Multi-scale interactions among macro-MHD, micro-turbulence and zonal flows

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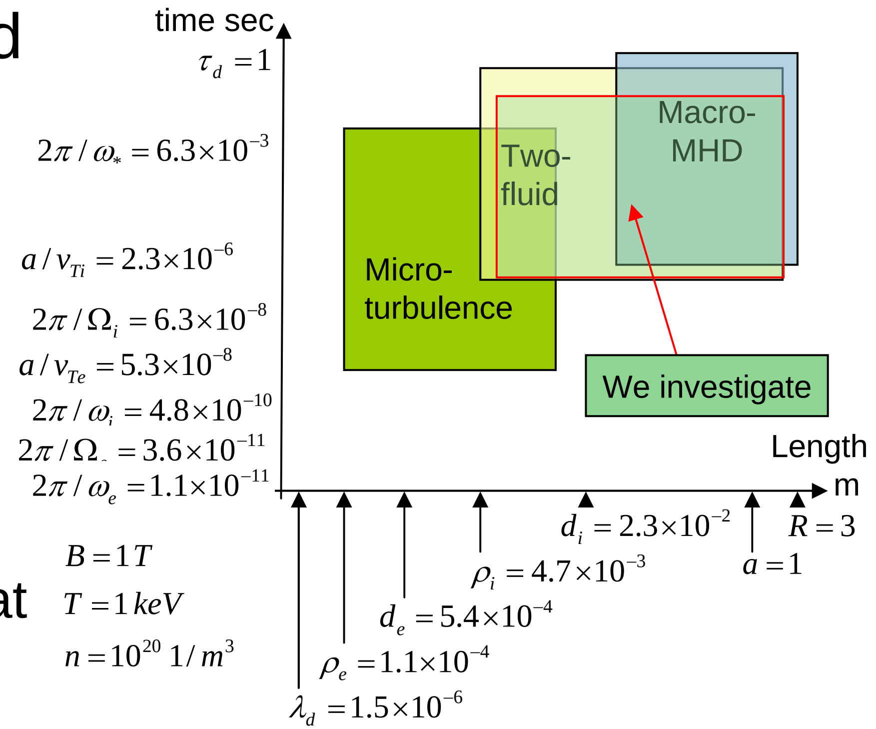
Background and motivation

- 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.
  - Micro-turbulence is observed in Large Helical Device plasmas that usually exhibit MHD activities.

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

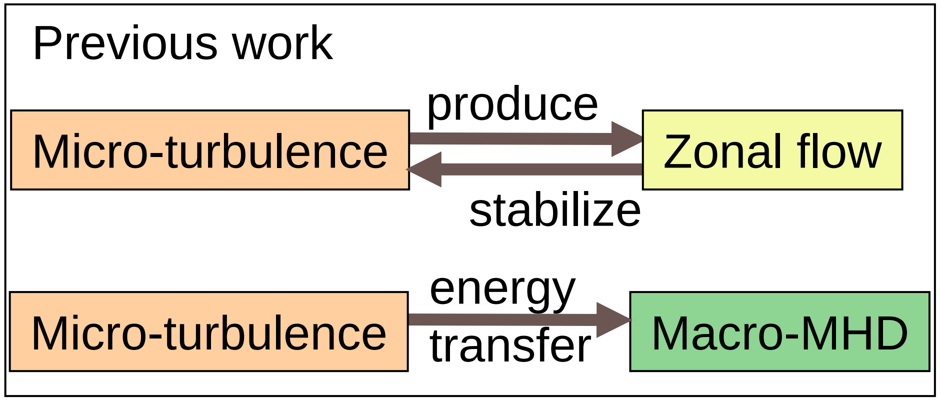
  - MHD activities are observed in reversed shear plasmas with a transport barrier related to zonal flows and micro-turbulence.

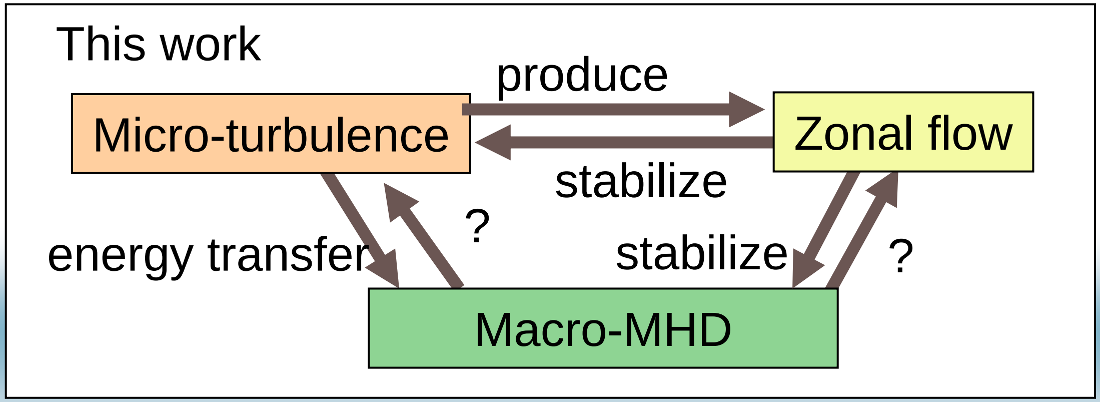
    Takeji, et.al., Nuclear Fusion (2002)



Background and motivation II

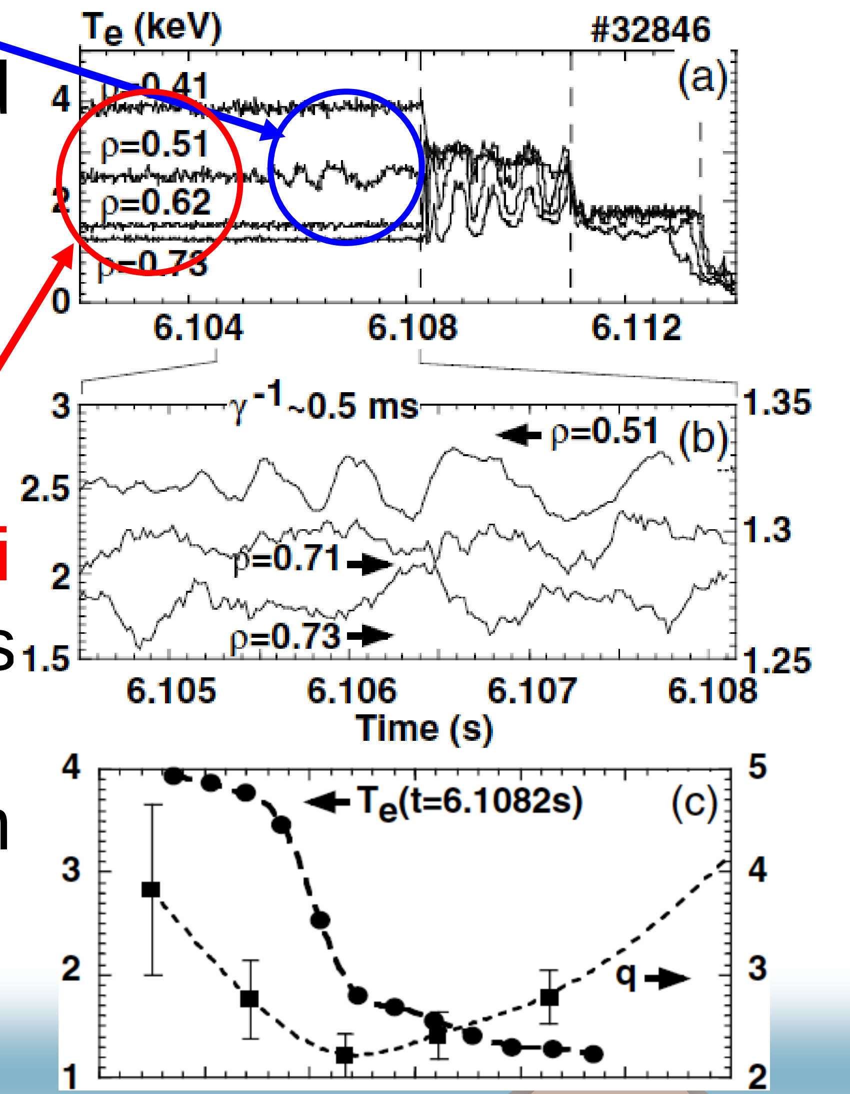
- Our goal is to understand multi-scale-nonlinear interactions among micro-instabilities, macro-scale-MHD instabilities and zonal flows.





