Multi-scale interaction between micro-turbulence and macro-MHD

--- Effect of turbulence on tearing modes ---

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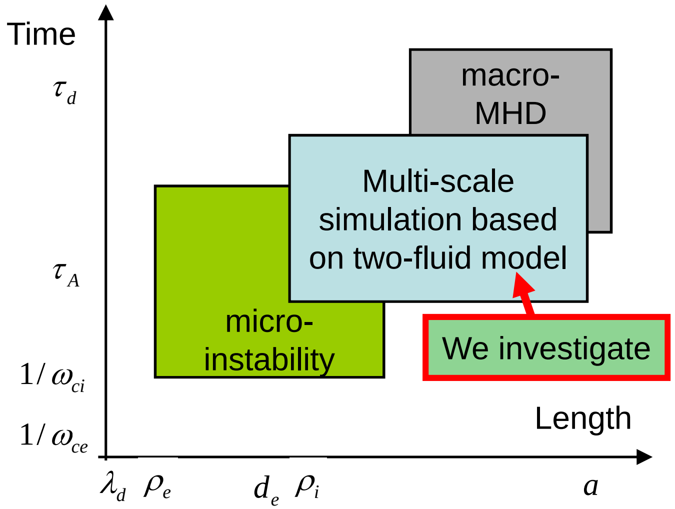
Dallas, November 21, 2008

1. Background and motivation

- Effects of MHD instabilities and micro-turbulence on plasma confinement have been investigated separately.
- But these instabilities usually appear in the plasma at the same time.
- In the experiments
  - Micro-turbulence is observed in Large Helical Device plasmas that usually exhibit MHD activities.

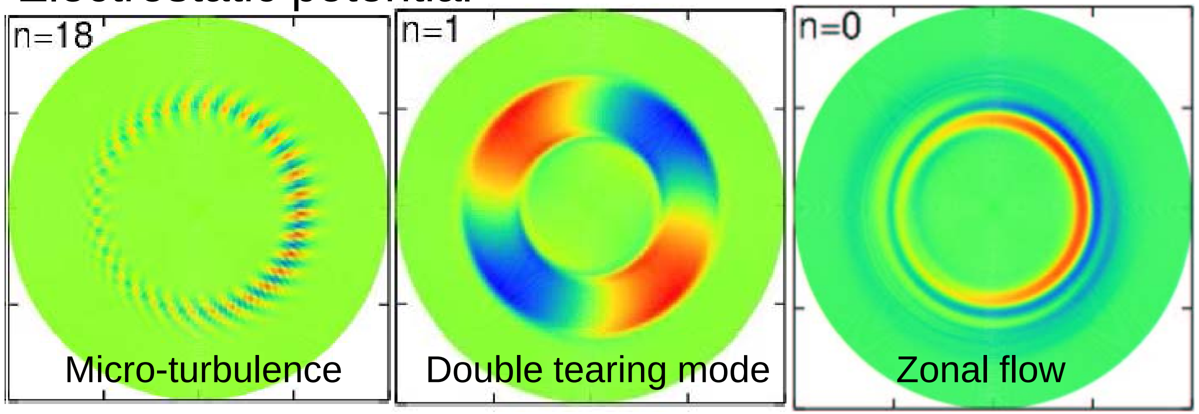


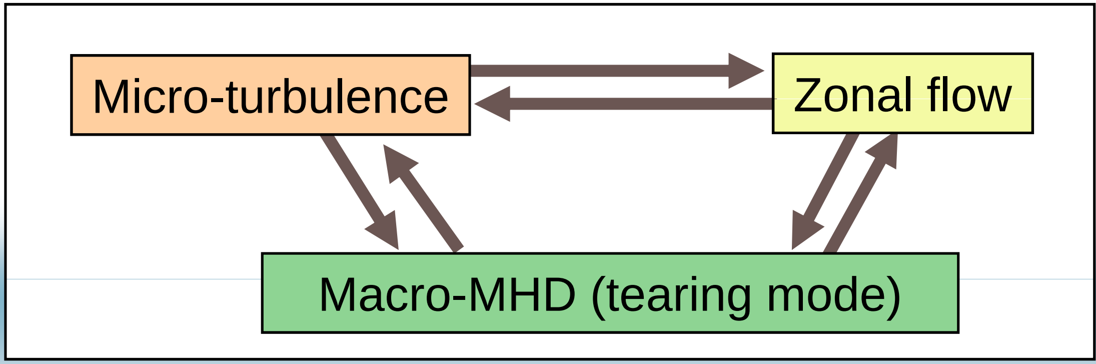
K. Tanaka, et al., Nuclear Fusion (2006)

Background and motivation II

- Our goal is to understand multi-scale-nonlinear interactions among micro-turbulence, macro-scale-MHD instabilities and zonal flows.

