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n=1 Mode Global Motion on Field-Reversed-Configuration Plasmas

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Abstract

An n = 1 mode motion of a field-reversed-configuration plasma is investigated using a mirror configuration and a cusp configuration of the bias field. The n = 1 mode motion reaches 20~40 % of the plasma radius in the former configuration, although it is at a low level in the latter configuration. It is experimentally confirmed that the violent n = 1 motion can be controlled by a multipole field. The critical strength of the multipole field needed to push back the plasma to the equilibrium position is theoretically derived using a simple model which includes the conductor effect of the wall, and is compared with an experimentally obtained value. The two values agree within the range of experimental reproducibility.

Keywords:

field-reversed configuration, FRC, n = 1 mode, global motion, multipole field, theta pinch

1. Introduction

A field-reversed-configuration (FRC) plasma is formed by the negative-biased theta-pinch method [1]. Since the separatrix surface of the FRC with a radius r_s at the center is far from the coil wall r_w, for instance r_s/r_w = 0.3~0.4, the wall stabilization effect on the plasma motion is weak. Therefore, the plasma possesses much freedom of movement in the confinement field. It is well known that the FRC plasma deviates slightly from the equilibrium position and moves slowly around it. This motion is called the n = 1 mode motion.

When the FRC plasma is translated from a formation region into a quasi-static field in order to confine the plasma for a long time and to heat it using a neutral beam [2], the possibility that the deviation of the plasma becomes large during the translation arises, even if it is small in the formation region. Therefore, the n = 1 mode motion must be controlled to a low level in the formation region.

An experimental method to produce an FRC plasma without a violent n = 1 mode motion is first described. Secondly, the effect of a multipole field on the n = 1 mode motion is shown. Lastly, the critical strength of the multipole field required to control the motion is discussed and compared with the experimental results.

2. Experimental Setup

The FRC plasma is formed using a theta-pinch device called NUCTE-III which has a one-turn coil with 1.5m length and 0.34 m bore at the center (z = 0). It is possible to generate the two kinds of bias field configurations shown in Fig. 1 by changing the coil construction. The strengths of the bias field and the confinement field at z = 0 are $B_b = -3.2\times10^{-2}$ T and B_e =

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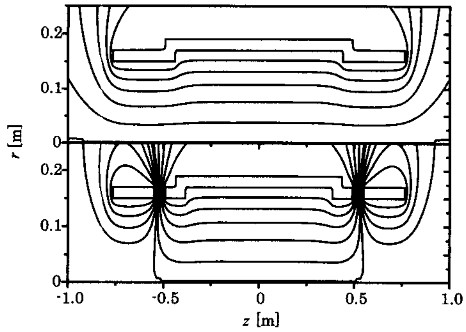

Fig. 1 Bias field configurations: (a) a mirror field and (b) a cusp field

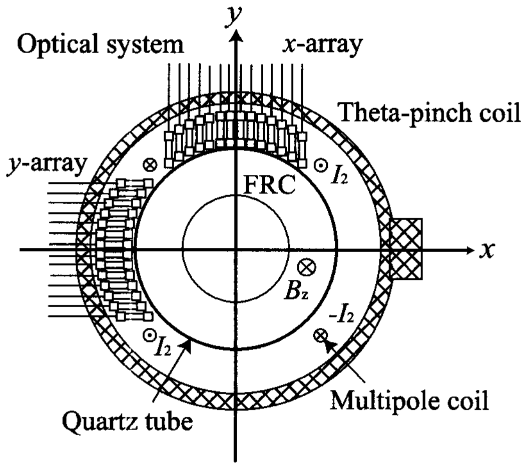

Fig. 2 Arrangement of optical fibers and quadrupole field coil

0.5 T, respectively. The FRC plasma is generated using deuterium gas at 10mtorr fill. Two kinds of multipole coils are installed at $r_m = 0.14$ m between the theta-pinch coil and the vacuum vessel made of a transparent quartz tube. The coils produce a quadrupole field ($m = 2$) and hexapole field ($m = 3$). Each field is separately applied to the FRC plasma just after its formation. Other constituents of the device are described elsewhere [1].

