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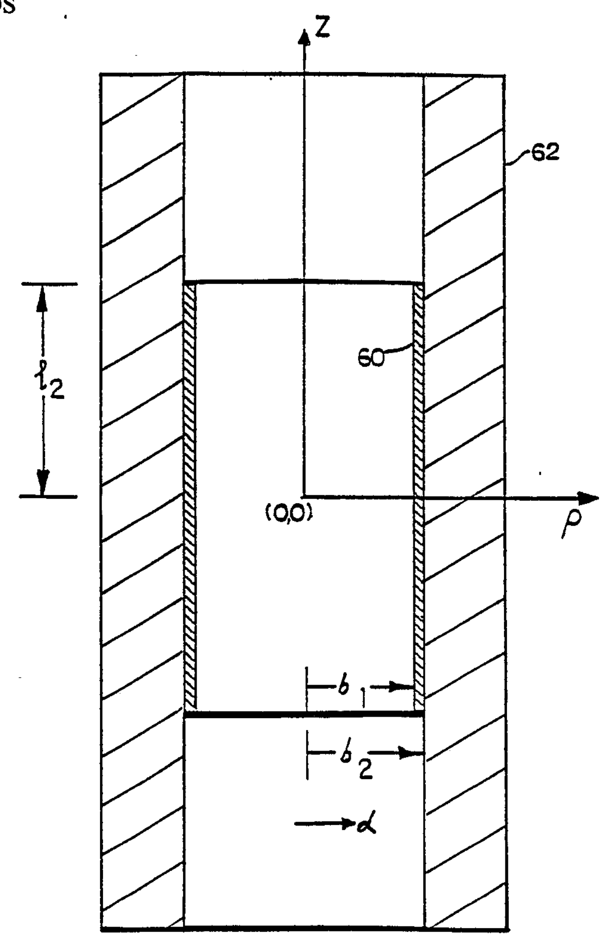
(54) Title: SHIELDING SUPERCONDUCTING SOLENOIDS

(57) Abstract

A self-shielding system of closed superconducting circuits (60, 62) shields a specific volume from changes in an external magnetic field in which the circuits (60, 62) are located; the configuration of circuits (60, 62) is chosen so that induced currents in the circuits (60, 62), arising from magnetic flux conservation for each closed circuit (60, 62), tend to cancel any change in the external magnetic field. In another aspect, a single closed self-shielding superconducting circuit (70, 72) comprised of more than two circular loops (70) connected in series shields a specific volume from changes in an external magnetic field in which the circuit (70, 72) is located; the configuration of the circuit (70) is chosen so that induced currents in the circuit (70), arising from magnetic flux conservation for the circuit (70, 72), tends to cancel any change in the external magnetic field.



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Shielding Superconducting Solenoids

Background of the Invention

This invention relates to shielding superconducting solenoids.

In some applications of superconducting solenoids, such as NRM, MRI, and mass spectroscopy of particles in an ion trap, variations in the high (e.g., 6 Tesla) magnetic fields produced within the solenoid must be limited to no more than, for example, 6 nanoTeslas (nT) per hour. This degree of stability is hard to achieve because of the influence of relatively greater fluctuations (e.g., between 10 nT and 10 μT per hour) of the ambient magnetic field produced by, for example, ionospheric conditions, solar activity, and elevators or subways.

Shielding a high magnetic field solenoid from the ambient magnetic field is impractical using highly permeable metals, like iron, (because they become saturated by the high field), or using type I superconductors, such as lead or niobium (because the high field exceeds the critical field for such materials).

In A. Dutta et al., Rev. Sci. Instruments, volume 58, page 628 (1987), a cylinder of type II superconductor was used to screen ambient magnetic field fluctuations from a very small sized high magnetic field region.

R. S. Van Dyck, Jr. et al., Rev. Sci. Instruments, volume 57, page 593 (1986), describe using two serially connected, concentric, coplanar superconducting loops to impose a tunable gradient on a high magnetic field. The radii of the loops were chosen to minimize the shift of the high magnetic field at the center as the gradient was tuned; Ambient magnetic field fluctuations were expected to be reduced by a factor of ten at the center.

Summary of the Invention

In general, in one aspect, the invention features a self-shielding system of closed superconducting circuits which shields a specific volume from changes in an external magnetic field in which the circuits are located; the configuration of circuits is chosen so that induced currents in the circuits, arising from magnetic flux conservation for each closed circuit, tend to cancel (preferably cancelling exactly) any change in the external magnetic field.

In another aspect, the invention features a single closed self-shielding superconducting circuit comprised of more than two circular loops connected in series, which shields a specific volume from changes in an external magnetic field in which the circuit is located; the configuration of the circuit is again chosen so that induced currents in the circuit, arising from magnetic flux conservation for the circuit, tends to cancel (preferably cancelling exactly) any change in the external magnetic field.

Preferred embodiments of the invention include the following features. The system is arranged to come as close as desired to satisfying the condition

$$g^T L^{-1} A = 1$$

where components of column vector g specify the magnetic field produced in the shielded volume per unit current in a circuit, components of column vector A are effective areas of the circuits referred to the location of the shielded volume and

L is the inductance matrix. The shielded volume lies at an arbitrary location with respect to the circuits, and the column vectors g and A are defined with respect to the location of the shielded volume. Each closed superconducting circuit includes one or more solenoids connected in series. The system is arranged to produce an intense magnetic field in the shielded volume with the magnetic field having a high degree of spatial uniformity. In some embodiments there is but a single circuit having a single solenoid connected in a closed loop. In other embodiments there are two solenoids each connected in a closed loop, one within the other. For example, a main solenoid may be used to generate a desired magnetic field, and a second compensating solenoid is located inside (or in other cases outside) the main solenoid. The second solenoid may have two spaced apart segments. The two solenoids are cylindrical and coaxial. Where the external magnetic field changes are relatively small compared to the magnetic field within the shielded volume, then in addition to the circuits which generate the desired magnetic field with a nominal spatial homogeneity in the shielded volume, the system includes one or more additional circuits configured to produce shielding with substantially no distortion of the nominal spatial homogeneity in the shielded volume, or to provide shielding while carrying only current induced by the changing external magnetic field, thereby producing a magnetic field gradient in the volume in response to the changing external magnetic field, the magnetic field gradient producing substantially no distortion of the nominal spatial homogeneity in the volume.

The self-shielded solenoid systems of the invention are relatively straightforward to design. Available solenoids may be modified to achieve the self-shielding advantage while retaining the other benefits of the original design, for example, spatial homogeneity. A variety of configurations are possible. The resulting solenoids are especially useful for mass spectroscopy, NMR, and MRI work.

