

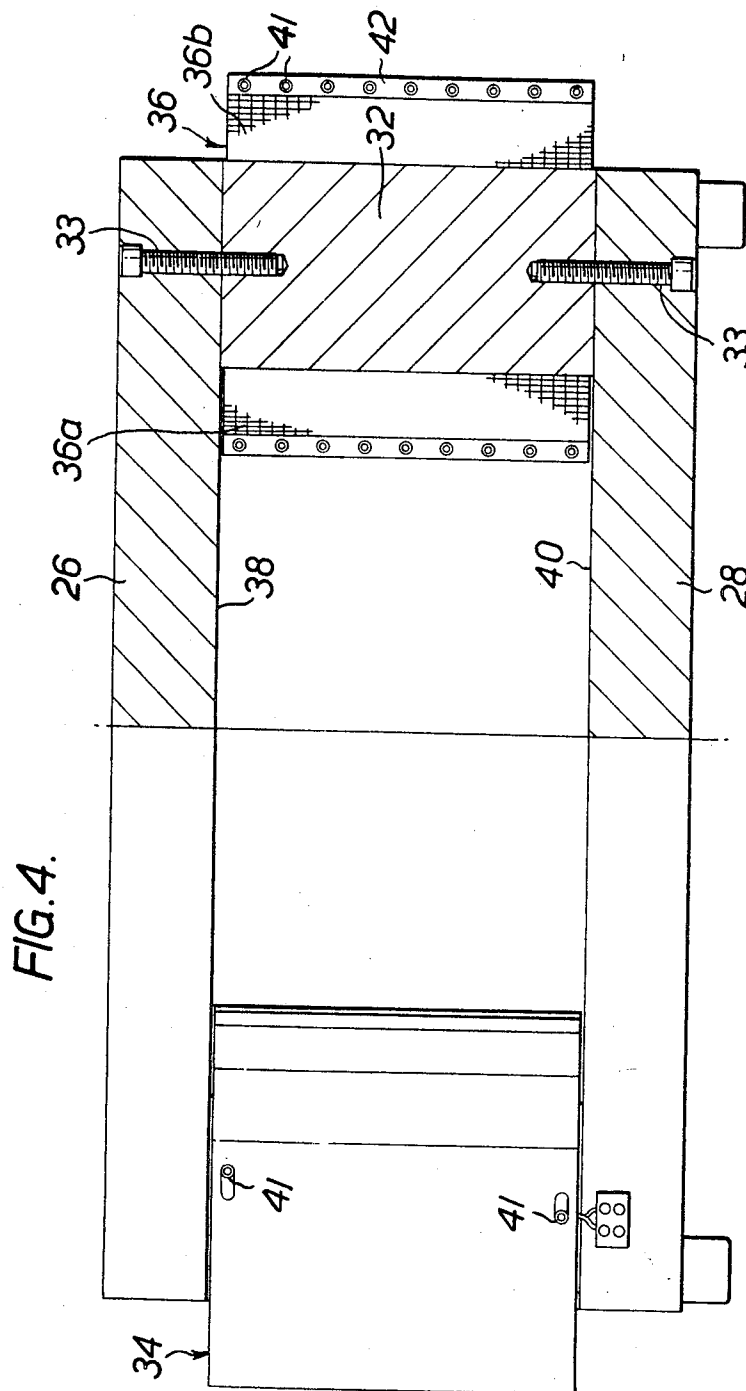
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E. WATSON ET AL
MAGNET ASSEMBLIES

3,513,422

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3 Sheets-Sheet 2



INVENTORS

EDWARD WATSON
DEREK WALTER PARKER
By Young & Thompson
ATTYS.

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FIG. 5.

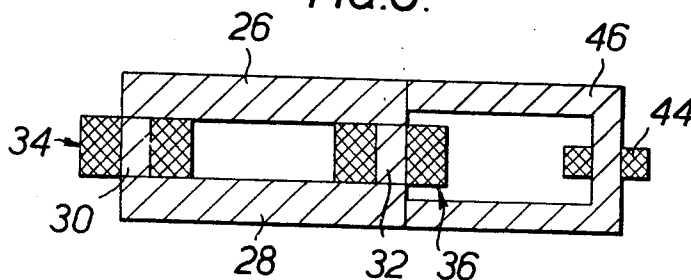


FIG. 6a.

