Joint ICTP-IAEA College on Advanced Plasma Physics
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Structure /Dynamics of Fluctuation in Fusion Plasmas

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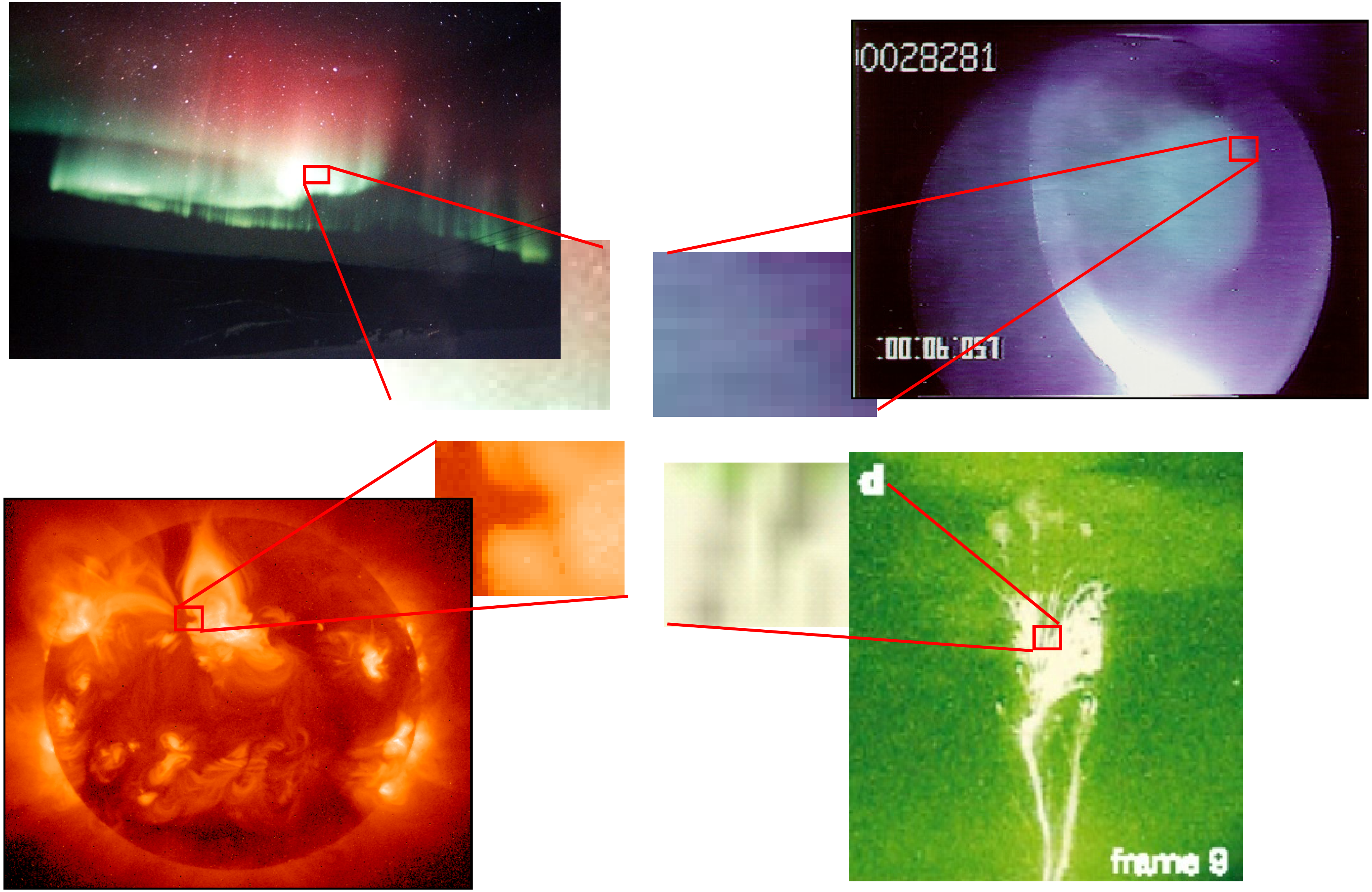
- August 19 : Structure/dynamics of fluctuations in fusion plasmas
- August 19 : Nonlinear instability and plasma dynamics
- August 21 : Interaction between different scales

Group discussion (fusion) :

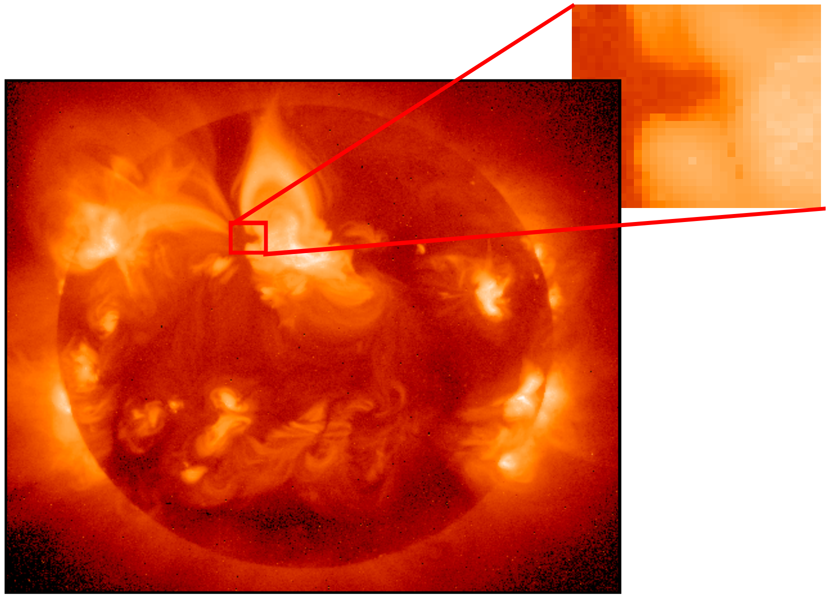
✓ More information for confinement including experiments, why we need to focus on fluctuation, e.g. what is fluctuation, how micro-turbulence is related to global confinement

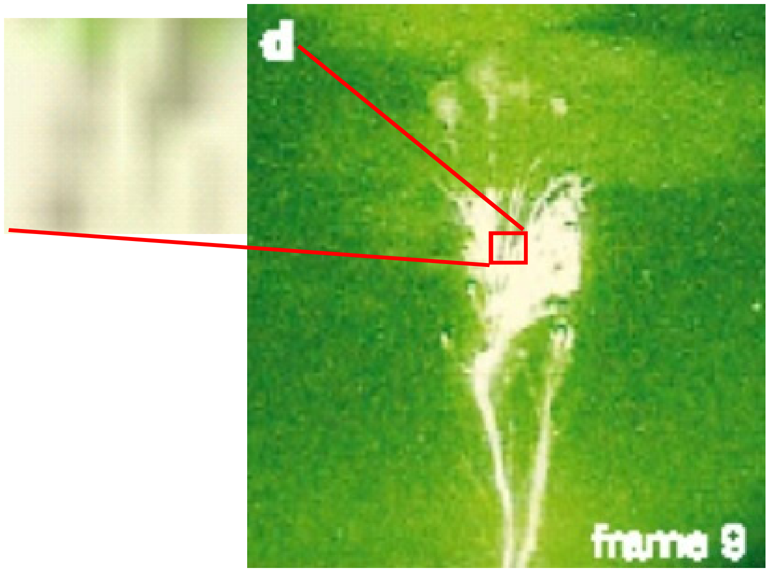
Understanding plasmas is to understand nature



Understanding plasmas is to understand nature

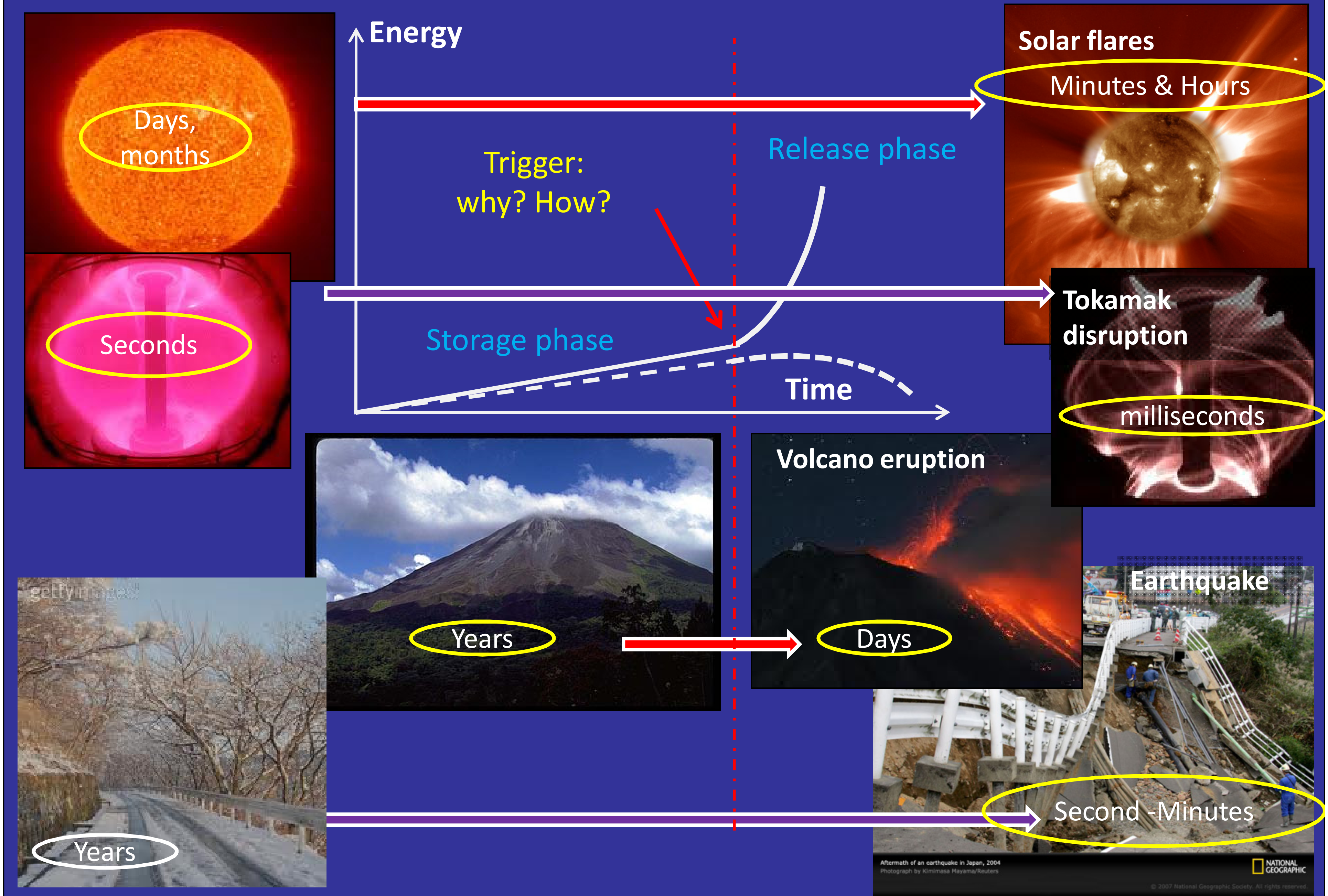
- ✓ Looking at a "part", it is uncertain existence, but looing at a "whole" far away from the object, it exhibit clear and beautiful "structure" and "dynamics" with no specific symmetry.
- ✓ Careful investigation is necessary in choosing proper scales in "space" and "time"
- ✓ "Small scale structure" and "large scale structure" are incorporated through "long range force" and "short range force".



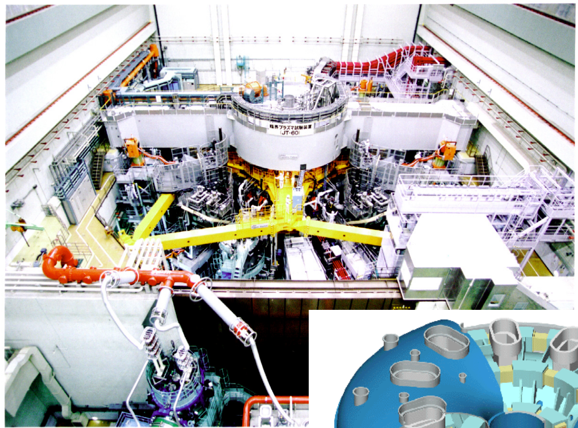


sudden events in nature

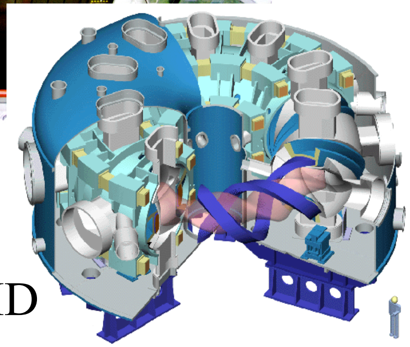
Courtesy of Dr. Miho Janvier



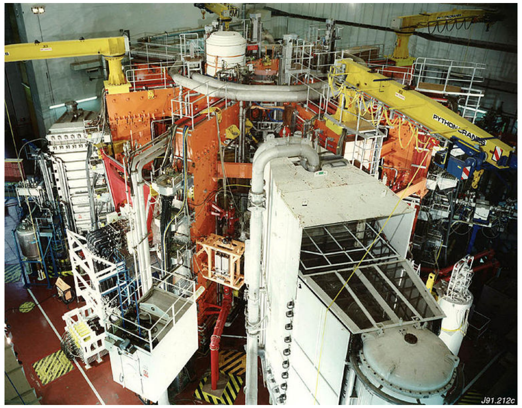
Magnetic fields in fusion device



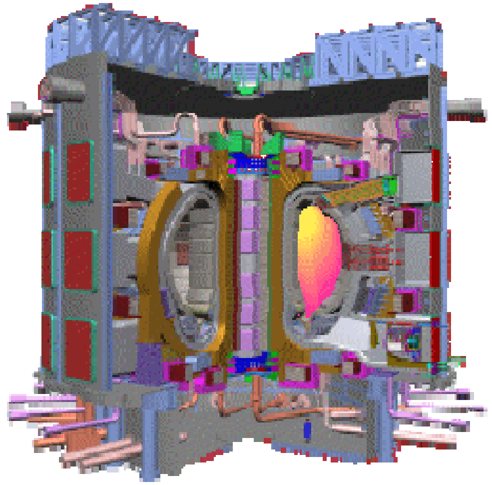
JT-60U



LHD



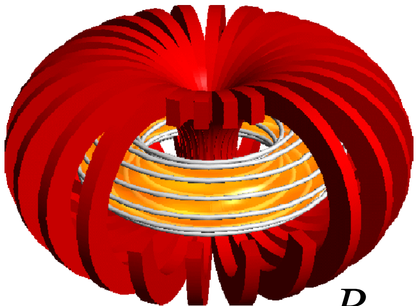
Joint European Torus (JET)



IETR

$$\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He}(3.52\mathrm{MeV}) + \mathrm{n}(14.6\mathrm{MeV})$$

Limited volume covered by a infinite set of nested magnetic surface (magnetic cage)

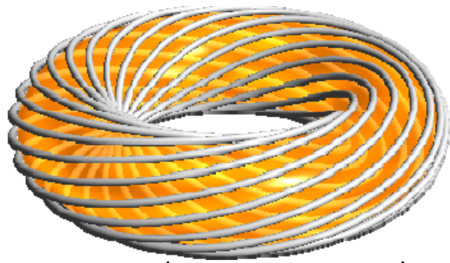


B_T

+

B_P

→



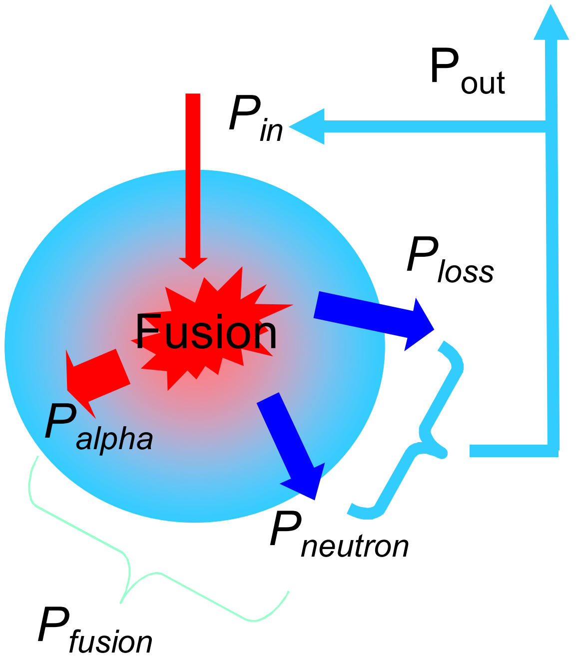
$$\boldsymbol{B} = \left(B_T \hat{\varphi} + B_P \hat{\theta}\right)$$

