28th IAEA Fusion Energy Conference (FEC 2020)

Contribution ID: **797** Type: **Regular Poster**

Non-resonant global mode in LHD partial collapse with net toroidal current

Wednesday 12 May 2021 12:10 (20 minutes)

A transition from an interchange mode with high mode numbers (m, n) for m (poloidal) and n (toroidal) to a non-resonant $(m, n) = (1, 1)$ mode is found in the nonlinear magnetohydrodynamic (MHD) simulation for a Large Helical Device (LHD) plasma with net toroidal current. This transition occurs when the rotational transform is closed to unity in the core region. Because partial collapses caused by (1,1) modes are observed in the LHD experiments with net toroidal current, this transition to the non-resonant mode is a candidate for explaining the partial collapses.

In the magnetic confinement of plasmas, it is crucial that the plasmas are stable against MHD instabilities. Therefore, the stability property is extensively studied in the LHD experiments. In such experiments, partial collapse phenomena are observed when net toroidal current is driven by the neutral beam injection so that the rotational transform $\iota/2\pi$ is increased [1]. These collapses are always caused by (1,1) modes. These modes are considered to be pressure driven modes because the equilibria are strongly Mercier unstable. However, according to the theory of the pressure driven modes, the linear growth rate is larger for higher mode numbers. Therefore, it has been required to explain why the partial collapses are caused by the (1,1) modes in LHD.

This problem is investigated by means of three-dimensional nonlinear MHD simulations for LHD plasmas with net toroidal current. In the simulations, the HINT[2] and the MIPS[3] codes are utilized for the equilibrium and the nonlinear dynamics calculations, respectively. In the equilibrium calculation, the vacuum magnetic configuration corresponding to the experiment in Ref.[1] is used. The pressure profile P_{eq} and the axis beta β_0 are employed as $P_{eq} = P_0(1 - 0.68\rho^2 - 0.32\rho^4)$ and $\beta_0 = 1.6\%$, respectively. Here ρ denotes the square root of the normalized toroidal magnetic flux. The current density of the net toroidal current is assumed as $J_{eq} = J_0(1 - \rho^2)^4$ and the total current $I = 80\text{kA}$ for $B_0 = 3\text{T}$ are chosen. The values of β_0 and I are close to those of the experiment in Ref.[1]. In this equilibrium, $\iota/2\pi$ is close to unity and a no-shear point appears in the core region as shown in Fig.1 (a) and (b). Similar rotational transform profiles are often observed in the experiments.

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In the nonlinear dynamics calculation, the values of $t/\tau_A = 500$, $t/\tau_A = 800\text{m}I = 80/\text{s}$ are employed for the magnetic Reynolds number, the viscosity and the perpendicular heat conductivity, respectively. These values are relevant to the experiments. Also, $S = 5.6 \times 10^6$ is assumed for the parallel heat conductivity. At $\nu = \chi_\perp = 2.5$ in the early nonlinear phase, the (3,3) component is dominant as shown in Fig.1 (a), where ^{2} denotes the Alfv$\chi_\parallel = 10^3\chi_\perp$n time. This mode is a typical interchange mode resonant at the $t/\tau_A = 500$ surface. These mode numbers are higher than those in the observations. However, at τ_A in the further nonlinear phase, the (1,1) component appears and becomes dominant as shown in Fig.1 (b), which corresponds to the observations. This mode is not resonant at the é surface but is localized around the no-shear region. Therefore, a transition from the resonant (3,3) mode to the non-resonant (1,1) mode occurs. Figure 2 (a) shows that the magnetic field becomes locally stochastic in the unstable region due to the $\iota/2\pi = 1$ global convection. This convection also causes the partial collapse of the total pressure from one poloidal direction as shown in Fig.2 (b). This collapse tendency is similar to the experimental observation as shown in Fig.2 (c).

The case with no net toroidal current ($t/\tau_A = 800$) is also examined as a reference. Here, $\iota/2\pi = 1$ is employed. As shown in Fig.3 (a), the rotational transform has a monotonically increasing profile. In early nonlinear phase, the (3,2) component is dominant and the (1,1) component is negligibly small. This perturbation is a typical interchange mode resonant at the $m = 1$ surface. The total pressure profile decays with a triangular deformation as shown in Fig.3 (b). In the further time evolution, other sideband modes are enhanced and the total pressure decays in multiple poloidal directions. These mode numbers and decay property do not match the observed partial collapse shown in Fig. 2(c). Therefore, it is necessary for the transition that the rotational transform is changed by the net toroidal current so as to have no-shear region where the value is close to unity. Such a profile in the safety factor can appear also in tokamak sawtooth collapses. Therefore, extension of the analysis for flat rotational transform profiles is expected to provide common knowledge for avoiding collapses in current carrying plasmas.

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Session Classification: P3 Posters 3

Track Classification: Magnetic Fusion Theory and Modelling