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A SIMPLE METHOD OF EQUILIBRIUM DETERMINATION AND ITS APPLICATION TO A RFP PLASMA WITH THIN SHELL

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Abstract—A simple method is proposed to determine the equilibrium quantities (such as the plasma position and Shafranov's parameter Λ) in Tokamaks and RFPs. This method is available in the transient phase of a discharge, in which the plasma equilibrium is maintained by time-varying vertical fields, e.g. in the case where the plasma is surrounded by a thin shell. In this method, the external fields measured are matched to the approximate solution of the Grad–Shafranov equation in a vacuum, by a fitting procedure. In the case of a circular plasma boundary, only a small number ($\geqslant 6$) of the field measurements can provide a stable and rapid determination of equilibrium. A successful application to the REPUTE-1 RFP plasma with thin shell reveals that in most cases the plasma starts to move outward and downward before the plasma current begins to fall.

1. INTRODUCTION

IDENTIFICATION of the equilibrium configuration is a basic measurement in plasma confinement devices such as Tokamaks or RFPs. Information on the plasma shape and position is especially important for studying the MHD equilibrium and instability, and is also necessary for other plasma diagnostics. Recently, several RFP devices (ASAKURA *et al.*, 1986; GOFORTH *et al.*, 1986; ALPER *et al.*, 1989) have been operated with a thin shell in order to observe how plasmas behave when the discharge duration exceeds the shell's skin time τ_{shell} for the penetration of vertical fields. The equilibrium then of plasma is maintained partially by the shell and partially by the externally applied vertical fields, i.e. the vertical fields due to both of them are time-dependent with a time scale of τ_{shell}. This means that the equilibrium is in a transient state rather than in a steady state. Therefore, it is important to have a diagnostic system which can provide information on the plasma position with a sufficiently fast time response, in order to investigate effects of the thin shell on the plasma equilibrium and instability.

Basically, the determination of equilibrium is to solve the MHD equilibrium equation as a free boundary problem, so as to match the externally measured fields and poloidal flux (LUXON and BROWN, 1982; DESHKO *et al.*, 1983; LAO *et al.*, 1985; BRAAMS *et al.*, 1986; ALLADIO and CRISANTI, 1986) or diamagnetic inductance (LAO *et al.*, 1985; KUZNETSOV *et al.*, 1986; LAZZARO and MANTICA, 1988) in Tokamaks. However, one must assume an explicit form for the current distribution inside the plasma, and the computation time consuming, which is difficult for application as a real-time routine.

If only the plasma shape and position are of interest, there are several methods (ZAKHAROV and SHAFRANOV, 1973; WOOTTON, 1979; LEE and PENG, 1981; SWAIN and NEILSON, 1982; DESHKO *et al.*, 1983; CHE *et al.*, 1988; HOFMANN and TONETTI, 1988) which have been used successfully. The conventional one is the current moment method (ZAKHAROV and SHAFRANOV, 1973; WOOTTON, 1979; CHE et al., 1988), whose principle is based on straight relations between the equilibrium quantities and the external fields given by Shafranov's toroidal equilibrium theory (MUKHOVATOV and SHAFRANOV, 1971). These relations are available in the case where the equilibrium is maintained by the ideal shell only or by the externally applied vertical fields only. However, in the transient phase of a discharge Shafranov's relations are not available. For example, when the plasma is surrounded by a thin shell, penetration of the magnetic fields through the shell takes place on the time scale of τ_{shell} and thus the ideal shell condition is violated.

A fast method has been introduced to obtain the plasma shape and position, in which the plasma current I_p is represented by discrete six-current filaments (SWAIN and NEILSON, 1982) or a finite-element model (HOFMANN and TONETTI, 1988). The magnitudes of the currents which are flowing in the external windings are used in the calculation. In the thin shell case, however, it is not appropriate to use these values directly because the field penetration through the shell takes a finite time. One must replace the external coil currents by at least four current filaments outside the plasma, and thus the equilibrium determination requires a lot (at least 10 in principle, more for a stable calculation) of measurement of the external fields or flux loops. Furthermore, it is difficult to include the effect of the iron core by this method.

Another method has been proposed to determine the plasma shape and position, and has been tested numerically. LEE and PENG (1981) and DESHKO et al. (1983) extended the poloidal flux Ψ in terms of the eigenfunctions of the Grad–Shafranov equation in a vacuum, and used a fitting technique to determine their coefficients. Each eigenfunction is an associated Legendre function, denoting a Fourier component of the plasma shape with respect to the poloidal angle θ.

