Explosive Growth and Nonlinear Dynamics of the Forced Magnetic Island

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Introduction

In this study, we show new features of the magnetic island, which is driven by the externally applied perturbation for the tearing stable resonant surface in the rotating plasma.

Even for the tearing stable rational surface, the magnetic island is excited by the external perturbation like as the error field, MHD instability etc..

This kind of the magnetic island is thought as an important source of the seed island for the neoclassical tearing mode.

In the previous studies, the critical external perturbation for the explosive growth of the magnetic island is mainly investigated.

However, long term evolution of the forced magnetic island is also important to the tokamak plasma performance.

In this study, we investigate the time evolution of the forced magnetic island in the rotating plasma and show the existence of the new evolution phase, which becomes important in the low collisionarity regime.

Model Equations

Resistive reduced MHD eqs. in cylindrical geometry (incompressible, strong B_z, zero β)

$$\frac{\partial}{\partial t}\Psi = \frac{1}{r}\left[\Psi,\phi\right] + \frac{B_0}{R_0}\frac{\partial}{\partial\varphi}\phi + \eta J$$

$$\frac{\partial}{\partial t}U = \frac{1}{r}\left[U,\phi\right] + \frac{1}{r}\left[\Psi, J\right] + \frac{B_0}{R_0}\frac{\partial J}{\partial\varphi} + \mu\nabla_\perp\left(U - U_0\right)$$

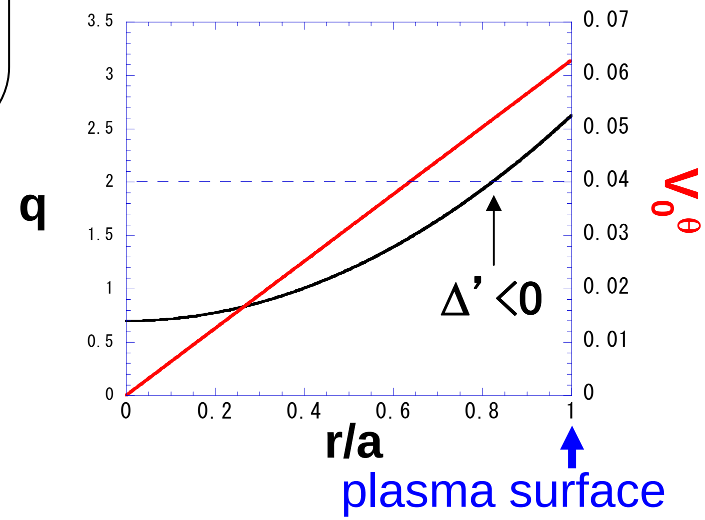
$$J = \nabla_\perp^2\psi \qquad U = \nabla_\perp^2\phi$$

Ψ : poloidal flux function

U : vorticity

η : resistivity

μ : viscosity



☆ Consider q=2 surface which is set to be tearing stable.

☆ Assume the flow potential of m/n=0/0.

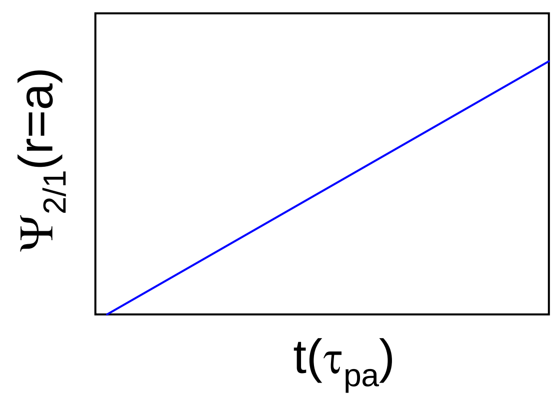
$$\phi_{0/0} = -\frac{2\pi}{\lambda\tau}\left(1 - r^{\lambda}\right)$$

In this study, λ is set to 2, which means the rigid rotation.

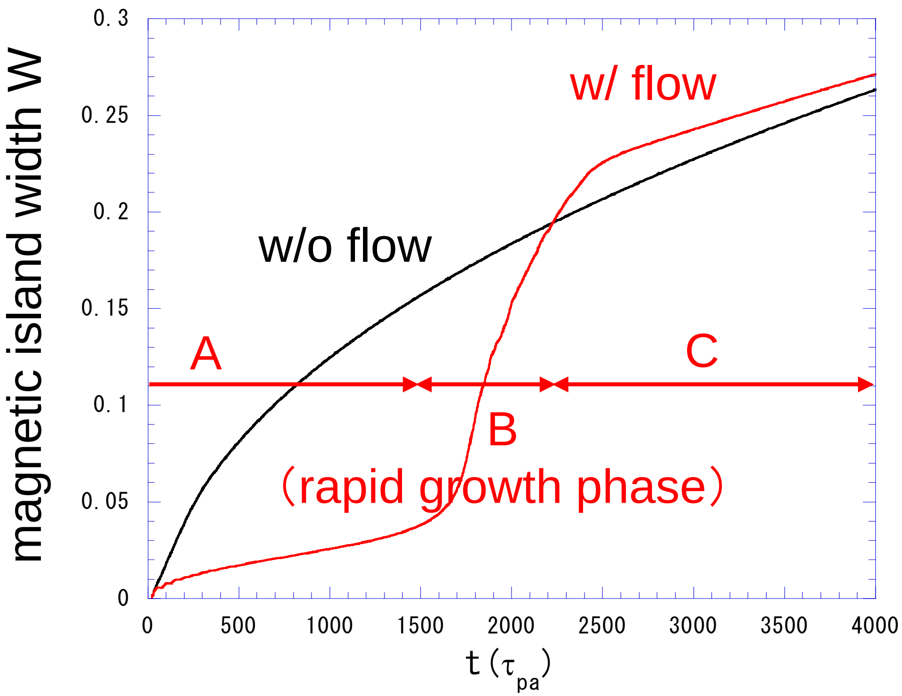
☆ Apply the external perturbation of the magnetic flux at the plasma surface

