United Kingdom Atomic Energy Authority

RESEARCH GROUP

Preprint

AN AXIALLY-FED 100 kG PULSED FIELD COIL

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1967

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A B S T R A C T

A fractional turn axially-fed coil, of 8 cm diameter by 8 cm long is
described.   It is designed to give a peak magnetic field of 100 kG at a
current of 1·25 MA rising in 2·5 μsecs.   The coil winding consists of
ten parallel strips of 1·1 turns spirally wound on a slotted aluminium
alloy flux excluder, which also withstands the magnetic forces.   With
such a coil the magnetic flux surfaces may in principle have any arbit-
rary shape, provided axial symmetry is maintained.

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June 1967   (MEJ)

C O N T E N T S

1. INTRODUCTION

The fast rising magnetic fields used in plasma compression experiments are usually set up by energising a one-turn coil from a parallel-plate transmission line connected along the entire length of the coil. This method is impractical where the space outside the coil is everywhere surrounded by a vacuum chamber and is not available for connecting purposes. In this case, it is necessary to feed the coil axially. Such a coil consists of a number of spirally wound strips, arranged in two layers, and connected in parallel at one end of the coil, as in Fig.1. Straight cylindrical coils of this type have been proposed or constructed elsewhere[1,2,3,4]. The theoretical principles of axially-fed coils of a more general shape have also been derived[5]. With these coils a fractional number of turns is easily obtained, which facilitates design optimisation. Also field non-uniformities associated with feeding arrangements in side-fed coils are largely avoided.
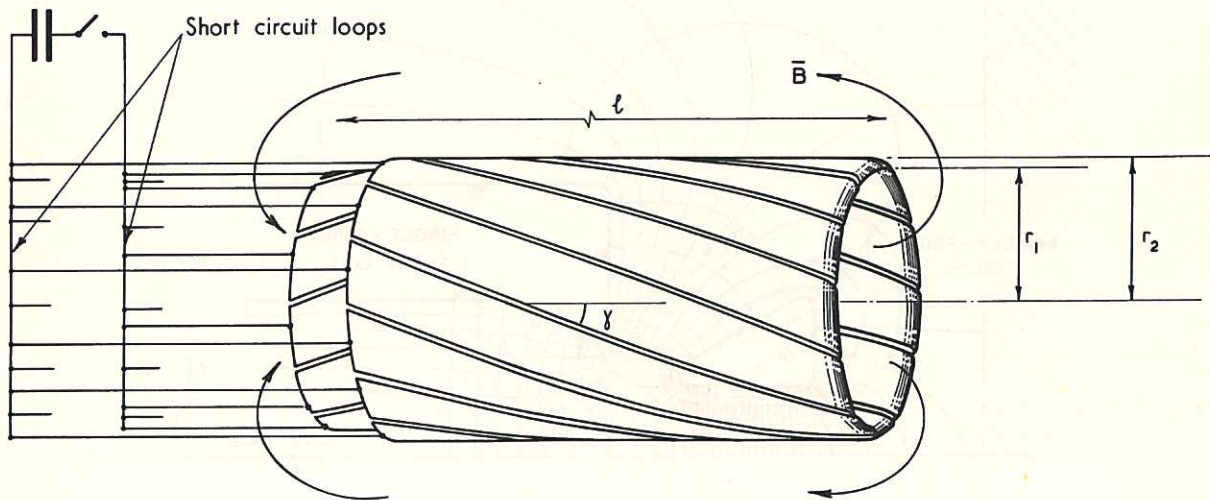

Fig. 1 Straight cylindrical coil

The coil described below differs from previous designs in that the two winding layers are not placed close to each other, and are not of the same shape, though axial symmetry is still maintained. A metal flux excluder, in the space between the winding layers, ensures that no extra leakage-inductance is introduced. One of the disadvantages of axially fed coils is that the windings are not mechanically very strong for withstanding large radial magnetic pressures. In the present design this difficulty is overcome by arranging that these forces are contained by the flux excluder.

