Numerical MHD Analysis of LHD Plasmas with Magnetic Axis Swing

K. ICHIGUCHI, **S. SAKAKIBARA, S. OHDACHI** (*National Institute for Fusion Science, JAPAN*),
B. A. CARRERAS (*BACV Solutions Inc.,USA*)

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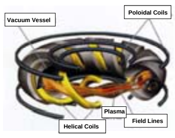
ABSTRACT

Experimental result of magnetic axis swing operation in the Large Helical Device (LHD) plasma is analyzed with a nonlinear MHD simulation.
Real time control of the background field in the operation is incorporated by means of a multi-scale numerical scheme.
The simulation result indicates that the observed collapse is due to the enhancement of an infernal-like mode in the change of the background field.

Introduction

Large Helical Device (LHD)
(NIFS,Japan)

Largest machine in a heliotron configuration

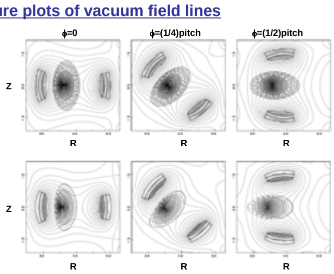


Horizontal position of vacuumu magnetic axis (Rvax) is shifted by change of poloidal field.

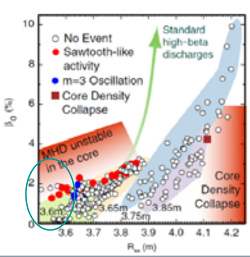
Puncture plots of vacuum field lines

Rvax=3.60m

Rvax=3.50m



Dependence of Experimental MHD Property on Rvax.
(A.Komori et al., NF (2009) 104015.)

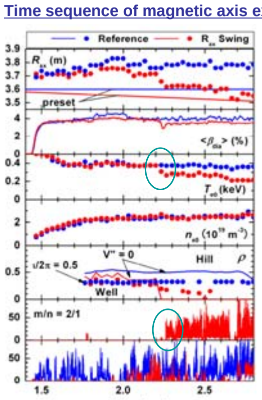


Stability bounday on Rvax is not clear for small Rvax.

Magnetic Axis Swing Operation

Magnetic axis swing operations were carried out for investigation of the stability boudary.
(S.Sakakibara et al., 23rd IAEA-FEC 2010 EXS/P5-13.)

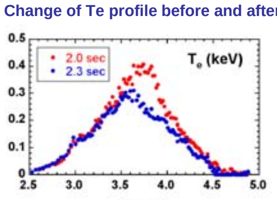
Time sequence of magnetic axis experiment



In the swing case, Te suddenly drops Rvax~3.55m.

Magnetic fluctuations of (m,n)=(2,1) mode are observed coincidently.

Change of Te profile before and after Te0 drop



Minor collapse occurs in the core region.

Mechanism of the collapse is analyzed numerically with a multi-scale MHD simulation scheme.

Necessity of Multi-Scale Scheme

In the simulation of magnetic axis swing experiment, equilibrium quantities changes due to the background field variation.
Time evolutions of both perturbations and equilibrium quantities must be treated simultaneously.

Big difference in the time scale between perturbation and equilibrium.

- Equilibrium evolution ~ 10ms : Long
- Dynamics of Perturbation ~ 0.5μs : Short

Multi-scale scheme has been developed.
(K.Ichiguchi, B.A.Carreras, NF (2011) 053021)

Basic idea of the multi-scale scheme :
Carry out Long time-scale calculation every certain time evolution of Short time-scale calculation

Short time scale : Continuous calculation of perturbation dynamics with the NORM code

Long time scale : Update of 3D static equilibrium with the VMEC code Incorporation of deformation of the pressure profile due to the dynamics.

Basic Equations for Nonlinear Calculation

Nonlinear MHD Dynamics Calculation : NORM code

Basic Equations : 3-Field Reduced MHD Equations for
Ψ (poloidal flux) Φ (stream function) P(pressure)

Inclusion of diffusion of background equilibrium pressure and continuous heating

Variables are separated in different way.