Toroidal magnetic field

Poloidal magnetic field

Tilted Magnetic cage

Schedule and key aspect



$$Q \equiv \frac{P_{fusion}}{P_{in}} \sim \frac{\left\langle n^2 \langle \sigma v \rangle E_f \right\rangle}{\langle nT \rangle / \tau_E} \sim (n\tau_E)\left(\frac{\langle \sigma v \rangle E_f}{T}\right)$$

key aspect :

- high pressure state in limited volume
  (not free space, cf. space/universe)
  → high fluctuation level inevitable as Q increases

- Open system, but high autonomous system
  as Q increases

How we can understand and explore control methodology of high pressure plasma medium with a high fluctuation level, maintaining the autonomous nature

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Group discussion (fusion) :

✓ Larger devise (lower fluctuation), which promises stable operation

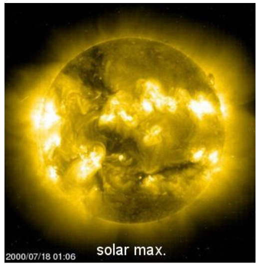
✓ Smaller device (higher fluctuation), but, uncertain in stable operation

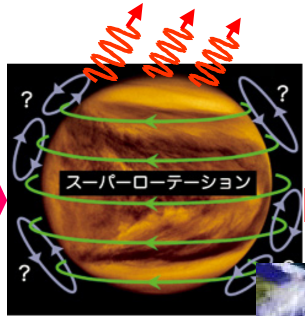
Planetary environment and fusion plasmas

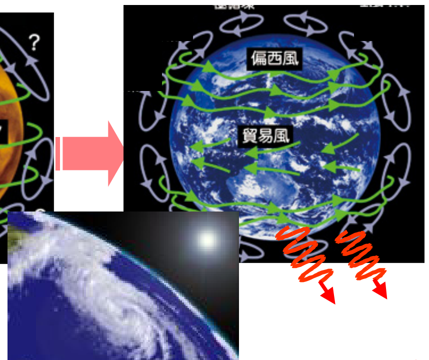
World dominated by

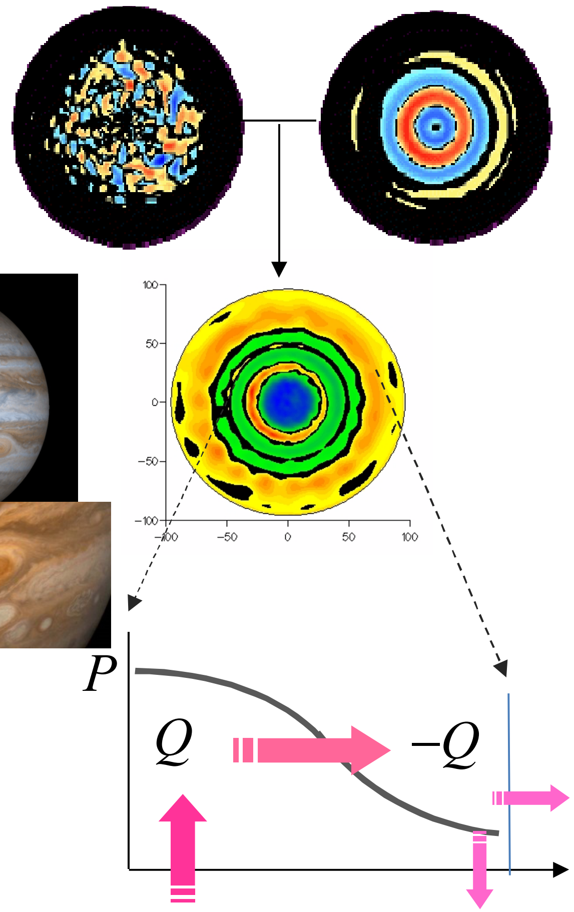
- Micro-turbulences $E^{(turb)}$
- Macro-flows $E^{(ZF)}$
  (sometime with low mode)
- Large scale structure $E^{(LSS)}$

Micro-scale vortices are embedded in macro-scale flows

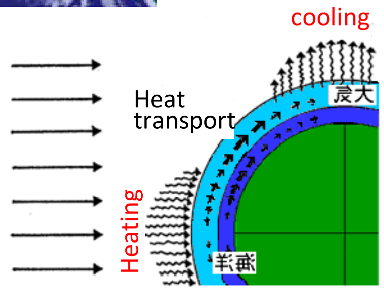








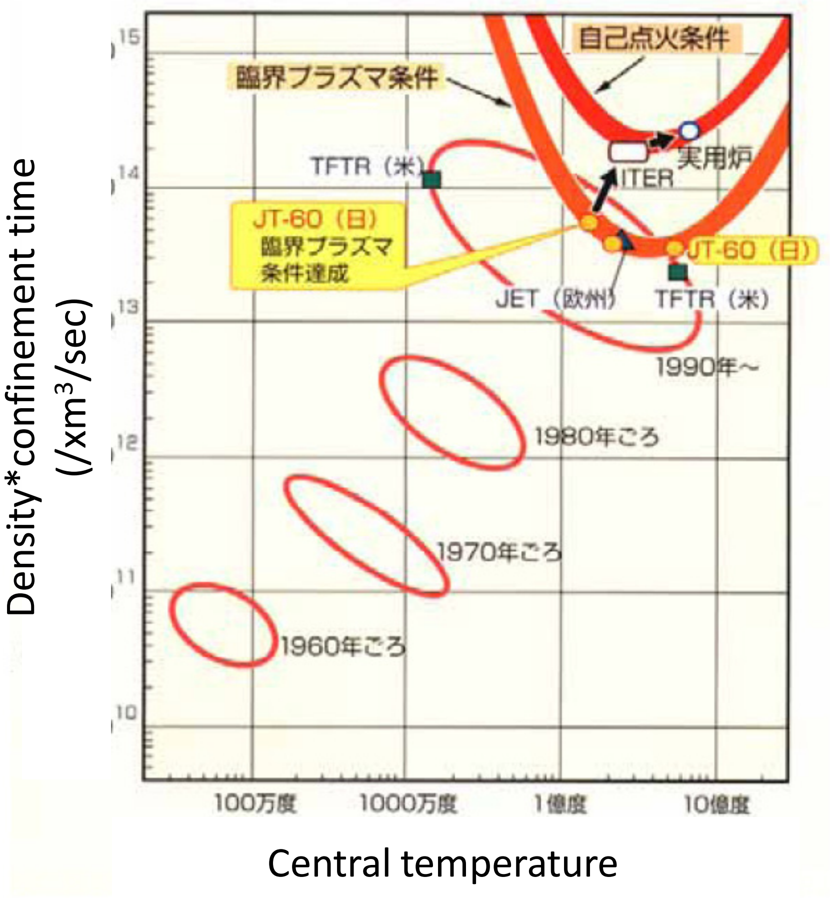
No external heating
Fully self-sustained

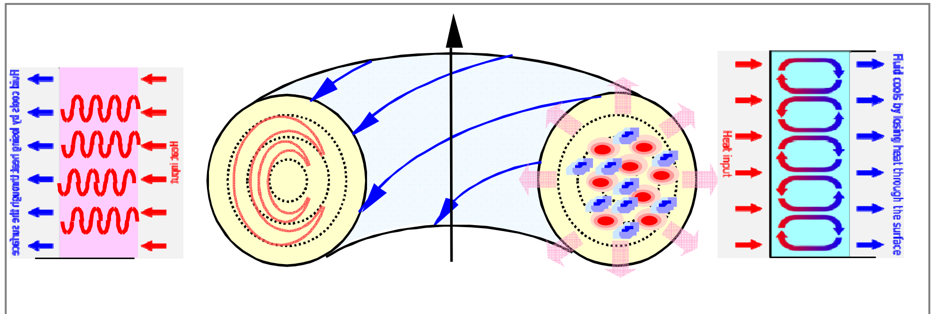


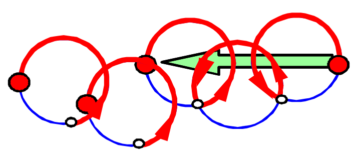
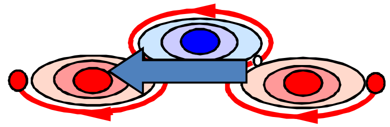
$$\eta_{ZF} \equiv \frac{E^{(ZF)}}{E^{(tot)} + E^{(ZF)} + E^{(LSS)}}$$

$$\eta_{ZF} \equiv \frac{E^{(ZF)}\tau_{ZF}}{E^{(turb)}\tau_t + E^{(ZF)}\tau_{ZF} + E^{(LSS)}\tau_{LSS}}$$

What is the role of ZF and LSS on transport ?





Collisional transport	Turbulent transport
 $\Delta x \sim \rho_p$ $\tau \sim \tau_{coll}$ Particle dynamics in a given field	 $\Delta x \sim \Delta r$ $\tau \sim \tau_{auto}$ Particle dynamics in a self-consistent field
$D \propto \frac{n}{B^2 T^{1/2}}$	$D \propto \frac{T}{B}$

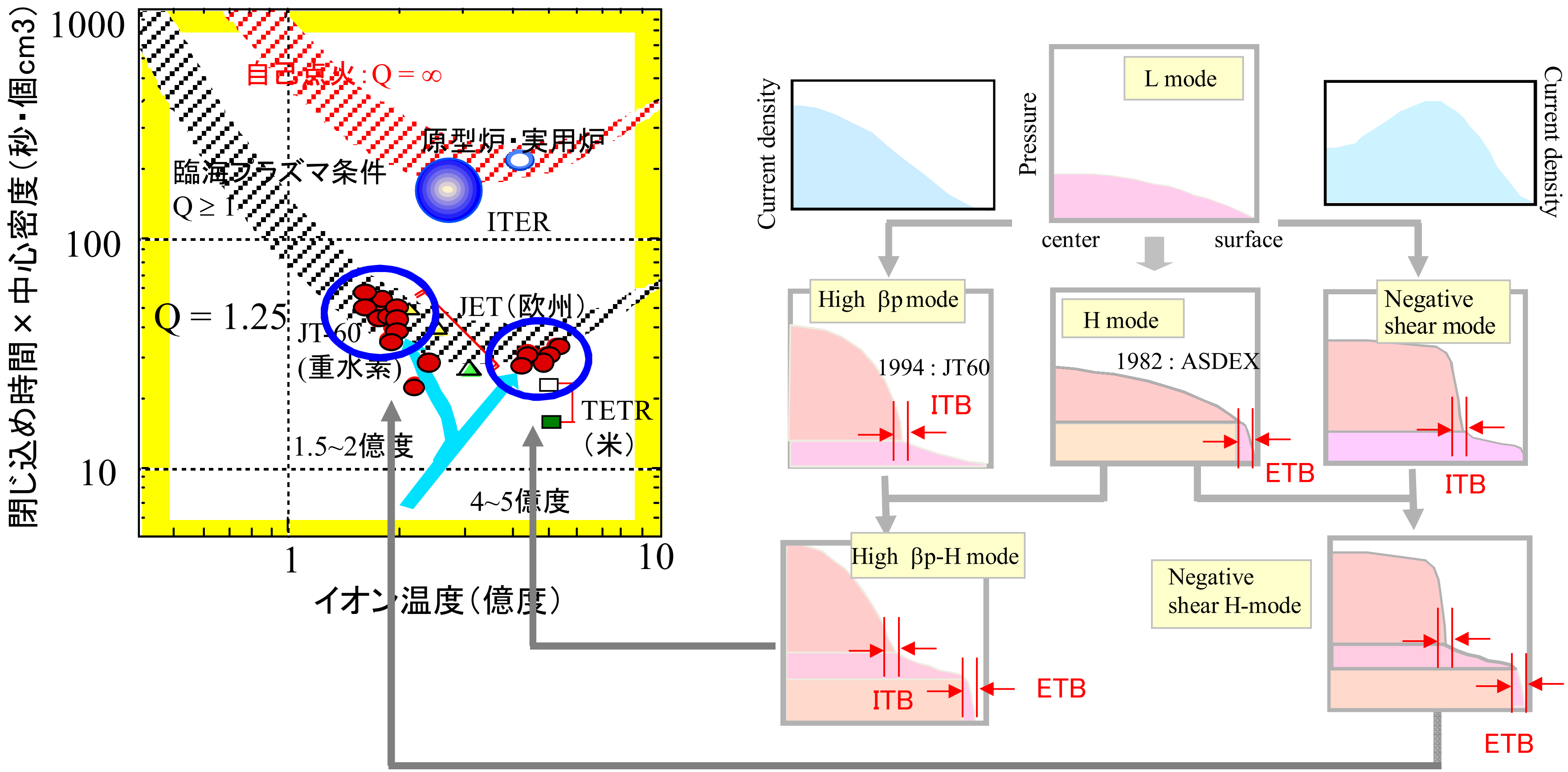
$$Q \sim n\tau_E T$$

Serious challenge

Opposite dependence to the goal

(Bohm scaling)

“Selection of pass” and structure formation in high pressure state leading to burn, i.e. Q~1



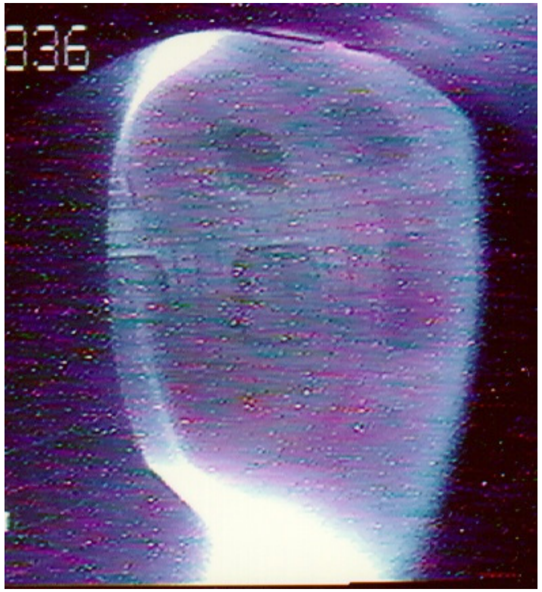
JT-60 High Performance Shot

June 11, (June 25 :press) 1998
Shot number E31872 , $Q_{DT} \sim 1.25$

- Reversed magnetic shear configuration
- Internal transport barrier formation

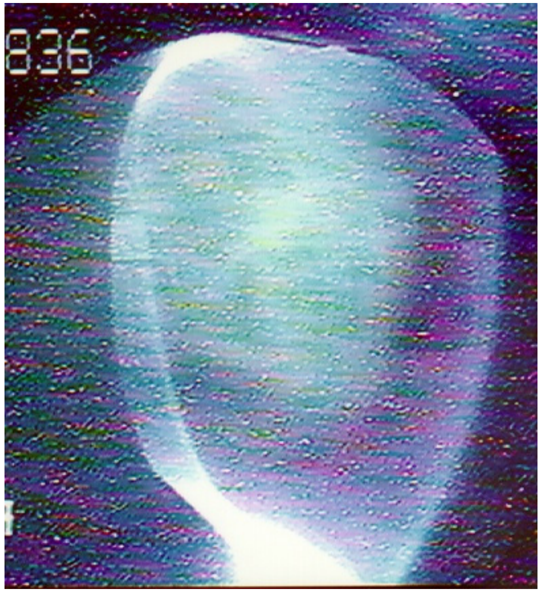
[*Ishida, et al.,IAEA,'98, NF, '99*]

