CLM - P 302

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Preprint

THE APPLICATION OF FOURIER ANALYSIS OF THE AZIMUTHAL FIELD DISTRIBUTION TO A STUDY OF EQUILIBRIA AND INSTABILITIES IN A TOROIDAL PINCH DISCHARGE

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ABSTRACT

The equilibrium displacement of a current carrying plasma column in a torus has been determined from measurements of the first order fourier component of the azimuthal field using coils with the number of turns per unit length varying sinusoidally. The displacement cannot be obtained directly if currents flow outside the plasma column, but an independent measurement of the displacement then yields information about the current distribution. Parameters associated with helical equilibria and instabilities such as growth, radius and wavelength, are obtained from the fourier components.

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1. Introduction

The equilibrium motion of a plasma in toroidal pinch devices is usually studied by measuring the azimuthal field component, B_θ, by means of magnetic field coils positioned close to the conducting shell or outer surface. Two such coils placed diametrically in the plane of the motion give a difference signal which is related to the displacement of the plasma. This method has been used to study equilibrium on TOKAMAK's(1) and on diffuse pinch devices, for example ZETA(2).

The displacement is not obtained directly because of toroidal curvature and partly because the current distribution to some extent screens the coils from the real magnetic centre. In addition any change of shape of the plasma, instability or large displacement leads to an additional signal which further confuses the interpretation.

Coils aligned to measure both the azimuthal and radial field components are used for studying instabilities but these have the disadvantage of being sensitive to any type of instability and for example measurements of the azimuthal mode number(3) require correlation techniques.

The equilibrium(4) and magnetohydrodynamic instabilities(5) produced in the high-β toroidal experiment have been studied using both radial field coils and sets of Rogowski coils wound so that the number of turns per unit length, $n(\theta)$, is a function of the azimuthal angle. The latter coils have some significant advantages over single coils measuring the azimuthal field at a position r,θ. A coil wound with $n(\theta) = n \cos \theta$ will produce no signal if a current-carrying conductor is exactly at the centre of the coil, but if the conductor is moved towards a region of higher winding density then a larger signal will result from these turns than from those furthest away from the conductor. Consequently the coil acts as a primitive form of difference amplifier and in this case gives a signal directly proportional to the displacement.

In general we can expand $B_\theta(r,\theta)$ in a fourier series

$$B_\theta(r,\theta) = \sum_{m=o}^{\infty} (B_{1\theta}^{m} (r) \cos m\theta + B_{2\theta}^{m} (r) \sin m\theta)$$

and so
$$B_{\substack{1\theta \\ 2}}^{m} = \frac{1}{\pi} \int_o^{2\pi} B_\theta(r,\theta) \begin{matrix}\cos m\theta \\ \sin m\theta\end{matrix} \, d\theta \ . \tag{1}$$

A Rogowski coil at position r determines $B_{1\theta}^{o}$, and coils wound with $n(\theta) = \sin\theta$, $\cos\theta$ determine $B_{2\theta}^{1}$, $B_{1\theta}^{1}$ and $n(\theta) = \sin 2\theta$ determines $B_{2\theta}^{2}$ and so on. Therefore a set of such coils wound as $\sin m\theta$, $\cos m\theta$ permits us to determine $B_\theta(r,\theta)$ which may result from equilibrium motion or specific azimuthal mode number, m, instabilities.

A fourier analysis of this kind was made by Aitken et al[6] using small single coils on a linear hardcore device. Single coils connected so as to form approximations to $\sin\theta$, $\cos\theta$, were used by Haberstich and Forman[7] to study the stability of a linear pinch device. Rogowski coils of variable winding density have also been discussed by Van Heijningen et al[8].

We shall describe the theory of coils with $\sin m\theta$ and $\cos m\theta$ winding densities and illustrate their uses with measurements made on both equilibrium motion and instabilities of a plasma in a toroidal device[4].

2. Construction and Calibration

Coils with $n(\theta) = n \sin \theta$, $\cos \theta$ etc. have been produced using a former which moves over a template on which the winding wire is tightly affixed in the appropriate functional form. With this arrangement the total number of turns is about 150 and the area of a turn is set by the size of the former which can be insulated to 50 kV and installed in the interspace between the conducting shell and the quartz vacuum vessel. Increased sensitivity was achieved by increasing the total number of turns to 750 and increasing the area of the former, partly at the expense of the frequency response of the coils. Such an increase has been achieved using an automatic winding machine which can produce any functional form. Care must be excercised in positioning the reversal point of the coils such that there is no loop area available to pick up the axial field B_z which is normal to the plane of the coil, as this field can be much larger than the azimuthal field, B_θ.

Calibration of the coils has been undertaken using the system shown in Fig. 1. Two low voltage condenser banks supply current to a linear section of the toroidal plasma device. The transverse dimensions of the linear section are identical to those of the toroidal machine. Pulsed currents of up to 300 A pass through a thin rod(s), which is an approximation to a current filament, and return through the aluminium shell. The latter is split along its axis to permit the rapid penetration of the axial field, B_z, which is used to test the coils for pick-up from this field. The coils are mounted on an insulating cylinder inside the shell and the rod(s) can be moved in any radial direction. Helical current channels are simulated by winding a current filament on a rigid former with a variety of pitches and radii, which is continuously rotated.