The coil is 8 cm inside diameter, 8 cm long, and its outside conical surface varies from 10 cm to 16 cm diameter. It is designed to give a peak magnetic field of 100 kG, at a current of 1·25 MA, rising in 2·5 μsecs. It is connected to a 40 kV low inductance capacitor bank by coaxial cables, a collector plate and a coaxial transmission line.

2. MAGNETIC FIELD CONFIGURATION

The coil is required to give the magnetic field configuration shown in Fig.2 (polar co-ordinates r,θ,z are used), inside the coil the magnetic field is generally in the z direction, while outside the field lines are required to take up a specified conical form, so that the field $B_W = \sqrt{B_r^2 + B_z^2}$. In the outer region the field is influenced at one end by an adjacent single turn coil of opposite polarity, and at the other by the presence of a metal wall of the vacuum chamber. The latter forms a short-circuited turn, and so prevents field lines passing outside it.
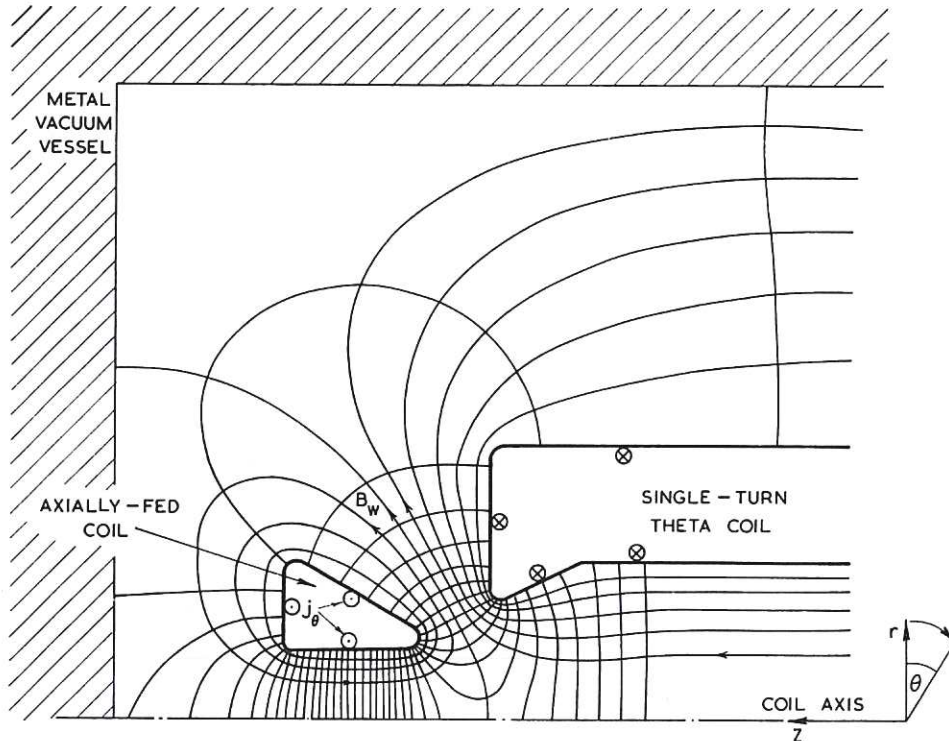

Fig. 2 Magnetic field plot

The annular flux excluder shown in Fig.3 reduces the space occupied by the B_θ field that exists between the inner and outer winding layers, because the field cannot penetrate the metal appreciably during the current pulse. It consists of a continuous ring at its wide end to ensure that it has sufficient mechanical rigidity. The magnetic flux cannot pass through this short circuited region and therefore emerges through the ten flux shots (Fig.3). In this region the winding strips are directed axially and positioned between the slots so that the latter are not obstructed by metal conductors. The slots are continued to the narrow end of the flux excluder by means of 1 mm wide slits to prevent the coil being short-circuited. If the number of parallel winding strips is m, the fractional number of turns per strip that can be obtained with the arrangement is a multiple of $1/m$.

