J. Plasma Fusion Res. SERIES, Vol. 2 (1999) 286–290

Effects of Pressure Flattening in Heliotron Plasma

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(Received: 8 December 1998 / Accepted: 15 April 1999)

Abstract

The effects of pressure flattening at the rational surfaces on the magnetohydrodynamic (MHD) properties are studied numerically by using a model pressure profile in the Large Helical Device (LHD) configurations. The interchange mode is effectively stabilized by flattening the pressure at the resonant surface with much narrower flattened width than the mode width. The bootstrap current is locally reduced at the flattened region, however, the current density profile is not affected in other region in the case that the width is as narrow as the interchange mode can be stabilized.

Keywords:

pressure flattening, interchange mode, LHD, bootstrap current

1. Introduction

In the Large Helical Device, ten pairs of the local island divertor (LID) coil are provided in order to generate a magnetic island at the peripheral region of the plasma [1]. The enhancement of particle pumping is expected by setting a closed divertor at the O-point region. The magnetic island can be generated also inside the plasma column by controlling the currents in the coils, which leads to flattening the pressure profile at rational surfaces. In this paper, we discuss the effects of such local pressure flattening on the MHD properties by using a model profile of the pressure.

The horizontal position of the LHD plasma can be controlled by the vertical magnetic field [2]. The configuration with $\Delta_v = -15$ cm is called the standard configuration, where Δ_v denotes the horizontal distance of the vacuum magnetic axis from the center of the helical coils. The inward-shifted configuration with $\Delta_v <$ -15 cm is unfavorable in the point of the Mercier stability at low beta value because of the enhancement of the magnetic hill. On the contrary, it is favorable in the point of the confinement of the energetic particle because of the reduction of the orbit loss. Hence, the good operation will be achieved if the interchange mode can be stabilized in the inward-shifted configuration. Thus, we consider how the pressure flattening affects the stability for the interchange mode in the case of the low-beta inward-shifted plasma firstly.

As the beta value increases, the plasma column is shifted outward due to the diamagnetic effect without the position control by the vertical field. Hence, the inward-shifted plasma at low beta may move to the position of the standard configuration. Furthermore, the effect of the bootstrap current on the MHD properties becomes significant as the temperature is increased [3,4]. Thus, we study the effects of the pressure flattening on a high beta equilibrium with the bootstrap current in the standard configuration secondly.

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2. Numerical Procedure

In order to investigate the three-dimensional (3D) MHD equilibria with a pressure flattened region at a rational surface, we used the VMEC code [5]. Because the existence of the nested surfaces is assumed in this code, the pressure flattened region is also simulated with the nested surfaces. The constraint of specifying the net toroidal current is employed for the study of the no net current or the self-consistent bootstrap current equilibria. In this case, the profile of the rotational transform cannot be specified before the calculation. Therefore, some iterations for adjusting the flattened position to the rational surface are carried out.

The RESORM code [6] is used in the study of the global linear stability of the equilibria calculated with the VMEC code. This code solves the reduced MHD equations based on the modified stellarator expansion method for the poloidal magnetic flux Ψ, the stream function Φ and the plasma pressure P, which are given by

$$\frac{\partial \Psi}{\partial t} = -\left(\frac{R}{R_0}\right)^2 \boldsymbol{B}\cdot\nabla\Phi + \eta\nabla_\perp^2\Psi, \tag{1}$$

$$\rho_m \frac{\mathrm{d}\nabla_\perp^2\Phi}{\mathrm{d}t} = -\boldsymbol{B}\cdot\nabla\nabla_\perp^2\Psi + R_0^2\nabla\Omega\times\nabla P\cdot\nabla\zeta \tag{2}$$

and

$$\frac{\mathrm{d}P}{\mathrm{d}t} = 0. \tag{3}$$

Here R and ζ denote the major radius and the toroidal angle, respectively, and the subscript 0 means the value at the magnetic axis. The averaged magnetic curvature, Ω, is given by

$$\Omega = \frac{1}{2\pi}\int_0^{2\pi} \mathrm{d}\zeta \left(\frac{R}{R_0}\right)^2 \left(1 + \frac{|\boldsymbol{B} - \bar{\boldsymbol{B}}|^2}{B_0^2}\right), \tag{4}$$

where $\bar{\boldsymbol{B}}$ denotes the axisymmetric part of the magnetic field. The magnetic differential operator and the convective time derivative are written as

$$\boldsymbol{B}\cdot\nabla = \frac{R_0 B_0}{R^2}\frac{\partial}{\partial\zeta} - \nabla\Psi\times\nabla\zeta\cdot\nabla \tag{5}$$

and

$$\frac{\mathrm{d}}{\mathrm{d}t} = \frac{\partial}{\partial t} + \boldsymbol{v}_\perp\cdot\nabla_\perp, \quad \boldsymbol{v}_\perp = \left(\frac{R}{R_0}\right)^2 \nabla\Phi\times\nabla\zeta, \tag{6}$$

respectively, and $\nabla_\perp \equiv \nabla - \nabla\zeta\,(\partial/\partial\zeta)$. η denotes the resistivity which is set to 0 for the ideal modes.

