Three-Dimensional MHD Analysis of Pressure Driven Modes in RMP-Imposed LHD Plasmas

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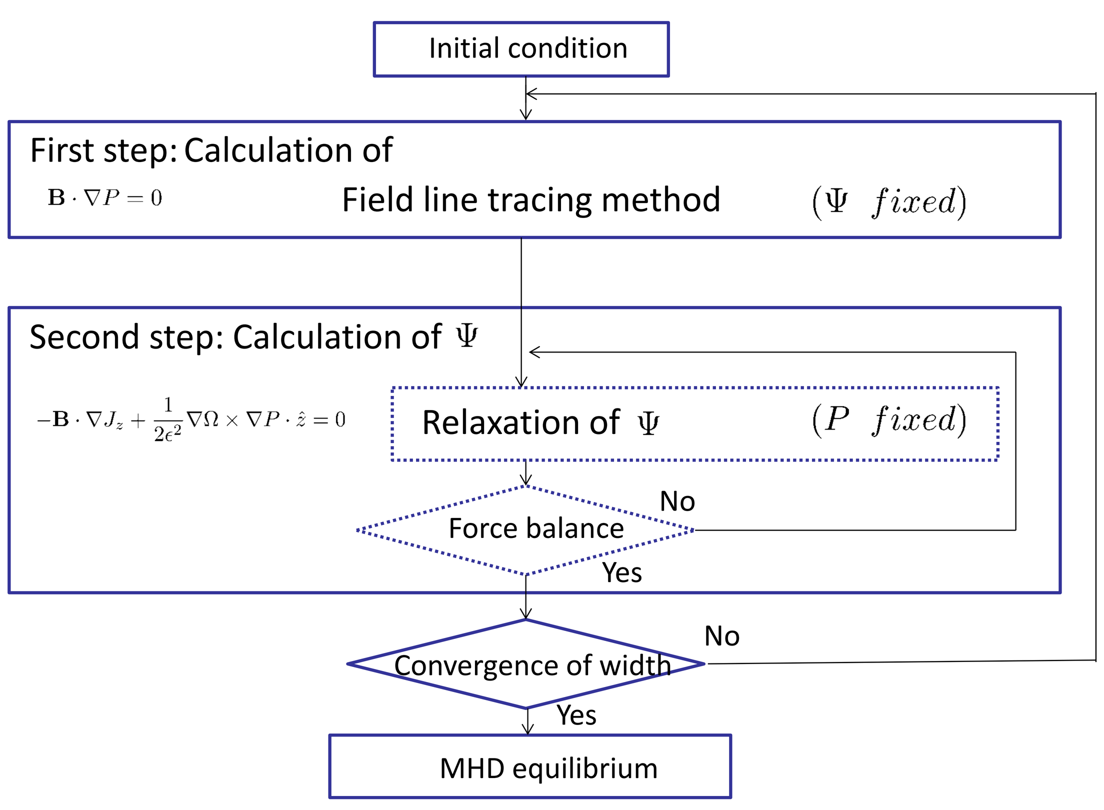
PURPOSE : Effects of m=1/n=1 RMP on MHD Stability in LHD configuration

