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Passive Control of *n* = 1 Mode Motion on Field-Reversed Configuration Plasmas

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Abstract

An n = 1 mode motion of a field-reversed configuration plasma is investigated from the point of a magnetic structure of confinement field. The investigation suggests that the plasma having high separatrix elongation is preferable for reducing the amplitude of the n = 1 mode motion because of a small negative gradient of the confinement field around the plasma. In order to produce highly elongating plasmas, auxiliary conductors are installed into a device. The observed amplitudes of the n = 1 mode motion are controlled at about a half level of that without any auxiliary conductors, which is explained well from the magnetic structure.

Keywords:

field-reversed configuration, theta pinch, n = 1 mode motion, wobble motion, passive control, magnetic structure

1. Introduction

A field-reversed configuration (FRC) is an elongated compact toroid consisting of a poloidal field only [1]-[5]. It can confine plasmas with a high β value, which is the ratio of plasma pressure p to confinement field pressure $B_e^2/2\mu_0$. It is possible to attain an average β value of about 0.9 inside a separatrix. Moreover, the magnetic configuration has natural divertors to lead fusion products like α-particles and protons to a direct energy converter.

From these outstanding features, it is recognized that the FRC has potential application in a future reactor burning an advanced fuel as deuterium and helium 3. There is a translation region between the formation and the burning regions in the reactor [6]. The FRC plasma must be moved from the formation region into the burning region through the translation region along the guide field. The deviation of the FRC from the guide field may cause particle loss due to the magnetic reconnection between both fields inside and outside the separatrix. Moreover, a high-energy neutral beam for heating the plasma can damage a vacuum wall, when the FRC plasma deviates largely from its planned position in the burning region.

The deviation of the plasma is observed as an oscillating motion around the equilibrium position. This motion is called a wobble motion in theta-pinch experiments [7], [8], and a radial shift and a tilt motion in the FRC experiments [9]-[11]. It is also generalized by an n = 1 mode motion (n is a toroidal mode number).

Control of the motion in the FRC experiment by active methods using a multipole field [12] or a neutral beam [13] has been attempted. We show in the present article that the motion can also be controlled by a passive method. For this purpose, the source of the n = 1 mode motion is investigated from the point of view of the magnetic structure of the confinement field. It is found that the behavior of the n = 1 mode motion can be well explained from a negative gradient of the confinement field around the plasma. Then, we demonstrate a reduction of the n = 1 mode motion by installing two kinds of auxiliary conductors into an experimental device.

2. Magnetic structure

It is generally known that field lines in a mirror coil have a bad curvature in the central region although a good curvature in the mirror region. In order to investigate the effect of the curvature of the field lines outside the plasma on the n = 1 mode motion, the following Grad-Shafranov equation for a flux function ψ without pressure and toroidal current is solved in the region between the separatrix and the coil [14]:

$$\frac{\partial^2\psi}{\partial r^2} - \frac{1}{r}\frac{\partial\psi}{\partial r} + \frac{\partial^2\psi}{\partial z^2} = 0\,. \qquad (1)$$

In these calculations, the theta-pinch coil (ψ = 1) has a half length ℓ_c = 0.75 m and a radius r_w = 0.17 m at the center. A mirror field is produced using end coils with 0.3 m width and 0.15 m radius. The separatrix shape of a FRC plasma introduced into the coil (ψ = 0) has an elliptical form as $(r/r_s)^2 + (z/\ell_s)^2 = 1$, where r_s is a separatrix radius at the

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midplane (z = 0) and ℓ_s is a half separatrix length. It should be noted that an edge-layer plasma outside the separatrix is neglected in Eq. (1) because of its thin width. It has been known that the half width of the layer is few ion-radii in the confinement field corresponding to a value less than 10% of r_s [2], [15].

Calculated magnetic fields at the z = 0 plane are shown in Fig. 1, where $x_s = r_s/r_w$ and $z_s = \ell_s/\ell_c$. It is found that the radial gradient of the field has a positive sign in vacuum and becomes negative by introducing the FRC plasma. The strength of the field normalized by the wall one changes the value by about 3% between the separatrix and the wall on a fat FRC with x_s = 0.3 and z_s = 0.3, although it is almost constant on a slender FRC with x_s = 0.2 and z_s = 0.5.

