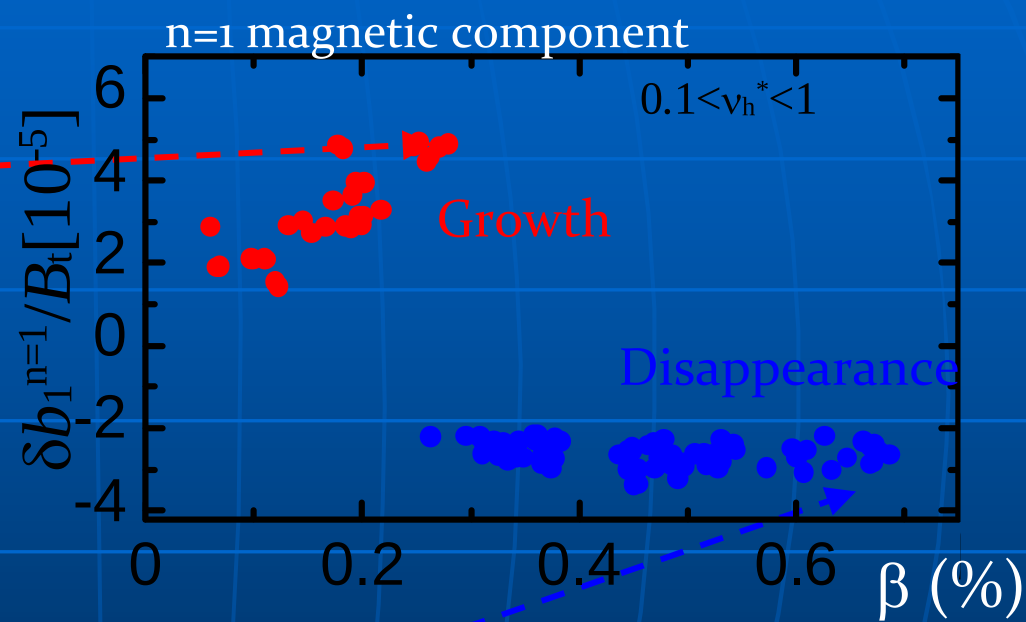
Significant reduction of transport is observed inside the magnetic island