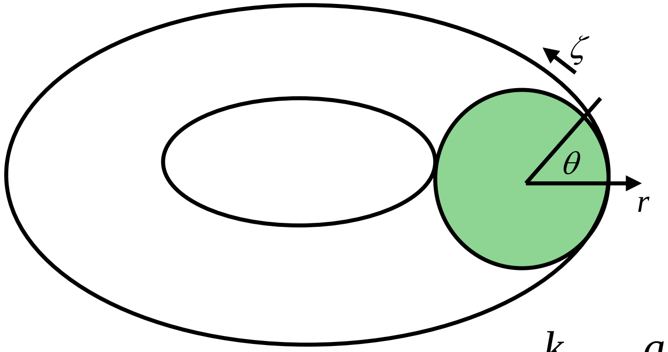
Background and motivation III

- MHD activities are observed in reversed shear plasmas with a transport barrier related to zonal flows and micro-turbulence.
- We will make an initial quasi equilibrium that corresponds to the equilibrium in the experiment. This equilibrium can be formed by a balance between micro-turbulence and zonal flow.



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

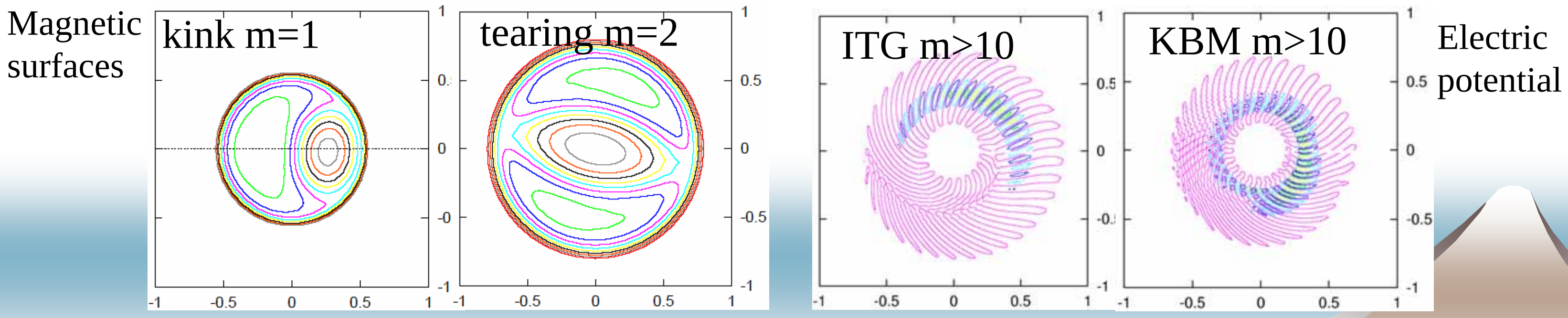
Reduced two-fluid equations



- Basic assumptions
  - Flute approximation
  - Large aspect ratio
  - High-beta ordering

$$\frac{k_{//}}{k_{\perp}} \approx \frac{a}{R} \approx \beta \approx \varepsilon$$

- Extends the standard four-field model by including temperature gradient effects.
- We can describe the nonlinear evolution of tearing modes, interchange modes, ballooning modes and ion-temperature gradient modes.



Reduced two-fluid equations

$$\frac{d}{dt}n = -n_{eq}\nabla_{//}v_{e//} + \mathrm{K}(n_{eq}\Phi - \tilde{d}_i\beta p_e)$$

$$n_{eq}\frac{d}{dt}v_{//} = -\beta\nabla_{//}p$$

$$n_{eq}\frac{d}{dt}Q = -\nabla_{//}J - \beta\mathrm{K}(p) + \tilde{d}_i\beta\nabla_{\perp}\cdot[\nabla_{\perp}\Phi, p_i]$$

$$\frac{\partial}{\partial t}A = -\nabla_{//}\Phi + \tilde{d}_i\beta\nabla_{//}p_e + \eta_L v_{e//} + \eta J$$

$$\frac{d}{dt}T_i = -(\Gamma-1)T_{eq}\nabla_{//}v_{//} - (\Gamma-1)\kappa_L\tilde{T}_i$$
$$-T_{eq}\mathrm{K}((\Gamma-1)(\tilde{\Phi} + \tilde{d}_i\beta\tilde{T}_i + \tilde{d}_i\beta T_{eq}/n_{eq}\tilde{n}) + \Gamma\tilde{d}_i\beta\tilde{T}_i)$$

$$Q = \nabla_{\perp}^2\Phi$$

$$J = \nabla_{\perp}^2 A = -J_{//}$$

$$T = T_i + T_e$$

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

$$T_e = \tau T_{eq}$$

$$n = n_{eq} + \tilde{n}$$

$$p = p_i + p_e = Tn =$$
$$= (1+\tau)n_{eq}T_{eq} + (1+\tau)T_{eq}\tilde{n} + n_{eq}\tilde{T}_i$$

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

$$p_e = T_e n = \tau T_{eq}n_{eq} + \tau T_{eq}\tilde{n}$$

$$v_{e//} = \tilde{v}_{//} + \tilde{d}_i\tilde{J}/n_{eq}$$

$$\tilde{d}_i = \tilde{\rho}_i/\sqrt{\beta}$$

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

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + [\Phi, f] = \frac{\partial f}{\partial t} + \mathbf{v}_E\cdot\nabla, \quad \Phi: electric\ potential, \quad \mathbf{v}_E = \mathbf{b}\times\nabla\Phi$$

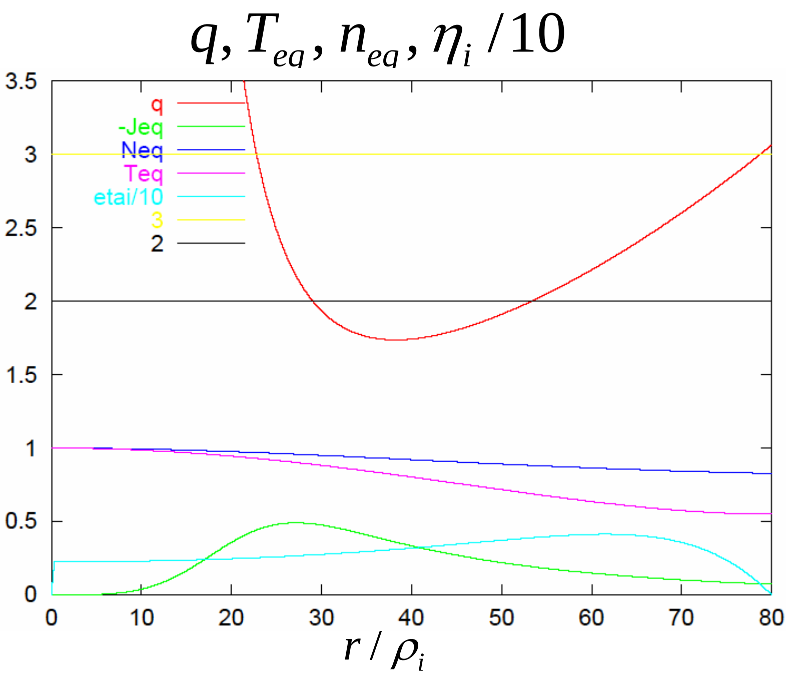
$$\mathrm{K}(f) = 2\varepsilon[r\cos\theta, f], \quad \nabla_{//}f = \varepsilon\partial_{\zeta} - [A, f]$$