The circuit parameters are such that the fields and currents rise in about 10 μsec which is comparable with the rise times on the toroidal device. The frequency response of the coils with 150 turns is 14 Mc/sec and with 750 turns 5 Mc/sec. The output voltage for the 150 turn coils with a time constant of 100 μsec is typically 0.5V.

Such coils wound as sin θ/ cos θ possess an output which is directly proportional to the displacement of a current filament as it is moved radially outwards from the centre of the coil (Section 3), and this is shown in Fig. 2. From the slope of the curve, the constant of proportionality is determined and then the coil is mounted inside the shell of the toroidal machine. Coils wound as sin 2θ/cos 2θ are calibrated by moving two straight current filaments with equal currents radially outwards such that the current centroid remains fixed at the centre of the coil (Fig. 3(b)). The output in this case is proportional to the square of the displacement of the current filaments from the centre.

3. Equilibrium Studies of a Toroidal Plasma

The field inside a perfectly conducting cylinder due to a current filament displaced a distance Δ from the axis of the cylinder is calculated by assuming that a mirror current filament exists at a distance b^2/Δ from the centre of the cylinder, Fig. 3(a) which makes $B_r(r=b) = 0$. Therefore the azimuthal field at position r, and angle θ for an infinitely thin current filament is given by

$$B_\theta(r,\theta) = 2I\left[\frac{r - \Delta\cos\theta}{r^2+\Delta^2-2r\,\Delta\cos\theta} - \frac{r - \frac{b^2}{\Delta}\cos\theta}{r^2+\frac{b^4}{\Delta^2} - \frac{2b^2 r}{\Delta}\cos\theta}\right] \qquad (2)$$

so the output from a cos-coil with radius r and its axis of symmetry aligned in the same direction as the displacement is

$$V_{cos} = nA \int_0^{2\pi} \dot{B}_\theta \,(b,\theta) \cos\theta \, d\theta$$

$$= nA \, 2\pi \frac{\dot{I}}{b} \left(1 + \frac{b^2}{r^2}\right) . \frac{\Delta}{b} \qquad (3)$$

where n is the maximum winding density of the cos-coil (total number of turns 4n) and A is the cross-sectional area. As the major radius of the coil is usually close to that of the shell, $r \lesssim b$, the output is twice that obtained without the conducting shell. Note that the output is proportional to Δ. Two diametrically placed B_θ coils, from equation (2), have an output proportional to $\frac{\Delta}{1 - \frac{\Delta^2}{b^2}}$, so the linearity, shown in Fig.2, of the sin, cos coil is a distinct advantage.

A cos 2θ/sin 2θ coil is calibrated using two current filaments, as shown in Fig. 3(b). The field $B_\theta(r,\theta)$ due to the two current and mirror current filaments, each carrying a current I, can be readily calculated as in (2), then the output from a cos 2θ coil is given by

$$V_{cos\,2\theta} = 4\pi nA \frac{\dot{I}}{b} \frac{\Delta^2}{b^2} \left(\frac{r}{b} + \frac{b^3}{r^3}\right) . \qquad (4)$$

Detection of the $B_\theta{}^2(r)$ component of $B_\theta(r,\theta)$(Eqn.1) is rather sensitive to $\frac{\Delta}{b}$, indeed detection of such a component may only be possible if the plasma radius (assuming the plasma to be approximately circular) is not much smaller than the shell radius. The calibration constant, nA, is now determined by measuring the output as a function of $\frac{\Delta^2}{b^2}$. More generally the output from a cos mθ coil due to a single displaced current filament is given by

$$V_{\cos m\theta} = 4\pi nA \frac{\dot{I}}{b} (\frac{\Delta}{b})^m$$

for the major radius of the coil equal to the conducting shell radius.

In the case of a toroid, Shafranov[9] has shown that to first order in the aspect ratio the azimuthal field can be written in terms of the asymmetry factor, Λ, in the form

$$B_\theta(r,\theta) = B_\theta(r)(1 + \frac{r}{R} \Lambda (r) \cos \theta) \tag{5}$$

$$\text{where } \Lambda (r) = \underbrace{\int_0^r \frac{B_\theta^2(r')r'dr'}{B_\theta^2(r)r^2}}_{\frac{1}{2}\ell i} + \frac{8\pi\left[\frac{2}{r^2}\int_0^r p(r')r'dr' - p(r)\right]}{B_\theta^2(r)} - 1,$$

ℓi is the self inductance per unit length and p the plasma pressure.

The output from a cos coil is therefore in the presence of a conducting wall

$$V_{\cos} = 2\pi nA \frac{\dot{I}}{R} \Lambda(r) \tag{6}$$

which is a direct measure of the asymmetry factor, Λ. For tight tori this will be in error by a term of order $(\frac{b}{R})^2$. Two diametrically placed B_θ coils also measure the quantity Λ directly, and this has been compared with equation (5) for a variety of diffuse pinch configurations[2], with good agreement.