In this paper we introduce a simple method, which is similar to that of LEE and PENG (1981), based on fitting the approximate solution of the Grad–Shafranov equation in a vacuum to the measured fields. However, our method differs from LEE and PENG's (1981) in two respects. First, as fitting parameters, we choose physically meaningful ones such as displacements of the plasma center, instead of the eigenfunction's coefficients which have no direct physical meaning. Second, as an approximation, we use truncated forms of eigenfunctions which are expressed as an infinite power series of the inverse aspect ratio, so that we can denote the fitting function in a simple analytic form, provided the aspect ratio is large. Using this method, there is no necessity to consider effects of the iron core and the thin shell especially, and the plasma position can be determined at every moment, even if the discharge is in a transient phase. Note that there is no need to make any assumptions of explicit current distributions inside the plasma. In Section 2, we describe the equilibrium model and method of determining the fitting parameters in detail.

The REPUTE-1 device (ASAKURA et al., 1986) is characterized by a thin shell of 5 mm thick stainless steel whose skin time τ_{shell} is 1 ms. Since discharges presented in this paper were obtained without the limiters, the plasma is limited by the inner surface of the liner, which has a major radius of 82 cm and a minor radius of 22 cm. Optimum discharges, whose duration $\tau_{duration}$ are about three times τ_{shell}, have been obtained. In spite of various efforts including vertical-Ohmic coil series connection experiments (TOYAMA et al., 1987), toroidal ripple reduction experiments (HATTORI et al., 1988) and port bypass plate installation experiments (TOYAMA et al., 1989; SHINOHARA et *al.*, 1989), $\tau_{duration}$ is still at present limited to 3.2 ms. Hence, it is necessary to measure the plasma position accurately in order to understand what terminates the discharge. In Section 3, as an application of the present method, we determine the time evolution of the plasma position from the flat-top phase to the termination phase, when the plasma begins to lose its equilibrium. Conclusions are given in Section 4.

2. DESCRIPTION OF THE METHOD

2.1. *Plasma equilibrium model*

For simplicity we consider the first Fourier component of the poloidal angle θ. In other words, we can assume that the plasma has a circular outermost magnetic surface which has a radius a. We choose this circular center as the center of the coordinate (r, θ), and let R denote the major radius of the plasma. Outside the plasma $r > a$ we use the vacuum solution of the Grad–Shafranov equation in the first-order approximation of the expansion in r/R (MUKHOVATOV and SHAFRANOV, 1971):

$$\Psi(r,\theta) = \frac{\mu_0 R I_p}{2\pi}\left(\ln\frac{8R}{r}-2\right) - \frac{\mu_0 I_p}{4\pi}\left[\ln\frac{r}{a}+(\Lambda+\tfrac{1}{2})\left(1-\frac{a^2}{r^2}\right)\right] r\cos\theta. \quad (1)$$

Here $\Lambda = \beta_p + l_i/2 - 1$, β_p is the poloidal beta and l_i is the internal inductance of the unit length of the plasma column. Equation (1) satisfys the boundary conditions at the plasma surface $r = a$:

$$B_\theta(a,\theta) = B_a\left(1+\frac{a}{R}\Lambda\cos\theta\right), \quad (2)$$

$$B_r(a,\theta) = 0, \quad (3)$$

where $B_a = -\mu_0 I_p/2\pi a$. Note that we use the first Fourier component of θ in the first-order approximation of a/R only. From equation (1), the poloidal and radial fields at position (r, θ) outside the plasma are:

$$B_\theta(r,\theta) = \frac{a}{r}B_a + \frac{a}{2R}B_a\left[\left(1+\frac{a^2}{r^2}\right)(\Lambda+\tfrac{1}{2})+\ln\frac{r}{a}-1\right]\cos\theta, \quad (4)$$

$$B_r(r,\theta) = \frac{a}{2R}B_a\left[\ln\frac{r}{a}+(\Lambda+\tfrac{1}{2})\left(1-\frac{a^2}{r^2}\right)\right]\sin\theta. \quad (5)$$

Since the vacuum fields are completely determined by the boundary conditions at the plasma surface [equations (2) and (3)], there is no need to make any assumptions about the boundary condition outside the plasma, such as the ideal shell condition that the normal component of the fields vanishes at the inner surface of the ideal shell. Moreover, the effects of the thin shell and the iron core are automatically included in equations (4) and (5), therefore one can apply this model directly without any other modifications.