Other features and advantages of the invention will become apparent from the following description of the preferred embodiments, and from the claims.

<u>Description of the Preferred Embodiments</u>

We first briefly describe the drawings.

Fig. 1 is a diagrammatic cross-sectional side view of a superconducting solenoid.

Fig. 2 lists equations for determining the requirements for shielding a solenoid circuit.

Fig. 3 is a graph relating shielding factor to solenoid aspect ratio.

Fig. 4 is a diagrammatic cross-sectional side view of a generalized superconducting solenoid.

Fig. 5 lists equations for determining the requirements for shielding a multiple solenoid system and in a general multiple solenoid, multiple circuit system.

Figs. 6, 8 are diagrammatic cross-sectional side views of self-shielding two solenoid systems.

Fig. 7 is a curve relating shielding factor to the length of the inner solenoid of Fig. 6.

Structure and Operation

Introduction

Many applications require high magnetic fields which are provided by superconducting solenoids. Most common are NMR and MRI (nuclear magnetic resonances and magnetic imaging) applications. Also of interest is the mass spectroscopy of particles in an ion trap using, for example, a 6 Telsa field. For these and other high field applications, it is often desirable that these fields be very stable in time. For example, to compare the masses of a proton and antiproton to a desired precision of 1 part in 10^9 in a 6 Telsa magnet field requires a time stability better than 6 ηT per hour. Unfortunately, the fluctuations in the ambient field in which the superconducting solenoid is placed varies in this time period from 10 ηT to 10 μT depending upon ionospheric conditions, solar activity, the proximity to subways and elevators, etc. These fluctuations limit the time stability which can be realized in a high field region, even though the high field solenoid system itself produces a more stable field.

Many techniques are available for shielding out such fluctuations in the presence of small magnetic fields, but it is much more difficult to shield them out of a region of high magnetic field. One reason is that highly permeable materials like iron and "mu metal" are severely saturated and hence useless for shielding within the high-field region. Another is that shields made of type I superconducting materials like lead and niobium cannot be used because the large field is above the critical field for type I superconductors. Finally, a type II superconductor has been used to screen external fluctuations from a very small high-field region, but there was trouble with flux jumps associated with the shield.

In the invention, the external fluctuations are screened using superconducting circuits. As is well known, magnetic flux through a closed superconducting circuit is conserved. For example, coupled superconducting circuits may be configured so that this flux conversation insures that external field fluctuations are screened from a region of interest. In particular, the solenoid systems used to provide the high field can be designed so that they themselves screen out the fluctuations in the ambient field. In simple cases, the superconducting circuits are composed of solenoids which are axially symmetric about a z axis. In general, the z component of the external field B_e is reduced by a shielding factor S to B_e/S and the objective is to make S as large as possible.

A self-shielding solenoid system (a system for which S is large) can be constructed using a wide variety of circuit configurations. Therefore, self-shielding systems can be designed to preserve a variety of other properties. For example, a high degree of spatial homogeneity is often also required in the high-field region in order that very narrow resonance linewidths can be obtained. Time stability is then required to allow measurement of the narrow lines, several hours being required for some mass spectroscopy experiments. The examples of self-shielding solenoid systems discussed below were chosen to suggest ways that such systems can be designed with minimal distortions of the field homogeneity. More complicated solenoid systems may be analyzed in the same way.

The magnetic shielding achieved by the invention applies in principle to external field fluctuations which are arbitrarily fast. High-field solenoids, however, are typically wound on copper or aluminum cyclinders which readily support eddy currents, especially when cold. External field fluctuations more rapid than 1 Hz typically are already severely screened by the cyclinder.

Single Superconducting Solenoid Circuit

To illustrate the basic shielding scheme, consider a single, axially symmetric solenoid (i). The solenoid 10 shown in Fig. 1 is made of superconducting wire 12 and its ends 14, 16 are connected to make a closed circuit (not shown). The potential difference around the shorted solenoid is zero. Referring also to Fig. 2, by Faraday's law, an externally applied field B_e induces a current I_i in the solenoid which in turn produces a magnetic field B_i sufficient to keep the flux through the solenoid from changing. (Equation 1, Fig. 2). We take the conserved value of the flux to be 0 so that we can focus on fluctuations from some steady state. The subscript on the integral indicates integration over the loop by loop area of the solenoid. The induced current persists since the resistance around the superconducting circuit is zero.

In what follows, we shall use cylindrical coordinates ρ and z so that $B_i = B_i(\rho,z)$, for example. The net field at the center of the solenoid $B_e(0,0) + B_i(0,0)$ can be written in terms of the shielding factor S as $B_e(0,0)/S$ so that equation 2 of Fig. 2 applies. In light of the flux conservation criterion of equation 1, this can be written as in equation 3 of Fig. 2. To aid intuitive interpretation, note that S^{-1} is linear in the ratio of two averaged fields (equation 4), where the two averaged fields are defined as in equations 5 and 6. Here $\int dA$ is the total area involved in the flux integration for circuit i. Perfect shielding requires a solenoid for which the normalized average values of the external field and solenoid field are equal, $b_e = b_i$.

Without explicit calculation, one can immediately see that complete shielding of spatially uniform fields is possible with a single superconducting solenoid circuit, even if the solenoid has many layers of windings. For spatially uniform external field B_e, we have $b_e = 1$ and the shielding is given by equation 7. For a short solenoid, the magnetic field near the windings is larger than the magnetic field near the center. The average value b_i is thus greater than 1 so that S^{-1} is positive. For a long solenoid, the average magnetic field produced by the solenoid is slightly less than the field at the center because of the fringing field as its ends. Thus b_i approaches 1 from below and S^{-1} approaches 0 from below. Since S^{-1} must cross zero between these two limits, complete shielding is obtained with an appropriate choice of dimensions.

To facilitate explicit calculation, we eliminate the induced current from the expression for the shielding factor using factors g_i and L_{ii} which depend only upon the geometry of the solenoid circuit. The field at the center is proportional to the current (equation 8) as is the flux through the solenoid (equation 9). The latter proportionally factor L_{ii} is the self-inductance for solenoid i. Substituting these two expressions in equation 3 yields equation 10. For a spatially uniform external field, A_i, is the total area $\int_i dA$ used to calculate the flux through circuit i. More generally, A_i is an effective area which depends on the spatial distribution of B_e (equation 11).

In Fig. 3, we plot S^{-1} as a function of the solenoid aspect ratio l/a for a single layer, densely wound solenoid. The necessary techniques for calculating inductances are well known (see F. W. Grover, Inductance Calculations, (Van Nostrand, New York, 1946)) and efficient calculation techniques have been discussed (see M. W. Garrett, J. Appl. Phys. 34, 2567 (1963)). The qualitative features discussed above are readily apparent. The self-shielding is complete (i.e., $S^{-1} = 0$) at the aspect ratio l/a = 0.88 (point 50, Fig. 3) for a densely wound solenoid in the limiting case of vanishing wire diameter.