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

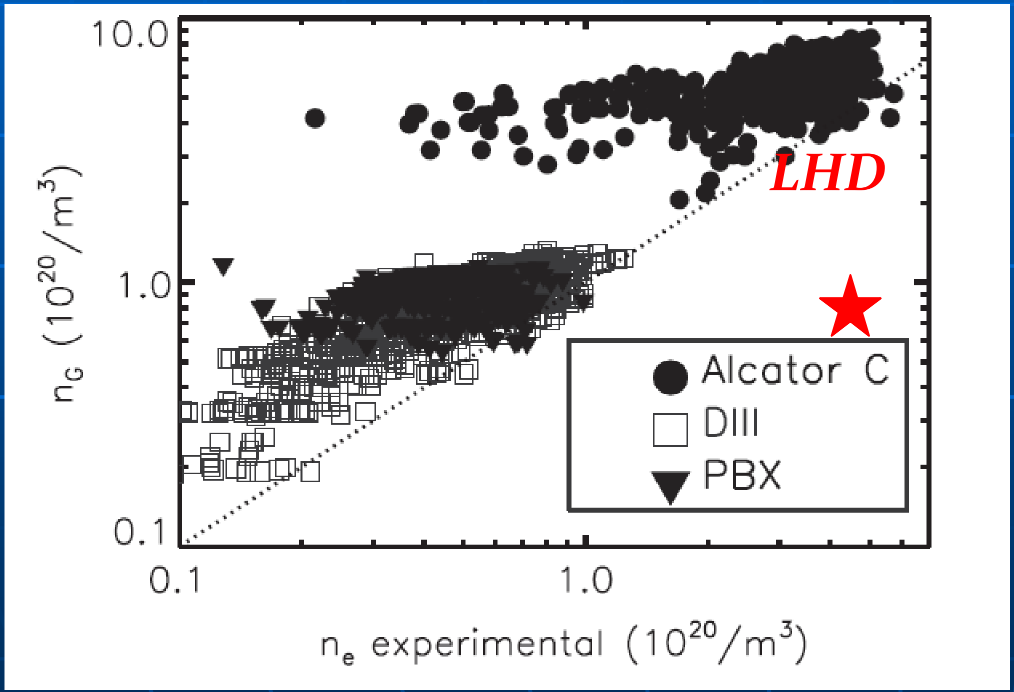
➔ Control of NTM

Y.Narushima et al. Nucl.Fusion 2008

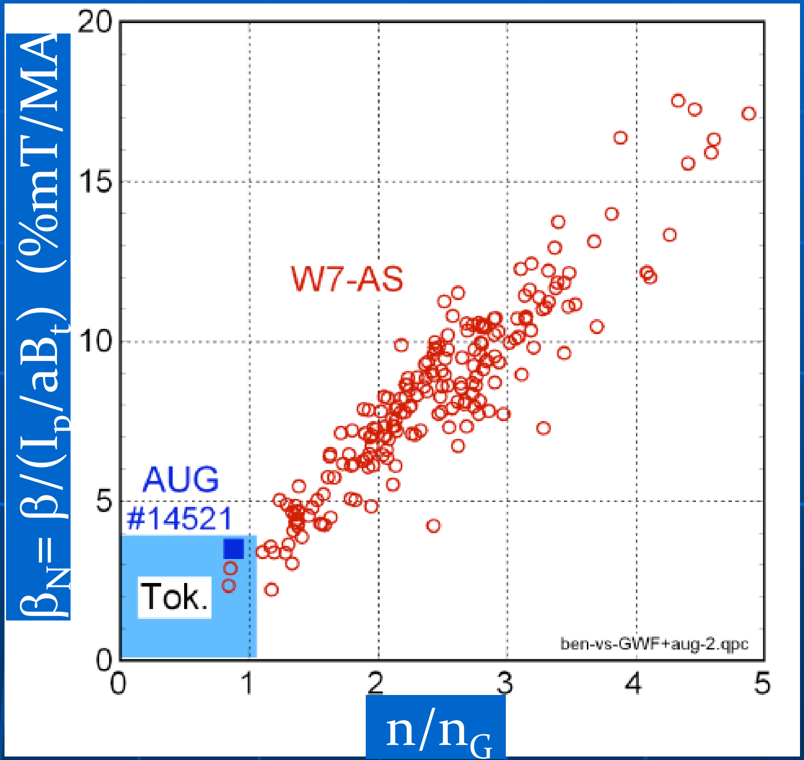
Helical systems can be operated in much higher density regime than tokamaks