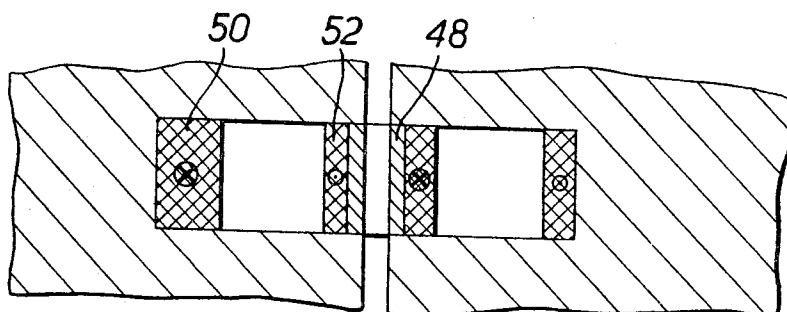
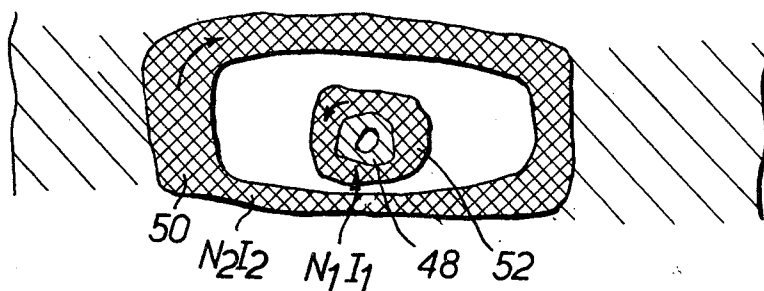


FIG. 6b.



INVENTORS

EDWARD WATSON

DEREK WALTER PARKER

By Young & Thompson
ATTYS.

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MAGNET ASSEMBLIES

Edward Watson, Hayling, and Derek Walter Parker, Newport, England, assignors to Newport Instruments Limited, Newport Pagnell, Buckinghamshire, England

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5 Claims

ABSTRACT OF THE DISCLOSURE

An electromagnet of basically open-ended rectangular configuration comprises two low-reluctance pole pieces and a pair of parallel yoke pieces therebetween, current loops being wound around the yoke pieces such that any cross-section through the windings is a rectangular of constant height equal to the spacing of the pole pieces, such that the current density in the windings has a predetermined distribution, and that the ampere-turns of the windings are equal and opposite.

This invention relates to electromagnets for producing highly homogeneous magnetic fields, as are required, for example, in conducting experiments on and observations of gyromagnetic resonance.

British patent specification No. 1,110,172 describes magnet assemblies which will provide a large useful volume of homogeneous magnetic field, wherein the magnetomotive force is generated either by permanent magnets or by current loops.

The field in the gap of a conventional electromagnet is set up between two surfaces which are defined by the pole tips and which are approximately equipotentials. The ratio of tip diameter to the gap length largely determines the homogeneity of the field in the gap. The homogeneity of the field can be improved by the use of shims, by careful treatment of the faces of the pole tips, and by ensuring that the pole tips are correctly aligned.

It is an object of the present invention to provide an improved electromagnet which provides a relatively large volume of highly homogeneous magnetic field.

In accordance with the present invention, an electromagnet comprises two spaced pole pieces of magnetic material of very low reluctance providing opposed plane parallel surfaces, a pair of parallel yoke pieces between said pole pieces, and a plurality of current loops wound around each yoke piece to provide a pair of coil portions inwardly of said yoke pieces which with said pole piece surfaces define the boundaries of an air gap between said pole pieces, wherein any cross-section through said coil portions is a rectangle of constant height equal to the perpendicular distance between said pole pieces, wherein the current density distribution in said coil portions is such that at any point on a line perpendicular to said pole piece surfaces at a constant distance from the edge of the coil portion $J_x = \text{constant}$, $J_y = \text{constant}$ and $J_z = 0$ where J is current density and x , y and z are mutually perpendicular axes with the z axis along said line, and wherein the ampere-turns of said coil portions are equal and opposite.

