Control of an n=1 mode motion by multipole field

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1. Introduction

It is well known that an n=1 mode motion occurs on field-reversed configuration (FRC) plasmas. The motion is observed by the displacement of the separatrix surface as

$$r_s(z) = r_{se}(z) + \xi(z)\sin\theta$$

where r_{se}(z) and $\xi(z)$ is the equilibrium position of the separatrix and the radial displacement, respectively, as shown in Fig.1.

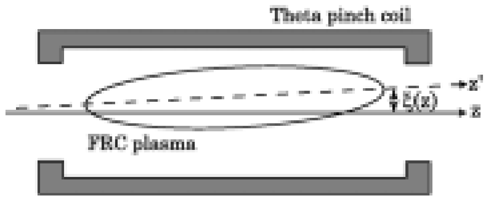

Fig.1 n=1 mode motion

This mode hasn't been studied because it doesn't disrupt the FRC like the n=2 mode rotational instability. However, the displacement of the FRC at the formation region increases during the translation to the confinement region. And it will disrupt the magnetic structure near the X-points on the separatrix surface. In case of the NBI heating, the motion of the FRC gives a bad effect to the heating efficiency. From these reasons, it is needed to fix the FRC axis on the magnetic axis of the confinement field at all times.

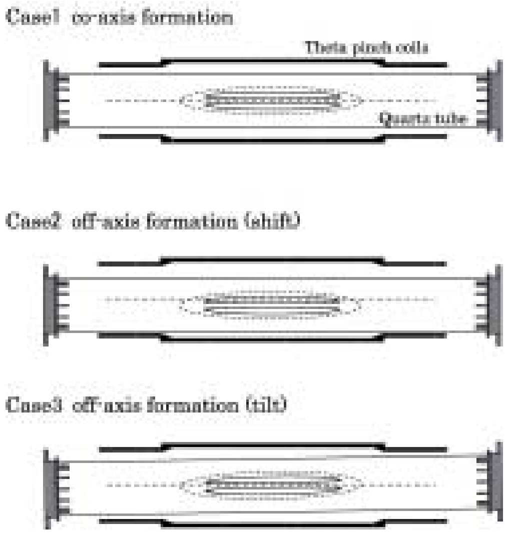

Fig.2 Experimental plan

We have an experimental plan consisting of three cases as shown in Fig.2. Case1 is the co-axis formation (standard operation). Case2 is the off-axis formation which is a model experiment of the shift motion. Case3 is that of the tilt motion. Following three subjects are discussed at the present report.

1. Over all behavior of the n=1 mode motion (Case1)
2. Control of the n=1 mode motion by the multipole field (Case1)
3. Behavior of the shifted FRC (Case2)

2. Experimental setup

The experimental device, NUCTE-Ⅲ, is shown in Fig.3.

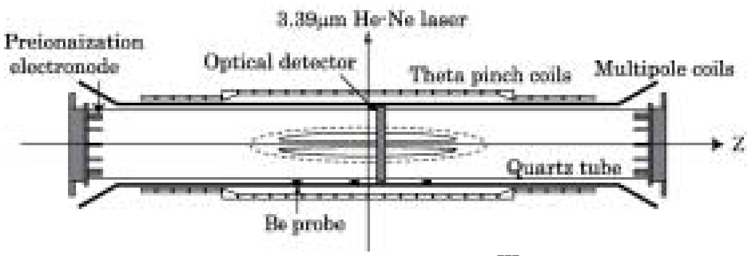

Fig.3 Schematics of NUCTE-Ⅲ

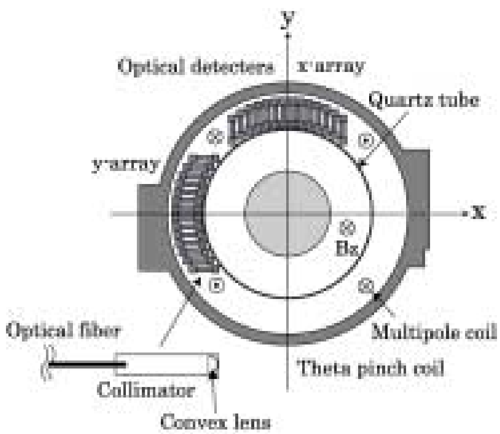

Fig.4 Arrangement of the optical detectors and the quadrupole field coil

It is constructed by a theta-pinch-coil, a quartz tube, preionaization electronodes and a multipole coil. And we use a 3.39μm He-Ne laser interferometer, optical detectors, B_θ probes, B_z probes and a one-turn loop to diagnose the plasma.

