Ciemat 728
Sp ISSN 614-087-X

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CENTRO DE INVESTIGACIONES
ENERGETICAS, MEDIOAMBIENTALES Y TECNOLOGICAS

MADRID, 1994

CLASIFICACION DOE Y DESCRIPTORES

700320
TOKAMAK DIVECES
PLASMA DIAGNOSTICS
MAGNET COILS
PLASMA RADIAL PROFILES
MAGNETIC FIELD CONFIGURATIONS

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Los descriptores se han seleccionado del Thesauro del DOE para describir las materias que contiene este informe con vistas a su recuperación. La catalogación se ha hecho utilizando el documento DOE/TIC-4602 (Rev. 1) Descriptive Cataloguing On-Line, y la clasificación de acuerdo con el documento DOE/TIC.4584-R7 Subject Categories and Scope publicados por el Office of Scientific and Technical Information del Departamento de Energía de los Estados Unidos.

Este trabajo se ha recibido para su impresión en Marzo de 1993.

Depósito Legal nº M-19027-1993
ISBN 84-7834-201-X
ISSN 614-087-X
NIPO 238-94-025-7

IMPRIME CIEMAT

Measurements of Plasma Position in TJ-I Tokamak

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Abstract: This report presents the experimental measurements of plasma position in TJ-I tokamak by using small magnetic probes. The basis of method has been described in our previous work[1] in which the plasma current is considered as a filament current. The observed relations between the disruptive instabilities and plasma displacements are also shown here.

1. Introduction

Determination of plasma position in tokamaks are based on measuring the external magnetic field produced by the plasma current. The measurements can be performed with magnetic probes at several points (Mirnov method)[2], or along a closed contour (the multipole-moment method)[3,4] around the plasma column. In TJ-I, however, there are some restrictions on installing the magnetic probes in device: it is only possible to locate some small magnetic coils behind the limiters which are two straight bars installed near the top and bottom walls of vacuum vessel (see Fig.1). This means that we cannot measure the magnetic field along a closed contour, neither at those points in the equatorial plane of device, to derive the horizontal plasma displacement, as these have always been done in other devices.

In the previous work[1] we have shown that, even with these restrictions in TJ-I, we can still estimate the plasma position by using the small magnetic probes located off the equatorial plane, with the aid of a filament model. Here, we present the experimental measurements of plasma position in TJ-I. In Section 2 are described the diagnostic system, experimental arrangement and the basis of method. The measurements of plasma position, the comparison with other related diagnostics as well as the tests of controlling plasma position are given in Section 3. In Section 4, we show the observed relations between the plasma displacements and the disruptive instabilities, and the conclusions follow in Section 5.

2. Diagnostic

Two sets of magnetic coils were installed inside the vacuum vessel of TJ-I device, at a toroidal port about 90° away from that port of the limiters. Each set consists of 8 small magnetic coils separated by an equal distance of 2cm. The coils were wound densely in double-layer with total 140 turns for each, the diameter and length of coil is about 2.5mm and 10mm, respectively. Before being installed, these coils were calibrated by means of a standard magnetic field, the relative errors between their outputs are less than 5%.

To measure the horizontal and vertical plasma displacements simultaneously, at least four coils are needed. Their positions on the cross-section, indicated by the numbers 1-4 in Fig.1, are determined by two distance parameters A and D. The value of A can be 2cm, 4cm or 6cm, and D should be larger than b_L for safety, where b_L is limiter radius. The coils are oriented horizontally and supposed to pick up only the horizontal components of magnetic fields. Note that only that magnetic field produced by the plasma current is used, which is obtained by subtracting the field produced by the external field windings alone from the total magnetic field. The effect of coupling between the plasma current and the external field windings are considered to be negligible.

Here we outline the basis of method, the more details can be found in Ref.1. One can obtain the following two quantities from B_i (i=1,2,3,4), the magnetic-field signals of those four coils shown in Fig.1:

$$D_y = D \frac{B_2 - B_4}{B_2 + B_4}$$

$$D_x = \frac{D^2}{2A} \frac{B_3 - B_1}{B_3 + B_1} \qquad (1)$$

these two quantities D_y and D_x are the cylindrical approximations (i.e., $R_0 \rightarrow \infty$) to the horizontal and vertical plasma displacements $\Delta_\perp$ and $\Delta_\parallel$, respectively. The plasma displacements $\Delta_\perp$ and $\Delta_\parallel$ are then estimated by the expansions in D_y and D_x as follows:

$$\Delta_{\perp} \approx \alpha_0 + \alpha_1 D_y + \alpha_2 D_y^2 + \alpha_3 D_y^3 ,$$
$$\Delta_{\parallel} \approx \beta_0 + \beta_1 D_x + \beta_2 D_x^2 + \beta_3 D_x^3 , \quad (2)$$

where the coefficients $\alpha_i(\Delta_{\parallel})$ and $\beta_i(\Delta_{\perp})$ are given by the filament model (the models involving some certain forms of plasma current density profile can also be used to determine the coefficients α_i and β_i). For example, given those magnetic coils with A=2cm and D=11cm, the coefficients β_i (i=0,1,2,3) obtained are shown in Table-I, as the vertical displacement $\Delta_{\perp}$ changes between ±3cm. While for D=10-12cm, only the coefficient α_1 is dorminant which reachs order unity, others are ignorable small (α_0, $\alpha_2 \sim 10^{-6}$, $\alpha_3 \sim 10^{-3}$). The coefficient α_1 is also very weakly dependent on the horizontal displacement $\Delta_{\parallel}$, one can replace it in the first formula of Eq.(2) approximately by a constant equal to that value of α_1 obtained as $\Delta_{\parallel}$=2cm. In practice, for D=11cm coils we take $\alpha_1=0.92(\alpha_0, \alpha_2, \alpha_3=0)$, the value obtained as $\Delta_{\parallel}$=2cm, in estimating the vertical plasma displacement $\Delta_{\perp}$. In this case the error bar is less than 8%, provided the horizontal plasma displacement $\Delta_{\parallel}$ varies within ±3cm.

