J. Plasma Fusion Res. SERIES, Vol.1 (1998) 75–79

MHD Physics on LHD

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(Received: 30 September 1997/Accepted: 26 January 1998)

Abstract

The Large Helical Device (LHD) has a flexible coil system making various vacuum configurations. The characteristics of such vacuum configurations are basically expressed in terms of toroidally bended corresponding straight helical configurations. The MHD physics of finite β LHD plasma is understood from the competitive or synergetic relation between helicity and toroidicity. The former comes from the vacuum configurations and the properties still remain in the plasma periphery even for high β equilibria. The latter is brought about by the essentially axisymmetric large Shafranov shift, which is strongly influenced by the toroidal current conditions and pressure profiles, and such effects become significant in the plasma core region as β increases. Throught the local and global properties of the finite β MHD equilibria in the planar axis LHD vacuum configuration, the ideal MHD stability of interchange and ballooning modes is addressed.

Key words:

LHD, MHD equilibria and stability, interchange and ballooning modes

1. Introduction

The Large Helical Device (LHD)[1] has a flexible coil system, *i.e.*, one pair of two helical coils, three pairs of two poloidal coils, and ten coils making an $(m/n) = (1/1)$ fairly large magnetic island that acts as a Local Island Divertor (LID)[2]. Each helical coil has such independent current feeders that the coil current can be fed in a balanced or unbalanced manner. Also, each helical coil has three multiple layers with independent current feeders, which is used to change the minor radius of the current center of helical coils. The poloidal coil system can control the vacuum magnetic axis shift, the shape of the poloidal cross sections, and so on. Such the flexible coil system creates four types of typical vacuum configurations making the relatively low rotational transform ι near the magnetic axis, which leads to a large Shafranov shift or Pfirsch-Schlüter current even for fairly low β values. In contrast with it, both the Pfirsch-Schlüter current and the bootstrap current are significantly reduced in W7-X[3] and hence the properties of the vacuum magnetic field still remain in whole plasma region for fairly high β values. Thus, such the flexible coil system and the large Shafranov shift of LHD give us an absolutely contrastive concept to W7-X as plasma confinement device. In this paper, we will concentrate our attention on one of the key issues of plasma performances, namely, the ideal MHD stability of the MHD equilibria in the $L/M = 2/10$ planar axis vacuum configurations without LID through the understanding of the vacuum configurations and the MHD equilibria.

In Section 2, the characteristics of the $L/M = 2/10$ planar axis vacuum configurations are described. The characteristics of the finite β MHD equilibria in such vacuum configurations are given in Sec. 3 including effects of pressure profile and net toroidal current. Section 4 is devoted to the characteristics of the ideal MHD stability in such MHD equilibria, where the properties of interchange and ballooning modes are mainly examined. The summary is given in Sec. 5.

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2. Characteristics of Vacuum Configurations

The $L/M = 2/10$ planar axis vacuum configurations are examined. The characteristics of such vacuum configurations are basically expressed in terms of toroidally bended $L/M = 2/10$ straight helical configurations, so that such vacuum configurations have the clear separatrix magnetic field lines ($\iota_s \sim M/L = 5$), the stellarator-like magnetic shear, and the magnetic hill near the periphery.

By the control of the poloidal coil system, the magnetic axis shift and the shape of flux surfaces are changed keeping the distribution of the field strength almost unchanged. Since the toroidal magnetic field is inversely proportional to the major radius, the vacuum magnetic flux surfaces shift to the outside of the torus. Thus, the inward shift of the vacuum magnetic axis can restore straight helical-like properties, and the outward shift enhances toroidal effects. By the inward shift of the vacuum magnetic axis, the equilibrium beta limit increases, the magnetic hill becomes high, and the orbits of deeply trapped particles in helical ripples become better. The outward shift makes the opposite properties.

3. Characteristics of MHD Equilibria

The characteristics of finite β MHD equilibria in the $L/M = 2/10$ planar axis vacuum configurations are examined by using VMEC code[4] under the fixed boundary condition. Since the LHD plasmas have a relatively high magnetic shear, the nested flux surfaces are assumed to exist by neglecting the small magnetic islands if any.