The optical detectors we newly developed have the most important roll to measure the n=1 mode motion. Arrangement of the detectors and the quadrupole field coil are seen in Fig.4. The FRC is observed by fourteen optical detectors with a convex lens, a collimator and an optical fiber each. The typical example obtained from the x-direction array of the detectors is shown in Fig.5. We draw a half value of the maximum intensity by a dotted line. The center of this line gives the central position of FRC, ξ_x. The y-direction array gives ξ_y. The radial displacement ξ can be calculated by $\xi = \sqrt{\xi_x{}^2 + \xi_y{}^2}$.

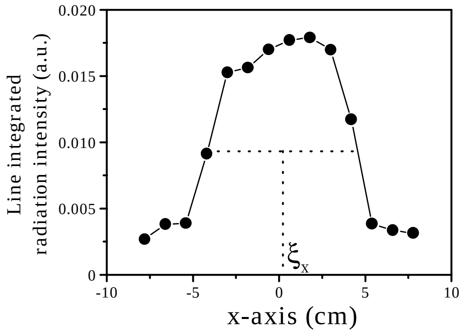

Fig.5 Determination method of ξ_x

3. Behavior of the n=1 mode motion on the co-axis FRC formation

Time evolution of a line integrated electron density without the multipole field is shown in Fig.6 (a). We can know overall behavior of the FRC from this signal. The n=2 mode rotational instability occurs about t=30μs and the lifetime of the FRC is about 70μs. The radiation profiles are shown in Fig.7 (a). Though the profiles of the x-axis and the y-axis array have a similar form near t=20μs, a difference appears at t=40 μs. It comes from the n=1 mode motion. The time evolutions of ξ and azimuthal field B_θ are shown in Fig.8. It can be seen the n=1 mode motion rapidly grows from about t=20μs. Maximum ξ is more than 1cm, that corresponds to 20% of the separatrix radius. After t=40μs, we can't get the central position