Therefore, the measured plasma position presented in this paper is interpreted as the position of toroidal filament current, unless where it is specified.

Table-I: Coefficients beta in Eq.(2)

$\Delta_{\perp}$(cm)	-3.0	-2.5	-2.0	-1.5	-1.0	-0.5	0	0.5	1.0	1.5	2.0	2.5	3.0
β_0	1.06	1.01	0.96	0.91	0.86	0.81	0.76	0.71	0.65	0.60	0.55	0.50	0.45
β_1	1.49	1.39	1.30	1.21	1.11	1.03	0.95	0.87	0.79	0.72	0.64	0.57	0.51
$\beta_2(\times 10^{-2})$	4.3	3.9	3.6	3.2	2.9	2.6	2.3	2.1	1.8	1.6	1.4	1.2	1.1
$\beta_3(\times 10^{-2})$	1.8	1.6	1.5	1.3	1.2	1.1	0.94	0.83	0.73	0.64	0.56	0.49	0.42

3. Experimental results

TJ-I is a rectangular tokamak with the main parameters being: R=30cm, b/a=12.5/9.5cm, limiter radius b_L=10-12cm, toroidal magnetic field B_T=(1.0-1.4)T and plasma current I_P=(30-40)kA. The equilibrium position of plasma column is mainly determined by the pre-programmed vertical field and the horizontal field which is under dc operation to compensate the stray horizontal fields.

Figure 2 shows an example of shots and the plasma position measured: the temporal evolution of the applied vertical field $B_{\perp}$, the plasma current I_P, and the measured horizontal and vertical plasma displacements, $\Delta_{\parallel}$ and $\Delta_{\perp}$, respectively. It is seen that, during the plateau of plasma current, the plasma stays around the centre of vacuum vessel, with small movements in both horizontal and vertical directions. But near the end of discharge, the plasma column has the larger displacements from the centre, especially in the horizontal direction, the plasma starts to move inward since the time 4-5ms before the end of discharge, and is finally pushed onto the inside wall. The reason is that the vertical field applied exceeds the required value near the end of discharge, its decrease is slower as the plasma current decreases. Due to the dc operation of external horizontal field, the plasma has also an up movement as the plasma current decreases. The minor radius of plasma column during the temporal evolution is determined by: $a_P = \min\{a - |\Delta_{\parallel}|, b_L - |\Delta_{\perp}|\}$.

To check the method of plasma position measurement, the comparative experiments are performed with the multichannel diagnostics of H_α observations[5] and Bolometry[6] being run on TJ-I. Under the steady state conditions, the relative movement of plasma column can be figured out from those signals of different channels of these diagnostics, by means of interactions between the plasma and the wall/limiters. For example, the inner and outer H_α detectors observe the plasma column vertically near the inside and outside walls, their signals depend partly on the horizontal plasma displacement $\Delta_{\parallel}$, while the top and bottom bolometers view the plasma column horizontally at the top and bottom limiters, the signals of them are related to the vertical plasma displacement $\Delta_{\perp}$.

Comparison between two H_α signals and the horizontal plasma displacement $\Delta_{\parallel}$ measured is shown in Fig.3. In this shot it is seen, as the plasma column goes outward during the early phase of discharge, H_α^{out} signal increases and H_α^{in} signal decreases. When the measured $\Delta_{\parallel}$ signal has indicated that the plasma column starts moving inward since ~11ms, an increase in H_{α}^{in} signal and a decrease in H_{α}^{out} signal have been observed simultaneously.

The vertical plasma displacements $\Delta_{\perp}$ measured are also concordant with the signals from the top and bottom bolometers. For the shot shown in Fig.3, for example, the bottom bolometer receives only the background radiation during the discharge, but the top bolometer receives an increasing radiation since ~14ms of discharge. The measured $\Delta_{\perp}$ signal in this shot has indicated that the plasma column is displaced upward all the time, and goes more upward from ~14ms of discharge.

The equilibrium plasma position is determined by the external vertical and horizontal fields. By changing the external vertical and horizontal fields, the control of plasma position in TJ-I can be tested. Figure 4a-4c show the case for controlling the vertical plasma displacement $\Delta_{\perp}$ by changing the current in horizontal-field coil alone. In the series of shots, the current in horizontal-field coil is: I_h=16A, 18A and 12.5A, respectively. It is seen that as the current in horizontal-field coil is I_h=16A, it moves the plasma column downward with $|\Delta_{\perp}|<0.5$cm. As this current is increased up to I_h=18A, the plasma has been displaced further downward and $|\Delta_{\perp}|$ is around 1cm. When the current in horizontal-field coil is adjusted to a suitable value I_h=12.5A, the plasma has been centred vertically with a minimal vertical displacement $|\Delta_{\perp}|\approx 0$. Note that the example shown in Fig.4 does not mean that the current value I_h=12.5A will be suitable for all discharges in TJ-I, this current value will change as the parameters of other external fields are changed.

