Effects of Plasma Rotaion on Interchange Modes in LHD

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Outline

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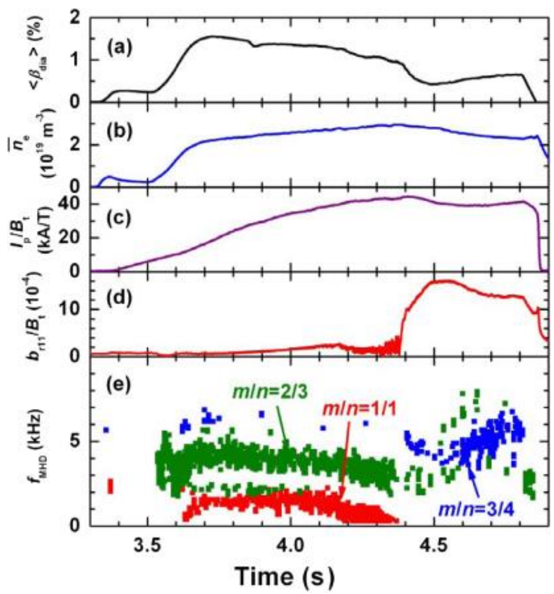
Motivation

- Observation of flow and partial collapse in LHD experiments

Rotation stop & collapse

Sakakibara et al., NF (2013) 043010 .

Rax=3.6m, γc=1.18, <βdia>~1.5%

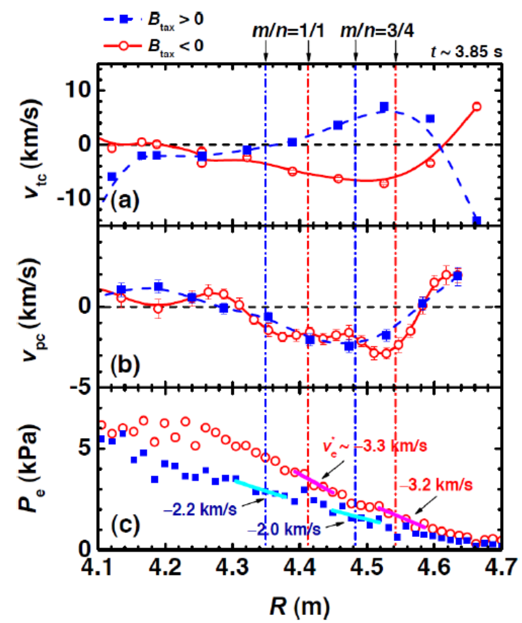


When the rotation of m=1/n=1 mode stops, the mode abruptly grows and beta value drops.

Typical carbon flow in LHD

Y.Takemura et al., PFR (2013) 140123 .

Rax=3.6m, γc=1.254, <βdia>~1.5%



Maximum poloidal carbon flow is a few km/s.

- **The rotation may suppress the mode growth.**

Numerical Method of 3D MHD Simulation

- We would like to study the effects of global shear flow on the stability of interchange modes in a Large Helical Device (LHD). by utilizing 3D numerical equilibrium and dynamics codes.

- However, a 3D equilibrium calculation scheme consistent with global flow has not been established for heliotrons.

- Static equilibrium is employed and a model poloidal flow is incorporated as the initial perturbation of the dynamics calculation.

- The HINT2 code (Y.Suzuki, et al. NF(2006)L19) is utilized for the 3D static equilibrium calculation.

  The HINT2 code solves the 3D equilibrium equations without any assumptions of the existence of the nested flux surfaces

- The MIPS code (Y.Todo, et al. PFR(2010)S2062) is utilized for the 3D dynamics calculation.

