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DIFFUSION OF ANTI-PARALLEL BIAS MAGNETIC FIELD DURING THE INITIAL STAGES OF A THETA-PINCH

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ABSTRACT

In a study of the early stages of a theta pinch in reversed bias magnetic field it has been found experimentally that some of the bias flux is lost before the start of the implosion. The loss is a consequence of the hydromagnetic expansion of plasma and trapped field that occurs whilst the driving field reverses polarity. The amount of diffusion depends on the magnitude of the bias field relative to a certain critical field.

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The effect of bias magnetic field on the behaviour of the plasma in Theta-Pinch experiments has been the subject of study in several laboratories[1-4]. Usually it has been assumed that, when the initial conditions are defined by pre-ionization of the gas, the plasma has a sufficiently high conductivity that the bias field is trapped in the plasma at the start of the radial implosion.

In this note we present experimental data which show that with antiparallel bias field, not all the initial flux stays trapped but part is lost.

The experiments have been performed with the Megajoule Theta-Pinch facility at the Culham Laboratory[5]. The bias magnetic field is produced by discharge of a high inductance critically damped capacitor bank into the single turn coil. The field rises to maximum value, variable up to 8 kG, in 60 μsec and decays in 200 μsec. The gas is ionized at the time of peak bias magnetic field by an axial current pulse of 4 μsec duration. The main capacitor bank is triggered during the afterglow of the pre-ionization discharge at a time when the gas is ionized to a level greater than 30%, has a temperature of 2 eV, and is uniformly mixed with the bias magnetic field.

We have measured the plasma diamagnetism S, which is related to the plasma area A_p[6]

$$S = BA_p - \varphi \qquad \dots (1)$$

where B is the magnetic field external to the plasma and φ is the flux trapped in the plasma. The variation of the diamagnetism with time, traced out from oscilloscope records, is shown in Fig. 1 for discharges at 20 millitorr initial pressure with various bias magnetic fields.

The signal for zero bias rises linearly for 0.08 μsec and then curves over, passing through a maximum at 0.12 μsec. From equation (1), it can be seen that the linear phase corresponds to the time when the external field is rising linearly but the plasma has not left the tube wall. No flux diffusion occurs in this time due to the high conductivity and φ stays zero. Hence

$$S = A_T \cdot \dot{B}\, t$$

where A_T is the internal cross-sectional area of the tube,

$\dot{B}$ is the initial rate of rise of field

t is the time

(At these times $t \ll$ bank period and $B = \dot{B}t$).

As the field strength increases the plasma accelerates radially inwards and A_p starts to decrease more rapidly than B increases. This produces a decrease in the diamagnetism S.

In the case of antiparallel bias field equation (1) applies, but φ is a negative quantity. However, provided φ is constant, the variation of S with time should be similar to that when φ is zero. The diamagnetism should still have an initial linear rise until the plasma has accelerated away from the wall. The external field now has to overcome the pressure of the bias field before the plasma can move inwards, so that the linear phase should last longer and S should rise to a higher value, the higher the bias field strength. This description is adequate for bias fields up to 2 kG.

At higher values of bias, however, the linear rise is not present at the start, but its onset is delayed (see Fig.1). We postulate that this is due to a loss of the initial flux. The amount of flux lost can be estimated from the vertical displacement of the signals (see Fig.1) and data obtained in this way is plotted in Fig.2.

One mechanism of flux loss is the radial expansion of plasma and magnetic field which occurs whilst the external field is changing sign. Prior to the main discharge the plasma is contained by the bias magnetic field but its pressure is small and it perturbs the field only slightly. When the main condenser bank is discharged into the coil the field, in the region between the plasma and the coil, falls to zero and reverses. However, the magnetic field within the plasma cannot change so rapidly because of the high conductivity of the plasma. Consequently the magnetic pressure within the plasma is greater than that outside during this time, and this causes the plasma to expand.

Due to the high conductivity the plasma and magnetic field expand together to the wall, the particles being tied to the lines. We postulate that when the particles collide with the wall they are neutralised and absorbed in the wall, allowing the magnetic field lines to diffuse out and be lost. The rate of loss of flux should thus depend on the rate of expansion of plasma and field.

On the basis of this model we have been able to compute the diamagnetic signal S as a function of time using the code developed by Hain and Roberts[7] and modified for partially ionized gases by Roberts[8].

The equations which describe the expansion of the plasma are contained in the programme. We have had to modify the boundary conditions to allow for absorption of particles at the wall upon collision, (they already allow for loss of flux at the wall).