In general, with fast rising fields, the winding strips must be connected in parallel sufficiently far from the coil, so that the resulting short-circuited loop (Fig.1) does not affect the coil flux distribution. The winding strips cannot therefore be made by splitting the central region of a cylindrical tube, as has been proposed previously[4].
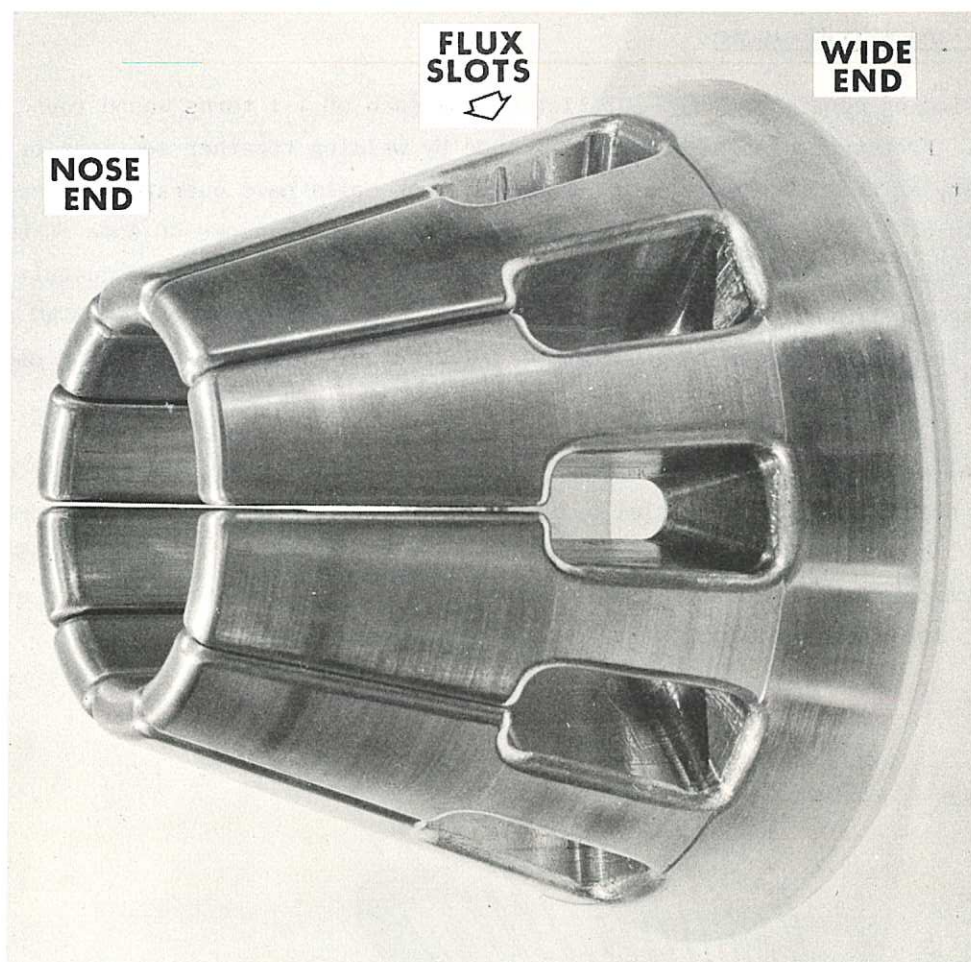
FLUX SLOTS

