PPPL-1979

UC20-A,F

PPPL-1979

Dr. 1215

①
I-8097

PPPL--1979

DE83 007248

198
2-28-83
②

DIAMAGNETIC FLUX MEASUREMENT USING THE PDX TF COILS

By

P. Thomas

FEBRUARY 1983

PLASMA
PHYSICS
LABORATORY

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

MASTER

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CHO-3073.

REPRODUCTION OF THIS DOCUMENT IS UNLIMITED

DIAMAGNETIC FLUX MEASUREMENT USING THE PDX TF COILS

P. Thomas*

Plasma Physics Laboratory

Princeton University

Princeton, N.J. 08544

U.S.A.

ABSTRACT

The diamagnetism of plasmas in PDX has been measured using the toroidal field coils as the equivalent of the conventional diamagnetic loop. The extremely low inductive coupling between the toroidal and poloidal coil systems makes the measurement feasible. The main difficulty arises from the change in the TF coil resistance due to Joule heating, compounded by the nonlinearity and sharp temperature dependence of the resistance of the joints in the TF coils. The measurement method, details of the experimental system, and illustrative results are presented.

*Present address: JET Joint Undertaking, Abingdon, U.K.

I. INTRODUCTION

The use of the diamagnetic flux to measure total pressure has been standard in many different devices used in controlled fusion research. In tokamaks, this measurement has achieved a certain notoriety for its difficulty and unreliability. This is to some degree intrinsic because tokamaks are low β devices so that stray couplings to the toroidal field system can cause large errors. This is especially true of machines with poloidal divertors such as PDX. The cross-sectional area of the vacuum vessel, around which diamagnetic flux loops must be run, is much greater than the plasma, thus increasing the relative strength of stray couplings. The measurement described here makes use of the care that was taken in the construction of PDX to ensure that the toroidal and poloidal field systems are not inductively coupled. It is a tribute to the skills of the engineers involved that the measurement was possible at all.

The diamagnetic flux may be obtained from the pressure balance equation

$$2 \mu_0 \langle p_{\perp} \rangle = B_{\theta}^2(a) - \langle B_{\phi 0}^2 - B_{\phi}^2 \rangle, \quad (1)$$

where $p_{\perp}$ is the perpendicular pressure, $B_{\phi 0}$, the toroidal field in the absence of the plasma, and B_{ϕ} the actual toroidal field. The total diamagnetic flux is given by rearrangement of Eq. (1) and is

$$\psi_d \approx \frac{(\mu_0 I_p)^2}{8\pi B_{\phi 0}} (1 - \beta_{p\perp}) \quad (2)$$

where I_p is the plasma current and $\beta_{p\perp}$ the perpendicular poloidal beta. Note that the equilibrium is determined by the average of perpendicular and parallel pressures so that perpendicular neutral beam injection should cause

the diamagnetic beta estimate to be larger than that obtained from the equilibrium. From Eq. (2) it may be seen that the determination of the poloidal beta value requires the measurement of plasma current, toroidal field current, plasma major radius, and the diamagnetic flux. The first three are reliable to the one percent level so that it is the latter on which the accuracy of the measurement hinges.

Conventional measurements make use of two loops coupled to the toroidal flux and decoupled from the poloidal flux. They are chosen to have the same mutual inductances to the toroidal field coils. However, the plasma threads one but not the other. The difference between the total fluxes coupling to them should give the diamagnetic flux. In practice, the poloidal field coupling is nonzero and different for the two coils. This difficulty is compounded on PDX because the vacuum vessel, to which the loops are mounted, vibrates during the plasma shot so that the coupling to the poloidal field is not constant. Although the coupling to the poloidal field windings can be measured, the coupling to the plasma current must be inferred from measurements with a reversed toroidal field (or reversed plasma current).