Results obtained from computation are shown in Fig.3 for a pressure of 20 millitorr, with an initial ionization of 40%, for cases with zero bias and with 3.45 kG antiparallel bias. Comparison is also made with the experimental signals for these cases.

The details of the plasma expansion can be examined from the computation. Fig.4 shows the radial profile of the magnetic field at various times during the field reversal for a typical case. A disturbance in the magnetic field propagates into the plasma as a rarefaction wave reaching the centre in 0.145 μsec. Its mean velocity of 28 cms/μsec compares with the Alfvén velocity $[B_0/(4\pi\rho_0)^{\frac{1}{2}}]$ of 24 cms/μsec.

From these results it can be seen that the amount of flux lost depends on the distance travelled by the rarefaction wave during the field reversal time. For low Alfvén velocities and short reversal times the wave will not travel far and the lost flux can be estimated using one-dimensional approximation:-

$$\Delta\varphi \sim \frac{2\pi R\ B_0^3}{\dot{B}\ (4\pi\rho_0)^{\frac{1}{2}}}$$

where R is the tube radius.

Above a certain velocity the rarefaction wave reaches the centre and the greater part of the flux is lost

$$\Delta\varphi \rightarrow \varphi_o$$

The division between these two regions of behaviour should occur at such a field value that the distance moved by the wave in the reversal time is equal to the tube radius, i.e.

$$\frac{B_o^2}{\dot{B}\,(4\pi\rho_o)^{\frac{1}{2}}} = R.$$

For our parameters this occurs when B_o is 3 kG. At lower bias fields $\Delta\varphi$ rises steeply with B_o but the data is not sufficiently precise to test the B_o^3 prediction.

To conclude, the change in character of the diamagnetic signals at high values of reversed trapped bias field can be explained as a loss of trapped flux. This loss can be understood as the hydromagnetic expansion of the plasma during the reversal of the external field and becomes appreciable above a value given by the expression

$$\begin{aligned} B_o^2 &= \dot{B}\,R\,(4\pi\rho_o)^{\frac{1}{2}} \\ &= 5\times10^3\,E\,(\alpha p)^{\frac{1}{2}} \end{aligned}$$

where E is the electric field at the tube wall in volts/cm, and α the fraction of gas ionized and p_o the initial deuterium pressure in millitorr.

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REFERENCES

1. BODIN, H.A.B., GREEN, T.S., NIBLETT, G.B.F., PEACOCK, N.J., QUINN, J.M.P., REYNOLDS, J.A. and TAYLOR, J.B. Nucl. Fusion 1962 Suppl., pt.2, 511 (1962).

2. BODIN, H.A.B., GREEN, T.S., NIBLETT, G.B.F., PEACOCK, N.J., QUINN, J.M.P. and REYNOLDS, J.A. Nucl. Fusion 1962 Suppl., pt.2, 521 (1962).

3. LITTLE, E.M., QUINN, W.E. and RIBE, F.L. Phys. Fluids, 4, 711 (1961).

4. KOLB, A.C., LUPTON, W.H., ELTON, R.C., McLEAN, E.A., SWARTZ, M., YOUNG, N.P., GRIEM, H.R. and HINTZ, E. 2nd Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Culham, 1965. Proceedings. Paper no. CN-21/98. (To be published)

5. BODIN, H.A.B., GREEN, T.S., NEWTON, A.A., NIBLETT, G.B.F. and REYNOLDS, J.A. 2nd Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Culham, 1965. Proceedings. Paper no. CN-21/34. (To be published)