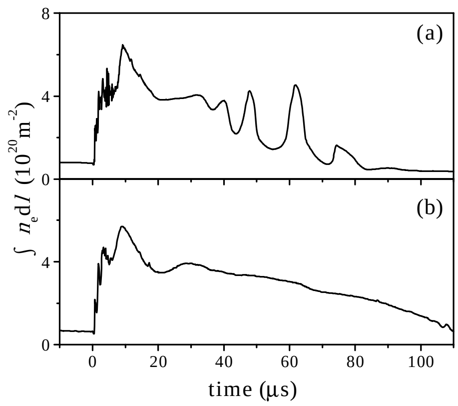

Fig.6 Time evolution of line integrated density

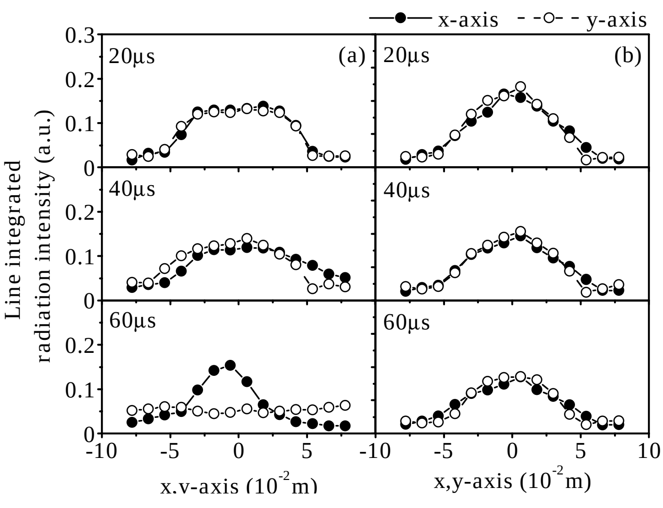

Fig.7 Radiation profiles

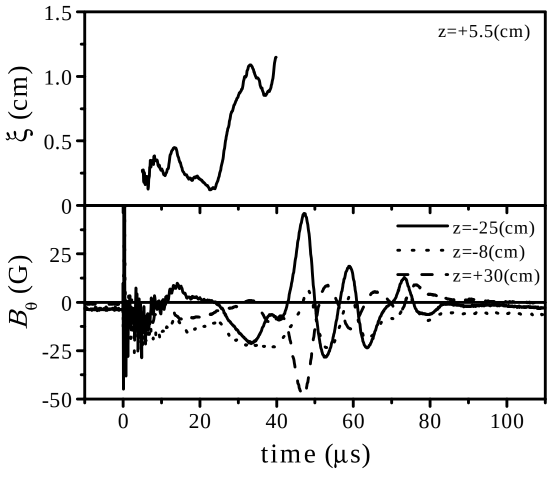

Fig.8 Time evolution of ξ and B_θ

because of the onset of the n=2 mode rotational instability. B_θ signal contains the effects of not only the n=1 mode but also other modes. The large gain can be seen around t=30μs, that corresponds to the n=1 mode. The large amplitude oscillations after t=40μs are occurred by the n=2 mode rotational instability. Trajectory of the center of the FRC on the x-y plane is shown in Fig.9 (a). It is plotted from t=5 to 40μs. The FRC is formed near the center of the coil and is moved around it.

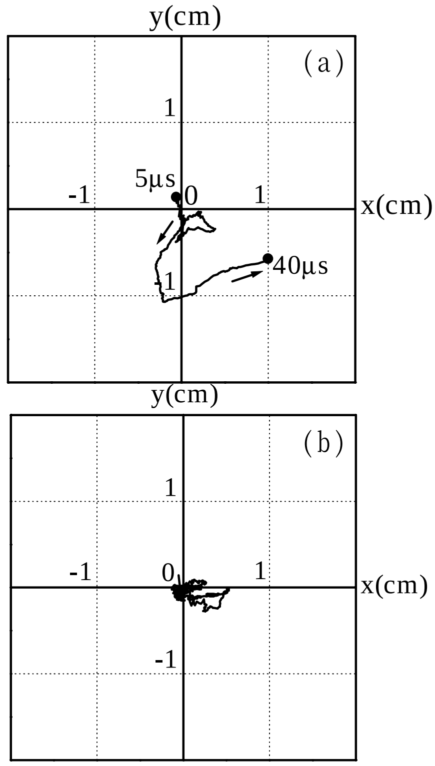

Fig.9 Trajectory of the center of the FRC

4. Effect of the multipole field

We applied the quadrupole and the hexapole field to control the n=1 mode motion. The time evolution of the line integrated electron density is shown in Fig.6 (b), where the quadrupole field produced by the 48kA in the coil is applied. The n=2 mode rotational instability is completely suppressed. The FRC continues till about t=100μs. The radiation profiles are shown in Fig.7 (b). All of these profiles become triangles. It is considered that the quadrupole field affects the equilibrium shape of the separatrix. Trajectory of the center of the FRC on the x-y plane is shown in Fig.9 (b). It is plotted from t=5 to 105μs. The n=1 mode motion becomes weak and ξ is less than 10% of separatrix radius. So we can say the n=1 mode motion is depressed by the quadrupole field.

The effect of the multipole field is summarized in Fig.10, where ξ is normalized by the separatrix radius and I_{2m} is the current in the multipole coil. All data are averaged the displacements from t=25 to 35μs. The circle means the FRC without multipole field, the triangles are with the quadrupole field and the squares are with the hexapole field. The error bars mean the standard deviations. It can be seen that the n=1 mode motion decreases with increase of I_{2m}. If we