4.24 sec



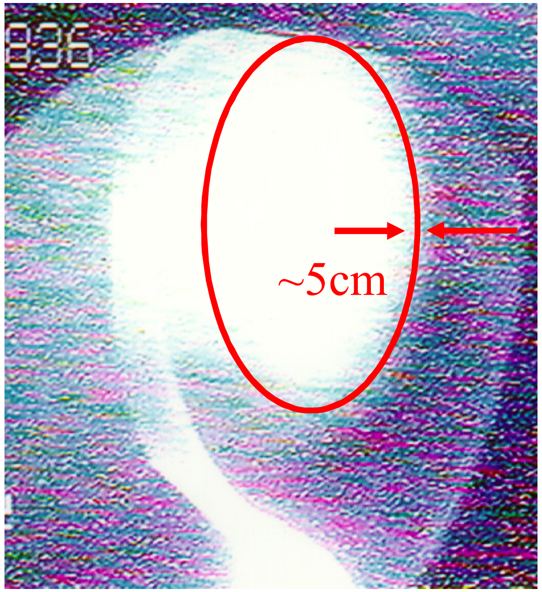
Tem. : 7 keV
Den. : 1.5x1013／cm3

4.82 sec



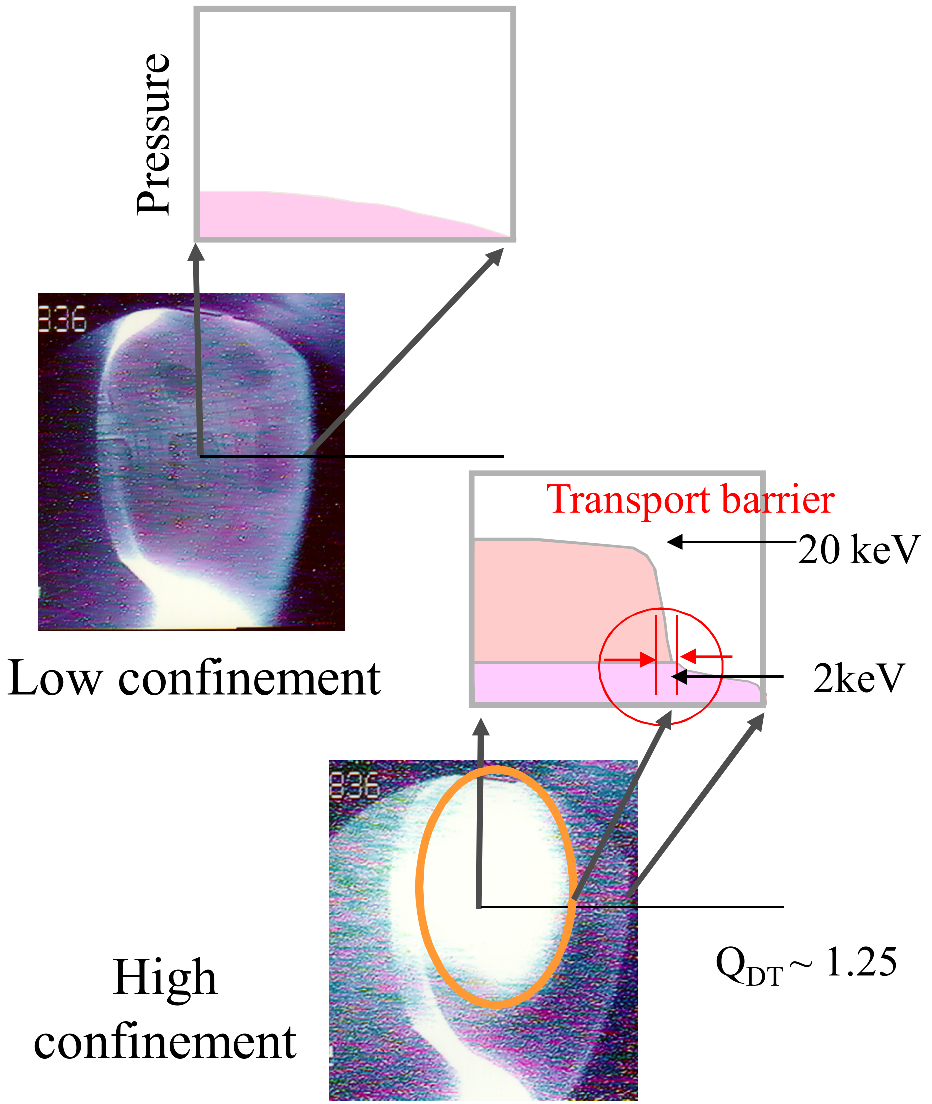
Tem. : 14 keV
Den. : 3.1x1013／cm3

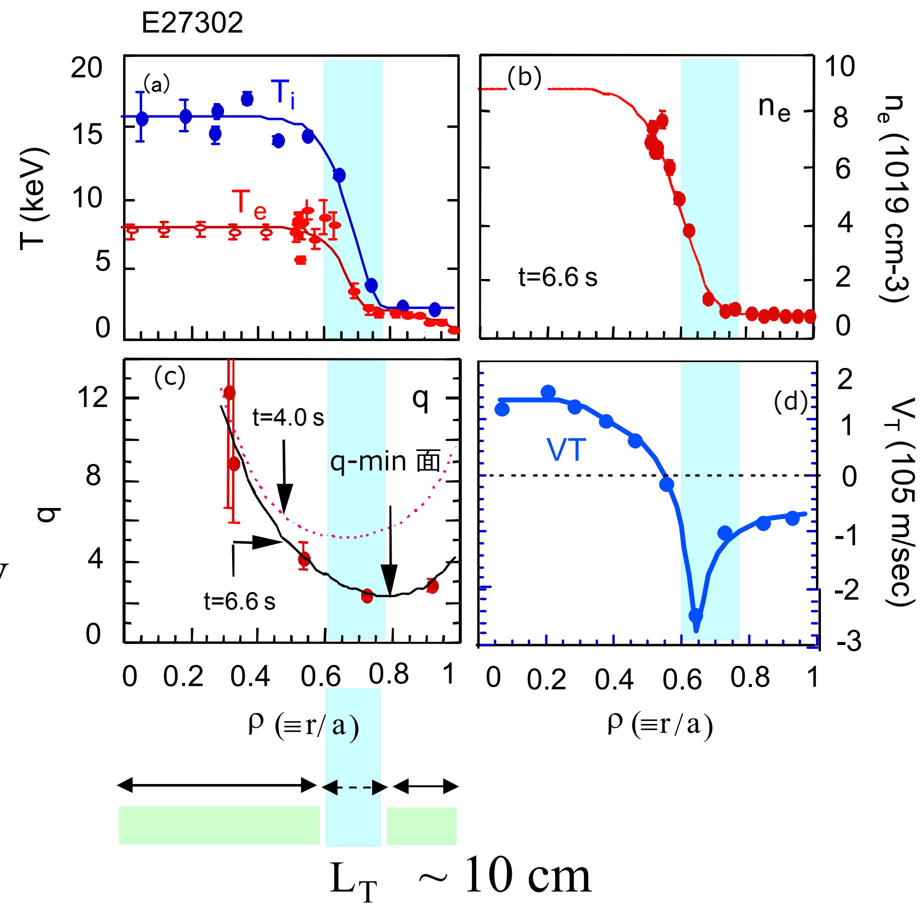
6.43 sec



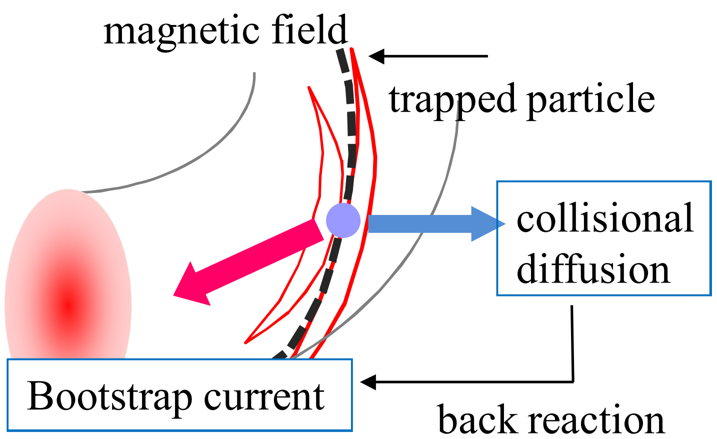
Tem. : 19 keV
Den. : 4.8x1013／cm3

High performance plasma (internal transport barrier : ITB) achieved by having a structure

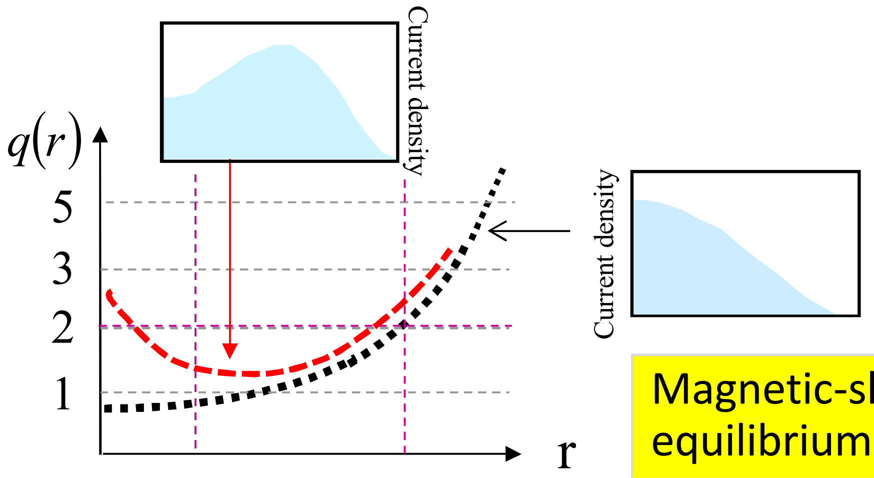


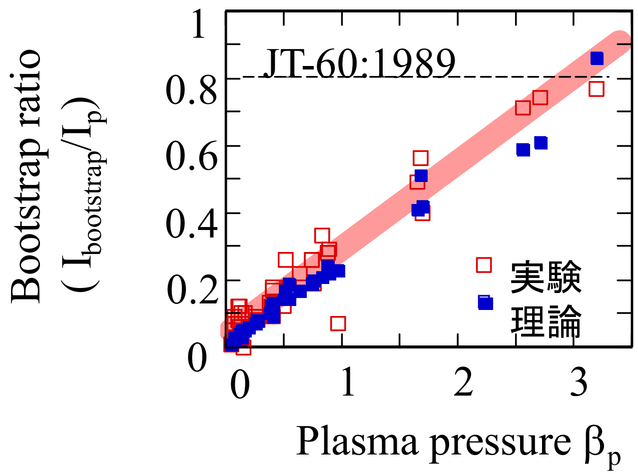


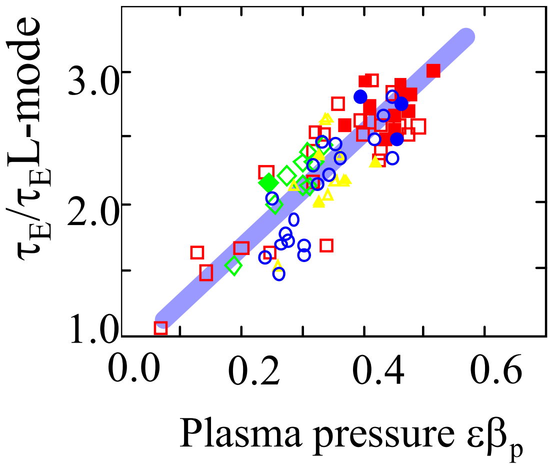
Synergetic relation between self-sustainment of current and increase of confinement (self-organization realized)



$$J_b = \frac{\sqrt{\varepsilon}}{B_p}\frac{dp}{dp} \qquad \frac{I_{BS}}{I_{total}} \propto \sqrt{\varepsilon}\beta_p \qquad \left(\beta_p \equiv \frac{p}{B_p^2/2\mu_0}\right)$$







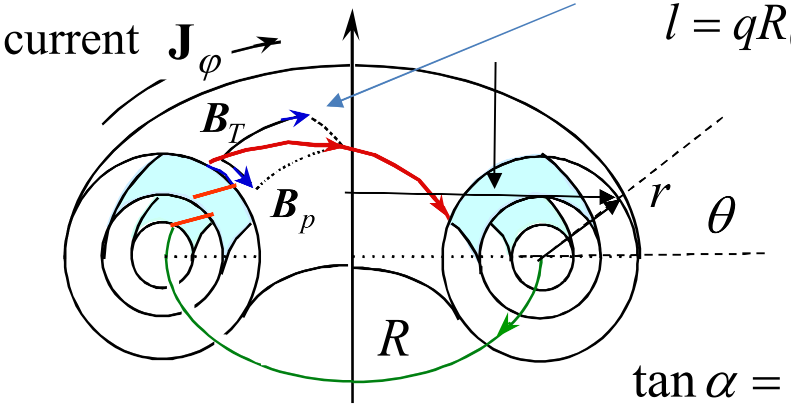
Magnetic-shear reversal equilibrium established → Should be unstable from the linear aspect

Magnetic fields in fusion device

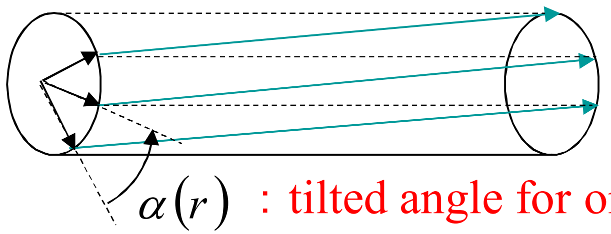
$$\boldsymbol{B} = \left(B_T\hat{\varphi} + B_P\hat{\theta}\right)$$

Length of field line for
the poloidal angle

$$l = qR_0\theta$$

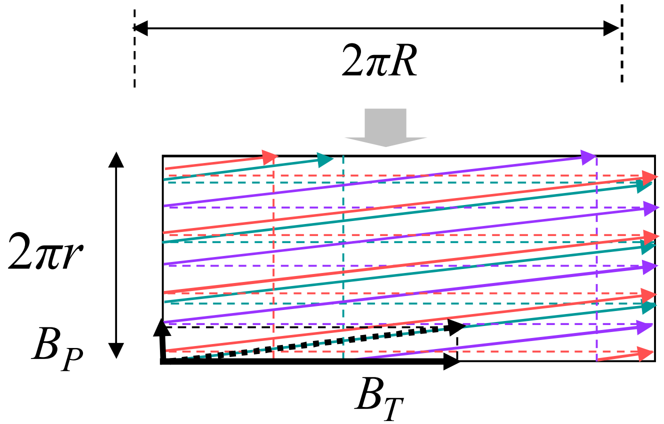


$$\tan\alpha = \frac{r}{R}\left(\frac{\alpha}{2\pi}\right) = \frac{B_p}{B_T}$$



: cylinder model

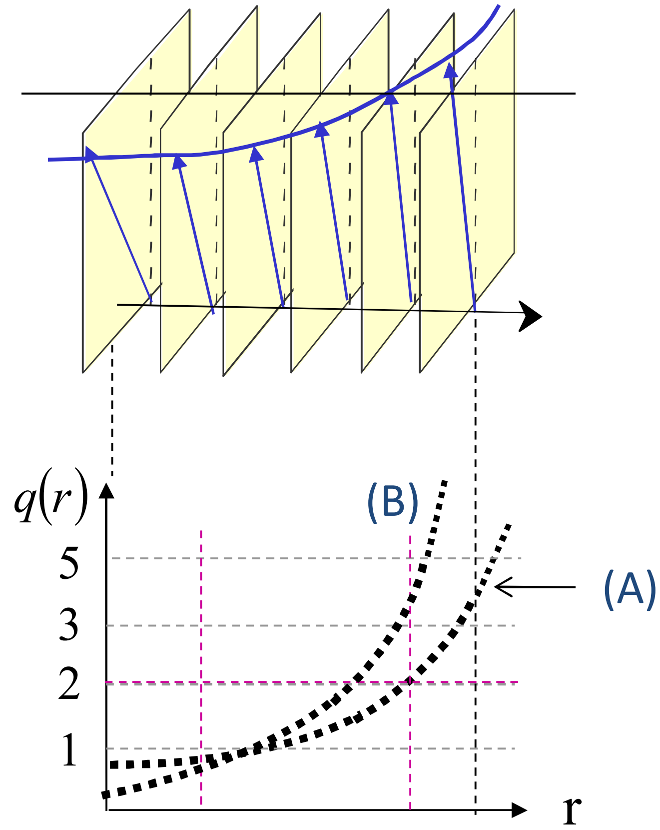
$\alpha(r)$: tilted angle for one toroidal turn



