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Aspects of a Pulsed Superconducting Bending Magnet

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Zusammenfassung

Verschiedene Wicklungsquerschnitte zur Erzeugung homogener Felder in gepulsten supraleitenden Synchrotronmagneten werden beschrieben. Zur Kühlung wird die Einfügung von senkrechten Kühlkanälen in den Wicklungsquerschnitt vorgeschlagen, durch die das Kühlmittel strömt. Es wird gezeigt, daß eine Dipolkonfiguration mit Stromrückführungen an den Wickelköpfen senkrecht zur Magnetachse und gleichlangen longitudinalen Wicklungsabschnitten ein über die Apertur konstantes $\int$Bdl erzeugt.

Diese Gesichtspunkte werden in einem Konstruktionsvorschlag für die Wickelkonfiguration eines 50-KGauss-Biegemagneten berücksichtigt. Die Aufteilung in Einzelspulen und deren Herstellung aus einfach zu wickelnden Flachspulen wird beschrieben.

Abstract:

Various winding **cross** sections for generation of uniform fields in pulsed superconducting synchrotron magnets are described. For cooling the insertion of vertical cooling channels in the winding cross section is proposed through which the coolant flows.

It is shown that a dipole configuration with current return paths at the coil ends perpendicular to the magnet axis and longitudinal straight winding sections of equal length generates a $\int$Bdl constant over the aperture.

These points are taken into account in a proposal for the coil design of a 50-KGauss bending magnet. The subdivision into coil packets and the fabrication of the single coils are described.

Contents:

1. Introduction

Since superconducting multifilament wires are commercially available, which exhibit good stability and low losses during pulsed operation it seems favorable to construct superconducting synchrotron magnets.

At the achieved high fields (~ 50 KGauss in dipoles) the usual magnet design with field shaping iron is senseless. Dipole and quadrupole fields are therfore generated with aircored coils and iron is only located around the coil for shielding and field enhancement.

For coil design the $\cos\vartheta$ -current distribution (1)($\cos 2\vartheta$ for quadrupoles) and the intersecting ellipses type with uniform current density (4)have been studied. Theoretically there exists an infinite number of coil cross sections giving a pure dipole or quadrupole field which normally cannot be derived analytically. In 2.4 a numeric procedure is described which iteratively generates dipole configurations from a zeroth approximation.

During cycling the a.c. —losses should not rise the conductor temperature by more than 0.1 - 0.2 K against the coolant temperature. In the proposed dipole version cooling is provided by vertical cooling channels in the winding and immersion of the whole assembly into liquid helium.

The beam optical properties of a bending magnet are governed by the dependence of $\int Bdl$ across the useful aperture.

A non uniform $\int Bdl$ has two sources of error:

a) a non uniform field in the aperture; $\frac{\Delta B}{B}$ should be less than 10^{-3} in the useful aperture.

b) end fields produced by finite magnet length and current return paths.

Errors from a) arise mainly from mechanical tolerance in coil dimensions.

The influence b) of magnet ends on $\int Bdl$ is difficult to evaluate. But in the following a method in described to estimate the influence of winding ends and giving hints for a design with minimum variation of $\int Bdl$.

2. Generation of uniform magnetic fields.

2.1 $\cos\vartheta$-current distribution

An axial current distribution $I(\vartheta) = I_n \cos n\vartheta$ on a cylinder of infinite length produces in the cylinder a pure 2n-pole field. $I(\vartheta) = I_1 \cos\vartheta$ produces thus an uniform field. $I(\vartheta)$ must not be confined to an infinitesimal thin layer.

The $\cos\vartheta$-current distribution is approximately realized by winding blocks of uniform current density as shown in fig. 1a,b. By choosing the sector angles ϑ_i adequately, a number of disturbing multipole components in the aperture can be made zero.

With this system a number of dipoles and quadrupoles have been built[2)3)] with superconducting tapes and braids.

For the desired high field quality some difficulties arise to meet the mechanical tolerance requirements for this shape with SC wires or cables.

2.2 Intersecting ellipses

In the intersecting area of two ellipses with half axes a and b and counterflowing uniform current densities, which are horizontally displaced for 2X1 a dipole field

$$B = 0.8\pi \frac{X1 \cdot b}{a+b} \quad (\text{Gauss, A/cm}^2\text{,cm})$$

can analytically be derived [4)](Fig.2).

For two reasons this ideal configuration is not easy to realize, first a wire or cable winding with a complicated outer contour is difficult to manufacture with sufficient accuracy and second in the winding cross section heat removal by heat drains or cooling channels is essential to prevent temperature rise and resulting reduction of the critical current.

2.3 Approximation by rectangular winding packets.

Without affecting the field homogenity seriously the winding area may be subdivided into coils with rectangular cross section which are easier to fabricate. This is shown in Fig. 3 for a intersecting ellipses dipole giving 50 KGauss at an average current density in the winding of 50 KA/cm^2.

The grade of subdivision is governed by the field tolerances and the cooling requirements.