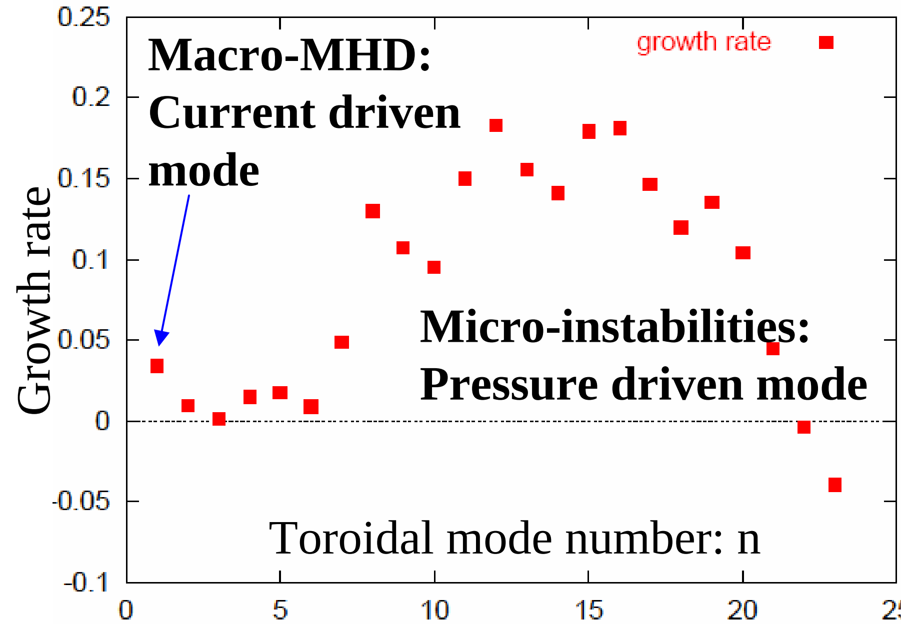
$$\eta_L = \tilde{\rho}_i\sqrt{\frac{\pi}{2}\tau\frac{m_e}{m_i}}|\varepsilon k_{//}|$$