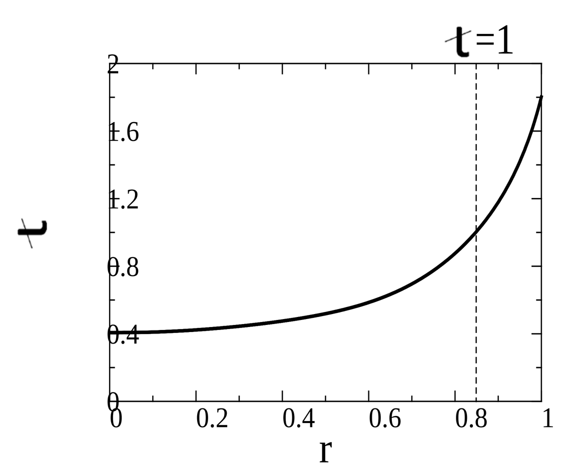
Cylindrical Analysis

Equilibrium Calculation — FLEC code

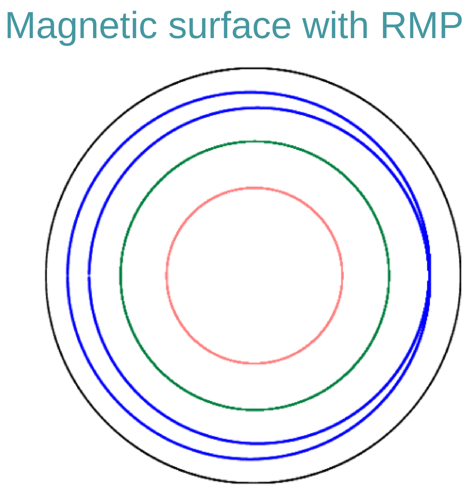
Numerical Scheme of FLEC code



Rotational transform without RMP

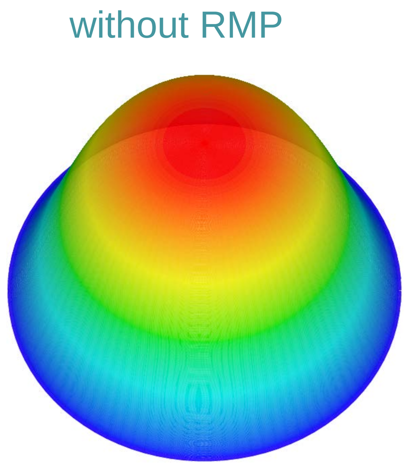


Magnetic surface with RMP

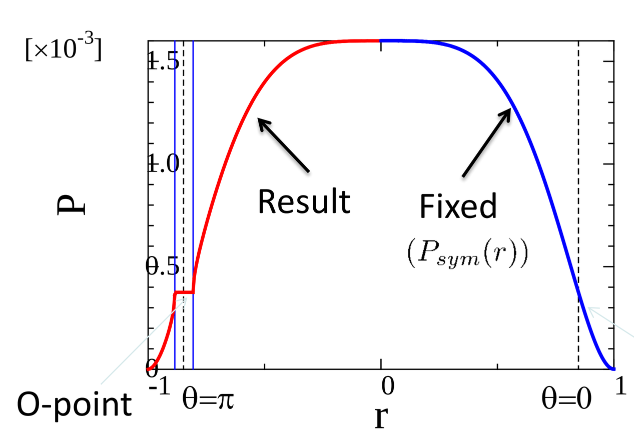


Equilibrium Pressure

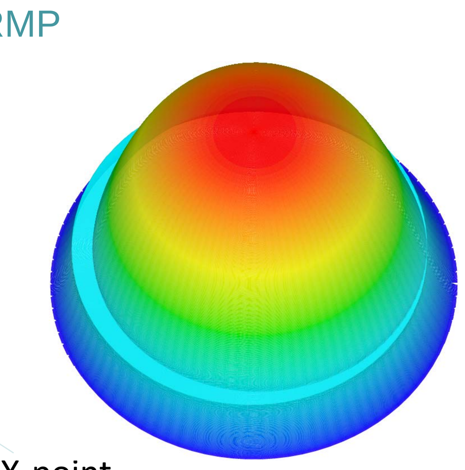
without RMP



$P_{sym}(r) = \beta_0(1-r^4)^2$



with RMP



Stability Calculation — NORM code

Basic Equation : Reduced MHD Equations

Ohm's Law

$$\frac{\partial \tilde{\Psi}}{\partial t} = -\mathbf{B}\cdot\nabla\tilde{\Phi} + \frac{1}{S}\tilde{J}_z$$