  The MIPS code solves the full MHD equations by following the time evolution with the HINT2 solution in (R, ϕ, Z) coordinates

Flow model

◆ Flow model

Coordinate transform between cylindrical and flux coordinates

$$(R,\phi,Z) \Longleftrightarrow (\rho,\theta,\phi)$$

Assumptions : $\boldsymbol{V}\cdot\nabla P_{eq}(\rho)=0 \quad V_\theta^2 = V_R^2 + V_Z^2$

$$V_R = \frac{1}{A^2}\left[-\frac{1}{R}\frac{\partial P_{eq}}{\partial\phi}\frac{\partial P_{eq}}{\partial R}V_\phi \pm K\frac{\partial P_{eq}}{\partial Z}\right]$$

$$V_Z = \frac{1}{A^2}\left[-\frac{1}{R}\frac{\partial P_{eq}}{\partial\phi}\frac{\partial P_{eq}}{\partial Z}V_\phi \mp K\frac{\partial P_{eq}}{\partial R}\right]$$

$$A^2 = \left(\frac{\partial P_{eq}}{\partial R}\right)^2 + \left(\frac{\partial P_{eq}}{\partial Z}\right)^2$$

$$K = \left[A^2V_\theta^2 - \left(\frac{V_\phi}{R}\frac{\partial P_{eq}}{\partial\phi}\right)^2\right]^{1/2}$$

Focus on poloidal flow : $V_\phi = 0 \quad \text{and} \quad V_\theta = V_\theta(\rho)$

Magnetic configuration and equilibrium results

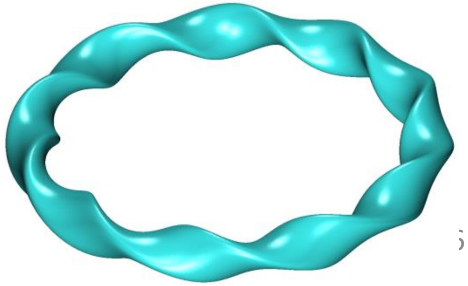
- **Magnetic configuration**

  Rax=3.6m, γc=1.13, β0=4.4%
  no net toroidal current constraint

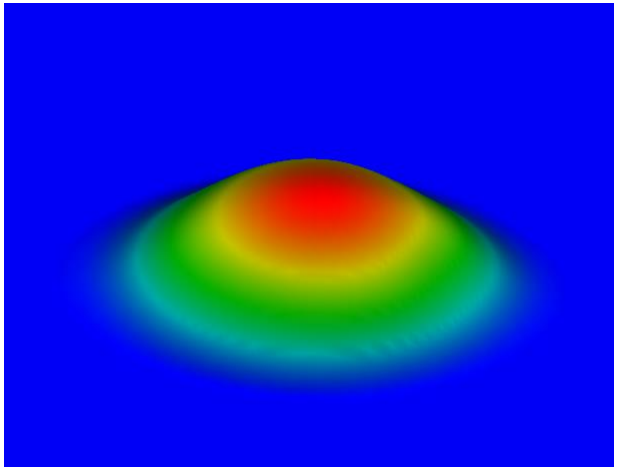
- **Equilibrium results with model profiles of pressure and flow**