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



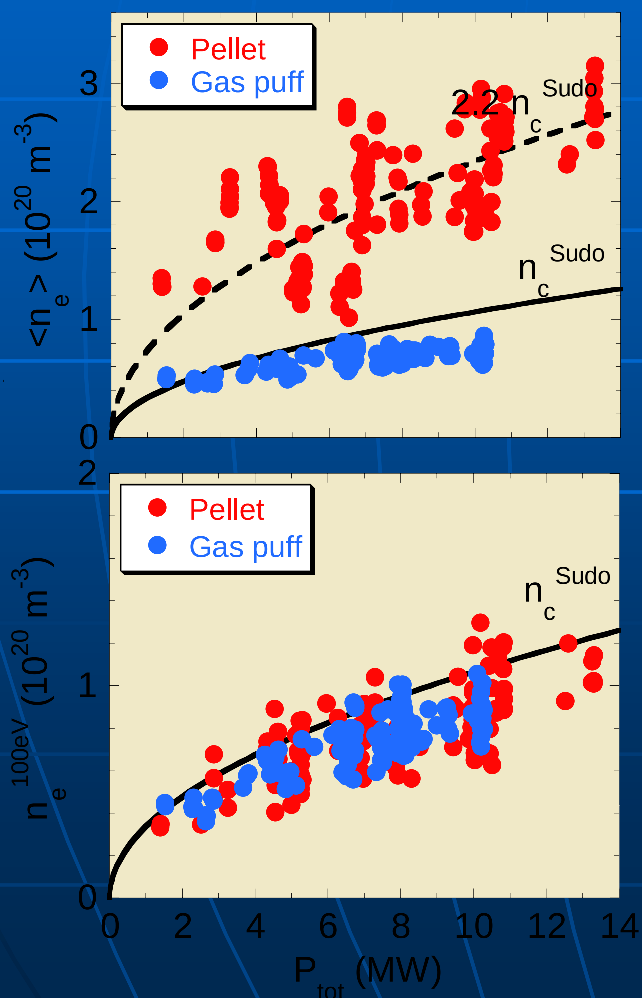
Courtesy of A.Weller

Clarification of underlying physics of density limit

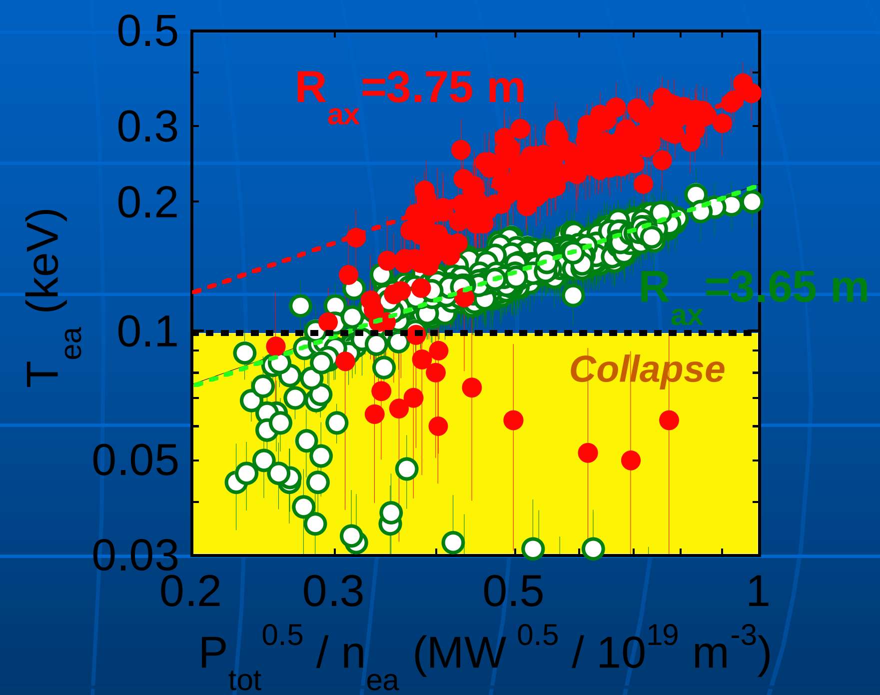
Density limit in helical systems is determined by radiation collapse, i.e., power balance

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 pr is enhanced by IDB

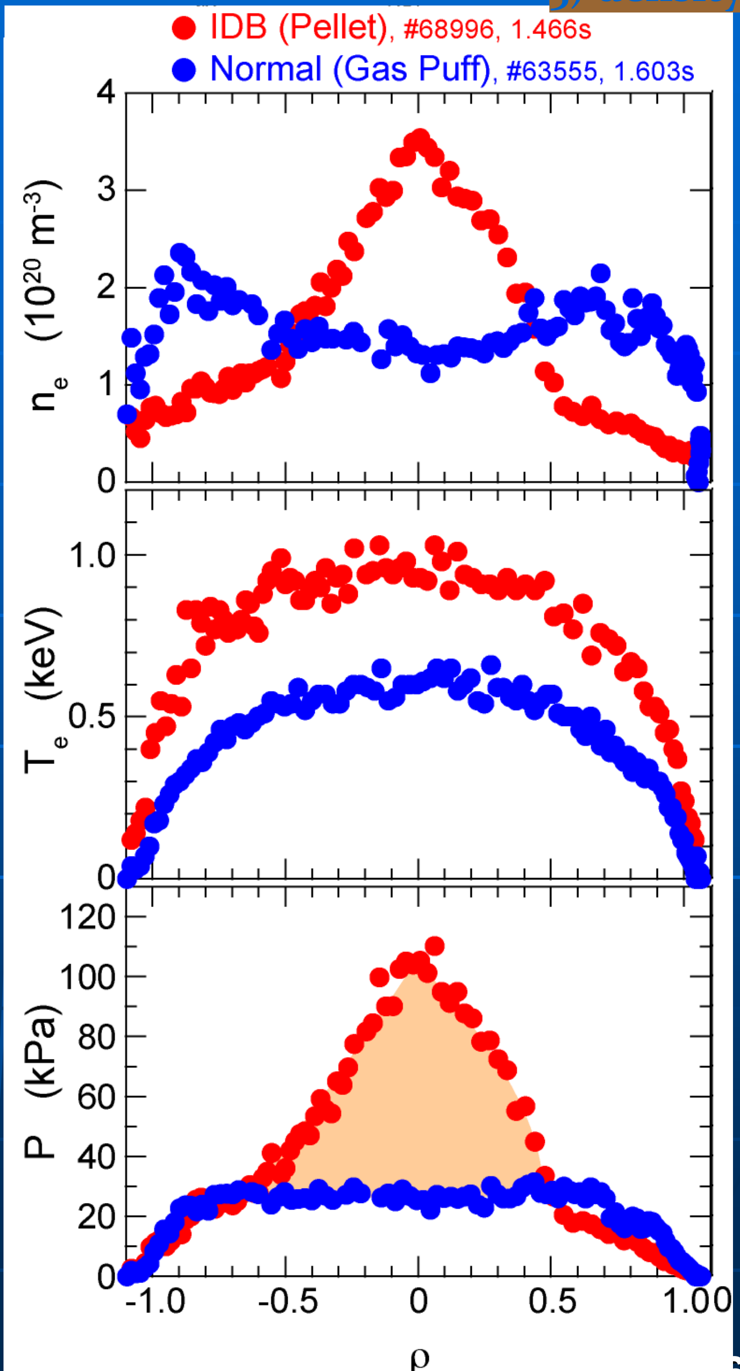
- ✓ Gas-fueled discharge :
  hollow density profile
- ✓ Density profile in the plasma with an IDB :
  highly peaked density profile
- ✓ Large Shafranov shift reaching a half the radius