S :Magnetic Reynolds number

Vorticity Equation

$$\frac{d\nabla_\perp^2\tilde{\Phi}}{dt} = -\mathbf{B}\cdot\nabla\tilde{J}z + \nabla\Omega_{eq}\times\nabla\tilde{P}\cdot\hat{z} + \nu\nabla_\perp^2(\nabla_\perp^2\tilde{\Phi})$$

ν :Viscosity

Pressure equation

$$\frac{d\tilde{P}}{dt} = (\hat{z}\times\nabla\tilde{\Phi})\cdot\nabla P_{eq} + \kappa_\perp\nabla_\perp^2\tilde{P} + \kappa_\parallel\mathbf{B}\cdot\nabla(\mathbf{B}\cdot\nabla P)$$

$\kappa_\perp, \kappa_\parallel$:Heat conductivity

"eq": equilibrium quantity, "~": perturbed quantity

Perturbations

$$\tilde{\Psi}(r,\theta,z) = \sum_{n=0,m=n}^{N}\hat{\Psi}_{m,n}(r)\cos(m\theta - nz)$$

$$\tilde{\Phi}(r,\theta,z) = \sum_{n=0,m=n}^{N}\hat{\Phi}_{m,n}(r)\sin(m\theta - nz)$$

$$\tilde{P}(r,\theta,z) = \sum_{n=0,m=n}^{N}\hat{P}_{m,n}(r)\cos(m\theta - nz)$$

Magnetic field: $\mathbf{B} = \hat{z} + \hat{z}\times\nabla\Psi$

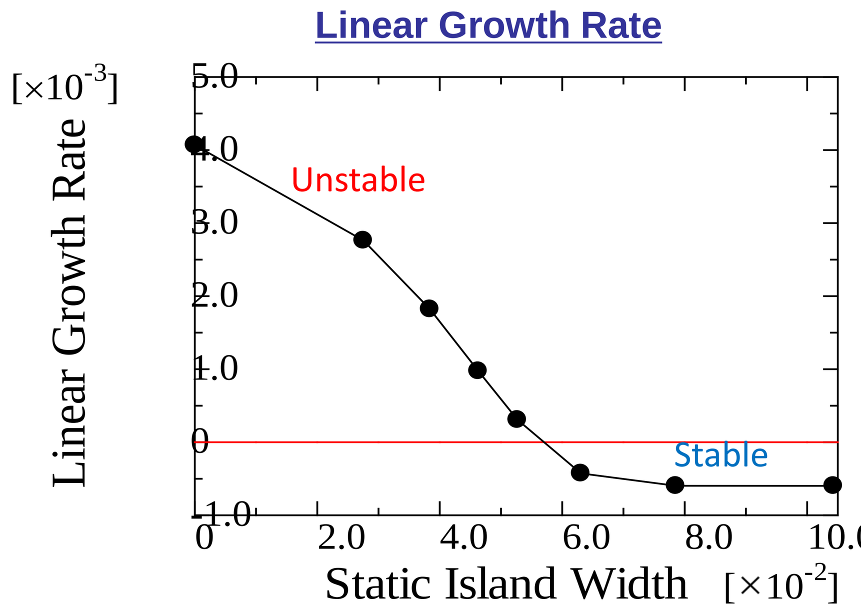
Current density in z direction: $\tilde{J}z = \nabla_\perp^2\tilde{\Psi}$