In order to know an axial dependence of the field gradient, average fields are calculated along field lines from z = 0 to $z = \ell_s$ as

$$\bar{B} = \frac{\int_0^{\ell_s} B\mathrm{d}\ell}{\int_0^{\ell_s} \mathrm{d}\ell} . \tag{2}$$

The radial profiles of $\bar{B}/\bar{B}_w$ are shown in Fig. 2, where the abscissa denotes radial positions of the field lines at z = 0 and $\bar{B}_w$ is an averaged value along a field line near the wall.

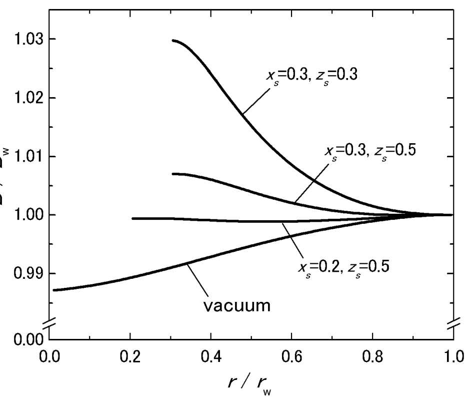

Fig. 1 Radial profiles of magnetic field outside FRCs at the midplane for a mirror coil.

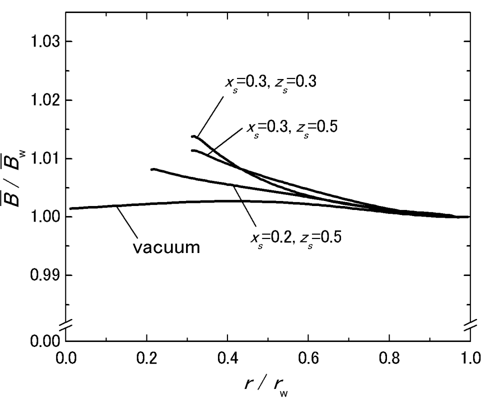

Fig. 2 Radial profiles of averaged magnetic fields calculated from z = 0 to $z = \ell_s$.

The average field in vacuum is calculated from z = 0 to $z = \ell_c/2$. These radial profiles are similar to the B/B_w profiles in Fig. 1 except a small variation of the gradient on the vacuum field and the fat FRC. The variation is that the radial gradient of the average field becomes almost zero on the vacuum field and reduces to about one-third of the B/B_w profile on the fat FRC.

It can be known from these calculations that the confinement field around the plasma forms a hill structure in which the field gradient has a negative sign to the wall. The field gradient becomes large with decrease of the separatrix elongation E (= ℓ_s/r_s). This structure suggests that the plasma is possible to move toward the wall until the magnetic hill disappears due to the wall effect of the theta-pinch coil. Therefore, it is anticipated that the plasma having a small E will deviate largely from the equilibrium position.

3. Experimental setup and plasma parameters

FRCs are produced with deuterium at 15 mTorr fill pressure in a 1.5-m-long theta-pinch coil. The inner radii of the coil are 0.17 m at the center and 0.15 m at the ends, which are the same sizes as the calculations in Sec. 2. This coil geometry produces a magnetic field profile with a mirror ratio R_M = 1.28 on the z-axis in vacuum. The strength of the negative bias field is 32~48 mT at the initiation of the confinement field (t = 0) which is 0.6 T at the peak and has a 120 μs decay time. Conducting rings consisting of three sets of single-turns copper wires with 6 mm diameter are attached to both ends of the coil. They have a smaller radius $r_{c.r.}$ = 0.13 m than the mirror coils. The nearest ring is apart from the coil end by 0.05 m. And a set of resistive metal liners can be installed under the mirror coils. They have a radius $r_{m.l.}$ = 0.14 m and a width $w_{m.l.}$ = 0.25 m.

The separatrix radius and length are obtained from a single-turn loop and a magnetic probe array [16]. Electron density at z = 0 is measured using a helium-neon interferometer. The sum of electron and ion temperatures is estimated from the equilibrium equation: $\langle\beta\rangle = 1 - x_s^2/2$ [17]. Sixty-channels optical detectors are used to observe the n = 1 mode motion [18]. Each optical detector has a wavelength sensitivity in the range $\lambda = 550 \pm 5$ nm. It is confirmed using a monochromator that radiation from the FRC plasma consists mainly of bremsstrahlung in the wavelength range.