NOSE END

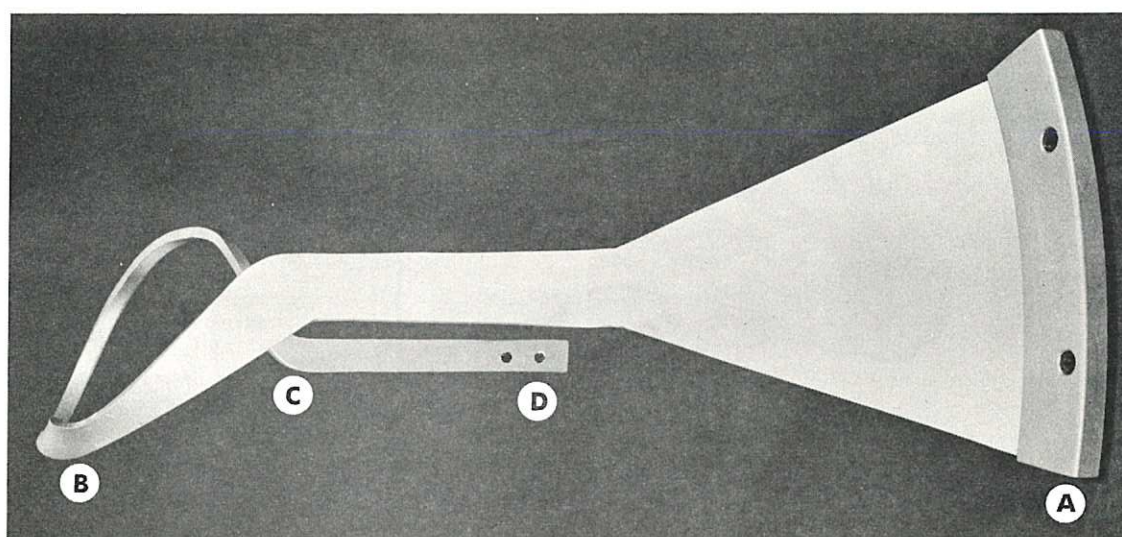WIDE END

Fig. 3 Flux excluder

B

C

D

A

Fig. 4 Winding strip

3. COIL CONSTRUCTION

Winding Strips and Flux Excluder

The coil winding consists of ten parallel strips each of 1·1 turns wound round the flux excluder. Prototype winding strips were made by welding together sections of aluminium alloy sheet, as this made manufacture easier. Such coils have operated successfully at a peak field of 50 kG. However, during preliminary tests fracture of some of the strips occurred at a weld near the nose of the coil, where the strips were not adequately supported. This suggests that a welded construction will not be satisfactory at 100 kG and so strips formed from a continuous length of 5 mm thick copper sheet are now being used as in Fig.4.