Velocity: $\mathbf{v}_\perp = \nabla\Phi\times\hat{z}$

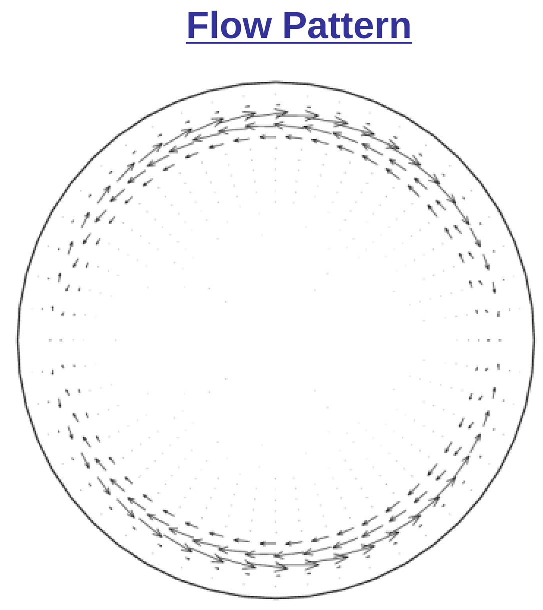
Time derivative: $\frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{v}_\perp\cdot\nabla$

$$\beta_0 = 1.5\%, S = 10^4, \nu = 8.5\times10^{-6}, \kappa_\perp = 2.0\times10^{-5}, \kappa_\parallel = 2.0$$

Linear Growth Rate



Flow Pattern

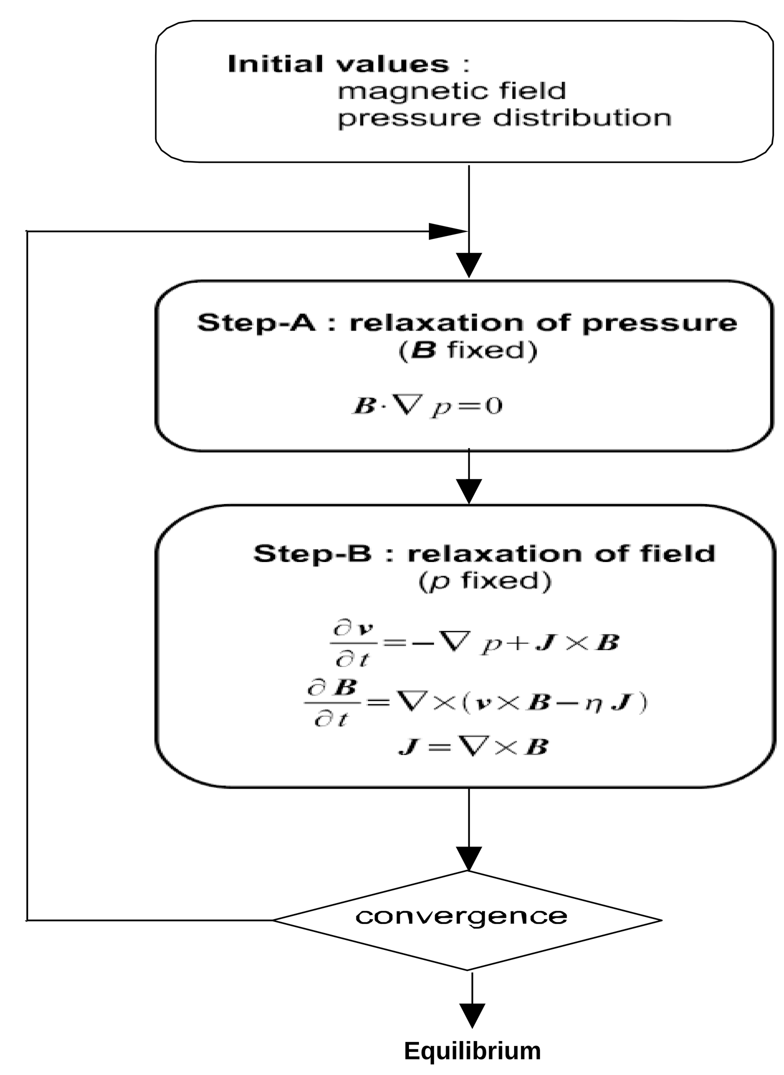


RMP has a STABILIZING effect.