$$f = \sum_{m,n} f_{m,n}(r,t)\exp(im\theta - in\zeta)$$

$$\kappa_L = \sqrt{\frac{8T_{eq}\beta}{\pi}}|\varepsilon k_{//}|$$

Initial equilibrium and linear analysis





$\beta = 0.01$

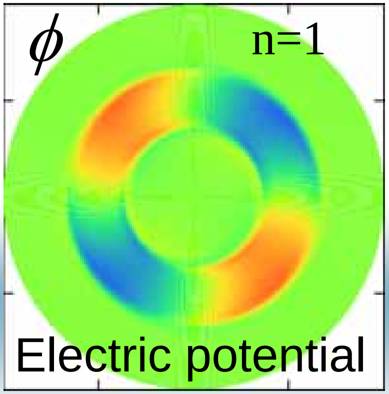
$\tilde{\rho}_i = 1/80$

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

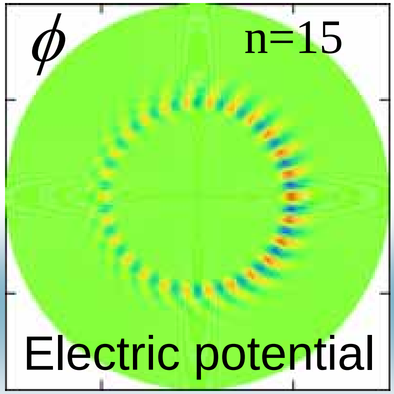
$S = 1.6 \times 10^6$

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

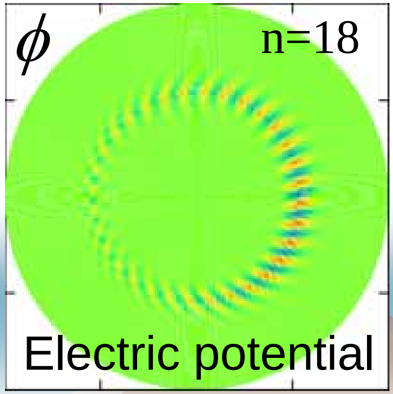
Macro-scale MHD
Double tearing mode



Micro-instability
Kinetic ballooning mode

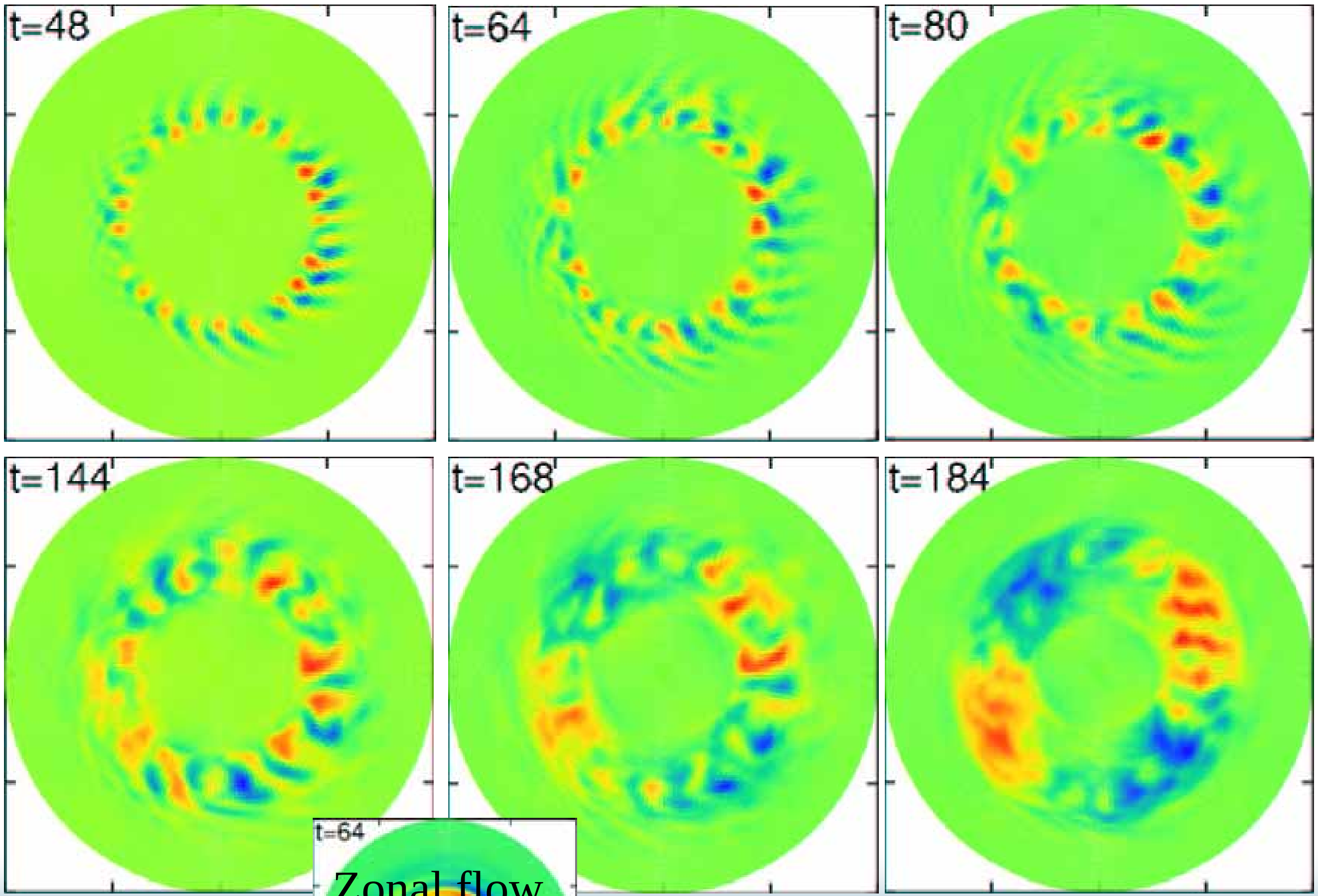


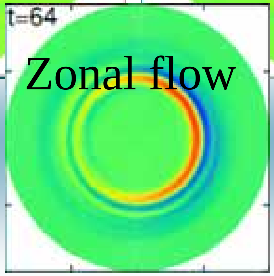
Micro-instability
Kinetic ballooning mode