From the solutions given in the Appendix of Shafranov's paper (SHAFRANOV, 1960), the magnitude of the second-order term of a/R compared to the first-order term is $\sim(a/R)^2/4$; thus in the case of large aspect ratio the second-order term can be ignored, to a good approximation. In REPUTE-1, for example, $a/R \sim 3.7^{-1}$ and $(a/R)^2/4 \sim 1.8\%$.

For a plasma which has a non-circular poloidal section, the second or higher Fourier component of θ, i.e. the $\cos 2\theta$ term etc., must be incorporated into our model discussed above. However, in the case of REPUTE-1, one expects that an approximation of circular outermost magnetic surface is a good one from the decay index of the vertical fields. Measurements of soft X-ray emissivity using a tomography technique indicate the circular contours near the plasma edge (ASAKURA *et al.*, 1989). Therefore, in the following sections, we restrict our analysis to the case of a circular plasma for simplicity.

2.2. *Determination of plasma position and* Λ

Assuming that the limiter surface is a circle, we define Δ_x, Δ_y as the horizontal and vertical displacement of the outermost magnetic surface from the limiter center. Let (ρ, ω) denote the coordinate whose center is positioned at the limiter surface center. Figure 1 shows the relation between the coordinates (r, θ) and (ρ, ω). If the plasma extends to the limiter surface, the plasma major and minor radius R and a are

$$R = R_L + \Delta_x, \tag{6}$$

$$a = a_L - \sqrt{\Delta_x^2 + \Delta_y^2}, \tag{7}$$

respectively, where R_L and a_L are the major and minor radius of the limiter surface, respectively.

We now consider the case where the magnetic probes are installed in the region

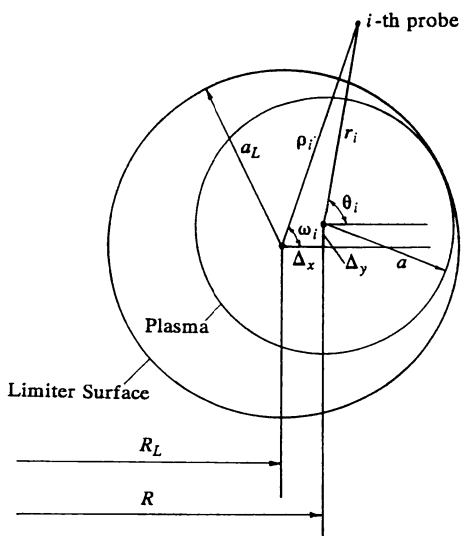

FIG. 1.—Displacement of plasma from limiter surface center, (ρ, ω) and (r, θ) coordinates and magnetic probes.

$\rho \geqslant a_L$, in order to measure the displacements of plasma Δ_x, Δ_y and Shafranov's Λ. Let the location of the ith probe be (ρ_i, ω_i) and (r_i, θ_i), as shown in Fig. 1. Here ρ_i and ω_i are constants, and r_i and θ_i are determined from Δ_x and Δ_y, as follows:

$$r_i = \sqrt{(\rho_i \cos \omega_i - \Delta_x)^2 + (\rho_i \sin \omega_i - \Delta_y)^2}, \tag{8}$$

$$\tan \theta_i = \frac{\rho_i \sin \omega_i - \Delta_y}{\rho_i \cos \omega_i - \Delta_x}. \tag{9}$$

From equations (4) and (5), we have the ω and ρ components of the field at the position of the ith probe,

$$B'_\omega(\rho_i, \omega_i) = \frac{a}{2R} B_a[C_0 \cos \omega_i + C_1 \cos (\omega_i - \theta_i) + C_2 \cos (\omega_i - 2\theta_i)], \tag{10}$$

$$B'_\rho(\rho_i, \omega_i) = -\frac{a}{2R} B_a[C_0 \sin \omega_i + C_1 \sin (\omega_i - \theta_i) + C_2 \sin (\omega_i - 2\theta_i)], \tag{11}$$

where

$$C_0 = \ln \frac{r_i}{a} + \Lambda, \quad C_1 = \frac{2R}{r_i}, \quad C_2 = \frac{a^2}{r_i^2}(\Lambda + \tfrac{1}{2}) - \tfrac{1}{2}.$$

