Numerical MHD Analysis of LHD Plasma with RMP

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Introduction

Background : Pressure gradient control by resonant magnetic perturbation (RMP) is focused in tokamaks and stellarators. In many analyses, pressure profile based on the nested flux surfaces is utilized for RMP analysis inconsistently.

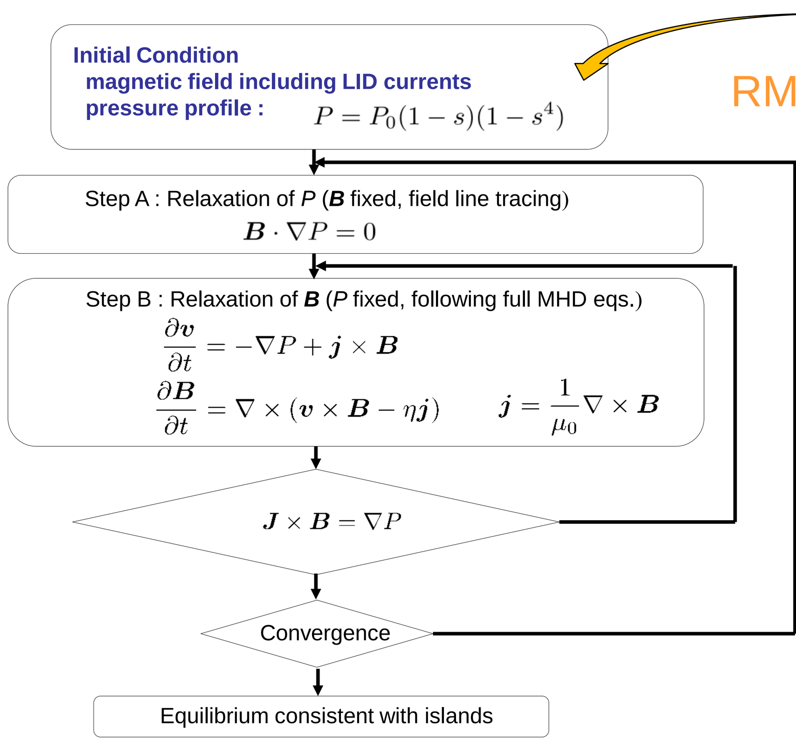
Purpose : To Investigate the effects of m=1/n=1 RMP on MHD stability in LHD configuration by using the equilibrium pressure consistent with magnetic field including RMP.

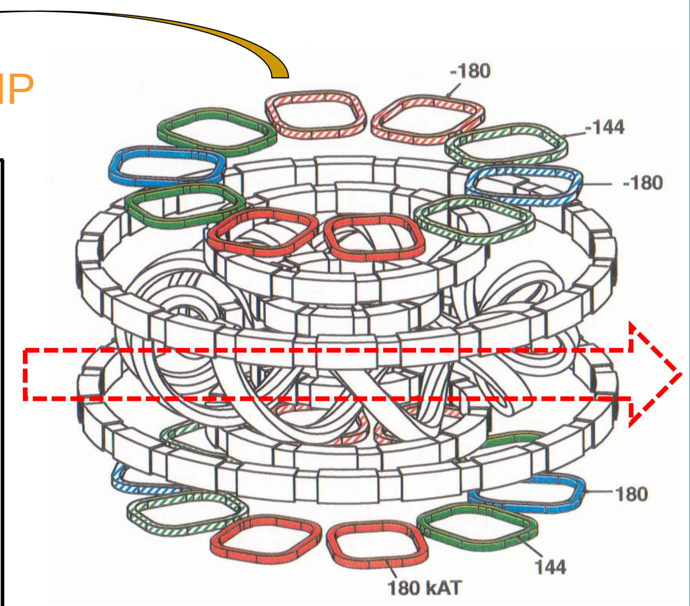
Equilibrium Calculation

HINT2 code

Numerical Scheme of HINT2 code

Y. Suzuki, et al., Nuclear Fusion Vol. 46 (2006) L19.





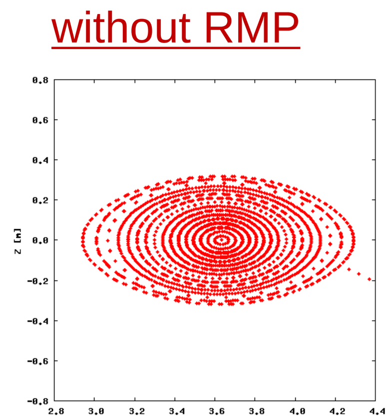
Coil System in LHD

RMP
LID coil current can control natural error field .