The equilibrium position of plasma is very sensitive to the applied vertical magnetic field in the horizontal direction. Given a vertical field $B_{\perp}$, it will displace the plasma column inward by Δ_B :

$$\Delta_B = \frac{2\pi\rho^2}{\mu_0}\frac{B_{\perp}}{I_P} \propto \frac{B_{\perp}}{I_P} \qquad (3)$$

where I_P is the plasma current, ρ is the minor radius of flux surface and $\rho = a_P$ is the plasma column surface. In experiments, the scaling relation between the changes in vertical field and in plasma major radius R is more useful, which is given as follows[7]:

$$\frac{\delta B_\perp}{B_\perp} = c\frac{\delta R}{R},$$

$$c = (n-2) + \frac{(1 \pm \varepsilon^{-1})}{(1-\gamma/4\gamma')}\left(\frac{1}{\gamma} - \frac{1}{\gamma'}\right) \tag{4}$$

where the quantities in the second formula are:

$$n \equiv -\frac{R}{B_\perp}\frac{\partial B_\perp}{\partial R},$$

$$\varepsilon = \frac{a_P}{R},$$

$$\gamma = (\ln(\frac{8R}{a_P}) + \Lambda - \frac{1}{2}), \quad \Lambda = \beta_\theta + \frac{\ell_i}{2} - 1,$$

$$\gamma' = (\ln(\frac{8R}{a_P}) + \ell_i - 2) \tag{5}$$

and β_θ is the poloidal beta, ℓ_i is the plasma internal inductance per unit length. The signs '±' in the second expression of Eq.(4) come from the assumption that changing the vertical field is only to move the plasma column back to the centre, i.e., $\delta a_P = |\delta R|$. In Fig.5 are plotted those relations of Eq.(4) for β_θ=0.1, 0.3, 0.5 and n=0.5, 1.0 and 1.3, where ℓ_i=0.917 has been used. Here, it is seen that if the plasma has been found to be displaced inward ~1cm, for the given n=0.5 and β_θ=0.1, the plasma can be then moved back to the centre by decreasing the vertical field $B_\perp$ about 5%.

In the shot shown in Fig.6a, the plasma has been found to be moved inward ~1cm during the plateau of plasma current, causing an earlier end of discharge. We then decreased the applied vertical field $B_\perp$ about 5% in the following shots, and found that the equilibrium position of plasma had been moved outward from the previous inside position, the discharge went to longer as well, as shown in Fig.6b. Certainly, here is only a rough test for controlling plasma position in TJ-I. The experiment has shown that for more precise control of plasma position, it should need optimizing the programmed vertical field or applying a feedback control system.

4. Disruptive instabilities

Disruptive instabilities in TJ-I are observed to be two kinds. Both are closely related to the horizontal plasma displacements. The features of the instabilities are: the decrease of plasma current, negative spikes in loop voltage and increase of MHD activities. Figure 7a shows one kind of disruptive instabilities, which may be called the small disruptions. It is seen that the instabilities are triggered by an outward displacement of plasma at 5ms, due to the interaction between the plasma and the wall. Then the instabilities cause a decrease in plasma current, but the plasma current can recover later as the plasma moves back to the centre. Another kind of disruptive instabilities is caused by a larger inward displacement of plasma, as shown in Fig.7b. The instabilities are very strong and cause a sharp decrease of plasma current, so that the discharge has been terminated very soon. This kind of disruptive instabilities is called the large disruptions.

The certain relations between the disruptive instabilities and the horizontal plasma displacements may be explained as follows. The contribution of vertical magnetic field $B_\perp$ to the equilibrium position of plasma is proportional to $B_\perp/I_P$, moving the plasma column always inward, and the disruptions will cause a decrease in plasma current. This means there is always an increasing inward force acted on the plasma, when the instabilities occur. In the case of small disruptions, this increasing inward force will make the plasma departure from the outside wall, thus the conditions are improved through reducing the interaction between the plasma and wall, and the plasma current can increase again then. However, when the large disruptions occur, the plasma has already had a large inward displacement, but the increasing inward force will still push the plasma further inward onto the inside wall, resulting in the end of discharge finally.

5. Conclusions

Measurements of plasma position in a rectangular tokamak TJ-I are performed by using small magnetic probes located off the equatorial plane of device, based on the method proposed in Ref.1. The plasma displacements obtained during shots are confirmed by other related diagnostics. With the measured plasma displacements, we have tested the control of plasma position, the experiments have shown that for a precise control, the optimization of programmed vertical field or a feedback control system should be needed. It is also found that the small and large disruptions, two kinds of disruptive instabilities observed in TJ-I, are closely related to a large outward and inward plasma displacements, respectively.

Although the measurements of plasma position are interpreted by a filament model in this paper, it would be easy to include the effect of plasma current density profile on the results, through the coefficients α_i and β_i in Eq.(2). For example, for a quadratic form of plasma current density profile, as discussed in Ref.1, the modification is only a few millimetres in the horizontal plasma displacements.

6. References

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7. Figure captions

Fig.1 Schematic diagram of experimental arrangements.

Fig.2 Example of a shot: the applied vertical field $B_\perp$(200G/div) the plasma current I_P(20kA/div), and the measured horizontal and vertical plasma displacements, $\Delta_\parallel$ and $\Delta_\perp$ (2cm/div).

Fig.3 Comparison of the horizontal plasma displacement measured with two channels of H_α signals during a shot.

Fig.4 Tests of controlling the vertical plasma displacement by changing the current in horizontal-field coil: (a) I_h=16A, (b) I_h=18A and (c) I_h=12.5A.

Fig.5 Relations between $\delta B_\perp/B_\perp$ and horizontal plasma displacements for β_θ=0.1, 0.3, 0.5 and n=0.5, 1.0 and 1.3, where ℓ_i=0.917 has been used: (a) outward and (b) inward displacements.

Fig.6 Tests of controlling the horizontal plasma displacement: decreasing the vertical magnetic field $B_\perp$ about 5% in (b) from that level in (a).

Fig.7 Relations between the disruptive instabilities and horizontal plasma displacements in the cases of (a) small disruptions and (b) large disruptions.