In general, the shielding produced by a persistent superconducting solenoid is far from complete. To illustrate, we use a solenoid 51 represented in Fig. 4, which is not unlike many high-field solenoids which are commercially available. The large solenoid is wound uniformly with n_1 turns and its dimensions and characteristics are given in Table I.

TABLE 1

	Dimensions	Calculated Parameters
Basic Solenoid	a_1 = 7.62 cm	L_1 = 232.3 H
	a_2 = 12.70 cm	A_1 = 2219 m^2
	l_1 = 25.40 cm	g_1 = .1469 T/A
	n_1 = 64,000	S = -2.95

This solenoid would produce a field of 6 T at its center for a reasonable current of approximately 40 A. By itself, we calculate that this solenoid will screen external field fluctuations by a factor of S = -2.9, which is typical for commercial superconducting solenoid systems used to produce intense magnetic fields. Improving the self-shielding requires more than a simple reshaping of the solenoid. A self-shielding solenoid of the same radial dimensions, for example, would be reduced in length by more than a factor of 9. Such a squat solenoid would have properties very different from the solenoid in Fig. 4. More practical modifications will be discussed next, involving more than one superconducting circuit.

Coupled Superconducting Circuits

Practical solenoid systems typically contain several circuits, one to produce the large field in a volume of interest within the system, and the others as shims to make the field near the center as homogenous as possible. We therefore generalize to a system of N closed superconducting circuits, each of which is axially symmetric. The subscript i now becomes an index i = 1, ..., N which labels the N circuits. A current I_i in circuit i produces the field $B_i(\rho,z)$. The currents can be represented by a column vector I and a related column vector g relates the field at the center to the currents with components defined as in equation 13, Fig. 5. The areas of the circuits are represented by column vector A with components as in equation 14, which may be generalized for the case of non-uniform B_e as was done in equation 11. The familiar symmetric inductance matrix L has components given by equation 15 of Fig. 5. A diagonal element L_{ii} is the self-inductance associated with circuit i and off-diagonal elements are the mutual inductances between circuits. The shielding factor is then as shown in equation 16 with the superscript T indicating transposition so that g^T is a row vector. For a single circuit, equation 16 reduces immediately to equation 10. Complete shielding occurs under the condition of equation 17. This is the condition for a self-shielding solenoid system.

As an illustration, consider a system of two superconducting circuits. One solenoid circuit is characterized by L_1, A_1, and g_1 and the other by L_2, A_2, and g_2. The mutual inductance between two circuits is M. One circuit could be a commercially constructed NMR solenoid to produce a 6T magnetic field, for example, and the other circuit could be a solenoid added to make a self-shielding system. From equation 16, the shielding factor is given by equation 18N For M $\rightarrow 0$, comparison with equation 10 shows that each coil contributes independently to the shielding. In general, however, the mutual inductance significantly modifies the shielding.

Computing S^{-1} is rather involved and lengthy, even in this simple two-circuit system. Many of the needed quantities, however, can be measured. This may be useful when modifications or additions to commercially constructed solenoid systems are contemplated, since their internal designs are often difficult to obtain. The self-inductance L_2 can be measured in conventional ways, most easily for a large solenoid by measuring the increase of current with time for an applied charging potential V_2 (equation 19). For two coupled superconducting circuits, the mutual inductance can be measured by introducing a current I_1 in circuit 1. A current I_2 is induced in the second circuit to conserve flux through circuit 2. Thus M may be determined from equation 20 when L_2 is already known. Circuit areas A_1 and A_2 can be determined by measuring the shielding factor S for each coil individually.

For a specific example of a two-circuit system, consider in Fig. 6 the addition of a second superconducting solenoid circuit 60 inside the one (circuit 62) shown in Fig. 4. Each solenoid is connected as a separate closed circuit. The added inner solenoid is uniformly wound with the same wire as the big solenoid and its radial dimensions are shown in Table II, section (a).

TABLE II

	Dimensions	Calculated Parameters
(a) Inner Solenoid	$b_1 = 6.99$ cm	
	$b_2 = 7.62$ cm	
(b) Inner Solenoid		
for Complete	$l_2 = 4.92$ cm	$L_2 = 0.2931$ H
Shielding	$n_2 = 1550$	$M = 3.839\ H_2$
		$A_2 = 25.98\ m^2$
		$g_2 = 1.106 \times 10^{-2}$ T/A

Its inductance, area and g values will change as a function of its length in a calculable way, as will the mutual inductance between the two solenoid circuits.

Correspondingly, S^{-1} for the composite system changes with the length ($2l_2$) of the inner solenoid as shown in Fig. 7. Ideal self-shielding $S^{-1} = 0$ occurs at $2l_2 = 9.8$ cm in this example (point 62, Fig. 7). Characteristics of the inner solenoid for complete self-shielding are shown in Table II, section (b). This shielding configuration may be used even inside existing solenoid systems whose internal geometries are not well known. Probably the easiest approach in practice is to measure the shielding for inner solenoids of various lengths and then interpolate to determine the appropriate length for complete self-shielding.

An alternative way of constructing a two-circuit self-shielding system is shown in Fig. 8. Here a second solenoid circuit 70 is added in two segments on the outside of the basic solenoid 72 of Fig. 4. Since only small correction fields must be produced by the additional solenoid, it can be located relatively far from the central, high-field region. An advantage of this second configuration is that the bore of the magnet remains open for experimental apparatus and the additional coil to produce self-shielding can be added to an existing system. The properties of the added exterior solenoid are listed in Table III.

TABLE III

	Dimensions	Calculated Parameters
(a) Outer Solenoid	$c_1 = 12.70$ cm $c_2 = 15.24$ cm	
(b) Outer Solenoid for Complete Shielding	$l_3 = 17.87$ cm $n_3 = 9520$	$L_3 = 15.58$ H $M = 31.59$ H $A_3 = 582.8$ m^2 $g_3 = 6.978 \times 10^{-3}$ T/A

Solenoid Circuits

In practical solenoid systems, each of N closed superconducting circuits is formed by connecting a subset of N solenoids in series, with N $\geq$ N. Since each solenoid can have a different geometry and current density, we have found it very convenient to first calculate column vectors (g', **A'**) and an inductance matrix (**L'**) for the solenoids. These are defined analogously to their circuit counterparts (g, **A** and **L**), which in turn can be obtained by a simple contraction. To accomplish this, an N x N matrix Ω is defined such that the currents in the solenoids and circuits, I and I, are related by equation 21. In simple cases where solenoids are connected in series with their currents flowing in the same rotational sense about the z axis, we have $\Omega_{ik} = 1$ if circuit i includes solenoid k and $\Omega_{ik} = 0$ otherwise. Negative elements may be used to represent currents flowing with opposite helicity with respect to the z axis. The resulting transformation rules are set forth as equations 22, 23, and 24. The screening is determined by using the contracted values of equations 22-24 in equation 16.