If the plasma of radius a, internal inductance ℓi is surrounded by a vacuum out to the coil or conducting wall radius, b, then the displacement is

$$\Delta = \int_a^b \frac{r}{R}(\Lambda(r)+1)dr = \frac{b^2}{2R}\left(\log\frac{b}{a} + (1-\frac{a^2}{b^2})(\Lambda(a)+\tfrac{1}{2})\right) \qquad (7)$$

$$\Lambda(a) = \frac{\ell i}{2} - 1 + \beta_\theta, \quad \beta_\theta = 8\pi . \frac{2}{a^2}\int_o^a \frac{p(r)r\,dr}{B_\theta{}^2(a)}$$

and therefore when the coil is positioned at r = b

$$V_{cos} = 2\pi nA\frac{\dot{I}}{b}\left(\frac{2\Delta}{b(1-\frac{a^2}{b^2})} - \frac{b}{2R}\left(1 + \frac{\ell n^b/a}{1-\frac{a^2}{b^2}} \cdot \frac{2a^2}{b^2}\right)\right)$$

which for a current filament or small plasma radius ($\frac{a}{b} << 1$) gives

$$V_{cos} = 2\pi nA\frac{\dot{I}}{b}\left(\frac{2\Delta}{b} - \frac{b}{2R}\right) \qquad (8)$$

- consequently the term $\frac{b}{2R}$ is the toroidal correction to the formulae of equation (3). If less currents flow outside the plasma column then the coil output is less than that given by equation (8) by a factor depending on the current distribution. For example a plasma of radius a surrounded by force-force currents such that the azimuthal field is much less than the axial one, i.e. $B_\theta \propto r$, gives an output from a cos coil:

$$V_{cos} = \frac{2\pi nA\dot{I}}{b}\left(\frac{2\Delta}{b} \cdot \frac{a^2}{b^2(1-\frac{a^2}{b^2})} - \frac{b}{4R}\left(3 + \frac{a^2}{b^2}\right)\right) \qquad (9)$$

which for small $\frac{a}{b}$, is very insensitive to the displacement. A more general expression for a plasma surrounded by force-force currents is obtained by assuming that $B_\theta(r)$ is as given by the force-free paramagnetic model[10] or the constant pitch model, $B_\theta = \frac{Cr\theta/b}{1+\frac{r^2\theta^2}{b^2}}$

where $\theta = \frac{B_\theta(b)}{B_z(b)}$. The output from the coil for $\frac{a}{b} \ll 1$, is then given by

$$V_{cos} = \frac{2\pi n A\dot{I}}{b}\left(\frac{\Delta}{b}\frac{(1+\theta^2)^2}{\left(\frac{b^2}{2a^2}\left(1-\frac{a^2}{b^2}\right) + 2\theta^2 \log\frac{b}{a} + \frac{\theta^4}{2}\left(1-\frac{a^2}{b^2}\right)\right)} - \frac{b}{R}\gamma\left(\theta,\frac{a}{b}\right)\right) \quad (10)$$

which in the limit of small θ reduces to (9) and in the large θ limit (vacuum fields) gives equation (8). The expression for $\gamma(\theta,\frac{a}{b})$ is complicated and for small $\frac{a}{b}$ varies from $\frac{1}{2}$ to $\frac{3}{4}$ as θ varies from $0 \to \infty$.

If the displacement, Δ, can be determined independently, for example from laser light scattering measurements of the density profile, microwave or optical measurements of the density, then the output from the coil (essentially Λ) can be used to determine the form of the (force-free) current distribution outside the plasma. Expression (8) has been used on the high-β toroidal experiment[4] ($\frac{b}{R}$ = .075) to determine Δ and compare with Shafranov's formula (7) as a function of $\frac{a}{b}$. The results are shown in Fig. 4 for the toroidal displacement of a stabilized z-pinch. The theoretical curve for the displacement agrees quite well with the experimental points, if we use independently measured values for β_θ = 0.46 and ℓi = 0.8.

Optical measurements of the toroidal displacement of a screw pinch have been made, which agree with the simple relationship[4] $\Delta = \frac{b^2}{2R}\frac{\beta}{\theta^2}$ and which is obtained by assuming a force-free current outside the plasma. The optical displacement observed is compared with the displacement as calculated from equation (10) as a function of time in Fig. 5. The displacement obtained from equation (8), by assuming vacuum fields outside the plasma, is much smaller than that observed optically, thereby confirming the presence of force-free currents outside the plasma.

4. Instability Studies

Magnetohydrodynamic or resistive instabilities in cylindrical or toroidal geometry lead to radial eigenfunctions or displacements of the form $\xi_r(r) \exp(i(m\theta + kz))$, where k is the axial wavenumber, - consequently $\sin m\theta$, $\cos m\theta$ coils placed at a position z_o will be sensitive to their particular m number instability only, and the relative output from the two coils will give the angle in space at position z_o. A similar determination at positions z_1, z_2 will permit a measurement of the wavenumber k, or wavelength of the instability, with the possible ambiguity that the wavelength could be 3, 6, 9 .... times less than that obtained from the three positions. Varying the magnetic fields, B_θ, B_z slightly and considering the range of wavenumbers possible for instability makes the wavelength determination virtually unambiguous.

For such helical instabilities or equilibria the displacement is not simply given by equation (8), because the helical nature of the current-carrying column will affect the azimuthal fields. If the wavelength is sufficiently long, i.e. the pitch length of the helix is greater than the radius of the conducting shell then equation (8) is satisfactory but as the wavelength becomes shorter or of the order of the conducting shell radius then the sensitivity to the displacement will be much reduced.