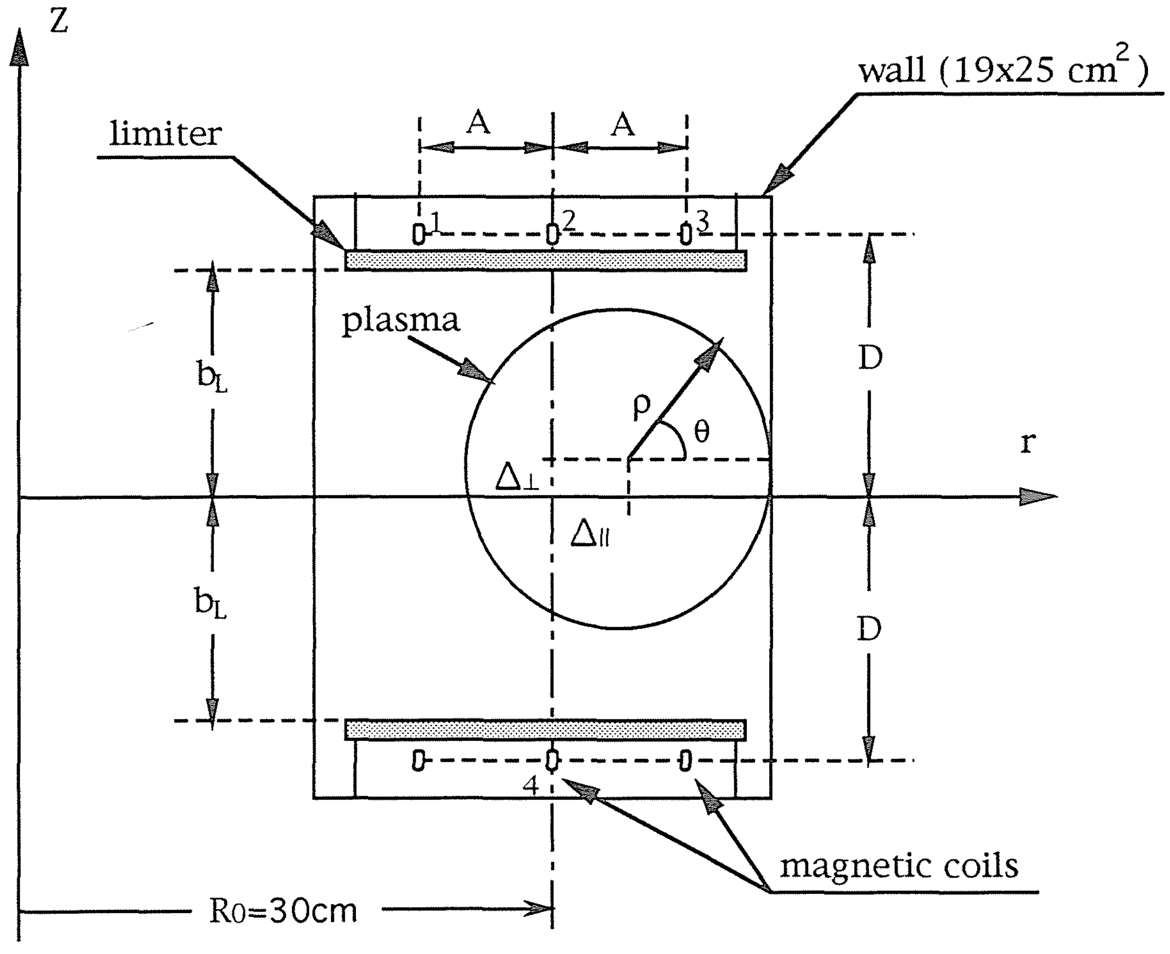

Z
wall (19x25 cm^2)
limiter
A
A
1
2
3
plasma
b_L
D
ρ
θ
r
$\Delta_\perp$
$\Delta_\parallel$
b_L
D
4
magnetic coils
R0=30cm

