MHD Simulation of Heliotron Plasma in Change of Background Field

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Abstract

A partial collapse observed in the Large Helical Device (LHD) experiments with the change of the background field is analyzed with a nonlinear MHD simulation. A multi-scale numerical scheme is utilized for the analysis. It is obtained that the collapse is caused by the destabilization of an infernal-like mode.

1. Introduction

MHD collapses must be avoided in future reactors. However, the stability boundary based on the collapses has not been established in heliotron configurations. Recently, in experiments of the Large Helical Device (LHD), magnetic axis swing operations were carried out to find out the collapse boundary concerning with the position of the vacuum magnetic axis, R_{vax}[1]. In the experiments, the background magnetic field is actively controlled during each shot so that the corresponding vacuum magnetic axis position is shifted inwardly. In the case where the background magnetic field is changed from $R_{vax} = 3.60$m to $R_{vax} = 3.50$m, a collapse is observed in the electron temperature for $R_{vax} \lesssim 3.55$m during the discharge. The collapse occurs around the magnetic axis and accompanied with $(m,n) = (2,1)$ magnetic fluctuations, where m and n are the poloidal and the toroidal mode numbers, respectively. Thus, we investigate the mechanism of the collapse by means of a numerical MHD simulation.

To analyze the experimental results, we have to treat two different time scales simultaneously, the time scales of the equilibrium evolution due to the field change and the nonlinear dynamics of the perturbations. The difference of the time scales is in the order of $\sim 10^5$. In order to solve such problems, we have developed a multi-scale numerical scheme[2]. In the scheme, time-dependent nonlinear dynamics calculations and updates of a static equilibrium are iterated. The dynamics is calculated with the NORM code[3], which is based on the reduced MHD equations. The equilibrium is updated with the VMEC code[4]. In the equilibrium update, the deformation of the pressure profile due to the nonlinear dynamics is incorporated.

In the previous work[5], we applied this multi-scale scheme to the analysis of the magnetic axis swing plasma and obtained a preliminary result showing a pressure collapse. In this analysis, however, the change rate of the background field was much faster than that in the experiments. The collapse was obtained at $R_{vax} = 3.4$m, which is out of the range used in the experiment. Thus, in the present analysis, we reduce the change rate of the background magnetic field and examine whether the collapse can occur in the range of the background field corresponding to the experiment.

2. Time Evolution with Change of Background Magnetic Field

We follow the time evolution of the plasma with the multi-scale scheme. The background magnetic field is linearly changed so that $R_{vax} = 3.550$m at $t = 0$ and $R_{vax} = 3.525$m at $t = 30000\tau_A$, where τ_A is the Alfvén time. We employ the profile of $P = P_0(1-\rho^2)^3$ and $\beta_0 = 5.0\%$ as the initial pressure profile, where ρ denotes the square-root of the normalized toroidal flux. We incorporate a constant heat source in the pressure equation, so that both the axis beta and the average beta almost constant when no unstable mode is excited. The profile of $Q(\rho) = Q_0(1-\rho^2)^{21}$ is employed for the heat source. The values of $\varepsilon = 0.1566$ and $S = 1.0\times10^7$ are used for the inverse aspect ratio of the plasma and the magnetic Reynolds number, respectively. The coefficients of the viscosity and the perpendicular and the parallel heat conductivities are assumed to be $\nu = 1.0$, $\kappa_\perp = 1.0\times10^{-6}$ and $\varepsilon^2\kappa_\parallel = 4.0\times10^{-3}$. respectively. These coefficients are normalized by $\tau_A/(a^2\rho_m)$, τ_A/a^2 and τ_A/R_0^2, respectively, where a and R_0 are the minor and the major radii of the plasma, respectively, and ρ_m denotes the mass density. For comparison, we also calculate the time evolution of the case without the change of the background field. In this case, the magnetic field is fixed to the field of $R_{vax} = 3.55$m. In both cases, the $n = 1$ mode grows dominantly and nonlinear saturation is observed.

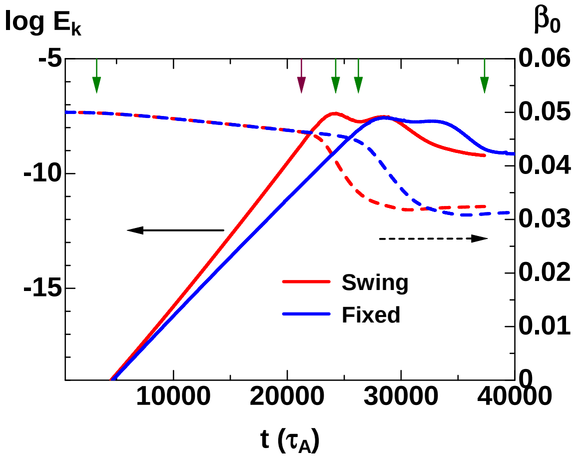

Fig.1 Time evolution of the kinetic energy of $n = 1$ modes (E_k) and axis beta (β_0).