We have analyzed in detail a commercial NMR solenoid system (Nalorac 6.0/100/118) which involves 2 superconducting circuits with several solenoids making up each circuit. This system has a calculated shielding factor of $S = -4.45 \pm 0.10$ which agrees with the measured value. The uncertainty reflects some imprecision in our knowledge of the location of the windings and inaccuracy in our inductance calculation. We have studied, moreover, the possibility of adding a simple inner solenoid circuit, in the spirit of the example shown in Fig. 6, to make the solenoid system self-shielding.

Finally, we note that this approach is related to a technique wherein two concentric, coplanar superconducting loops were used to make a tunable gradient in a large magnetic field. The two loops were connected in series such that the current flowed in the same direction. The radii of the loops were chosen to minimize the shift of the magnetic field at the center of the loops which occurred when the gradient was tuned. Accordingly, external field fluctuations were expected to cancel by perhaps a factor of 10 at the center of the loops, albeit at the expense of changing the field gradient. This configuration is not generally useful for shielding because of the gradients introduced. Still, it could be analyzed by treating each loop as a "solenoid", with the two loops connected in series to form a circuit. A complete analysis would also include the mutual inductances between these loops and the superconducting solenoid used to produce the large magnetic field being stabilized.

Spatial Field Homogeneity

It is extremely important that modifications to make a high-homogeneity solenoid system self-shielding do not spoil the spatial homogeneity. Fortunately, the condition for a self-shielding system in equation 16 allows for many possible self-shielding configurations. The approach taken in Figs. 6 and 8 has minimal effect on field homogeneity. The basic solenoid, optimized to provide the desired level of homogeneity, is left unchanged. A separate additional solenoid is added which would carry no current if the ambient field was stable. Since it only carries the very small current required to cancel out the changes in the external field, it produces only a small field gradient. Suppose, for example, that fluctuations of the ambient field B_e as large as 6 μT are encountered. This means that the added solenoid at most must produce a field which is 10^{-6} of the 6 T field produced by the system used for mass spectroscopy. The fractional homogeneity requirement on the center solenoid is thus reduced by this factor. For the inner solenoid in Fig. 6, the field at a distance d from the center varies from the field at the center by $(d/l)^2$ which is approximately 10^{-2} so that a homogeneity of 10^{-8} over a sphere 1 cm in diameter would not be compromised by the addition of such a coil. This homogeneity is comparable to that produced by the unmodified solenoid system. Either the inner solenoid of Fig. 6 or the outer solenoid of Fig. 8 could be shaped to improve the homogeneity further, if this were required.

Spatial homogeneity is also important when shielding factors are being measured. For example, we applied an external field to a Nalorac Solenoid system to measure the shielding using a pair of square solenoids with side length of 2 meters. The coils were separated by 2 meters rather than being in a Helmholtz configuration. Even with these large coils, we calculate that the spatial inhomgeneity in the applied external field over the volume of the solenoid system reduces the shielding from S = -4.45 in equation 28 to S = -4.10 which is what agrees with our measurements. To calculate this reduction it is necessary to use the generalized definition of effective areas shown in equation 11 taking B_e to be the nonuniform field of the external coils.

Spatial uniformity of the fluctuating ambient field over the solenoid system is essential to attain complete self-shielding for the configurations of the examples discussed above. There are cases, however, where it is possible to shield the high-field region from a changing magnetic field which is not uniform over the shielding coil. For example, the highest magnetic fields are produced using multi-strand superconducting wire. Solenoids so constructed often are not completely persistent but have a field which decays in time very slowly. If the spatial distribution of this decaying field is known near the center, it may be taken as B_e and used to calculate the effective area of a small, single-strand superconducting coil located near the center. The dimensions of this interior coil are then suitably chosen to compensate the drift in the field.

Other embodiments are within the following claims.

Claims

1. A self-shielding system of closed superconducting circuits which shields a specific volume from changes in an external magnetic field in which the circuits are located, the configuration of said circuits being chosen so that induced currents in the circuits, arising from magnetic flux conservation for each closed circuit, tend to cancel any change in the external magnetic field.

2. A single closed self-shielding superconducting circuit comprised of more than two circular loops connected in series, which shields a specific volume from changes in an external magnetic field in which the circuit is located, the configuration of said circuit being chosen so that induced currents in the circuit, arising from magnetic flux conservation for the circuit, tends to cancel any change in the external magnetic field.

3. The systems of claim 1 or 2 arranged to come as close as desired to satisfying the condition

$$g^T L^{-1} A = 1$$

where components of column vector g specify the magnetic field produced in the shielded volume per unit current in a circuit, components of column vector A are effective areas of the circuits referred to the location of the shielded volume and L is the inductance matrix.

4. The system of claim 1, 2, or 3 wherein the shielded volume lies at an arbitrary location with respect to the circuits, and the column vectors g and

A are defined with respect to the location of the shielded volume.

5. The system of claim 1, 2, or 3 wherein there is but a single said circuit having a single solenoid connected in a closed loop.

6. The system of claim 1, 2, or 3 wherein each said closed superconducting circuit comprises one or more solenoids connected in series.

7. The system of claim 4 wherein each said closed superconducting circuit comprises one or more solenoids connected in series.

8. The system of claim 5 wherein each said closed superconducting circuit comprises one or more solenoids connected in series.

9. The system of claim 1, 2, or 3 arranged to produce an intense magnetic field in the shielded volume.

10. The system of claim 4 arranged to produce an intense magnetic field in the shielded volume.

11. The system of claim 5 arranged to produce an intense magnetic field in the shielded volume.

12. The system of claim 6 arranged to produce an intense magnetic field in the shielded volume.

13. The system of claim 12 also arranged to produce simultaneously produce in the shielded volume a magnetic field with a high degree of spatial uniformity.

14. The system of claim 6 wherein there are two said solenoids each connected in a closed loop, one within the other.

15. The system of claim 14 comprising a main solenoid for generating said desired magnetic field, and a second compensating solenoid inside said main solenoid.

16. The system of claim 14 comprising a main solenoid for generating said desired magnetic field, and a second compensating solenoid outside said main solenoid.

