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DISPLACEMENT OF THE CURRENT DISTRIBUTION IN A HIGH CURRENT TOROIDAL DISCHARGE

D. C. ROBINSON

Culham Laboratory
Abingdon Berkshire

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DISPLACEMENT OF THE CURRENT DISTRIBUTION IN A HIGH CURRENT TOROIDAL DISCHARGE

by

D.C. ROBINSON

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ABSTRACT

The toroidal movement of the current carrying plasma column in the ZETA device has been studied and experimental results are compared with theoretical predictions. The paper describes the experimental method and shows that observations are in good agreement with calculated displacements.

U.K.A.E.A. Research Group,
Culham Laboratory,
Abingdon,
Berks.

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1. INTRODUCTION

The toroidal displacement of a diffuse pinch has been studied in the ZETA device. The results have been compared with the theory of Shafranov (1963) using field configurations, generated by a model, which are close to those observed experimentally. It is of interest to note that in certain operating regimes of the TOKAMAK devices an anomalous displacement is observed (ARTSIMOVICH et al. 1968); in addition, a small vertical displacement has been observed in ZETA using a multi-coil probe inserted into the discharge (ROBINSON and KING, 1968). Therefore it is important to compare the theory with experiment not only below the Kruskal-Shafranov limit but also above. The method of measurement is essentially the same as that described by Mirnov (1964).

2. METHOD

Four small magnetic field coils, aligned to measure the azimuthal component of the magnetic field $-B_{\theta}$, were placed symmetrically in a cross section of the toroid as shown in Fig.1. An additional coil was also aligned to measure B_{φ}. The coils were mounted inside the liner and covered by a plasma shield. After integration a difference amplifier was used to measure $B_{\theta_2} - B_{\theta_1} = u$, $(B_{\theta_2} + B_{\theta_1})/2 = v$ and the variation of u/v as a function of the pinch configuration parameter θ was obtained. $\theta = 2I/dB_0$ - where I is the gas current, B_0 is the initial longitudinal field, and d the radius of the minor cross section.

The model used to generate the appropriate field configurations was obtained by writing $j_{\parallel} = \sigma_{\parallel} E_{\parallel}$, and $j_{\perp} = \sigma_{\perp} E_{\perp}$ and

$\underline{E} = (0, E_\theta(r), E_\varphi)$ where $\parallel$ and $\perp$ denote parallel and perpendicular to the mean field direction at a point. E_θ and $\sigma_\perp/\sigma_\parallel$ are chosen to give varying degrees of reversal of the longitudinal magnetic field $-B_\varphi$ at the edge of the plasma, and $\beta = \frac{8\pi p(0)}{B^2(0)}$. In particular the force free paramagnetic model (WHITEMAN, 1965) is obtained if $E_\theta = 0$ and $\sigma_\perp/\sigma_\parallel = 0$.

3. RESULTS

Measurements were made at a pressure of 2 mtorr D_2 and a gas current of 360 kA which includes discharges of the type discussed by ROBINSON and KING (1968). For θ values greater than 1·2 the observed field configurations show that the longitudinal field (and current) are reversed near the wall, as is indicated by the output from the inner B_φ coil shown in Fig.2. Indeed it can be shown from pressure balance above that for any B_φ distribution $\theta \approx 1{\cdot}2$ at the point of field reversal (provided β is not large). (A Schwartz inequality for this type of distribution gives $\theta \geqslant 1$, but for negative B'_φ and B''_φ $\theta < 1{\cdot}22$, and the effect of β is to increase this value by 5% for a central β of 10%). It is this type of configuration which has been found theoretically and experimentally to have favourable stability properties (ROBINSON and KING, 1968). The plasma is contained within a liner which is enclosed by an $A\ell$ body. Consequently we have corrected the above observed θ values for the amount of flux which has penetrated through the liner during the discharge, from the outer-space between the body and liner.

The first order toroidal correction to the azimuthal field is given by

$$B_\theta = B^0_\varphi(0)\left(b(r/a_1) + \frac{a_1}{R}\, b_1(r/a_1)\cos\theta\right) \qquad \dots (1)$$

where b is the cylindrical solution for B_θ normalised to B_φ at the centre, R is the major radius of the torus, and $a_1 = cB^0_\varphi(0)/4\pi\sigma_\parallel E_\varphi(0)$; the coordinate system is shown in Fig.1. b_1 is the first order toroidal correction to b and given by

$$b_1(x) = x\, b(x)\, \Lambda(x) + \Delta_1(x) \frac{db(x)}{dx}$$

$$\frac{d}{dx} \Delta_1(x) = x(\Lambda(x) + 1) = \int_0^x \frac{b^2(x')x'\, dx'}{x\, b^2(x)} + \frac{8\pi x[\frac{2}{x^2} \int_0^x p(x')x' dx - p(x)]}{b^2(x)} \qquad \ldots (2)$$

$$\Delta(r) = a_1^2\, \Delta_1\, (r/a_1)/R$$

where $p(x)$ is the cylindrical solution for the pressure variation. Allowing for a calibration factor $-\alpha$ between the two coils we find

$$u = B^0_\varphi(0) \left(b(r_2/a_1) - \alpha\, b(r_1/a_1) + \frac{a_1}{\sqrt{2R}} \left(b_1(r_2/a_1) + \alpha\, b_1(r_1/a_1) \right) \right) \qquad \ldots (3)$$

and for small displacements $-\Delta$,

$$b(r_2/a_1) = b(d/a_1) - \frac{\Delta}{\sqrt{2}a_1} \frac{d}{dx} b(x)$$

substituting into (3) and using (2) we obtain

$$\frac{u}{v} = \frac{2(1-\alpha)}{1+\alpha} + \sqrt{2}\, \frac{d}{R}\, \Lambda(d/a_1). \qquad \ldots (4)$$

Hence our measurements provide us with a direct measure of Λ, which is proportional to the sum of the inductance per unit length plus the average β of the plasma. For example, for small d/a_1 (or θ) and our model with $E_\theta = 0$,

$$\Lambda = \frac{\sigma_\perp}{\sigma_\parallel} - \tfrac{3}{4}\, .$$

The calibration factor α was determined by placing a current carrying conductor at the centre of the cross section including the coils and adjusted, by means of the integrating resistors, to make u/v positive ($\alpha = 0.72$).