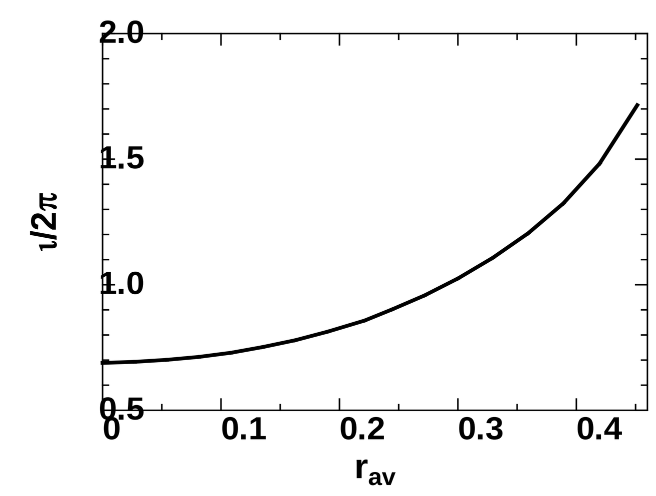
3D Analysis

Equilibrium Calculation — HINT2 code

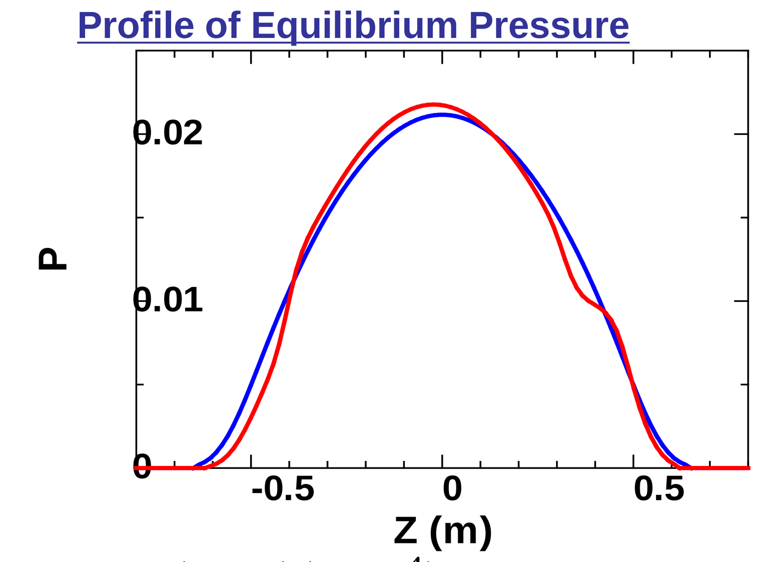
Numerical Scheme of HINT2 code



Profile of Rotational Transform without RMP



Profile of Equilibrium Pressure



$P = P_0(1-s)(1-s^4)$ for w/o RMP case

Stability Calculation — MIPS code

Basic Equation : Full MHD Equations

$$\frac{\partial\rho}{\partial t} = -\nabla.(\rho\boldsymbol{v}) + \chi\nabla^2\rho$$

$$\frac{\partial\boldsymbol{v}}{\partial t} = -\rho\boldsymbol{w}\times\boldsymbol{v} - \rho\nabla\left(\frac{v^2}{2}\right) - \nabla p + \boldsymbol{j}\times\boldsymbol{B} + \frac{3}{4}\nabla[\nu\rho(\nabla\cdot\boldsymbol{v})] - \nabla\times(\nu\rho\boldsymbol{w})$$

$$\frac{\partial\boldsymbol{B}}{\partial t} = -\nabla\times\boldsymbol{E}$$

$$\frac{\partial p}{\partial t} = -\nabla\cdot(p\boldsymbol{v}) - (\Gamma-1)p\nabla\cdot\boldsymbol{v} + (\Gamma-1)\left[\nu\rho w^2 + \frac{4}{3}\nu\rho(\nabla\cdot\boldsymbol{v})^2 + \eta\boldsymbol{j}\cdot(\boldsymbol{j}-\boldsymbol{j}_{eq})\right]$$