The hysteretic losses as main loss source give following the Kim-model a loss rate q per volume

$$q = \frac{1}{t} \cdot \frac{d}{2}\ \mu_o J_o H_o \ln \frac{H_1 + H_o}{H_o}$$

t (sec): cycle time
d (cm) filament diameter
H_1: Peakfield
$\mu_o H_o$: 10 KG typically
$\mu_o J_o H_o (\frac{Ws}{cm}4)$ averaged over winding

This leads to a quadratic temperature profile in the coil of thickness D with a maximum rise against the surface (at $\mu_o H$ = 50 KG, J_{max} = 50KA/cm^2)

$$\Delta T = \frac{D^2 d}{t} \cdot \frac{3.4}{\lambda} \quad (K)$$

λ is the heat conductivity of the winding transverse to the wire direction.

With an allowed ΔT of 0.1K, d = 0.001 cm, t = 6 sec, $\lambda = 2.10^3 \frac{W}{cmK}$ 6) a packet thickness D ≈ 0.6 cm results.

As was experimentally verified (7), a further temperature step of 0.01 - 0.1K occurs at the surface.

Helium circulation is supported in the vertical cooling channels by the ascending helium gas.

With the configuration of Fig.3 a field error $\leq 5 \cdot 10^{-4}$ in a circle with 3 cm radius was found by computer evaluation.

2.4 Computer generated Winding Configurations.

As mentioned, there exists an infinity of coil configurations generating an uniform field.

To be more flexible in the form of the aperture and to take into account an iron shield of arbitrary contour a FORTRAN program 5) was developed which analyses the (two dimensional) aperture field of an assembly of rectangular coil cross-sections and varies the coil dimensions (e.g. the height) such that undesired multipoles are partly reduced. Beginning with a zeroth approximation this procedure is repeated iteratively until the field quality is satisfying. Fig. 4 shows a dipole configuration so obtained without iron shield. At a number of points on the iron contour an iron induced multipole expansion is fitted so that the sum field meets the boundary condition for $\mu = \infty$ of vanishing tangential field component.

3. End fields.

3.1 Influence of the coil ends on $\int Bdl$.

For the dynamics of the particles in an accelerator in first approximation only the totally passed field, for a dipole $\int_{-\infty}^{+\infty} Bdl$, is significant.
From the middle part of the magnet a constant contribution over the aperture is achieved by a uniform field. The contribution of the end parts is difficult to evaluate in a straight forward manner by numerical integration of field values particulary if iron is involved. Thus a method is proposed to estimate the influence of ends and to give constructive hints for minimal perturbation of $\int Bdl$.

The considerations are presented in four steps:

a) The integral $\int_{-\infty}^{+\infty} Bdl$ is taken on straight lines parallel to the axis (Fig. 5a at point c).

b) The integration path can be cut into two parts and the two integrals can be interchanged:

$$\int_{-\infty}^{+\infty} Bdl = \int_{-\infty}^{c} Bdl + \int_{c}^{+\infty} Bdl = \int_{c}^{+\infty} Bdl + \int_{-\infty}^{c} Bdl$$

c) The integral value remains invariant if the magnet is thought to be cut by a plane perpendicular to the axis at point c and the two halves with the surrounding field are moved along the axis arbitrarily.

As this procedure is not really performed it does not matter that at c no current return is provided and the field step at point c does not meet the Poisson equation.

d) If the displacement performed is such that the straight longitudinal coil sections fit together as sketched in Fig. 5b for a single winding, the contribution of these current elements must add to the ideal field of an infinite long configuration.

If this generates a uniform field, the only contribution to a variation $\delta\int Bdl$ over the aperture arises from the solenoidal contribution of the current return paths.

3.2 Coil ends for constant $\int Bdl$

From the considerations in 3.1 if follows immediately that a constant $\int Bdl$-magnet can be designed, if all longitudinal portions of a uniform field configuration are of equal length and the currents in the return paths flow antiparallel (The same arguments hold for quadrupoles with constant integrated field gradient etc). The individual form of the return paths is irrelevant but should be perpendicular to the axis to prevent higher order effects on the particles.
The magnetic length is equal to the length of the longitudinal straight sections.
The arguments remain valid if a magnet in a infinite long iron shield with $\mu = \infty$ is regarded ("infinite long" means in practise, that the iron extends for one gap width beyond the coil ends).

4. Proposed coil design for a pulsed superconducting synchrotron bending magnet.

With the considerations developed before, the coil design for a pulsed superconducting synchrotron bending magnet is proposed. The length will be 100 cm, the maximum aperture field 50KGauss at an averaged current density in the winding of 50KA/cm^2. With respect to slow extraction a warm aperture of 7 x 4 cm was chosen.
For the uniform field coil configuration a type derived from the intersecting ellipses type may be applied or a computer generated type.
When iron shielding is included, even the intersecting ellipses have to be modified by the same computer procedure to eliminate iron induced multipoles.

The winding cross section is subdivided into vertical coil packets with thickness of 6 mm separated by cooling channels of 0.5 mm width as shwon in fig. 3 and 4. The coil packets are wound from multifilament wire, cable or braid and epoxy potted to give sufficient mechanical strength.