Application to LHD Configuration with Rax=3.6m, γ=1.13 (uniform horizontal RMP corresponding to error field)

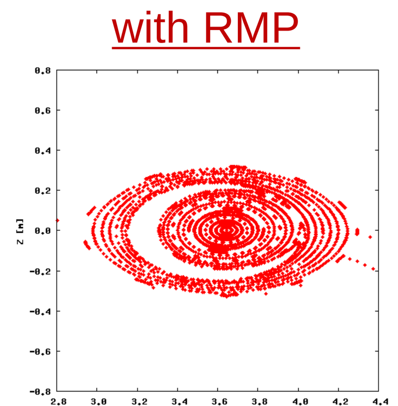
Plot of Field Lines

without RMP



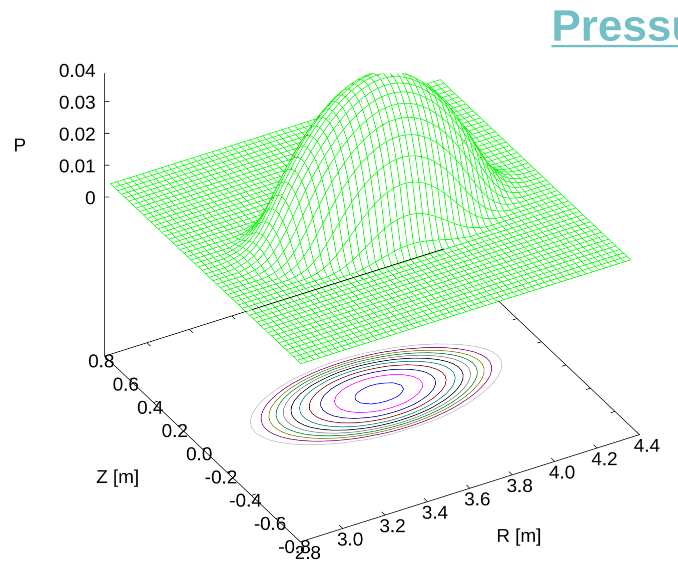
Nested flux surfaces exist.

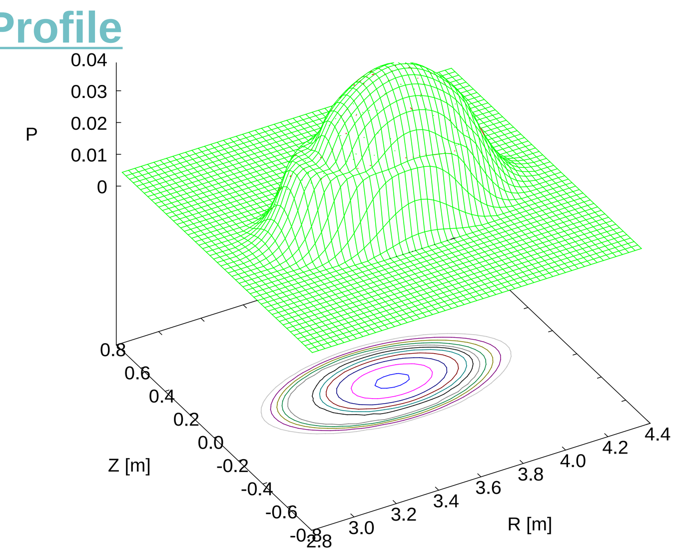
with RMP



Magnetic island with m=1/n=1 appears.