$$P_{eq} = P_0(1-\rho^2)(1-\rho^8)$$

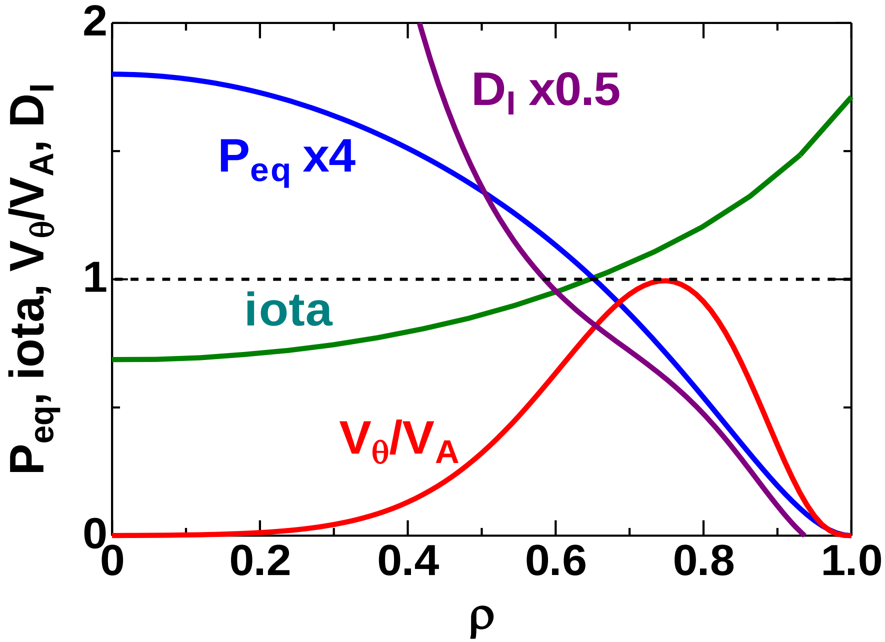
3D equilibrium



Peq profile



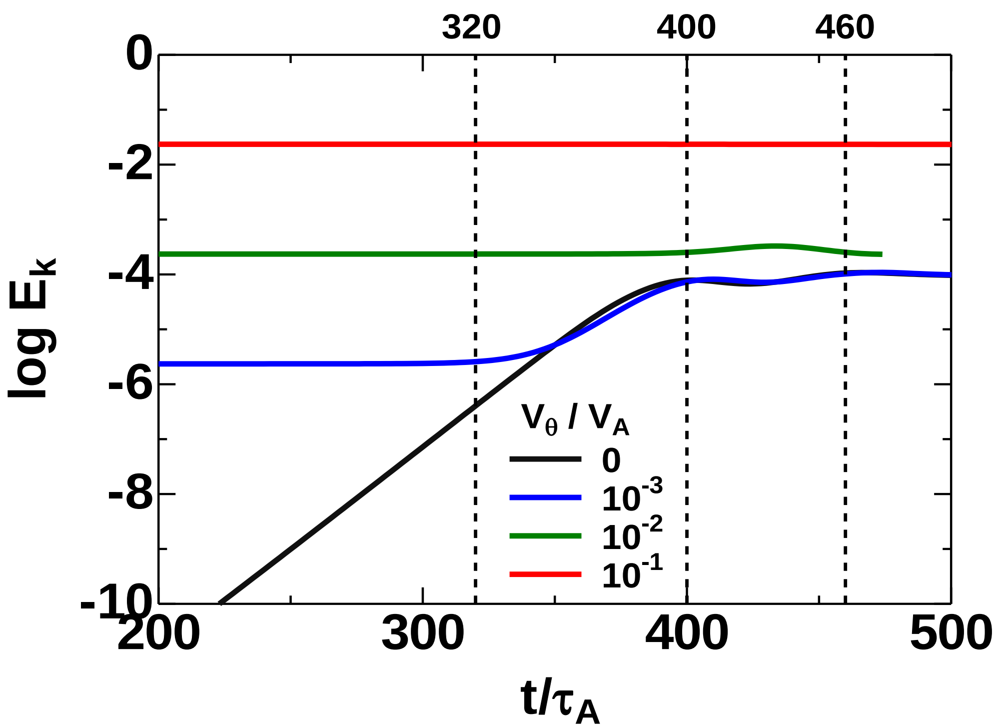
Equilibrium pressure, rotational transform, poloidal flow, Mercier stability



$$V_A = 4.87 \times 10^6 (m/s)$$
for
$$B_0 = 1(T), n_e = 0.2 \times 10^{20} (m^{-3})$$

Time evolution of pressure driven mode

- Time Evolution of kinetic energy



$V_\theta / V_A = 0$ (No flow)

After linear growth,
nonlinear saturation at t=400τA
Esat ~ 10^{-4}

$V_\theta / V_A = 10^{-3}$ (Ek(flow) << Esat)

After no interaction with flow
no-flow mode dominant for t>340τA

$V_\theta / V_A = 10^{-2}$ (Ek(flow) ~ Esat)

Small interaction appears in saturation.