The $n = 1$ mode motion is observed using a multichannel optical system that consists of an x-array and a y-array, as shown in Fig. 2. Each channel of the optical system can detect the radiation integrated along the optical path. The wavelength sensitivity of the system is limited to 550±5 nm by optical filters, which is the range where the radiation is mainly bremsstrahlung [3].

Typical examples of the line-integrated radiation profiles can be seen in Fig. 3, where the time noted in each frame was measured from the start of the confinement field. The closed circles and the open circles correspond to the x-array and the y-array, respectively. The profiles show much different shapes in the third frame of (a) where an $n = 2$ mode rotational instability occurs and (b) becomes triangular upon application of the quadrupole field. The amplitude of the $n = 1$ mode motion is measured from the center positions of each profile, ξ_x and ξ_y.

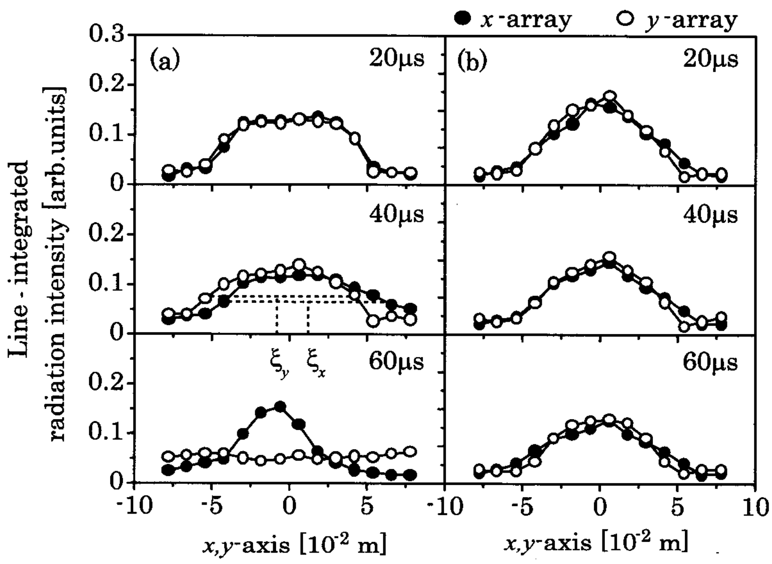

Fig. 3 Line-integrated radiation profiles from the x-array (closed circles) and the y-array (open circles), (a) without a multipole field and (b) with the quadrupole field

3. Experimental Results

The deviation of the FRC plasma in the case of the mirror bias configuration is plotted in Figs. 4(a) and 5(a). The traces are terminated at $t = 40$ μs because the radiation profiles include a significant error due to the growth of the large-amplitude $n = 2$ mode. It is seen that the FRC plasma remains for 25 μs near the origin and then moves to the opposite y-direction. After reaching $y \approx -0.01$ m, it turns to the x-direction.

The equilibrium FRC plasma has no azimuthal field B_θ. However, such a field is generated when the open field is distorted by the deviated plasma. The relationship between the FRC plasma motion and the B_θ field had been reported in reference 4. Following that relationship, the B_θ measured at $z = \pm 0.2$ m shown in Fig. 6(a) indicates that the axis of the FRC plasma shifts at $0.7 \sim 1.0 \times 10^{-2}$ m in parallel with the z-axis and tilts to $0.9 \sim 1.0 \times 10^{-2}$ radian for $t = 30$ μs.

Since the FRC plasma maintains $r_s = 0.05$ m during the trace in Fig. 5(a), the maximum deviation of the trajectory from the origin becomes 26 % of r_s. Although the FRC plasma depicts a different trajectory shot by shot, the deviation is within 20~40 %.