Thus the ideal uniform field cross section is realized only very coarsely but even so a calculated field accuracy of 2.10^{-4} in a circle of 6 cm diameter is obtainable.

The coilpackets are first wound as rectangular flat coils (Fig.6) on a removable former which can be bent for 90 degrees at two longitudinal axes after winding. After potting the so formed coil packets are piled to a dipole (or quadrupole) where the mean length of all longitudinal winding sections is equal and the return paths are perpendicular to the magnet axis to give a $\int Bdl$ as constant as possible (Fig.7).

Cooling is provided by simple immersion in liquid helium.

As this paper is only restricted to the shape and the fabrication of the winding itself, further important problems like shape of the iron shield, support of forces, cryostat design, selection of conductor etc. are not treated here.

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4) BETH, R.A.,	6th Conference High Energy Accelerators Cambridge, Mass. Sept. 11-15, 1967
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Figure captions

Fig. 1 a)b)	Approximations of ideal $\cos\delta$-current distribution for dipole magnets
Fig. 2)	Intersecting ellipses for uniform field. Aperture field 50K Gauss at current density of 50KA/cm^2.
Fig. 3)	Approximation to Fig.2 with coil packets
Fig. 4)	Computer generated coil geometry for uniform field: 53.6K Gauss at 50KA/cm^2.
Fig. 5 a)b)c)	Illustration for the derivation of end field influence
Fig. 6)	Fabrication of coil packets
Fig. 7)	Assembled dipole of intersecting ellipses type with vertical cooling channels and constant $\int Bdl$.