There are three fitting parameters to determine $B'_\omega(\rho_i, \omega_i)$ and $B'_\rho(\rho_i, \omega_i)$; Δ_x, Δ_y and Λ. We use the least-squares method to determine the fitting parameters which minimize

$$S = \sum_i \left[\left(\frac{B_\omega(\rho_i, \omega_i) - B'_\omega(\rho_i, \omega_i)}{\sigma_\omega(\rho_i, \omega_i)} \right)^2 + \left(\frac{B_\rho(\rho_i, \omega_i) - B'_\rho(\rho_i, \omega_i)}{\sigma_\rho(\rho_i, \omega_i)} \right)^2 \right], \tag{12}$$

where $B_\omega(\rho_i, \omega_i)$ and $B_\rho(\rho_i, \omega_i)$ are the ω and ρ components of field measured by the ith probe, and $\sigma_\omega(\rho_i, \omega_i)$ and $\sigma_\rho(\rho_i, \omega_i)$ are the standard deviations of errors in the $B_\omega(\rho_i, \omega_i)$ and $B_\rho(\rho_i, \omega_i)$ measurements. As a nonlinear problem, Δ_x, Δ_y and Λ are calculated using the Gauss–Newton Method based on the linear approximation, through an iteration process.

Test fittings were performed by using ideal data with random errors. It is clarified that, for a stable determination, B_ω and B_ρ must be measured at least at three proper poloidal positions, i.e. six signals in total, although in principle only three measurements of B_ω or B_ρ are required. The results are almost unchanged by increasing field measurements to more than three positions, e.g. eight positions.

Figures 2(a)–(c) show contours of constant S in the Δ_x–Λ, Δ_y–Λ and Δ_x–Δ_y planes, when both B_ω and B_ρ at eight poloidal positions are used in the calculations. Here, $\Lambda = -0.15$, $\Delta_x = 1.0$ cm and $\Delta_y = -1.5$ cm are taken as the "true" values. The values of σ_ω and σ_ρ are assumed to be 2.5% of B_ω and sin 1.5° of B_ω, respectively, as is the case in REPUTE-1. The errors in the fitting parameters are estimated from σ_ω and σ_ρ.

Figure 2(d) shows contours of constant S in the Δ_x–Λ plane when the conditions are the same as those in Figs 2(a)–(c) except that only B_ω at eight positions is used. Δ_x and Λ cannot be determined uniquely by B_ω measurements only, because of their strong negative correlation.

In order to investigate the sensitivity of the fitting results to experimental errors involved in the measured field, a series of test fittings with various magnitudes of