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

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

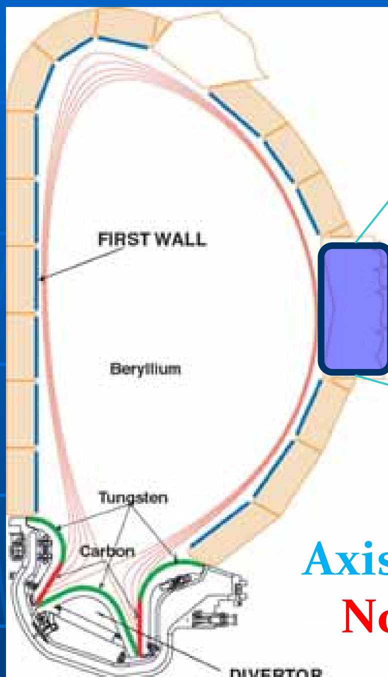
Central density reaches 1.1×10²¹m⁻³ at 2.5 T

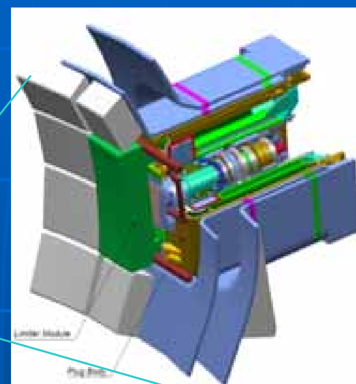
Note: Intermediate state between these two contrasting state does not exist



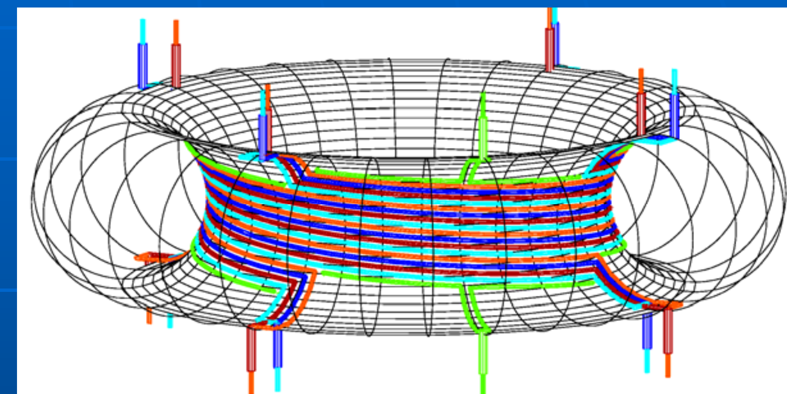
Edge plasma is essentially non-axi-symmetric even in tokamaks