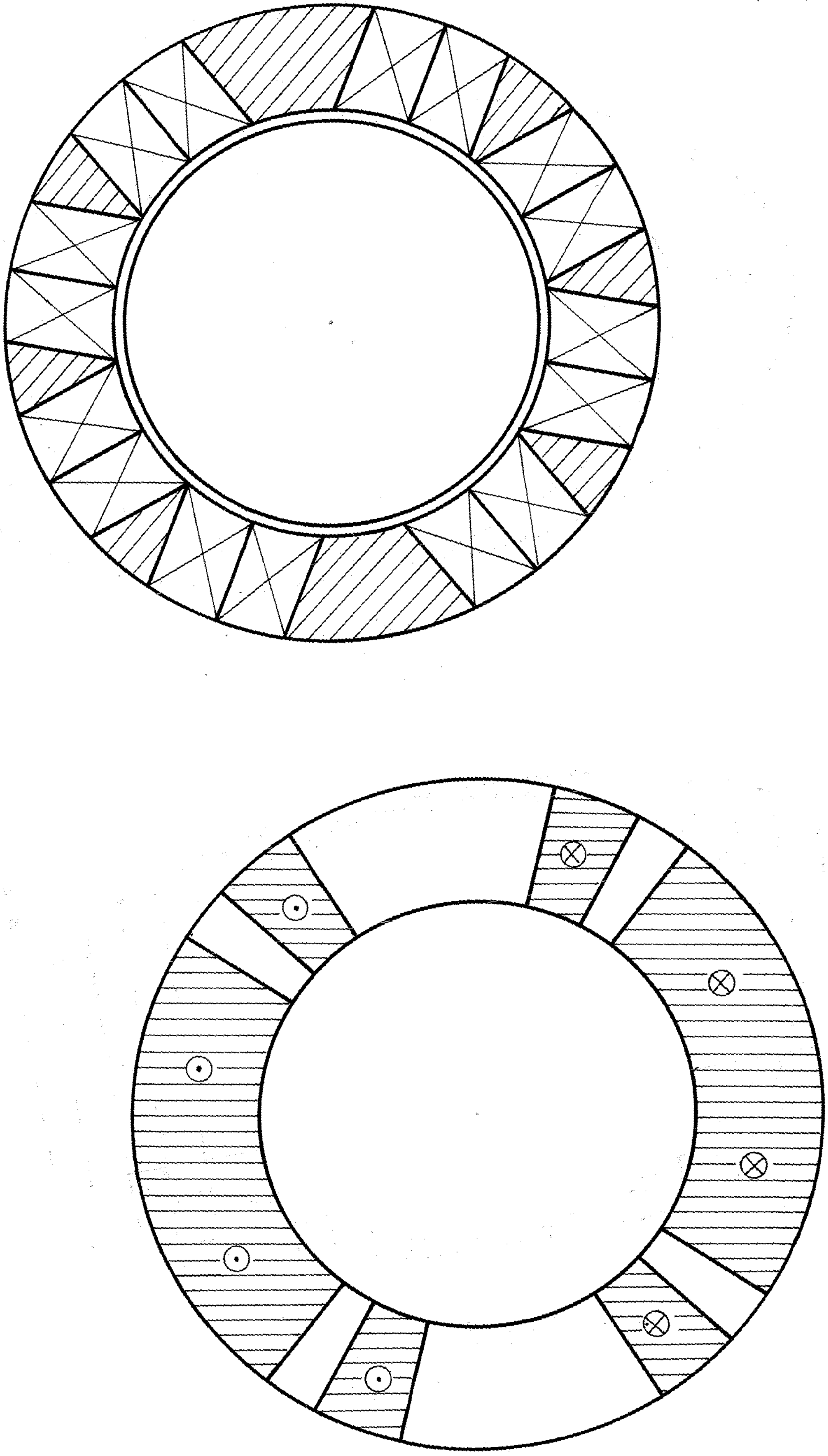

Fig.1

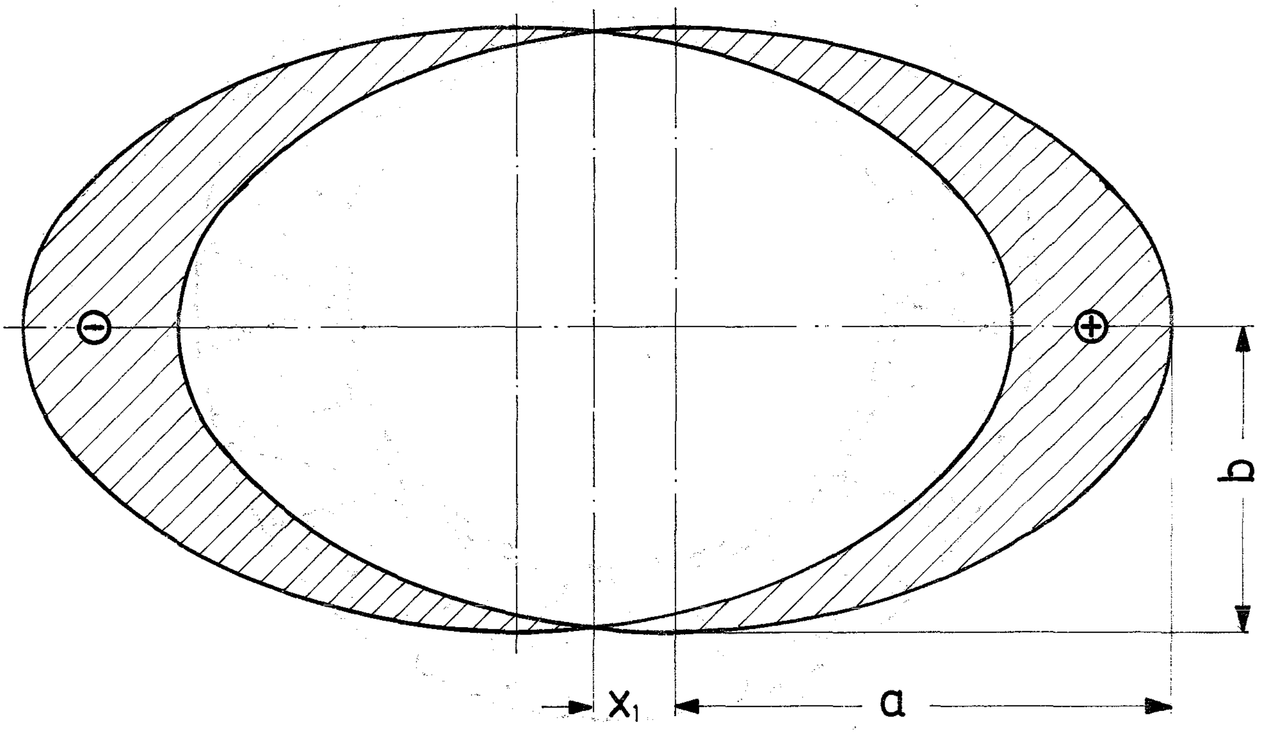