In order that the invention may be fully understood a number of embodiments in accordance therewith will now be described by way of example and with reference to the accompanying drawings, in which:

FIG. 1 is a schematic sectional view through one form of electromagnet which illustrates the theoretical aspects of the invention;

FIG. 2 is another schematic illustration of the field

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distribution between current loops having a very low reluctance external leakage path;

FIG. 3 shows schematically one practical design of electromagnet in accordance with the present invention;

FIG. 4 is an end elevation, with the right-hand half in cross-section, of an embodiment of electromagnet in accordance with the present invention;

FIG. 5 illustrates schematically a further embodiment of electromagnet having a number of current loops wound around the external leakage path; and,

FIGS. 6a and 6b are, respectively, a schematic plan view and a sectional view of a further form of electromagnet.

For the magnetic field in a given volume to be homogeneous it is necessary that the components of the magnetic circuit be so arranged that the equipotentials in the volume form a set of parallel planes. Any divergence from parallelism will reduce the degree of homogeneity.

Consider a coil made up of a set of current loops arranged for connection to a source of electric current and clamped between two blocks of magnetic material of very low reluctance which present opposing plane parallel faces. Suppose also that the coil is such that any cross-section thereof is a rectangle of constant height, but that the inner and outer perimeters can follow any configuration. Since the magnetic material of which the blocks are made is of very low reluctance it can be assumed that each block is at a constant magnetic potential throughout its volume. The magnetic field pattern occurring in and around the assembly is then of the form as shown in FIG. 1.

In FIG. 1 the blocks of low reluctance magnetic material are indicated at 10 and 12 and the coil is indicated generally at 14. As mentioned above, the coil is rectangular in cross-section and is of constant height between the two blocks 10 and 12 although of varying thickness between its inner and outer peripheral surfaces 16 and 18 respectively. The central volume in which the homogeneous magnetic field is to be established is defined by the inner peripheral surface 16 of the coil and by the upper and lower plane parallel surfaces 20 and 22 respectively of the magnetic material. The horizontal broken lines within the central volume are equipotentials, and their parallelism is indicative of the degree of homogeneity. Outside the coil the equipotential surfaces diverge as indicated. The continuation of the equipotential lines inside the coil 14 is shown as broken lines since inside the coil the concept of scalar magnetic equipotential no longer applies and these lines must be regarded as "lines of no work."

To produce a highly homogeneous field it is essential that the current density distribution in the coil 14 shall satisfy the condition that, at any point on a line such as the line EF at a constant distance from the outer peripheral surface 18 of the coil, $J_x = \text{constant}$; $J_y = \text{constant}$; and $J_z = 0$; where J is the current density, the z -axis is along the line EF, and the x and y axes are mutually perpendicular to the z -axis. This condition is met in practice by a layer-wound coil or a foil-wound coil of uniform resistivity. With this condition satisfied the magnetic circuit law is obeyed and the assertion of orthogonality is justified.

The lines AB and CD in FIG. 1 are section lines through the same line of current flow around the coil. This line of current flow is taken as the one in the region of the coil where there is zero field, i.e. it is the kernel of the system. Inside the region bounded by the line of current flow of which AB and CD are sections the flux will all be in one direction parallel to the edge of the coil. Outside this region the flux will all be in the opposite direction. The distribution of magnetic field will be as shown in the drawing. Along any line such as the line EF in the

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winding the magnetic field H will be equal to $1.26NI/l$, where NI is the ampere-turns crossing the area enclosed by ABEF and l is the length of the winding. When the inner edge of the winding is reached the field value is determined by the ampere-turns contained between AB and the edge 16 of the winding. However, the ampere-turns between the kernel of the winding and the inner edge 16 is a constant. Therefore, whatever section is taken through the structure the field at the inner edge 16 of the winding must be the same. As the coil is enclosed between two parallel equipotential surfaces 20 and 22 it follows that the field throughout the whole of the central volume must be uniform.

It can similarly be shown that the field distribution between the kernel and the outside surface 18 of the coil is such that all points on the outer surface 18 of the coil have a constant value of magnetic field. This value is not in general equal to that at the inner surface 16 of the coil, and the field distribution outside the coil 14 will not be uniform except for the lines which are coincident with the outer surface of the coil.

It should be noted from the field pattern shown in FIG. 1 that the portion between X and Y will be the same whatever transverse plane PQ through the magnet is chosen, but outside X and Y the field distribution will depend on the position of the transverse plane.