6. GREEN, T.S. Nucl. Fusion, 2, 92 (1962).

7. HAIN, K., HAIN, G., ROBERTS, K.V., ROBERTS, S.J., and KÖPPENDÖRFER, W. Z. Naturforch., 15A, 1039 (1960).

8. ROBERTS, K.V. J. Nucl. Energy pt.C, 5, 365 (1963).

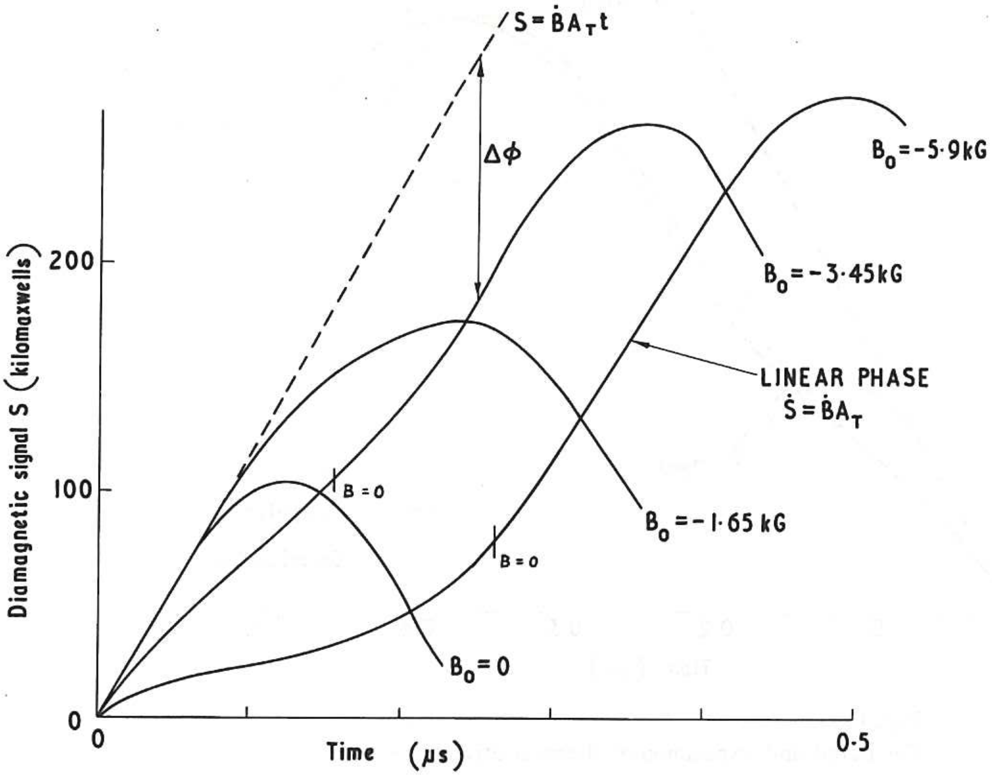

Fig. 1 (CLM-P 96)
Diamagnetic signal at various initial bias magnetic fields

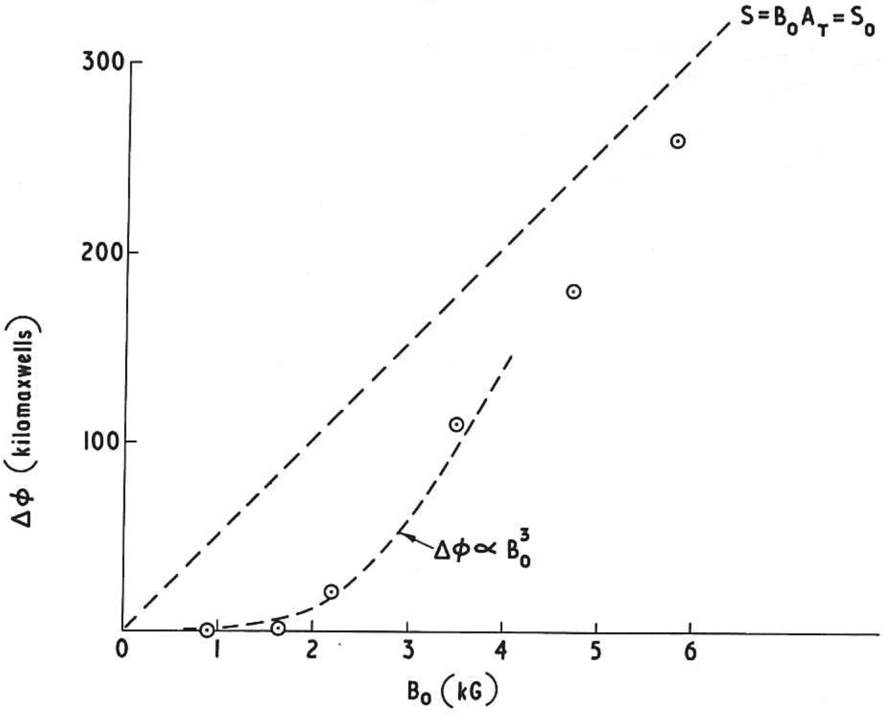