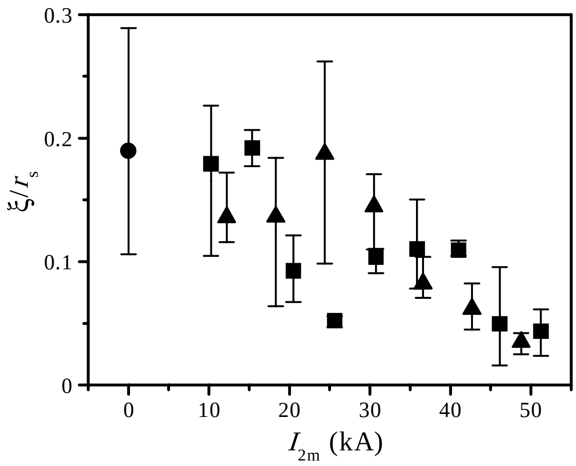

Fig.10 Multipole coil current dependence of the normalized n=1 displacement

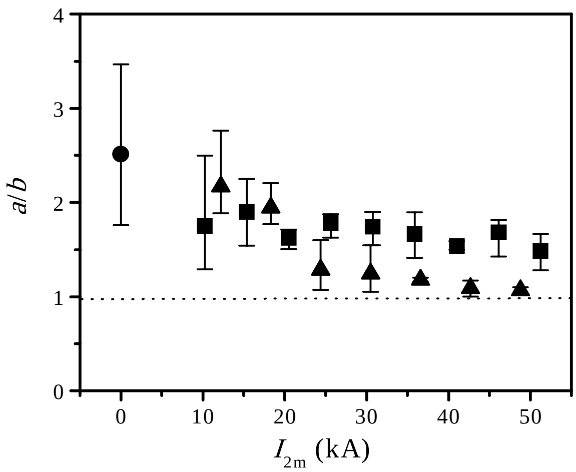

Fig.11 Multipole coil current dependence of the n=2 deformation rate

define the critical current I_{2m}^{1C} corresponding to ξ/r_s<10%, it is $I_4^{1C} \cong$ 40kA on the quadrupole field and $I_6^{1C} \cong$ 45kA on the hexapole field. The strengths of the quadrupole and the hexapole field on the separatorix surface are about 20% and 10% of the main field, respectively.

The stabilizing effect of the multipole field to the n=2 mode is shown in Fig.11. a and b of the coordinate mean a semi-major and a semi-miner axis of the elliptically deformed separatrix of the FRC. So a/b=1 corresponds to the circular cross section. According to this figure, the critical currents are I_4^{2C}=35kA on the quadrupole field and I_6^{2C}>50kA on the hexapole field. We cannot apply stronger current than 50kA because of restriction of the device.

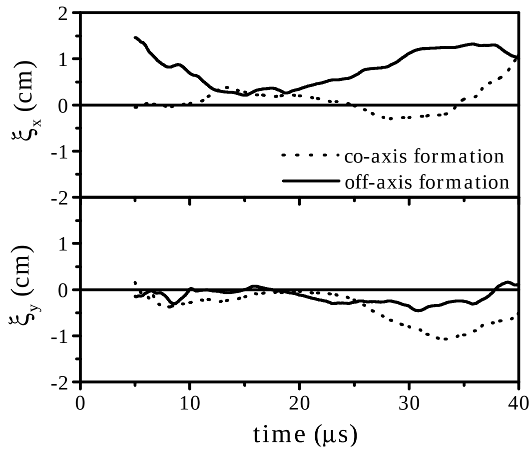

Fig.12 Time evolution of the center of the FRC

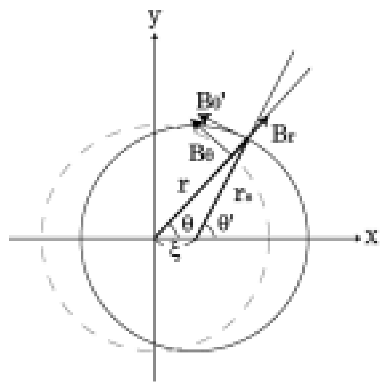

Fig.13 Geometrical relation

5. Off-axis FRC formation

The quartz tube is shifted 1cm to the x-direction in parallel with the axis of the theta pinch coil in order to occur the n=1 mode artificially. The motion of the FRC is shown in Fig.12, where the dotted line means the co-axis formation, and the solid line is the off-axis formation. It is seen on the off-axis formation that the FRC is formed near the tube axis and moved to the coil axis. Then it returns again to the tube axis, though it is anticipated that the FRC oscillates around the coil axis. It is needed to investigate the experimental result in more detail.