The general arrangement of the complete assembly is shown in Fig.5. The inside ends of the strips are connected in parallel by the continuous ring of the flux excluder. The other ends of the strips are terminated by the high voltage collector plate to 156 coaxial cables at 70 cms diameter. The termination can be enclosed and pressurised with air at up to 30 p.s.i.g. for working at 60 kV if required.
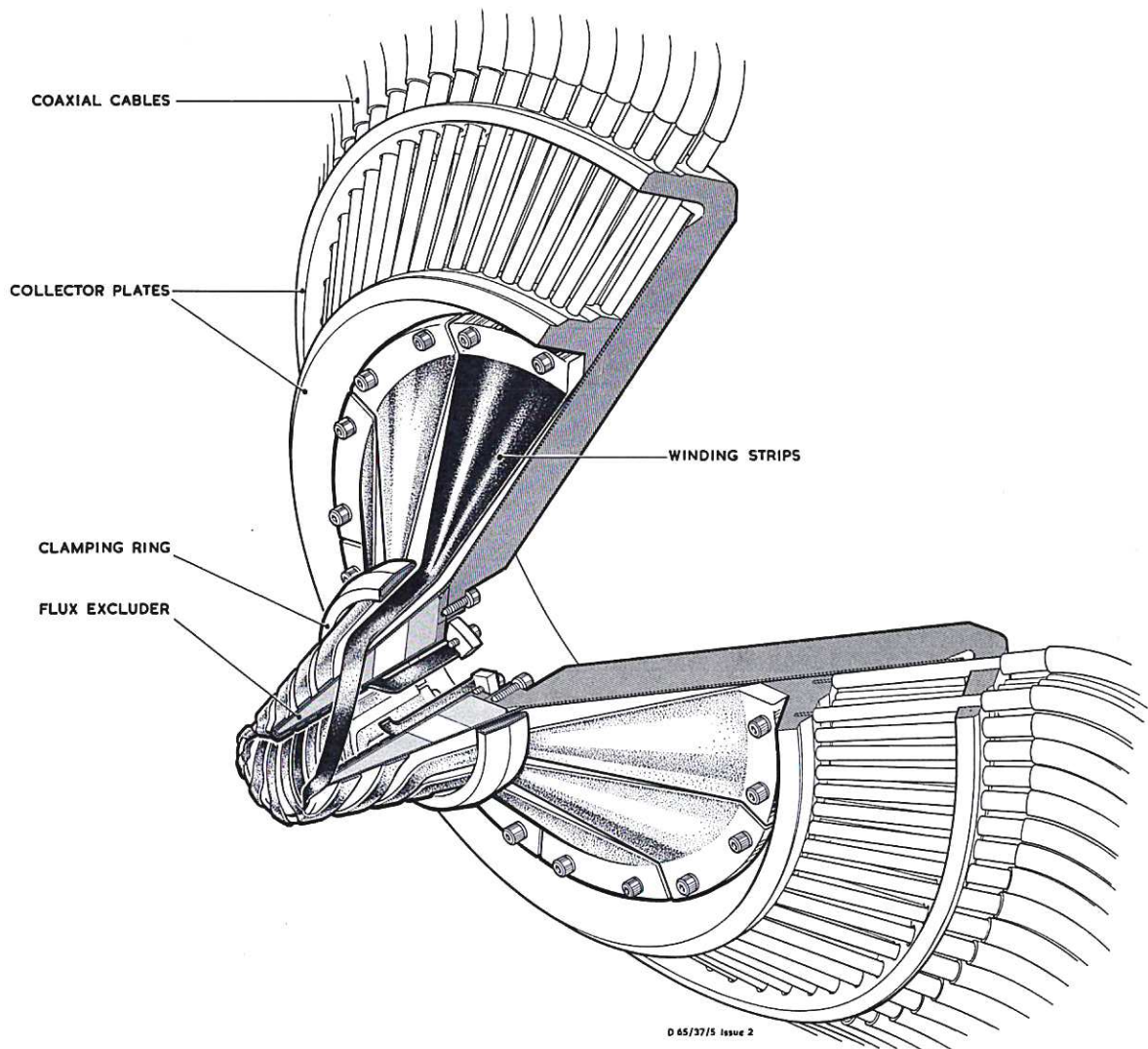

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Fig.5 Coil assembly

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The flux excluder and winding strips are insulated with moulded silicone rubber and polythene tape respectively. The main insulation between these two items is provided by a 1·5 mm polythene shroud, to give a total thickness of 2 mm.

Magnetic Forces

The resultant magnetic forces on the complete coil assembly, are due to the magnetic pressure $B_W^2/2\mu_0$ on the outside surface of the winding strips. At peak current there is an outward axial component of 30 tons due to repulsion by the adjacent single-turn coil, and a net radial load on each segment of the flux excluder of 3 tons per inch axial length. These segments can withstand the radial forces, because they are supported as cantilevers from the continuous ring of the flux excluder. The latter transmits the axial forces to the coil support structure.

If the B_θ field between winding and flux excluder exceeds the field B_W on the outside surface of the winding a magnetic pressure $\frac{1}{2\mu_0}(B_\theta^2 - B_W^2)$ is exerted on the winding, away from the flux excluder. In these regions (AB and CD in Fig.4) the winding is restrained by clamp rings, placed inside and outside the continuous ring of the flux excluder.

4. THEORETICAL PRINCIPLES

The general case of a winding of any arbitrary shape, with axial symmetry, mounted on a flux excluder of similar shape will now be considered. Fig.6 shows such a winding, only part of one strip being shown for clarity. The following symbols are used:-

$I_{(\theta)}$	-	coil ampere - turns
k	-	number of turns
I	-	total coil current (from capacitor bank)
w	-	co-ordinate along a line of intersection of the coil's surface with the r, z plane.
s	-	co-ordinate along a strip
ℓ_w	-	total length (both layers) along w co-ordinate
Δw	-	strip width in r, z plane
$\Delta x = r\Delta\theta$	-	strip width in the θ-plane
α	-	angle between z and w directions
β	-	angle between s and w directions
γ	-	angle between s and z directions
t	-	insulation thickness
m	-	number of strips