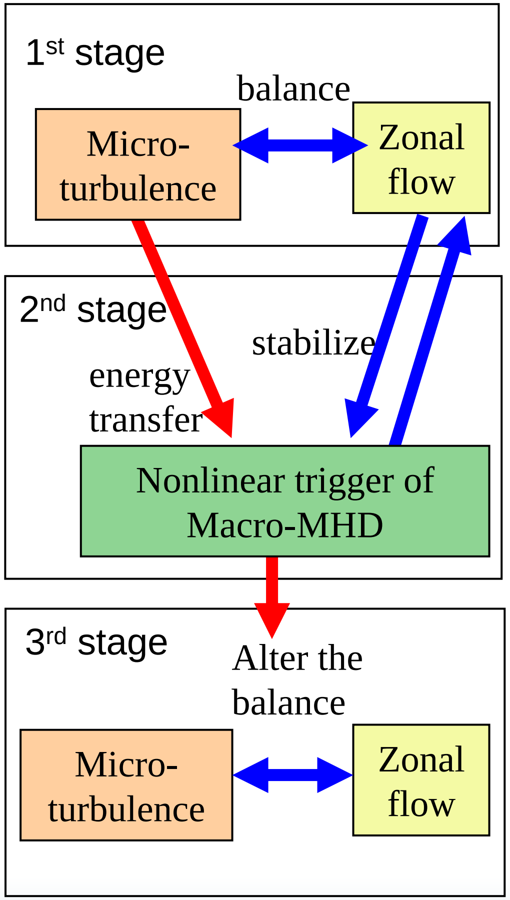


Overview of multi-scale-nonlinear interaction

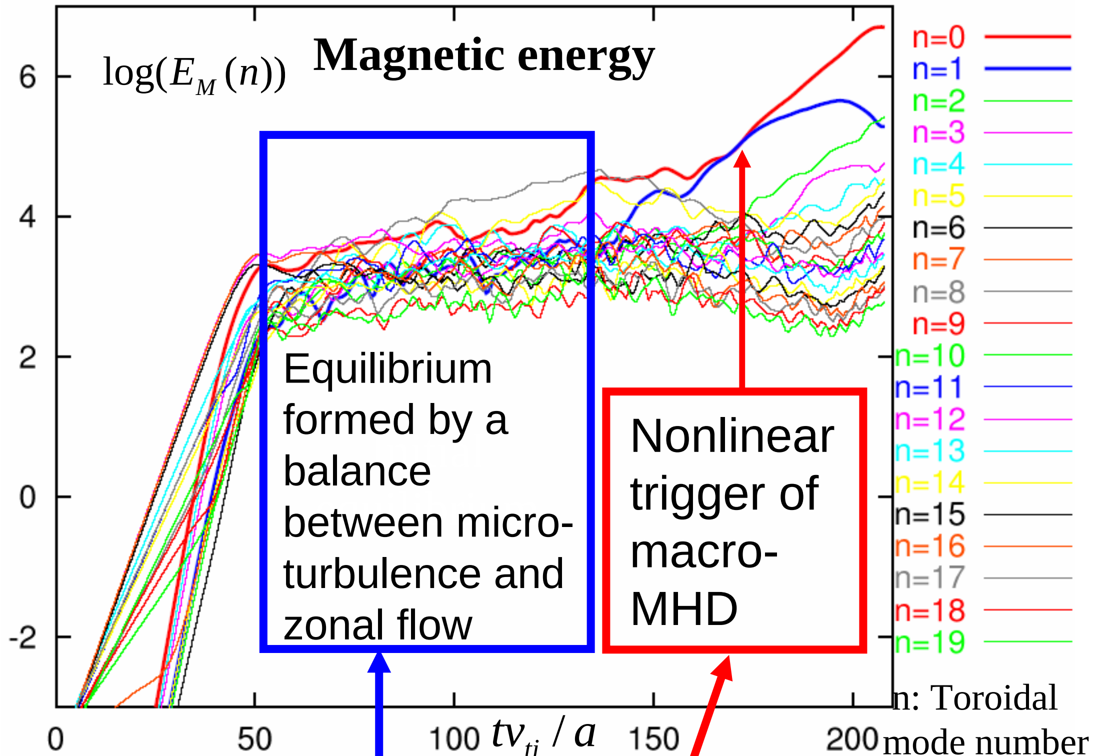
Electric potential

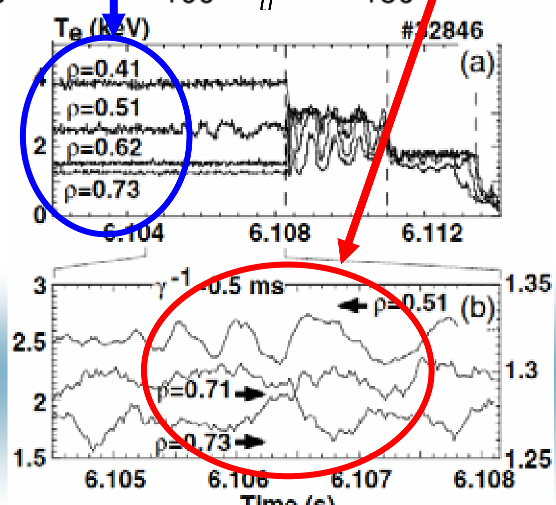




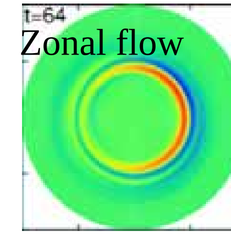


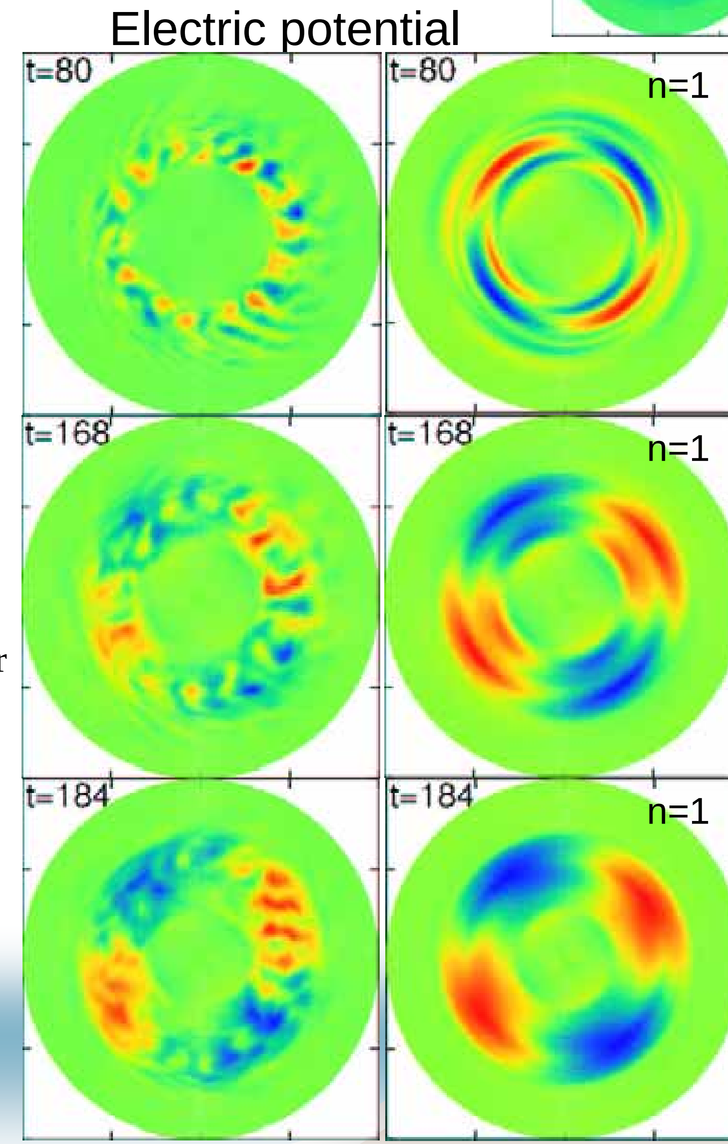
Excitation of macro-MHD



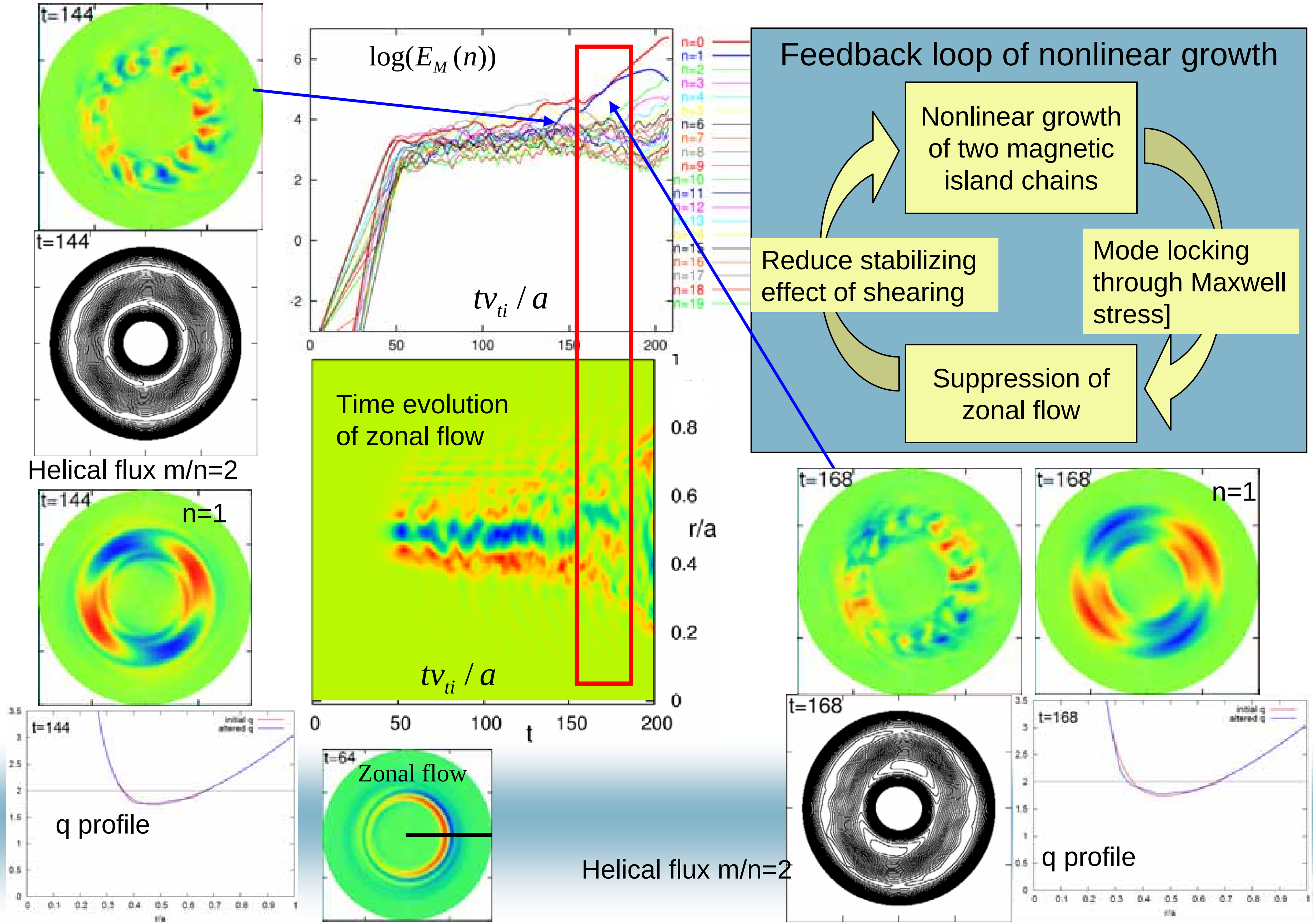


Takeji, et.al., Nuclear Fusion (2002)