To study this effect we have calculated the magnetic fields due to a thin helical conductor inside a cylindrical conducting shell, Fig. 3(c). We use helical coordinates in this case $\phi = \theta - \alpha z$ where $\alpha = \frac{2\pi}{L}$ (a helix is defined by ϕ = constant). The solution of

Laplaces equation for the potential Φ has the form

$$\Phi = \sum_{n=1}^{\infty} (a_n \, In \, (n \alpha r) + b_n K_n \, (n \alpha r)) \, (c_n \cos n\phi + d_n \sin n\phi) + (n = o \text{ terms})$$

where I_n , K_n are the modified Bessel functions. A helical filament of radius ρ carrying a current I has components in the z,θ directions given by

$$I_z = \frac{I}{(1+(\alpha\rho)^2)^{\frac{1}{2}}}$$

$$I_\theta = \frac{I\alpha\rho}{(1+(\alpha\rho)^2)^{\frac{1}{2}}}$$

then we obtain

$$\Phi^{\, r > \rho} = \frac{2I}{(1+(\alpha\rho)^2)^{\frac{1}{2}}} \left[\theta + 2\alpha\rho \sum_{n=1}^{\infty} I'_n \, (n\alpha\rho) \, K_n \, (n\alpha r) \sin n\phi \right]$$

Now the boundary condition at the conducting shell can be satisfied by supposing that there is a mirror harmonic helical current distribution for each harmonic having the property that the radial field vanishes at the conductor. The mirror conditions can only be given in a simple form for $\frac{2\pi b}{L} >> 1$ or $\ll 1$. The resulting azimuthal field is given by

$$B_\theta^{r > \rho}(r,\theta) = \frac{4I}{r} \cdot \frac{1}{(1+(\alpha\rho)^2)^{\frac{1}{2}}} \left[\frac{1}{2} + \sum_{n=1}^{\infty} n\alpha\rho \, I'_n \, (n\alpha\rho) \left[K_n(n\alpha r) - \frac{K'_n \, (n\alpha b)}{I'_n \, (n\alpha b)} I_n(n\alpha r) \right] \cdot \cos n\phi \right] \tag{11}$$

and therefore the output from a cos coil at position r is

$$V_{cos} = \frac{nA4\dot{I}}{r} \frac{\alpha\rho}{(1+(\alpha\rho)^2)^{\frac{1}{2}}} \frac{\pi}{2} (I_o(\alpha\rho) + I_2(\alpha\rho))\left(K_1(\alpha r) + \frac{K_o(\alpha b)+K_2(\alpha b)}{I_o(\alpha b)+I_2(\alpha b)} I_1(\alpha r)\right) . \cos \alpha z \quad (12)$$

By expanding the modified Bessel functions we arrive at three limiting expressions for a coil at r = b

(i) $\frac{2\pi b}{L} << 1$, long wavelength

$$V_{cos} = \frac{nA2\pi\dot{I}}{b} . \frac{\rho}{b}\left(2 - (\frac{2\pi b}{L})^2 \; (1+(\frac{\rho}{b})^2)\right) \cos \frac{2\pi z}{L} \quad (13)$$

which if z = o, $L \rightarrow \infty$ and $\rho \rightarrow \Delta$ gives expression (8).

(ii) $\frac{2\pi b}{L}, \frac{2\pi\rho}{L} >> 1$, short wavelength

$$V_{cos} = 2nA\pi\frac{\dot{I}}{b} . \frac{L}{2\pi b} (\frac{b}{\rho})^{\frac{1}{2}} e^{-\frac{2\pi b}{L}(1-\frac{\rho}{b})} . \cos \frac{2\pi z}{L} \quad (14)$$

(iii) $\frac{2\pi b}{L} >> 1, \frac{2\pi\rho}{L} << 1$, short wavelength small displacement

$$V_{cos} = nA \frac{2\pi\dot{I}}{b} . \frac{2\pi\rho}{L} . (\frac{L}{b})^{\frac{1}{2}} e^{\frac{-2\pi b}{L}} . \cos \frac{2\pi z}{L} \quad (15)$$

the output falls off exponentially in this case, thus very short wavelengths would be difficult to detect. The output from a cos coil as a function of $\frac{2\pi b}{L}$ is shown in Fig. 6(a) for $\frac{\rho}{b} = 0.33$ and in Fig. 6(b) for $\frac{\rho}{b} = 0.67$. Evidently wavelengths less than b lead to an order of magnitude reduction in output of the signal expected from expression (8). A measurement of the wavelength using three sets of such coils allows us to derive the displacement from the observed output using the curves of Fig. 6.

Using a helical current filament with a variety of pitch lengths, or values of α, and two values of ρ, expression (12) has been compared with experiment. The results are shown in Fig. 6(a) & (b) and there is agreement to $\pm$ 5% between theory and experiment. Only the point at $\frac{2\pi b}{L} = 9$ in Fig. 6(a) appears to be in error and this is probably because the axial field generated by the tighter helix is being picked up because of the imperfect alignment of the cos coil to such a field.

These coils have been used on the high β toroidal experiment to study the wavelength and displacement of instabilities[5]. A typical output in the case of a screw pinch is shown in Fig. 7 and the wavelength is usually that given by the pitch of the magnetic field lines at the wall, typically between 90 cms and 600 cms, so in these cases the correction to equation (8) for the displacement is less than 15%. A more serious effect in this case is due to the screening caused by the force-free currents outside the plasma.