The method to be described overcomes some of the difficulties with the conventional approach by measuring the current in and the voltage across the toroidal field coils. Using the values of toroidal field set inductance and resistance, the difference between the flux supplied by the generators and that used by the TF set can be obtained. This difference flux is that supplied by external sources such as plasma diamagnetism and poloidal fields. In PDX, the latter is nearly negligible. The main difficulty in the measurement arises from the change in the TF set resistance due to Joule heating. This difficulty is worsened in PDX by the nonlinearity and sharp temperature dependence of the resistance of the joints in the TF coils.

The method used in the measurement, details of the experimental system, and the results will be described below in separate sections. Suggestions for future improvement in the analysis will be made in the last section.

II. PRINCIPLE OF MEASUREMENT

The equation for the flux threading the toroidal field set is

$$V_T = L \dot{I}_T + R(t) I_T + \sum_i M_i \dot{I}_i + N \dot{\phi}_d, \quad (3)$$

where V_T is the TF voltage, I_T the TF current, L the TF self inductance, $R(t)$ the TF resistance, M_i the mutual inductance between the TF set and current I_i , N the number of TF turns, and ϕ_d the required flux as given by Eq. (2). The TF resistance depends on time and the current because of Joule heating and is given by

$$\frac{dR(t)}{dt} = R(t) \left(\frac{\theta}{C} I_T^2(t) R(t) - \frac{1}{\tau} \right), \quad (4)$$

with θ the temperature coefficient of the coil resistance, C its total thermal capacity, and τ the cooling time. The latter is approximately 50 s in PDX and so can be ignored when the TF pulse length is a few seconds. Therefore Eq. (4) may be approximately rewritten as

$$R(t) = R_0 \left(1 + \frac{R_0 \theta}{C} \int_0^t dt' I_T^2 \right), \quad (5)$$

where R_0 is the initial resistance.

The mass of copper in the TF set is 69.5 tonne, θ_{Cu} is $0.0038 \text{ } ^\circ\text{C}^{-1}$, and the specific heat $0.092 \text{ cal/gm}^\circ\text{C}$. The value of R_0 is approximately 39.5 m Ω so that

$$R(t)/R_0 = 1 + 5.55 \times 10^{-12} \int_0^t dt' I_T^2(t') . \quad (6)$$

The set of couplings M_i include those to the poloidal field system, plasma current, and the vacuum vessel. The latter is given by

$$0 = L_V \dot{I}_V + R_V I_V + M_V \dot{I}_T + \dot{\psi}_d . \quad (7)$$

The L/R time of the vacuum vessel is 10.5 msec. It was found in practice that the couplings to the poloidal field coils had considerable lags on them. These were modelled by single poles. Thus

$$M_i \dot{I}_i = M_{1i} \dot{I}_i + M_{2i} \dot{I}_{Li}$$

with

$$0 = \dot{I}_i + \dot{I}_{Li} + I_{Li}/\tau_i .$$

At the full field, the total flux LI_T stored in the PDX TF coils is approximately 8000 Wb. This is to be compared with a paramagnetic flux of 1 Wb when the plasma current is 300 kA. Therefore it is necessary to make an approximation to the diamagnetic flux using an analog computer in order to maintain a sufficiently small dynamic range for a 12 bit ADC. The signal that is digitized is

$$V_{out} \approx V_T - L_G \dot{I}_T - R_G I_T - M_V \dot{I}_V$$

$$= \sum_i M_i \dot{I}_i + \delta L \dot{I}_T + \delta R I_T + N \dot{\phi}_d \quad (9)$$

where L_G and R_G are the values for the TF inductance and resistance used in the analog computers. These parameters were adjusted to the point where the errors, δL and δR , were less than 1%. The mutual inductances M_i were determined by direct measurement. The errors δL and δR , including the heating term, are fitted for each shot on the rise and fall of the TF current. The remaining signal is the diamagnetic flux. Various effects not included in Eq. (9) are also taken into account. These are the slight inward movement of the TF coil set which introduces a term in the flux which is cubic in I_T and analog integrator drift. The error in the estimate of the vacuum vessel mutual inductance is also fitted, although this is a rather unimportant term. The resulting background flux is not exactly zero because of errors in the fit and the neglect of physical effects such as the time variation of the current distribution in the TF turns. In order to overcome this, it was assumed that the error during the discharge is linear with time, as it is during TF only shots, and the flux is zeroed at t_0 and when the plasma current goes to zero.