Fig.1

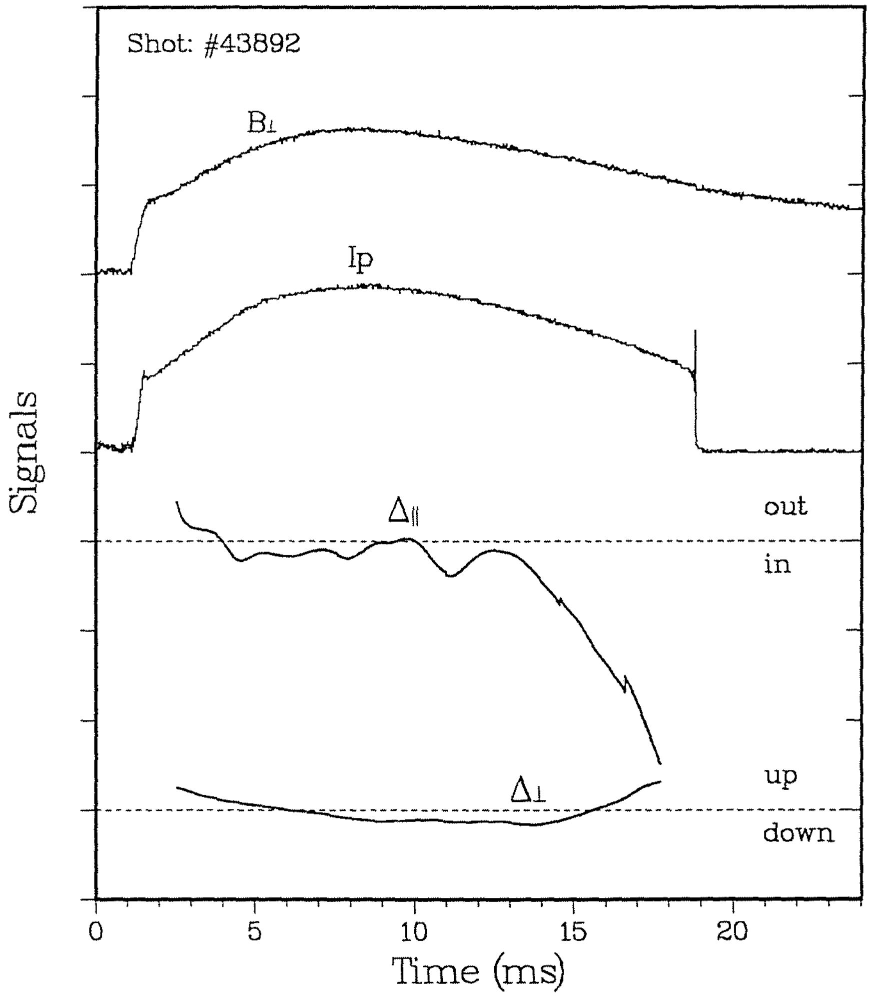


Fig.2

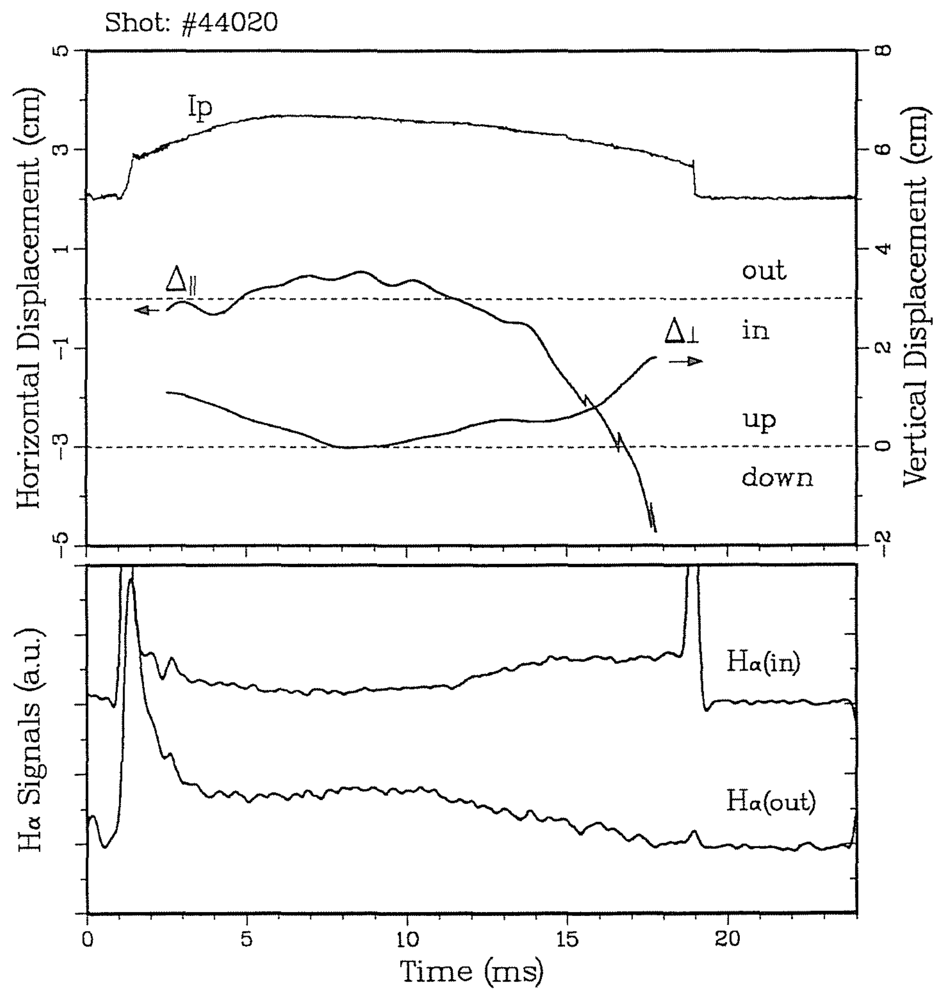

Shot: #44020
Ip
Δ∥
Δ⊥
out
in
up
down
Horizontal Displacement (cm)
Vertical Displacement (cm)
Hα(in)
Hα(out)
Hα Signals (a.u.)
Time (ms)