Fig. 8 shows a typical output for an instability produced by a well-compressed stabilized Z pinch; in this case the wavelength is about 28 cms so that the displacements derived from equations (8) and (12) differ by a factor of 3. At such wavelengths the helical nature also modifies the determination of the growth rate of the instability as the output is not linearily proportional to the displacement if $\frac{2\pi\Delta}{L}$ (or $\alpha\rho$ in (12)) approaches unity. Similar considerations apply to cos 2θ/sin 2θ coils when measuring the growth of $m = 2$ instabilities.

5. Conclusions

Measurements of the first order fourier components of the azimuthal field have been used to determine the position of a current carrying plasma in a torus. The higher order components can be used to determine the shape of the plasma column. When the plasma was surrounded by vacuum fields the measurements yielded the displacement directly, but when currents flowed outside the plasma the measured value of the displacement had to be increased by a factor depending on the current distribution. Optical measurements of the displacement were used to determine this factor and thereby deduce the form of the current distribution.

Several coils placed in major azimuth around the torus were used to study helical equilibria and the growth of m=1 instabilities. From such measurements the wavelength of the instability and the radius of the helix was obtained after taking into account the spiral nature of the current path.

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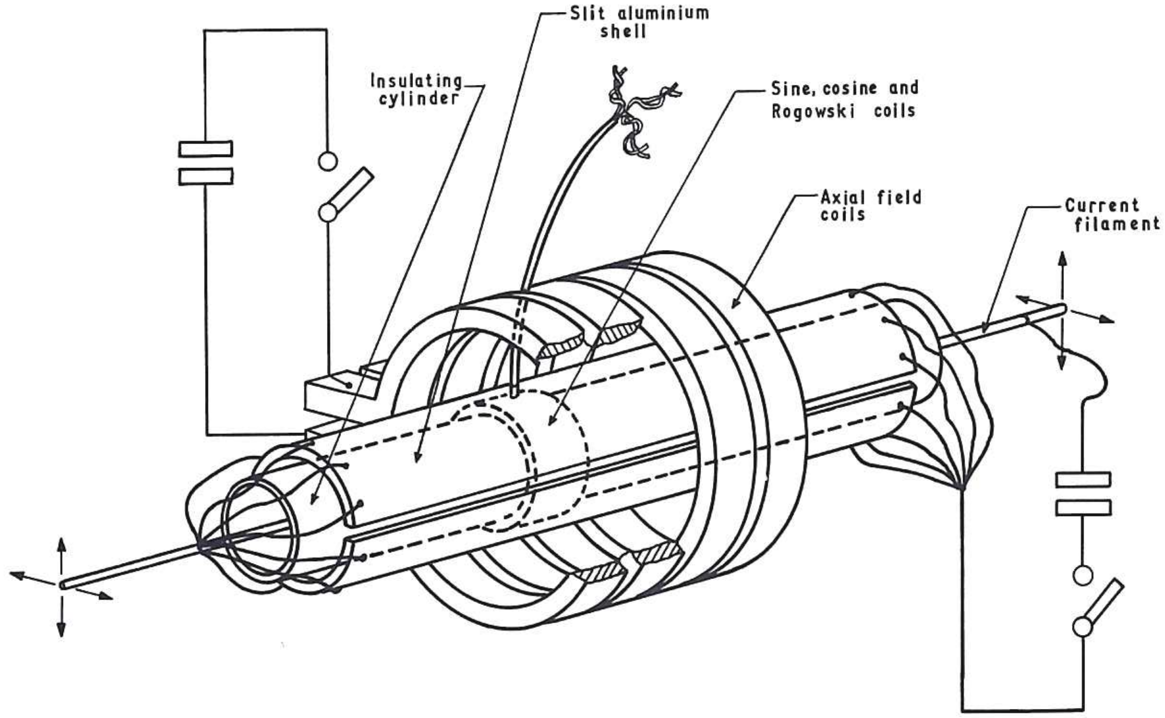

Fig.1 System used for calibrating sine/cosine coils.