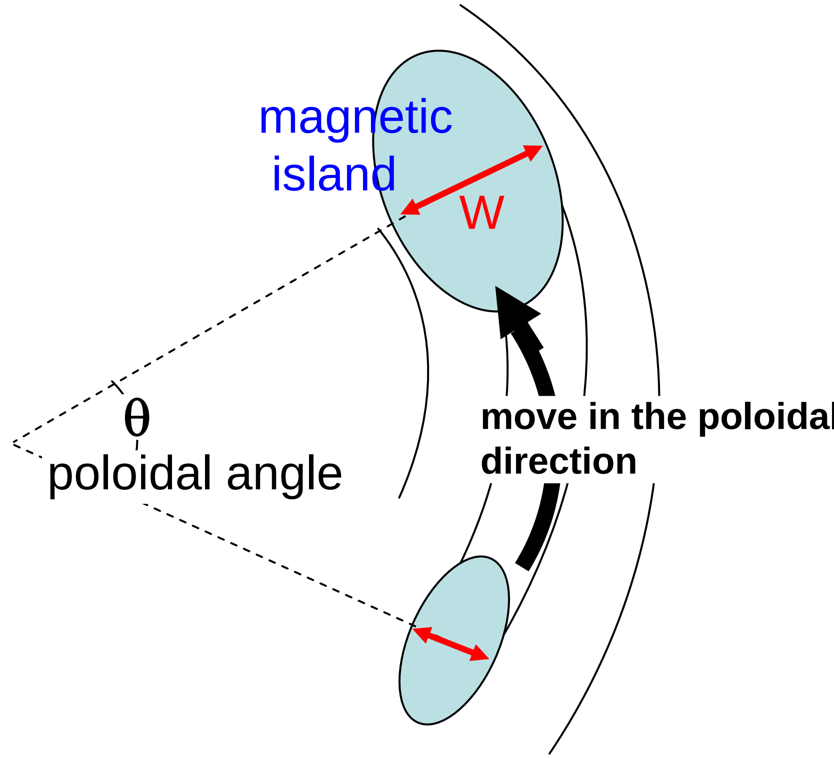
$$\psi_{2/1}(r = a) = \dot{\psi}_{2/1}(a) * (t - t_0)$$

$\dot{\psi}_{2/1}(a)$: increasing rate of poloidal flux function at the plasma surface



Island evolution and motion in the poloidal direction





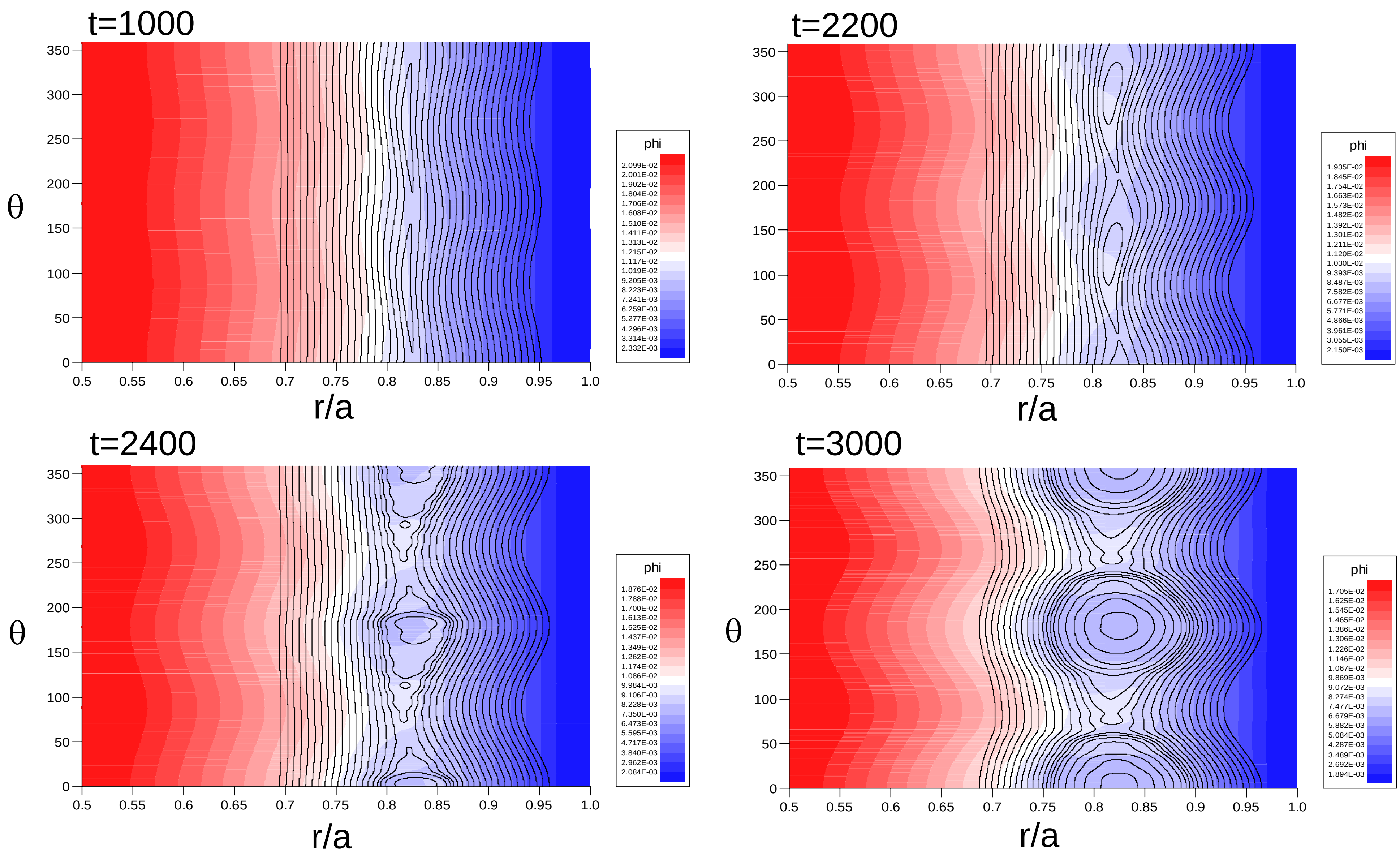
☆ w/o flow : magnetic island grows monotonically.

w/ flow : magnetic island grows rapidly after slow growth phase.
In phase B, magnetic island moves in the poloidal direction.

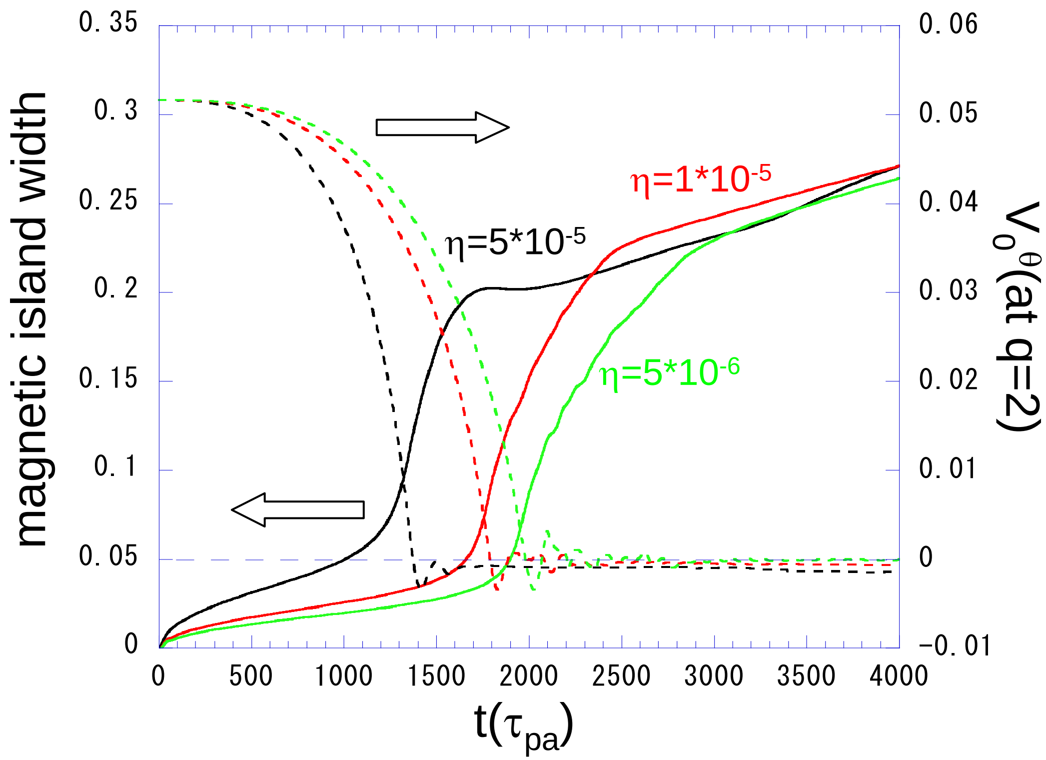
☆ A : flow-suppressed growth phase
B : rapid growth phase
C : Rutherford-like phase