III. DETAILS OF THE MEASUREMENT SYSTEM

The apparatus consists of a precision Rogowski to measure the TF current, a voltage divider across four of the TF coils, and the analog computer. A LeCroy 82312 was employed for the digitization. This was used in the pretrigger mode with the first 512 words read at 100 Hz, the next 1000 words at 1 kHz starting at t_0 , and the remainder up to 2048 per channel at 100 Hz. This covers the entire TF pulse with adequate time resolution for both the fit to the parameters appearing in Eq. (9) and the measurement of the plasma pressure.

The Rogowski coil was of somewhat unusual construction and is shown in Fig. 1. The main aim of the design was to reduce the coupling to the poloidal field by making the coil as symmetric as possible. In fact, the main coupling of the system to the poloidal fields is still through the Rogowski coil, but the total effective flux is at most 20% of the paramagnetic flux and more usually 10%. Since the coupling is largely through the Rogowski, the effect of the plasma current can be calculated. The field due to the plasma current and the EF coil are in the same direction at the location of the Rogowski coil. Therefore, it is assumed that the couplings are in the same ratio as the fields per unit current and that the lags are the same. Nothing can be done to check the latter assumptions, but the estimate of the static coupling to the plasma current seems to stand up well to reversal of the TF current.

The balanced voltage divider is connected across four TF coils. The two ends were brought together by connecting one to the supply bus adjacent to the Rogowski and by routing the other around the TF compensation loop. This ensured that the poloidal field coupling to the area between the TF coils and compensating loop is cancelled out. Two megohms of the divider resistance were connected to the hot end of the long lead so as to prevent any accidental grounding of the TF set. The case of the analog computer was used as the ground for the voltage divider in order to minimize mains pickup. The case is connected to building ground for safety.

The circuit diagram of the analog computer is shown in Fig. 2. It is entirely straight-forward in its construction. One percent metal oxide resistors are used throughout for stability, and the operational amplifiers are temperature stable, low offset types. The sensitivity for the I_T output is 10 kA/V; and for V_{out} , it is 10^{-2} V/V.

The voltage divider and V_{out} channel were calibrated directly using a precision voltage generator. The I_T channel was calibrated by connecting the voltage generator in series with the Rogowski and measuring the slope of the digitized signal. The coupling of the Rogowski to the TF bus was calculated from the known dimensions of the coil. It must be remembered that a few hundred amperes flow in the TF coils between shots. This is estimated from the value of V_{out} before the TF rise and the room temperature resistance of the TF set. The resulting total current agrees well with that obtained from the TF shunt.

IV. THE RESULTS

Shown in Fig. 3 is a comparison between the rate of change of V_{out} due to coil heating as calculated using Eq. (6) and that measured experimentally. It can be seen that the theoretical value is too small by a factor of two or so. Even when the effective coil resistance, R_0 , is changed to 90 mohm, the fit is not very good, although this form has been used to analyze the data taken to date. Notice that the data overshoot at low current and high current. This will produce a background flux error that varies quadratically with time. Since the flux is zeroed by the fitting program before and after the discharge, there will be an error in the diamagnetic flux which reaches a maximum at the middle of the discharge. This will cause the value of β_T to be overestimated at low field and underestimated at high field. This is seen to be the case in a comparison between β_T calculated from the kinetic data with the TRANSP code and the diamagnetic value for ohmic discharges as shown in Fig. 4. Fortunately, most of this year's injection discharges ended in a disruption! Therefore, the measurement time was close to a point where the flux was zeroed, which made the error small. The source

of the error appears to be the change in resistance of the joints in the coils. This squares well with the behavior with toroidal field current where one would expect the contact resistance of the joints to decrease as the forces on them increase. The β_T error is typically 0.1% for toroidal fields in the range 7 to 15 kG. This is a reasonably small error for beam-heated discharges, but is clearly rather important for high field ohmic discharges. The modifications that can be made to the analysis of the data to remove this source of error will be discussed in the next section.