Start-up with limiters in ITER



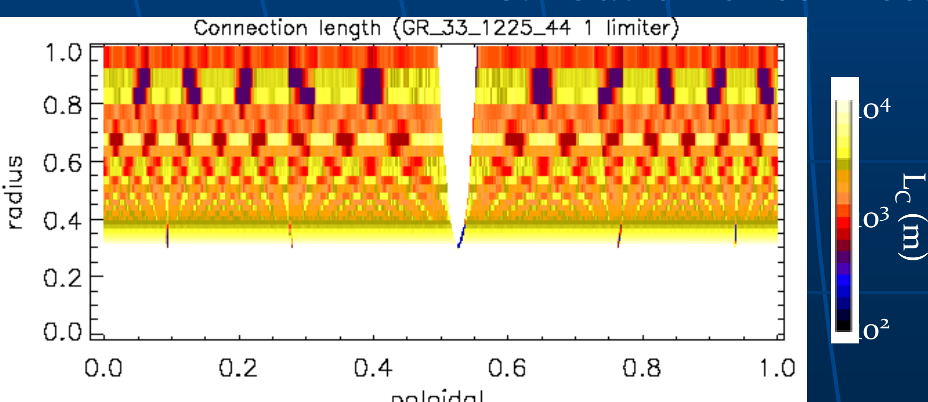


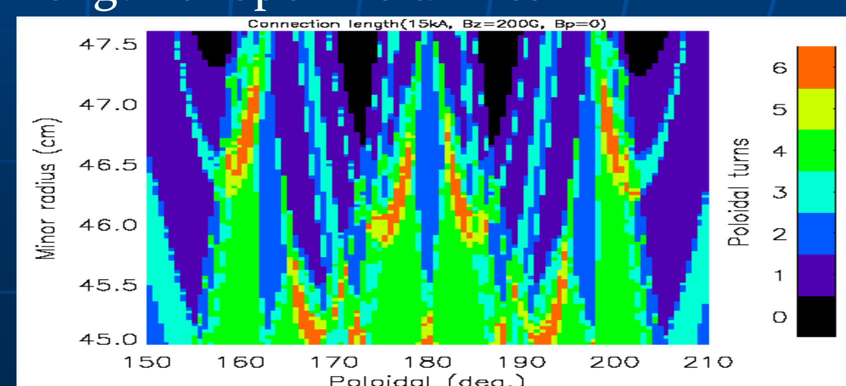
Resonant Magnetic Perturbation to control of ELM&RWM



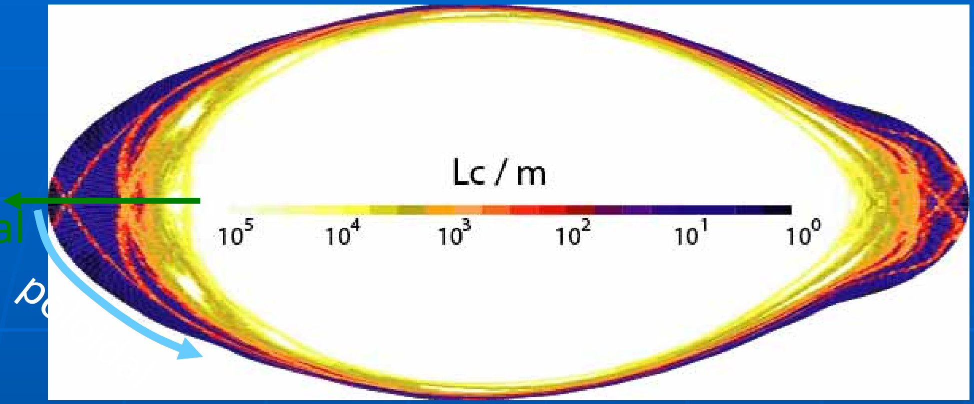
Axisymmetric field + Non-axisymmetric wall ⟺ Non-axisymmetric field + Axisymmetric wall