: slab model

safety factor:

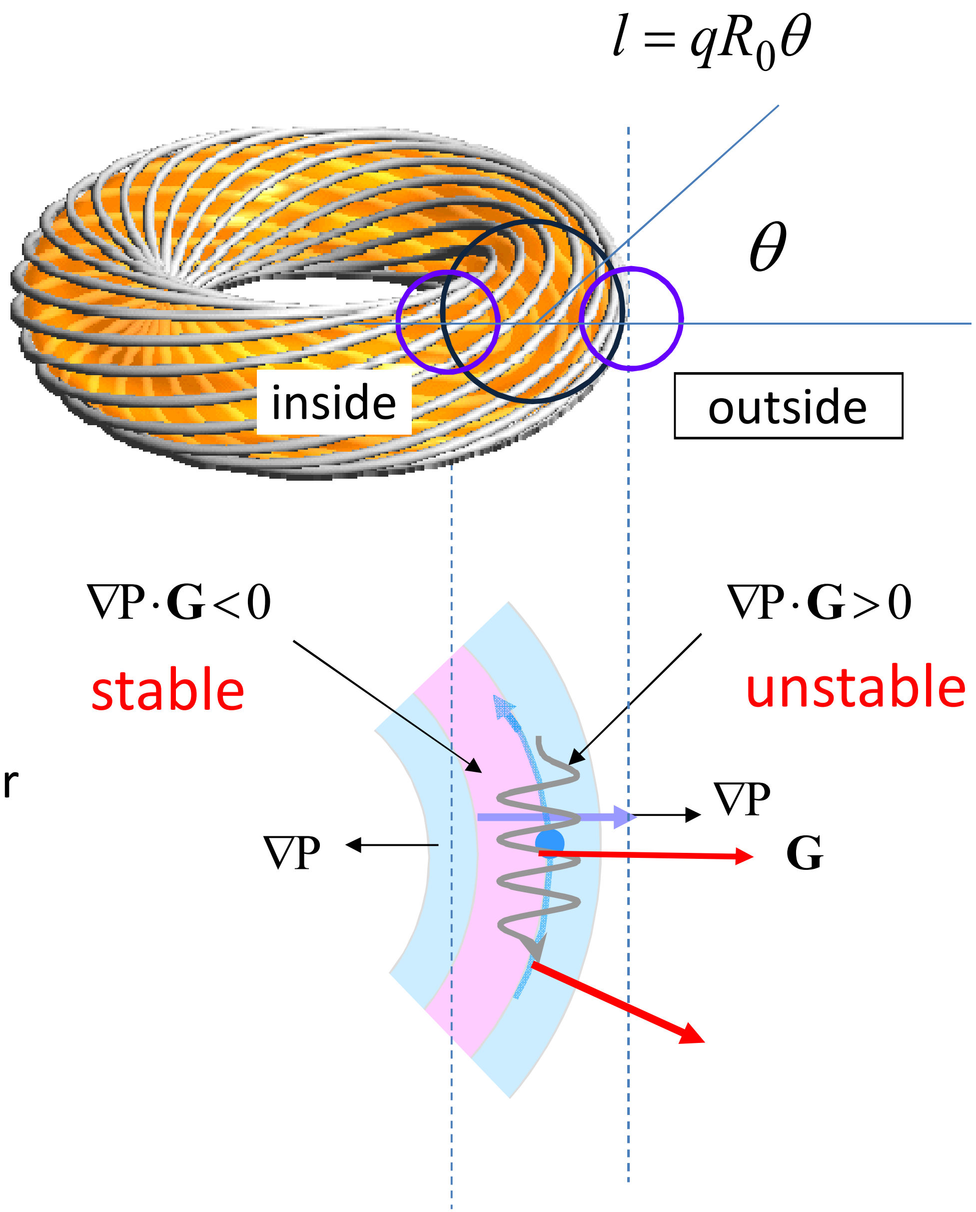
$$q(r) = \frac{2\pi}{\alpha} = \frac{r}{R}\left(\frac{B_T}{B_P}\right)$$

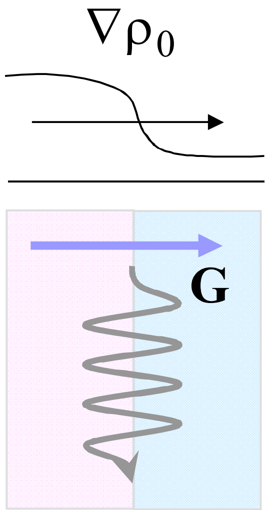


safety factor : $\hat{s} = \dfrac{r}{q}\dfrac{\partial q}{\partial r}$

Length from θ=0 (outside)
to θ=π (inside)

$$l = \pi q R_0$$

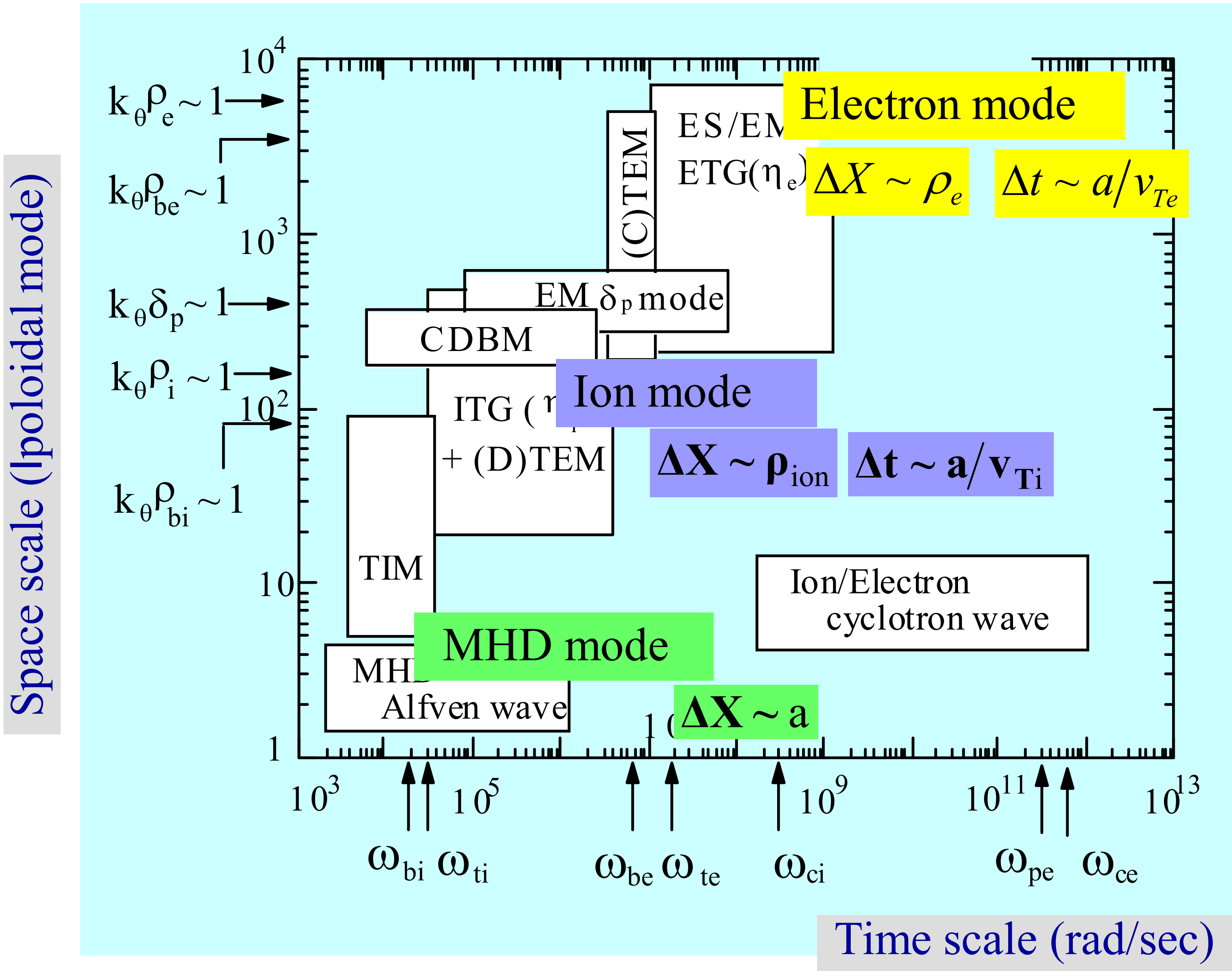




$$\nabla \rho_0 \cdot \mathbf{G} > 0$$

Rayleigh-Taylor Instability

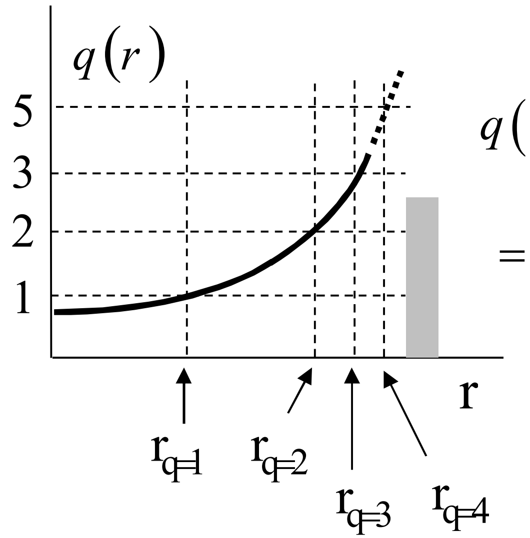
Fluctuations in magnetically confined plasma



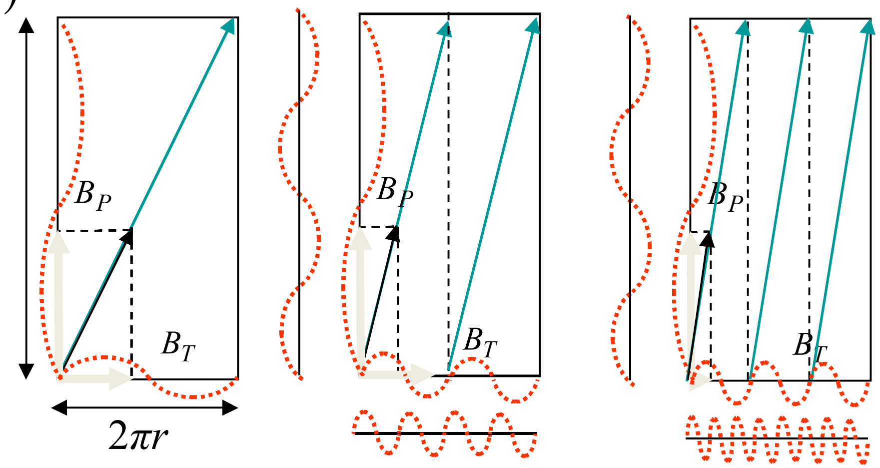
Coupling between magnetic structure and wave : resonance

perturbation $A(\mathbf{x},t) = A_0 \exp(-in\phi + im\theta - i\omega t)$

non-rational and non-rational surface :



$$q(r) \equiv \frac{2\pi}{\alpha} = \frac{m\,(\text{poloinal mode})}{n\,(\text{toroidal mode})}$$



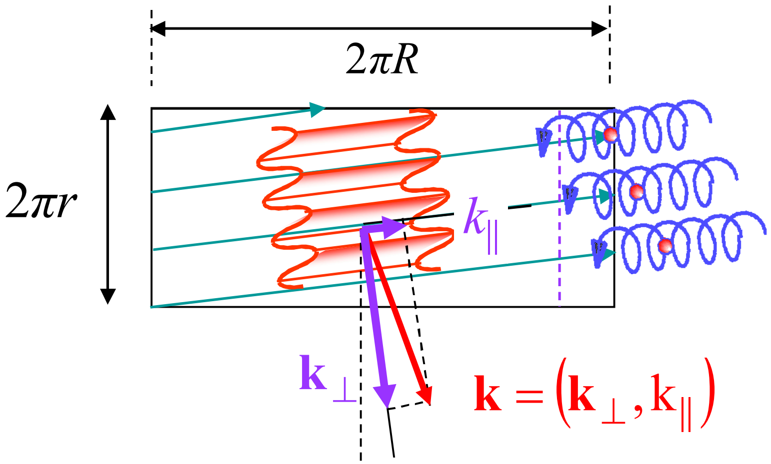
m/n = 1/1 = 2/2 = 3/3

m/n = 2/1 = 4/2 = 6/3

m/n = 3/1 = 6/2 = 9/3

Long wavelength : along field line

Short wavelength : perpendicular to field line



$$\mathbf{k} = \mathrm{k}_{\parallel}\mathbf{b} + \mathbf{k}_{\perp}$$

$$\mathrm{k}_{\parallel} = \hat{\mathbf{b}}\cdot\mathbf{k} = i\hat{\mathbf{b}}\cdot\nabla = i\left(\hat{\boldsymbol{\varphi}} + \frac{r}{qR}\hat{\boldsymbol{\theta}}\right)\cdot\left(\frac{\hat{\boldsymbol{\varphi}}}{R}\frac{\partial}{\partial\phi} + \frac{\hat{\boldsymbol{\theta}}}{r}\frac{\partial}{\partial\theta}\right)$$

$$= \frac{1}{R}\left(n - \frac{m}{q(r)}\right) \qquad k_{\parallel} = 0 \rightarrow q(r) = \frac{m}{n}$$

$$|\mathbf{k}_{\perp}| < \frac{1}{\rho_j} \qquad \mathrm{k}_{\parallel} << |\mathbf{k}_b| \qquad \left(\mathrm{k}_{\parallel} \sim \frac{1}{\mathrm{qR}}\right)$$

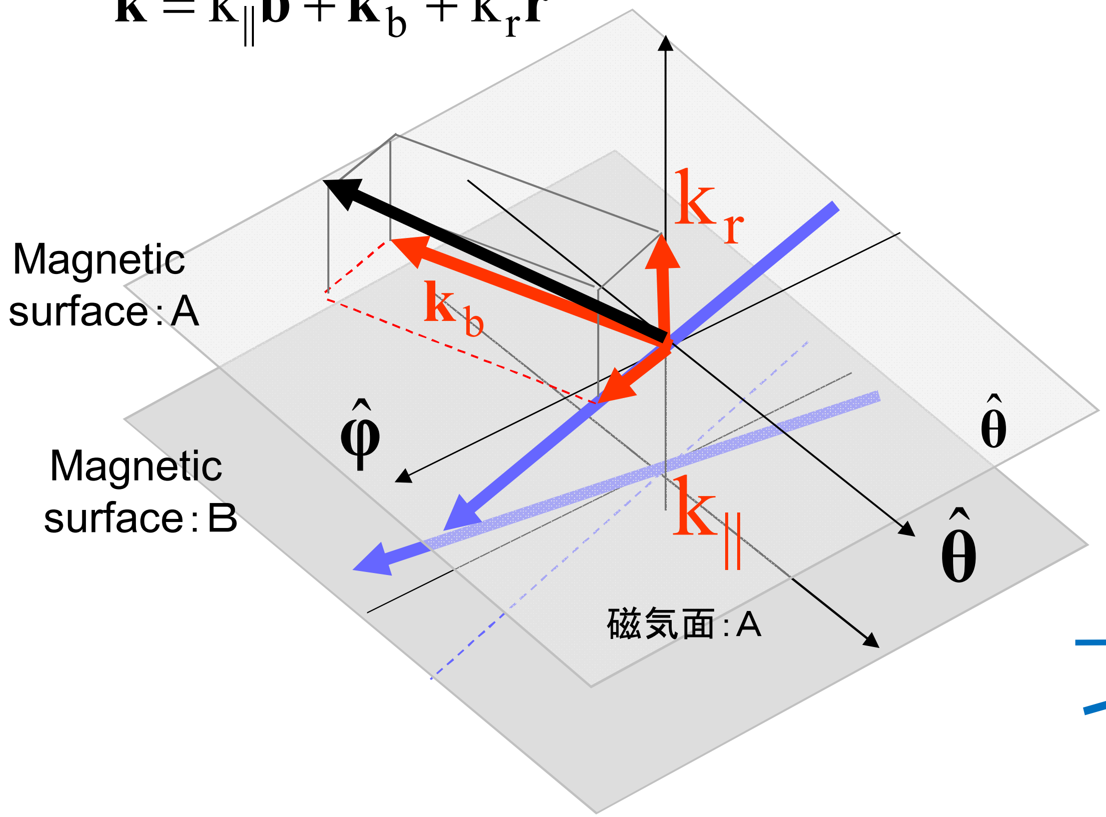
Radial localization of wave by having "magnetic shear"