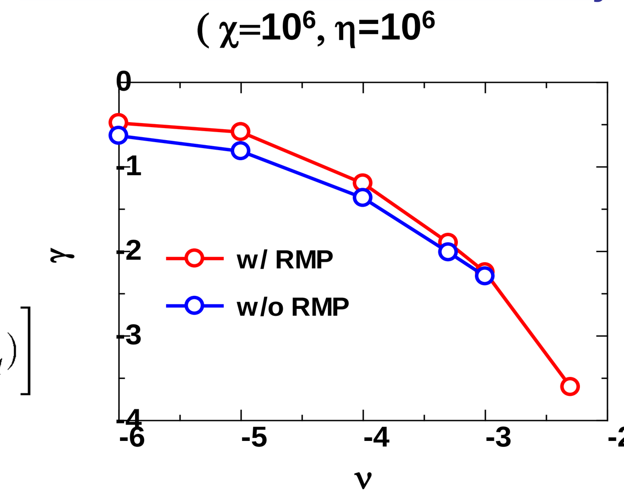
$$\boldsymbol{E} = -\boldsymbol{v}\times\boldsymbol{B} + \eta(\boldsymbol{j}-\boldsymbol{j}_{eq})$$

$$\boldsymbol{J} = \frac{1}{\mu_0}\nabla\times\boldsymbol{B}$$

$$\boldsymbol{w} = \nabla\times\boldsymbol{v}$$

Linear Growth Rate v.s. Viscosity

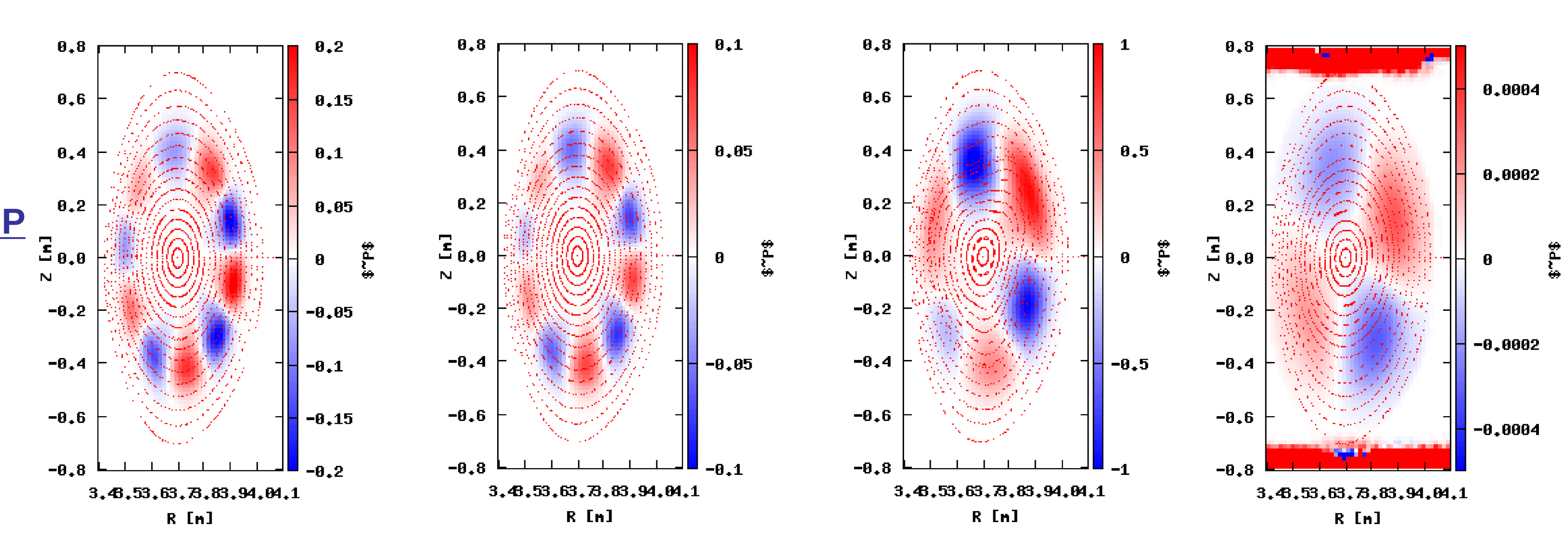
($\chi=10^6$, $\eta=10^6$)