Electrostatic potential

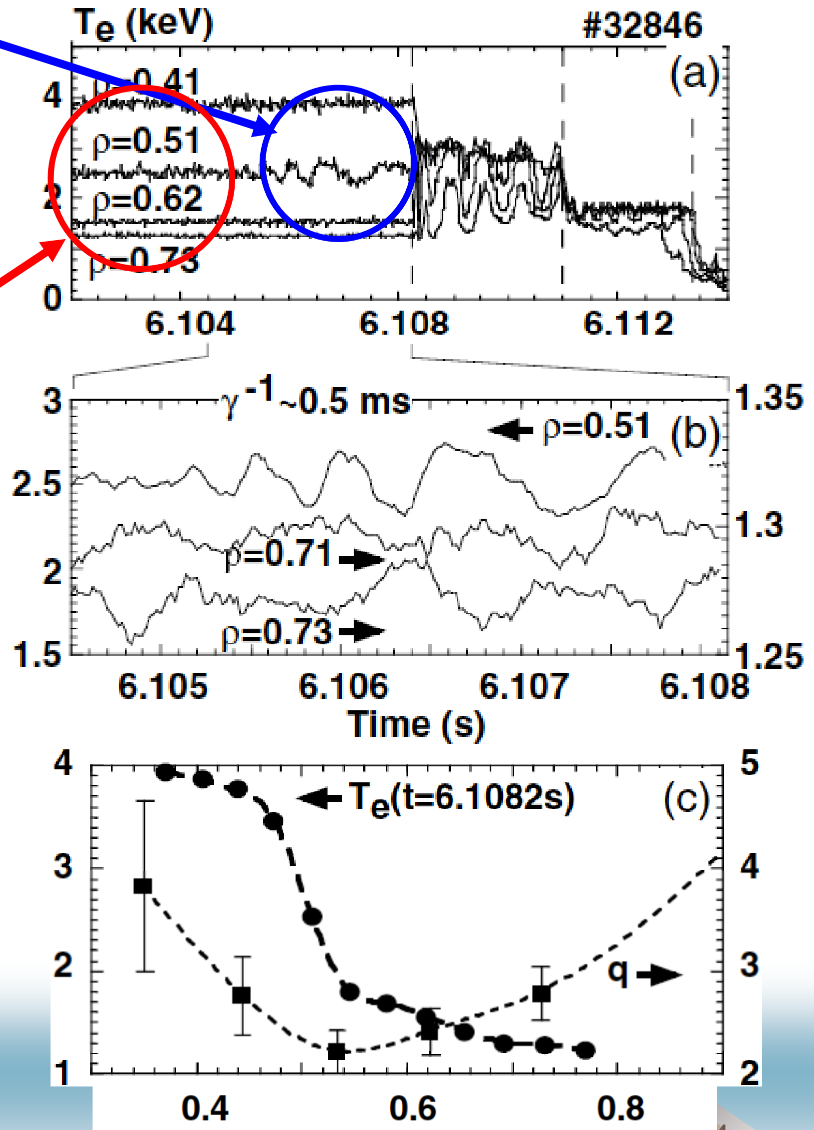




P.H. Diamond et.al., Phys. Fluids (1984)
D. Biskamp, Plasma Phys. Controlled Fusion (1984)
S.-I. Itoh et. al., Phys. Rev. Lett. (2003)
M. Yagi, et al., Nuclear Fusion (2005)
C.J. McDevitt et.al., Phys. Plasmas (2006)
A. Ishizawa and N. Nakajima, Phys. Plasmas (2007)

Background and motivation III

- Macro-scale MHD activities are observed in reversed shear plasmas with a transport barrier related to zonal flows and micro-turbulence.
- We think that micro-turbulence has already existed before macro-MHD instabilities arise, because micro-instabilities can appear without integer q surfaces. Thus, we consider a situation that macro-MHD mode appears in an equilibrium including turbulence and zonal flow.



Takeji, et.al., Nuclear Fusion (2002) ρ

Reduced two-fluid equations

$$
\begin{aligned}
n_{eq}\frac{d\nabla_\perp^2\Phi}{dt} &= -\nabla_{||}J - K[p] + \tilde{a}\nabla_\perp\cdot[\nabla_\perp\Phi, p_i] + \mu_Q\nabla_\perp^2\nabla_\perp^2\Phi,\\
\frac{dn}{dt} &= -n_{eq}\nabla_{||}v_{e||} + K[n_{eq}\Phi - p_e] + \mu_n\nabla_\perp^2 n,\\
n_{eq}\frac{dv_{||}}{dt} &= -\nabla_{||}p + \mu_v\nabla_\perp^2 v_{||},\\
\beta\frac{\partial\psi}{\partial t} &= -\nabla_{||}\Phi + \frac{1}{n_{eq}}\nabla_{||}p_e + \eta_L v_{e||} + \eta J,\\
\frac{dT_i}{dt} &= -(\Gamma-1)(T_{eq}\nabla_{||}v_{||} + \kappa_L T_i)\\
&\quad + T_{eq}K[(\Gamma-1)(\Phi + T_i + T_{eq}n/n_{eq}) + \Gamma T_i] + \mu_T\nabla_\perp^2 T_i,
\end{aligned}
$$

$df/dt = \partial f/\partial t + \tilde{a}[\Phi, f]$

$\nabla_{||}f = \epsilon\partial f/\partial\zeta - \beta\tilde{a}[\psi, f]$

$K[f] = 2\epsilon[r\cos\theta, f]$

$\kappa_L = \sqrt{\frac{8T_{eq}}{\pi}}\,\nabla_{||}$

$\eta_L = (\pi\tau m_e/2m_i)^{1/2}|\nabla_{||}|$

$J = \nabla_\perp^2\psi \quad \psi = \psi_{eq} + \tilde{\psi}/\tilde{a} \quad \Phi = \tilde{\Phi}/\tilde{a}$