Two theoretical curves from equation (4) are compared with the experimental results in Fig.3, where the coordinate d/a_1 has been converted into the θ-value for the configuration, by calculating the flux and total current. The upper curve shows the expected variation for the force-free paramagnetic model; however this fails to agree with the observations of Fig.2 as it possesses no longitudinal field reversal. The parameters of our model equations were chosen to fit the observations of Fig.2 - where the theoretical curve is shown. Equation (4) was then used to obtain the lower curve shown in Fig.3. Apart from a displacement in the absolute value of u/v which is probably due to the inaccuracy in our calibration (5%), the theoretical curve is in good agreement with the observations. No appreciable vertical displacement of the current column was observed, which suggests that the vertical displacement observed earlier (ROBINSON and KING, 1968) may be due to the insertion of the probe.

It is not necessary to use the model field configurations to derive the toroidal displacement as this can be evaluated from the results of Fig.2 and pressure balance; however this is a complicated procedure as θ is not linearly related to the radius. It should also be pointed out that ZETA is not a true toroid but a 'race track', and this may be a source of error.

For large values of θ where the toroidal displacement is also large, the observed agreement may be fortuitous as the toroidal effects are strong (aspect ratio 3) and the theory of Shafranov which uses an expansion in the aspect ratio, may be inapplicable.

4. CONCLUSION

We have considered the toroidal displacement of a current carrying plasma column in a situation where the displacement is strongly dependent on the detailed field configuration and the current is much greater than the Kruskal-Shafranov limit. The displacement has been studied in detail below this limit (ARTSIMOVICH et al., 1968; MIRNOV, 1964). We have used the measured radial variation of the longitudinal magnetic field to calculate the toroidal displacement according to the theory of SHAFRANOV (1963) and have shown that the resulting displacement is in good agreement with our observations.

5. ACKNOWLEDGEMENTS

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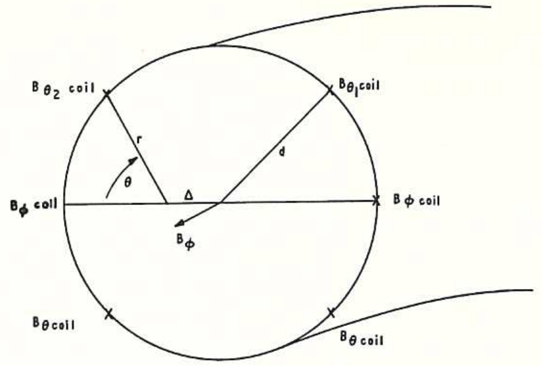

Fig. 1 Coil arrangement and co-ordinates (CLM - P 202)

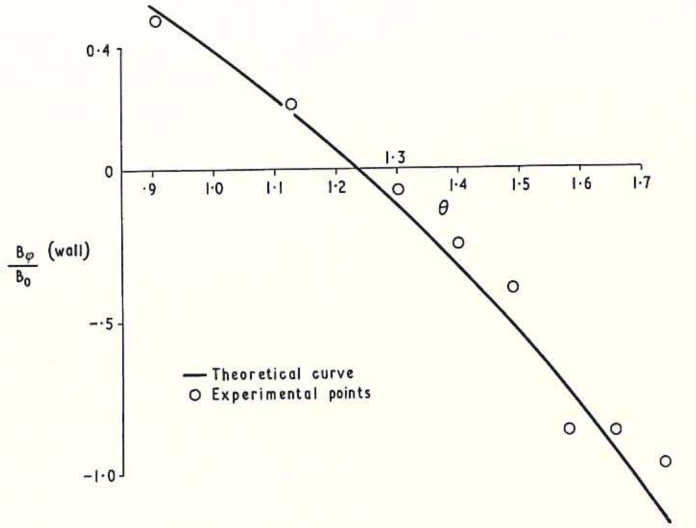

Fig. 2 (CLM - P 202)
Axial field at the wall as a function of θ (I = 360 kA , t = 1.9 msec)

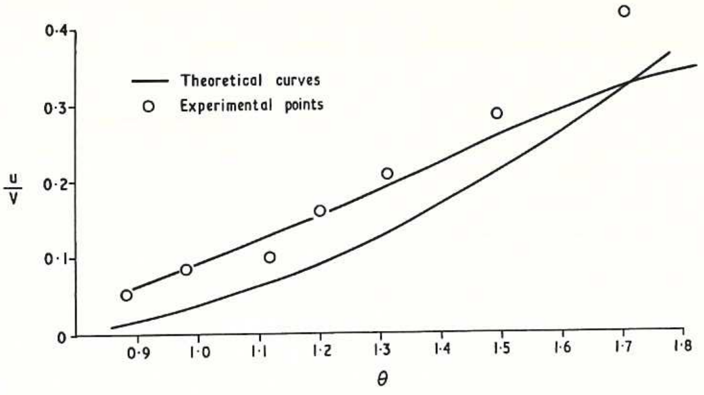

Fig. 3 (CLM - P 202)
Difference between azimuthal field signals at the wall as a function of θ. (I = 360 kA, t = 1.9 msec)
(For derivation of theoretical curves, see text)