Effects of Plasma Rotation on Interchange Modes in LHD

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1. Motivation  
   LHD experimental data for plasma rotation

2. Numerical method of 3D MHD simulation  
   Procedure of the analysis  
   Flow model

3. Simulation results with finite flow  
   Magnetic configuration and equilibrium results  
   Time evolution of pressure driven mode  
   Flow effects on linear modes  
   Flow dependence of nonlinear dynamics

4. Summary & Future Plan
Motivation

- Observation of flow and partial collapse in LHD experiments

**Rotation stop & collapse**
Sakakibara et al., NF (2013) 043010.
R_{ax}=3.6m, γc=1.18, <βDia>~1.5%

**Typical carbon flow in LHD**
Y.Takemura et al., PFR (2013) 140123.
R_{ax}=3.6m, γc=1.254, <βDia>~1.5%

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

- The rotation may suppress the mode growth.

Maximum poloidal carbon flow is a few km/s.
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 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, \( \phi \), Z) coordinates.
Flow model

Coordinate transform between cylindrical and flux coordinates

\[(R, \phi, Z) \leftrightarrow (\rho, \theta, \phi)\]

**Assumptions:**

\[V \cdot \nabla P_{eq}(\rho) = 0 \quad V_{\theta}^2 = V_{R}^2 + V_{Z}^2\]

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

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

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

**Focus on poloidal flow:**

\[V_\phi = 0 \quad \text{and} \quad V_\theta = V_\theta(\rho)\]
Magnetic configuration and equilibrium results

- Magnetic configuration
  \[ R_{ax} = 3.6 \text{m}, \ \gamma_c = 1.13, \ \beta_0 = 4.4\% \]
  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

\[ V_\theta / V_A = 0 \quad \text{(No flow)} \]

After linear growth, nonlinear saturation at \( t = 400 \tau_A \)

\( E_{\text{sat}} \sim 10^{-4} \)

\[ V_\theta / V_A = 10^{-3} \quad \text{(Ek(flow) \ll Esat)} \]

After no interaction with flow

no-flow mode dominant for \( t > 340 \tau_A \)

\[ V_\theta / V_A = 10^{-2} \quad \text{(Ek(flow) \sim Esat)} \]

Small interaction appears in saturation.

\[ V_\theta / V_A = 10^{-1} \quad \text{(Ek(flow) \gg Esat)} \]

Almost no interaction over whole time region
Flow effects on linear mode

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

- $V_\theta/V_A = 0$
  Interchange mode with $m=4$ grows.

- $V_\theta/V_A = 10^{-2}$
  A mode grows but mode number is reduced to $m=2$.

- $V_\theta/V_A = 10^{-3}$
  Almost the same as in no-flow case.

- $V_\theta/V_A = 10^{-1}$
  Any mode cannot be recognized.
Pressure and magnetic field lines in nonlinear saturation phase

\[ V_\theta/V_A = 0 \]

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

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

Pressure deformation and stochasticity are similar but slightly weak.

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

\[ \frac{V_\theta}{V_A} = 10^{-2} \]

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

\[ \frac{V_\theta}{V_A} = 10^{-1} \]

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

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

Rotation of mode structure is seen.
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.
- $E_k(\text{flow}) \ll E_{sat}$:
  Flow does not interact the mode in the linear phase and slightly weakens the collapse and stochasticity.
- $E_k(\text{flow}) \sim E_{sat}$:
  Flow reduces the mode number and mitigates the collapse and stochasticity with showing substantial rotation.
- $E_k(\text{flow}) \gg E_{sat}$:
  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**

  - 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 ratio is employed. ($\text{Rax}=3.6\text{m}, \gamma=1.13$)

  - 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)**

$$ B \cdot \nabla P = 0 $$

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

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

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

$$ j = \frac{1}{\mu_0} \nabla \times B $$

$$ J \times B = \nabla P $$

Convergence

Equilibrium consistent with RMPs
Solves the full MHD equations by following the time evolution.
  4th order central difference method for (R, \(\phi\), Z) directions.
  4th order Runge Kutta scheme for the time evolution.
The most unstable mode is detected.


\[ \begin{align*}
\frac{\partial \rho}{\partial t} &= -\nabla \cdot (\rho \mathbf{v}) \\
\frac{\partial \mathbf{v}}{\partial t} &= -\rho \mathbf{w} \times \mathbf{v} - \rho \nabla \left( \frac{v^2}{2} \right) - \nabla p + \mathbf{j} \times \mathbf{B} \\
&\quad + \frac{3}{4} \nabla [\nu \rho (\nabla \cdot \mathbf{v})] - \nabla \times (\nu \rho \mathbf{w}) \\
\frac{\partial \mathbf{B}}{\partial t} &= -\nabla \times \mathbf{E} \\
\frac{\partial p}{\partial t} &= -\nabla \cdot (p \mathbf{v}) - (\Gamma - 1)p \nabla \cdot \mathbf{v} + \chi_{\perp} \nabla^2 \perp (p - p_{eq}) + \chi_{\parallel} \nabla^2 \parallel p \\
\mathbf{E} &= -\mathbf{v} \times \mathbf{B} + \eta (\mathbf{j} - \mathbf{j}_{eq}) \\
\mathbf{J} &= \frac{1}{\mu_0} \nabla \times \mathbf{B} \\
\mathbf{w} &= \nabla \times \mathbf{v}
\end{align*} \]