Distribution of connection length of open field lines



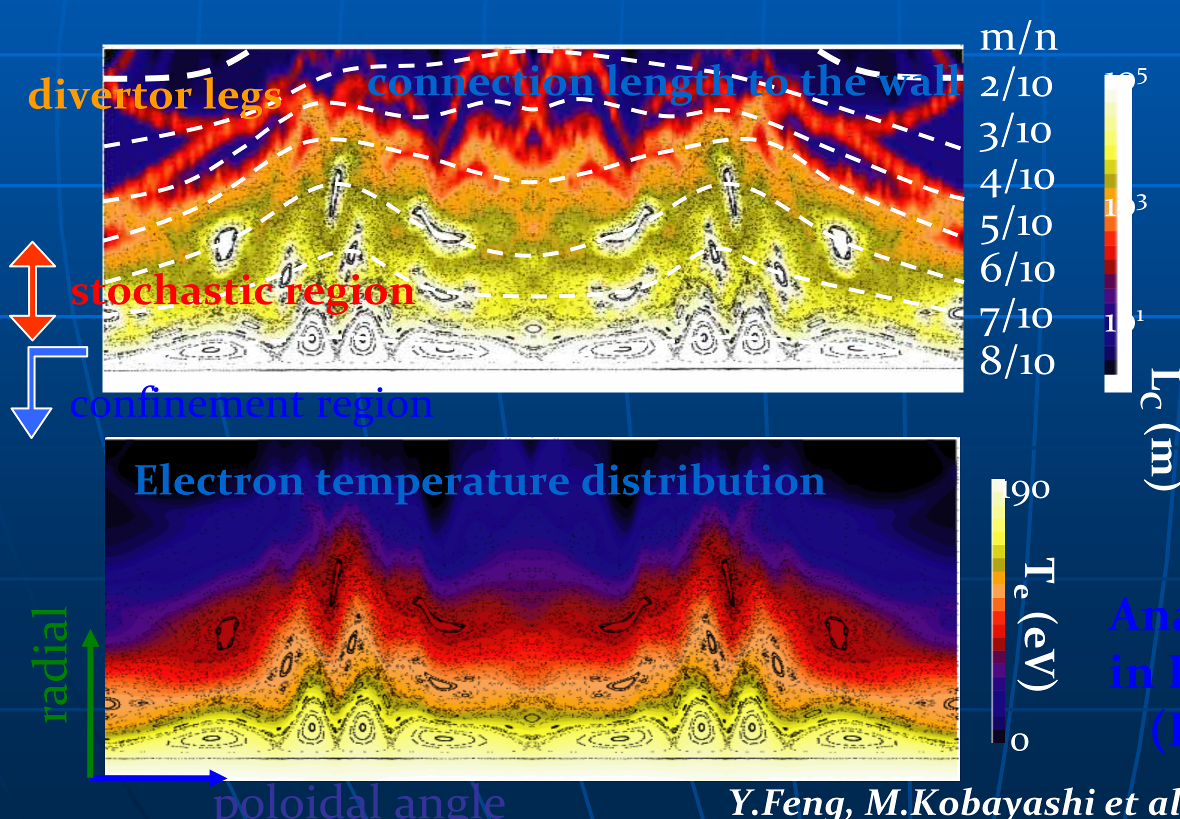


Research (Experience) in helical systems complements an idea and a scheme



Non-axisymmetric field
+ Non-axisymmetric wall

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



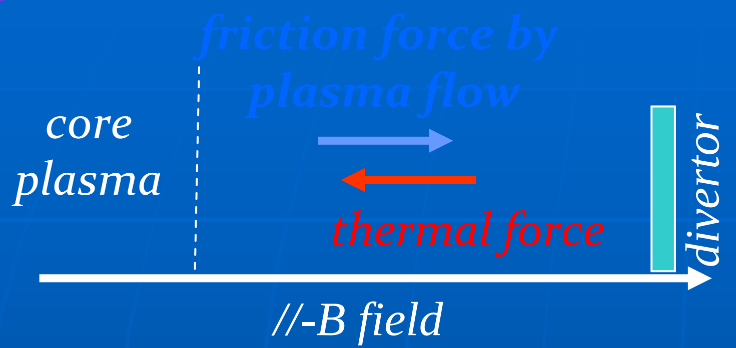
Stretch and fold due to magnetic shear and overlap of magnetic islands

- ✓ 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



//-impurity velocity

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

friction force by plasma flow ($V_{i/\!/}$)