$V_\theta / V_A = 10^{-1}$ (Ek(flow) >> Esat)

Almost no interaction over whole time region

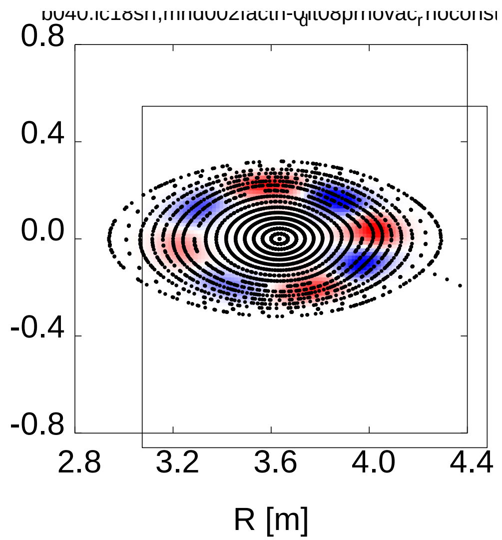
Flow effects on linear mode

- **Puncture plot and relative amplitude of perturbed pressure in linear phase**

t=320 τA

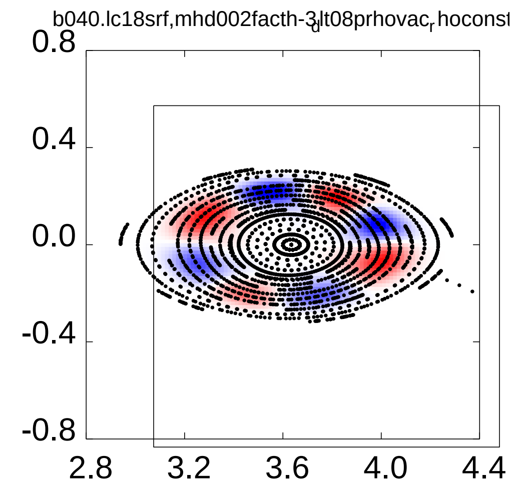
$V_\theta/V_A = 0$

Interchange mode with m=4 grows.



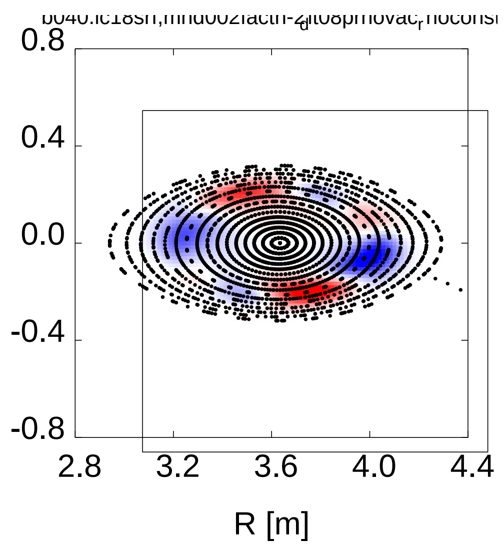
$V_\theta/V_A = 10^{-3}$

Almost the same as in no-flow case.



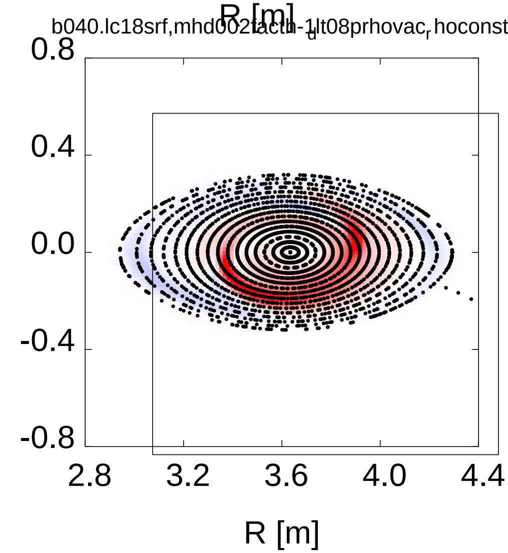
$V_\theta/V_A = 10^{-2}$

A mode grows but mode number is reduced to m=2.