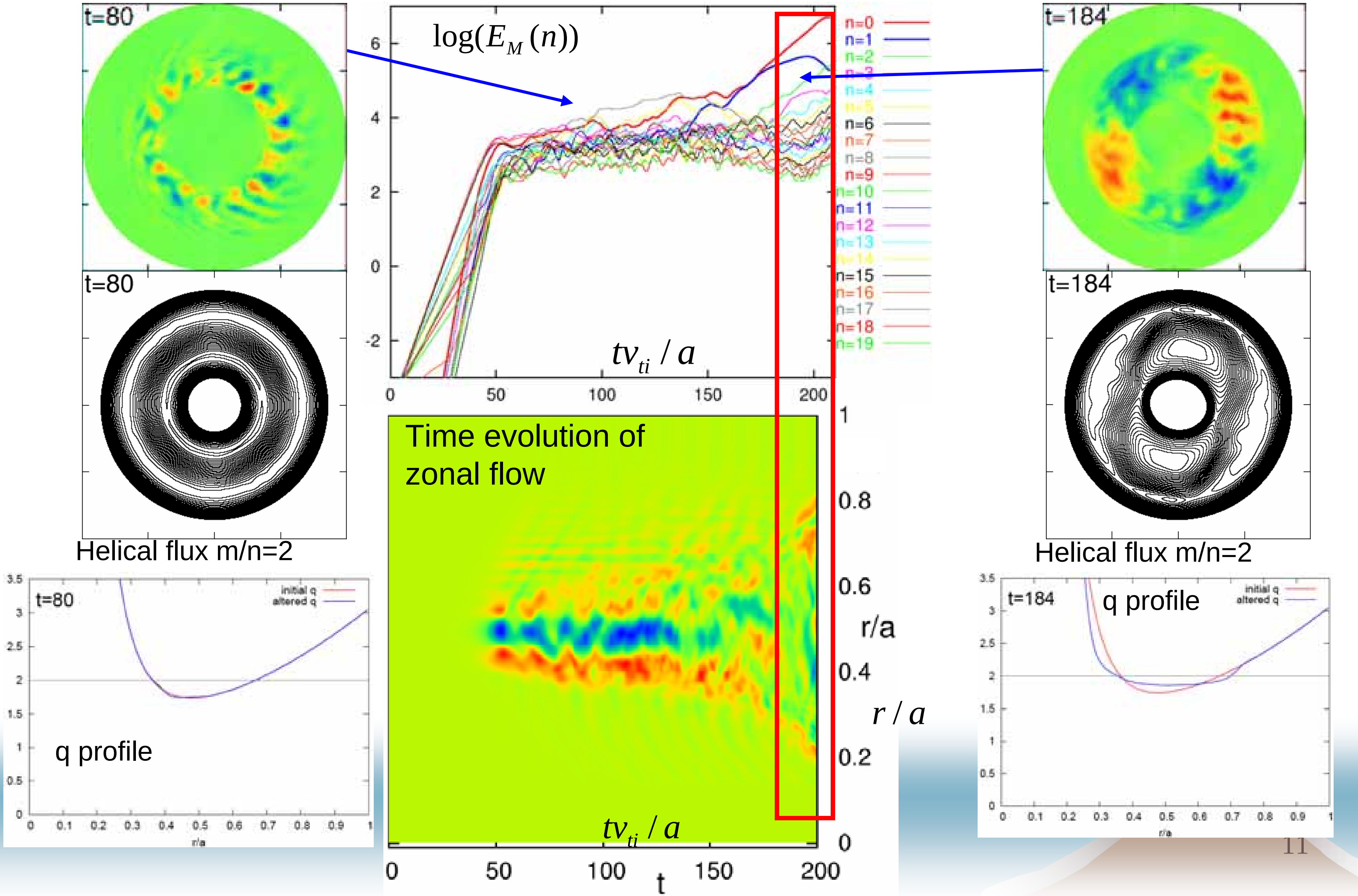




Mechanism of the excitation

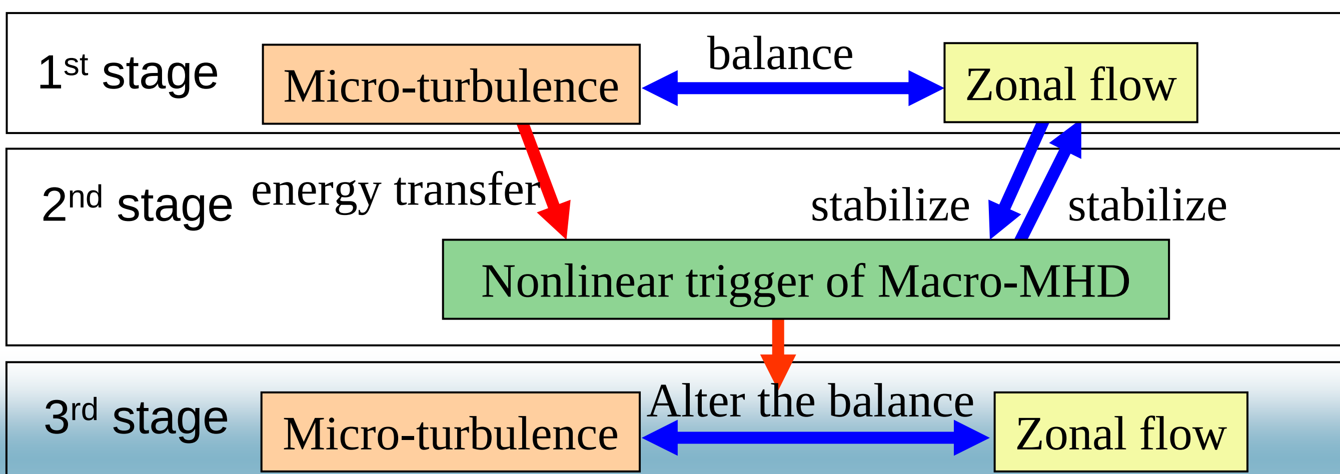


Macro-MHD changes the balance between turbulence and zonal flow



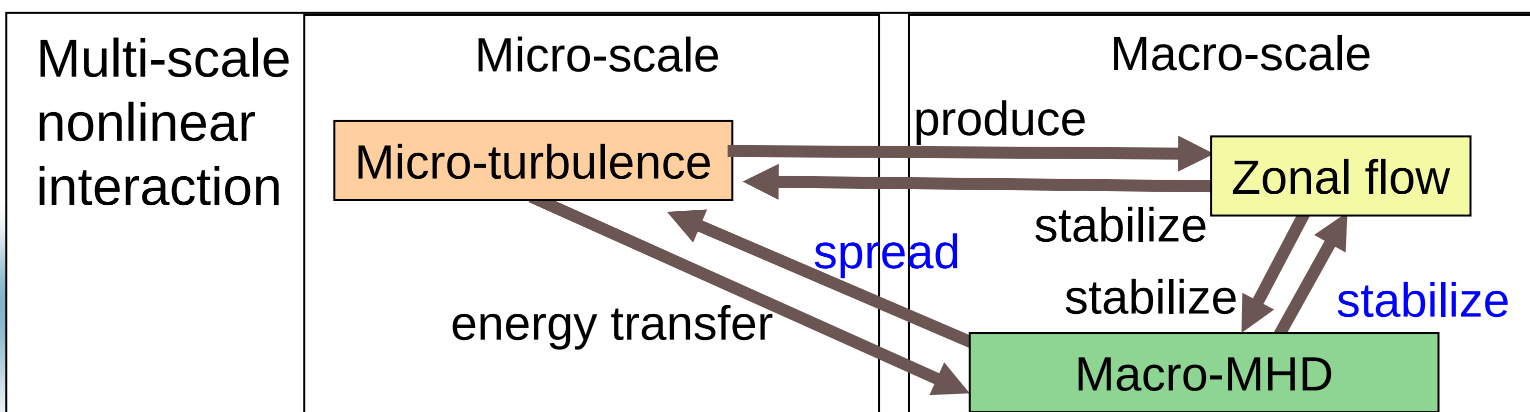
Summary

- We find that macro-scale MHD is nonlinearly triggered after a quasi-equilibrium is formed by a balance between micro-turbulence and zonal flow.
- This appearance of macro-MHD can explain the growth of macro-MHD fluctuation observed in tokamak experiment[1]. [1] Takeji, et.al., Nuclear Fusion (2002)
- This MHD activity alters the balance and spreads the turbulence over the plasma.