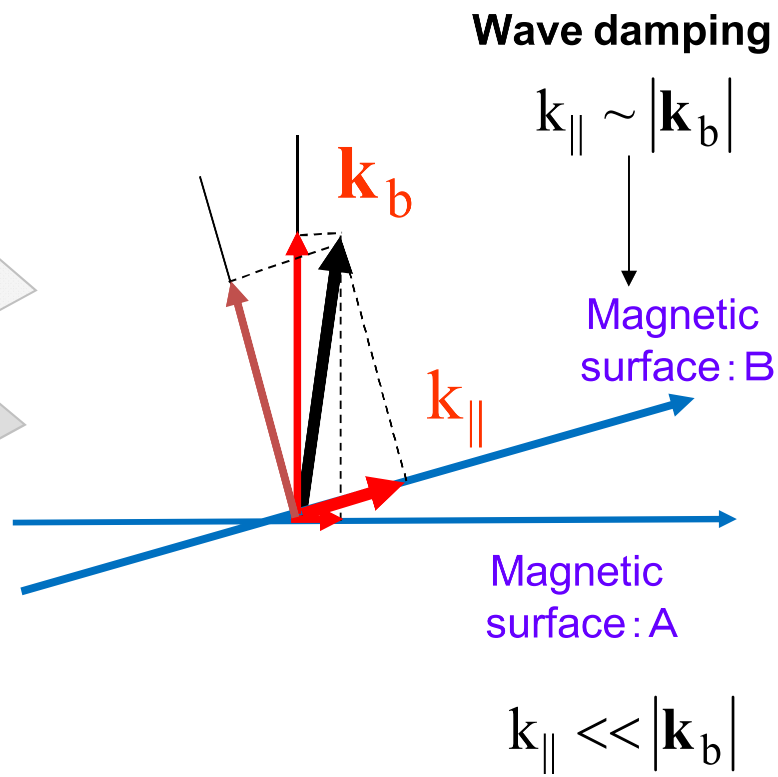
$$q(r) = \frac{2\pi}{\alpha} = \frac{r}{R}\left(\frac{B_T}{B_P}\right) \qquad \hat{s} = \frac{r}{q}\frac{\partial q}{\partial r}$$

$$(\hat{\mathbf{r}}, \hat{\boldsymbol{\theta}}, \hat{\boldsymbol{\varphi}}) \rightarrow (\hat{\mathbf{r}}, \hat{\mathbf{r}} \times \hat{\mathbf{b}}, \hat{\mathbf{b}})$$

$$(\mathrm{k}_r, \mathrm{k}_\theta, \mathrm{k}_\varphi) \rightarrow (\mathrm{k}_r, |\mathbf{k}_b|, \mathrm{k}_\parallel)$$

$$\mathbf{k} = \mathrm{k}_\parallel \hat{\mathbf{b}} + \mathbf{k}_b + \mathrm{k}_r \hat{\mathbf{r}}$$



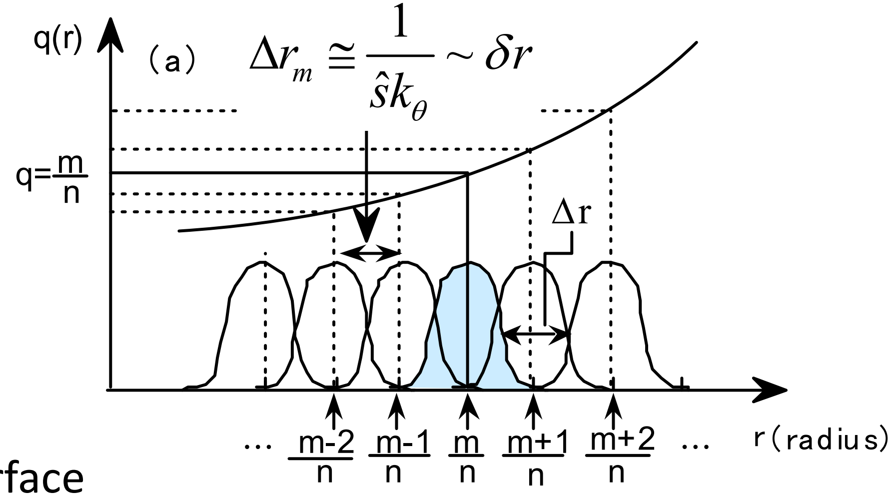


Typical radial mode width of the fluctuation

$$k_{\parallel} = \hat{\mathbf{b}} \cdot \mathbf{k} = \left(\hat{\boldsymbol{\varphi}} + \frac{r}{qR} \hat{\boldsymbol{\theta}} \right) \cdot \mathbf{k}$$

$$= \frac{1}{qR} \left[nq(r) - m \right]$$

$$q(r) = q(r = r_m) + \frac{\partial q}{\partial r}(r - r_m) + \cdots$$



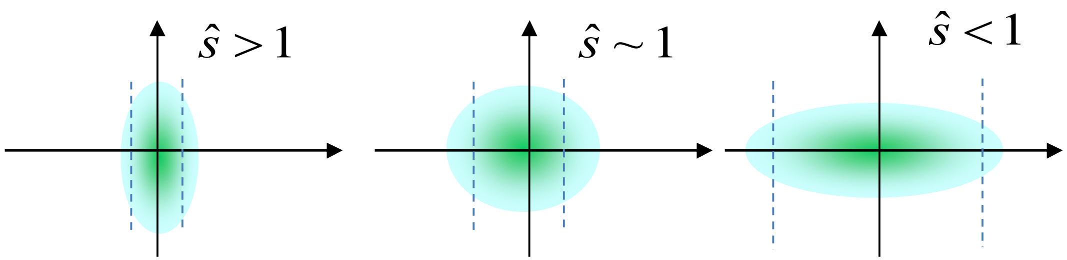
Distance between two different rational surface

$$\Delta r_m \cong \frac{1}{\hat{s} k_\theta} \qquad k_{\parallel} = \frac{\hat{s}}{qR} k_\theta (r - r_m) \sim \frac{1}{qR} \qquad \delta r \sim |r - r_m| \sim \frac{1}{\hat{s} k_\theta} \sim \frac{\rho_j}{\hat{s}} \qquad |k_\theta| \sim \frac{1}{\rho_j}$$

Distance of poloidal wave number for adjacent two rational surface

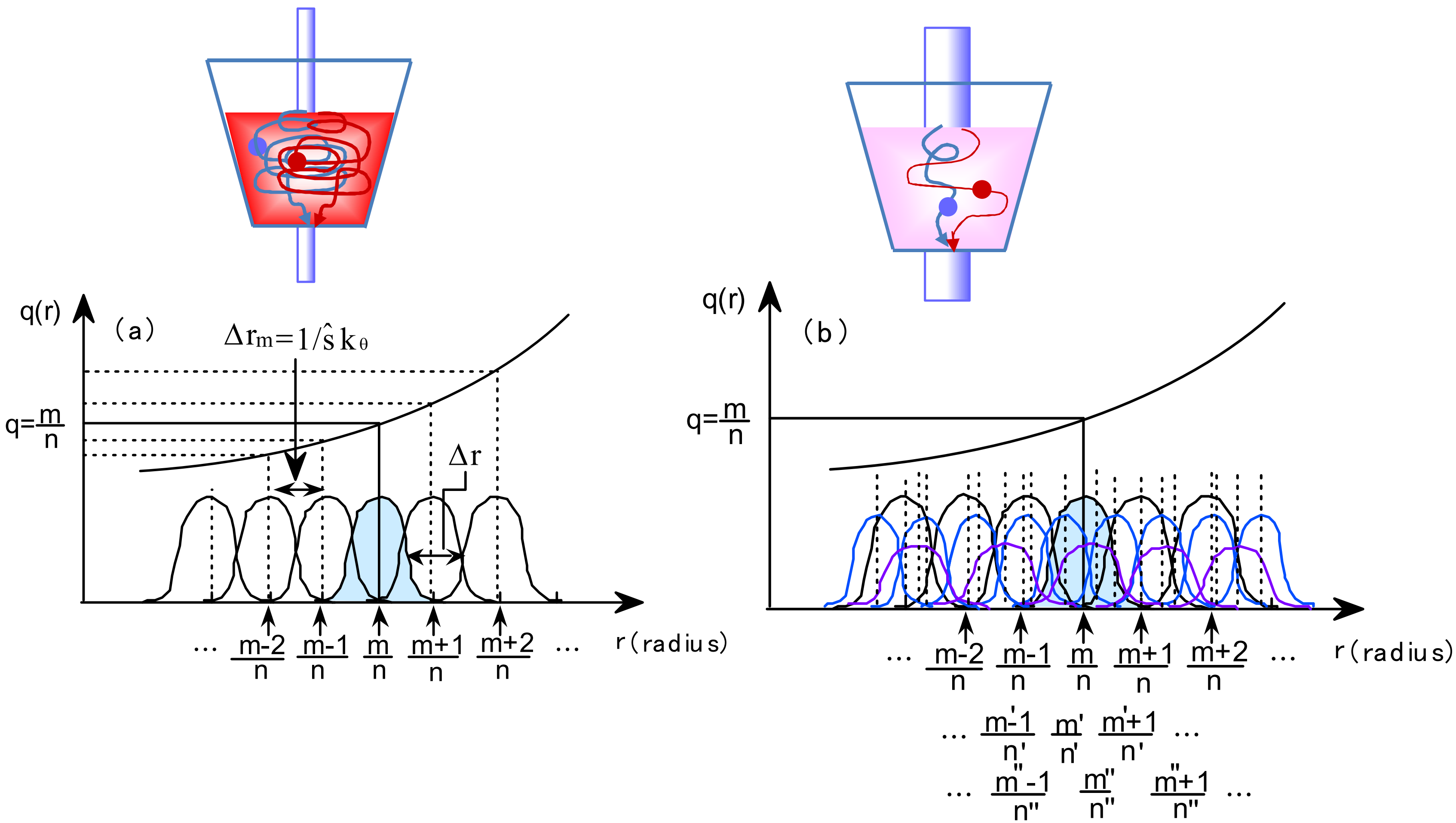
$$\Delta k_\theta = \left| \frac{m}{r_m} - \frac{m+1}{r_m + \Delta r_m} \right| \cong \frac{k_\theta}{m} \left| 1 - \frac{1}{\hat{s}} \right| < \frac{k_\theta}{m}$$

Wave excitation across the different rational surface with same toroidal number



Distribution of rational surface : incomplete cage

Origin of leaking of across the magnetic surface



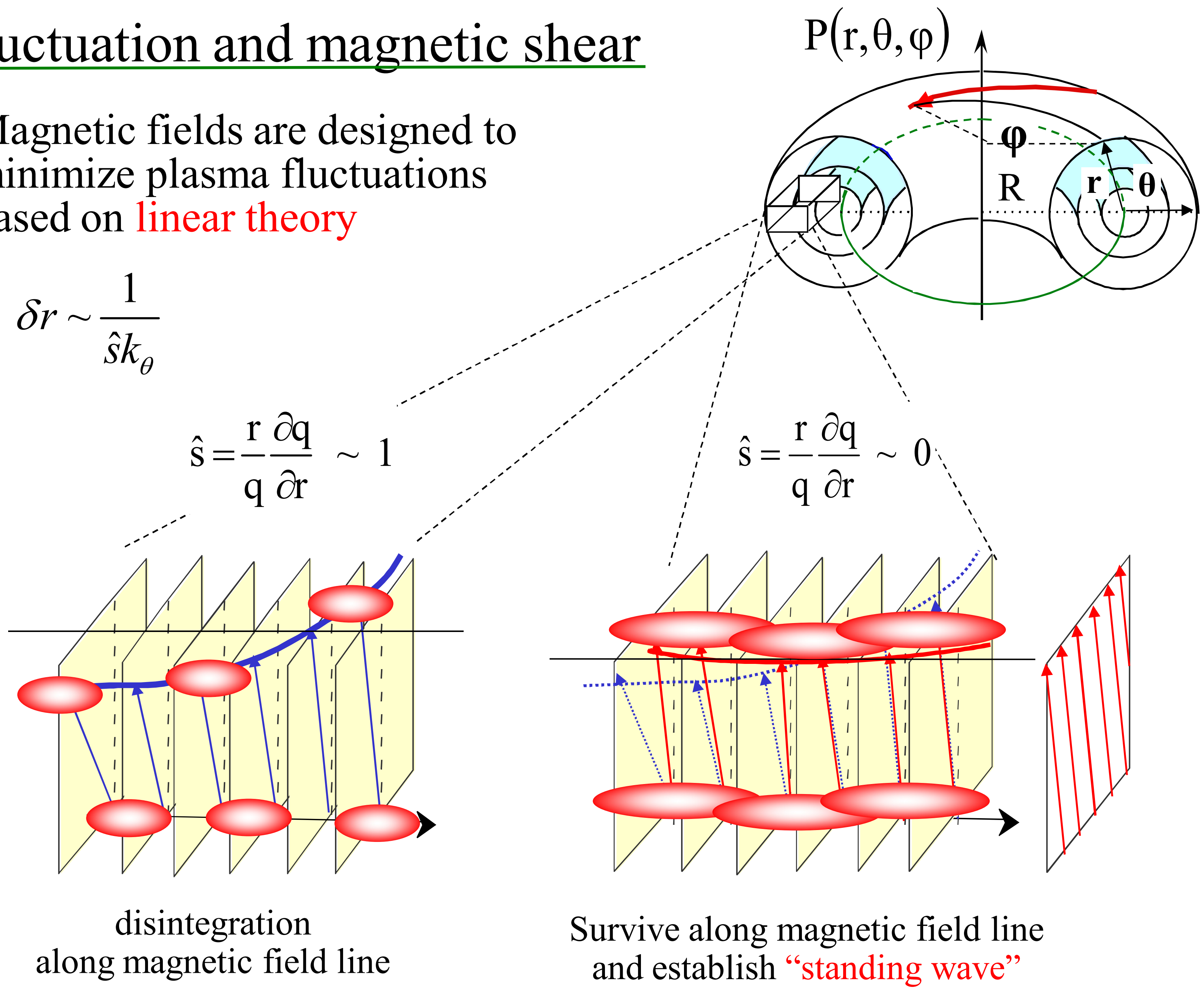
$$\Delta r_m \cong \frac{1}{\hat{s}k_\theta} \cong \delta r$$

$$\Delta r_{m,n} \cong \frac{1}{n^2 \left| \partial q / \partial r \right|} \cong \frac{\Delta r_m}{n}$$