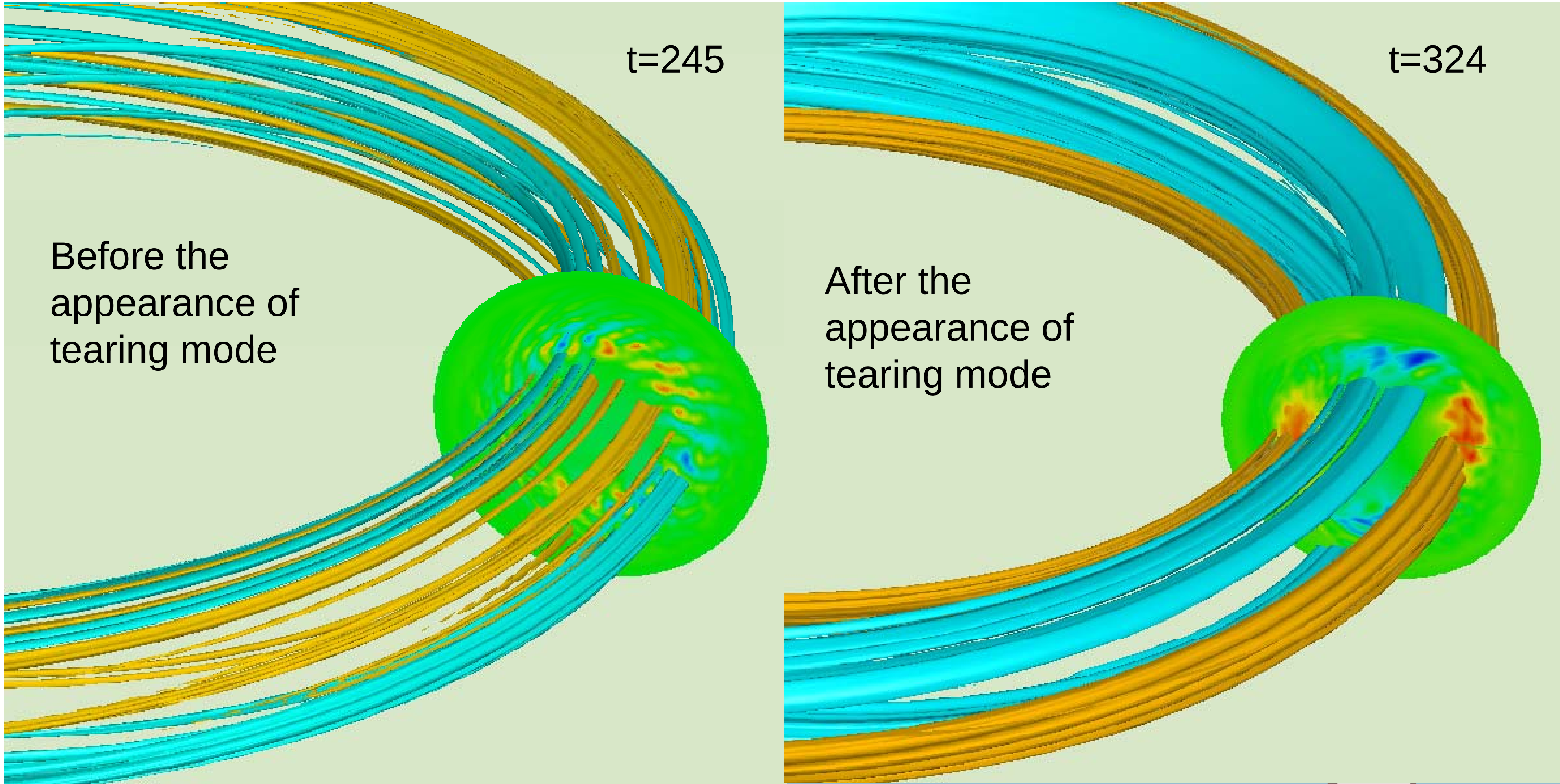
$p = p_i + p_e \quad p_e = \tau n_{eq}T_{eq} + \tau T_{eq}\tilde{n}/\tilde{a} \quad \tilde{a} = a/\rho_i$