Contour plots of poloidal flux function and flow potential

w/ flow solid line : poloidal flux function Ψ^* colored contour : flow potential Φ



Magnetic island evolution and flow damping



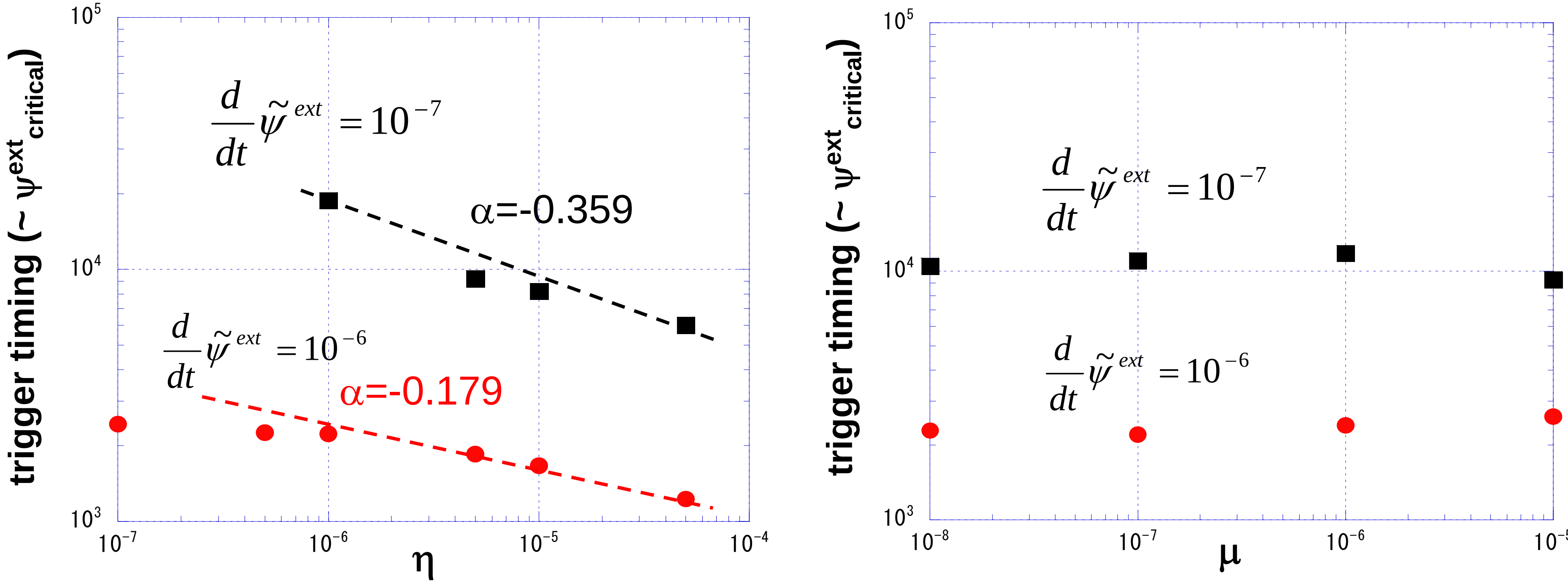
☆ The rapid growth of the forced magnetic island occurs when V_0^θ at q=2 rational surface becomes less than the critical value.

☆ Plasma flow decreases to zero around the resonant surface as the magnetic island grows.

☆ This relation ship between the trigger timing and the flow reduction is consistent with former studies.

Critical value for the onset of the rapid island growth

trigger timing ~ $\tilde{\psi}^{ext}_{critical} \propto \eta^{\alpha} \mu^{\beta}$