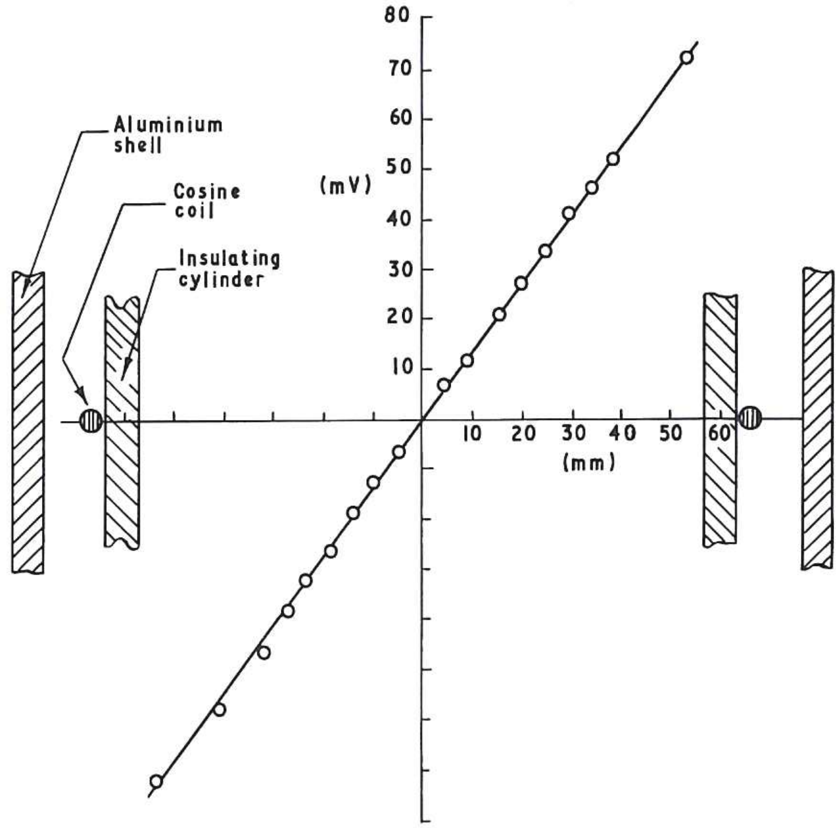

Fig.2 Cosine coil output as a function of horizontal displacement.

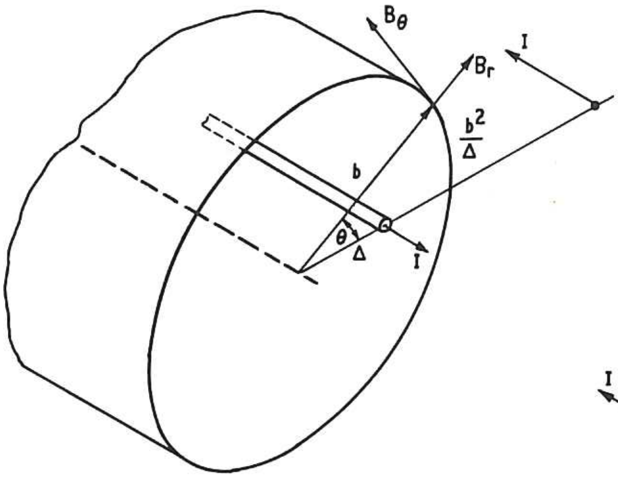

Fig.3(a) Coordinate system for a single current filament.

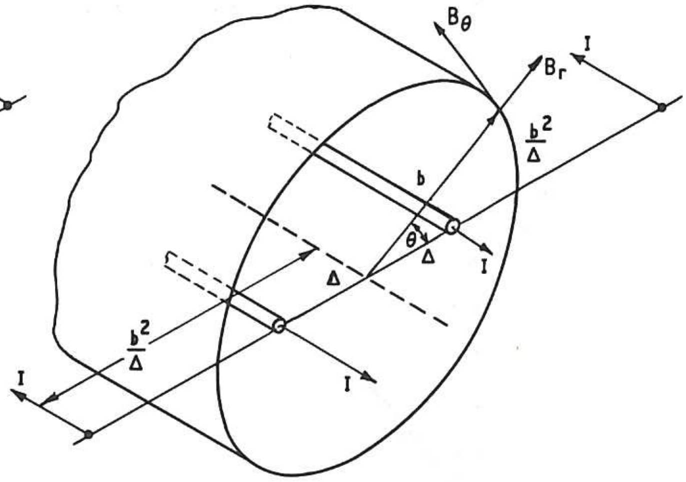

Fig.3(b) Coordinate system for two current filaments. The conducting shell radius b, and mirror current(s) at a radius b^2/Δ are also shown.

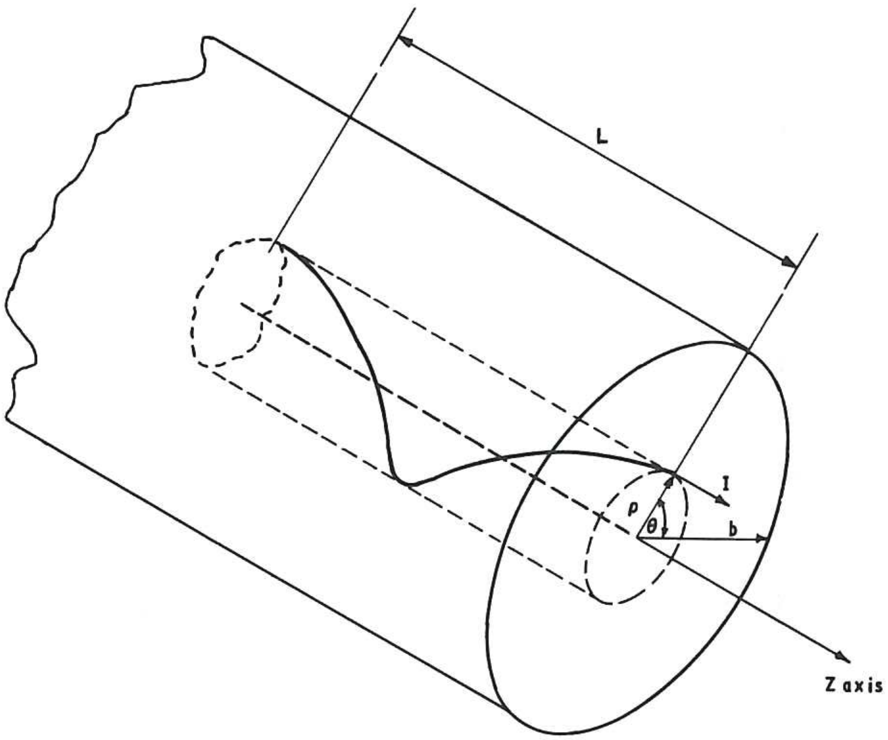

Fig.3(c) Coordinate system for the case of a thin helical conductor of radius ρ inside a conducting shell of radius b.