$p_i = n_{eq}T_{eq} + T_{eq}\tilde{n}/\tilde{a} + n_{eq}\tilde{T}_i/\tilde{a}$

$v_{e||} = v_{||} + J/n_{eq} \quad n = n_{eq} + \tilde{n}/\tilde{a}$

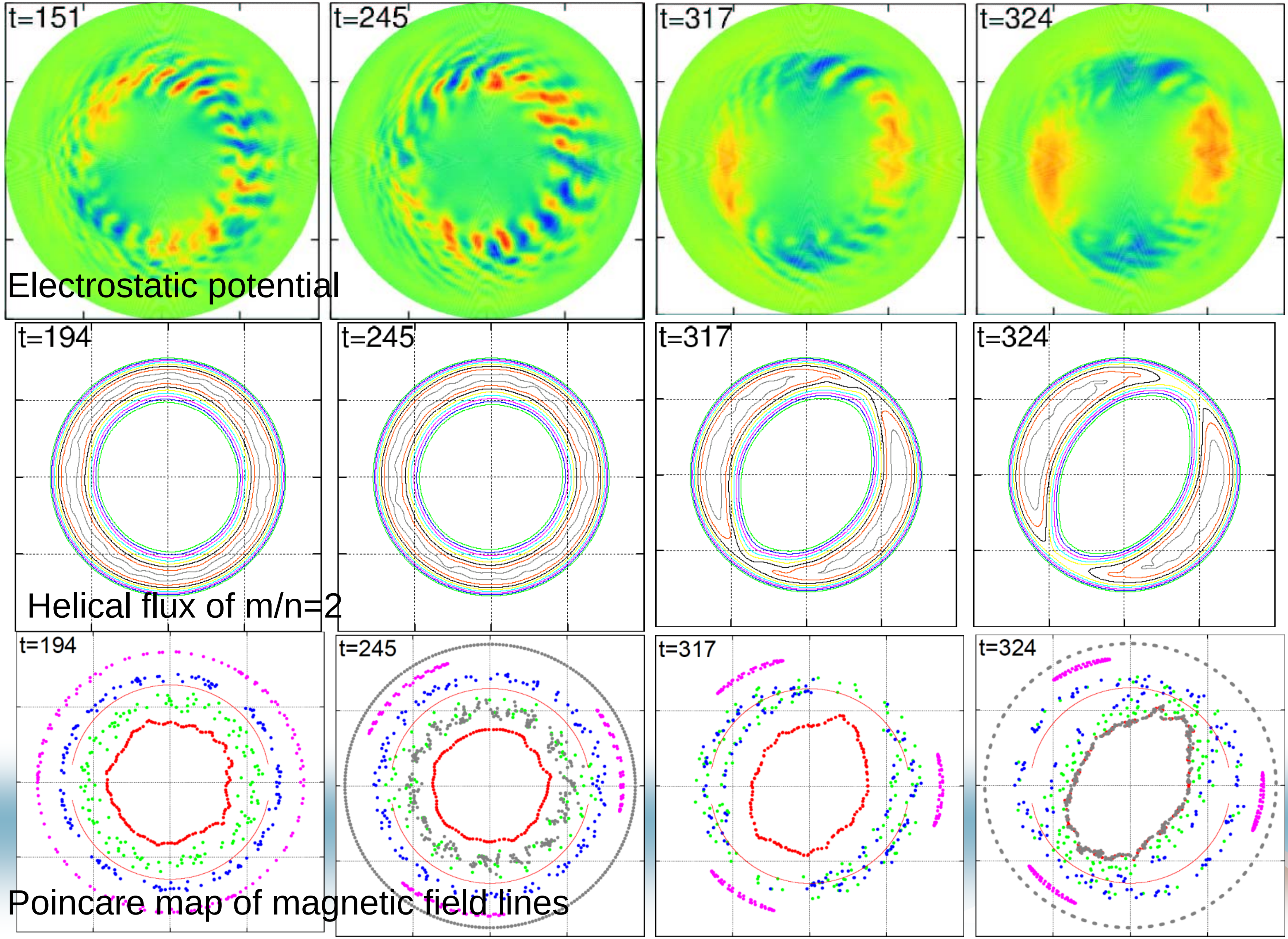
$T_i = T_{eq} + \tilde{T}_i/\tilde{a}$

Potential profile is changed by the appearance of macro-MHD mode

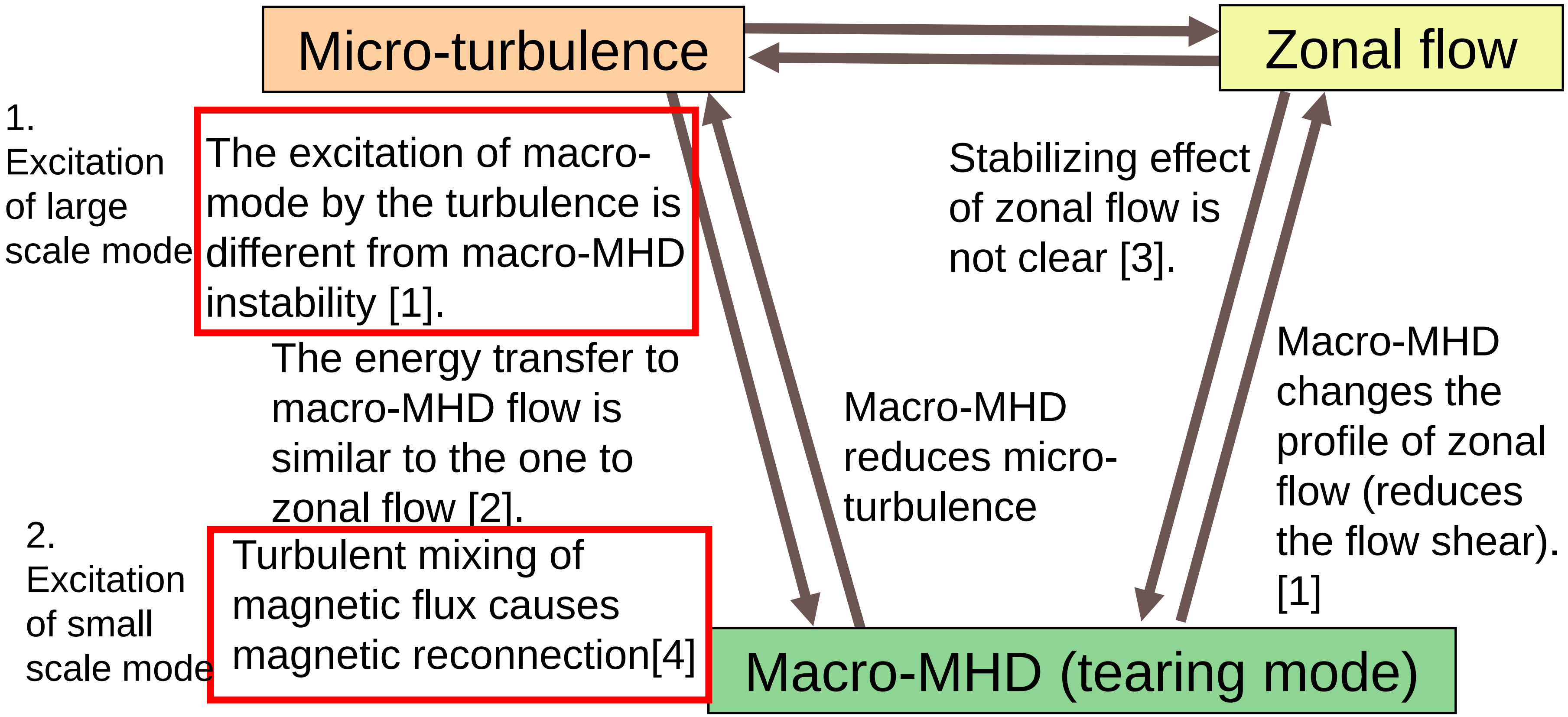


Ballooning structure of potential is altered by tearing mode.

Micro-turbulence and magnetic islands



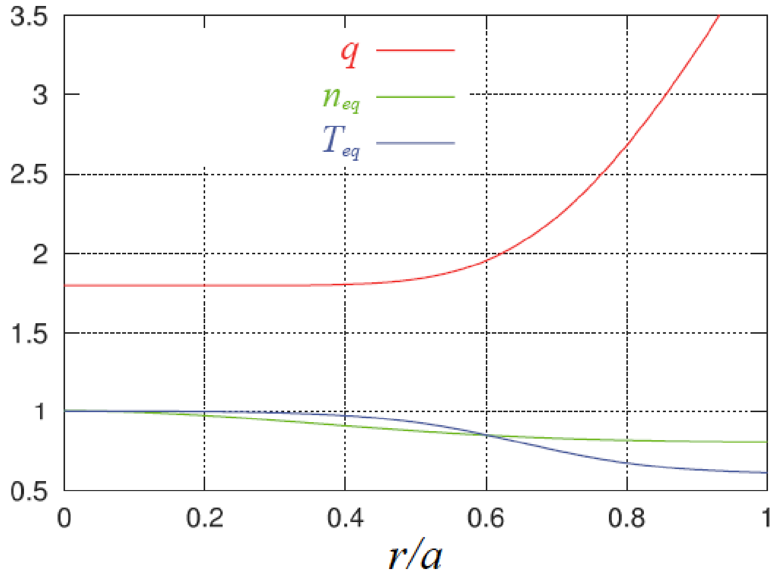
Our previous research on multi-scale interaction



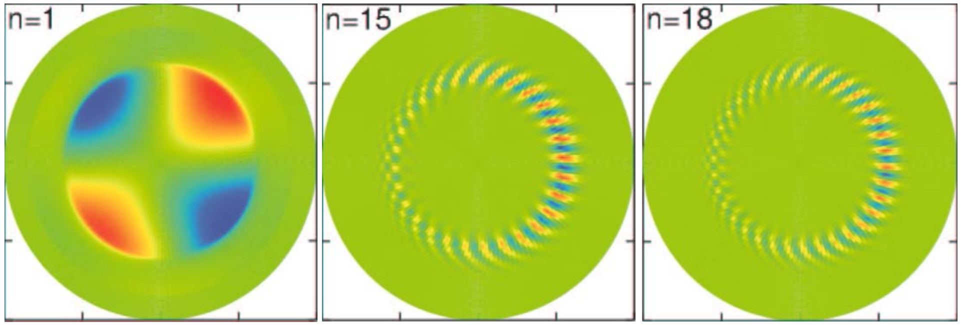
[1] A. Ishizawa and N. Nakajima, Phys. Plasmas (2007)
[2] A. Ishizawa and N. Nakajima, Nuclear Fusion (2007)
[3] A. Ishizawa and N. Nakajima, Phys. Plasmas (2008)
[4] A. Ishizawa and N. Nakajima, AIP Conf. Proc. (2008)