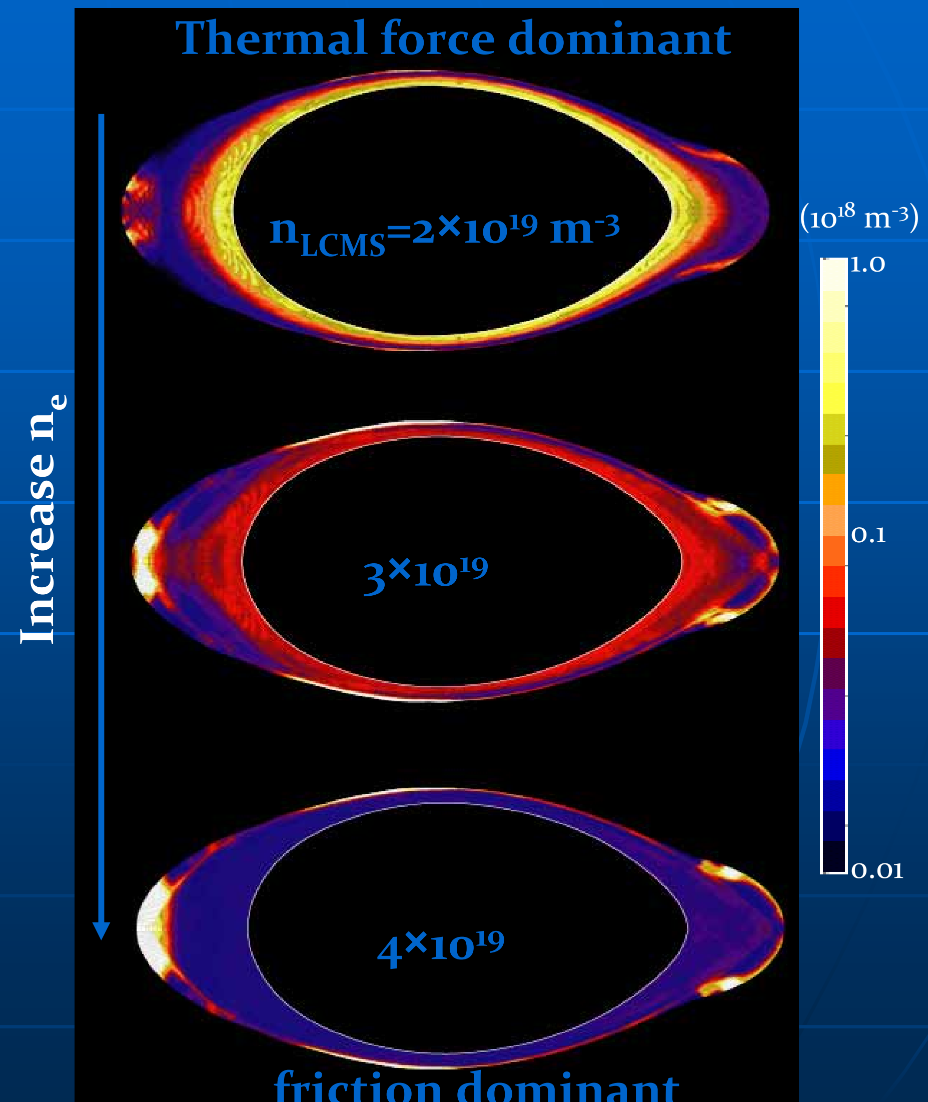
thermal force ($2.2\frac{\tau_{Zi}}{m_Z} Z^2 \nabla_{/\!/} T_i$)

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)



Name of Concept	Name	Main small-scale fluctuations	Generated global structure	Examples	Equations in fluid limit and fundamental drive
Electro-magnetic flow drive	$E \times B$ flow dynamo	EM and pressure fluctuations (drift waves)	$E \times B$ flow	Zonal flow in toroidal plasmas	MHD eq. Plasma response Pressure gradient
	MHD flow dynamo	EM and flow fluctuations	Magnetized flow	Bipolar jets	MHD eq. Gravitational force Coriolis force
Flow gene-ration	Neutral flow dynamo	Small-scale thermal convection	Zonal flow	Jobian belt Tidal current Jet stream, etc.	Navier-Stokes eq. Thermal convection Coriolis force
	Flow structure formation	Small-scale convection	Structured flow	Swirling flow, Asymmetry in pipe flow	Navier-Stokes eq. Drive of axial flow
Magnetic dynamo	Dynamo	Fluid motion (thermal convection)	Magnetic field	Geodynamo Solar dynamo	MHD eq. Thermal convection Coriolis force
	Magnetic structure formation	Magnetic fluctuations (kink, tearing)	Magnetic field	RFP torus	MHD eq. External toroidal current

Summary

- Plasmas are energetic and inevitably turbulent
- Complex and diversified dynamics with different temporal and special scales form structure

Self-organize global structure

State without a global structure
Uniform turbulent state

Choice:
highlight of open non-equilibirum system

Maximum entropy
Thermal death

- Confinement improvement is a product of control of this choice
- Non-linear phenomena in plasmas can be controlled by engineering
- Big challenge : Establishment of a control scheme for an autonomous system (plasmas)
- Fusion research is a leading pilot for the frontier of science and technology