3. Effects on Low β Equilibrium

In the low beta equilibria, the bootstrap current would be negligible. Hence, we studied the effects of the pressure flattening under the no net toroidal current constraint in the inward-shifted case with $\Delta_v = -25$ cm. Figure 1 shows the smooth pressure profile without the flattened region given by

$$P_s = P_0\,(1-\rho^2)^2, \tag{7}$$

where ρ is the square root of the normalized toroidal magnetic flux and the profile of the rotational transform, ι, at $\beta(0) = 2\%$ ($\beta(0)$ is the beta value at the magnetic axis). In this case, there is the rational surface with $\iota = 1/2$ in the plasma column. Hence, we calculated the stability against the $n = 1$ ideal mode, where m and n are the poloidal and the toroidal mode numbers, respectively. Substantial growth rates are obtained at the low beta values of 1, 2 and 3%, which are shown in Fig.2 at $w = 0$. Figure 3 shows the mode structure of the unstable mode at $\beta(0) = 2\%$. The dominant component is $m = 2$ which is resonant at the surface with $\iota = 1/2$ and shows a typical interchange type structure. The half-width of the component is 0.14 in ρ.

The effects of the pressure flattening is considered by assuming the profile of

$$P = P_s + \lambda(\rho-\rho_s)\exp\left[-\frac{1}{2}\left(\frac{\rho-\rho_s}{w}\right)^2\right]. \tag{8}$$

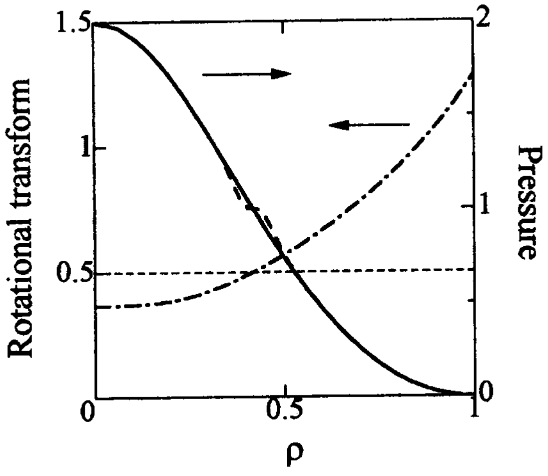

Fig. 1 Profiles of the rotational transform (dashed-dotted line) and the pressure at $\beta(0) = 2\%$ in the inward-shifted configuration. Solid and dashed lines show the smooth and the flattened ($w = 0.035$) pressure profiles, respectively.

Here w is the measure of the width of the flattened region, and λ is determined so as to satisfy $\mathrm{d}P/\mathrm{d}\rho = 0$ at a specified position, $\rho = \rho_s$. In this case, $\rho_s = \rho|_{\iota = 1/2}$ is chosen to see the stabilizing effects of the interchange mode. The flattened pressure profile for w = 0.035 is also plotted in Fig.1. The difference between the smooth and the flattened profiles is very small in this value of w. And this size of the flattened width does not influence the profile of the rotational transform. However, this small flattened region plays a significant role in the stability. Figure 2 shows the dependence of the growth rates at $\beta(0)$ = 1, 2 and 3% on the width of the flattened region. The interchange mode is effectively stabilized by enlarging the width. The larger width is needed in the stabilization for the mode with the larger growth rate, however, the mode is completely stabilized by the pressure flattening with w = 0.037 at $\beta(0)$ = 2% which is about a quarter of the half-width of the mode for the smooth pressure profile. In this case, the mode at $\beta(0)$ = 3% is more easily stabilized than that at $\beta(0)$ = 2%, because the driving force of the mode is weakened by the magnetic well beyond $\beta(0)$ = 2%.