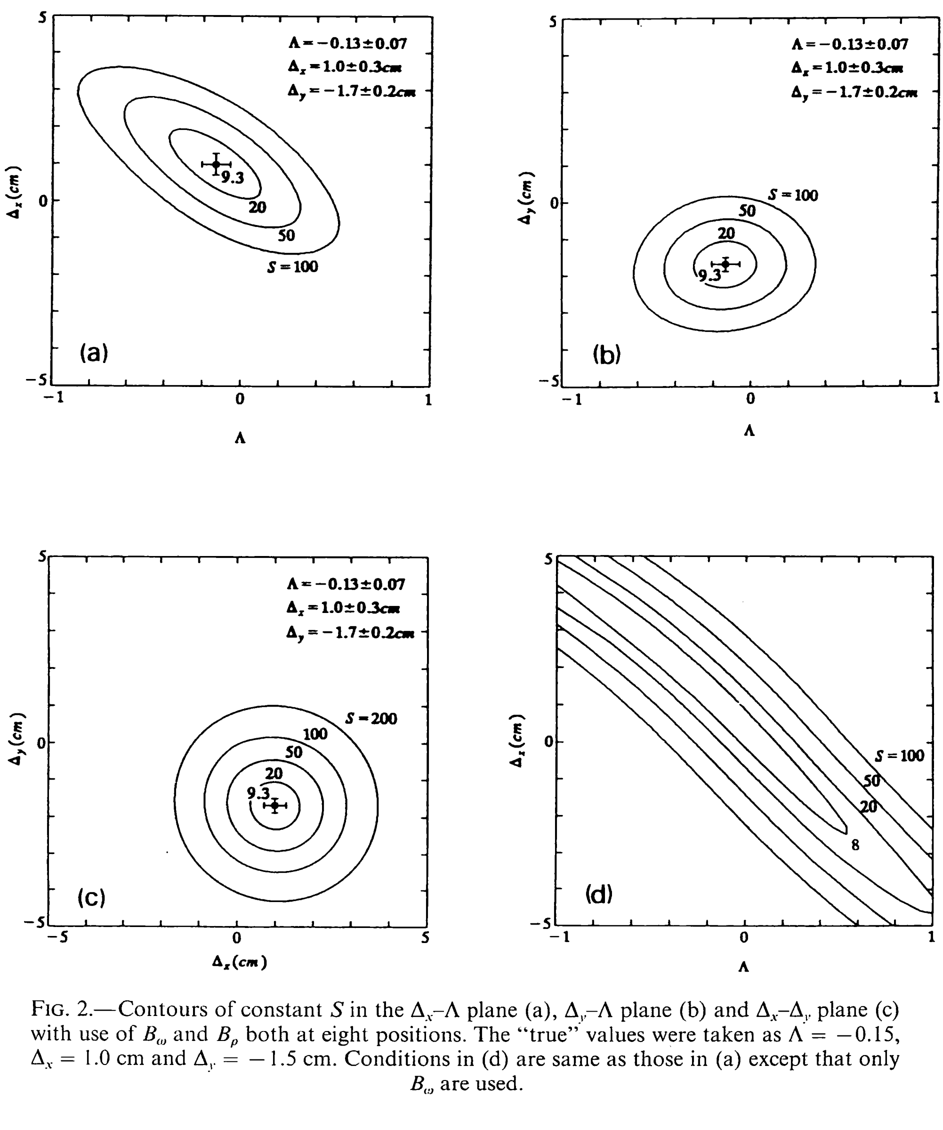

FIG. 2.—Contours of constant S in the Δ_x–Λ plane (a), Δ_y–Λ plane (b) and Δ_x–Δ_y plane (c) with use of B_ω and B_ρ both at eight positions. The "true" values were taken as $\Lambda = -0.15$, $\Delta_x = 1.0$ cm and $\Delta_y = -1.5$ cm. Conditions in (d) are same as those in (a) except that only B_ω are used.

TABLE 1.—TEST FITTING RESULTS WITH VARIOUS MAGNITUDES OF ERRORS σ_ω AND σ_ρ. THE "TRUE" VALUES WERE TAKEN AS $\Lambda = -0.15$, $\Delta_x = 1.0$ cm AND $\Delta_y = -1.5$ cm

Error magnitude		Fitting results		
σ_ω	σ_ρ	Λ	Δ_x (cm)	Δ_y (cm)
1% of B_ω	sin 1° of B_ω	-0.169 ± 0.043	1.03 ± 0.19	-1.50 ± 0.09
2% of B_ω	sin 1° of B_ω	-0.180 ± 0.055	1.01 ± 0.20	-1.50 ± 0.14
4% of B_ω	sin 1° of B_ω	-0.210 ± 0.087	0.99 ± 0.20	-1.51 ± 0.18
1% of B_ω	sin 1° of B_ω	-0.169 ± 0.043	1.03 ± 0.19	-1.50 ± 0.09
1% of B_ω	sin 2° of B_ω	-0.189 ± 0.079	1.13 ± 0.38	-1.49 ± 0.10
1% of B_ω	sin 4° of B_ω	-0.252 ± 0.146	1.45 ± 0.70	-1.49 ± 0.11

errors was performed. Table 1 shows the test fitting results, in which the conditions are the same as in Fig. 2 except for the values of σ_ω and σ_ρ. In the first three cases σ_ρ is fixed and in the last three cases σ_ω is fixed. It can be seen that by increasing σ_ω, the Λ obtained have relatively large uncertainties whilst Δ_x and Δ_y are almost undistorted. On the other hand, large σ_ρ values also bring an uncertainty in the Δ_x determination in addition to Λ. The parameter Δ_y is still robust to large values of σ_ρ. As a result, if B_ω pick-up coils are calibrated with an accuracy of $\pm 2.5\%$ and B_ρ pick-up coils are installed with an accuracy of $\pm 1.5°$ with respect to the radial direction in the REPUTE-1 case, then Λ, Δ_x and Δ_y can be determined with errors of ± 0.07, ± 0.3 cm and ± 0.2 cm, respectively.

