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Internal Magnetic Probe Data From ZT-40

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INTERNAL MAGNETIC PROBE DATA FROM ZT-40

by

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ABSTRACT

Measurements of magnetic field distributions as a function of time and radius were made in ZT-40 with its ceramic vacuum vessel. Data were obtained with a 10-station, 20-coil magnetic probe, measuring the B_p and B_ϕ orthogonal field components in deuterium plasma discharges. Sheath formation and diffusion, magnetic axis location and motion, the effect of the probe on the plasma, and the consistency of flux measurements with external probes are examined.

I. INTRODUCTION

Magnetic field distributions in ZT-40 were taken with the probe assembly containing 10 B_p coils and 10 B_ϕ coils. To obtain some insight on the behavior of the probes in a long duration discharge and also to examine the stability of the discharge, a preliminary study of the data has been made, mostly by hand. The data and results of the study are reported here.

The construction of the probe is shown in Fig. 1. The B_p and B_ϕ coils are nested one within the other with a spacing of 2.33 cm between adjacent coil pairs. With ten pairs of coils, the distance between the first and last coil pairs is 21 cm.

The probe system was inserted into the discharge tube along a major radius with distance measured on an arbitrary scale. In Fig. 2 the locations of individual probe coils are indicated with the probe assembly inserted at four positions (arbitrary numbers in mm units): 032, 106, 199, and 299. In Fig. 3 the positions of each coil are listed for each probe assembly position.

Fig. 1.
Mechanical construction of the magnetic probe assembly.

Calibration of individual coils was made with the probe assembly positioned at 032 (the probe coils extended over the inner half of the discharge tube diameter) and by firing the B_ϕ circuits with vacuum. The B_ϕ field was assumed to have a $1/R$ fall-off and the fields were normalized to the B_ϕ on axis as measured with a B_ϕ flux loop surrounding the porcelain tube. This value, divided by the flux loop area, gave the field.

II. DATA ANALYSIS

A. Vacuum Fields

By taking several shots at the four probe assembly positions listed above, the toroidal magnetic field radial distribution can be determined as shown in Fig. 4. The data in Fig. 4 represent discharges of B_ϕ in which either the B_ϕ probe coils or the B_p probe coils (with the probe assembly rotated 90°) were aligned with B_ϕ . The spread in the data points ($\sim 1.5\%$) is partially explained by the minimum step in the recording digitizers and the reproducibility in timing of the I_0 current and recording instruments. (Normalizations of fields ($80 - 140 \mu s$) to the flux loop, measured by the probe coils, were made over the time interval $80-140 \mu s$ of the B_ϕ cycle). In the figure, a R^{-1} curve has arbitrarily been drawn. Note the fall off in the B_ϕ field due to the hole, diameter 7.3 cm, in the aluminum primary, which allows insertion of the magnetic probes into the discharge chamber.

Fig. 2.

Schematic drawing of the positions of the coils with the probe assembly inserted at the four locations used in the experiment.

B. Plasma Discharges

When the probe assembly is inserted into the discharge tube with plasma, the toroidal current (I_ϕ), toroidal flux (ϕ_ϕ/A), and toroidal field at the wall ($B_{\phi(w)}$) are adversely affected (Fig. 5). Comparisons with a discharge in which the probe was removed show the faster decay rates with time in I_ϕ and ϕ_ϕ/A when the probe is present. The effects of the probe were further examined as a function of the distance the probe tip entered the discharge tube (Fig. 6). In the top figure, the discharge currents are normalized to the current at 144 μs when the probe is removed from the discharge tube. The effect of the probe is increased as it is inserted farther into the discharge. In the bottom figure, the discharge current at each position is normalized to the current at 144 μs at that position. The data indicate that the discharge current is increasingly perturbed as the probe is inserted to the minor axis but is not significantly further perturbed as the probe is moved towards the far wall. It appears that the probe can be inserted ≤ 5 cm into the discharge without seriously changing the discharge.

LOCATION OF MAGNETIC PROBE COILS

Distances are from minor axis, cms.

Probe system set at:

Probes	032	106	199	299	438
136,144	-17.9	-10.5	-1.2	8.8	22.7
135,145	-15.5	- 8.1	+1.2	11.2	25.1
136,146	-13.2	- 5.8	3.5	13.3	27.4
137,147	-10.9	- 3.5	5.8	15.8	29.7
138,148	- 8.5	- 1.1	8.2	18.2	32.1
139,149	- 6.2	1.2	10.5	20.5	34.4
140,150	- 3.9	3.5	12.8	22.8	36.7
141,151	- 1.6	5.8	15.1	25.1	39.0
142,152	0.7	8.1	17.4	27.4	41.3
143,153	3.1	10.5	19.8	29.8	43.7

Major Radius = 114.3 cm.

