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Global Motions of Highly Elongated Low Aspect Ratio Tokamak

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Abstract

An extremely highly elongated ($\kappa = 10$) low aspect ratio tokamak has been produced and confined in a negative-biased theta-pinch device. It is possible to induce a large plasma current I_p (= 280 kA) for a few microsecond by using a fast bank. In spite of a small current ratio $I_{tfc}/I_p = 0.01$ (I_{tfc}: toroidal coil current), the safety factor of the plasma becomes very high ($q \sim 30$). However, the plasma is easy to move since the plasma is confined away from the vacuum vessel. MHD fluctuations of the plasma are observed by using a magnetic probe array. It is discussed that the plasma shows a vertical displacement, a shift and a tilt motion, and an elliptical deformation of a toroidal cross-section. A scale length of each MHD event is estimated by the aid of an analytic model.

Keywords:
low aspect ratio tokamak, elongation, theta-pinch

1. Introduction

Many studies of a Spherical Tokamak (ST) intending a confinement of a high β plasma are progressing [1-8]. The aspect ratio of a ST is close to one, which is a large difference from conventional tokamaks. It is also known that the shape of the poloidal cross-section plays an important role to the equilibrium and the stability of the plasma. The shape is mainly characterized by an elongation ratio κ which is defined by the ratio of the minor radius and a half vertical length of a poloidal cross-section of the plasma. Almost all ST experiments have been carried out for $\kappa = 2 \sim 3$.

We have tried to produce a ST with $\kappa = 5 \sim 10$ [9] by modifying the theta-pinch device which is normally operated for a field-reversed configuration plasma. The purpose of the present experiment is to study the MHD behavior of the ST having such high κ.

Firstly, a producing method of the ST and a magnetic field structure of the plasma are explained. Secondly, experimental results concerning the MHD behavior of the plasma are shown. Finally, the experimental data are analyzed in comparison with analytic models to know the overall aspect of the MHD motion.

2. Experimental Apparatus

A schematic of the experimental device named NUCTE-ST is shown in Fig. 1. A conducting rod is installed into a vacuum vessel along the central axis of a theta-pinch coil. The rod is wrapped by a thin electrically isolated tape and covered by a quartz tube with 1cm radius to avoid the contact of a plasma with the tape. A toroidal field in the plasma is induced by the current I_{tfc} flowing in the rod.

The poloidal field and the vertical field are formed by a combination of a slow rising negative bias-current and a fast rising main-current in the theta-pinch coil. It

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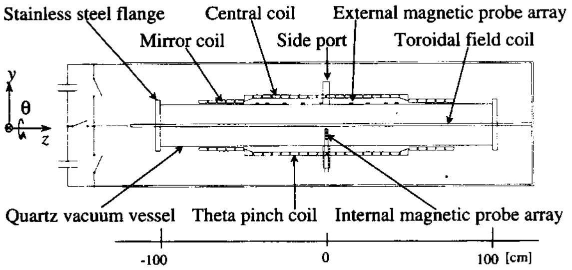

Fig. 1 NUCTE-ST

consists of a central coil with 100 cm length and 17 cm radius, and two end mirror coils with 25 cm each length and 14 cm radius. The magnetic field produced by the main-current heats quickly the plasma through similar radial and axial compression to the formation of a field-reversed configuration [10]. The I_{tfc} is applied at 20 μs before the start of the main-current. The e-folding times of the poloidal field and toroidal field are 0.08 ms and 0.1 ms, respectively. The vacuum vessel is made of a quartz tube with 200 cm length and 12.5 cm inner radius.

3. Experimental Result

Figure 2 shows the time evolution of the outer board radial position R_s of the separatrix surface and the line integrated electron density $n_e l$ at $z = 0$, where R_s is measured by the same magnetic method as the separatrix radius is estimated on a field-reversed configuration plasma [11]. The configuration lasts for 0.1 ms at I_{tfc} = 50 kA, though it disappears quickly at I_{tfc} = 30 kA. Then, the line integrated electron density keeps a constant value ($n_e l \sim 5 \times 10^{20}$ m^{-2}) at I_{tfc} = 50 kA during the lifetime, but it gradually decreases with time at a value less than 50 kA.