Equilibrium & Perturbed Parts

$$\Psi(\rho,\theta,\zeta;t) = \Psi_{eq}(\rho) + \tilde{\Psi}(\rho,\theta,\zeta;t)$$

$$\Phi(\rho,\theta,\zeta;t) = \tilde{\Phi}(\rho,\theta,\zeta;t)$$

Average & Oscillating Parts

$$P(\rho,\theta,\zeta;t) = \underbrace{\langle P\rangle(\rho;t)} + \widehat{P}(\rho,\theta,\zeta;t)$$

Background equilibrium pressure

Application to the reduced MHD equations

$$\frac{\partial \tilde{\Psi}}{\partial t} = -\nabla_{\parallel}\tilde{\Phi} + \frac{1}{S}\tilde{J}_{\zeta}$$

$$\frac{\partial \tilde{U}}{\partial t} = -[\tilde{U},\tilde{\Phi}] - \nabla_{\parallel}\tilde{J}_{\zeta} - [\tilde{\Psi}, J_{\zeta eq}] + \frac{1}{2\epsilon^2}[\Omega_{eq},\widehat{P}] + \nu\left(\frac{R}{R_0}\right)^2\nabla_{\perp}^2\tilde{U}$$

$$\frac{\partial \widehat{P}}{\partial t} = -\widehat{[P,\tilde{\Phi}]} + \kappa_{\perp}\widehat{\Delta_* P} + \kappa_{\parallel}\widehat{\nabla_{\parallel}^{\dagger 2} P}$$

$$\frac{\partial \langle P\rangle}{\partial t} = -\langle[\widehat{P},\tilde{\Phi}]\rangle + \kappa_{\perp}\langle\Delta_*\langle P\rangle\rangle + \kappa_{\parallel}\langle\nabla_{\parallel}^{\dagger 2}\langle P\rangle\rangle + Q(\rho;t)$$

- Anomalous transport due to MHD turbulence
- Classical diffusion of background pressure
- Continuous heat source

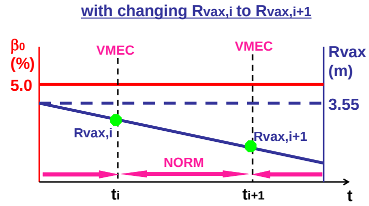
$$\left([y,z] = \frac{g}{\rho}\left(\frac{\partial y}{\partial\rho}\frac{\partial z}{\partial\theta} - \frac{\partial y}{\partial\theta}\frac{\partial z}{\partial\rho}\right), \nabla_{\perp}f = \nabla f - \nabla\zeta\frac{\partial f}{\partial\zeta}, \nabla_{\parallel}f = g\frac{\partial f}{\partial\zeta} + [\Psi,f], \nabla_{\parallel}^{\dagger 2}f = \nabla_{\parallel}\left[\left(\frac{R_0}{R}\right)^2\nabla_{\parallel}f\right]\right)$$

$$\Omega = \frac{1}{2\pi}\int_0^{2\pi}d\zeta\left(\frac{R}{R_0}\right)^2\left(1 + \frac{|B_{eq}(R,\zeta,Z) - \overline{B_{eq}}(R,Z)|^2}{B_0^2}\right), \quad v_{\perp} = \left(\frac{R}{R_0}\right)^2\nabla\Phi\times\nabla\zeta,$$

$$U = \hat{\nabla}_{\perp}^2\Phi = \left(\frac{R}{R_0}\right)^2\nabla\cdot\nabla_{\perp}\Phi, \quad J_{\zeta} = \Delta_*\Psi = \left(\frac{R}{R_0}\right)^2\nabla\cdot\left(\frac{R_0}{R}\right)^2\nabla_{\perp}\Psi$$

Numerical Multi-Scale Scheme

Predictor-Corrector calculation in each interval of $t_i<t<t_{i+1}$ with changing $R_{vax,i}$ to $R_{vax,i+1}$



1. VMEC calculation at $t=t_i$

$$P_{eq,i} = \langle P\rangle_i \Rightarrow E_{eq,i}$$

Predictor

$$P_{eq,i+1}^{pre} = \langle P\rangle_i + \Delta P(\rho) \Rightarrow E_{eq,i+1}^{pre}$$