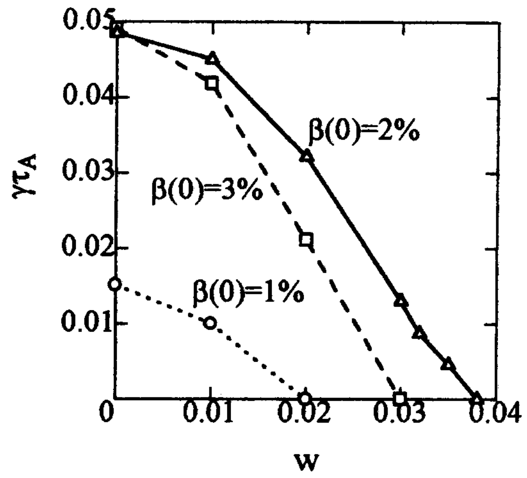

Fig. 2 Growth rate of the n = 1 ideal mode in the inward-shifted configuration at $\beta(0)$ = 1, 2 and 3% versus the width of the pressure flattened region.

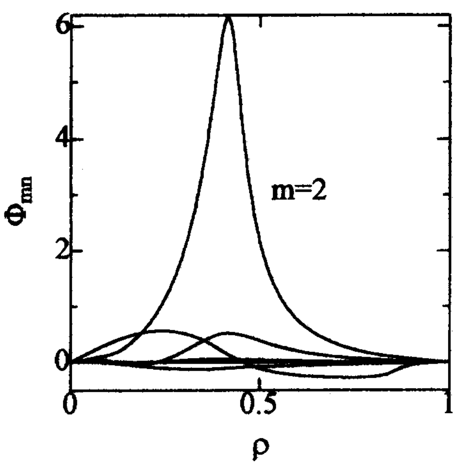

Fig. 3 Fourier components of the stream function of the n = 1 ideal mode at $\beta(0)$ = 2% with the smooth pressure profile in the inward-shifted configuration.

4. Effects on High β Equilibrium

The 3D equilibrium with self-consistent bootstrap current is obtained by iterating the MHD equilibrium calculation with the VMEC code and the evaluation of the bootstrap current based on the neoclassical transport. In the present study, we assumed that the plasma is composed of the electrons and the ions and the electron temperature is the same as the ion temperature.

For the smooth pressure profile, we used the profiles of the temperature and the density given by

$$T_s = T_0\,(1 - \rho^2), \quad n_s = n_0\,(1 - \rho^2). \tag{9}$$

The self-consistent bootstrap current obtained for T_0 = 3 keV, $n_0 = 0.2 \times 10^{20}$ m^{-3} ($\beta(0)$ = 4.82%) and the central magnetic field B_0 = 1 T is 81.4 kA [4]. This current increases the rotational transform by changing the

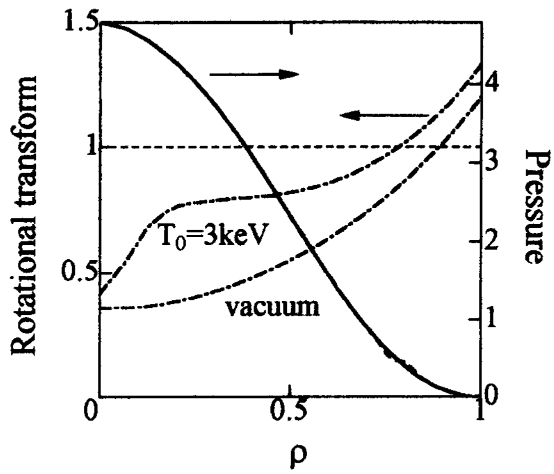

Fig. 4 Profiles of the rotational transform (dashed-dotted lines) for vacuum and T_0 = 3 keV cases and the pressure at T_0 = 3 keV in the standard configuration. Solid and dashed lines show the smooth and the flattened (w = 0.02) pressure profiles, respectively.

poloidal magnetic field as shown in Fig.4, which results in the shift of the surface of $\iota = 1$ toward the magnetic axis. The equilibrium carrying this current is unstable against the interchange mode resonant at $\iota = 1$ surface, while the no net toroidal current equilibrium at the same pressure is stable. This is because the magnetic well is reduced by the suppression of the Shafranov shift which results from the increase of the rotational transform.