Fluctuation and magnetic shear

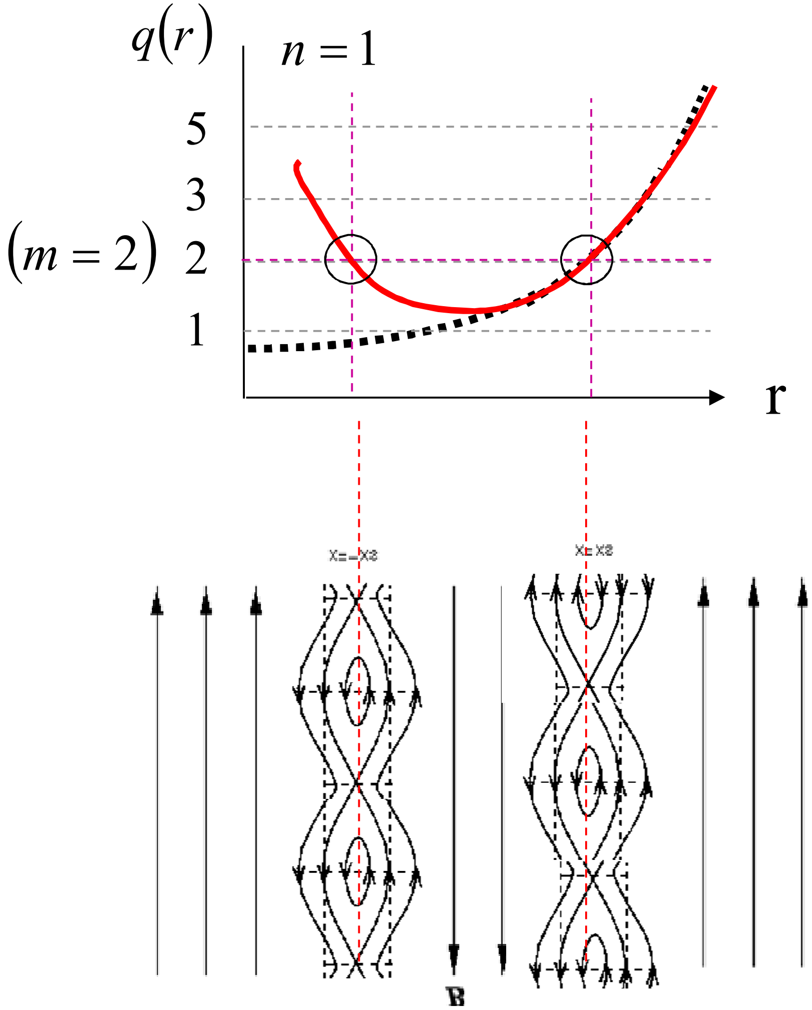
Magnetic fields are designed to minimize plasma fluctuations based on linear theory

$$\delta r \sim \frac{1}{\hat{s} k_\theta}$$

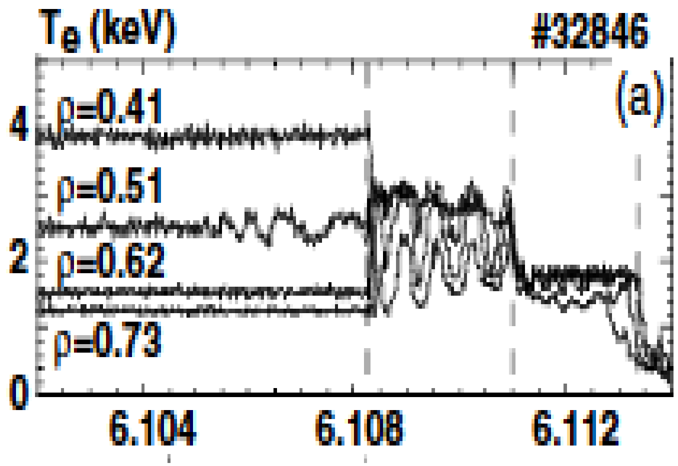


Reversed magnetic shear plasma and double tearing mode (DTM)

$$q(r) \equiv \frac{r}{R}\frac{B_T}{B_P} \sim \frac{m}{n}$$



S. Takechi et al., Nucl. Fusion 42, 5 (2002)



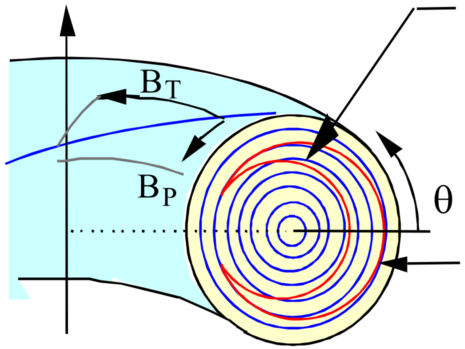
✓Disruptive event terminating high performance plasma

✓Explosive (sudden) nature with pre-curser

✓Double tearing mode (DTM) with multiple current sheet

Toroidal mode coupling of wave due to poloidal asymmetry

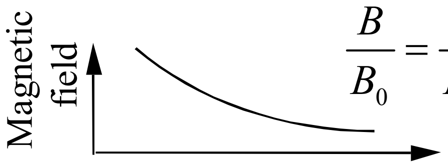
0-th order Ballooning mode local theory



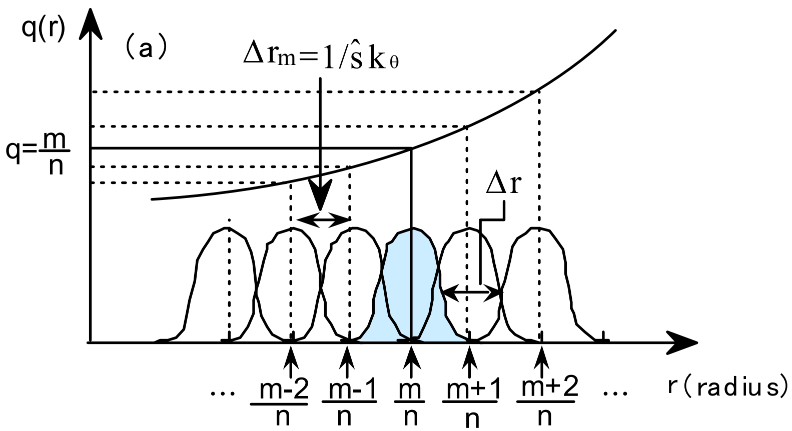
Rational surface :

$$q(r) \equiv \frac{r}{R}\frac{B_T}{B_P} \sim \frac{m}{n}$$

Particle orbit



$$\frac{B}{B_0} = \frac{1}{R} \sim \frac{1}{1 + (r/R)\cos\theta}$$



- Linear eigen-mode analysis

$$\Phi(\mathbf{x},t) = \phi(r,\theta)\exp(-in\varphi - i\omega t)$$

$$\phi(r,\theta) = \exp(im_0\theta)\sum_j \phi_j(r)\exp(ij\theta_j)$$

- Bloch theory (translational symmetry)

$$\phi_m(x) = \phi_{m-1}(x-1)\exp(i\theta_0) = \cdots$$

$$= \phi_0(x-m)\exp(im\theta_0)$$

θ_0 : Bloch angle

- Eigen mode analysis ：

$$\omega = \omega_r(\hat{s},x) + i\gamma_0(\hat{s},x)\cos\theta_0$$

$$\omega_r(\hat{s},x) \sim \omega_D \sim 2(k_\theta\rho_i)\frac{v_i}{R}$$

Radial mode width and Bloch angle undetermined

Global toroidal mode structure

J.Y. Kim and M. Wakatani, PRL 73, 2200 (1994)
Y. Kishimoto, J.Y. Kim, W. Horton, et al., Plasmas Phys. Controlled Fusion 41, A663 (1999)

- Mode-structure in non-uniform medium :
  (Extension to non-local ballooning theory)

$$\phi_j(r,x) = A(r)\,\phi_0(x-j)\exp(i\theta_0 j)$$

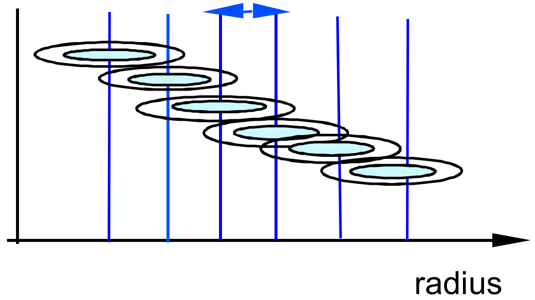
$\phi_0(x-j)$ → 0^{th} order eigen-function : (ω_r, γ_0)

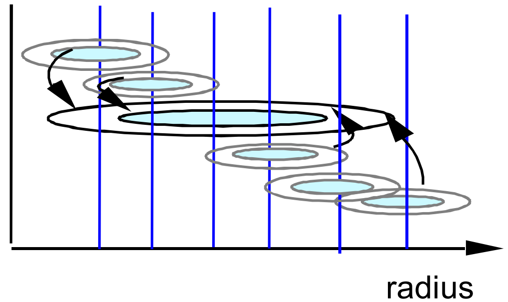
$$A(r) = \exp\left[-\frac{k_\theta \hat{s}}{2\gamma_0 \sin\theta_0}\left(\frac{\partial \omega_r}{\partial r} + \frac{\partial \omega_f}{\partial r}\right) r^2 \right]$$

$\frac{\partial \omega_r}{\partial r}$: Spatial variation of real frequency (diamagnetic shear)

$\frac{\partial \omega_f}{\partial r}$: Spatial variation of plasma rotation

$$\omega_f = k_\theta V_\theta + k_\varphi V_\varphi$$





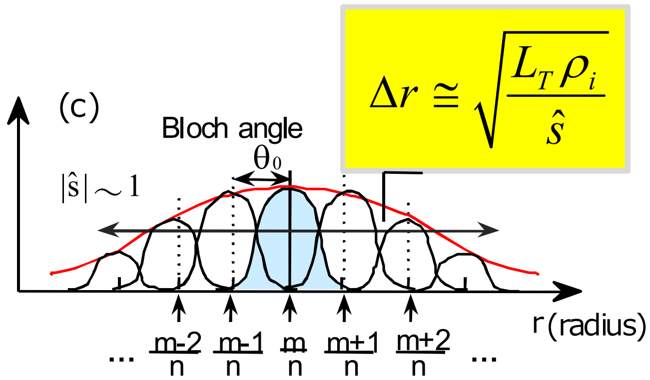
- Representation of 2d-structure : $(\Delta r, \theta_0)$

$$\Delta r \cong \left| \frac{2\gamma_0 \sin\theta_0 k_\theta \hat{s}}{k_\theta \hat{s}\left(\frac{\partial \omega_r}{\partial r} + \frac{\partial \omega_f}{\partial r}\right)} \right|^{1/2}$$

Growth rate reduction from mid-plane $\theta_0 = 0$

$$(\Delta\theta_0)_{max} \cong \mp \left| \frac{\left(\frac{\partial \omega_r}{\partial r} + \frac{\partial \omega_f}{\partial r}\right)}{2k_\theta \gamma_0 \hat{s}} \right|^{1/3}$$

$$\gamma(\theta_0) \simeq \gamma_0 \cos\theta_0$$

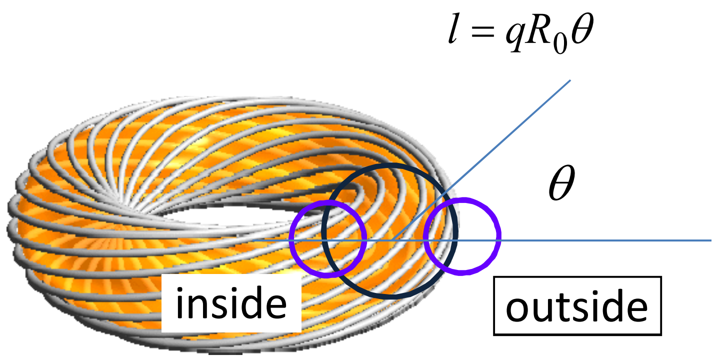


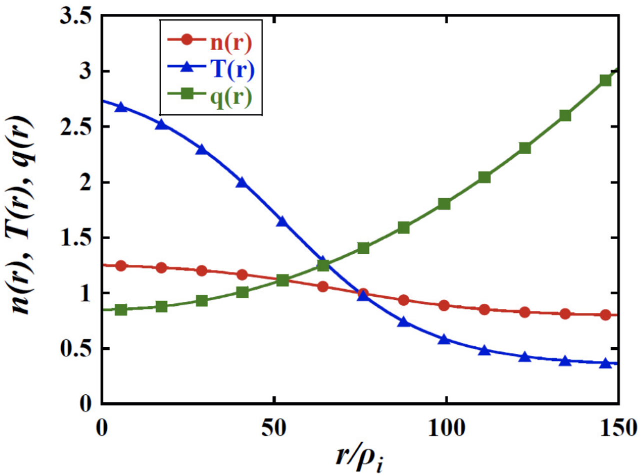
Global toroidal mode structure

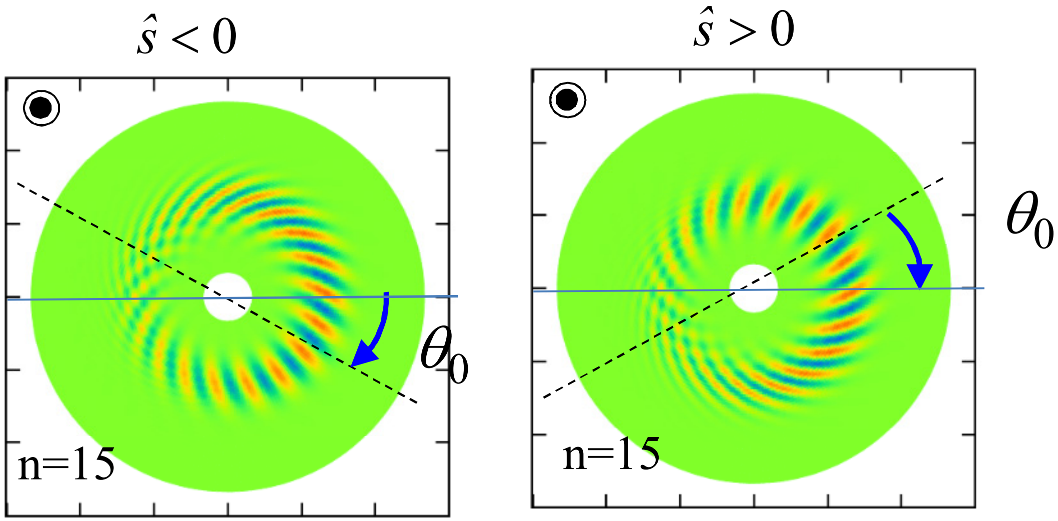
$$\Delta r \cong \left| \frac{2\gamma_0 \sin\theta_0 \hat{s}}{k_\theta \hat{s}\left(\frac{\partial\omega_r}{\partial r} + \frac{\partial\omega_f}{\partial r}\right)} \right|^{1/2} \cong \sqrt{\frac{L_T \rho_i}{\hat{s}}}$$

$^{1/3}$

$$(\Delta\theta_0)_{\max} \cong \mp \left| \frac{\left(\frac{\partial\omega_r}{\partial r} + \frac{\partial\omega_f}{\partial r}\right)}{2k_\theta \gamma_0 \hat{s}} \right|^{1/3} \cong \mp \left| \frac{1}{\hat{s} k_\theta L_T} \right|$$







$a / R_0 = 0.36$ $\quad R_0 / L_n = 2.22$

$R_0 / L_T = 10$ $\quad L_T = 41.7\rho_i$

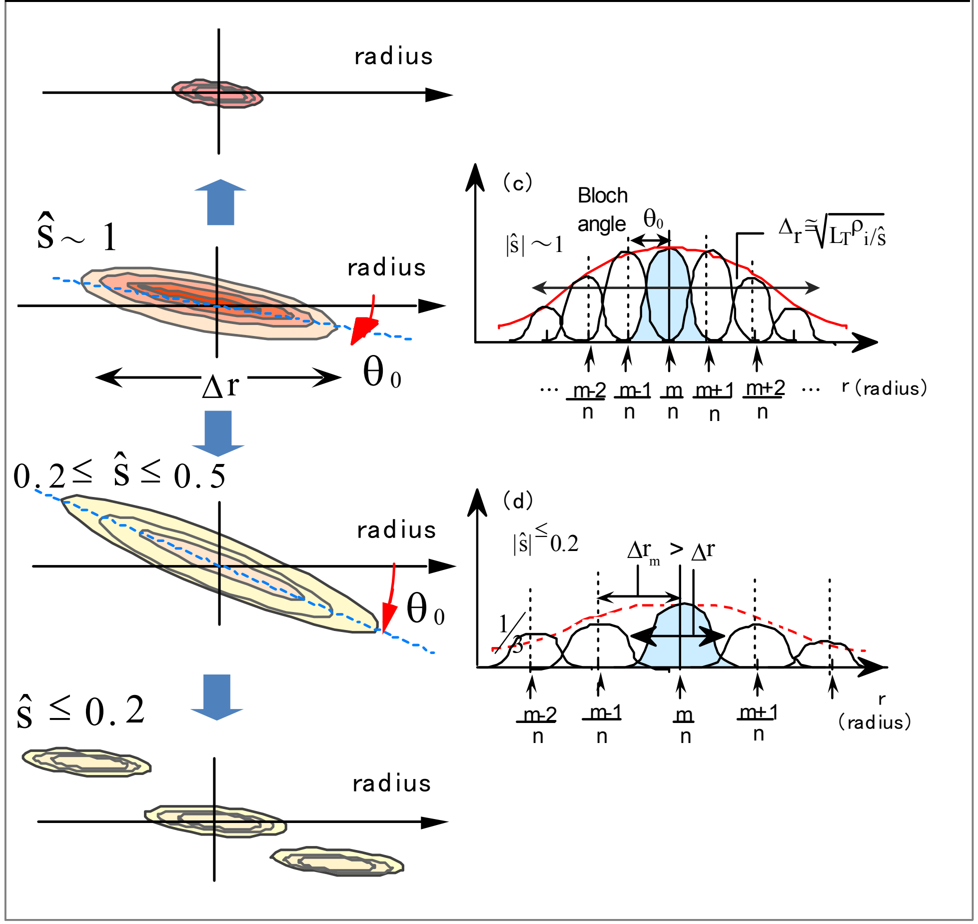
$$\gamma(\theta_0) \simeq \gamma_0 \cos\theta_0$$