The $n = 1$ mode motion for the case of the cusp bias configuration is shown in Fig. 4(b). The motion becomes mild comparing to that in the mirror bias configuration. The result of the cusp bias experiment is plotted at $I_m = 0$ in Fig. 7 where $\xi\,(=\sqrt{\xi_x^2+\xi_y^2}\,)$ of three FRC plasmas are averaged for $t = 20 \pm 5$ μs.

When the multipole field is applied to the FRC plasma, the observation of the $n = 1$ mode motion becomes possible for a longer time than that without the multipole field because the $n = 2$ mode is controlled to a low level [5]. When a weak multipole field is applied, the behavior of the $n = 1$ mode motion does not change significantly. However, the motion disappears abruptly upon increasing the field, except in the initial 20~30 μs,

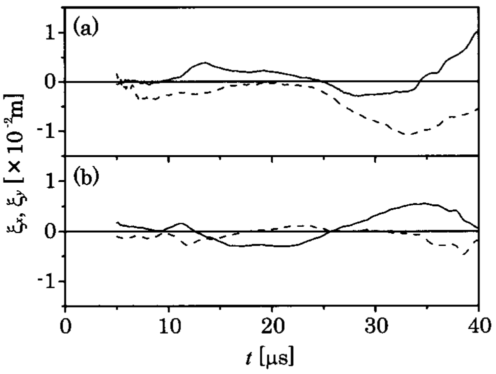

Fig. 4 Time evolution of deviation of an FRC along the x-axis (solid line) and the y-axis (dashed line): (a) mirror bias configuration and (b) cusp bias configuration

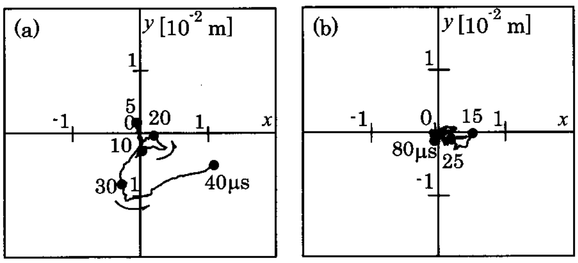

Fig. 5 Trajectories of an $n = 1$ motion on the $x - y$ plane (a) without a multipole field and (b) with the quadrupole field

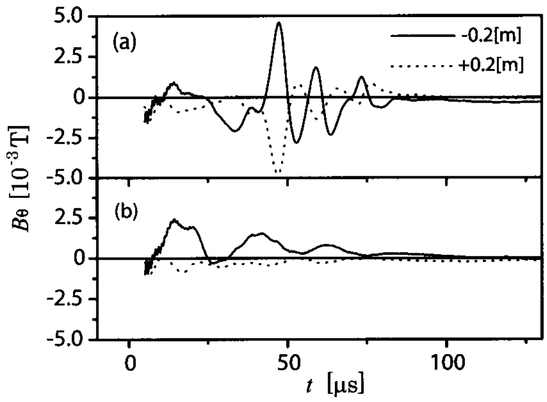

Fig. 6 Time evolution of an azimuthal field at $z = \pm 0.2$ m on the vacuum vessel (a) without a multipole field and (b) with the quadrupole field

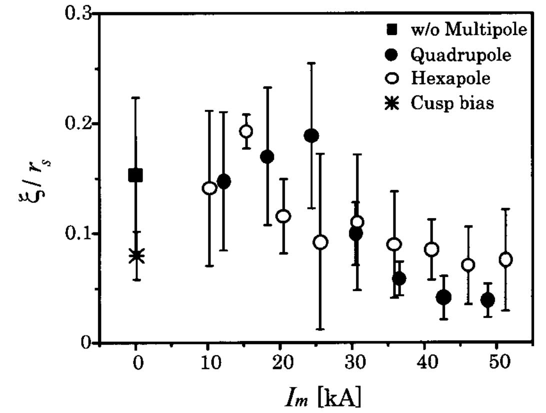

Fig. 7 Multipole coil current dependence of normalized $n = 1$ displacement

as seen in Figs. 5(b) and 6(b), where current $I_2 = 48$ kA flows in the quadrupole coil. The quadrupole current produces $B_\theta = 0.098$ T in vacuum at $r = 0.05$ m. The field does not exceed 20 % of the confinement field even when the conducting effect of the plasma and the theta-pinch coil is included.