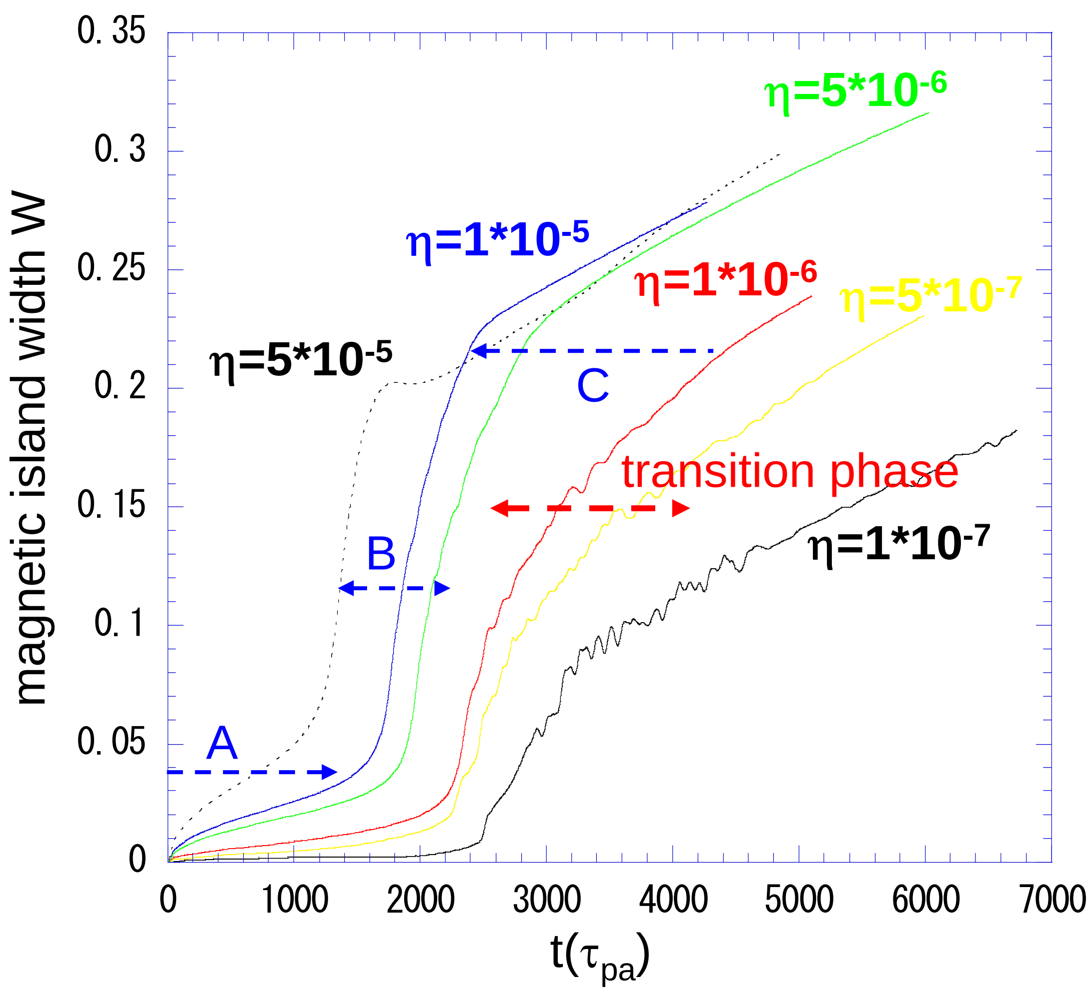


☆ ψ^{ext}_{crit} shows the dependence on η, and the exponent α increases as the increasing rate of the ψ^{ext} becomes small.

⇨ balance between the externally applied perturbation and the dissipation is important to the critical value.

☆ ψ^{ext}_{crit} shows the weak dependence on μ for both cases of $d/dt\,\tilde{\psi}^{ext} = 10^{-6}$ and $d/dt\,\tilde{\psi}^{ext} = 10^{-7}$ in the parameter region used in this study.

η effects on the nonlinear evolution of the magnetic island



In the high resistivity regime $\eta \geq 5 \times 10^{-6}$, the magnetic island growth is divided into three phases.

A : Flow-suppressed growth phase.
B : Rapid growth phase.
C : Rutherford-like phase

In the low resistivity regime, $\eta \leq 1 \times 10^{-6}$, the magnetic island growth seems to be divided into four phases.

1) The rapid growth phase breaks up to the two stages (transient phase)

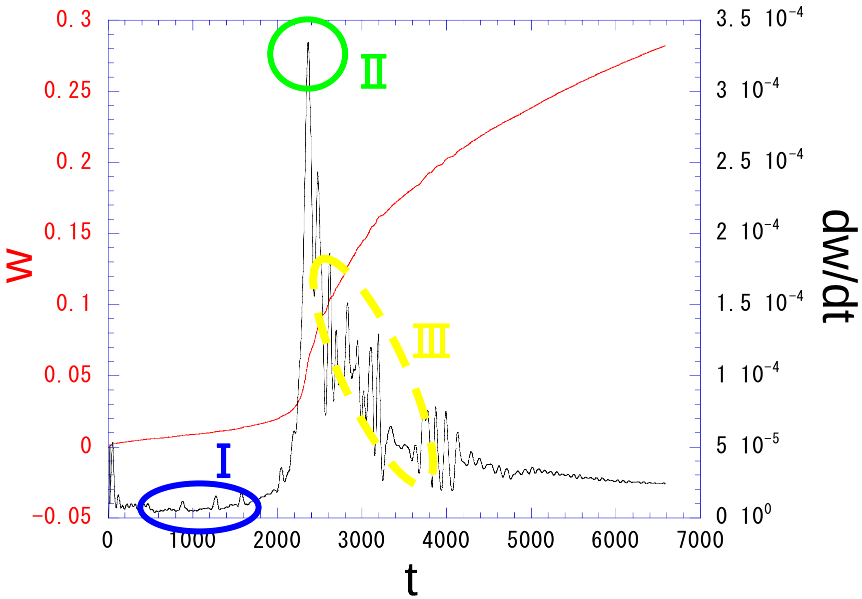
2) The second (reduced growth) stage shows some modulation of dw/dt.

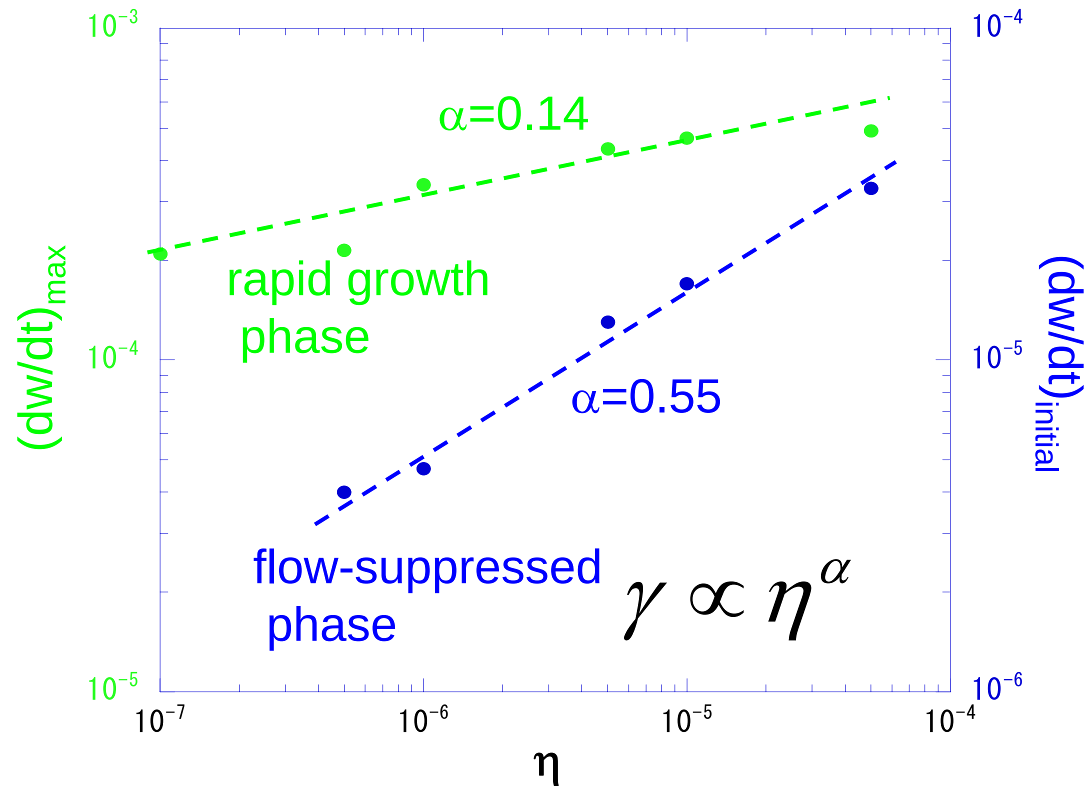
3) The growth rate at the transient phase is reduced by the resistivity.

4) Long term Rutherford-like feature is also affected by the reduction of the resistivity.

⇨ η effects becomes important not in high η regime but in the low η regime.