At first the currentless MHD equilibria are considered. The relatively low rotational transform ι near the magnetic axis in such planar axis vacuum configurations allows a large and essentially axisymmetric Shafranov shift or Pfirsch-Schlüter current even for fairly low β values, which leads to a large deformation of both the flux surfaces and the local pitch of the magnetic field lines in the core region, almost leaving the distribution of the magnetic field strength as it is in the vacuum configuration[5]. Thus, the essential characteristics of MHD equilibria are described by nearly axisymmetric large Shafranov shift (toroidicity dominant) in the core region and properties of the straight helical system (helicity dominant) near the periphery, resulting in the competitive or synergetic states between toroidicity and helicity. Such the large Shafranov shift can create the averaged magnetic well in the plasma core region with low magnetic shear and the resultingly enhanced stellarator-like magnetic shear in the periphery with the averaged magnetic hill, leading to the situtation favorable for interchange modes. In contrast with it, the large deformation of the local pitch of the magnetic field lines leads to the disappearance of the local magnetic shear in the region with stellarator-like magnetic shear, which is not favorable for ballooning modes[5]. By using the stellarator expansion under the high-β ordering ($\beta \sim O(\varepsilon_t)$), the Shafranov shift Δ is expressed by:

$$\Delta'(r) \equiv \frac{\mathrm{d}\Delta(r)}{\mathrm{d}r} = \frac{R_0\beta'}{4\iota^2} \sim O(1), \;\; \beta(r) = \frac{2P(r)}{B_0^2} \quad (1)$$

From Eq.(1), we can consider effects of the pressure profile[6] and the net toroidal current[6,7] on MHD equilibria.

Peaked pressure profiles make a large Shafranov shift, leading to the deep averaged magnetic well in the core region and to the situation that maximum pressure gradient easily exists in the magnetic well region. It follows, however, that broad pressure profiles create the opposite situation to that brought by peaked pressure profiles. Note that the beam pressure profile of NBI and deposition profiles by NBI, ECRH, and ICRF may affect the pressure profile. Parameters of vacuum configurations or MHD equilibria creating the large Shafranov shift from the sense of Eq. (1) have a tendency to bring about broad pressure profiles reducing the Shafranov shift from the aspect of particle orbits, and parameters making the Shafranov shift small have an opposite tendency. The experimental control of the pressure profile may become important.

The net toroidal currents such as bootstrap current, Ohkawa current, and ECRH-driven current affect the Shafranov shift through the rotational transform ι. The bootstrap current in the $1/\nu$ collisionality regime, the Ohkawa current due to co-injected NBI, and ECRH-driven current increasing ι reduce the Shafranov shift, whcih leads to the shallow magnetic well in the core region and weak stellarator-like magnetic shear in the periphery. As a result of it, MHD stability is deteriorated. The bootstrap current in the plateau collisionality regime, the Ohkawa current due to counter-injected NBI, and ECRH-driven current decreasing ι enhance the Shafranov shift and are favorable for the MHD stability. Note that the bootstrap current is strongly affected by both vacuum configurations and MHD equilibria themselves and that it is reduced by the positive radial electric field when electrons and ions exist in the $1/\nu$ and plateau collisionality regimes, respectively[8,9].

4. Characteristics of MHD Stability

The ideal MHD stability is examined under the fixed boundary condition. Current-driven modes in LHD are stable when the net toroidal current is less than about 300 kA (the net toroidal current due to bootstrap current is about 200 kA). Thus, examinations are concentrated on pressure driven-modes, namely, interchange modes and ballooning modes. The amplitudes of the interchange modes do not change so much along the resonant magnetic field lines, so that the stabilization effects due to the averaged magnetic well and the magnetic shear are important for their stability. In contrast with it, the amplitudes of the ballooning modes change along the magnetic field lines, so that the local magnetic well or hill and the local magnetic shear become important for their stability, the fact of which indicates that the ballooning modes can easily feel the three dimensional structure of the MHD equilibria.

From the previous discussion about the vacuum configurations and the MHD equilibria, it is found that peaked pressure profiles and the currentless or net toroidal current decreasing ι and the vacuum configuration with outward axis shift are favorable for interchange modes. Figure 1 shows the interchange stability diagram with equilibrium β-limit for currentless equilibria with the relatively peaked pressure profile: $P = P_0(1 - r^2)^2$[7]. D_I indicates the Mercier criterion and the five level surfaces of D_I are drown with $\Delta D_I = 0.1$. The horizontal axis denotes the vacuum axis shift Δ_V. The standard LHD configuration corresponds to $\Delta_V = -15$ cm. The standard LHD configuration is slightly Mercier unstable, however, it is practically stable upto