(In above, dimensions are positive with increasing major axis)

Fig. 3.

The distances of the magnetic probe coils from the geometric axis for five locations of the probe assembly.

In these preliminary studies of the probe data with plasma, three discharges were selected with the probe assembly positioned at each of the four positions mentioned above, 032, 106, 199, and 299 in mm. The twelve discharges were run under identical conditions. ZT-40, during these selected discharges, had a peak I_ϕ of ~500 kA, $\theta(144 \mu s) = 1.16$, $\theta(288 \mu s) = 1.78$, initial deuterium gas filling of 7 mtorr, and was run in the aided B_ϕ reversal mode.

Typical B_ϕ probe traces taken during two discharges are shown in Figs. 7 and 8. The probe assembly was located at the position 032. The time interval shown in the figure is 100-500 μs , which corresponds to 17 μs and 417 μs after the start of I_ϕ . Examination of these traces shows

1. Some evidence for electrical noise, for example, at about 70 μs in some traces and, at the start of current flow, some designated as 176 μs .

Fig. 4.

The measured vacuum toroidal magnetic field. The data represent the results of twelve runs with the probe assembly located at four positions to span the radial interval -20 to +30 cm. The data are normalized to the toroidal field on axis as measured by the toroidal flux loop.

Fig. 5.

The effect of the probe assembly on the toroidal discharge current, toroidal flux, and toroidal field at the wall.

2. Considerable fluctuations in the traces up to about 300 μs , with the traces becoming considerably smoother thereafter.

Fig. 6.

The decay of the toroidal current with the probe assembly inserted into the discharge tube. In the top figure the data are normalized to I_T (144 μs) with the probe located outside the tube. In the lower figure the data are normalized to I_T (144 μs) for each probe assembly position. The location of the probe tip, not the first set of probe coils, is shown measured in cm.

3. The magnetic axis, $B_p = 0$, moves about the geometric axis. This can be seen by examining the trace #143 where B_p varies between $\pm 2kG$. This movement of the magnetic axis will be discussed below.
4. Detailed examination of the probe traces shows at times the rise and fall of similar features, peaks and valleys, in several adjacent probes, indicating a common perturbation that encompasses a number of probe coils.

In Fig. 9 is shown a computer output of B_p and B_ϕ radial distributions at early times, $\sim 80 \mu s$, $85 \mu s$, and $90 \mu s$, for discharge #3771 (I_ϕ initiated at $\leq 80 \mu s$). In this discharge the probe assembly was located at 199 mm with the

Fig. 7.

Typical B_p coil signals as a function of time for discharge #3853. The probe assembly position was 032.

Fig. 8.

A second set B_p coil signals taken on the discharge following the one shown in Fig. 7.^P

first and second probe coils straddling the geometric axis. A spline fit of the data (not used in the analysis below) is also shown. Examination of these curves shows the formation of an I_ϕ current sheath at early times, which diffuses radially inward to the minor axis.

Fig. 9.

Toroidal and poloidal magnetic field distributions at early times (80, 85, 90, and 95 μ s) in the discharge, with spline fits given by the computer. I_T is initiated at ~ 80 μ s. The inward motion of a current sheath is clearly indicated.

Computer outputs for B_p and B_ϕ radial distributions at late times, 100, 200, 300, 400, and 500 μ s, are shown in Fig. 10 for the same discharge as in Fig. 9. The experimental probe data give a relatively smooth curve for all times. The spline fit, however, on the B_p data does not accurately give the

Fig. 10.

Toroidal and poloidal magnetic field distributions at late times (100, 200, 300, 400, and 500 μ s) in the discharge.

position of the magnetic axis passing close to the geometric axis, whereas connecting the experimental points shows shifts of the magnetic axis between +1 and -4 cm. (Good spline fits are made difficult with no data taken on the inner half of the discharge tube.) A negative B_ϕ magnetic field is seen during the time interval 200 to 300 μ s, which penetrates into the discharge ~ 1 cm from the porcelain wall. These data from the computer have not been corrected for the field perturbations due to the hole in the primary.

A first study of the magnetic field data involved the testing of data taken with the probe assembly located at the four radial positions. Did the fields match where they should overlap? In the upper figure of Fig. 11 is shown the B_p field distribution across the minor diameter, 61 μ s after the start of toroidal current when averaged over the 12 discharges, 3 with the probe assembly at 032, 3 at 106, 3 at 199, and 3 at 299 mm. Typical values of the average deviations of the data are also shown. In this figure the data are relatively smooth and there are no sharp discontinuities where the probes overlap.