Fig.3

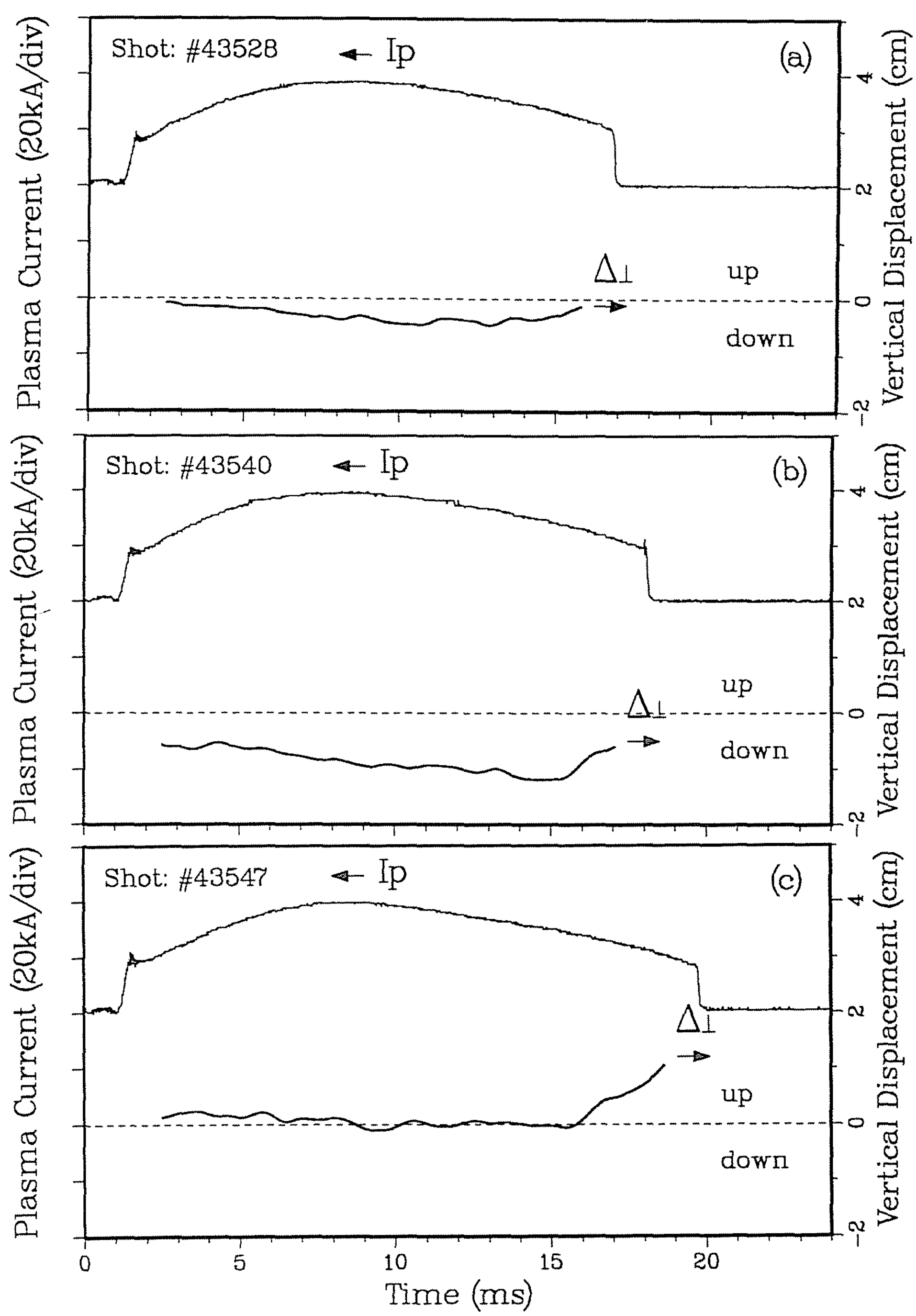

Shot: #43528
Ip
(a)
Δ⊥
up
down
Shot: #43540
Ip
(b)
Δ⊥
up
down
Shot: #43547
Ip
(c)
Δ⊥
up
down
Plasma Current (20kA/div)
Vertical Displacement (cm)
Time (ms)
0
5
10
15
20
-2
0
2
4

Fig.4

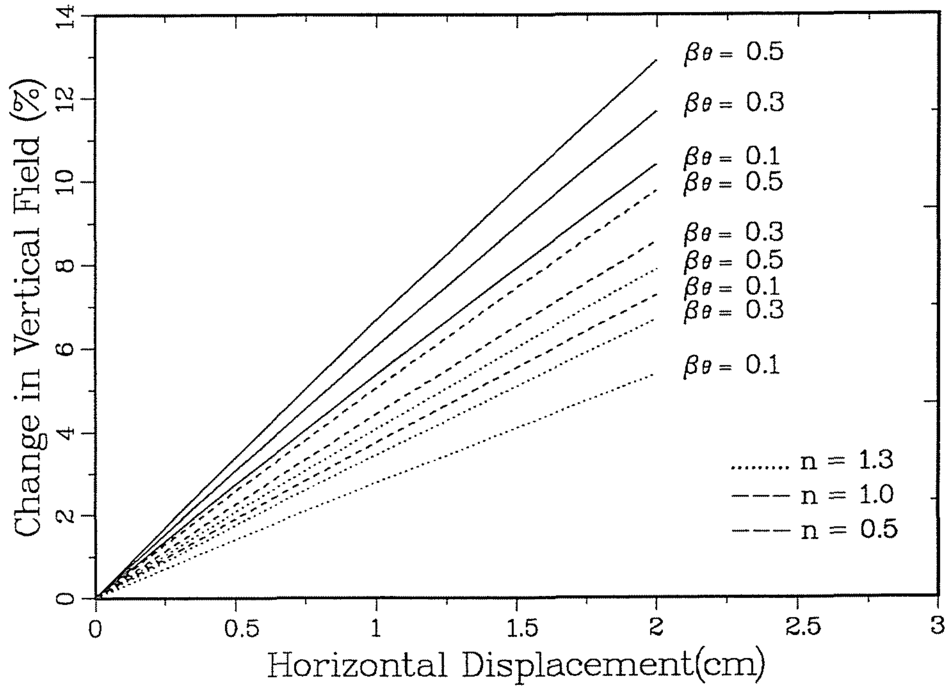

Change in Vertical Field (%)
0
2
4
6
8
10
12
14
0
0.5
1
1.5
2
2.5
3
Horizontal Displacement(cm)
βθ = 0.5
βθ = 0.3
βθ = 0.1
βθ = 0.5
βθ = 0.3
βθ = 0.5
βθ = 0.1
βθ = 0.3
βθ = 0.1
n = 1.3
n = 1.0
n = 0.5