2. Excitation of large scale mode by micro-turbulence

Linear analysis



Linear eigen function

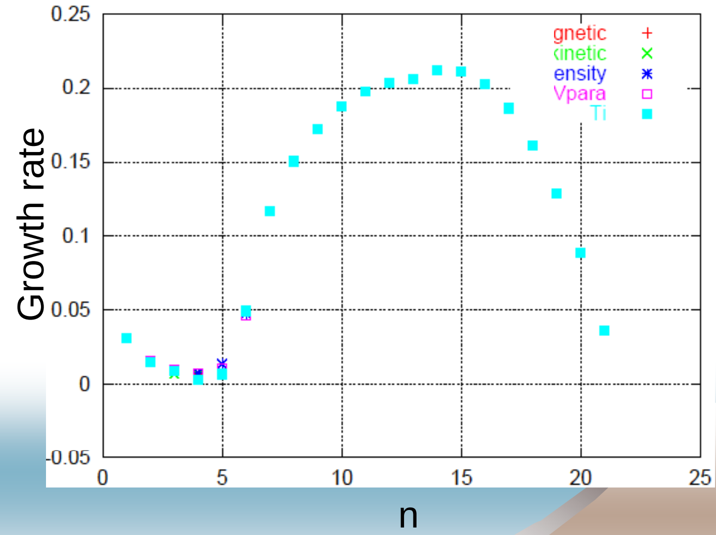


Macro-instability: Tearing mode
Micro-instability: Kinetic ballooning mode

$\beta = 0.01$ $\quad \nu = 2\times 10^{-12} m^4$

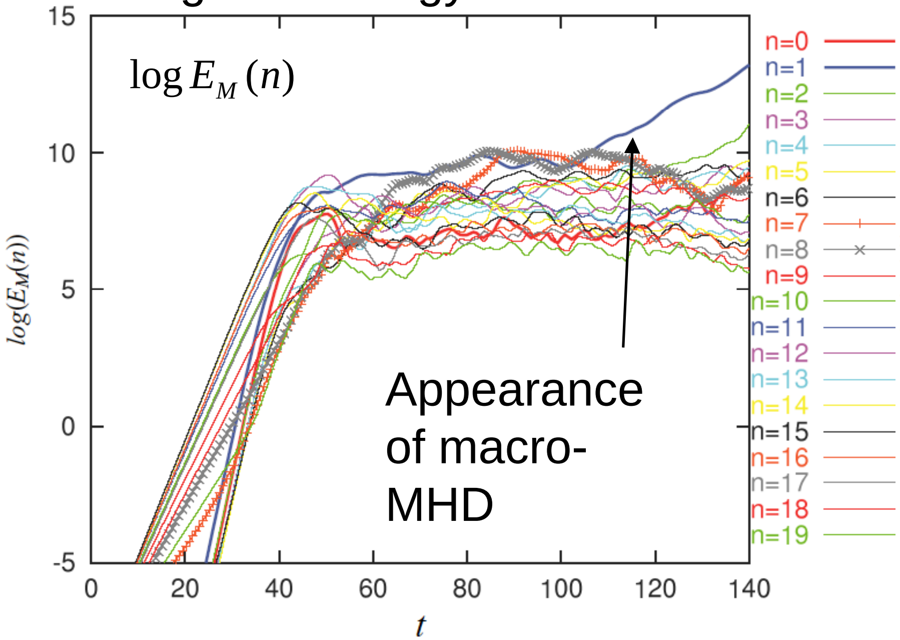
$\rho_i / a = 1/80$ $\quad S = 1.6\times 10^6$