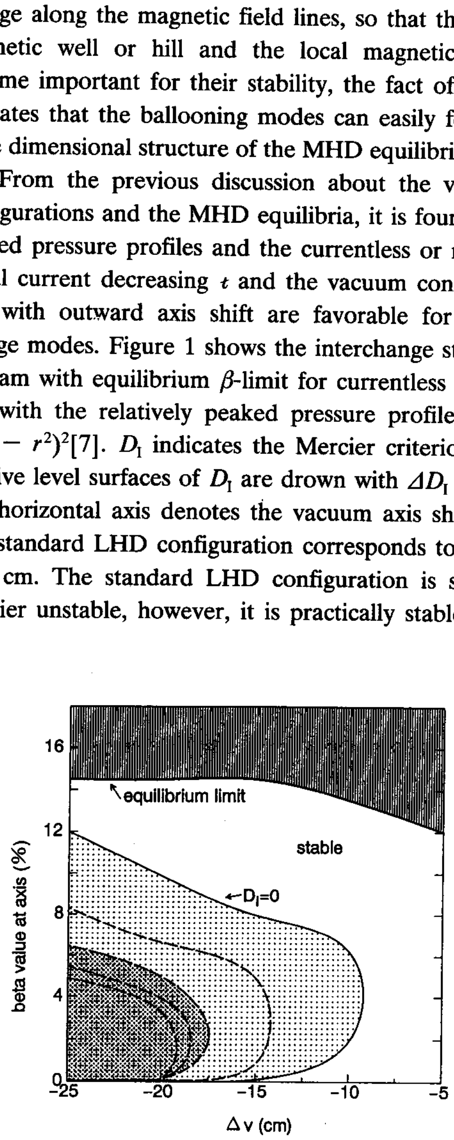

Fig. 1 Mercier stability diagram in the LHD configuration. Dotted area corresponds to unstable region. Dashed lines in this region are contours of D_I[7].

the equilibrium β-limit in the sense that in the region near the Mercier marginal stability with $D_I < 0.2$ the low-mode-number interchange modes are stable and that the high-mode-number interchange modes highly localize on their mode rational surfaces with the quite small growth rates[7].

As is well know, the ballooning modes are more stringent than interchange modes. Moreover, it is found out by using high-mode-number ballooning mode analysis that ballooning modes inherent to three dimensional (3-D) equilibria exist[6]. In the 3-D equilibria, the eigenvalue of the high-mode-number ballooning mode equation λ is a function with respect to ψ, θ_k, and α, where ψ and α are the labels of the flux surfaces and the magnetic field lines in the covering space, respectively, and θ_k is the radial wave number coming from WKB approxiamtion:

$$\lambda = \lambda(\psi, \theta_k, \alpha) \tag{2}$$

Note that λ becomes independent of α in axisymmetric tokamaks. Therefore, properties of λ inherent to 3-D equilibria appear throuth their α-dependence, which comes from the local magnetic curvature because the local magnetic curvature consists of two components, namely, one part due to toroidicity and the other part due to helicity. In the case of LHD, the locally unfavorable curvatures due to toroidicity and helicity are superposed in the outside of the torus on the horizontally elongated poloidal cross sections, however, on the vertically elongated poloidal cross sections the locally unfavorable curvature due to toroidicity is cancelled by the local favorable curvature due to helicity leading to locally favorable curvature even in the outside of the torus. These properties of local magnetic curvature and the disappearance of the local magnetic shear due to the large Shafranov shift make high-mode-number ballooning modes unstable in the region with the stellarator-like global magnetic shear. Figure 2 shows both schematic level surfaces of the unstable eigenvalue λ of high-mode-number ballooning modes in (ψ, θ_k, α) space (in the left column) and schematic positions where finite-mode-number ballooning modes would occur (in the right column) for tokamaks (in the top row), for strongly Mercier unstable 3-D equilibria (in the middle row), and for slightly Mercier unstable or completely Mercier stable 3-D equilibria (in the bottom row), respectively. In the axisymmetric tokamaks, the level surfaces of unstable λ of high-mode-number ballooning modes are topologically cylindrical because λ is independent of α. In the strongly Mercier unstable 3-D equilibria, such tokamak-like cylindrical level surfaces

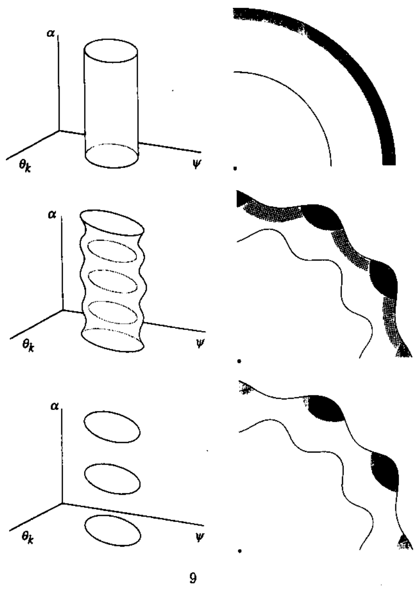

Fig. 2 Schematic pictures of level surfaces of unstable eigenvalues (in the left column) and positions where ballooning modes occur (in the right column) for three types of equilibria.