M.K.S. units are used ($\mu_0 = 4\pi \cdot 10^{-7}$)

The 'inside' surface of the winding is that facing the flux excluder, the other surface being the 'outside' surface. The magnetic field (or current density) at the inside and outside surfaces are referred to as the internal and external magnetic field (or current density) respectively.
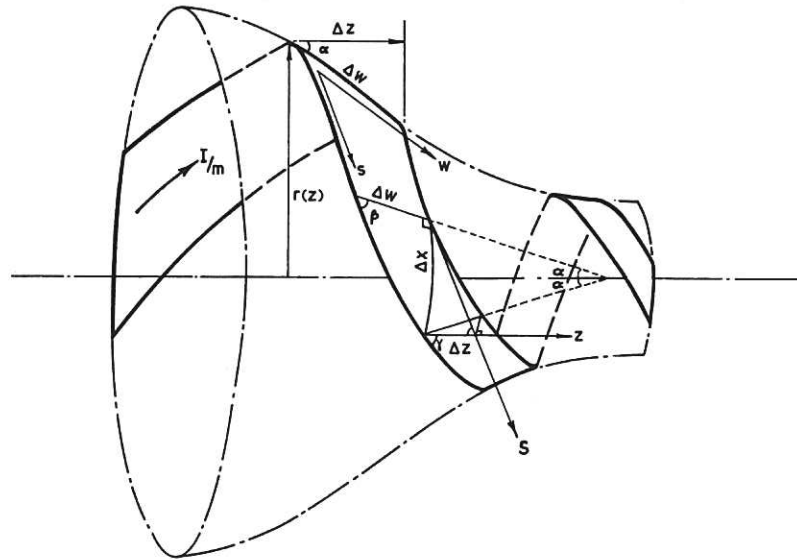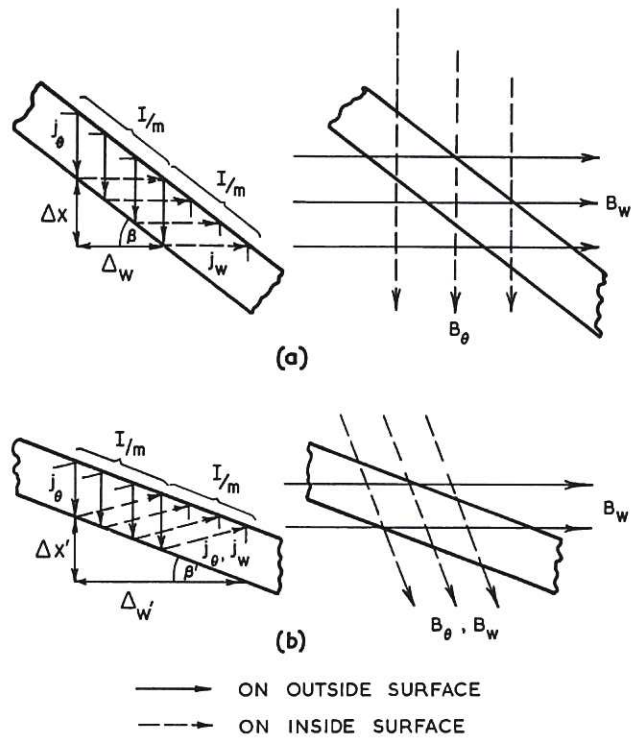
Fig. 6 Coil with varying radius

(a)

(b)

───────▶ ON OUTSIDE SURFACE

─ ─ ─ ─▶ ON INSIDE SURFACE

Fig. 7 Current distribution round a winding strip

Number of Turns (k) and External Field Configuration

Provided the field penetration depth is small compared with the conductor thickness, the skin currents on the conductor surface always flow perpendicular to the surface magnetic field. Thus the current flows in a thin skin on the outside surface of the winding in the θ-direction only, since the external field B_w is in the r,z plane. The line density j_θ of this external current is therefore:

$$j_\theta = \frac{B_w}{\mu_o} = \frac{\sqrt{B_r^2 + B_z^2}}{\mu_o} \qquad \dots (1)$$

B_w is deduced from the flux plot in Fig.2. Such a plot can be obtained using a digital computer, electrolytic tank or a field sketching method[6].