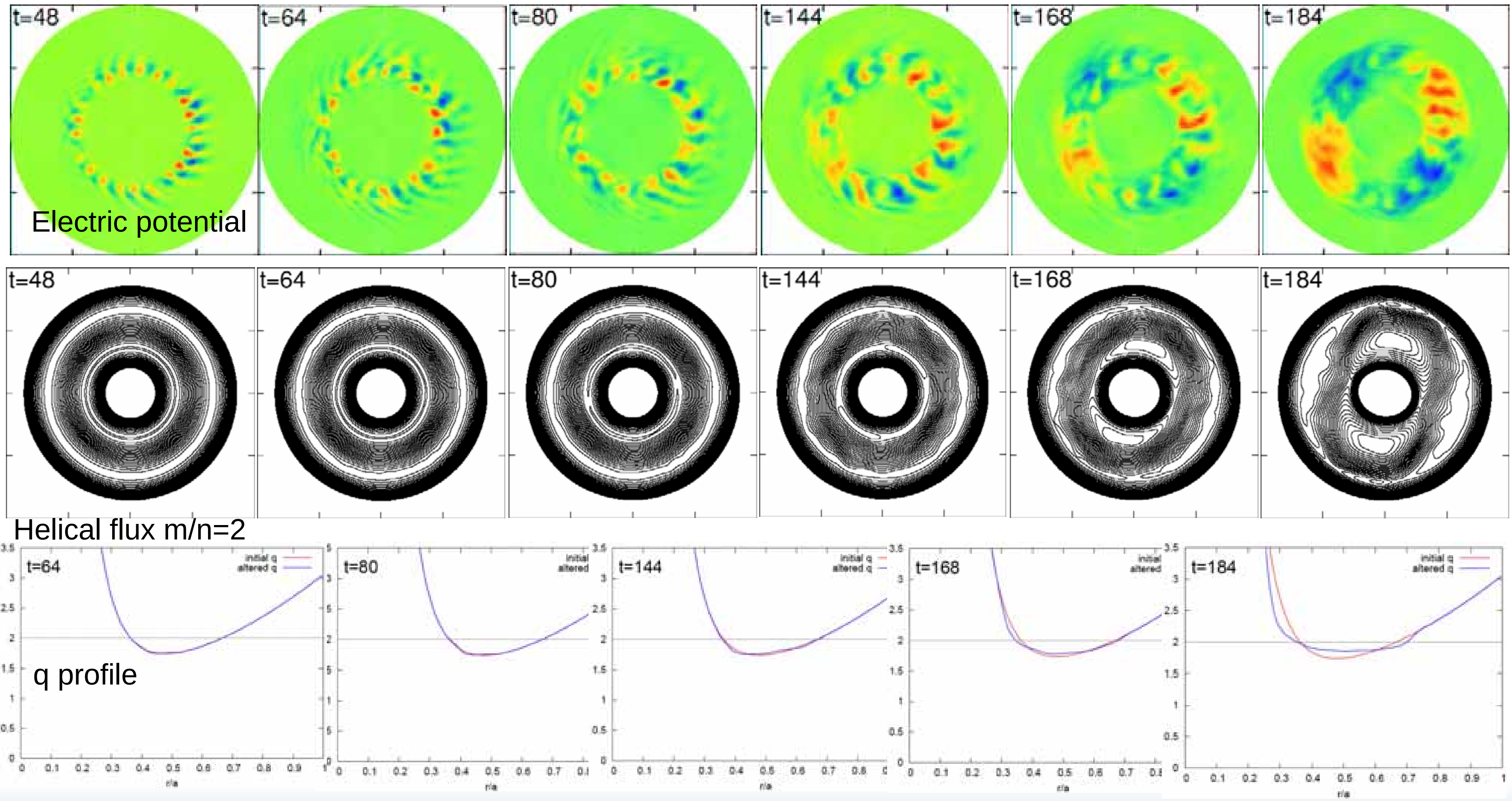


Summary of Multi-scale-nonlinear interaction

- Micro-turbulence, zonal flow, and macro-MHD directly interact each other.
  - Nonlinear trigger of macro-MHD activity
  - Macro-scale activity cause fatal effect on a balance between micro-turbulence and zonal flow.
- Future work of multi-scale interaction
  - Effects of the altered balance on transport
  - Energy cascade of the turbulence