The effects of the quadrupole field and the hexapole field on the mirror-biased plasma are summarized in Fig. 7. The abscissa is the current in the multipole coil. The ordinate is ξ normalized by the separatrix radius. The data are averaged for 10 μs at the middle of the discharge. The $n = 1$ mode motion is clearly depressed by applying quadrupole currrent above 35 kA. The hexapole field also shows a similar effect on the motion although higher current is needed than the quadrupole current.

4. Discussion

When the FRC plasma deviates from the equilibrium position, a restoring force due to the conductor effect of the theta-pinch coil arises. The motion of the FRC plasma can be revealed by a simple analysis of the following equation of motion:

$$M\frac{\mathrm{d}^2 r}{\mathrm{d}t^2} = -k_0 r\ ,\ k_0 \approx \frac{2\pi r_\mathrm{s}^4 B_\mathrm{e}^2}{\mu_0 r_\mathrm{w}^3} \qquad (1)$$

where r and M are the radial position of the center of mass and the total mass of the FRC plasma, respectively. The k_0 coefficient is derived from a model in which the FRC plasma is replaced by a magnetic dipole moment between two parallel plate conductors with a distance $2r_\mathrm{w}$.

Another restoring force is added to the FRC plasma when the multipole field is operated. The equation of motion becomes [6]

$$M\frac{\mathrm{d}^2 r}{\mathrm{d}t^2} = -\left(k_0 + k_m\right) r,\quad k_m \approx \frac{2\pi\left(m-1\right)B_\mathrm{s}^2}{\mu_0}. \qquad (2)$$

The magnetic field B_s is the vacuum field strength produced by the multipole coil at $r = r_\mathrm{s}$ as

$$B_s = \frac{\mu_0 m I_\mathrm{m}}{\pi r_\mathrm{m}}\left(\frac{r_\mathrm{s}}{r_\mathrm{m}}\right)^{m-1}, \qquad (3)$$

where $2m$, r_m and μ_0 represent the order of the multipole field, the radial position of the multipole coil and the permeability in vacuum, respectively. Therefore, the amplitude of motion without the multipole field ξ_0 can be controlled by the coil current I_m. The critical current I_mc that reduces the amplitude to $\xi_m = f\xi_0$ (f: reduction factor) is obtained from the relation $k_0\xi_0^2 = k_m\xi_m^2$ as

$$I_\mathrm{mc} = \frac{\pi r_\mathrm{m}^m r_\mathrm{s}^{3-m} B_\mathrm{e}}{\mu_0 f m\sqrt{\left(m-1\right) r_\mathrm{w}^3}}. \qquad (4)$$

The numerical values under the present experimental conditions give $I_{2\mathrm{c}} \approx 29$ kA for $m = 2$ and $I_{3\mathrm{c}} \approx 38$ kA for $m = 3$ at $f = 0.3$. These values explain well the experimental values in Fig. 7.

5. Summary

The $n = 1$ mode motion was investigated using two kinds of bias field configurations. It was found that the cusp bias configuration is preferable for generating the FRC plasma without violent $n = 1$ mode motion. However, in the mirror bias configuration, the amplitude of motion reached 20~40 % of the separatrix radius because of the asymmetrical reconnection at the formation phase of the FRC plasma. The motion can be controlled by the multipole field. The field strength needed to reduce the amplitude of the motion was derived considering the wall effect of the theta-pinch coil and was compared with the experimentally obtained value. The two values agree within the range of experimental reproducibility.

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