$V_\theta/V_A = 10^{-1}$

Any mode cannot be recognized.



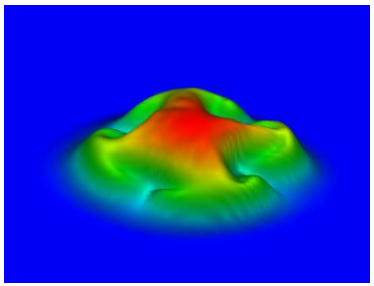
Flow dependence of nonlinear dynamics (1)

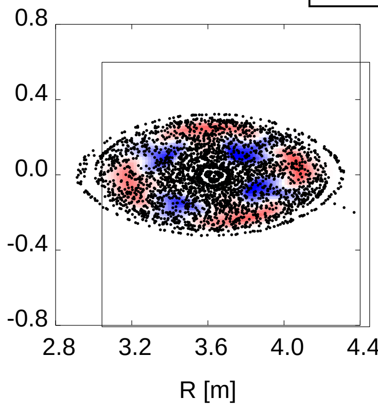
- **Pressure and magnetic field lines in nonlinear saturation phase**

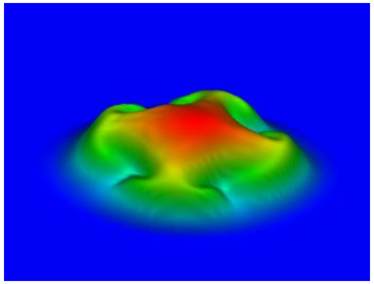
$V_\theta/V_A = 0$

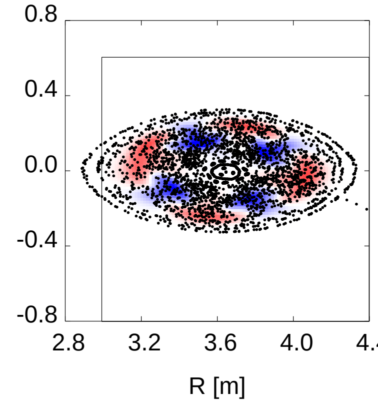
$V_\theta/V_A = 10^{-3}$

t=400 τA





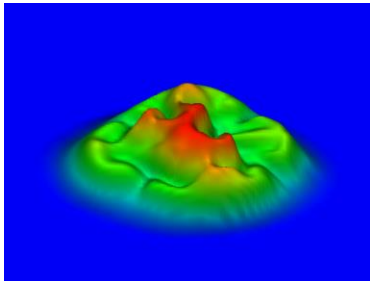


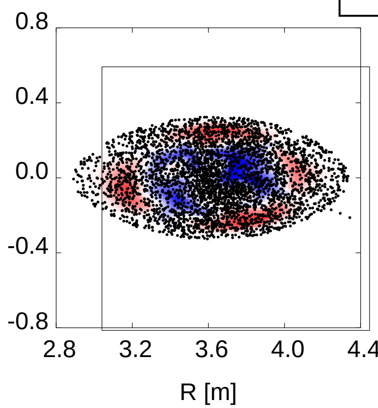


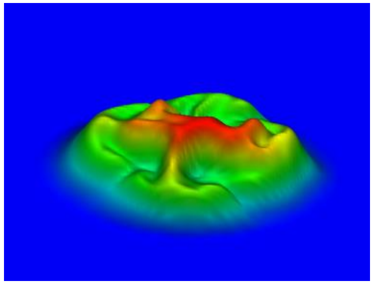
Pressure deformation with m=4 enhance
Core region is already stochastic.