Corrector

$$P_{eq,i+1}^{cor} = \langle P\rangle_i^{pre} + \Delta P(\rho) \Rightarrow E_{eq,i+1}^{cor}$$

2. Interpolation of equilibrium at every time step of NORM

$$E_{eq,ij}^{pre} = E_{eq,i} + \frac{j}{L}(E_{eq,i+1}^{pre} - E_{eq,i})$$

$$E_{eq,ij}^{cor} = E_{eq,i} + \frac{j}{L}(E_{eq,i+1}^{cor} - E_{eq,i})$$

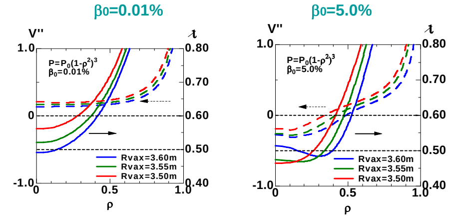
3. Determination heat source

$$Q(\rho) = \frac{\Delta P(\rho)}{t_{i+1} - t_i}$$

4. NORM calculation for nonlinear dynamics for $t_i<t<t_{i+1}$

Equilibrium Quantities

Rotational Transform & Magnetic Well



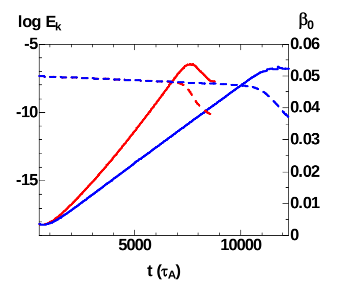
Rotational transform decreases to have ι=1/2 as beta increases.
Magnetic hill region becomes wider as Rvax decreases.

Nonlinear Time Evolution

Calculation Parameters

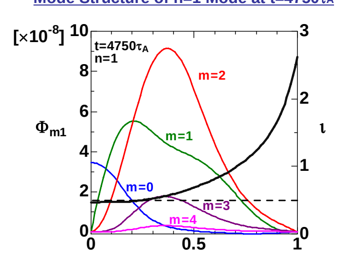
- Equilibrium calculation : Free boundary and no net-current (Rlim=4.6m)
- Initial condition : Initial profile of $P = P_0(1-\rho^2)^3$ at β0=5.0%
- Variation of Rvax : From Rvax=3.55m at t=0 to Rvax=3.46m at t=8750tA
- Heating profile : $\Delta P(\rho) = P_0(1-\rho^2)^{10}$
- Dissipation Parameters : $S = 10^6$, $\nu = 1.7\times10^{-4}$, $\kappa_{\perp} = 1.7\times10^{-6}$, $\kappa_{\parallel} = 1.7\times10^{-2}$

Time Evolution of Kinetic Energy of n=1 Mode and Axis Beta



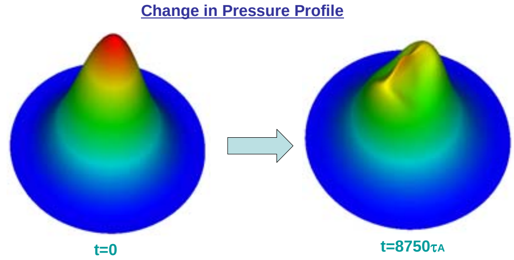
Unstable mode grows much faster in the case with axis swing than in the case without axis swing.
Abrupt drop of β0 is observed in the nonlinear saturtaion.

Mode Structure of n=1 Mode at $t=4750\tau_A$



The (2,1) component is dominant.
Mode structure is infernal-like.

Change in Pressure Profile



Pressure in the core region collapses with m=2 structure in the saturation phase.

Conclusions

A collapse phenomenon observed in the magnetic axis operation in LHD is numerically studied with a multi-scale analysis.
The simulation results qualitatively demonstrate the mechanism that the enhancement of the magnetic hill due to the change of the background field destabilizes an infernal-like mode to cause a minor collapse.