η dependence of the growth rate in the flow-suppressed and rapid growth phase



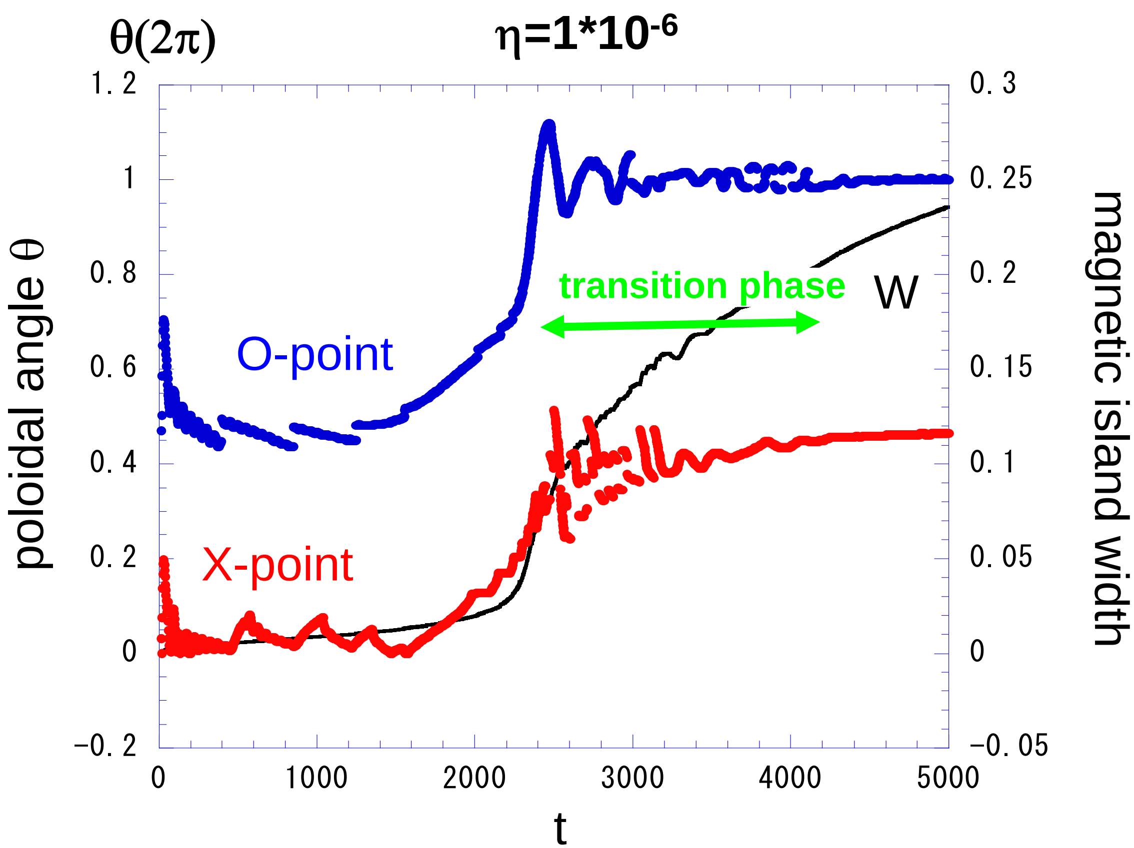


☆ In the flow-suppressed growth phase (A), the growth rate shows the strong dependence on the resistivity, η.

☆ In the rapid growth phase (B), the temporal growth rate shows the week dependence on the resistivity, η.

⇨ possibility of the phase instability

Trajectory of X-point and O-point in θ-direction



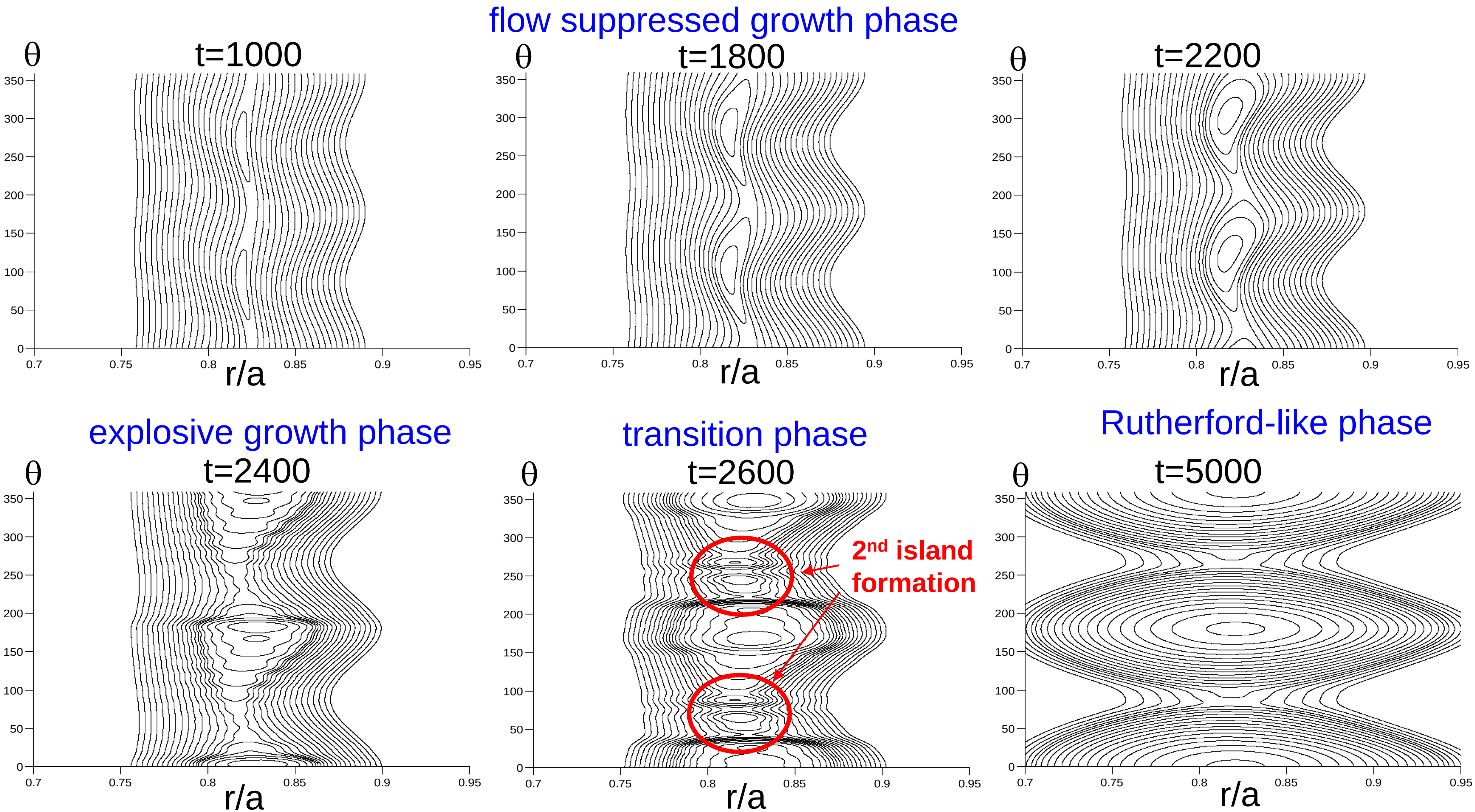
☆ In the rapid growth phase, the X- and O-point start to move in the poloidal direction.