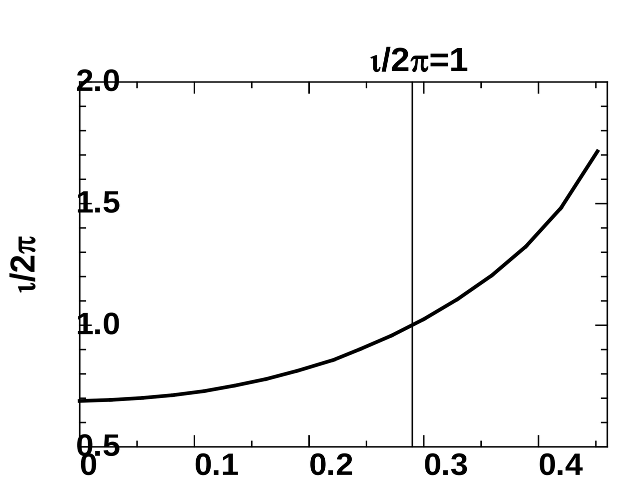
Pressure Profile





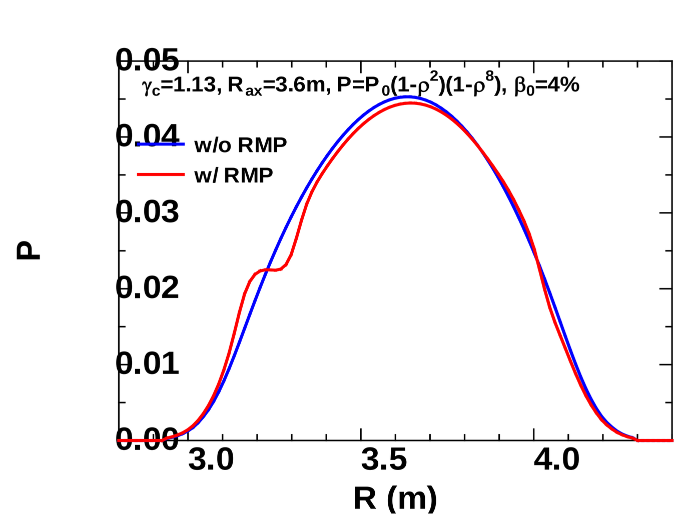
Pressure profile corresponds to the magnetic field.

Rotational Transform w/o RMP



The i/2p surface exists in the plasma column.

Profile of Equilibrium Pressure



Local flat region is generated at O-point and steep gradient is kept at X-point.

Dynamics Calculation & Linear Mode

MIPS code

Basic Equation : Full MHD Equations

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

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

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

$$\frac{\partial p}{\partial t} = -\nabla\cdot(p\boldsymbol{v}) - (\Gamma-1)p\nabla\cdot\boldsymbol{v} + \chi_\perp\nabla_\perp^2 p + \chi_\parallel\nabla_\parallel^2 p$$

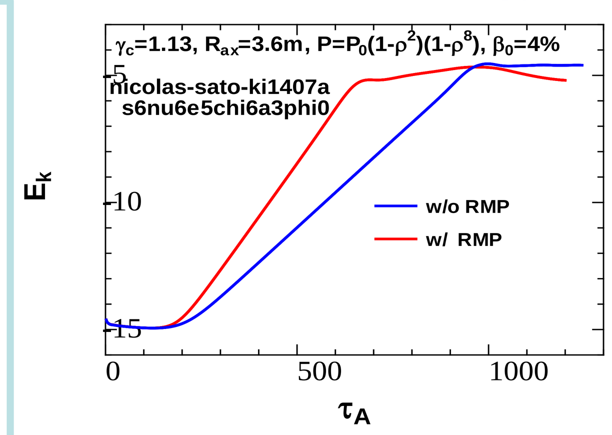
$$\boldsymbol{E} = -\boldsymbol{v}\times\boldsymbol{B} + \eta(\boldsymbol{j}-\boldsymbol{j}_{eq})$$

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

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

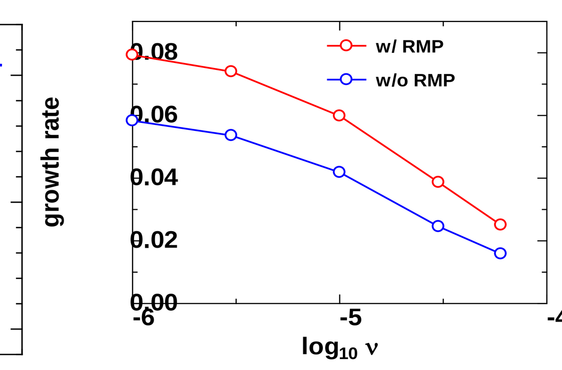
Central difference scheme with 4th order accuracy is implemented.
Todo et al., Plasma Fus. Res. 5 (2010) S2062.