The value of the magnetic field in the central volume depends on both the ampere-turns per unit length and the geometry of the structure. In FIG. 1 the field in the central volume is denoted by H_1 , the field at the outer edge 18 of the winding is denoted by H_2 , NI_1 is the ampere-turns contained within the kernel, NI_2 is the ampere-turns external to the kernel, P_1 is the permeance of the central volume, and P_2 is the permeance of the volume external to the coil. It is also assumed that the current density in the winding is uniform. Bearing in mind that as one moves along any line normal to the inner perimeter of the winding the magnetic field will change linearly, the flux contained between the inner surface 16 of the coil and the kernel ABCD and between the kernel and the outer peripheral surface 18 can be calculated. From this it can be shown that whatever values are assigned to the length of the internal perimeter of the coil, the length l of the coil, and the permeances P_1 and P_2 , the field within the central volume will be homogeneous. It can also be shown that the highest field that can be obtained from the available ampere-turns occurs when there is zero reluctance in the external leakage path.

FIG. 2 illustrates the special case of zero or substantially zero leakage reluctance. In this arrangement the coil 14 is surrounded by magnetic material 24 of negligible reluctance. Since the magnetic material constitutes one large mass of substantially zero reluctance it can be assumed that it is at a constant magnetic potential throughout its volume. Again, it is essential that the current density distribution in the winding should satisfy the conditions mentioned above, namely that $J_x = \text{a constant}$, $J_y = \text{a constant}$ and $J_z = 0$. Since the magnetic material surrounds the coil and is at a constant magnetic potential there will be no external field and therefore a zero reluctance leakage path.

Reference is now made to FIG. 3 of the drawings which shows schematically a practical embodiment of electromagnet incorporating the above-mentioned conditions for achieving a high degree of homogeneity, i.e. that the coil is of rectangular cross-section exactly filling the vertical space available, and that at any point on a given vertical line through the coil $J_x = \text{constant}$, $J_y = \text{constant}$, and $J_z = 0$. The electromagnet shown in FIG. 3 consists of a construction of right-angled elements; two rectangular blocks 26 and 28 respectively, two yoke pieces 30 and 32 respectively, and two coils 34 and 36 respectively positioned around the yoke pieces 30 and 32 of the assembly, leaving a rectangular cross-section tunnel therethrough which is open at both ends. The fact that the coil is in two

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separate sections does not affect the operation of the system provided that ampere-turns contained by the two inner coil sections 34a, and 36a are equal and opposite. The external return paths for the currents through the coil sections 34b and 36b do give rise to external leakage from the magnetic material, and this must be allowed for in determining the cross-section of the yoke pieces 30 and 32. An estimate of the leakage field can be made by assuming that the return path of one section of the coil is in contact with a semi-infinite plane of infinite permeability and by then applying the method of image currents.

FIG. 4 shows a practical embodiment of electromagnet in accordance with the invention, the left-hand half being an external end view and the right-hand half providing a sectional view through the winding. In FIG. 4 corresponding reference numerals have been used where applicable to the basically similar structure shown in FIG. 3. Thus, the electromagnet comprises upper and lower rectangular plates of mild steel 26 and 28 respectively providing opposed plane parallel surfaces 38 and 40. Between the two plates 26 and 28 are positioned two yoke pieces, one of which is indicated at 32, these yoke pieces being of the same material as the plates 26 and 28. The yoke pieces are secured to the plates 26 and 28 by a number of screws 33. As shown in FIG. 4 the yoke pieces extend parallel to each other along two edges of the plates 26 and 28 and are positioned at the outer edges of the plates to form a closed rectangular cross-section assembly which is open at both ends to permit access to the central volume of the electromagnet.

As seen more clearly from the right-hand half of FIG. 4, around each yoke piece is wound a multi-turn multi-layer wire coil 36 which thus provides a coil section 36a within the central chamber of the magnet and a return section 36b outside the yoke piece 32. It will again be seen that the coil is of rectangular cross-section and extends the full length of the gap between the plates 26 and 28. The coils also have uniform current density distribution therein. Around each coil is wound a number of turns of hollow tubing 41 encapsulated in a resin 42 or equivalent material. This tubing 41 is used to effect cooling of the windings when energised by the passage of a coolant therethrough.

In one preferred embodiment of the invention, the dimensions of the electromagnet are such that the width of the plates 26 and 28 transversely to the axis of the chamber therethrough is approximately twice the length of the plates along said axis, with said length of the plates 26 and 28 being approximately equal to the overall height of the magnet between the outer faces of the plates 26 and 28.