The calculations were usually carried out with less than ten iterations. They were fast enough to perform between shots of REPUTE-1 operation (three minutes minimum) as a real-time routine.

3. APPLICATION TO REPUTE-1 RFP

3.1. *Poloidal magnetic probe array*

A poloidal array of magnetic field pick-up coils with protective covers of 0.7 mm thick stainless steel, was installed at a port segment (2.4 mm thick Inconel-625) inside the vacuum vessel. A pipe of square cross-section which runs poloidally between the probes leads the coil signal wires to the feed-through and protects them from the plasma (Fig. 3). The array covers all poloidal angles equally at eight poloidal positions

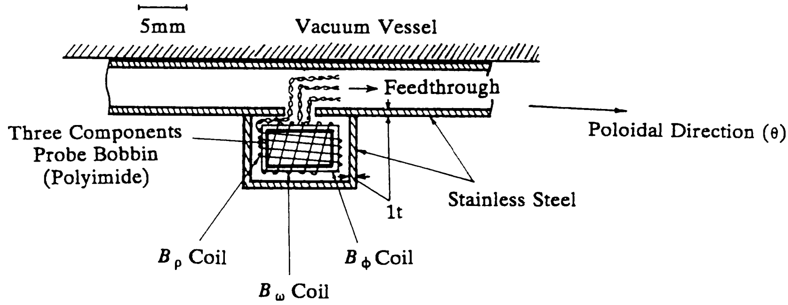

FIG. 3.—Poloidal array of magnetic probes, consisting of a pipe of square cross-section and the specially designed probe bobbins which can pick up three components of the fields.

with a 45° separation. At each position the three components of fields B_ϕ, B_ω and B_ρ can be measured by the specially designed probe bobbin simultaneously, with a frequency response up to 40 kHz.

3.2. *Results*

A typical example of REPUTE-1 RFP discharge is shown in Fig. 4(a). At $t \sim 1.4$ ms, the plasma current I_p has a maximum value of ~ 280 kA, the loop voltage $V_l \sim 150$ V and the chord-averaged electron density $\bar{n}_e \sim 5 \times 10^{19}$ m^{-3}. After $t \sim 1.4$ ms, I_p begins to fall down and V_l begins to rise. Figure 4(b) shows the time evolution of Λ, Δ_x, Δ_y and Δ_t, where the toroidal shift Δ_t presents the distance between the magnetic axis and the center of the outermost magnetic surface due to the toroidal effect,

$$\Delta_t = \frac{a^2}{2R}(\Lambda + \tfrac{1}{2}) \tag{13}$$

and typically Δ_t is about 1 cm.

The reversal ratio F and the pinch parameter Θ are also shown in Fig. 4(a), where solid lines and dashed lines indicate the values with and without correction according to the change of the plasma position, respectively. It is shown that the observed values of $F \sim -0.35$ and $\Theta \sim 2.25$ are reduced to reasonable values of $F \sim -0.25$ and $\Theta \sim 1.95$ after the correction of the plasma position at the current flat-top phase ($t \sim 1.4$ ms). The Λ–Θ diagram is shown in Fig. 5. Here the curve labeled BFM shows the trajectory in the Λ–Θ plane obtained using the Bessel Function Model in which $\mu \equiv \mu_0 \mathbf{j} \cdot \mathbf{B}/B^2 =$ const. and other curves labeled α show the trajectories in the Modified Bessel Function Model defined by $\mu \propto 1-(r/a)^\alpha$. The closed circles indicate the results obtained by the internal probe experiments (Ueda, 1985), where the values of l_i are calculated by the measured field distributions and $\beta_p \sim 0.1$ is assumed. The Θ dependence of Λ from the equilibrium determination is consistent with that from the direct measurements of internal field distributions. This fact indicates the accuracy and usefulness of our method in equilibrium determination.

As a typical case, the plasma column starts to move outward and downward from the linear center at $t \sim 1.1$ ms, before I_p begins to fall at $t \sim 1.4$ ms. This displacement of the plasma column is a candidate for the discharge termination, although its toroidal dependence is not yet known. It is not clear whether the outward movement is due to weak vertical fields and/or a short skin time of the shell.