Fig. 2 (CLM-P 96)
Variation of flux leakage with initial bias

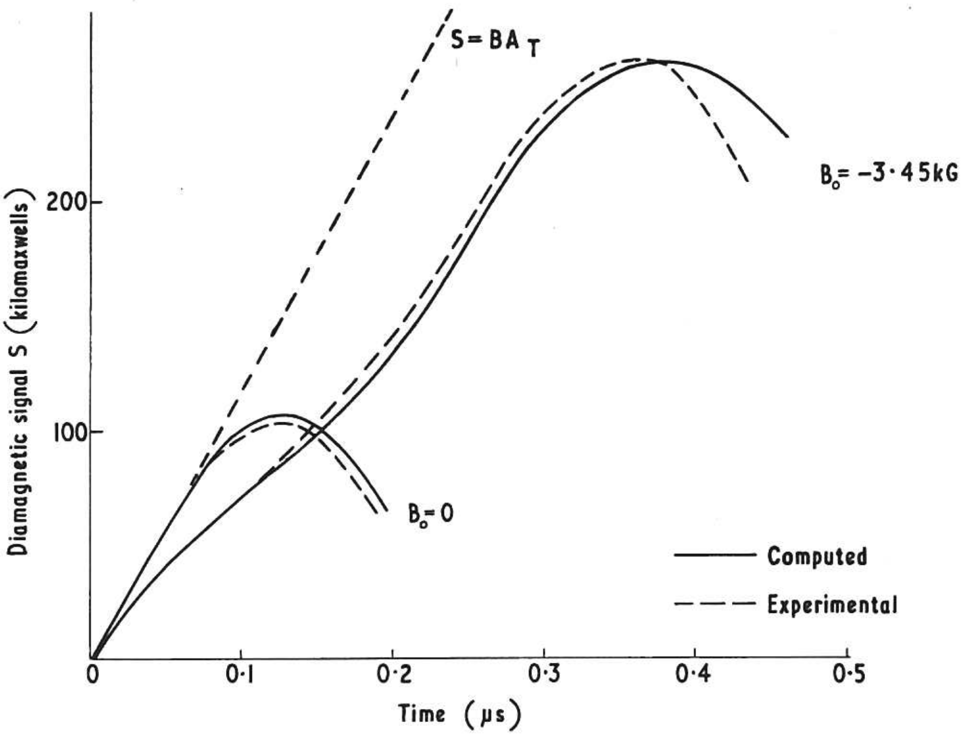

Fig. 3 (CLM-P 96)
Computed and experimental diamagnetic signals

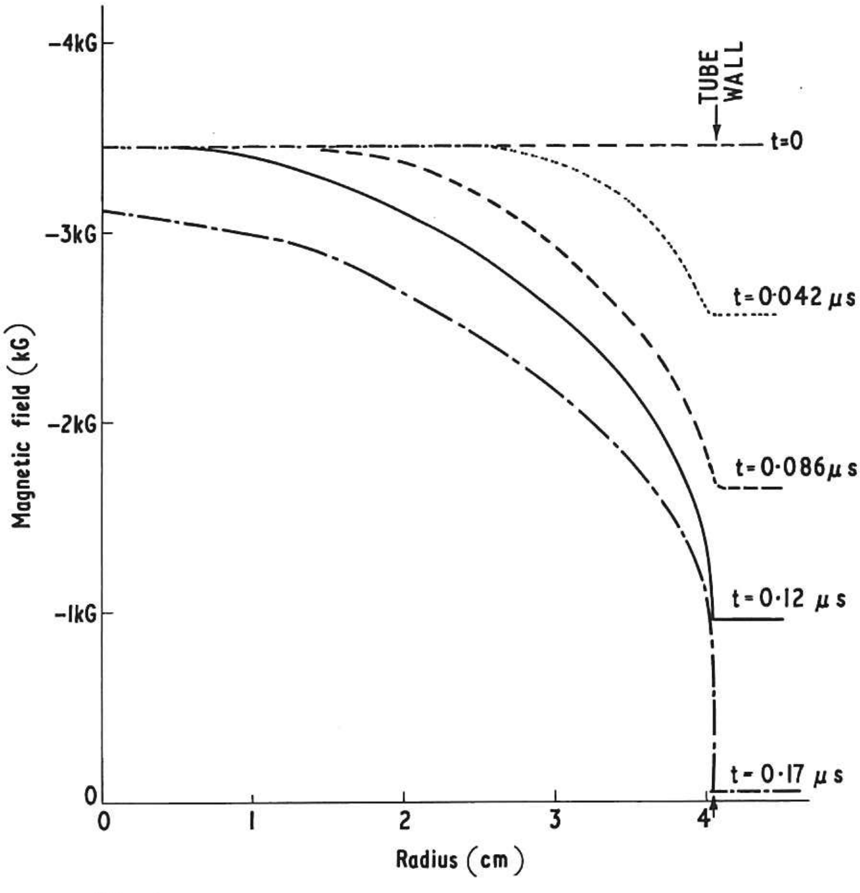

Fig. 4 (CLM-P 96)
Computed time dependence of radial profile of magnetic field
(P_o = 20 millitorr, 40% ionization, B_o = - 3.45 kG)