Fig. 2

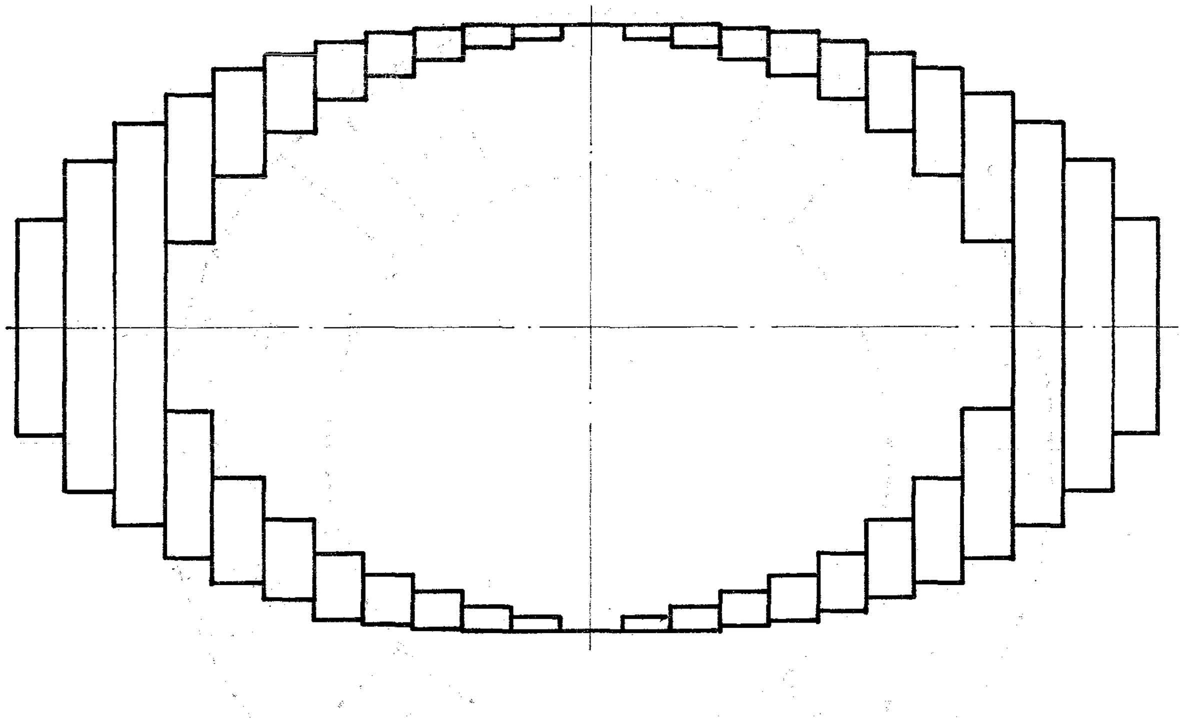

Fig. 3

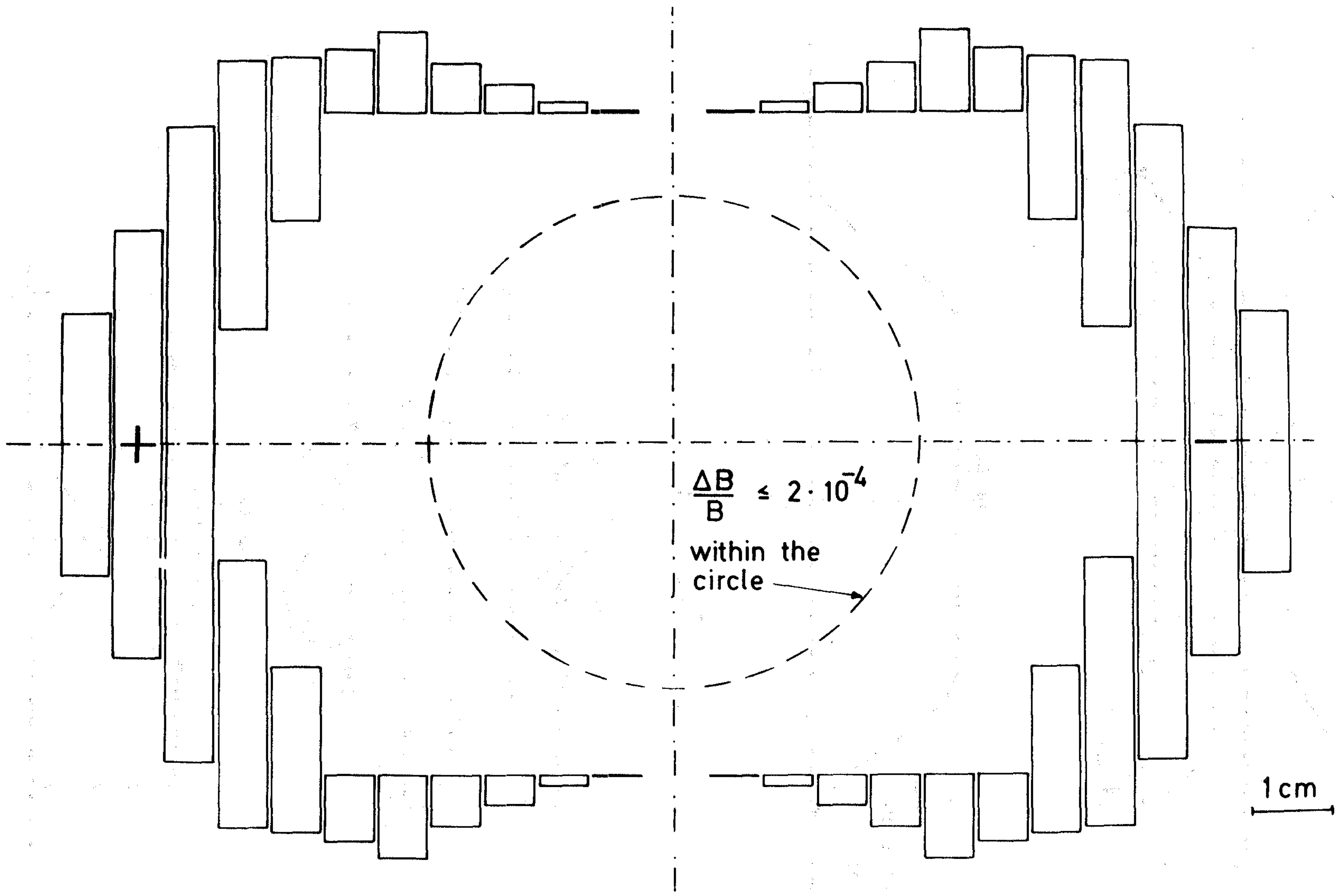