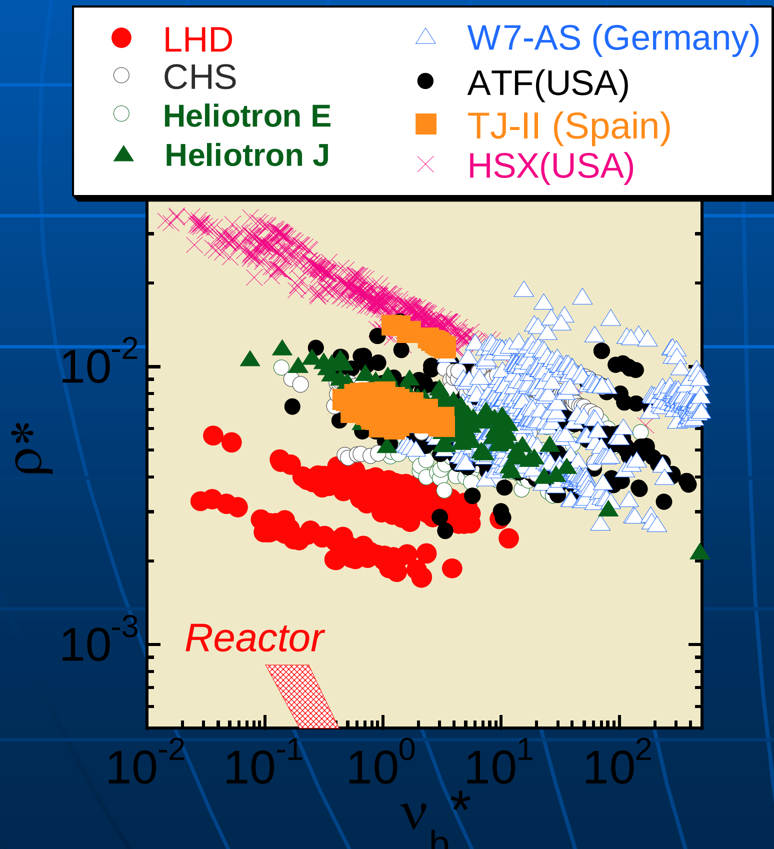
How LHD plasmas are approaching fusion relevant region

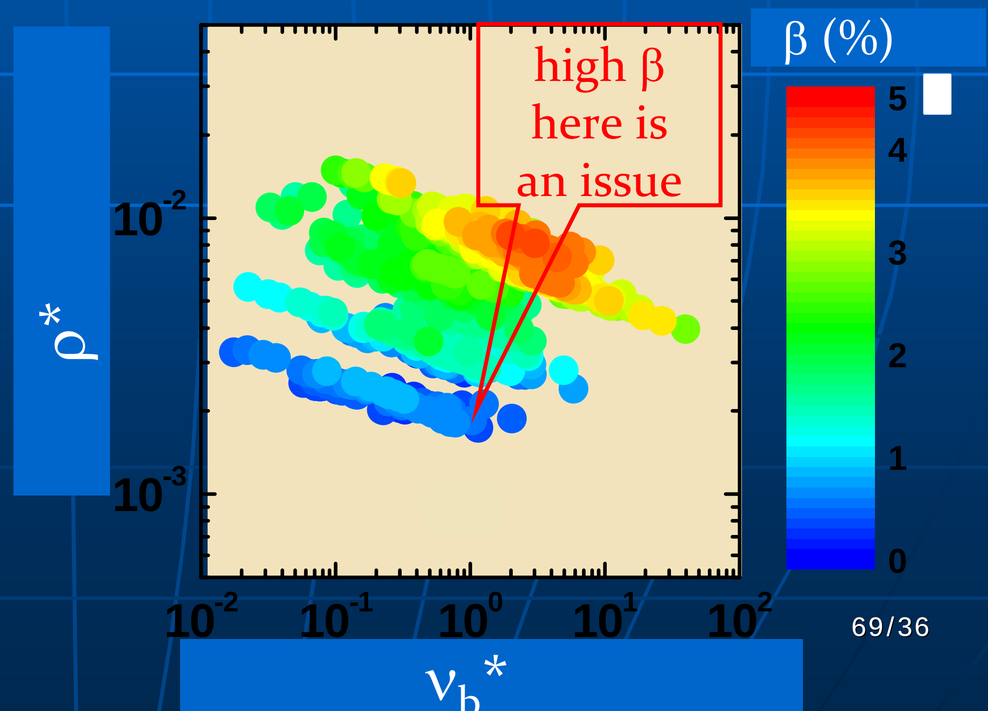
Three major essential non-dimensional parameter in high temperature plasma physics

1. Normalized gyro radius ρ*
2. Collisionality ν*
3. Beta β

➔ Plasmas with the same these parameters have the same physical property

LHD Experiment
ρ* needs factor of two extrapolation
ν*already lies in fusion relevant
High β in low ρ* and ν* is an issue
🡐 can be done by confinement improvement and increase of heating power





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.