☆ In transition phase, X- and O-points oscillate in the poloidal direction moving in the θ-direction.

☆ The oscillation term of the X- and O-point becomes longer as η becomes small.

☆ In the Rutherford-like phase, X- and O-points lock to the external perturbation.

2nd island formation in the transient phase



☆ Magnetic island deformation is caused by the flow and island motion in θ-direction.

☆ Second islands are formed at transition phase (phase C) around the initial X-point.

Torque analysis

$$\rho\left(\frac{\partial}{\partial t}\vec{V}+\vec{V}\cdot\nabla\vec{V}\right)=-\nabla P+\vec{J}\times\vec{B}+\mu\nabla^2\vec{V}$$

Electromagnetic torque $$T_\theta^{EM}(r,\theta)\equiv r\vec{e}_\theta\cdot\vec{J}\times\vec{B}$$

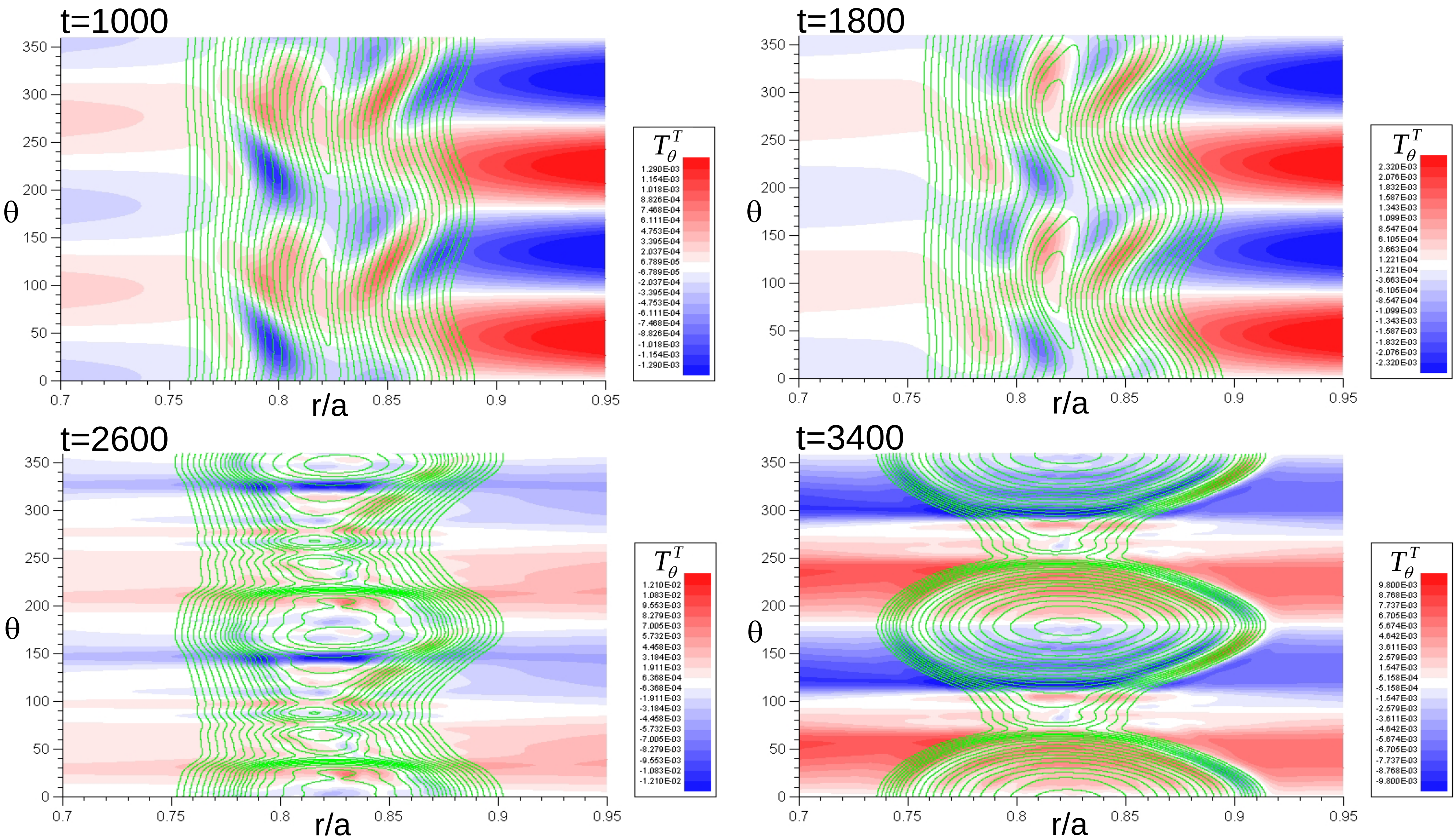
Inertial torque $$T_\theta^{I}(r,\theta)\equiv r\vec{e}_\theta\cdot\left(\vec{V}\cdot\nabla\right)\vec{V}$$

Viscous torque $$T_\theta^{V}(r,\theta)=r\vec{e}_\theta\cdot\mu\nabla^2\vec{V}$$

Total torque $$T_\theta^{T}(r,\theta)=T_\theta^{EM}(r,\theta)+T_\theta^{V}(r,\theta)-T_\theta^{I}(r,\theta)$$

(ρ=1 is assumed)