Fig. 4

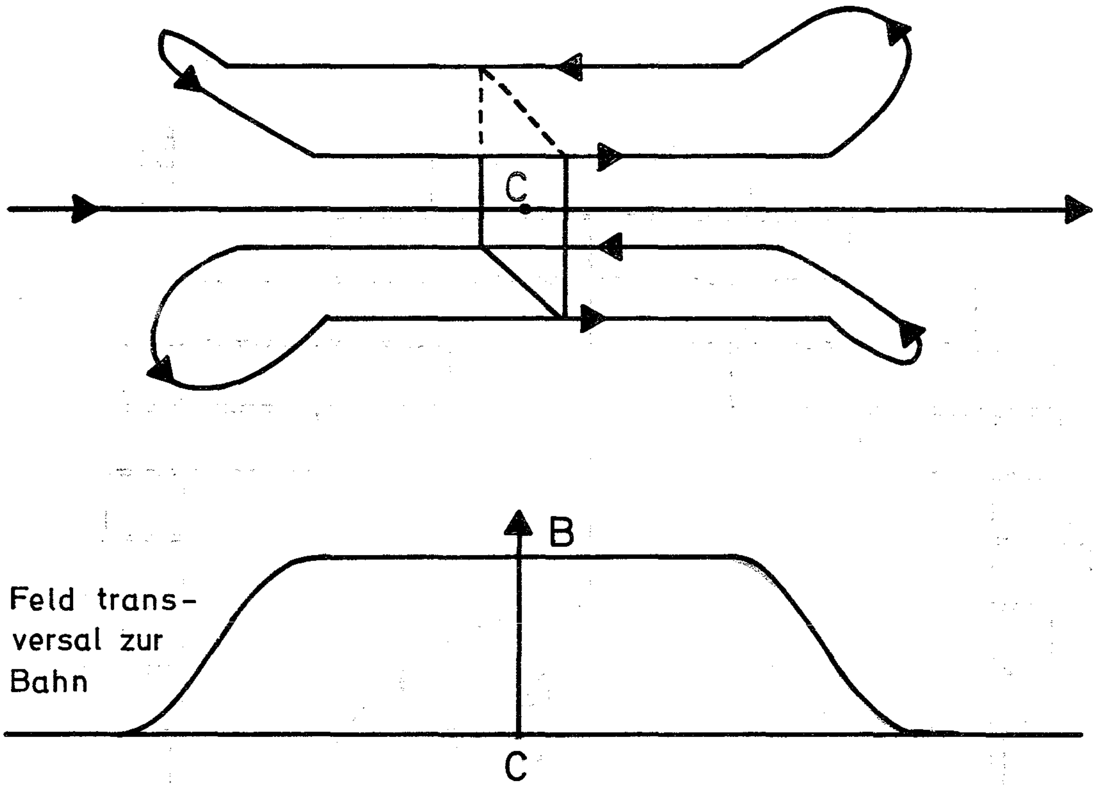

Fig. 5 a