From the internal probe measurements (REPUTE-1 Annual Report 1984/1985), the penetration of the vertical fields inside the shell is dependent on its distance from the torus center, i.e. the penetration outside the torus is faster than that inside the torus. This is due to the fact that the eddy current in the shell, preventing the penetration of external fields, is disturbed by a lot of big diagnostic holes outside the torus. As a result, the decay index $N \equiv -(R/B_v)\, \mathrm{d}B_v/\mathrm{d}R$ inside the shell has a negative sign during the penetration, in spite of a positive sign after penetration. This negative N induces an up–down instability of the plasma column and can terminate the discharge.

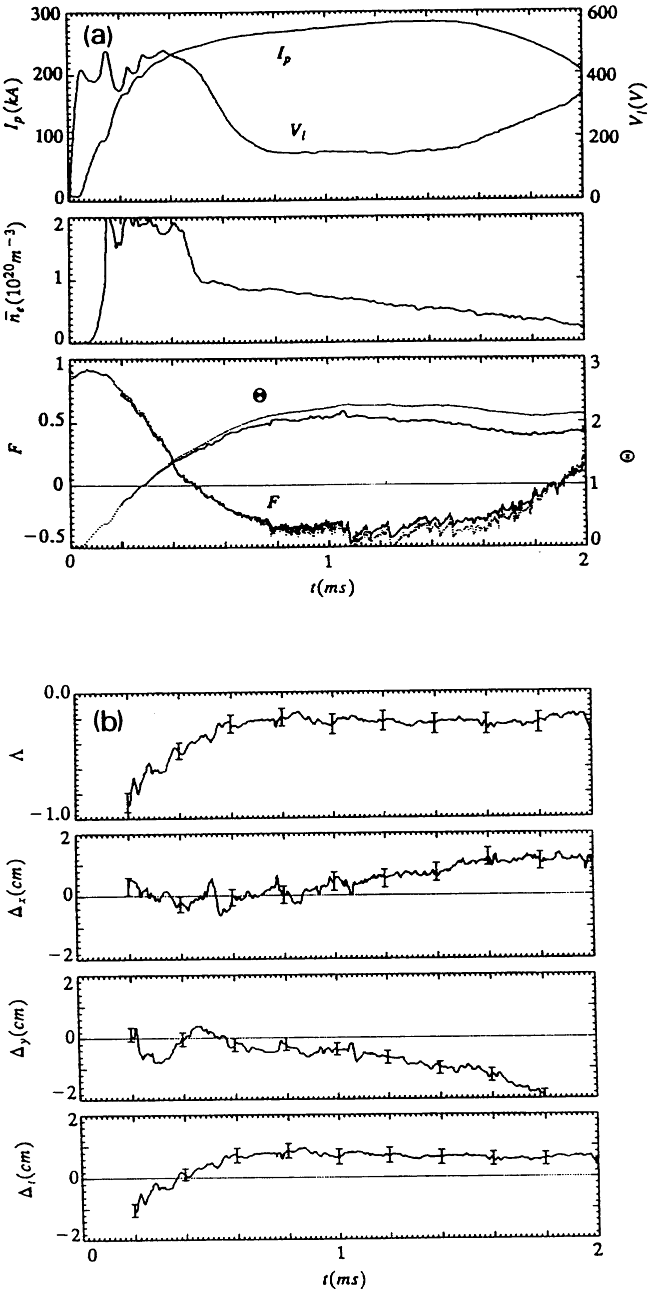

FIG. 4.—Waveforms of I_p, V_l, $\bar{n}_e$, F and Θ (a); Λ, Δ_x, Δ_y and Δ_t (b) in a typical discharge of REPUTE-1 RFP.

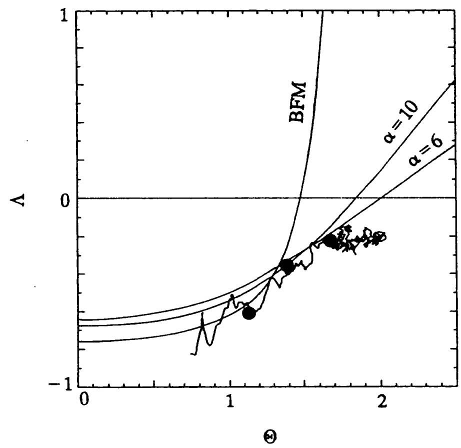

FIG. 5.—Λ–Θ diagram. Here BFM means Bessel Function Model and α is defined by $\mu \equiv \mu_0 \mathbf{j} \cdot \mathbf{B}/B^2 \propto 1-(r/a)^\alpha$. The closed circles indicate the results obtained by the internal probe experiments (UEDA, 1985).