Fig.5a

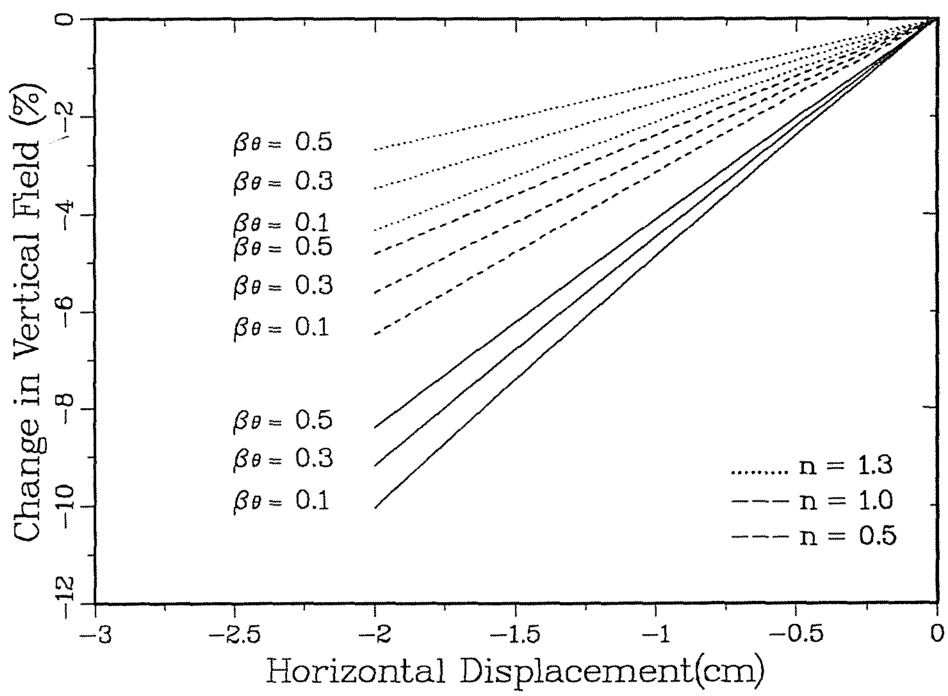
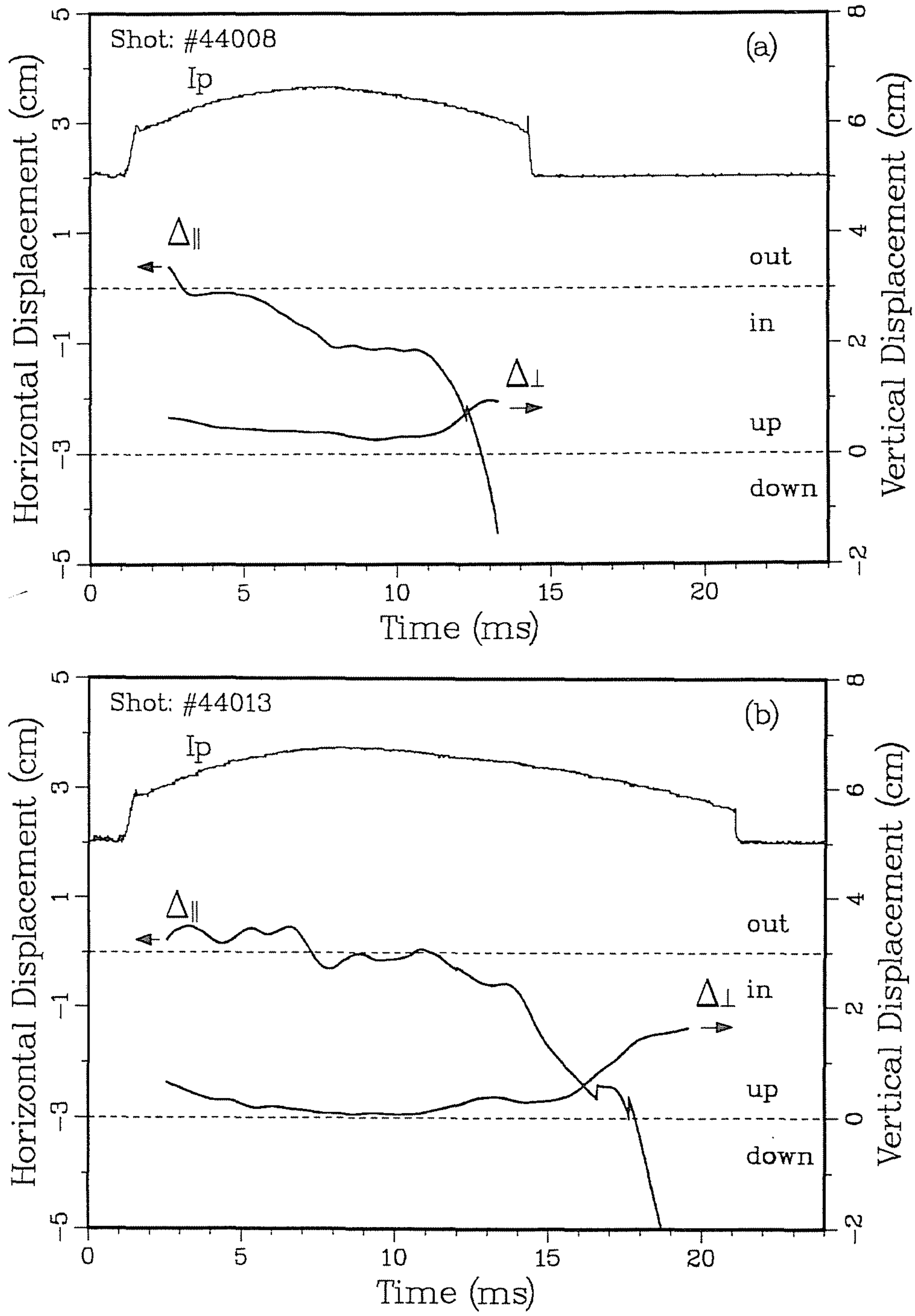

Change in Vertical Field (%)
0
−2
−4
−6
−8
−10
−12
$\beta\theta$ = 0.5
$\beta\theta$ = 0.3
$\beta\theta$ = 0.1
$\beta\theta$ = 0.5
$\beta\theta$ = 0.3
$\beta\theta$ = 0.1
$\beta\theta$ = 0.5
$\beta\theta$ = 0.3
$\beta\theta$ = 0.1
.... n = 1.3
−−− n = 1.0
−−− n = 0.5
−3
−2.5
−2
−1.5
−1
−0.5
0
Horizontal Displacement(cm)

Fig.5b



Shot: #44008
(a)
Ip
Δ∥
Δ⊥
out
in
up
down
Horizontal Displacement (cm)
Vertical Displacement (cm)
Time (ms)
Shot: #44013
(b)
Ip
Δ∥
Δ⊥
out
in
up
down
Horizontal Displacement (cm)
Vertical Displacement (cm)
Time (ms)