FIG. 5 shows a further embodiment of the invention which is basically similar to the embodiment of FIGS. 3 and 4 but which includes a plurality of current loops wound around the external leakage reluctance path. As shown in FIG. 5 the additional current loops take the form of a winding 44 wound around an extended arm 46 having connection with the pole plates 26 and 28. As discussed above, the electromagnet construction may be such that the reluctance of the external leakage path is zero or non-zero. If the electromagnet is constructed with zero reluctance in the external leakage path and with the additional winding 44, and if the number of ampere-turns in the external path has a value less than the ampere-turns of the coils 34 and 36 and acting in an opposing sense, then it can be shown that the magnetic field in the central volume of the electromagnet remains uniform provided that the ampere-turns of the additional winding 44 does not exceed the ampere-turns of the other windings, and provided also that the additional winding 44 does not act in the same sense as the other windings 34 and 36. However, with zero external reluctance, the external ampere-turns provided by the winding 44 cannot increase the intensity of the magnetic field within the central volume of the electromagnet.

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If, however, the reluctance of the external leakage path is not zero the additional winding 44 will enclose a part, but not the whole, of the external reluctance. In this case, it can be shown that the external ampere-turns provided by the winding 44 can increase the intensity of the magnetic field in the central volume of the central magnet up to but not beyond the value obtained in the case of zero external reluctance. There is no restriction on the uniformity of winding of the external coil 44 or on its shape, but its volume should preferably be small compared with the permeance enclosed by the external coil 44.

Referring now to FIGS. 6a and 6b it is seen that it is also possible to insert into the central volume of the electromagnet a vertical column 48 of any initially unmagnetized magnetic material, provided that it is homogeneous and exactly the same height as the surrounding coil 50, without upsetting the orthogonality of the magnetic field pattern. If around his inserted column 48 there is wound a coil 52 that satisfies the conditions that apply to the main coil 50, and if the ampere-turns $N_1 I_1$ of this coil are equal to the ampere-turns $N_2 I_2$ of the main coil and act in the opposite sense, then the magnetic field inside the inner periphery of the inner coil 52 will be zero. It is then possible to make a vertical hole through the assembly with any cross-section within the bounds of the column 48 without affecting the value of the magnetic field.

The electromagnet assemblies shown herein must remain sufficiently long for the effects of the open ends to be negligible, or alternatively, shims can be introduced to counteract the end effects.

Moreover, although the electromagnets shown herein use essentially right-angled elements, the invention is not to be considered as being limited to such elements, and various alternative configurations can be used which still give access to the central volume within the assembly.

We claim:

1. An electromagnet comprising two spaced pole pieces of magnetic material of very low reluctance providing opposed plane parallel surfaces, which are each continuous between a pair of parallel yoke pieces positioned between said pole pieces, and a plurality of current loops wound around each yoke piece to provide a pair of coil portions inwardly of said yoke pieces which with said pole piece surfaces define the boundaries of an air gap between said pole pieces, wherein any cross-section

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through said coil portions perpendicular to said pole piece surfaces is a rectangle of constant height equal to the perpendicular distance between said pole piece surfaces, wherein the current density distribution in said coil portions is such that at any point on a line perpendicular to said pole piece surfaces at a constant distance from the edge of the coil portion $J_x = \text{constant}$, $J_y = \text{constant}$ and $J_z = 0$ where J is the current density, and x , y and z are mutually perpendicular axes with the z axis along said line, and wherein the ampere-turns of said coil portions are equal and opposite.

2. An electromagnet as claimed in claim 1, wherein said pole pieces of a material of very low reluctance are connected by a low reluctance magnetic path.

3. An electromagnet as claimed in claim 1, wherein the yoke pieces are of the same material as said pole pieces.

4. An electromagnet as claimed in claim 1, wherein said pole pieces are provided with extension portions forming an external leakage path, said extension portions being provided with an additional winding thereon, and wherein the ampere-turns of said additional winding are less than the ampere-turns of said plurality of current loops on the yoke pieces and act in an opposite sense.

5. An electromagnet as claimed in claim 1, wherein the pole pieces are rectangular and have a width dimension at right-angles to the axes of said yoke pieces which is substantially twice the length dimension thereof, and wherein the distance between the outer faces of said pole pieces is substantially the same as said length dimension of the pole pieces.

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GEORGE HARRIS, Primary Examiner

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