The collimators of the optical detectors are arranged in parallel to the x-axis (x-array) and the y-axis (y-array). Since the vacuum vessel is made of a transparent quartz tube, the radiation can be observed at a given axial position. At the present measurement, three sets of the x-array and the y-array are installed at z = 0 and ± 0.22 m.

Typical plasma parameters at the quiescent phase (t = 15~25 μs) are $r_s \simeq 0.05$ m, $\ell_s \simeq 0.35$ m, an electron density $n_e \simeq 3\times10^{21}$ m^{-3}, and plasma temperatures $T_e \simeq T_i \simeq 100$ eV. Other constituents of the device and plasma parameters are described elsewhere [15].

4. *n* = 1 mode motion

The n = 1 mode motion is estimated from the radial shift of the radiation profiles formed by the optical detector arrays. For instance, the x-array and the y-array give the y-component of the shift ξ_y and ξ_x, respectively. The motion is shown in Fig. 3, where the radial shifts are simultaneously measured at three axial positions. The FRC plasma starts to move at t = 5 μs toward the wall of the vacuum vessel and comes back near the z-axis after reaching $\xi_m \simeq 0.011$ m at $t \simeq 20$ μs, where ξ_m is the maximum of $\xi = \sqrt{\xi_x^2 + \xi_y^2}$. The motion can be observed during t = 5~30 μs until the onset of the n = 2 rotational instability [19] and [20]. It is also found that the FRC moves almost in phase along the z-axis. This denotes that the n = 1 mode motion is not a tilt motion, but a radial shift in parallel to the z-axis.

The shift motion emerges in all FRCs in the present experiment although the direction and the amplitude of the trajectories change on a shot-by-shot basis. However, it is found that there is a clear dependence of ξ_m on the separatrix elongation. In order to form FRCs with variable elongation, strength of the negative bias field is changed. The experimental results are marked by closed circles in Fig. 4, where $\bar{E} = \bar{\ell}_s/\bar{r}_s$ ($\bar{\ell}_s$ and $\bar{r}_s$ are, respectively, a time averaged value of ℓ_s and r_s from t = 5 μs to the time reaching ξ_m). The deviation ξ_m increases with decreasing $\bar{E}$ and reaches $\xi_m \simeq$ 0.03 m at $\bar{E} \simeq 6.0$, which corresponds to about 60% of $r_s \simeq$ 0.05 m.

5. Passive control

The calculations in Sec. 2 suggest that the amplitude of the n = 1 mode motion can be reduced if FRCs having a large E are formed. For this purpose, two types of auxiliary conductors are installed into the device. The first is a set of resistive metal liners under the mirror coils, which have a short time constant $\tau \simeq 4$ μs. The second is a set of conducting rings, which have a long time constant $\tau \simeq 6.5$ ms.

The role of the resistive metal liners is expected to retard the pinch time in the mirror regions at the formation phase. The radial implosion of the plasma becomes uniform along the coil similar to that in the straight coil. Consequently, a FRC having a long separatrix length is formed in spite of using the mirror coil. When the conducting rings are installed, almost all the lines of force of the negative bias field are curved and pulled out from the narrow regions between the ends of the coil and the conducting rings. The negative bias field connects quickly with the confinement field as soon as it is applied. Since closed lines occupy the full length of the coil, a FRC having a long separatrix length will be formed. On the other hand, the separatrix radius may remain unchanged at the equilibrium phase because of the constraint of a radial pressure balance.

The deviations of the FRCs which are controlled by the conducting rings and the resistive liners are shown by open circles and triangles, respectively, in Fig. 4. It is seen that the elongation $\bar{E}$ = 5.5~7.0 is increased to $\bar{E}$ = 6.0~8.0 by the effect of the auxiliary conductors and the deviation is reduced to $\xi_m \leq 0.01$ m from ξ_m = 0.01~0.03 m.

6. Summary

The magnetic field structure outside the separatrix is calculated relating to the n = 1 mode motion of FRC plasmas. It is found that the field profile has a negative gradient to the wall at the midplane of the separatrix. The averaged values of the field along lines of force show also the negative gradient although it is smaller than that at the midplane. The gradient becomes large with decreasing the separatrix elongation. These calculations suggest that the n = 1 mode motion is always possible to occur in the confinement field and becomes violent on the FRC with small elongation.

In order to reduce the n = 1 mode motion, it is needed that the FRCs with large elongation are formed. For this purpose, two kinds of auxiliary conductors, which are the conducting rings and the resistive liners, are installed into the device. It is observed that the amplitude of the n = 1 mode motion can be controlled at about a half level of that without any auxiliary conductors.