6. Discussion

The restoring force due to the multipole field when the FRC is displaced from the equilibrium position to x=ξ can be calculated. Here, the FRC is assumed as a cylindrical conductor with a radius r_s. In the case of r<a, the multipole field is approximately written in vacuum as follows.

$$B_r \cong -\left(\frac{m\mu I}{\pi a}\right)\left(\frac{r}{a}\right)^{m-1} \sin m\theta , \quad B_\theta \cong -\left(\frac{m\mu I}{\pi a}\right)\left(\frac{r}{a}\right)^{m-1} \cos m\theta$$

where a is a radial position of the multipole coil and 2m is the order of the multipole field. From the geometrical relation of the displaced FRC as shown in Fig.13, B_θ' becomes

$$B_\theta' \cong -\left(\frac{m\mu I}{\pi a}\right)\left(\frac{r}{a}\right)^{m-1} \cos\{\theta' + (m-1)\theta\}$$

The restoring force is obtained by integrating the x-component of the magnetic pressure along the separatrix surface.

$$F_{\mathrm{x}} = -\int_0^{2\pi} \frac{(2B_\theta')^2}{2\mu} r_s \cos\theta' \mathrm{d}\theta' = -\frac{2\pi(m-1)}{\mu} B_{\mathrm{s}}^{\,2} \xi$$

where the factor 2 in the numerator of the middle term comes from the conducting effect of the FRC and $B_{\mathrm{s}} = \frac{\mu m I}{\pi a}\left(\frac{r_{\mathrm{s}}}{a}\right)^{m-1}$.

The n=1 mode motion is modeled as a harmonic oscillator moving on the x-axis. In order to control the n=1 mode, the energy done by the restoring force has to excess the kinetic energy of the FRC at x=0.

$$\frac{1}{2}\pi r_{\mathrm{s}}^{\,2} \rho v_0^{\,2} < \int_0^{\xi} F_{\mathrm{x}} \mathrm{dx}$$

where ρ is the mass density. The kinetic energy can be replaced by the potential energy of the oscillator with the angular frequency ω_1 as

$$\frac{1}{2}\pi r_{\mathrm{s}}^{\,2} \rho v_0^{\,2} = \frac{1}{2}\mathrm{k}\xi^2$$

where $\mathrm{k}=\pi r_s^2 \rho \omega_1^2$. From these relations we obtain the critical current in the multipole coil.

$$I_{2\mathrm{m}}^{\ 1\mathrm{C}} = \pi r_{\mathrm{s}} a \mathrm{w}_1 \left(\frac{a}{r_{\mathrm{s}}}\right)^{m-1} \sqrt{\frac{\mathrm{r}}{2\mu m^2 (m-1)}}$$

The numerical values of I_{2m}^{1C} calculated from the plasma parameters are listed in Table1. The theoretical estimations explain well the experimental results. On the other hand, the theoretical value of the n=2 mode was developed by Ishimura[Phys.Fluids 27, 2139(1984)]. The n=2 mode is suppressed by about one-third the theoretical value.

Table1 Critical currents for the n=1 and 2 modes

m		2	3	4
$I_{2\mathrm{m}}^{\ 1\mathrm{C}}$(kA)	exp.	40	45	---
	theory	46	53	81
$I_{2\mathrm{m}}^{\ 2\mathrm{C}}$(kA)	exp.	35	>50	---
	theory	108	113	170

7. Summery

The n=1 mode motion is observed till the onset of n=2 mode rotational instability. The FRC moved around the theta-pinch-coil axis and the maximum displacement from the axis reaches to 20 to 40% of the separatrix radius. It can be depressed by the multipole field. The critical current in the multipole coil to control the n=1 mode agrees well with the estimated value from the simple theoretical model. The off-axis FRC formation is also tried. The FRC is formed near the axis of the quartz tube and oscillates between both axes of the tube and the theta-pinch-coil.