17. The system of claim 16 wherein said second solenoid comprises two spaced apart segments.

18. The system of claim 14, 15, 16, or 17 wherein said two solenoids are cylindrical and coaxial.

19. The system of claims 1, 2, or 3 wherein said circuit or circuits comprise one or more cylindrical coaxial solenoids.

20. The system of claim 1, 2, or 3 wherein said external magnetic field changes are relatively small compared to the magnetic field within said shielded volume, so that in addition to the circuits which generate said desired magnetic field with a

nominal spatial homogeneity in said shielded volume, the system comprises one or more additional circuits configured to produce shielding with substantially no distortion of said nominal spatial homogeneity in said volume.

21. The system of claim 1 wherein in addition to the circuits generating a desired magnetic field with a nominal spatial homogeneity in said volume, said system comprises one or more additional circuits to provide shielding while carrying only current induced by said changing external magnetic field, thereby producing a magnetic field gradient in said region in response to said changing external magnetic field, said magnetic field gradient producing substantially no distortion of the nominal spatial homogeneity in said volume.

22. The system of claim 1, 2, or 3 wherein said changes in said external magentic field are exactly cancelled within said shielded volume.

23. A self-shielding superconducting solenoid comprising a single superconducting coil connected in a closed loop in which magnetic flux is conserved, said coil being configured to generate a desired magnetic field in a region of interest while simultaneously shielding said region of interest so that said desired magnetic field is unaffected by changes in an external magnetic field to which said solenoid is subjected.

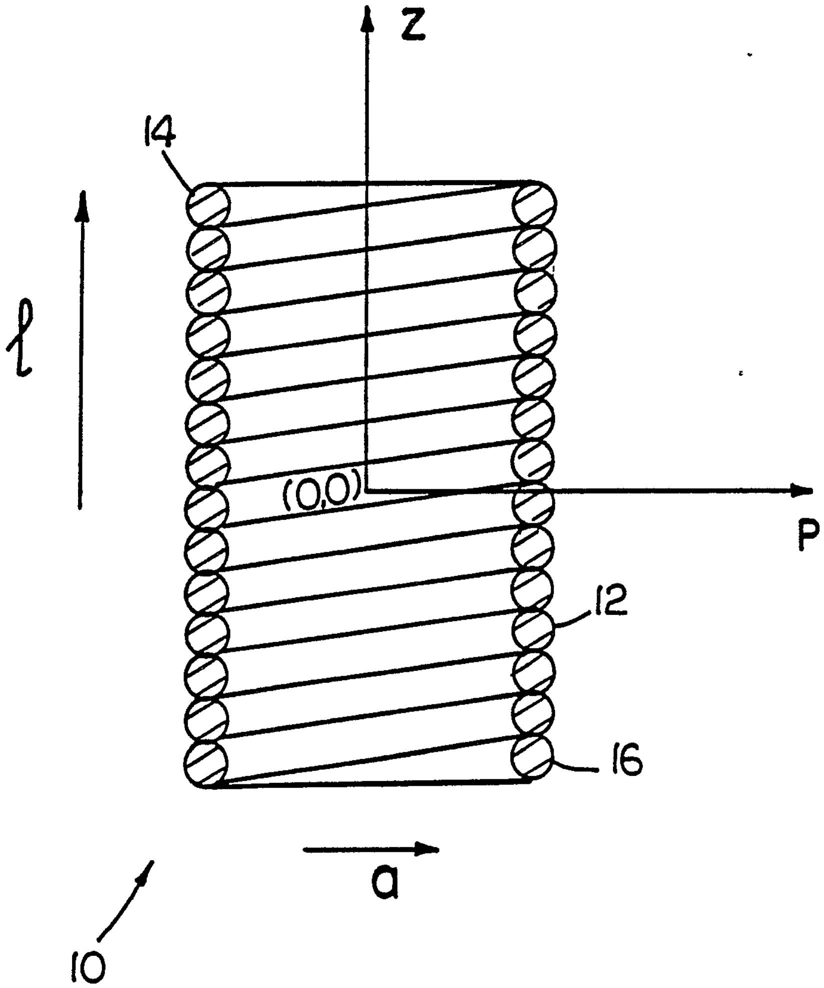

FIG.1

$$\int [B_e + B_i] dA = 0. \qquad (1)$$

$$S^{-1} = 1 + \frac{B_i(0,0)}{B_e(0,0)} \qquad (2)$$

$$S^{-1} = 1 - \frac{\int B_e dA / B_e(0,0)}{\int B\ (\rho, z) dA / B_i(0,0)} \qquad (3)$$

$$S^{-1} = 1 - \frac{\overline{b_e}}{\overline{b_i}} \qquad (4)$$

$$\overline{b_e} = \frac{\int_i B_e dA}{B_e(0,0) \int_i dA} \qquad (5)$$

$$\overline{b_i} = \frac{\int_i B_i(\rho, z) dA}{B_i(0,0) \int_i dA} \qquad (6)$$