Figure 1 shows the time evolution of the kinetic energy of the $n = 1$ modes. In the case of the change of the background magnetic field, the growth rate is increasing during the linear phase. The increase is due to the fact that the magnetic hill is enhanced as shown in Fig.2. The maximum growth rate γ is $\gamma\tau_A = 7.47\times10^{-4}$ which is obtained at $t = 21250\tau_A$. Figure 3 shows the mode structure of the stream function of the $n = 1$ mode in the linear phase. The dominant component is the (2, 1). This component peaks at a radial position shifted from the position of the $\iota = 1/2$ surface. Furthermore, the sideband components have comparable amplitudes and the same sign. These properties may suggest that the mode is like an infernal mode [6, 7] rather than an interchange mode.

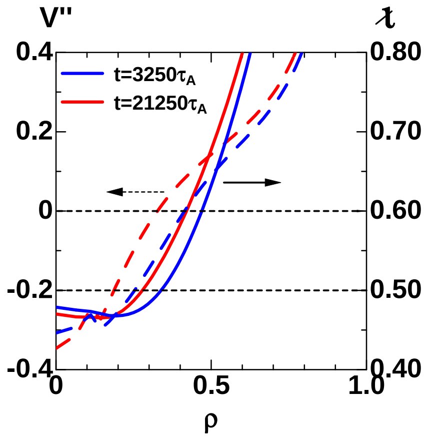

Fig.2 Profiles of V'' and ι at $t = 3250\tau_A$ and $21250\tau_A$.

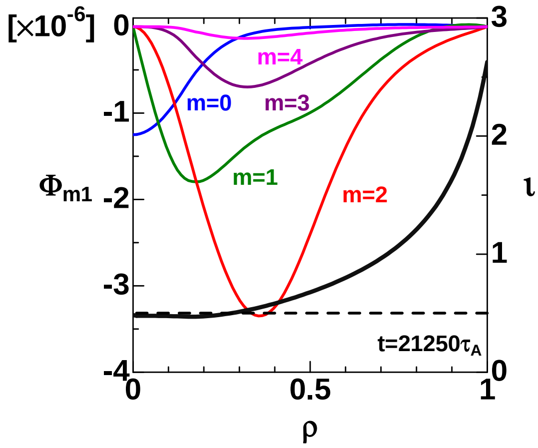

Fig.3 Profiles of $n = 1$ components of the stream function at $t = 21250\tau_A$.

Figure 4 shows the time evolution of the average pressure and the rotational transform in the nonlinear phase. The pressure decays in the core region in a short time. The decay indicates a partial collapse. Simultaneously, the rotational transform in the vicinity of the magnetic axis is increased so that the $\iota = 1/2$ surface disappears from the plasma column. As shown in Fig.5, the pressure profile deforms into an $m = 2$ structure in the collapse. The deformation is caused by the convection due to the infernal mode shown in Fig.3.

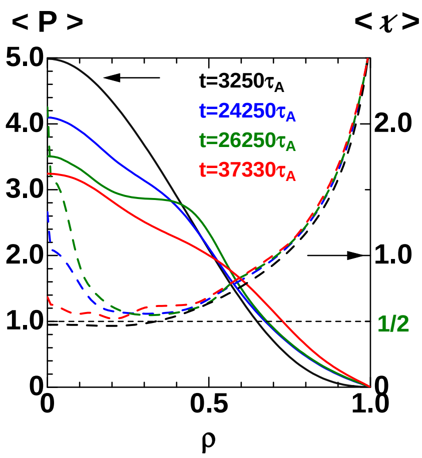

Fig.4 Time Evolution of profiles of average pressure and rotational transform.

Even in the case of the fixed background magnetic field, the linear growth and the nonlinear degradation of the pressure are obtained as shown in Fig.1. However, the linear growth rate is $\gamma\tau_A = 5.77 \times 10^{-4}$ which is smaller than the rate of the change of the background magnetic field. Furthermore, the saturation level is lower than that in the case with the change of the background magnetic field. These results show that the change of the background field degrades the stability. This tendency is consistent with the experimental results[1].

3. Conclusions

The mechanism of the partial collapse observed in the magnetic axis swing operation in LHD experiments is investigated with a multi-scale MHD numerical simulation. The enhancement of the magnetic hill due to the change of the background field degrades the stability of an infernal-

Fig.5 Bird's eye view of the pressure profiles at $t = 3250\tau_A$ (left) and $t = 26250\tau_A$ (right).

like mode. The mode numbers of the dominant component coincide with those of the observed fluctuation. In the nonlinear saturation of the mode, substantial reduction of the core pressure occurs, which corresponds to the observed collapse.

Thus, the present simulation clarifies the mechanism qualitatively. However, some features observed in the experiments remains unresolved. Particularly, the mode is unstable even in the fixed background field in the simulation, while the plasma is stable in the experiments. Besides, the mechanism of the onset of the linear growth is not explained. Both of the problems may be related to the choice of the initial pressure. It will be needed to resolve the problem to look at the experimental data of the pressure profile just before the collapse precisely and incorporate the properties in the simulation.

Acknowledgments

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