In the lower figure of Fig. 11, the integration of B_p flux inward and outward from the magnetic axis is shown. The data, of course, are first corrected for the $1/R$ effect of the toroidal geometry. Because the two fluxes are not equal, an estimate is made, shown by the dotted line, of the correction needed to make the fluxes equal and which could indicate the perturbation in the magnetic field profile caused by the hole in the primary. With this correction, the centers of circles that enclose a constant B_p flux are determined. These centers pass from the magnetic axis, where the fluxes are zero, to the geometric axis, which is the center of the aluminum primary. The loci of these centers are shown in the figure.

In Fig. 12 the average B_p radial distribution and the correction made by the estimate from B_p flux considerations for the data 61 μ s after the start of toroidal current are shown. The correction is somewhat larger than that inferred from measurements of B_ϕ in vacuum, and there may be other effects that must be considered. Also shown in the figure are the values of B_p at $r = \pm 20$ cm, calculated from the toroidal current. The value at $r = -20$ cm is in good agreement with probe measurements, whereas that at $r = +20$ cm is only in fair agreement. Possible reasons for these differences are discussed below.

Fig. 11.

In the top figure is shown the poloidal field distribution 61 μ s after the start of toroidal current. The data from ten shots are averaged with a number of typical average deviations of the data shown. In the lower figure is shown the integral of the poloidal flux outwards from the magnetic axis (ϕ_p).

Fig. 12.

The average poloidal magnetic field distribution with the correction to the measured magnetic field as indicated by the integral of toroidal flux.

The average radial distribution of B_ϕ for the same twelve discharges, 61 μ s after the start of toroidal current, is shown in Fig. 13. In the lower curve, the data are corrected for toroidal geometry and the centers of the circles where B_ϕ is equal on both sides of the distribution are also shown. The B_ϕ distribution is relatively smooth and is similar to profiles seen in other experiments.

The B_p and B_ϕ magnetic field distributions at a later time, 288 μ s, are shown in Fig. 14. In the upper figure, the B_p data for each of the 12 discharges are plotted with a straight line connecting the measured field at each probe position. Note that each curve extends over 21 cm, the distance between the first and last probe coil. From these data it is clear that the magnetic axis is not fixed at one position for all discharges at this time, but varies between -0.5 cm and +6 cm in the horizontal direction. Examination of individual probe traces in Figs. 15 and 16 shows that the traces from the probe located close to the B_p zero fluctuate widely; for example, in Fig. 15, discharge #3852, probe #142 varies between ~ -3 and $\sim +1.7$ kG in 10 μ s.

Fig. 13.

The radial toroidal field measured at 61 μ s after the start of toroidal current. In the lower figure is the toroidal field calculated in cylindrical geometry.

Fig. 14.

In the upper figure the poloidal field measured in twelve individual discharges is shown 208 μ s after the start of toroidal current. In the lower figure the average toroidal field is shown for the same time.

The motion of the magnetic axis as a function of time was determined for four different discharges. The probe assembly was in position 106 for two of the discharges, #3862 and 3863, and in position 199 for #3856 and 3858. The intent of examining two positions of the probe assembly was to determine if the probe repelled or attracted the center of the discharge, that is, the magnetic axis. The positions of the magnetic axis relative to the geometric axis are shown in Fig. 17 for these discharges. The discharges are seen in general to move radially outward, +2 to +4 cm, as expected. There are also rapid motions of the magnetic axis by as much as ~ 3 cm in 14 μ s (discharge #3858 at 296 μ s). The motion of the magnetic axis does not, however, appear to be much different for the two positions of the probe assembly (except for times after 270 μ s in discharge #3863, where the magnetic axis lies close to the geometric axis). Runs #3862 and #3856 are almost identical.

Fig. 15.
Typical poloidal magnetic field traces measured by the ten probe coils, with the probe assembly in positions 032 (top) and 106 (bottom). The times indicated (200 to 260 μ s) are those from the computer, $\sim 80\mu$ s the $I_T(0)$.

Fig. 16.
A second set of probe signals to those given in Fig. 15.
(Probe position 032.)

Returning to Fig. 14, the lower curve shows the B_ϕ field distribution. The experimental points shown are the averages of the three discharges at one probe assembly position. At the inner wall, $r = -20$ cm, the B_ϕ is reversed and this reversal extends radially inward to $r \sim -15$ cm, whereas at the outer wall, $r = +20$ cm, no reversal is indicated. The behavior of the perturbation in the primary for the case of a field reversal is not understood, especially if the reversal point lies inside $r = +20$ cm.