4. CONCLUSIONS

We have introduced a simple method of measuring the plasma equilibrium quantities, in the transient phase of RFP and Tokamak discharge. It is not necessary to consider the effect of the iron core especially. We have tested the method, in the simplest case that only the first order of r/R of the first Fourier component of θ is involved in the model, and applied it to the REPUTE-1 RFP plasma with thin shell. The stable position determination requires only a small number (≥ 6) of field measurements. The plasma position is computed between shots in the case of REPUTE-1 experiments as a real-time routine. It should be noted that in addition to the plasma position, information about Λ or $\beta_p + l_i/2$ can be obtained by this method. The parameters Λ, Δ_x and Δ_y can be determined with accuracies of ± 0.07, ± 0.3 cm and ± 0.2 cm, respectively. Of course, higher Fourier components of θ and higher orders r/R can be involved by increasing the number of field measurement and the fitting parameter, if necessary.

Measurements on the REPUTE-1 RFP plasma surrounded by a thin shell show that the plasma starts to move outward and downward before I_p begins to fall in most shots. Downward movement can be explained as a result of a negative N during the penetration of the vertical fields inside the shell. This suggests that a faster and more precise feedback control in the vertical field coils system is necessary.

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REFERENCES

ALLADIO F. and CRISANTI F. (1986) *Nucl. Fusion* **26**, 1143.

ALPER B. *et al.* (1989) *Plasma Phys. Contr. Fusion* **31**, 213.

ASAKURA N. *et al.* (1986) *Proc. 11th International Conf. on Plasma Physics and Controlled Nuclear Fusion Research*, Vol. 2, p. 433. IAEA, Vienna.

ASAKURA N. *et al.* (1989) *Nucl. Fusion* **29**, 893.

BRAAMS B. J. *et al.* (1986) *Nucl. Fusion* **26**, 699.

CHE H. Y. *et al.* (1988) *Rev. Scient. Instrum.* **59**, 1057.

DESHKO G. N. *et al.* (1983) *Nucl. Fusion* **23**, 1309.
GOFORTH R. R. *et al.* (1986) *Nucl. Fusion* **26**, 515.
HATTORI K. *et al.* (1988) *Nucl. Fusion* **28**, 311.
HOFMANN F. and TONETTI G. (1988) *Nucl. Fusion* **28**, 519.
KUZNETSOV YU. K. *et al.* (1986) *Nucl. Fusion* **26**, 369.
LAO L. L. *et al.* (1985) *Nucl. Fusion* **25**, 1611.
LAZZARO E. and MANTICA P. (1988) *Plasma Phys. Contr. Fusion* **30**, 1735.
LEE D. K. and PENG Y.-K. M. (1981) *J. Plasma Phys.* **25**, 161.
LUXON J. L. and BROWN B. B. (1982) *Nucl. Fusion* **22**, 813.
MUKHOVATOV V. S. and SHAFRANOV V. D. (1971) *Nucl. Fusion* **11**, 605.
REPUTE-1 ANNUAL REPORT 1984 (1985) University of Tokyo, p. 33.
SHAFRANOV V. D. (1960) *Sov. Phys. JETP* **37**, 775.
SHINOHARA S. *et al.* (1989) *Proc. 16th European Conf. on Controlled Fusion and Plasma Physics*, Pt. 2, 741.
SWAIN D. W. and NEILSON G. H. (1982) *Nucl. Fusion* **22**, 1015.
TOYAMA H. *et al.* (1987) *Proc. 14th European Conf. on Controlled Fusion and Plasma Physics*, Pt. 2, 544.
TOYAMA H. *et al.* (1989) *Proc. 16th European Conf. on Controlled Fusion and Plasma Physics*, Pt. 2, 737.
UEDA, Y. (1985) Doctoral Thesis, University of Tokyo.
WOOTTON A. J. (1979) *Nucl. Fusion* **19**, 987.
ZAKHAROV L. E. and SHAFRANOV V. D. (1973) *Sov. Phys. Tech. Phys.* **18**, 151.