$N_m \times N_n \times N_r = 256\times 128\times 256$

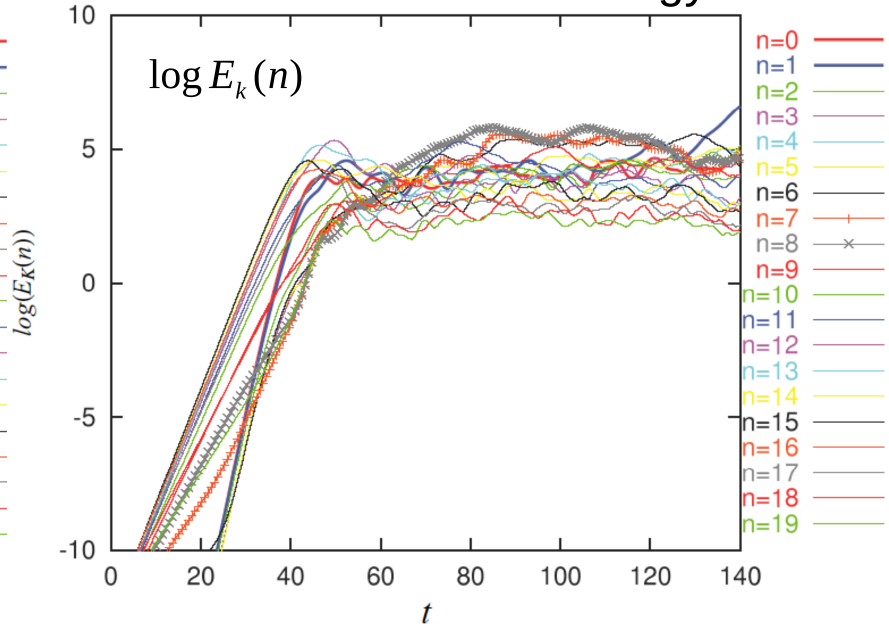


Appearance of macro-MHD mode in micro-turbulence

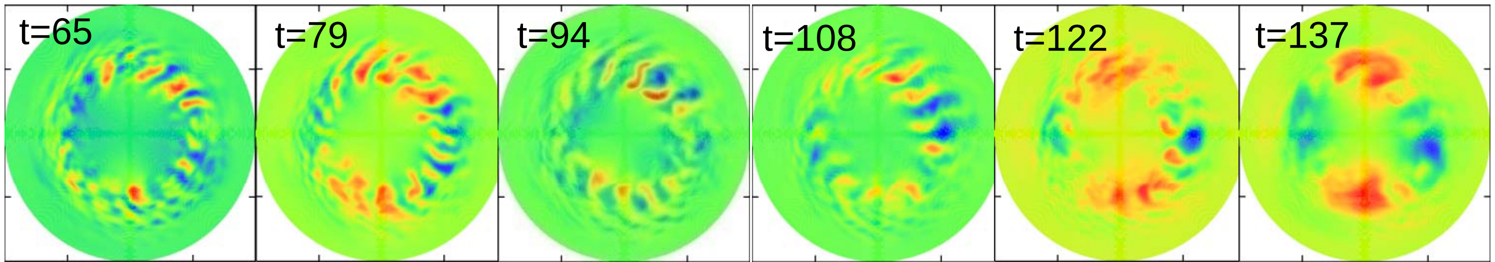
Magnetic energy



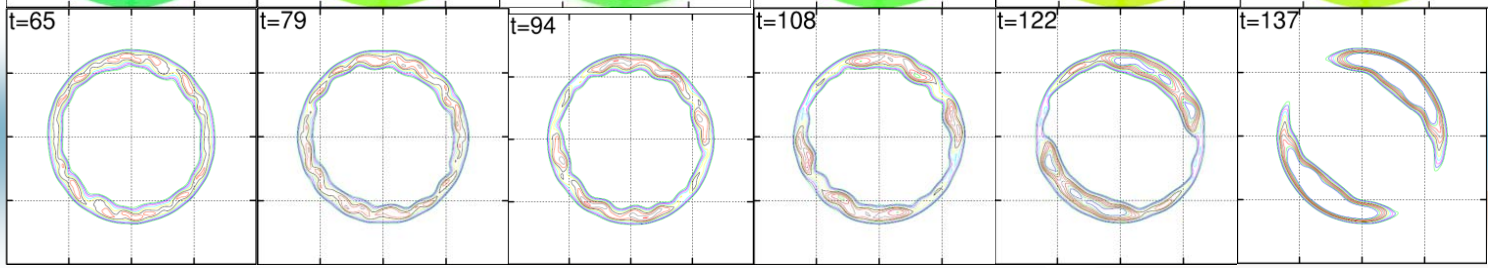
Kinetic energy



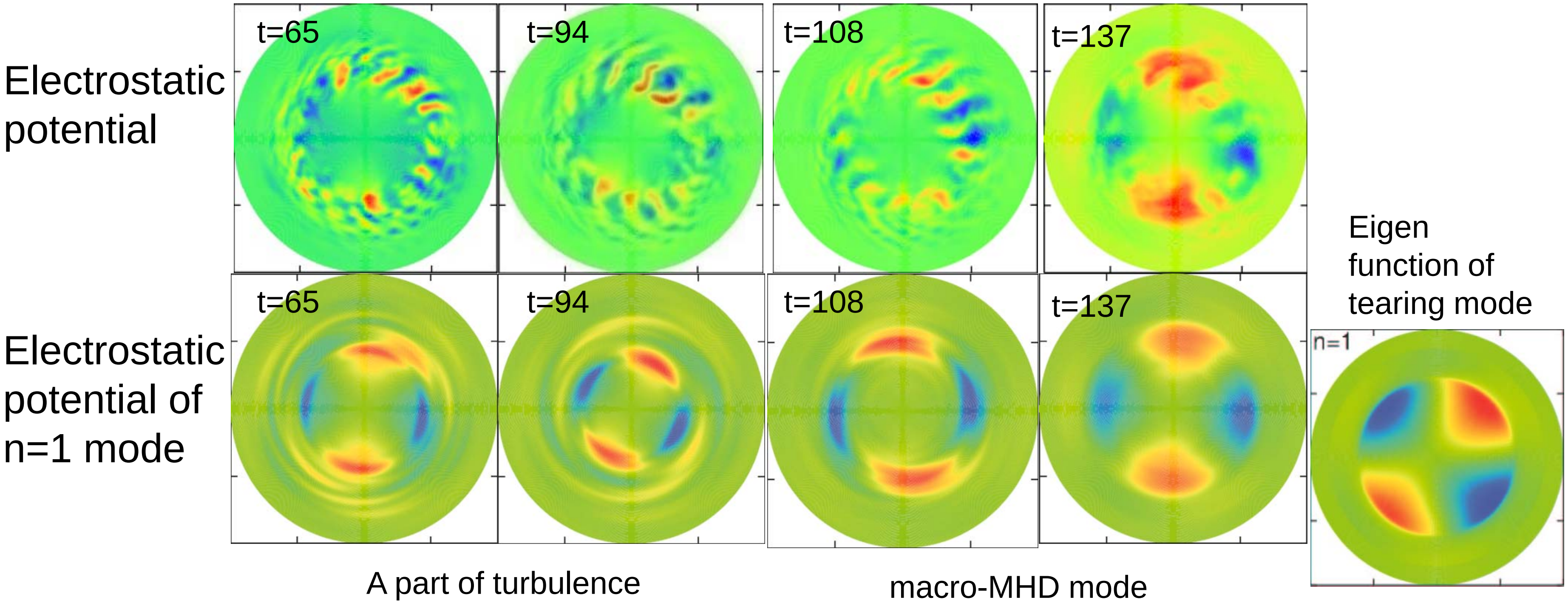
Electrostatic potential



Helical flux function of m/n=2

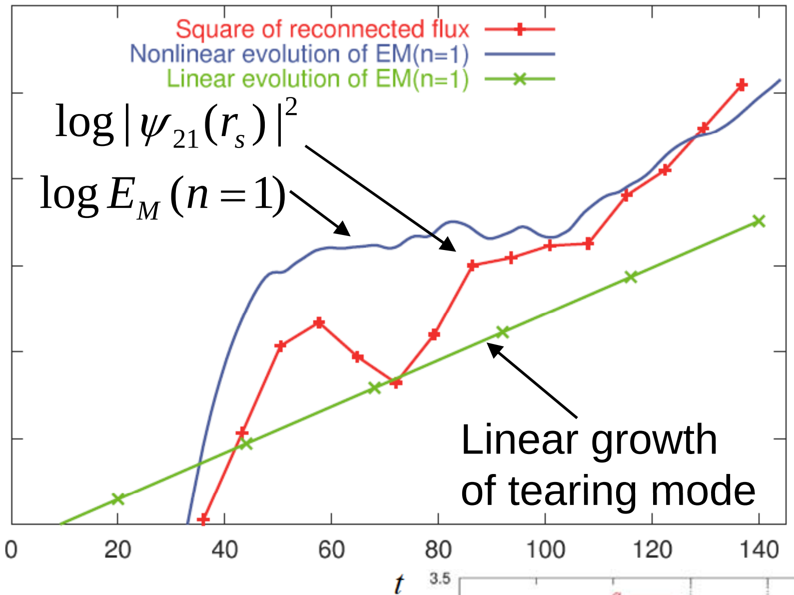


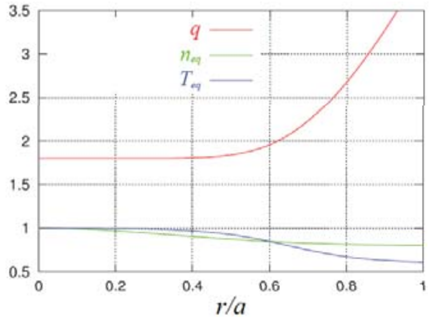
Excitation of n=1 mode by micro-turbulence

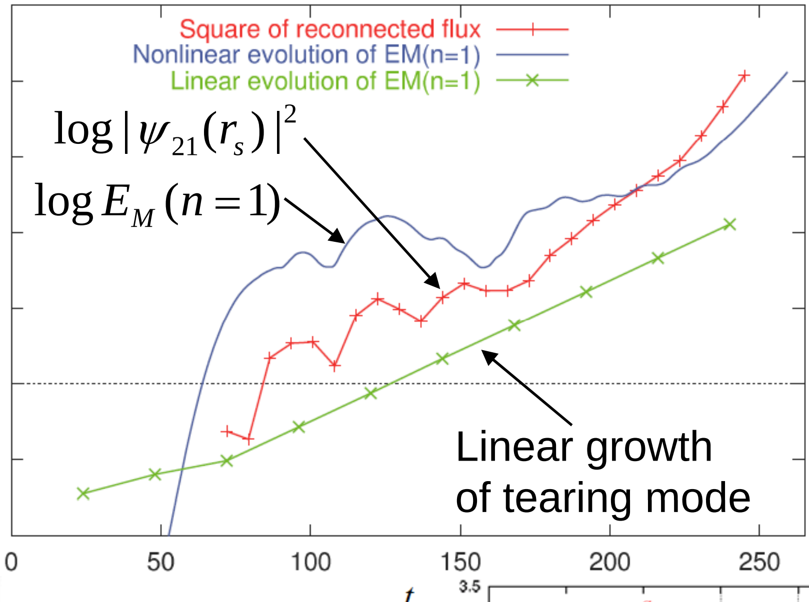


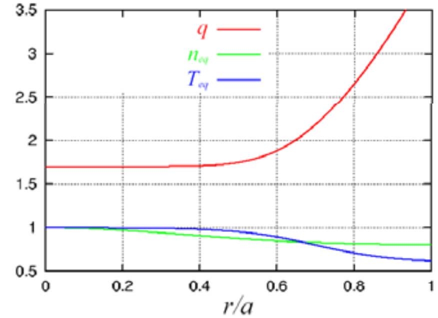
Nonlinear mode coupling of micro-scale turbulence causes macro-scale mode at t=60, but it is different from the macro-MHD instability because the spatial profile of induced macro-scale mode is significantly different from the profile of double tearing mode.

Reconnected flux