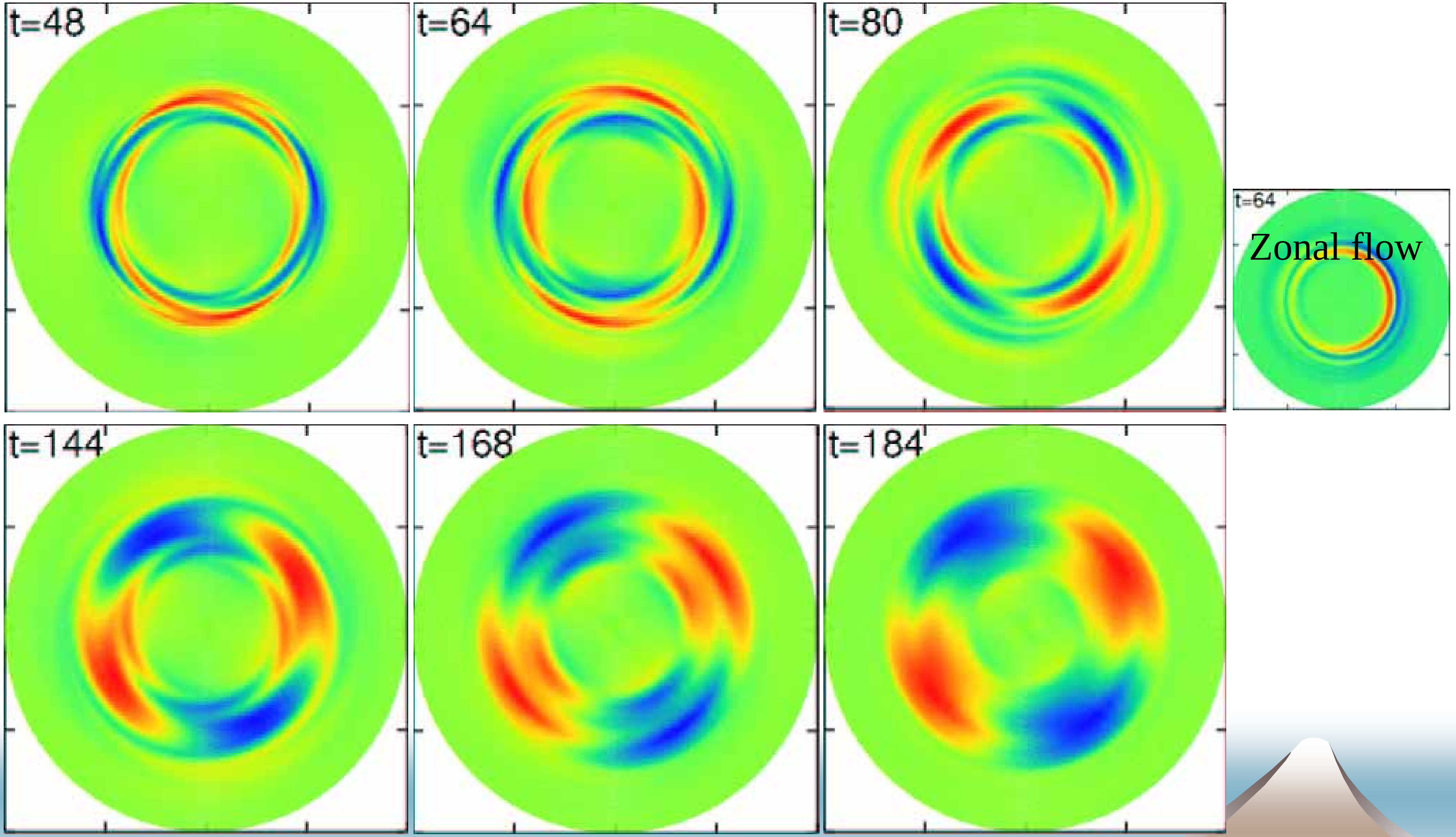


App.1: electric potential, helical flux, q-profile

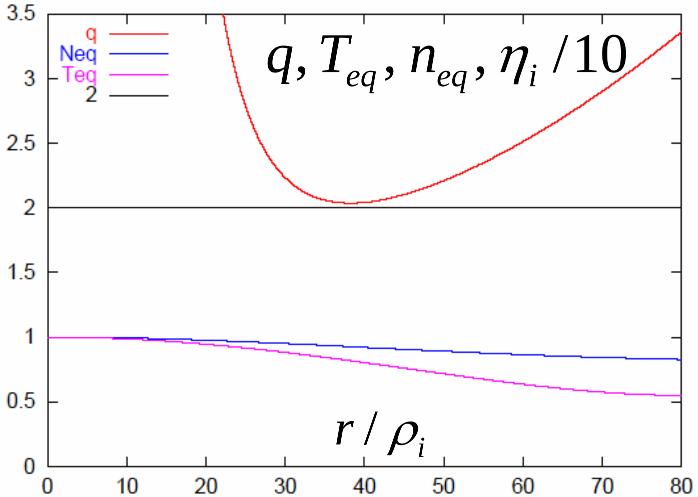


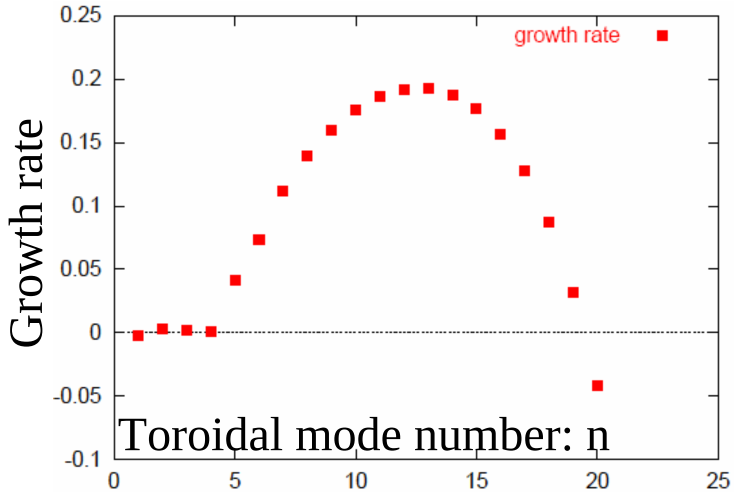
Poincare plot of
magnetic field
lines

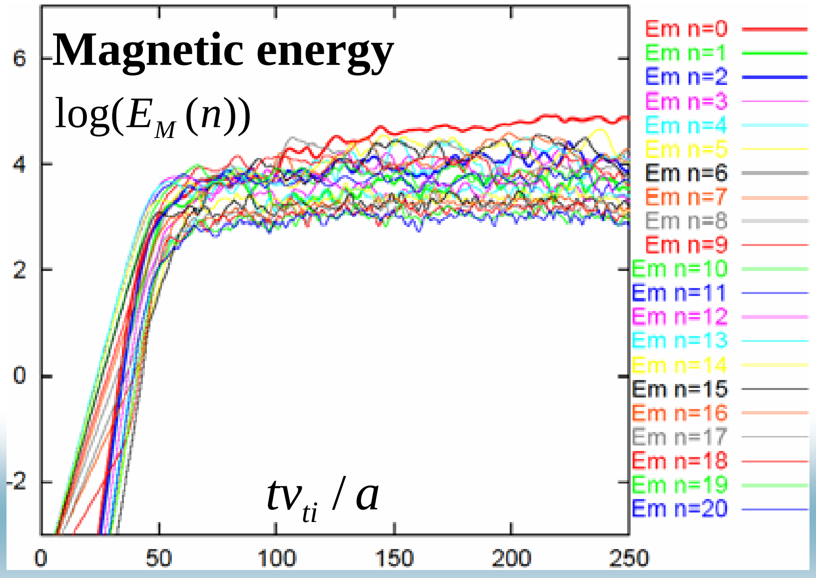
Appendix 2:
Evolution of n=1 double tearing mode

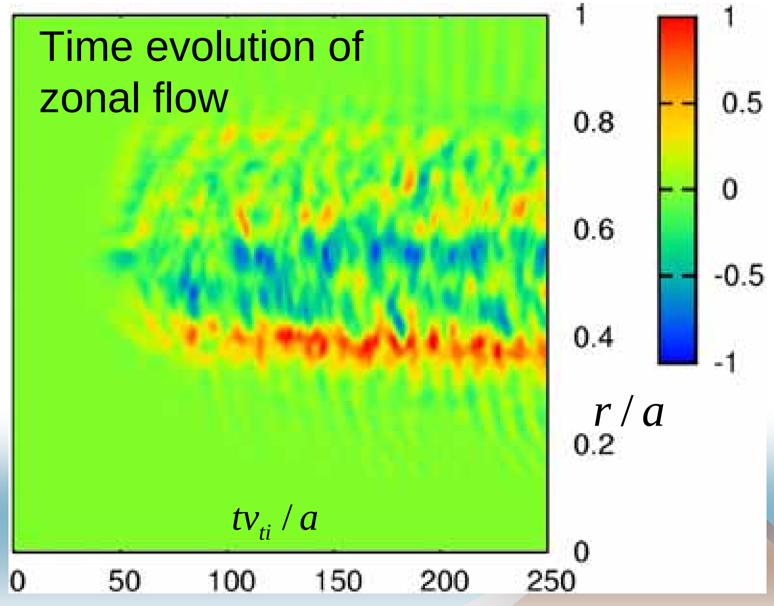


Appendix 3: Macro-MHD does not appear when the MHD is stable against the initial equilibrium



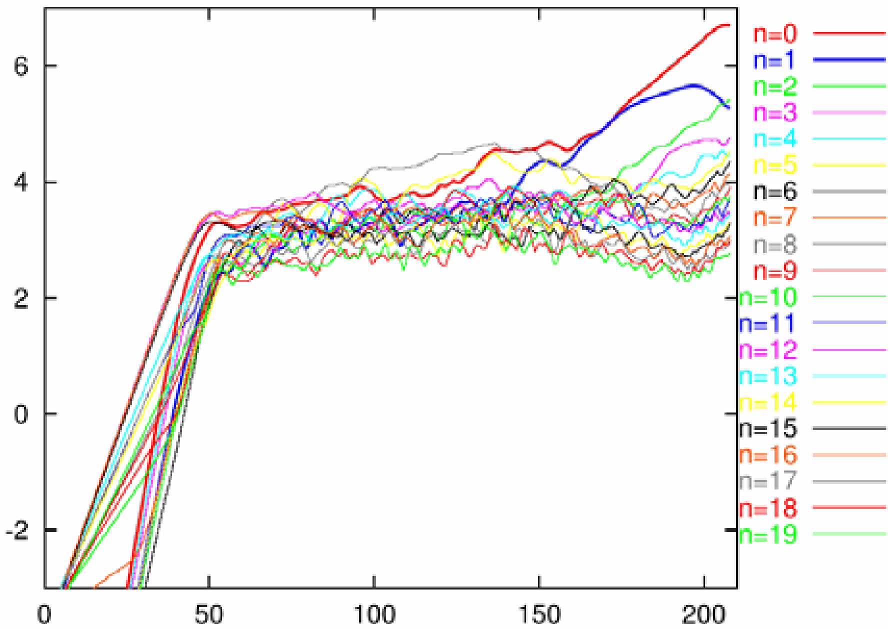






Appendix 4:
Time evolution of energy

Magnetic energy



Kinetic energy