In Fig. 18, upper figure, is shown the radial B_p field distribution at 288 μ s when all the data shown in Fig. 15 at one radial position are averaged. In the lower curve, the integrations of B_p flux from the magnetic axis is shown. An estimate to have equal ϕ_p on both sides of the magnetic axis is also indicated. If the estimate is converted back into $B_p(r)$, the result is shown as the dotted curve in the upper figure. It appears that the difference

Fig. 17.

Positions of the magnetic axis as a function of time for two locations of the probe assembly (106 and 199).

Fig. 18.

The three average poloidal magnetic field distributions and a calculated correction to the distribution due to the perturbation in the primary. The time is 208 after $I_T(0)$. In the lower figure, the integration of B_p (ϕ_p) outwards is shown.

between the estimate correction and the measured profile is again excessive and cannot all be owing to the field perturbation because of the hole in the primary. Note that the values of B_p at $r = \pm 20$ cm, calculated from I_ϕ , are in fair agreement with the probe data.

Another example of $B_p(r)$ and $B_\phi(r)$ is shown in Fig. 19 for the time 324 μ s, 240 μ s after I_ϕ is initiated. In the upper curve, the average value of the magnetic field for the three discharges at the same probe assembly position are shown. In the lower curve, the average $B_p(r)$ for all the data is shown together with the values of B_p at $r = \pm 20$ cm, calculated from I_ϕ . The ϕ_p for the inner and outer regions of the discharge is calculated as described above and is shown in the upper figure in Fig. 20. In this case the difference between the inner and outer fluxes is very large, 35 to 18 (in arbitrary units), and cannot result from the hole in the aluminum primary. We suggest that the discharge has developed a kink at this time, with a radius of

Fig. 19.

The three average poloidal magnetic field distributions (upper) and the correction (bottom) indicated for the wall perturbation. The time is 240 μ s after $I_T(0)$.

curvature less than the major radius of the torus. The B_p magnetic field lines are then further compressed on the inward side, with a corresponding expansion of flux lines on the outside. In the lower figure of Fig. 20 are the results of flux calculations on the inner and outer halves, with the assumptions of radii of curvatures of 80, 40, and 30 cm. Agreement between the two fluxes can then be approached with reasonable kinking of the discharge, a radius of curvature ~ 30 cm in this case.

A summary of the calculations of ϕ_p , the ratio of ϕ_p flux on the inside and outside halves of the discharge, the ratio of the ϕ_ϕ flux from the measured B_ϕ field distributions and that from the ϕ_ϕ flux loop, and θ for the four times in the discharge cycle considered in this study are shown in Fig. 21. The deviations from unity in the ratios of ϕ_p and ϕ_ϕ , as defined above, can be explained by a kinking of the discharge and the perturbation in the primary. Variations in ϕ_p have been discussed above. Again, if the discharge kinked and moved vertically up or down from the horizontal median

Fig. 20.

The integral of poloidal field, ϕ_p , (upper) and the variation of poloidal field (bottom) with assumptions of pinch major radius of curvatures of 80, 40, and 30 cm.

Time	$\frac{\int B_p dr}{\int_{-20}^{+20} B_R}$ Ratio	$\frac{2\pi \int B_\phi dr}{\int F/A}$ Ratio	θ
144	1.32	0.99	1.16
288	1.54	0.78	1.78
324	2.26	0.79	1.64
418	1.07	0.95	1.70

(No Correction for Hole in Primary)

Fig. 21.

The ratio of 1) the integral of poloidal fluxes calculated inward and outward from the magnetic axis and 2) the toroidal magnetic flux calculated from probes to that measured by the flux loop for four times in the discharge cycle ($I_T(0)$ is 80 μ s). θ is also shown.

plane, the calculation of ϕ_ϕ from $B_\phi(r)$, assuming symmetry about the horizontal median plane, will be too small with the result shown in the figure.

The values of θ at late times are large, ~ 1.6 - 1.7 , and may account for some of the fluctuations in the probe traces and the kinking of the discharge. Incidentally, no quiet periods were observed during these probe runs.