The poloidal shape of the separatrix is also obtained from the R_s profile along the z-direction. Open circles in Fig. 3 are experimental data at I_{tfc} = 50 kA and the solid line is the separatrix shape which is fitted to the following parametric expressions [12].

$$R = R_0 + a\cos(\phi + \sin^{-1}\delta\sin\phi) \quad (1)$$

$$z = z_0 + \kappa a\sin(\phi + \zeta\sin 2\phi) \quad (2)$$

where ϕ is an azimuthal angle from a major radius, and R_0, a, δ, ζ, and z_0 are major radius, minor radius, triangularity, squareness, and vertical displacement, respectively. The solid line is depicted by R_0 = 6.2 cm, a = 5.2 cm, δ = 0.4, κ = 9, ζ = 0.3 and z_0 = 5 cm. From these data the aspect ratio is also estimated to $A = R_0/a$

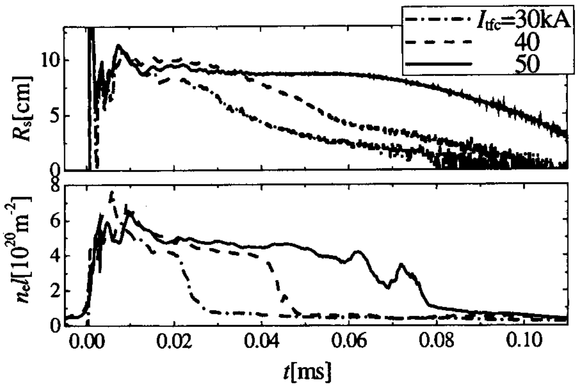

Fig. 2 Time evolution of R_s and $n_e l$.

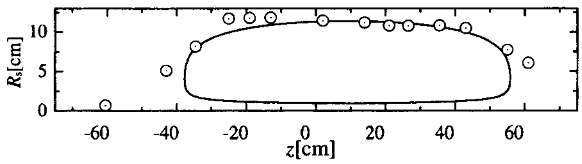

Fig. 3 Separatrix shape at a current ratio I_{tfc}/I_p = 50 kA/ 240 kA.

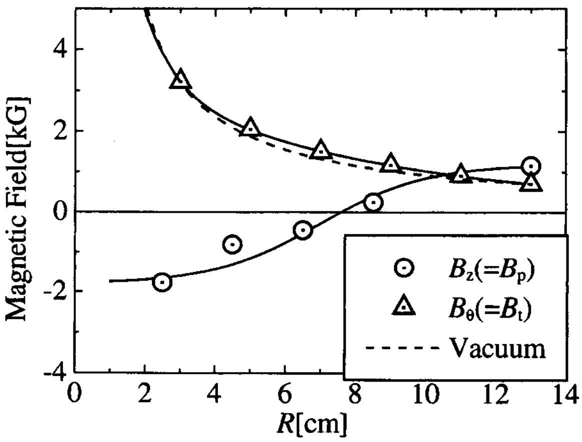

Fig. 4 Internal magnetic field profiles

= 1.2. The elongation can be reduced to κ = 5 by shortening the center coil of the device.

Internal magnetic field profiles are measured by using a magnetic probe array inserted into the plasma from a side port of the vacuum vessel at z = 0. Triangles and open circles in Fig. 4 mean measured toroidal and poloidal fields, respectively. A dotted line means a vacuum toroidal field B_{vt} produced by I_{tfc} = 50 kA. In the outer board region near R = 12 cm, the poloidal field is larger than the toroidal field, but smaller than that at the inner region. The poloidal field is reversed at $R \sim 8$ cm where the toroidal field strength is about 1.2 times the vacuum field. This field amplification can be explained from a paramagnetic current flow, which is one of the characteristics of a ST. The amplification rate becomes large at small I_{tfc}. The toroidal field, for example, at I_{tfc} = 10 kA reaches almost four times the vacuum field. The edge safety factor estimated from this field configurations and the separatrix shape shown in Fig. 3 is approximately $q_{edge} \sim 90$.

The internal field profiles give an averaged beta value $\langle\beta\rangle = 2\mu_0\langle p\rangle/B_e^2 = 0.5$, where B_e is a field strength between the outside the separatrix surface and the theta-pinch coil and the average plasma pressure $\langle p\rangle$ is calculated from the internal magnetic field profiles shown in Fig. 4.

The MHD activity of the plasma is diagnosed by using a magnetic probe array. The vertical motion of the plasma can be known from a time evolution of z_0 in eq. (2). A typical displacement at I_{tfc} = 30 kA is about 6 cm on $\kappa = 5$, which corresponds to about 10% of the full vertical length of the plasma, and about 1 cm at $\kappa = 10$. These behaviors are summarized in Fig. 5. The large scatters of the data points come from the reproducibility of the discharges.

Large amplitude fluctuations of toroidal field are also detected around the vacuum vessel at $z = 0$. The amplitude reaches 10~20% of the vacuum field. It is found that the $n = 1$ and 2 modes are main components of the fluctuations. They continue from the start of the formation of the ST till the disappearance time of the paramagnetic component of the toroidal field as shown in Fig. 6. The amplitudes of both modes become small with increase in I_{tfc} and decrease in the vertical field.

4. Discussion

The MHD behavior of the plasma can be known from the analysis of the fluctuating components of the toroidal field ΔB_t. The $n = 1$ mode is generated from a shift and a tilt motion of the plasma as shown in Fig. 7. When the highly elongated spherical tokamak moves to the conducting wall (theta-pinch coil), the toroidal field around the separatrix is strengthened at the narrowed region and weakened at the widen region. Another mechanism generating ΔB_t is that a vertical field is curved correlating with the tilt motion of the plasma [13].