The excited n=1 mode causes magnetic reconnection that is the initial perturbation of tearing mode.

3. Excitation of small-scale mode by micro-turbulence

Turbulent mixing of magnetic flux

$$\beta \frac{\partial \psi}{\partial t} = -\nabla_{//}\Phi + \frac{1}{n_{eq}}\nabla_{//} p_e + \eta_L v_{e//} + \eta J$$

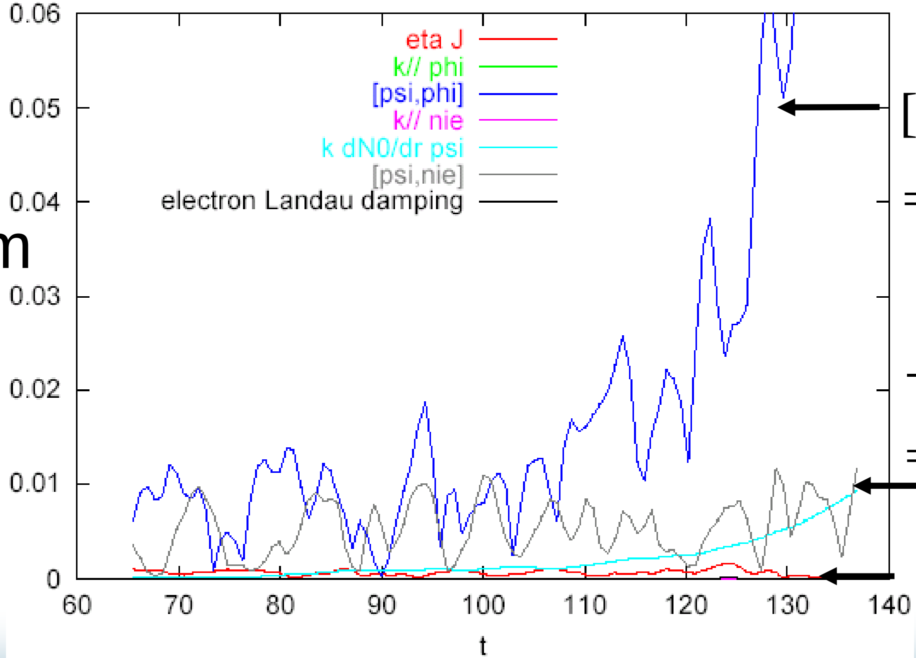
Equation of (m,n)=(2,1) mode on the resonant surface of tearing mode

$$\beta \frac{\partial \tilde{\psi}_{21}}{\partial t} = \underbrace{\beta[\tilde{\psi},\tilde{\Phi}]_{21} - \frac{\beta}{n_{eq}}[\tilde{\psi},\tilde{p}_e]_{21}}_{\text{Turbulent mixing terms}} + \underbrace{\beta[\tilde{\psi},\tilde{\Phi}_{00}]_{21} - \beta\tilde{a}[\tilde{\psi}, p_{eeq}]_{21}}_{\text{Rotation of island}} + \eta\tilde{J}_{21}$$

$$f = f_{eq} + \tilde{f}/\tilde{a}$$

$$\tilde{a} = a/\rho_i$$

Absolute value of each term



$$[\tilde{\psi},\tilde{\Phi}]_{21} = -(\tilde{\mathbf{v}}_{ExB}\cdot\nabla\tilde{\psi})_{21}$$