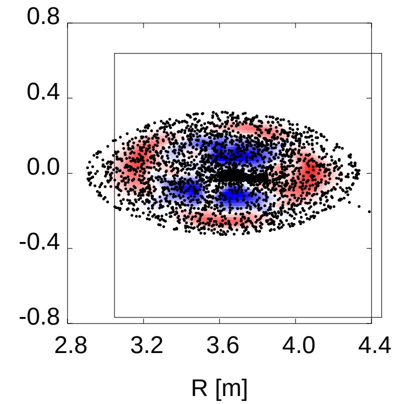
Pressure deformation and stochasticity are similar but slightly weak.

t=460 τA









Pressure collapses with stochastic field lines.

Slightly weak pressure collapse and stochastic field lines are observed.

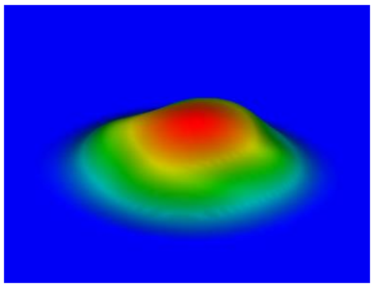
Flow dependence of nonlinear dynamics (2)

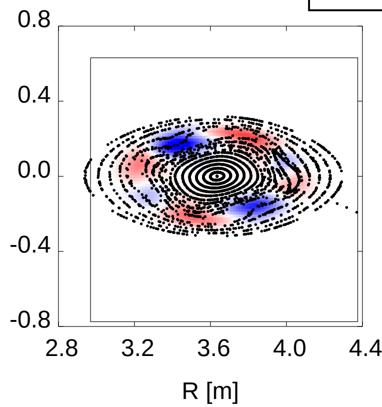
- **Pressure and magnetic field lines in nonlinear saturation phase**

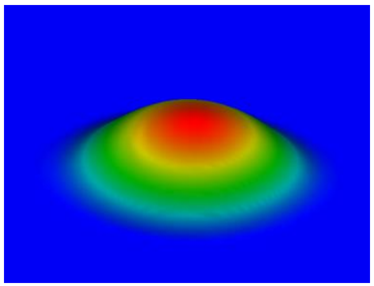
$$V_\theta/V_A = 10^{-2}$$

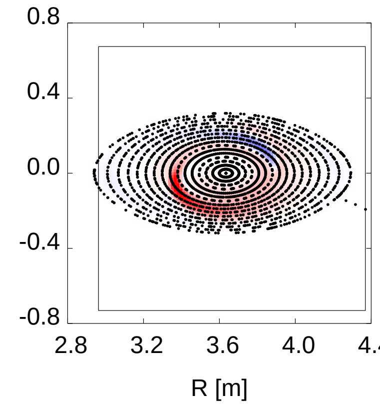
t=400 τA

$$V_\theta/V_A = 10^{-1}$$





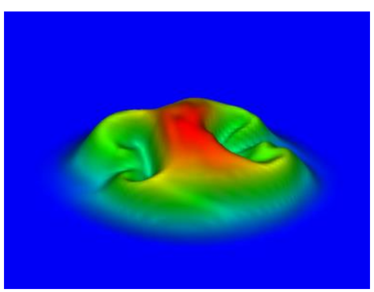


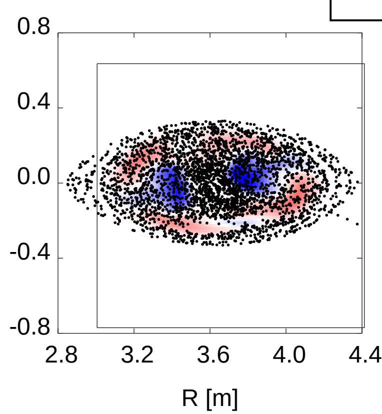


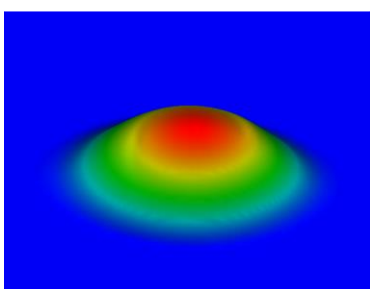
Small pressure deformation with m=2 appears and flux surfaces remain.