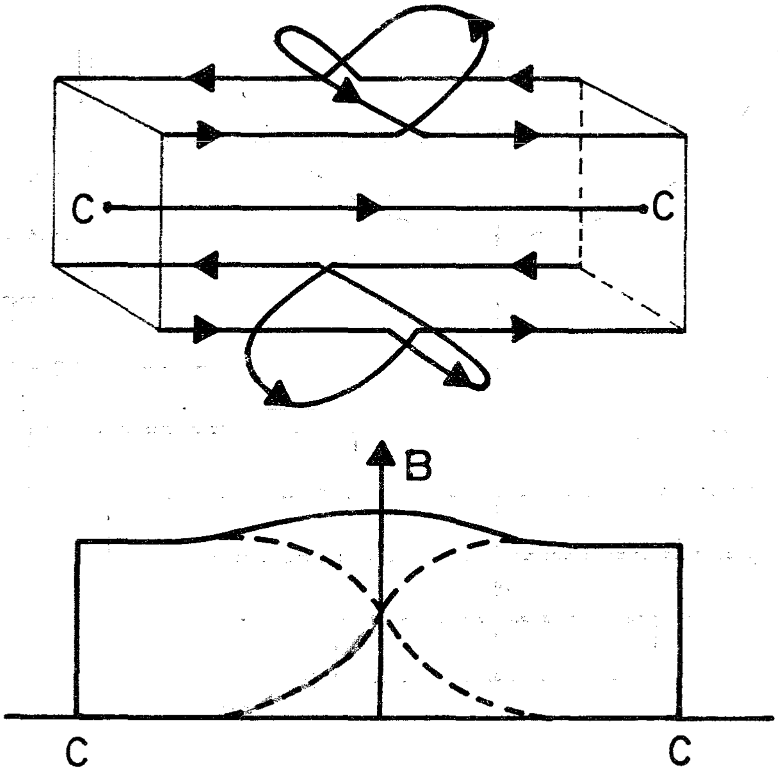

Fig. 5 b

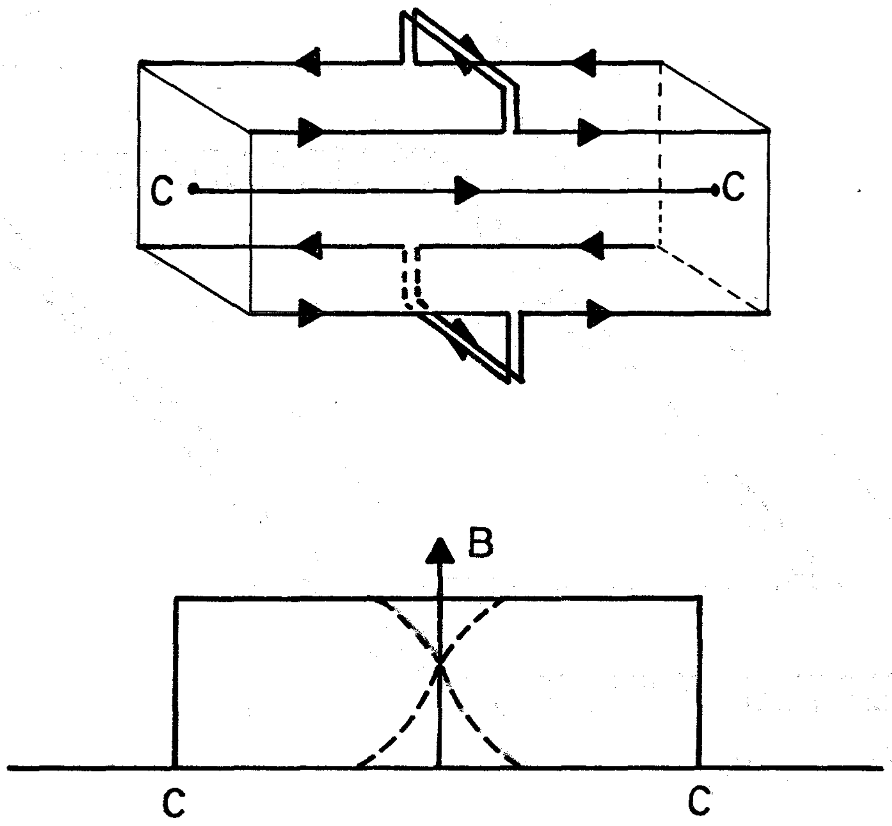

Fig 5c