$$S^{-1} = 1 - \frac{1}{\overline{b_i}}. \qquad (7)$$

$$B_i(0,0) = g_i\ I_i, \qquad (8)$$

$$\int B_i(\rho, z) dA = L_{ii}\ I_i. \qquad (9)$$

$$S^{-1} = 1 - \frac{g_i A_i}{L_{ii}} \qquad (10)$$

$$A_i = \frac{\int_i B_e dA}{B_e(0,0)}, \qquad (11)$$

FIG. 2

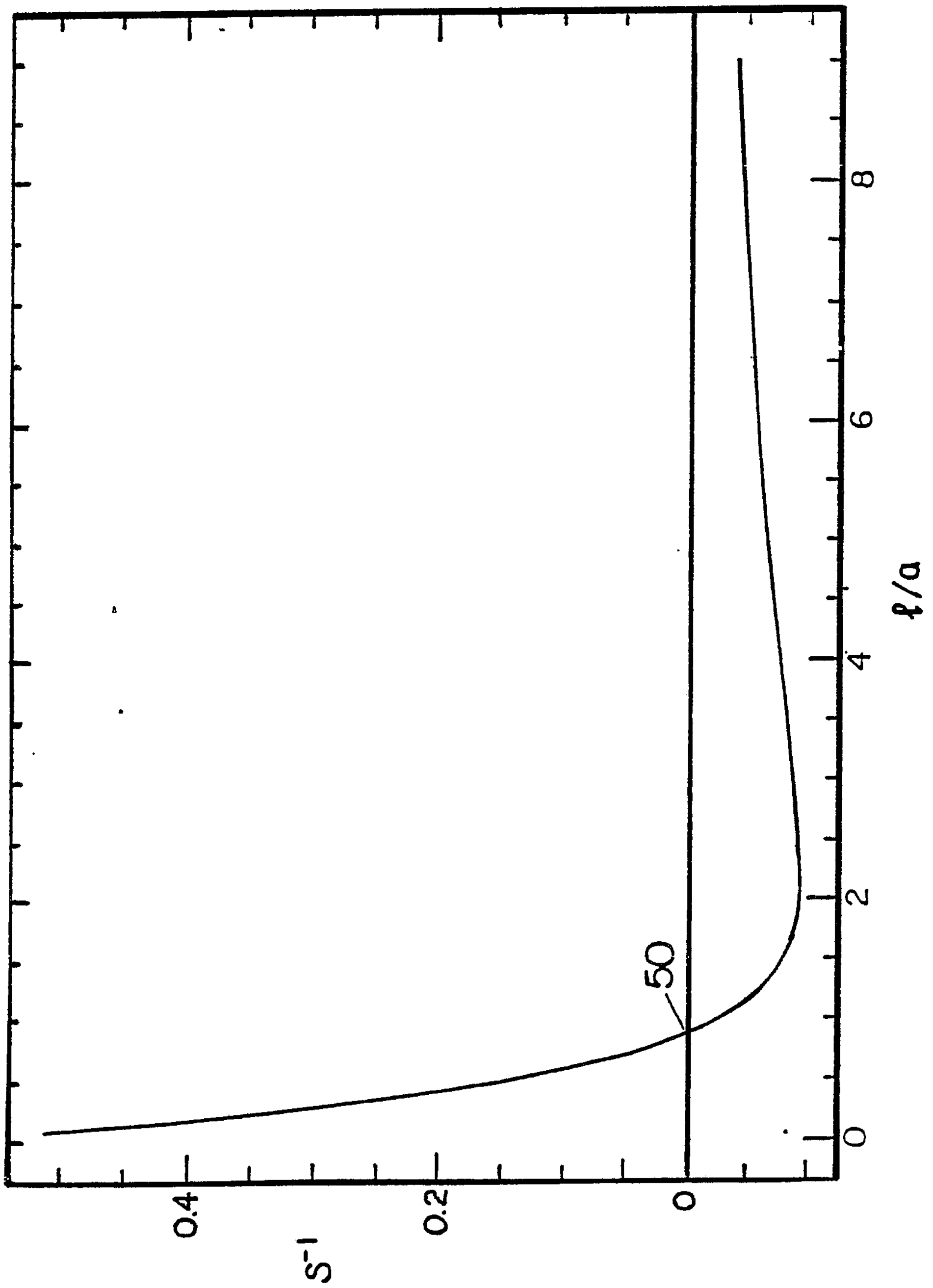

FIG.3

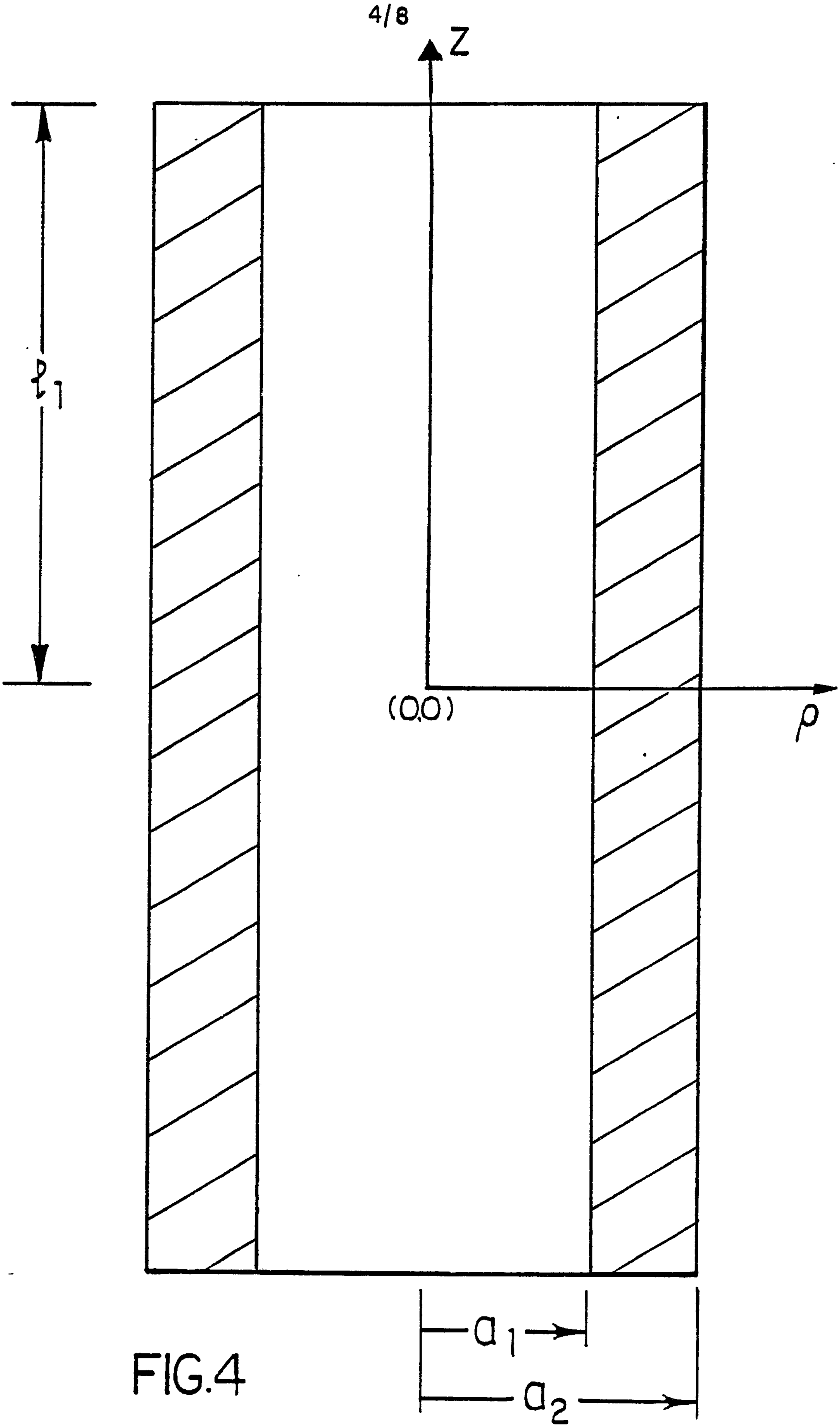

FIG.4

$$B(0,0) = g \quad I \tag{13}$$

$$A_i = \int dA \tag{14}$$

$$\int B_j(\rho, z) dA = L_{ij}\, I_j. \tag{15}$$

$$S^{-1} = 1 - \mathbf{g}^T \mathbf{L}^{-1} \mathbf{A}, \tag{16}$$

$$\mathbf{g}^T \mathbf{L}^{-1} \mathbf{A} = 1. \tag{17}$$

$$S^{-1} = 1 - \left[\frac{g_1 A_1}{L_1} + \frac{g_2 A_2}{L_2} - \frac{M}{L_1 L_2}(g_2 A_1 + g_1 A_2) \right] \left[1 - \frac{M^2}{L_1 L_2} \right]^{-1} \tag{18}$$