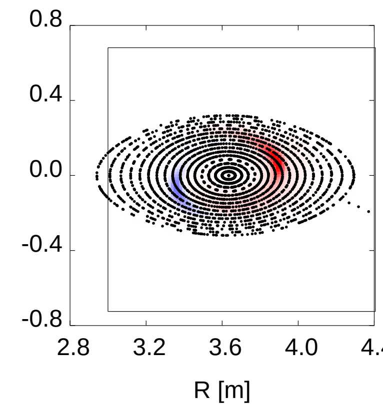
Almost no change in pressure and field lines.

t=460 τA









Pressure collapse and stochasticity are mitigated.

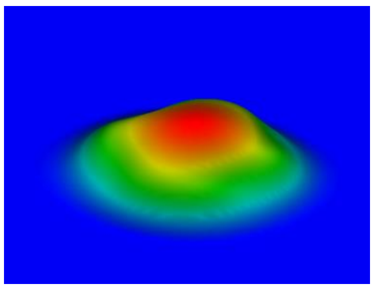
Almost no change in pressure and field lines.

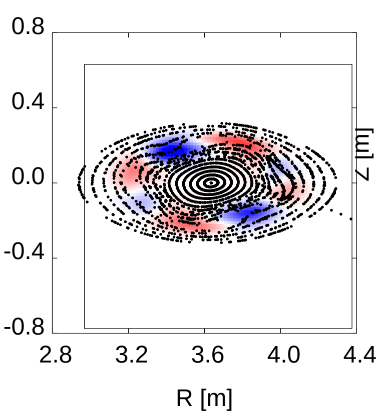
Flow dependence of nonlinear dynamics (3)