Time Evolution of Kinetic Energy



$(\eta/\mu_0 = 10^{-6}, \nu = 6\times10^{-5}, \chi_\perp = 10^{-6}, \chi_\parallel = 10^{-3})$

Viscosity Dependence



Growth rate with RMP is more strongly reduced than that without RMP.

Perturbations in Linear Phase

Mode Pattern of Perturbed Pressure

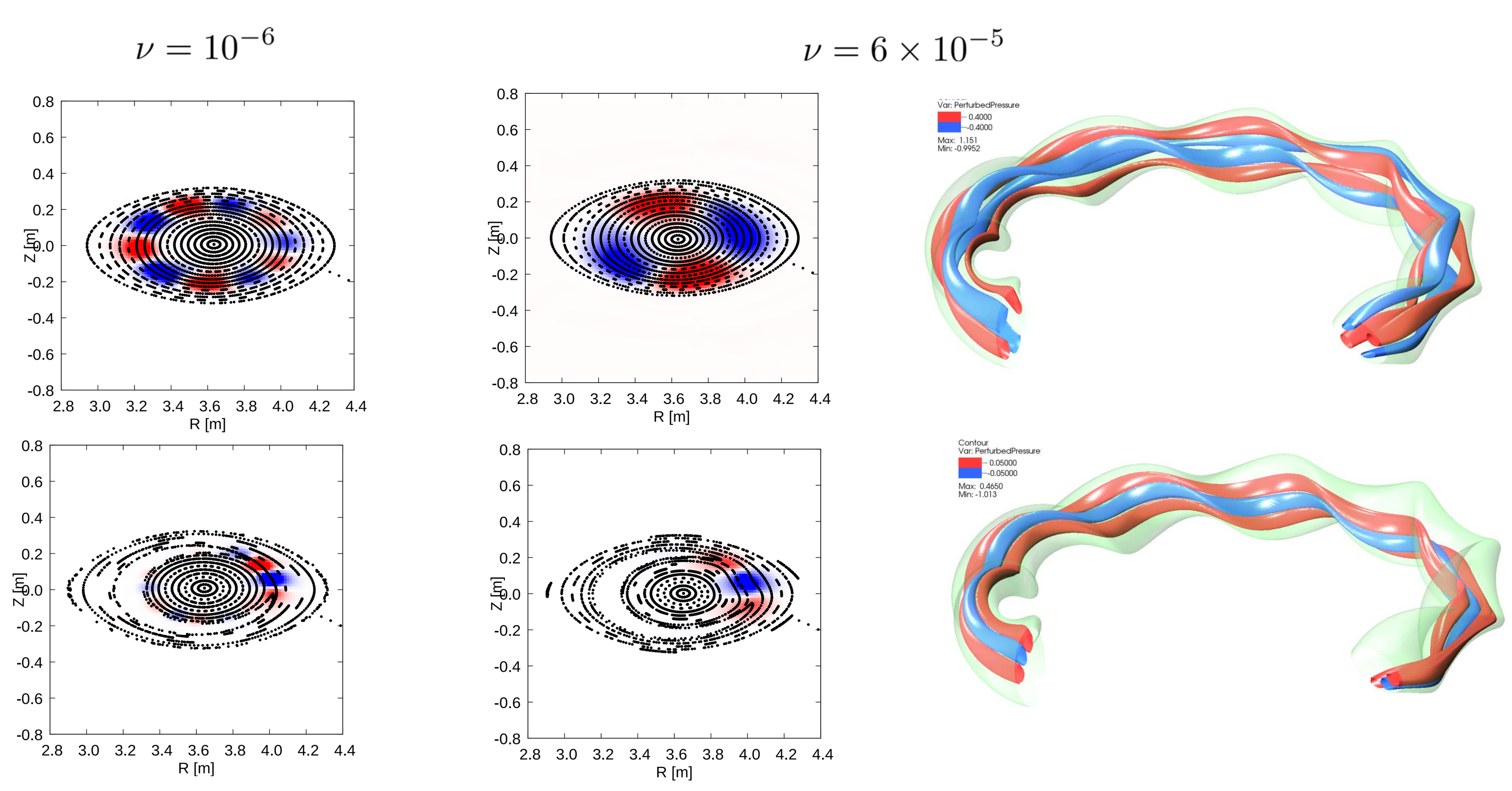
$\nu = 10^{-6}$ $\nu = 6\times10^{-5}$

without RMP

Typical low n interchange mode localized at ι/2π=1 surface.

with RMP

Ballooning-like structure localized at X-point with steep pressure gradient.