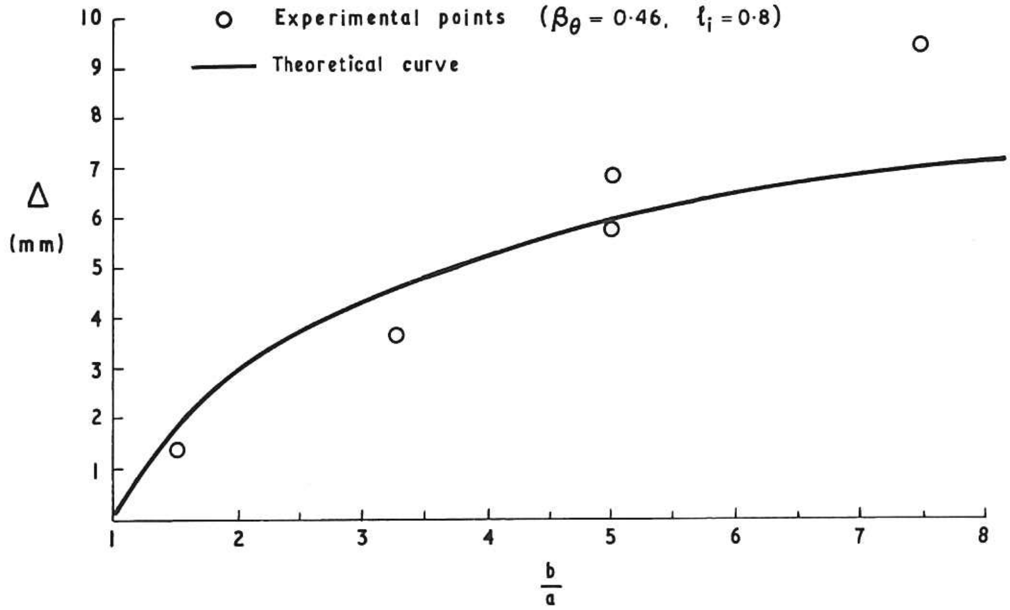

Fig.4 A comparison of the measured toroidal displacement in a stabilized z pinch as a function of b/a, compared with the theoretical curve for measured values of β_θ and ℓ_i.

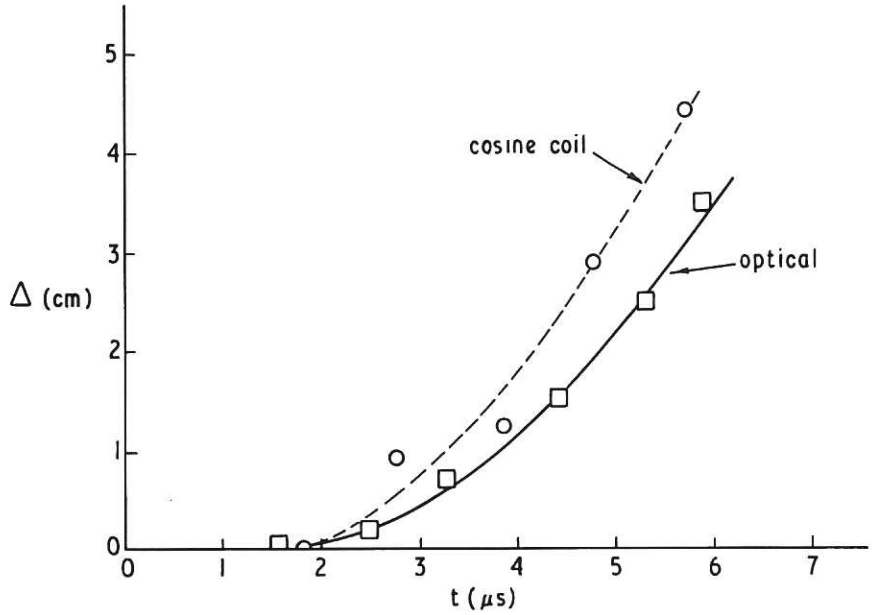

Fig.5 Displacement of the plasma column as measured optically and as determined from the output of a cosine coil, assuming a force free current flowing outside the column.