Growth rate reduction
as the tilting angle increase

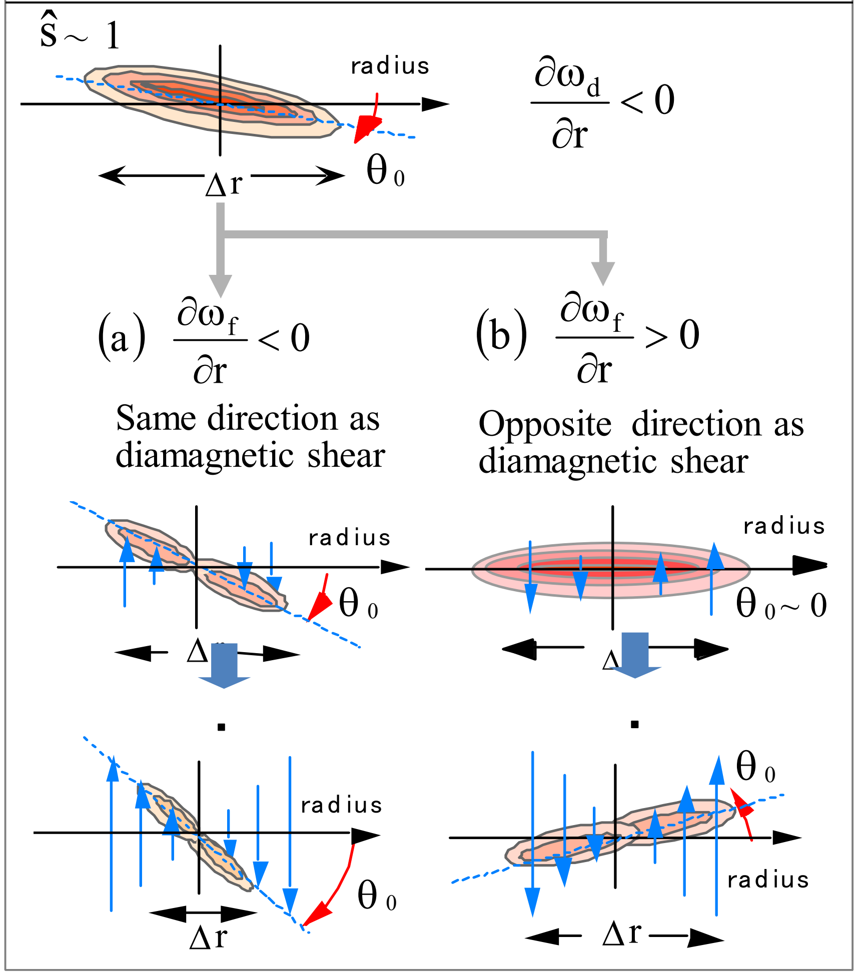
Global toroidal ITG mode structure including profile effect

$$\Delta r \cong \frac{2\gamma_0 \sin\theta_0}{k_\theta \hat{s}\left(\frac{\partial \omega_r}{\partial r} + \frac{\partial \omega_f}{\partial r}\right)} \qquad (\Delta\theta_0)_{max} \cong \mp \left| \frac{\left(\frac{\partial \omega_r}{\partial r} + \frac{\partial \omega_f}{\partial r}\right)}{2 k_\theta \gamma_0 \hat{s}} \right|^{1/3} \qquad \gamma(\theta_0) \simeq \gamma_0 \cos\theta_0$$

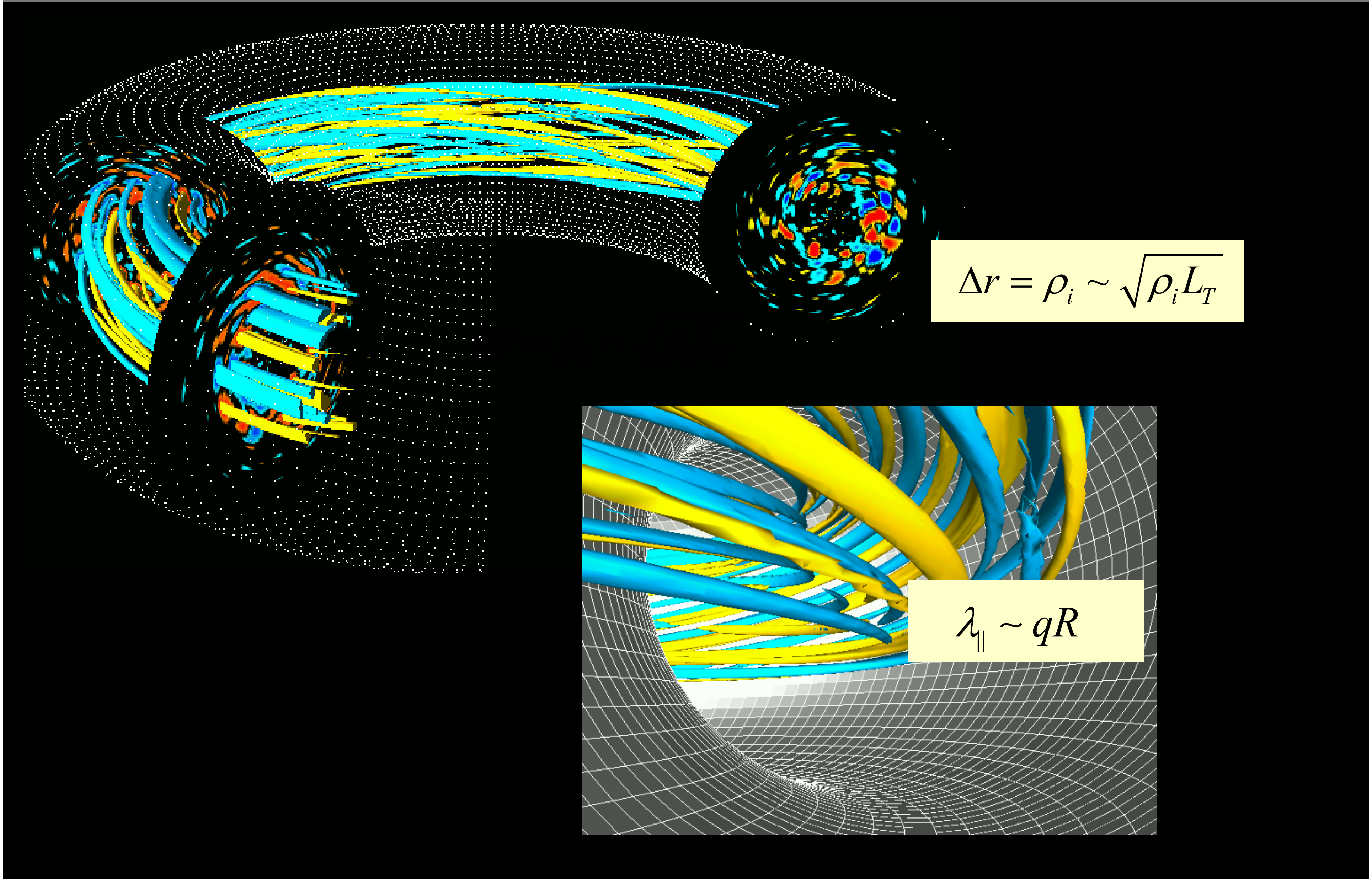
- Effect of magnetic shear



- Effect of plasma rotation

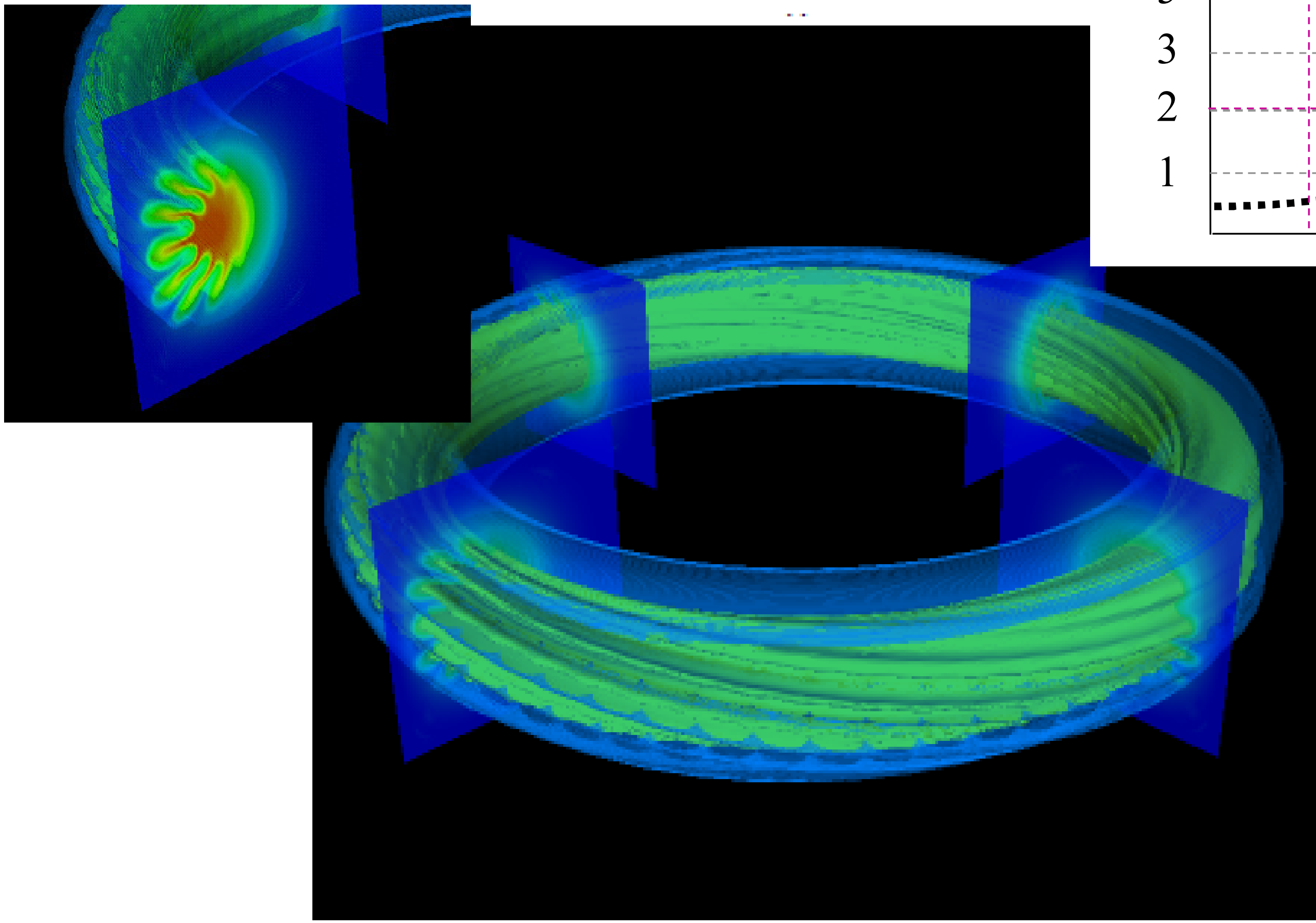


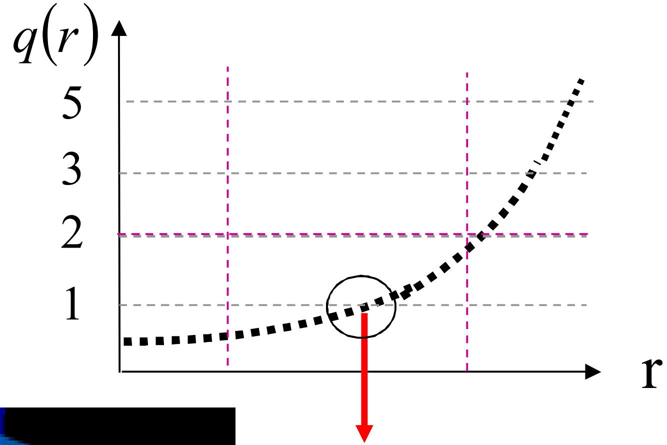
Global turbulent simulation of ion temperature gradient mode (ITG)



Interaction between 1/1 internal kink and high-m/n ballooning mode

Y. Kagei and Y. Kishimoto:
Full set non-linear MHD simulation 2006, JPS





$$q(r) \equiv \frac{r}{R}\frac{B_T}{B_P} \sim \frac{m}{n}$$

$$\frac{m}{n} = \frac{1}{1}$$

and

$$\frac{m}{n} \sim \frac{30}{30}$$

Development of toroidal full-f GK code

Developed by Imadera/Kishimoto : Kyoto University

$$\frac{\partial f}{\partial t}+\frac{dr}{dt}\frac{\partial f}{\partial r}+\frac{1}{r}\frac{d\theta}{dt}\frac{\partial f}{\partial \theta}+\frac{1}{R}\frac{d\varphi}{dt}\frac{\partial f}{\partial \varphi}+\frac{dv_\parallel}{dt}\frac{\partial f}{\partial v_\parallel}=C_{coll}$$

GK Vlasov Eq.

$$\begin{cases}
\dfrac{dr}{dt}=\dfrac{1}{B_\parallel^*}\left(-\dfrac{v_\parallel^2+\mu B}{R}\sin\theta-\dfrac{1}{r}\dfrac{\partial\langle\Phi\rangle_\phi}{\partial\theta}+\dfrac{r}{qR_0R}\dfrac{\partial\langle\Phi\rangle_\phi}{\partial\varphi}\right)\\
\dfrac{1}{r}\dfrac{d\theta}{dt}=\dfrac{1}{B_\parallel^*}\left(\dfrac{v_\parallel}{qR}-\dfrac{v_\parallel^2+\mu B}{rR}\cos\theta+\dfrac{1}{r}\dfrac{\partial\langle\Phi\rangle_\phi}{\partial r}\right)\\
\dfrac{1}{R}\dfrac{d\varphi}{dt}=\dfrac{1}{B_\parallel^*}\left[\left(B+\dfrac{2-\hat{s}}{qR_0}v_\parallel\right)\dfrac{v_\parallel}{R}+\mu B\dfrac{r\cos\theta}{qR_0R^2}-\dfrac{r}{qR_0R}\dfrac{\partial\langle\Phi\rangle_\phi}{\partial r}\right]\\
\dfrac{dv_\parallel}{dt}=\dfrac{1}{B_\parallel^*}\left[-\mu B\dfrac{r\sin\theta}{qR^2}-\dfrac{1}{qR}\dfrac{\partial\langle\Phi\rangle_\phi}{\partial\theta}-\left(B+\dfrac{2-\hat{s}}{qR_0}v_\parallel\right)\dfrac{1}{R}\dfrac{\partial\langle\Phi\rangle_\phi}{\partial\varphi}+\dfrac{v_\parallel}{R}\left(\dfrac{\partial\langle\Phi\rangle_\phi}{\partial r}\sin\theta+\dfrac{\partial\langle\Phi\rangle_\phi}{\partial\theta}\dfrac{\cos\theta}{r}\right)\right]
\end{cases}$$

$$\left(B_\parallel^*=B+\frac{R_0+(1-\hat{s})R}{qR_0R}v_\parallel\right)$$

GK Q.N. Eq.

$$\Phi-\langle\langle\Phi\rangle\rangle_\phi+\frac{1}{T_{e0}(r)}\left(\Phi-\langle\Phi\rangle_f\right)=\frac{1}{n_{i0}(r)}\iint\langle f_1\rangle_\phi B_\parallel^* dv_\parallel d\mu$$

DK Collision

$$C_{coll}(f)=\frac{\partial}{\partial u}\left[\frac{3\sqrt{\pi}}{2}\frac{n}{v_{th}}\frac{\Phi(v)-\Psi(v)}{2v}\frac{\varepsilon^{3/2}}{q_0R_0}\nu_*\left(\frac{\partial f}{\partial u}+\frac{u}{v_{th}^2}f\right)\right]-\frac{1}{n}\left[aF(x)+bG(x)\xi+cH(x)\right]f_M$$

$$\Phi(v)=\frac{2}{\sqrt{\pi}}\int_0^v e^{-x^2}dx,\ \Psi(v)=\frac{\Phi(v)-v\Phi'(v)}{2v^2}=\frac{1}{2v^2}\left(\frac{2}{\sqrt{\pi}}\int_0^v e^{-x^2}dx-\frac{2v}{\sqrt{\pi}}e^{-v^2}\right)$$

[G. Dif-Pradalier, *et.al.* Phys. Plasmas, 18, 62309 2011).] [S. Satake , *et.al.*,, Comput. Phys. Comm. 181, 1069 (2010).]