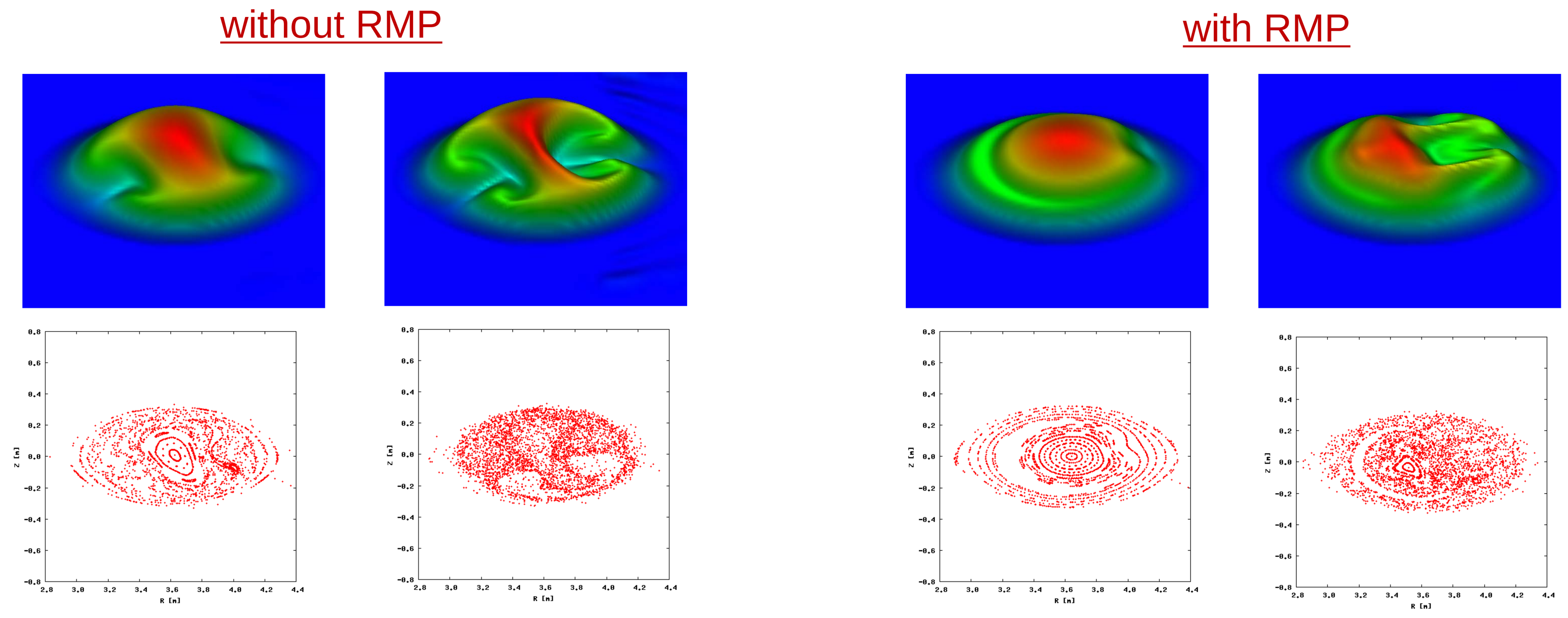


Nonlinear Dynamics

without RMP | with RMP

Pressure profile

Puncture plot of field line

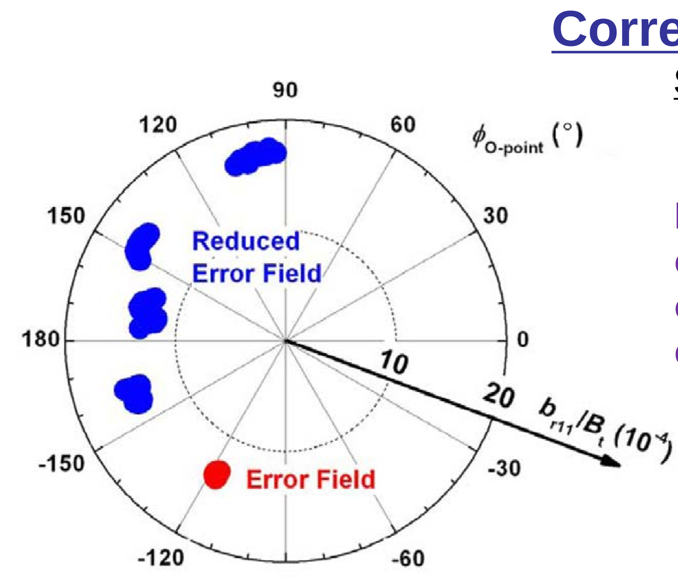


without RMP: Pressure collapses due to the interchange convection. There is no special phase of the collapse.

with RMP: Collapse occurs from the X-point and spreads out to core region. Mode phase is fixed.

Correspondence with LHD experiment

S.Sakakibara et al.,NF53(2013)043010

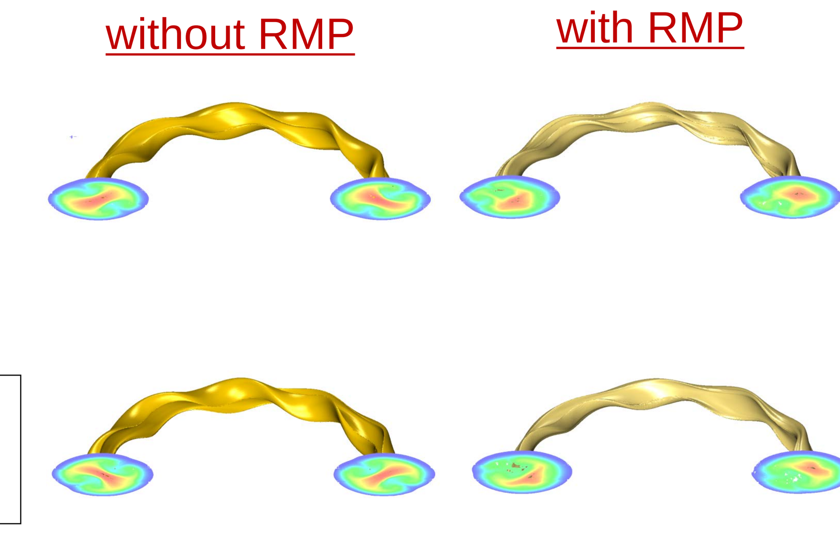


Fixed phase of collapses is observed in the error field cases.

without RMP | with RMP

Initial toroidal phase = 0

Initial toroidal phase = π/2



Summary

- ◆For MHD analyses of resonant magnetic perturbations (RMPs), 3D equilibrium calculation including RMPs is crucial, because RMPs can change the structure of pressure driven modes through the change of the equilibrium pressure profile.
- ◆In the case of an LHD plasma, a horizontally uniform RMP changes the mode structure from an interchange type to a ballooning type localized around the X-point.
- ◆In the increase of viscosity, the mode is stabilized by not only the viscosity itself but also the extension of the structure to the small gradient region.
- ◆The spatial phase of the nonlinear collapse is fixed corresponding to the geometry of the magnetic island.
- ◆Similar fixed phase is observed in the LHD experiments with the error field.
- ◆To investigate the detailed mechanism in the experiments, we need further analyses including RMP penetration and plasma rotation, and precise comparison.