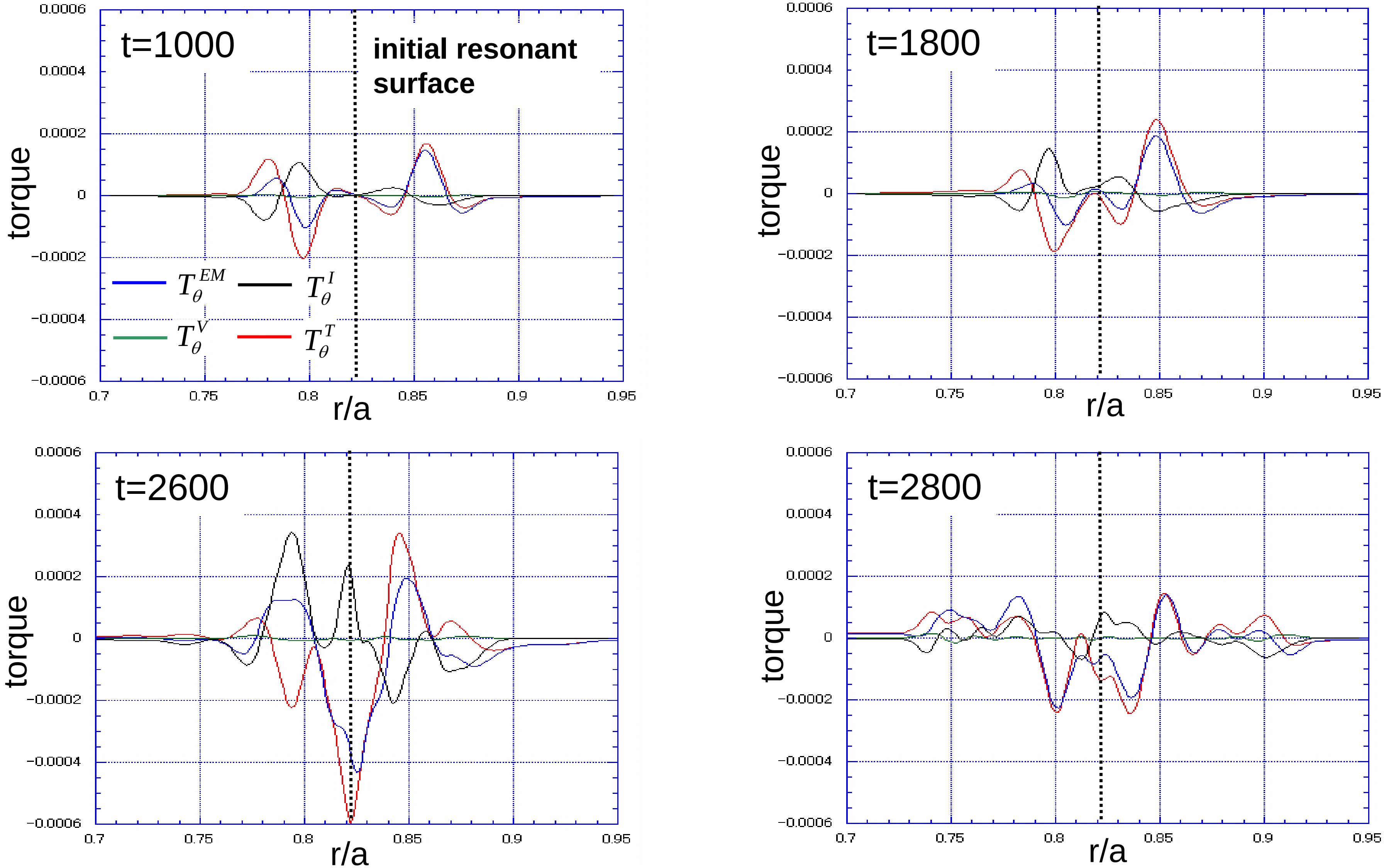
Contour plots of the total torque and magnetic island ψ*



☆ Total torque becomes positive around O-point and negative around X-point.

☆ Non-monotonic profile of total torque causes the complex poloidal motion.

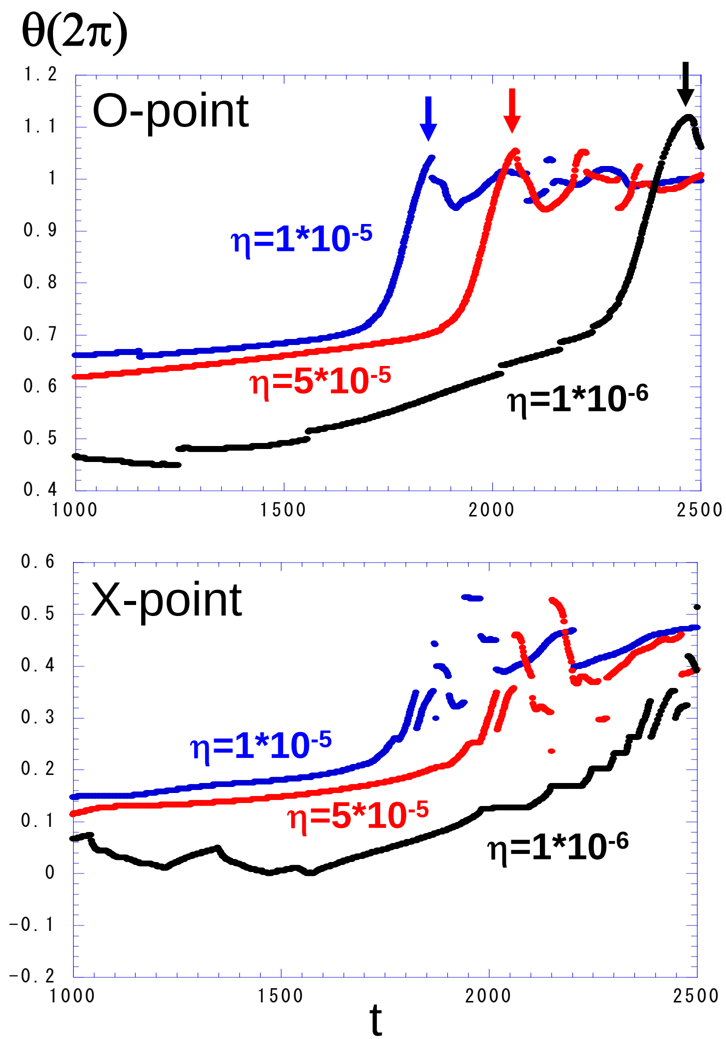
Radial profile of the flux-surface averaged torque

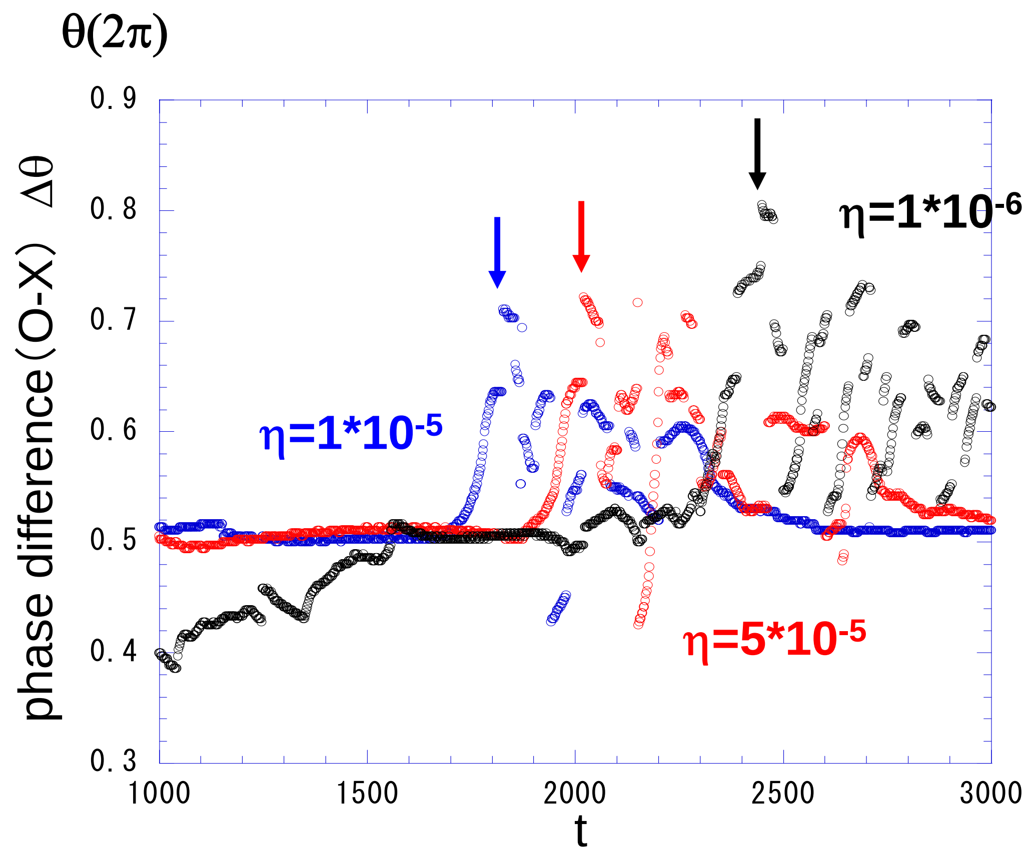


☆ In flow-suppressed growth phase, T_θ^{EM} is dominant and T_θ^{I} is small.