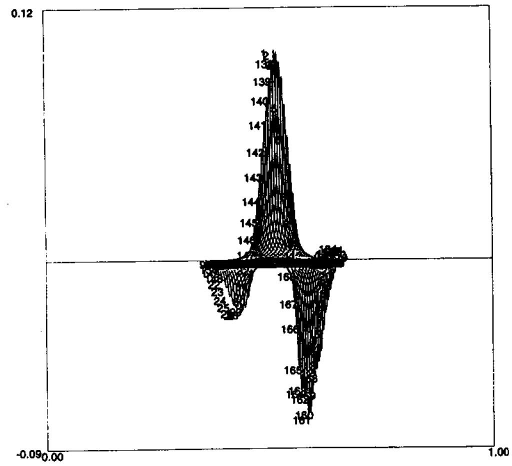

Fig. 3 Radial structure of the finite-mode-number ballooning mode.

and spheroidal level surfaces coexist, and only spheroidal level surfaces exist in the slightly Mercier unstable or completely Mercier stable 3-D equilibria. The high-mode-number ballooning modes with the spheroidal level surfaces are inherent to 3-D equilibria. As is shown in the right column of Fig. 2, finite-mode-number modes leading to high-mode-number modes with cylindrical level surfaces of λ are considered to occur outside of the torus without localization in the toroidal direction. In contrast with them, finite-mode-number modes leading to high-mode-number modes with spheroidal level surfaces of λ are considered to localize in the locally unfavorable region of the outside of the torus. To confirm the properties of such ballooning modes expected from the high-mode-number analysis, the global mode analysis with finite-mode-number is being performed by using CAS3D stability code[10], where a strongly Mercier unstable equilibrium is used. When the Fourier modes of the perturbation are selected as centered in low toroidal mode numbers ($n \ll M$ = 10), only interchange modes appear. For medium toroidal mode numbers ($n \sim M$), takamak-like ballooning modes appear with only one dominant toroidal mode number. As the toroidal mode numbers are increased more and more ($n \gg M$), ballooning modes with both poloidal and toroidal mode couplings appear. One example is shown in Fig. 3 where four group exist with the different toroidal mode numbers, namely, from left to right, $n = -56$, -66, -76, and -86. From these results, we can expect that the finite-mode-number modes leading to high-mode-number modes with the spheroidal level surfaces of the eigenvalues have quite so large and many poloidal and toroidal mode numbers that they localize in the toroidal direction as well as in the poloidal direction.

5. Summary

The Large Helical Device (LHD) has a flexible coil system making various vacuum configurations. In the case of the planar axis vacuum configurations, the inward shift of the magnetic axis creates more straight helical-like properties, and the outward shift enhances toroidal effects. The essential characteristics of MHD equilibria of such planar axis vacuum configurations are described by nearly axisymmetric large Shafranov shift (toroidicity dominant) in the core region and properties of the straight helical system (helicity dominant) near the periphery. The net toroidal current and pressure profiles mainly determined by the experimental conditions strongly influence on the Shafranov shift. Since the Mercier stability of LHD is established by both the magnetic well in the core region and stellarator-like magnetic shear near the periphery, the negative or zero toroidal currents and peaked pressure profiles are favorable for the Mercier stability. High-mode-number ballooning modes are still destabilized by the disappearance of the local magnetic shear in the region with stellarator-like magnetic shear, even if the Mercier criterion is satisfied. Those modes inherent to helical systems are expected to highly localize in the toroidal direction as well as the poloidal direction and to become harmless by the kinetic effects such as the Finite Larmor Radius (FLR). To clarify FLR effects on such ballooning modes, the dominant poloidal and toroidal mode numbers are being examined from global mode analysis.

The analysis of pressure-driven resistive modes is another important issue of MHD physics. Since the magnetic hill always exist in the plasma periphery, the peaked pressure profiles are better for those modes as well as ideal MHD modes. Kinetic and dissipative effects on MHD modes will be continuously examined in order to clarify the MHD physics of LHD.

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