- **Pressure and magnetic field lines in nonlinear saturation phase**

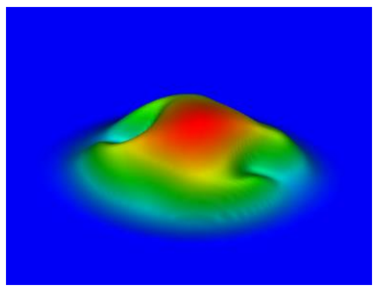
$$\boxed{V_\theta / V_A = 10^{-2}}$$

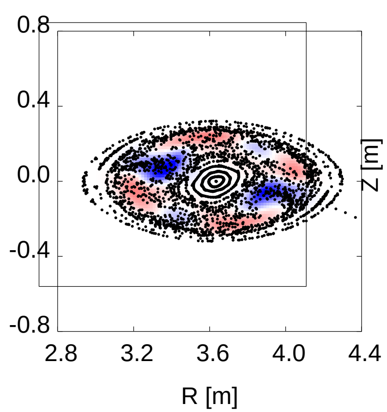
t=400 τA



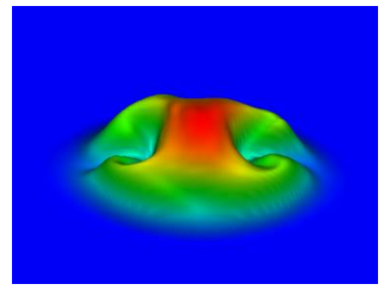


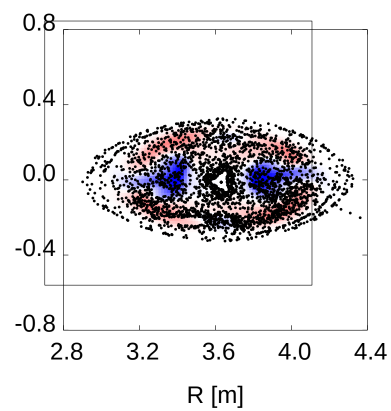
t=420 τA



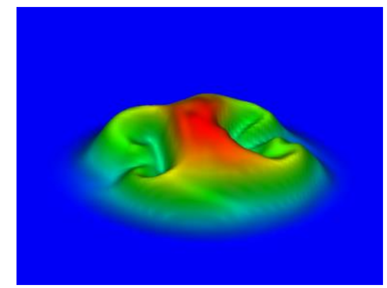


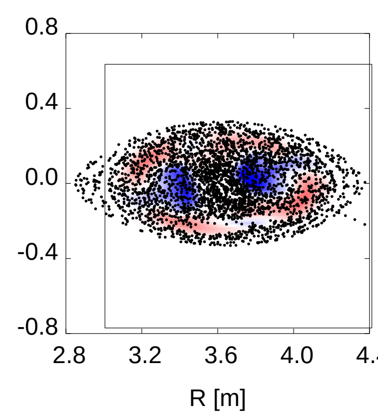
t=440 τA





t=460 τA





Rotation of mode structure is seen.

Summary

- Effects of poloidal shear flow on the stability of interchange modes in a Large Helical Device (LHD) configuration are studied utilizing 3D numerical codes.

- Static equilibrium is employed and a model poloidal flow is incorporated as the initial perturbation.

- Stabilizing effects of the shear flow are observed :
  - No flow :
    - Growth of an interchange mode leads to pressure collapse and field line stochasticity.
  - Ek(flow) << Esat :
    - Flow does not interact the mode in the linear phase and slightly weakens the collapse and stochasticity.
  - Ek(flow) ~ Esat :
    - Flow reduces the mode number and mitigates the collapse and stochasticity with showing substantial rotaion.
  - Ek(flow) >> Esat :
    - The mode is completely stabilized.

- More systematic analyses are necessary in future.

Future Plan – Stationary state with flow

- Stability analysis procedure of stationary state consistent with flow.

1. Low beta static equilibrium is calculated with the HINT code, which is slightly unstable against interchange modes.

2. With the plasma flow in the initial perturbation, the time evolution of the plasma dynamics is followed with the MIPS code.

(Up to this point, the procedure is the same as the present case.)

3, The nonlinear saturation phase is recognized as the stationary state consistent with the flow, which is stable for the interchange modes.

4. The stability of the stationary state is examined against the perturbation generated by the change of equilibrium quantity.

a. beta ramp up with heat source term
b. rotational transform change with increasing net current

3D Equilibrium Calculation

● HINT2 code

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

- The HINT2 code solves the 3D equilibrium equations without any assumptions of the existence of the nested flux surfaces. (suitable for the equilibrium analysis including RMPs)
- An LHD configuration with an inwardly shifted vacuum magnetic axis and a high aspect ration is employed. (Rax=3.6m, γ=1.13)
- Calculation starts with the parabolic pressure profile with $\beta_0 = 4.4\%$.

Initial Condition

vacuum magnetic field

pressure profile : $P = P_0(1-s)(1-s^4)$

Step A : Calculation of *P* (*B* fixed, field line tracing)

$$\boldsymbol{B}\cdot\nabla P = 0$$

Step B : Calculation of *B* (*P* fixed, following MHD eqs.)

$$\frac{\partial \boldsymbol{v}}{\partial t} = -\nabla P + \boldsymbol{j}\times\boldsymbol{B}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla\times(\boldsymbol{v}\times\boldsymbol{B} - \eta\boldsymbol{j}) \qquad \boldsymbol{j} = \frac{1}{\mu_0}\nabla\times\boldsymbol{B}$$

$$\boldsymbol{J}\times\boldsymbol{B} = \nabla P$$

Convergence

Equilibrium consistent with RMPs

3D MHD Dynamics Calculation

- **MIPS code** (Todo et al., Plasma Fus. Res. (2010) S2062)

  Solves the full MHD equations by following the time evolution.

  4th order central difference method for (R, ϕ, Z) directions.

  4th order Runge Kutta scheme for the time evolution.

  The most unstable mode is detected.

Basic equations

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

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

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

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

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

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

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