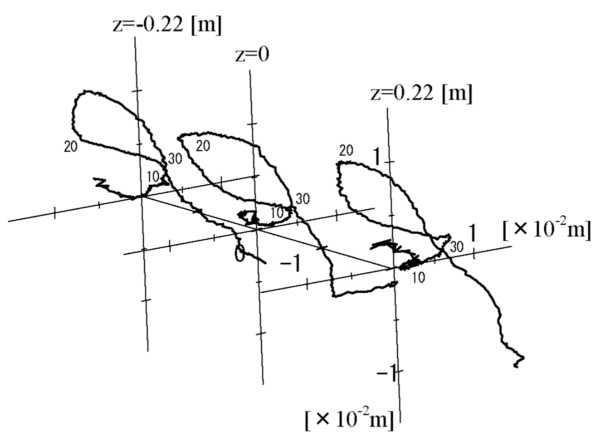

Fig. 3 Trajectories of a plasma column on the x-y plane at three axial positions, where Arabic numerals denote the time in μs from a start of the confinement field.

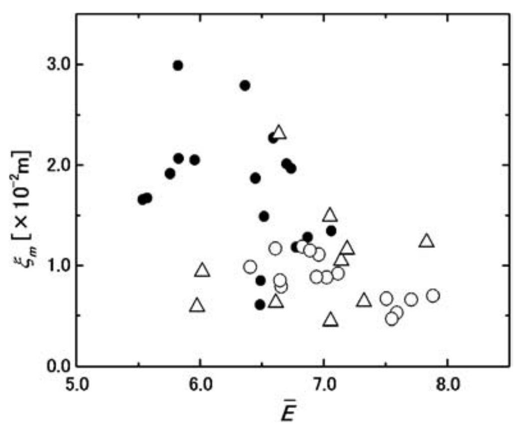

Fig. 4 Elongation dependence of n = 1 mode motions of FRCs with the conducting rings (open circles), the resistive liners (triangles), and without those (closed circles).

References

[1] D.J. Rej *et al.*, Phys. Fluids **29**, 852 (1986).
[2] M. Tuszewski, Nucl. Fusion **28**, 2033 (1988).
[3] A.L. Hoffman and J.T. Slough, Nucl. Fusion **33**, 27 (1993).
[4] A. Shiokawa and S. Goto, Phys. Fluids **B 5**, 534 (1993).
[5] Y. Ohkuma *et al.*, Nucl. Fusion **38**, 1501 (1998).
[6] H. Momota *et al.*, Fusion Technol. **21**, 2307 (1992).
[7] C. Ekdahl *et al.*, Phys. Fluids **23**, 1832 (1980).
[8] H.A.B. Bodin *et al.*, in Plasma Physics and Controlled Nuclear Fusion Research 1965, **1**, 193 (1966).
[9] M. Tuszewski *et al.*, Phys. Rev. Lett. **66**, 711 (1991).
[10] J.T. Slough and A.L. Hoffman, Nucl. Fusion **28**, 1121 (1988).
[11] S. Kumashiro *et al.*, J. Phys. Soc. Jpn. **62**, 1539 (1993).
[12] K. Fujimoto *et al.*, Phys. Plasmas **9**, 171 (2002).
[13] T. Asai *et al.*, Phys. Plasmas **10**, 3608 (2003).
[14] H. Gota *et al.*, Rev. Sci. Instrum. **74**, 2318 (2003).
[15] H. Gota *et al.*, Phys. Plasmas **10**, 4763 (2003).
[16] M. Tuszewski and W.T. Armstrong, Rev. Sci. Instrum. **54**, 1611 (1983).
[17] W.T. Armstrong *et al.*, Phys. Fluids **24**, 2068 (1981).
[18] T. Takahashi *et al.*, *Proceedings of 1st General Assembly of Asian Plasma and Fusion Association Joint with 3rd Asia Pacific Plasma Theory Conference*, Beijing, 1998, edited by X.-T. He (Chinese Physics Society (Chinese Physics Letters), Beijing, China, 2000), p. 92.
[19] S. Ohi *et al.*, Phys. Rev. Lett. **51**, 1042 (1983).
[20] S. Shimamura and Y. Nogi, Fusion Technol. **9**, 69 (1986).