The coil-ampere turns $I_{(\theta)}$ are obtained by integrating B_w or j_θ round a closed path along the w co-ordinate in the r,z plane.

$$I_{(\theta)} = \frac{1}{\mu_o} \oint_w B_w d_w = \oint_w j_\theta dw .$$

$I_{(\theta)}$ is the current that would flow in a conventional single turn theta-coil, to set up the same magnetic field, and equals the effective coil ampere-turns. The required coil current I is related to the capacitor bank parameters and the current rise time in the usual way. The required number of turns k can then be deduced from the ratio $I_{(\theta)}/I$ and is related to j_θ by:

$$k = I_{(\theta)}/I = \frac{1}{I} \oint_w j_\theta dw. \qquad \dots (2)$$

Winding Angle (β) and Internal Field Configuration

It is desirable that the winding angle β be chosen such that there are only B_θ and j_w components on the inside surface of the winding strip. Failure to do this (though still maintaining correct number of turns k) introduces parasitic internal j_θ components, with corresponding flux entering or leaving the inside of the winding between the edges of the conductors. This causes increased magnetic forces and ohmic losses, and may give rise to local regions of very high current density and magnetic pressure.

The current distribution and magnetic field for correct and incorrect values of β, are given in Fig.7a and 7b respectively. In the former case B_θ is the internal magnetic field and j_θ and j_w are the external and internal current line densities respectively. From Fig.7a it follows that:

$$j_\theta = \frac{I/m}{\Delta w} \qquad \dots (3)$$

$$j_w = \frac{I/m}{\Delta x} = \frac{1}{2\pi r} .$$

The winding angle β should therefore satisfy:

$$\tan \beta = \frac{\Delta x}{\Delta w} = \frac{j_\theta}{j_w} = j_\theta \cdot \frac{2\pi r}{I}. \qquad \dots (5)$$

It follows from equations (2) and (5) that:

$$k = \oint_w \frac{\tan \beta}{2\pi r} \, dw \qquad \qquad \dots (6)$$

In the case of a straight cylindrical coil as in Fig.1 where ℓ is the coil length and Υ is the winding angle, equation (6) becomes:

$$k = \frac{I_{(\theta)}}{I} = \frac{2\ell}{2\pi r} \tan \Upsilon . \qquad \qquad \dots (7)$$

It should be noted that $I_{(\theta)}$ does not equal $I \sin \Upsilon$, the component of I in the θ-direction, as implied previously[1].

Fig.7 shows that the current flows spirally round each strip. In the present application most of the return flux is close to the outside diameter of the coil (Fig.2), and the corresponding values of j_θ and the angle β are appreciable in this region. However, the maximum value of j_θ occurs at the inside diameter of the coil and therefore a still higher value of β is required there.

Coil Parameters

If φ_w is the total external flux (i.e. outside the winding) the associated inductance L_w, referred to the winding current I, is:

$$L_w = \frac{k \, \varphi_w}{I} = \frac{k^2 \varphi_w}{I_{(\theta)}} . \qquad \qquad \dots (8)$$

The magnetic flux φ_θ, inside the winding, links the total winding current I, and gives rise to a leakage inductance L_θ. If B_θ is the θ-component of the internal magnetic field (the only component for correct value of β), then:

$$B_\theta = \frac{\mu_o I}{2\pi r} \quad \text{at} \quad r, z \qquad \qquad \dots (9)$$

$$L_\theta = \frac{\varphi_\theta}{I} = \frac{t}{I} \int_0^{\ell_w} B_\theta \, dw = \frac{\mu_o t}{2\pi} \int_0^{\ell_w} \frac{dw}{r} . \qquad \qquad \dots (10)$$