The raw data and the analyzed results for one shot are shown in Fig. 5. It can be seen that the signal due to plasma diamagnetism when the neutral beams come on is as large as that due to errors in inductance and resistance. The small signal during the OH magnetization stage also illustrates how small the poloidal field coupling is. Most of the signal during the rise in plasma current is due to the plasma paramagnetism.

Figure 6 shows the comparison between the equilibrium and diamagnetic betas and also the kinetic and diamagnetic betas. The agreement is very good except at the highest betas in the latter case. This disagreement is believed to be caused by the "fishbone" oscillations throwing beam ions out of the plasma. The diamagnetic beta is expected to be larger than the equilibrium beta because of the anisotropy of the slowing-down beam ions and this is seen to be the case experimentally. The magnitude of the difference is consistent with what is expected from the thermal analyses.

V. SUGGESTIONS FOR IMPROVING THE ANALYSIS AND CONCLUSIONS

It is apparent from the previous section that this method of diamagnetic flux measurement can work well. It is not obvious that it will be applicable to all machines. For example, those tokamaks with SCR bridges at the output

of the TF power supplies might have so much high frequency harmonic content appearing on the voltage divider output that the noise level would be too high. Also, TF coils with turns of large cross section cause problems due to changes in the current distribution.

In PDX, the main source of measurement error has been the nonideal temperature dependence of the TF resistance. The obvious way to deal with this is to measure carefully the effective resistance as a function of current and modify the analysis code accordingly. It is not obvious that the joint resistance will be constant in time or shot numbers. The analysis code has been modified to subtract a background flux that is both linear and quadratic in time. This is done by fitting the background to those parts of the TF flattop where the plasma current is zero. Unfortunately, the flattop has not been long enough during most of this year's operation. However, some of the 15 kG ohmic discharges had the flattop end at $t_0 + 1.5$ seconds and the peak beta was brought into good agreement with the TRANSP value.

Other improvements that might be made are to correct for timing errors due to the pretrigger mode of ADC operation and bit noise on the stored TF current waveform. These are not essential but would certainly increase the accuracy of the measurement. There is a jitter in the delay between the different rates of ADC data collection. This leads to an error in the estimate of the change in TF resistance due to coil heating. This could be corrected by storing a voltage ramp on one of the data channels and estimating the timing gaps by matching the signal between the different regions. The bit noise on the TF current is only troublesome because of the effect that this has on the estimate of the vacuum vessel current. The resolution of the TF current digitization is 25A and the error in the mutual coupling to the vacuum vessel is a few percent. Therefore, the bit noise can introduce effective

flux changes that are tens of percent of the paramagnetic flux. This has been cured in the analysis program by fitting a polynomial to the TF current during the flattop. It would be better to modify the analog computer so that the vacuum vessel coupling can be matched more precisely, so reducing the effect of bit noise in the analysis program.

ACKNOWLEDGMENT

The PDX project is supported by the U.S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

FIGURE CAPTIONS

- FIG. 1 Shows the design of the Rogowski coil used in this measurement. Note that it does not have a break in it so that it was coupled to the TF current by removing a length of the TF bus and slipping it over the end.
- FIG. 2 Shows the circuit diagram of the analog computer.
- FIG. 3 Shows the rate of change of V_{out} with time due to coil heating as deduced from experimental data and from the heating model with $R_0 = 40$ and $90 \text{ m}\Omega$. (θ_{Cu} and $2.5 \times \theta_{Cu}$).
- FIG. 4 Shows the difference between diamagnetic and TRANSP beta values for ohmic heating discharges against toroidal field.
- FIG. 5 Shows the raw V_{out} signal and the analyzed output of β_T and β_p for the same shot.
- FIG. 6 Shows the comparison between (a) equilibrium and diamagnetic betas and (b) the TRANSP and diamagnetic betas.

#82x0935

Fig. 1

83x0050

Fig. 2

82X0938

Fig. 3

Fig. 4

#83X0049

Fig. 5

Fig. 6a

Fig. 6b