Perturbed Pressure in Linear Phase

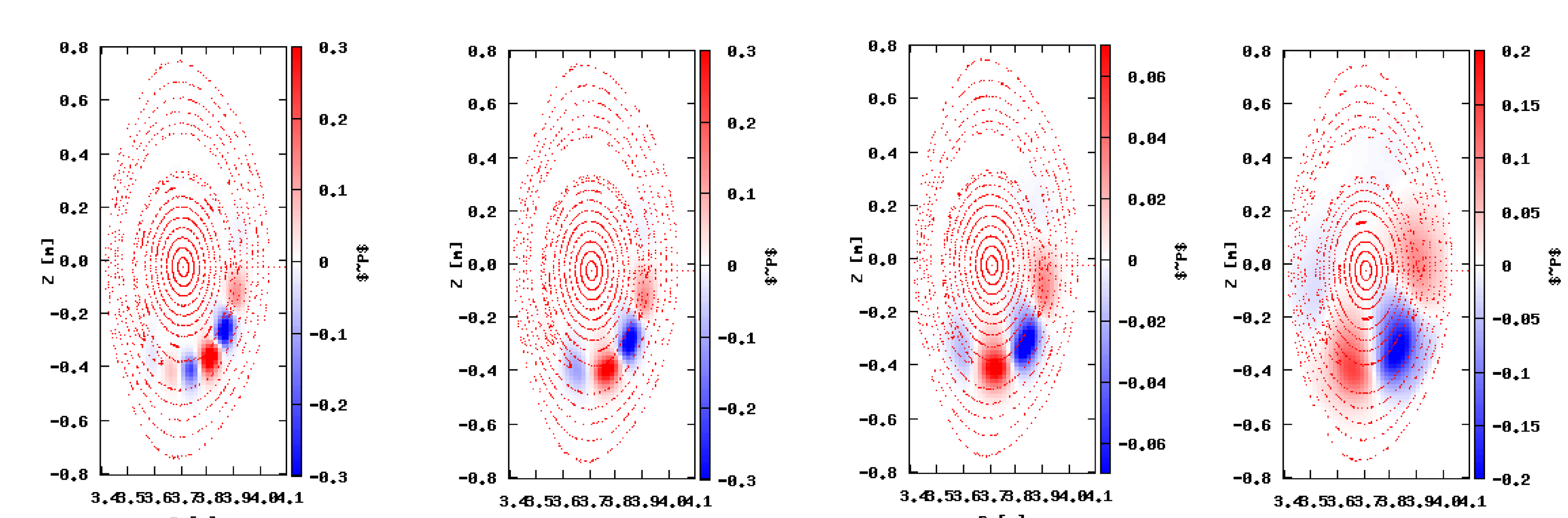
($\chi=10^6$, $\eta=10^6$)

without RMP



$\nu=10^6$　$\nu=10^5$　$\nu=10^4$　$\nu=10^3$

with RMP



$\nu=10^6$　$\nu=10^5$　$\nu=10^4$　$\nu=10^3$

RMP has a DESTABILIZING effect.

Conclusions

In the cylindrical case, the RMP has a stabilizing effect on the interchange mode.
In the 3D case, the RMP has a destabilizing effect on the interchange mode.
The mode structure is changed from the interchange type to the ballooning type, which localized at the X-point, even in the small m case (large viscosity) .
The destabilization is attributed to
1) the localization at the X-point is allowed, where the pressure gradient is maximum around the island
2) the pressure gradient is steeper than that without RMP.
More systematic analysis will be needed.