☆ In rapid growth and transition phases, T_θ^{I} increases.

Trajectory of X-point and O-point in θ-direction for Different η

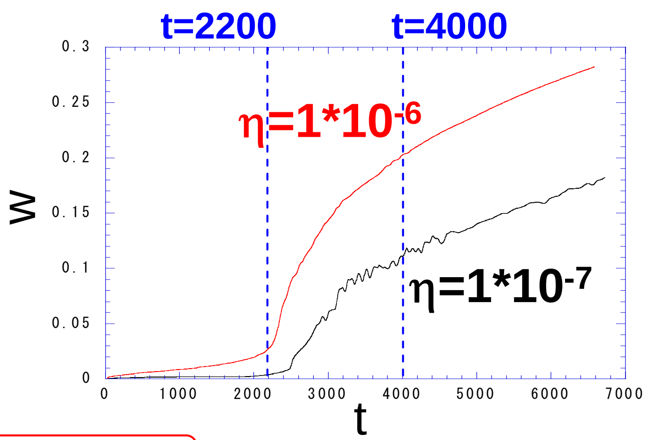




☆ Deviation of the Δθ(O-X) phase difference from π/2 is interpreted as formation of the Y-type reconnection region.

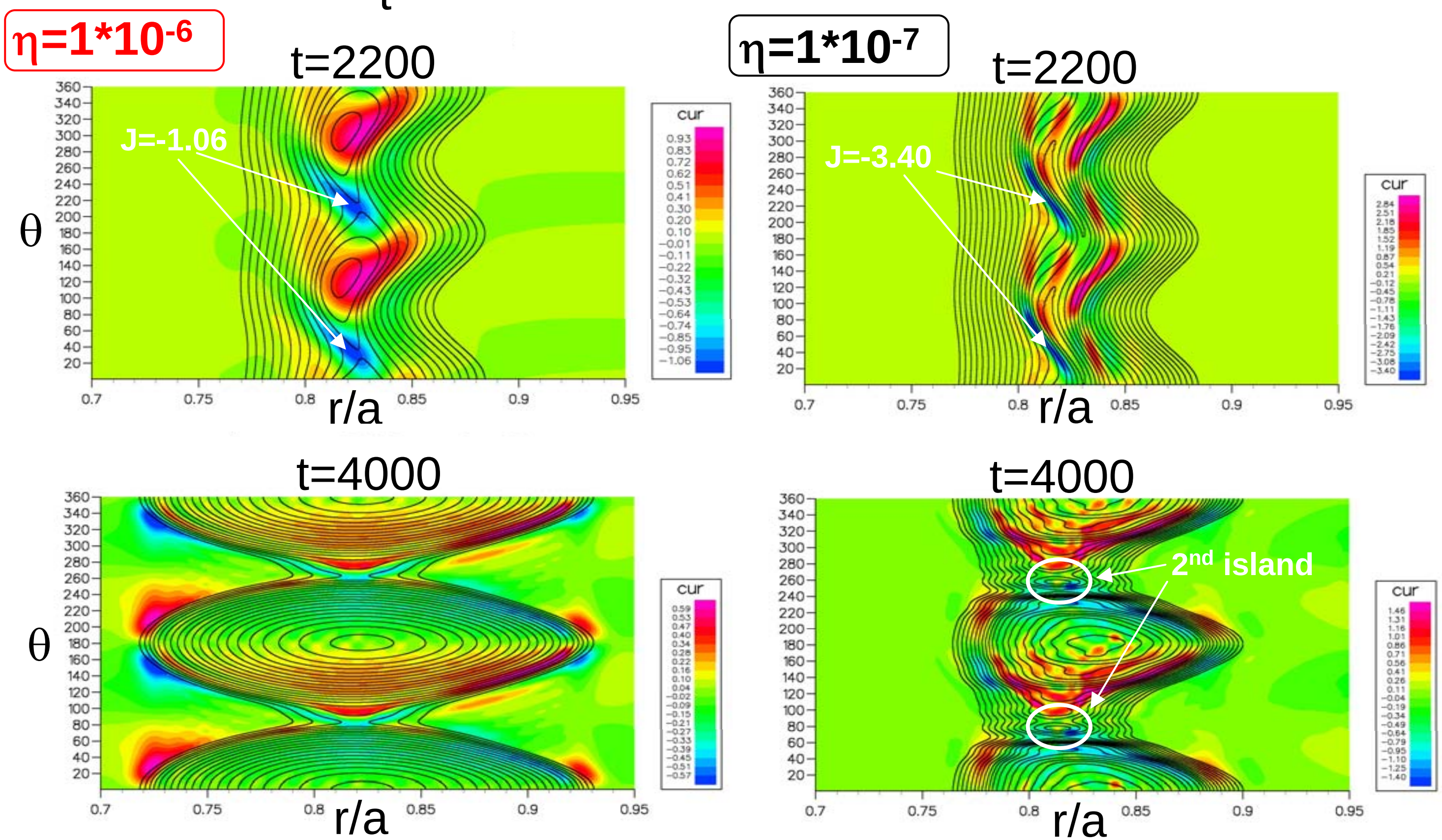
☆ Δθ(O-X) becomes large as η is decreased. ⇨ Strong island deformation in the low η region.

Current Peak for the Different Resistivity



☆ Increasing rate of the external perturbation is the same for η=1*10^{-6} and 1*10^{-7} cases.

☆ Before the rapid growth phase, in the lower η case, current peak is larger than that in the high η case.



☆ As the resistivity becomes low, the current diffusion rate becomes low.
Hence, in the low resistivity case, it take longer time to finish the 2nd island formation process.

⇨ Transient phase becomes long.

solid line : ψ^*

colored contour : J

Summary

☆ Time evolution of the forced magnetic island in the rotating plasma can be divided into four phases.

Phase A : flow-suppressed phase

Phase B : explosive growth phase

Phase C : transition phase

Phase D : Rutherford-like phase

As the resistivity becomes low, phase C becomes more dominant.

1) Phase C starts at early time, when the magnetic island with is still small.

2) Duration of phase C becomes longer as η becomes small.

☆ The second island formation by the stretching the X-type reconnection region to the Y-type one is found. This change of the reconnection region is caused by the flow driven island deformation.

☆ It is shown that the 2-dimensional non-monotonic torque profile is important to the complex island motion.

☆ The second island formation around the initial X-point may be an important mechanism for the NTM threshold.