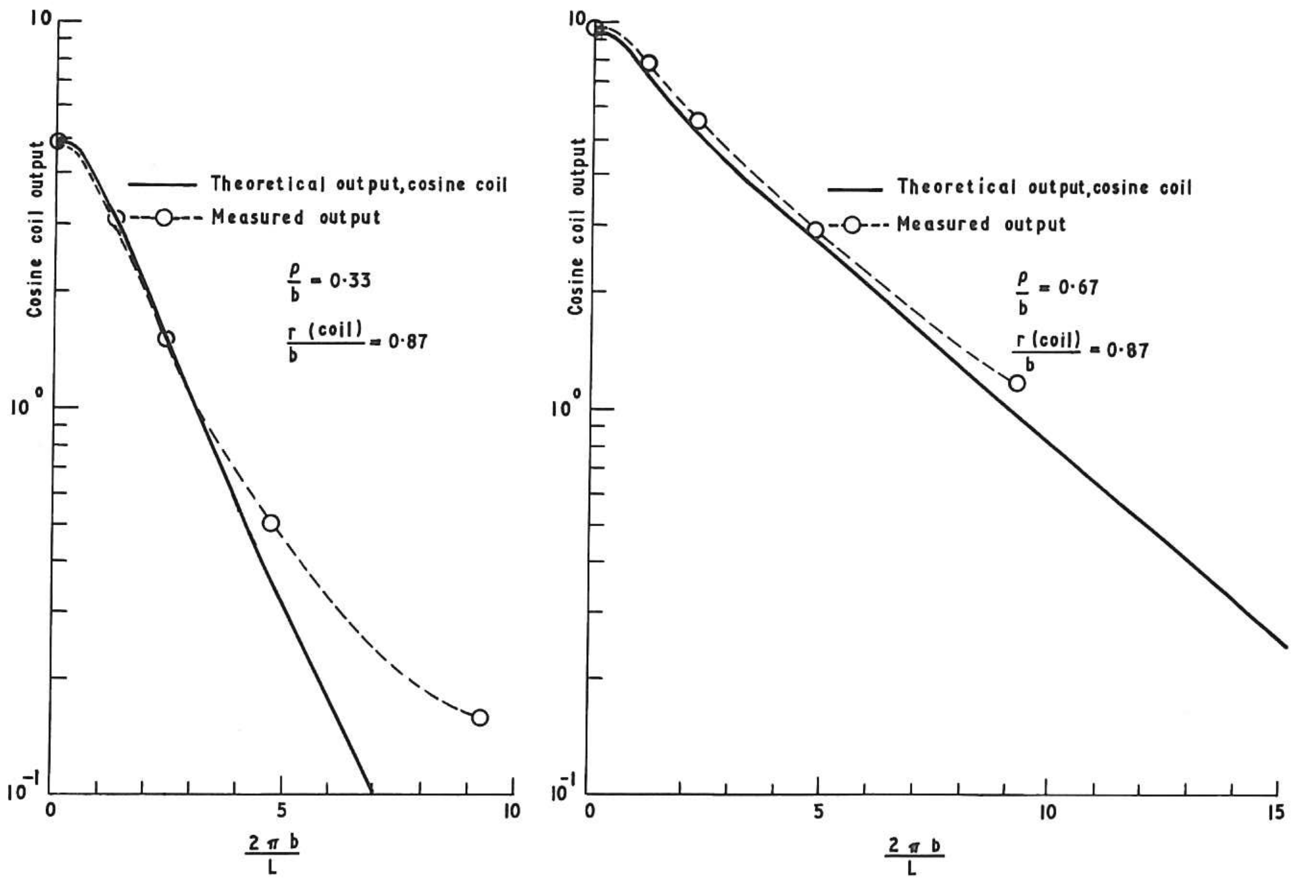

Fig.6(a) and (b) Theoretical and experimental cosine coil outputs as a function of inverse pitch length for two different radii, ρ of the helical current filament.

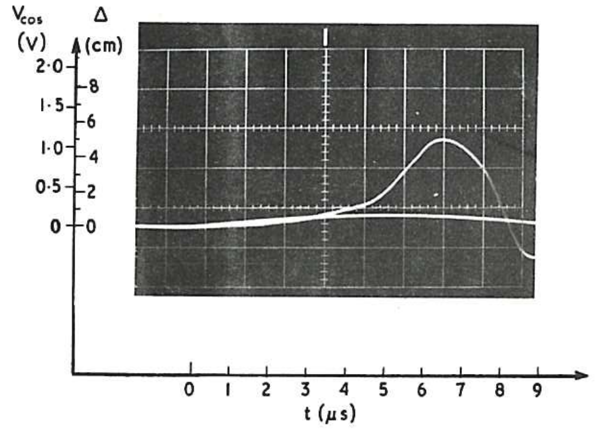

Fig.7 Output from a cos-coil for an unstable screw pinch. The displacement is calculated allowing for the force free currents outside the plasma.

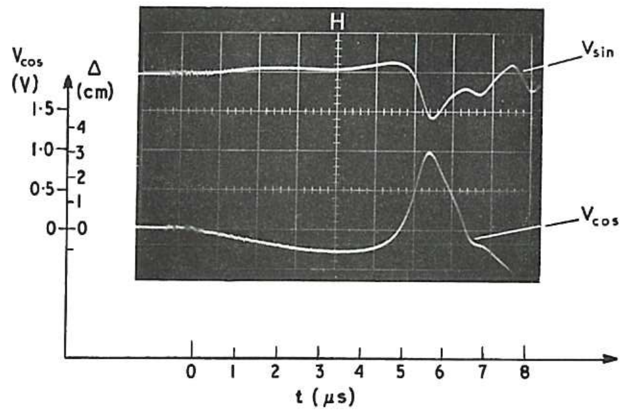

Fig.8 Output from cos and sin coils in the case of a well compressed stabilized z pinch. The displacement at the time of instability, 6 μs, is calculated after taking into account the spiral nature of the current path.