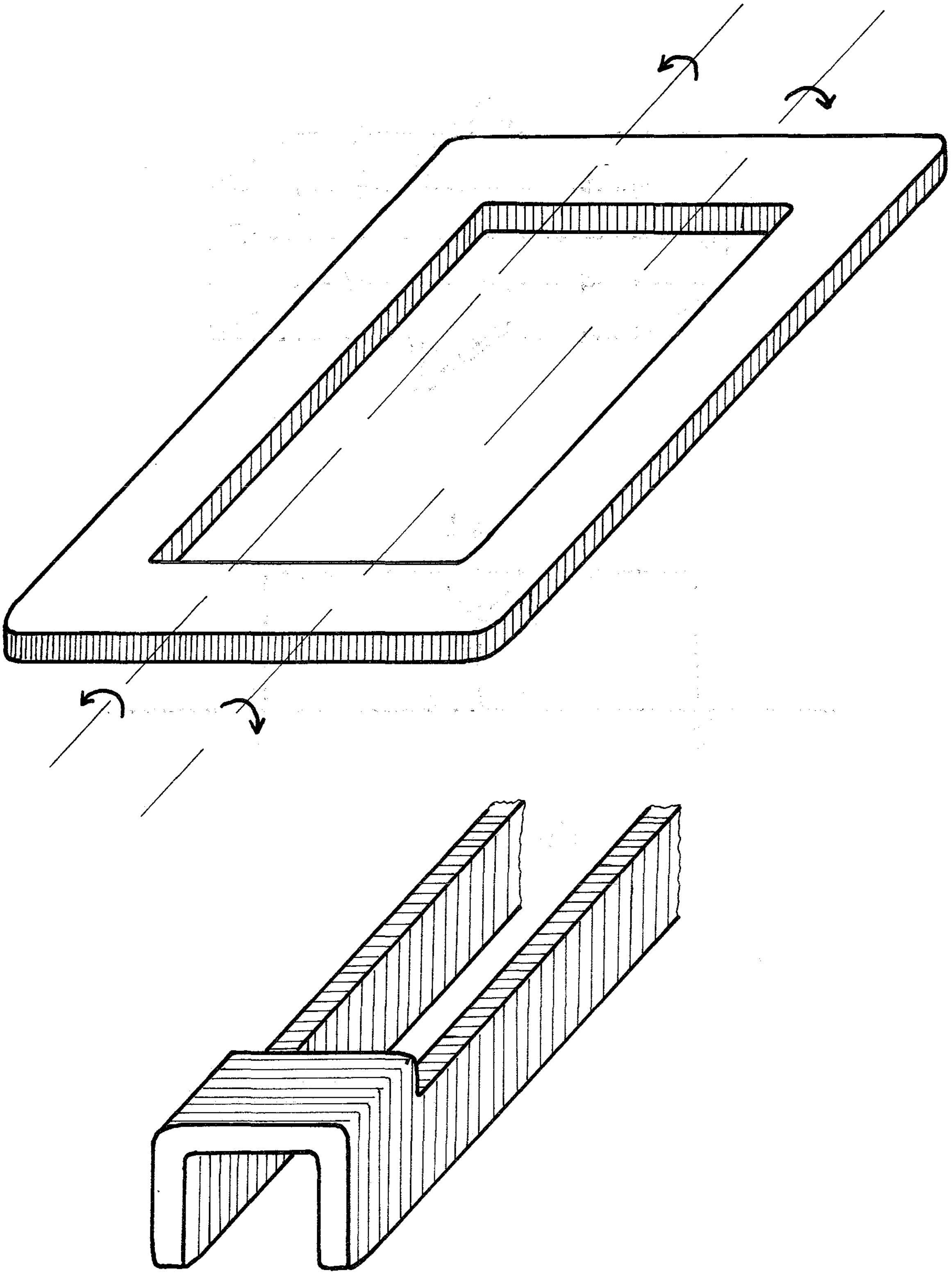
Fig. 6

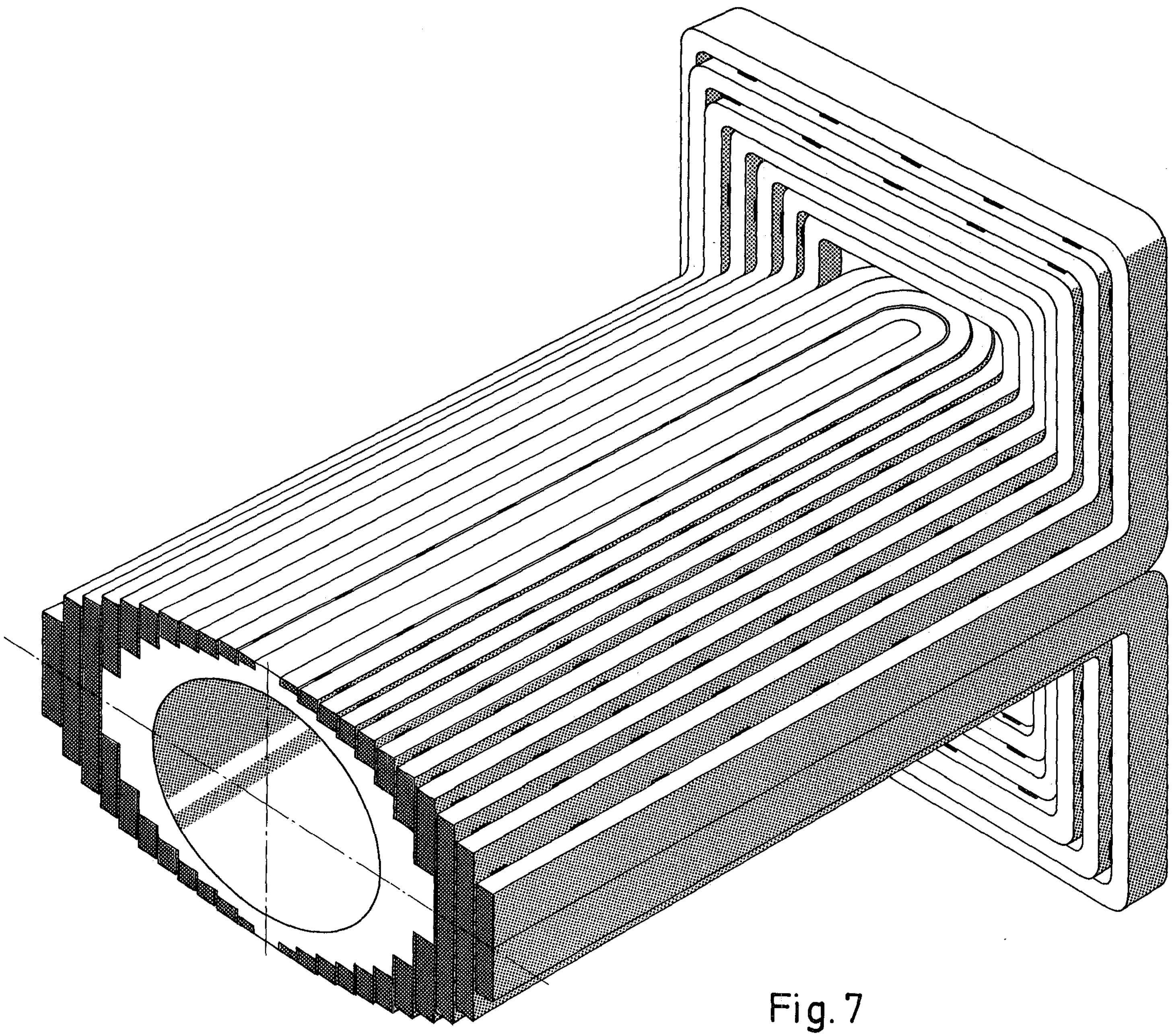

Fig. 7