Fig.6

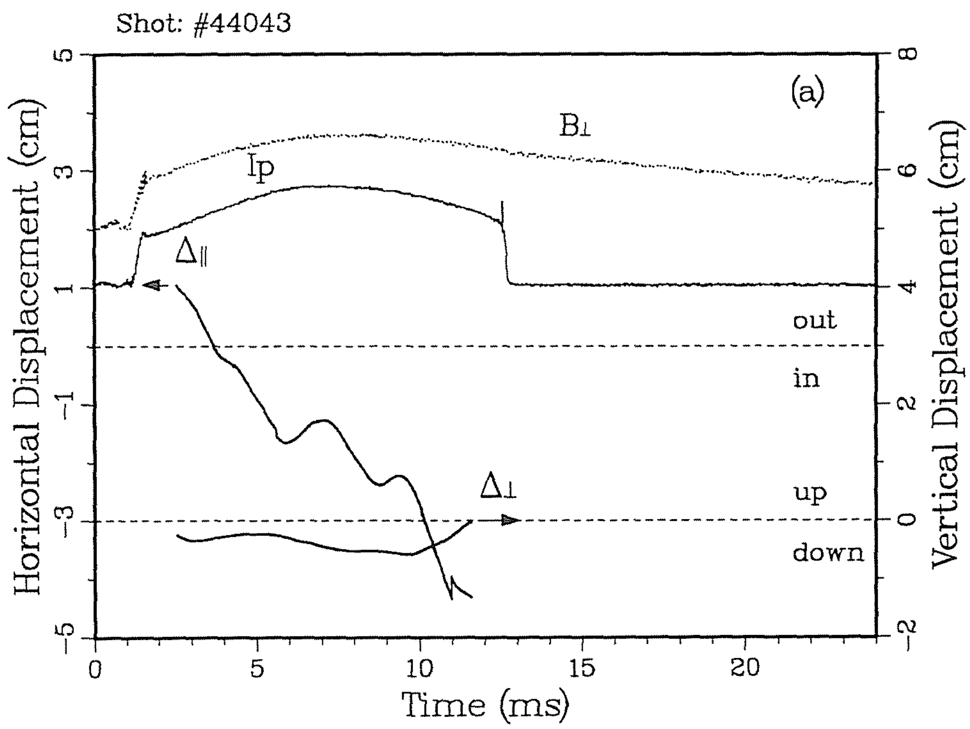

Shot: #44043
(a)
B⊥
Ip
Δ∥
Δ⊥
out
in
up
down
Horizontal Displacement (cm)
Vertical Displacement (cm)
Time (ms)
5
3
1
−1
−3
−5
8
6
4
2
0
−2
0
5
10
15
20

Fig.7a

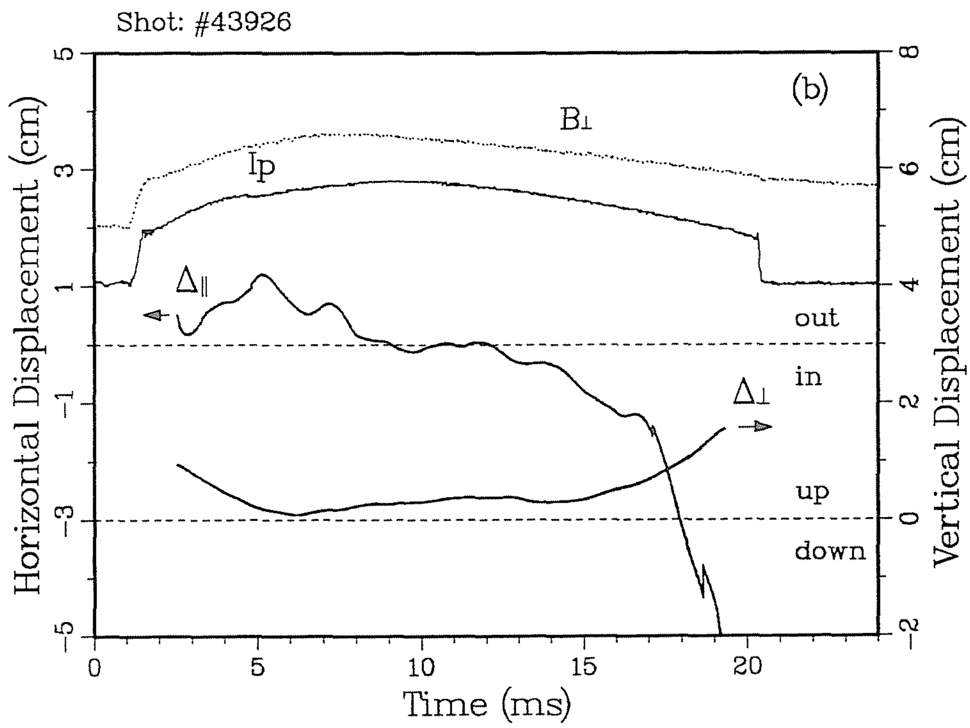

Shot: #43926
(b)
B⊥
Ip
Δ∥
Δ⊥
out
in
up
down
Horizontal Displacement (cm)
Vertical Displacement (cm)
Time (ms)
5
3
1
−1
−3
−5
8
6
4
2
0
−2
0
5
10
15
20

Fig.7b

CIEMAT-728

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"Medidas de la posición del plasma en el Tokamak TJ-I."

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Este informe presenta las medidas experimentales de la posición del plasma en TJ-I mediante el uso de bobinas magnéticas. La base de este método ha sido descrita en un trabajo previo (1), considerando la corriente del plasma como corriente filamental. Asímismo se analizan las relaciones entre las inestabilidades disruptivas y los desplazamientos de plasma.

CLASIFICACION DOE Y DESCRIPTORES: 700320. Tokamak Devices. Plasma Diagnostics. Magnet Coils. Plasma Radial Profiles. Magnetic Field Configurations.

CIEMAT-728

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