The total coil inductance L is given by:

$$L = L_w + L_\theta = \frac{k}{I_{(\theta)}} \, (k\varphi_w + \varphi_\theta) . \qquad \qquad \dots (11)$$
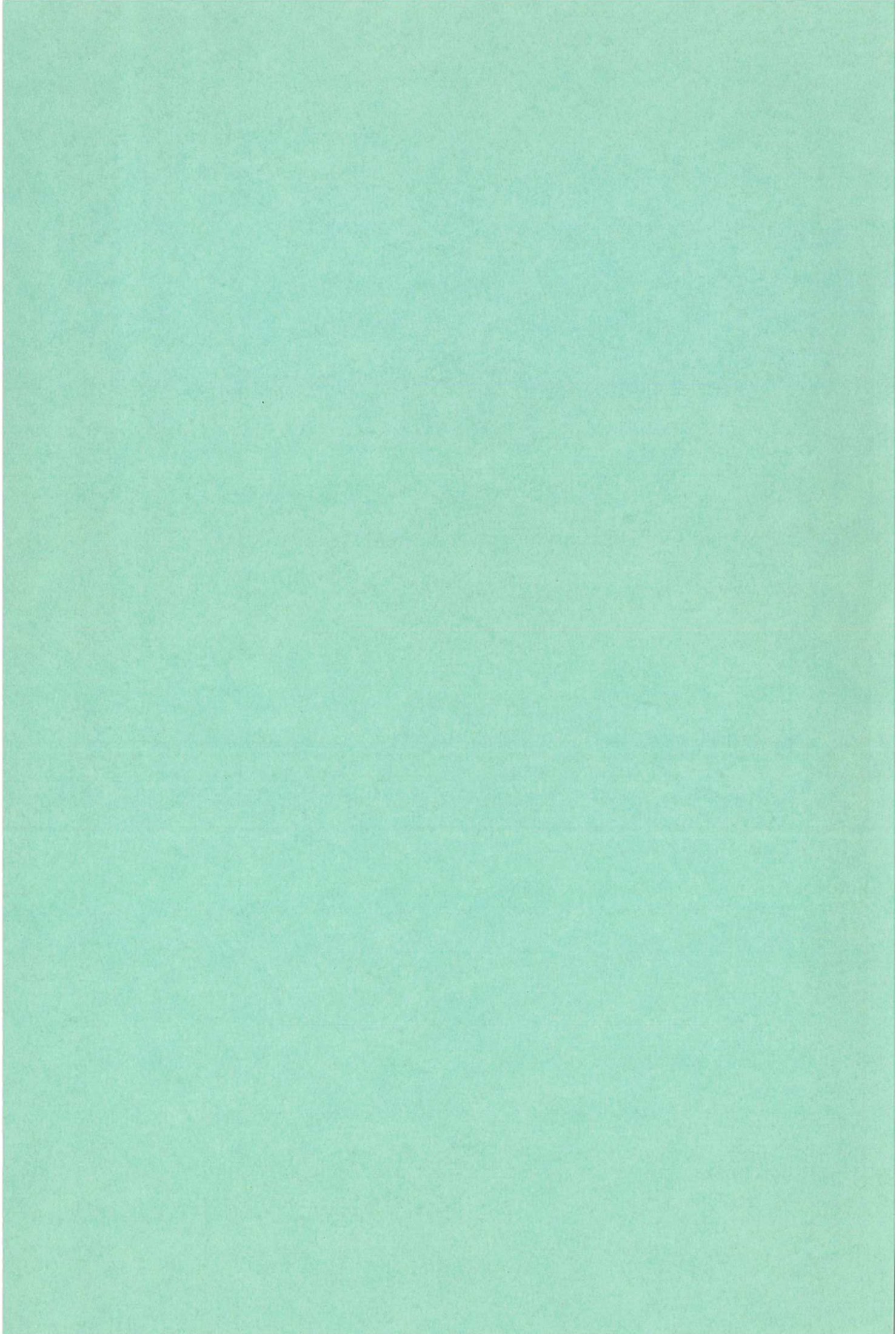
The inductances of the present coil design are:

Inductance L_w	40 nH
Leakage inductance L_θ	8 nH
Coil inductance	48 nH (confirmed experimentally)

5. ACKNOWLEDGEMENTS

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