Examination of Fig. 22 shows that at 418 μ s (335 μ s after the start of I_ϕ) the calculated ϕ_p and ϕ_ϕ are relatively well behaved. We have then assumed that the $B_\phi(r)$ and $B_p(r)$ profiles are not greatly modified by a kink and can be used to calculate a plasma pressure distribution. In the left of Fig. 22 is shown the $B_\phi(r)$ and $B_p(r)$ profiles for the outer half of the discharge. The $B_p(r)$ profile has been corrected, as shown by the dotted line, to balance the ϕ_p in the inner and outer halves and to first-order-correct for the perturbation of the hole in the primary. Note that there is an indicated outward shift of the magnetic axis of 2 cm.

The data shown in Fig. 22 are presented in cylindrical geometry in Fig. 23. Note that the toroidal shift radially outward has not been removed. The toroidal magnetic field has been corrected for the wall perturbation.

The radial plasma pressure was then calculated for this case with the assumptions of (1) cylindrical geometry and (2) symmetry about $r = +2$ cm. Calculations of the pressure for the two cases, the measured $B_p(r)$ and that connected for the perturbations, give plasma pressure distributions shown on

Fig. 22.

Magnetic field distributions (left) and calculated plasma pressure distributions 335 μs after $I_T(0)$. The correction due to wall perturbation is shown.

Fig. 23.

The poloidal and toroidal radial magnetic field distributions measured at 335 μs after the start of the toroidal current. The data are the same as that shown in Fig. 22 (left) but are presented in cylindrical geometry. Note that there has been no correction for the toroidal shift radially outward.

the right-hand figure. If one accepts the above assumptions, peak plasma pressures of 8×10^4 and 4×10^4 dynes/cm² result for the two cases. If the number of particles is one-half that initially in the gas fill, and $T_e = T_i$, peak temperatures of ~ 105 and 54 eV are indicated for these two pressures. These values are probably a bit high for this relatively late time in the discharge cycle. If a β calculation is carried out, a β of $\sim 6\%$ results. The

minimum in pressure found about the magnetic axis is not considered at this time to be significant.

The input volt-second measured at the header of one quadrant is compared with the experimental ϕ_p (inner half) from probe data multiplied by the length of a quadrant in Fig. 24 as a function of time. Up to $\sim 40 \mu s$ after the start of I_ϕ the agreement is good, showing that only a small amount of ϕ_p has been annihilated on axis up to this time. After $\sim 40 \mu s$ a large disparity between the ϕ_p input and ϕ_p in the discharge is found; at peak current ($\sim 200 \mu s$ in the figure, $\sim 100 \mu s$ after I_ϕ starts) $\sim 33\%$ of the input flux has been annihilated on axis. Calculation of the time rate of flux annihilation on axis gives the voltage per quadrant on axis and is shown in the right-hand figure. With a discharge current of $\sim 300 kA$ and a voltage of ~ 600 volts (and the assumption of a well-behaved plasma, that is, a uniform E_z with radius), a resistance is calculated of $2.7 m\Omega$ per quadrant, which is about what we have measured in these discharges. The data also show that a power crowbar voltage of ≥ 600 volts per quadrant is necessary to support the resistance losses and sustain a constant current discharge.

Fig. 24.

$\int V_T dt$ and calculated poloidal flux (left) and calculated voltage on axis (right) as a function of time.

III. CONCLUSIONS

From the preliminary investigations of the probe runs with ZT-40, the following conclusions can be made.

- a) Insertion of the probe into the discharge degrades the discharge with the current falling considerably faster than without the probe. The fall in current is increased as the probe is inserted up to the minor axis and then remains relatively constant as the probe is inserted still farther up to the far wall. A probe insertion of ~ 5 cm into the discharge may be tolerated.
- b) To date there is no strong evidence that the discharge is either repelled or attracted to the probe--the measured magnetic field distributions do not appear to change as the probe is inserted a greater or lesser distance into the discharge. It also appears, on examination of adjacent probe traces, that important information can be obtained on the behavior of the discharge, such as plasma oscillations (frequency and amplitude) and their correlation lengths.
- c) The calculated ϕ_p and ϕ_ϕ in general appear to be in good agreement with that from the input $\int V_\phi dt$ (at early times) and that from the ϕ_ϕ flux loop. Where there are differences, rather large in some cases, the cause may be a kink instability. From these preliminary data it appears that the probes give reliable data out to at least 340 μs after the start of the toroidal current.
- d) In the discharges examined, there is clear evidence for the equilibrium position of the discharge to move radially outward $\sim 2-4$ cm. Instabilities further cause the magnetic axis to move away horizontally and vertically from the equilibrium position. At this time it appears necessary to average several shots or, probably somewhat better, to average over some finite time interval on one shot to have magnetic field profiles that can be used to calculate a plasma pressure profile.

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