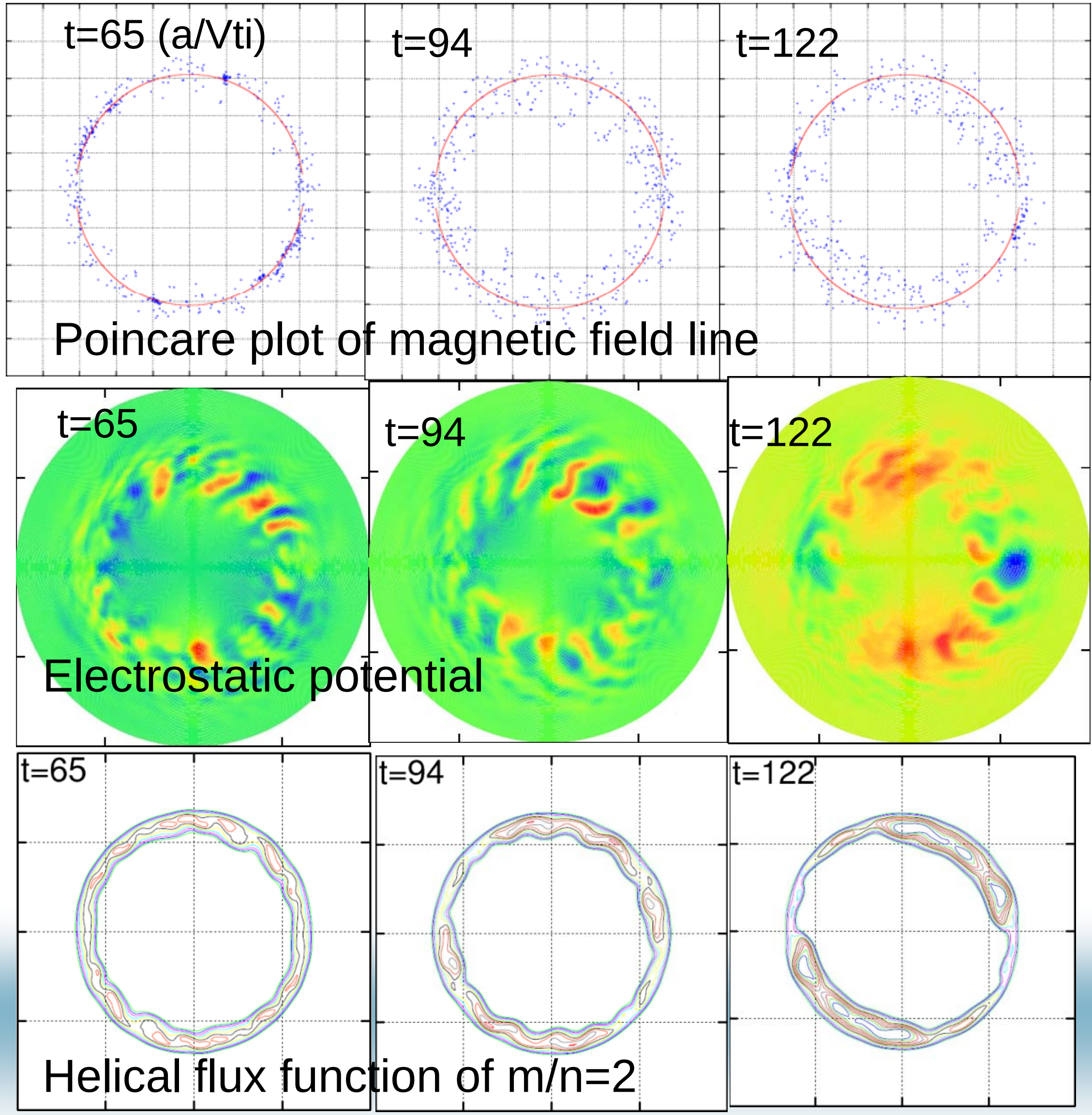
$$-[\tilde{\psi},\tilde{p}_e]_{21} = (\tilde{\mathbf{v}}_{De}\cdot\nabla\tilde{\psi})_{21}$$

Turbulent mixing

ηJ_{21} Normal resistivity

Turbulent flow mixing terms are much larger than normal resistivity and causes magnetic reconnection of tearing mode.

Stochastic field lines: Small scale reconnections take place on the resonant surface



$$[\tilde{\psi}, \tilde{\Phi}]_{21} = -(\tilde{\nabla}_{//}\tilde{\Phi})_{21}$$

$$[\tilde{\psi}, \tilde{p}_e]_{21} = -(\tilde{\nabla}_{//}\tilde{p}_e)_{21}$$

Magnetic surface is broken and magnetic field lines are stochastic at the resonant surface of macro-MHD. This is similar to anomalous growth of tearing modes reported in Waddell (1978), Diamond (1984).

4. Summary

- We have found that macro-scale MHD appears in a quasi-equilibrium including micro-turbulence and zonal flow.
- Effect of turbulence on macro-MHD instability
  - Excitation of large scale modes
    - Nonlinear mode coupling of micro-scale turbulence causes macro-scale mode, but it is different from the macro-MHD instability because the spatial profile of induced macro-scale mode is significantly different from the profile of eigen-function of tearing mode.
  - Excitation of small scale modes
    - Turbulent flow mixing terms are much larger than normal resistivity term and play an important role in the growth of non-ideal macro-MHD mode.
  - Both of them affect tearing mode because it is long wave length and non-ideal MHD instability.