In order to study the effects of the pressure flattening, we assumed the temperature and the density profiles as

$$T = T_s + \lambda_T(\rho - \rho_s)\exp\left[-\frac{1}{2}\left(\frac{\rho-\rho_s}{w}\right)^2\right] \tag{10}$$

and

$$n = n_s + \lambda_n(\rho - \rho_s)\exp\left[-\frac{1}{2}\left(\frac{\rho-\rho_s}{w}\right)^2\right], \tag{11}$$

respectively. Here λ_T and λ_n are also determined so that $dT/d\rho = 0$ and $dn/d\rho = 0$ at $\rho = \rho_s$, respectively, and we chose $\rho_s = \rho|_{\iota=1}$. Figure 5 shows the profile of the bootstrap current density for $w = 0.02$ with the profile of the temperature. The current density is reduced at the pressure flattened region. The small enhancement of the current density is seen in both sides of the flattened region, which reflects that the gradient of the temperature and the density profiles becomes steeper so that the flattened region should be generated. However, the profile of the current density remains unchanged in other region with this width of the flattened region, and the total current is 81.2 kA which is almost the same as that for the smooth profiles.

It is obtained that the $n = 1$ ideal interchange mode is completely stabilized with $w = 0.015$. As is in the low beta cases, the flattened width needed for the stabilization is much less than the half-width of the dominant $m = 1$ component. Figure 6 shows the structure of the mode with $w = 0.01$. It is seen that the mode is stabilized with the dominant $m = 1$ component shrinking from only the outside region. This tendency is also obtained in the low beta cases and in the straight helical models.

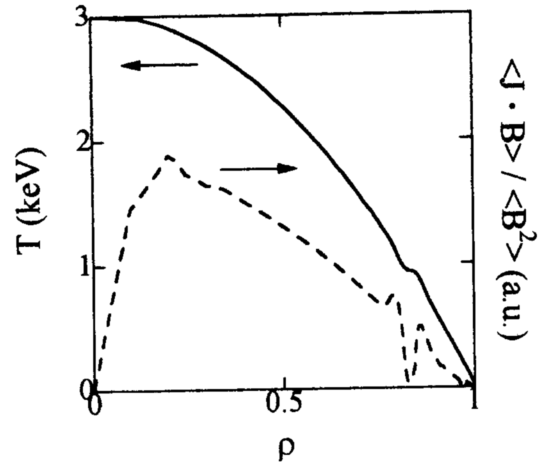

Fig. 5 Profiles of the temperature (solid line) and the bootstrap current density (dashed line) with w = 0.02 in the standard configuration.

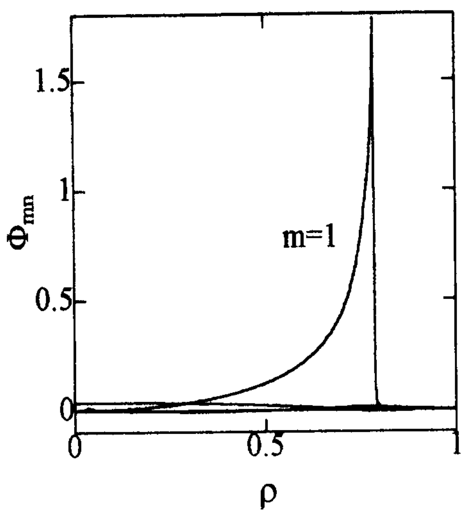

Fig. 6 Fourier components of the stream function of the n = 1 ideal mode at T_0 = 3 keV with w = 0.01 in the standard configuration.

5. Conclusions

Effects of pressure flattening on the MHD properties are studied in two cases of LHD equilibria.

In the inward-shifted configuration, a significant interchange mode can be unstable in the low-beta currentless equilibria because of the enhancement of the magnetic hill. This mode is effectively stabilized by flattening the pressure at the resonant surface with much narrower width of the region than the half-width of the mode. It is easily expected that the rotational transform is also deformed by the pressure flattening and such deformation may reduce the magnetic shear stabilization. However, the width needed for the stabilization of the instability is too small to affect the profile of the rotational transform in this case. It might be another good method for the stabilization to enhance the magnetic shear at the resonant surface with a local current drive.

Substantial bootstrap current can flow at the standard plasma position which has a destabilizing contribution for the interchange mode. The interchange mode is also completely stabilized with a small flattened region. In this case, the current density is only locally reduced at the resonant surface and the effect on the other region is negligible.

In the LHD plasma, the LID coil might be useful in the control of the pressure flattening at the rational surfaces, such as $\iota = 1$ and $1/2$. In the present study, the assumption of the nested surfaces is used in order to focus on only the effects of the pressure flattening. However, this assumption may not be adequate for the case of the existence of the islands. The analyses of the interchange modes and the bootstrap current at the islands are future study.

Acknowledgment

This work is partly supported by a Grant-in-Aid from the Ministry of Education, Science, Sports and Culture in Japan.

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