The strength of the fluctuating field at the vacuum vessel ($R = R_t$) can be estimated from an assumption of

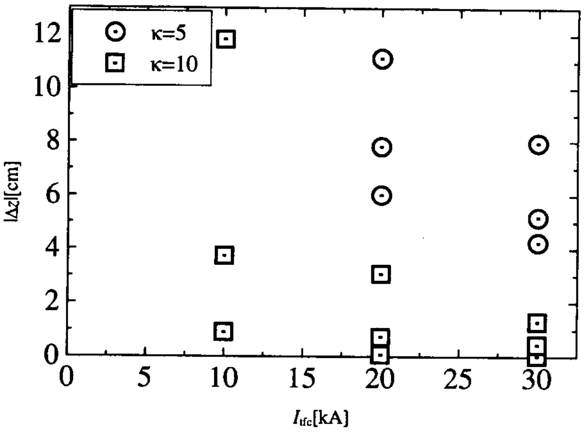

Fig. 5 I_{tfc} dependence of vertical displacement.

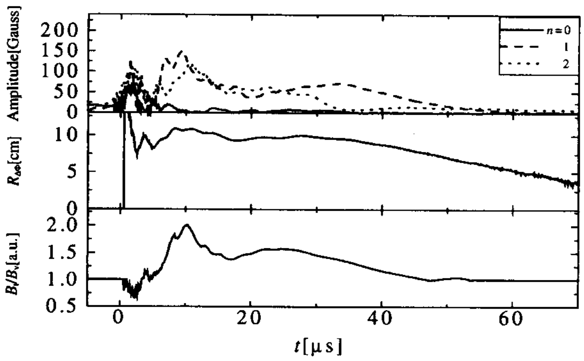

Fig. 6 Excitation of n = 1 and 2 modes and paramagnetism of the toroidal field at I_{tfc} = 50 kA.

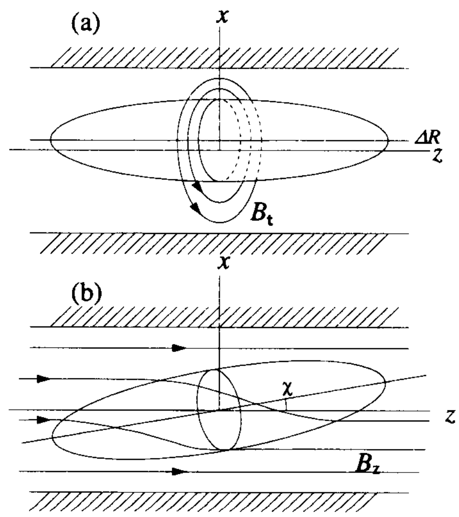

Fig. 7 (a) Radial shift, and (b) tilt of major axis of a highly elongated ST.

a flux conservation at the vacuum region between the plasma and the coil as follows.

$$\Delta B_{t1}(\text{shift}) \approx \frac{\Delta R}{R_t}\left(1+\frac{R_t^2}{R_w^2}\right) B_t(R_t)\sin\theta \qquad (3)$$

$$\Delta B_{t1}(\text{tilt}) \approx \frac{\chi R_s}{R_w - R_s} B_z(R_t)\sin\theta \qquad (4)$$

where R_w, ΔR and χ are the conducting wall radius, the distance from the geometrical axis to the wall and the tilt angle of the plasma, respectively, $B_z(R_t)$ is a vertical field near the vacuum vessel.

By substituting experimental data ΔB_{t1} = 50 G, $B_t(R_t)$ = 600 G, $B_z(R_t)$ = 2.6 kG, R_w = 17 cm, R_t = 13 cm, R_s =10 cm for both eqs. (3) and (4), ΔR = 0.7 cm and χ = 0.01 rad are obtained. In order to decide which motion dominates ΔB_{t1}, another diagnostic method like an optical measurement would be needed.

The n = 2 mode is generated from an elliptical distortion of the toroidal cross-section. In this case the fluctuating field can be estimated from a similar constraint as the n = 1 mode.

$$\Delta B_{t2} \approx (E^2-1)\frac{R_s^2}{2R_t^2}\left(1+\frac{R_t^4}{R_w^4}\right) B_t(R_t)\sin 2\theta \qquad (5)$$

where E is an elongation factor of the toroidal cross-section that is the ratio of the semi minor axis to the semi major axis. From the above experimental data and ΔB_{t2} = 50 G, E = 1.1 is obtained to the present plasma.

In summary, a spherical tokamak with $\kappa \approx 10$ is produced and confined for 0.1 ms in the theta-pinch device. A fluctuating toroidal field is detected near the vacuum vessel. It is discussed that the sources of the fluctuations are such MHD motions as the shift and the tilt of the major axis of the plasma, and the deformation of the toroidal cross-section.

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