Development of toroidal full-f GK code

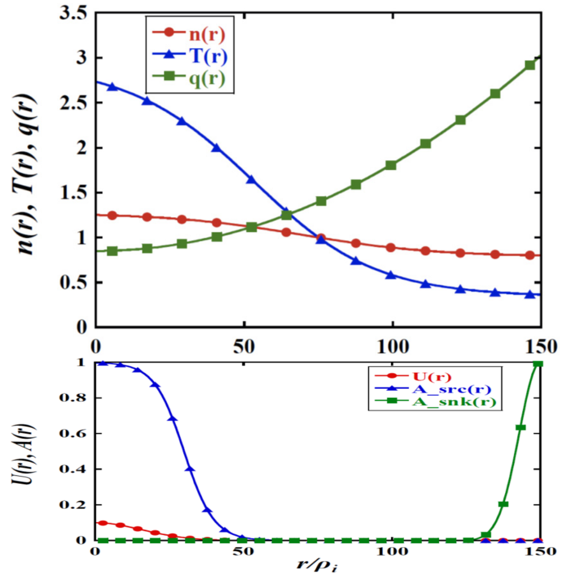
Developed by Imadera/Kishimoto : Kyoto University

- Vlasov solver : 4th-order Morinishi scheme
- Field solver : FDM(LU decomposition, r)
  + Fourier expansion(θ-φ)
- Time integration : 4th-order RKG scheme
- Parallelization: 3D(r-θ-μ) MPI decomposition
- Heat source and sink

$$S_{src} = A_{src}(x)\tau_{src}^{-1}\left\{f_M\left(2\overline{T}_0\right) - f_M\left(\overline{T}_0\right)\right\}$$

$$S_{snk} = -A_{snk}(x)\tau_{snk}^{-1}\left\{f(t) - f(t=0)\right\}$$

[Y. Idomura, *et. al.*, Nucl. Fusion 49, 065029 (2009).]



- Typical simulation parameter

$$\begin{cases} \rho_* = \dfrac{\rho_{ti}}{a} = \dfrac{1}{150} \\ \varepsilon = \dfrac{a}{R_0} = 0.36 \\ \dfrac{R_0}{L_T} = 10 \\ \dfrac{R_0}{L_n} = 2.22 \end{cases}$$

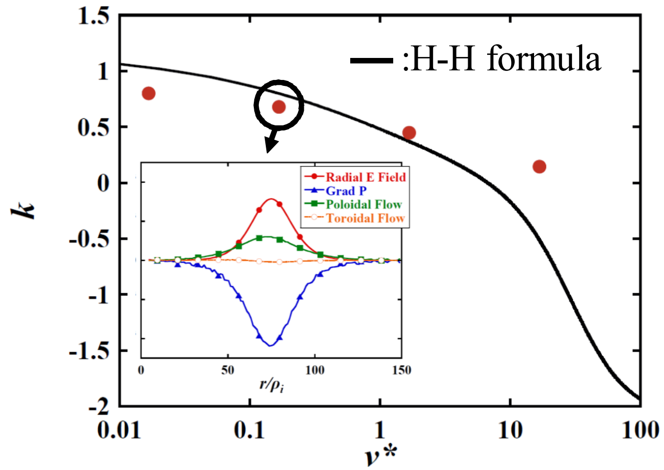
$$(N_r, N_\theta, N_\varphi, N_{v_\parallel}, N_\mu) = (128, 128, 64, 32, 16)$$

$$(L_r, L_\theta, L_\varphi, L_{v_\parallel}, L_\mu) = \left(150\rho_{ti}, 2\pi, \pi, 12v_{ti}, 18v_{ti}^2 / B_0\right)$$

$$P_{in} = 4[MW], 16[MW]$$

$$\tau_{snk}^{-1}\frac{R_0}{v_{ti}} = 0.25, \quad v_*\frac{R_0}{v_{ti}} = 0.5$$

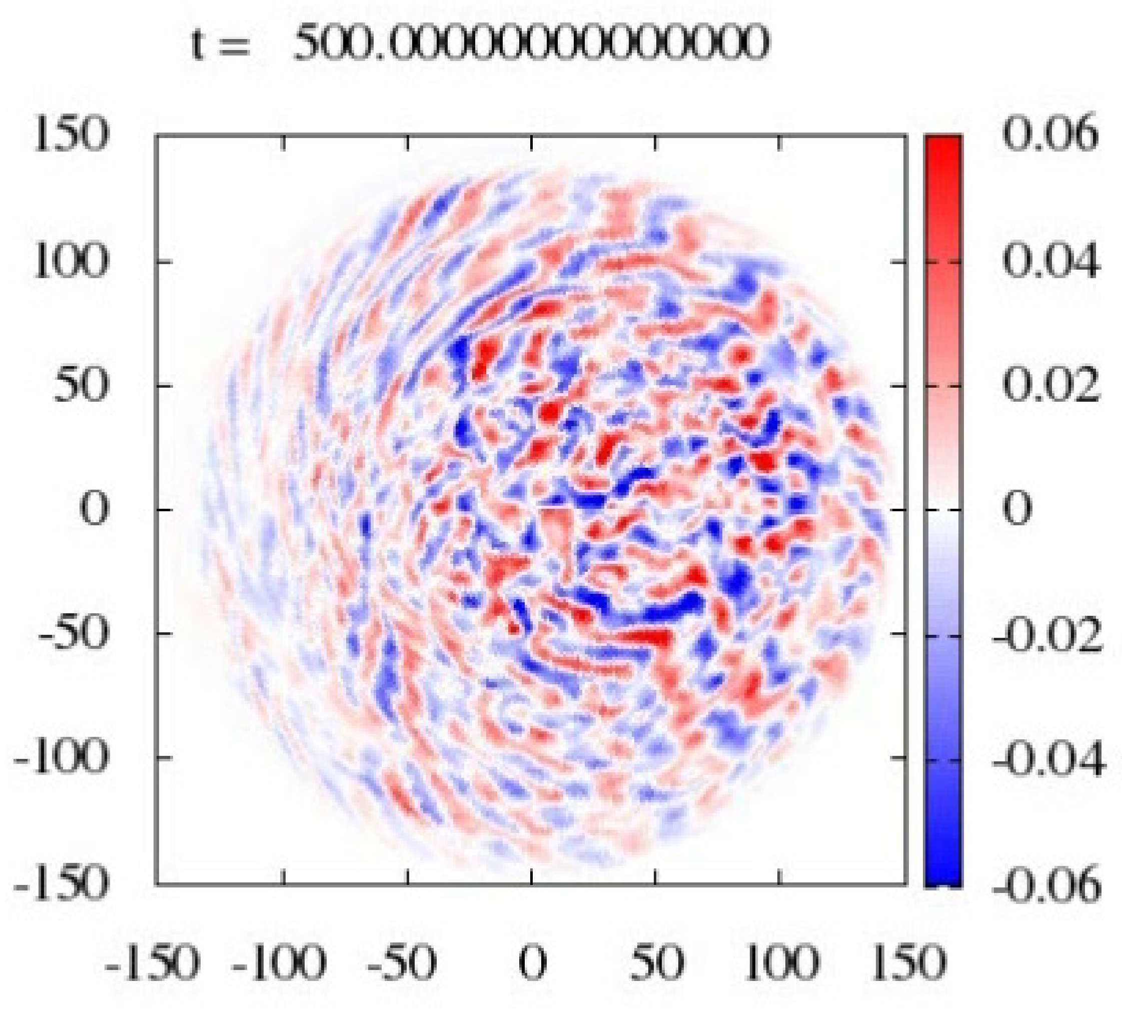
$$E_r + v_\theta B_\varphi - v_\varphi B_\theta = \frac{1}{n}\frac{dP}{dr}, \quad v_\theta = \frac{k}{B}\frac{dT}{dr}$$



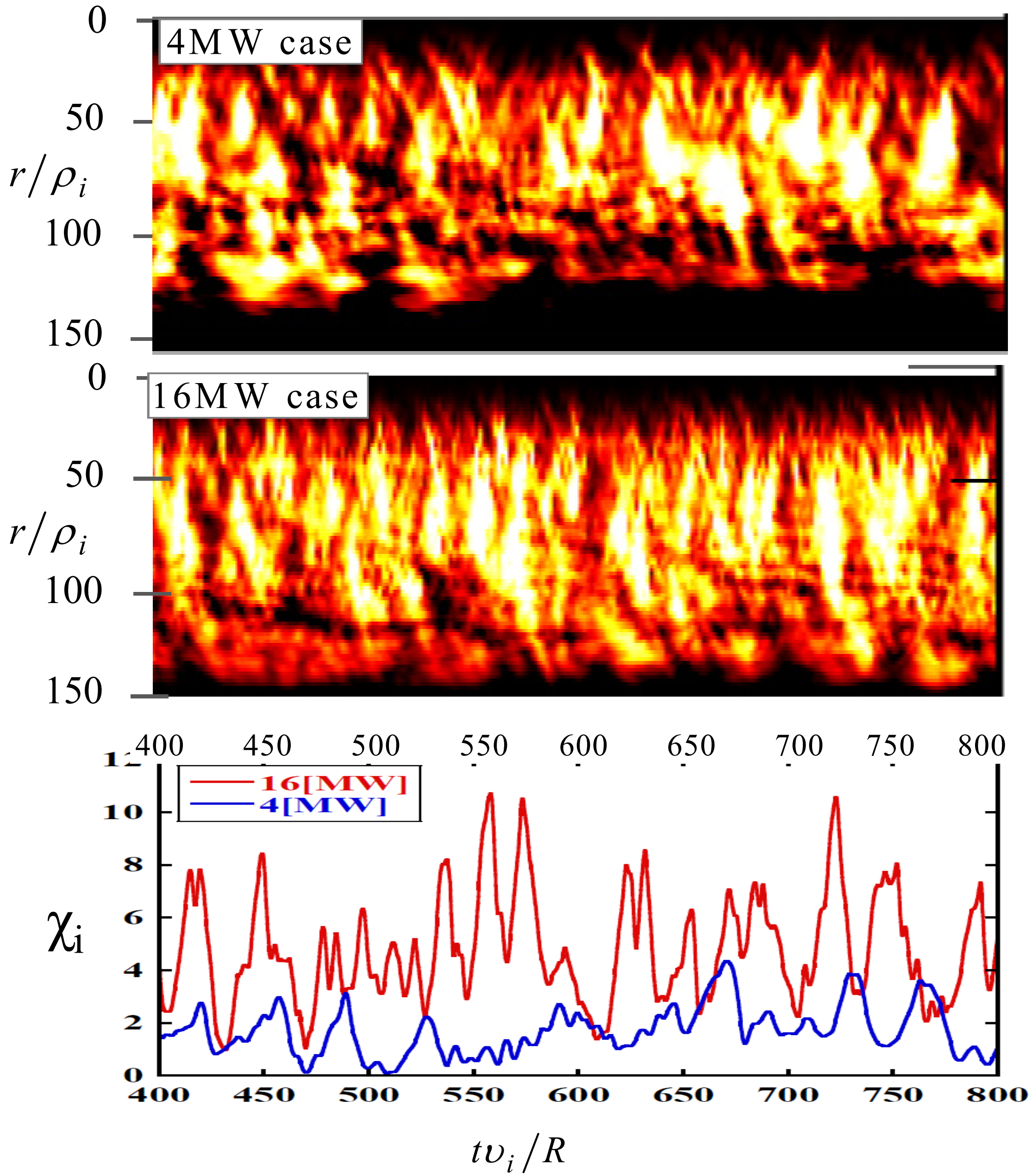
$t = 534$

$t = 556$

$t = 574$

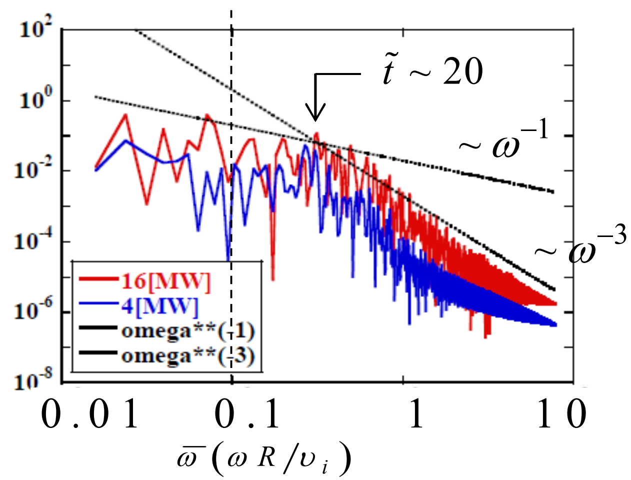


ITG turbulence and profile formation



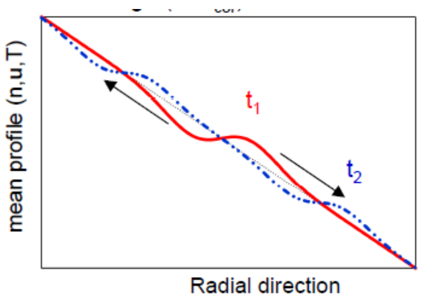
- Various types of heat event
  ① Heat avalanches radially propagates both down an up-words
  $$\upsilon_{av} \le 2.5\upsilon_b \sim 2.5C_s\left(\rho_i^*/A\right) \sim C_s\rho_i^*$$
  ② Radially extended bursts (meso-macro scales)
  $$\ell_c \sim \left(L_T\rho_i\right)^{1/2} - L_T$$
  $$\Delta\tau_c \sim \tau_{rec} \sim 20-100\tau_d$$

- Frequency spectrum of heat

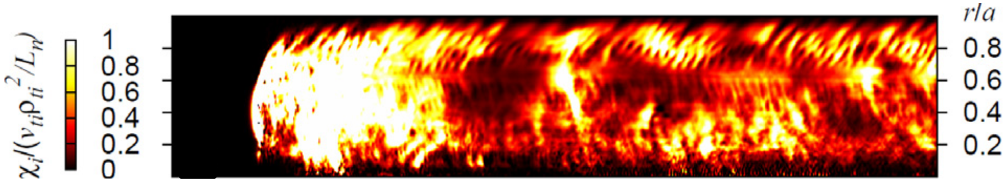


Avalanche transport

Ballistic propagation of localized heat event



Diamond-Hahm
PoP (1995)



[Y. Idomura, *et al*. Nucl. Fusion, 49, 065029 (2009).]
[Y. Sarazin, *et.al*. Nucl. Fusion, 50, 054004 (2010).]
[B. F. McMillan, Phys. Plasmas, 16, 022310 (2009)]

- Propagating velocity~ $\pm\rho_{ti}v_{ti}/R_0$
- Long positive PDF tails
- The direction depends on the sign of the E × B shear determined by the neo-classical Er shear.