$$V_2 = -L_2 \frac{dI_2}{dt}. \tag{19}$$

$$M I_1 + L_2 I_2 = 0 \tag{20}$$

$$\bar{\mathbf{I}}^T = \mathbf{I}^T \Omega. \tag{21}$$

$$\mathbf{g} = \Omega \bar{\mathbf{g}}, \tag{22}$$

$$\mathbf{A} = \Omega \bar{\mathbf{A}}, \tag{23}$$

$$\mathbf{L} = \Omega \bar{\mathbf{L}} \Omega^T \tag{24}$$

FIG.5

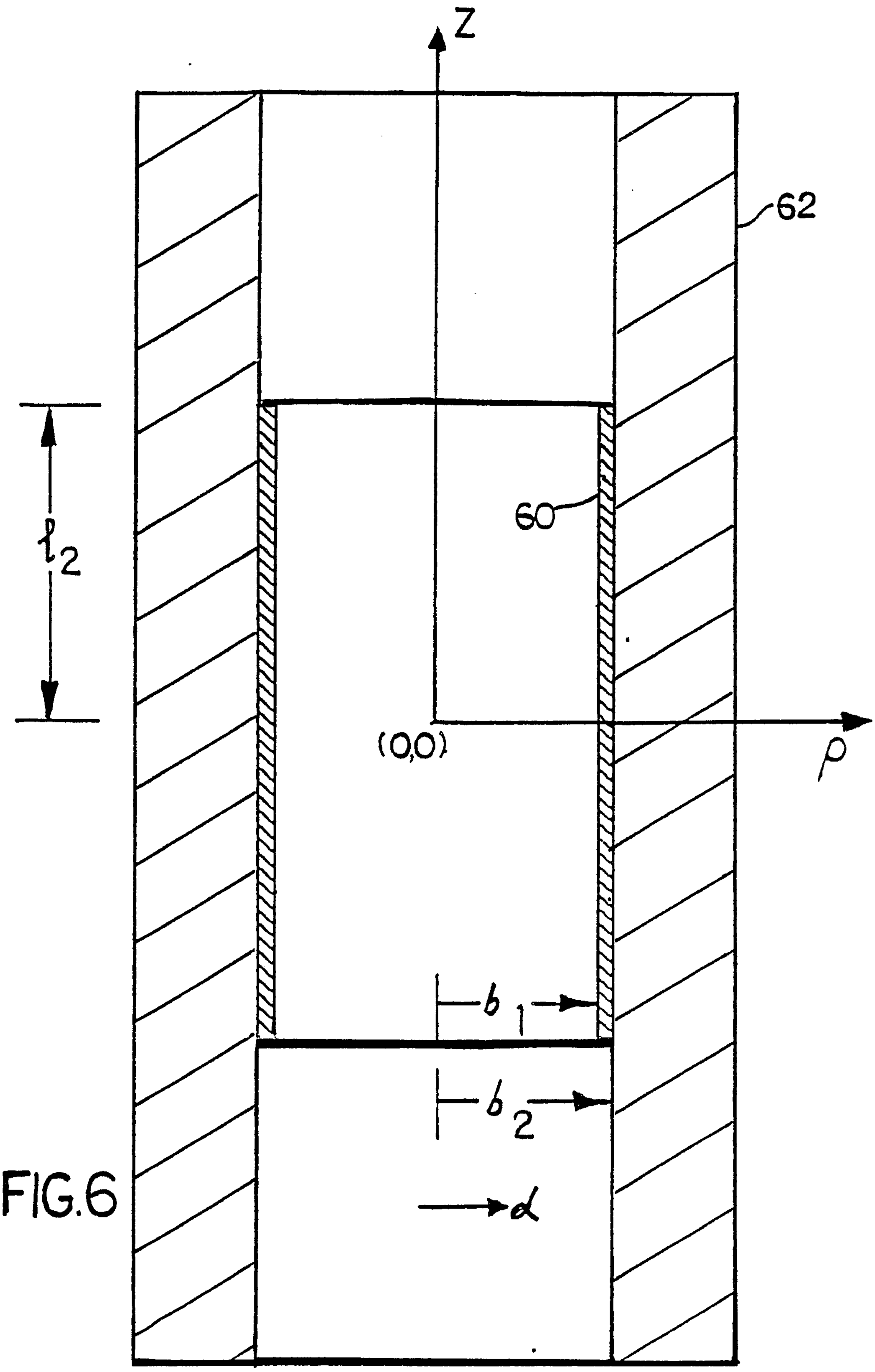

FIG.6

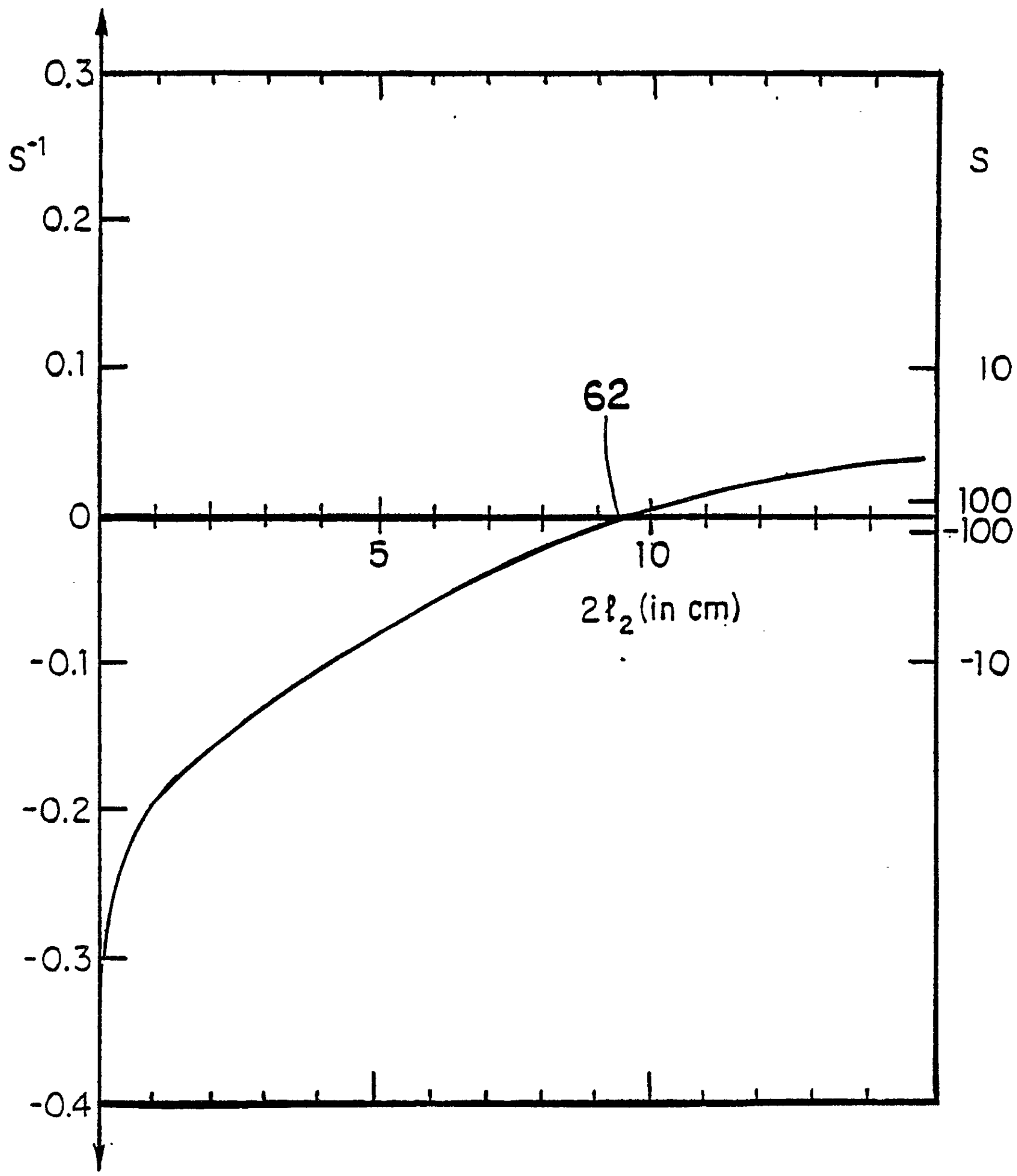

FIG. 7

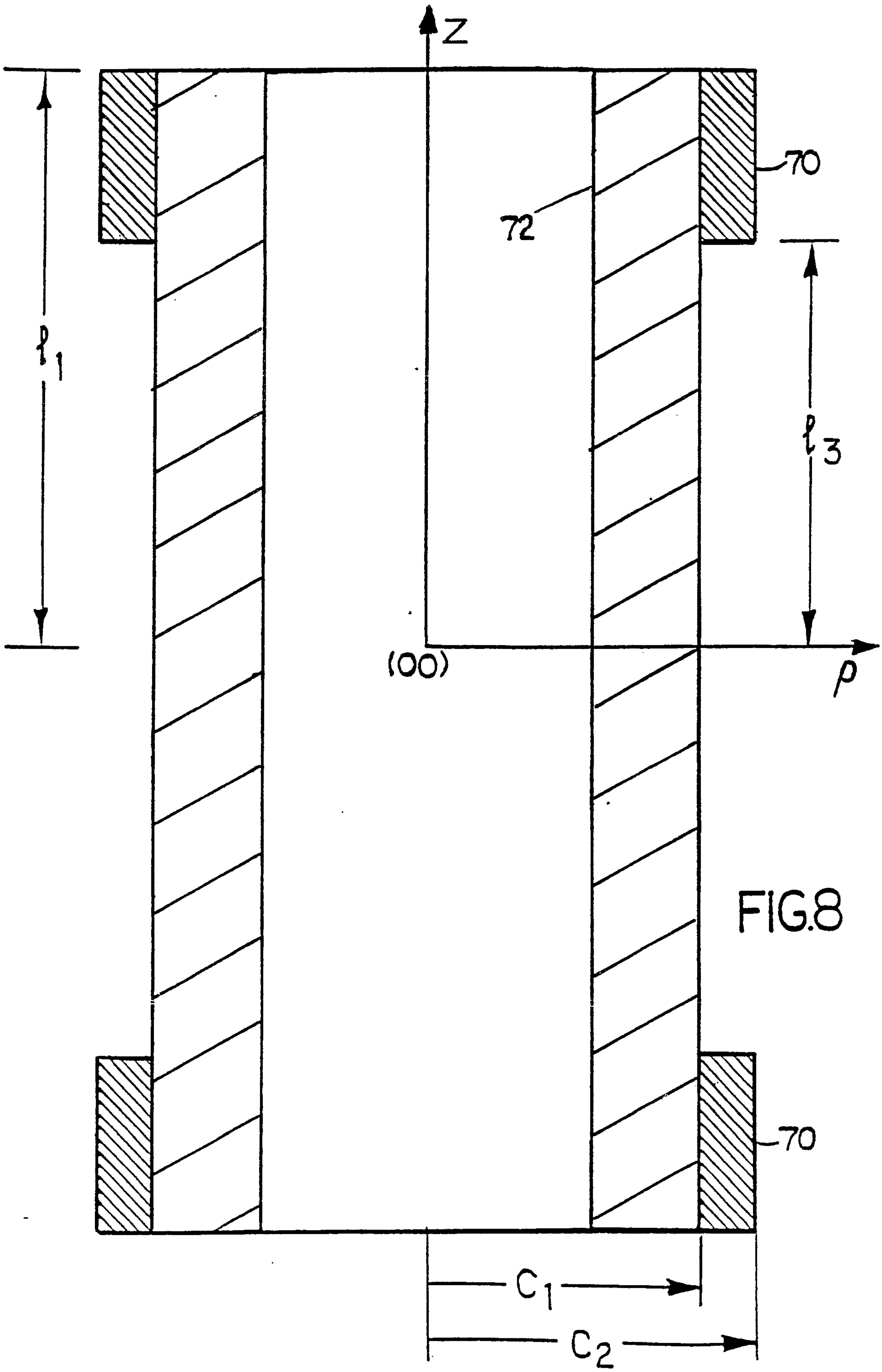

FIG.8

INTERNATIONAL SEARCH REPORT

International Application No. PCT/US89/01066

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC (4): H01F 5/08, H01F 7/22

U.S. CL. 361/141

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
U.S.	361/19,141 324/320,322 335/216

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
X	US,A, 3,818,396 (RAPHAEL) 18 June 1974 See entire document.	1-23
X,P	US,A, 4,733,189 (PUNCHARD et al.) 22 March 1988 See entire document.	1-23
X	GB,A, 0,251,342 (BROWN et al) 07 January 1988 See entire document.	1-23
A	US,N, Rev. Sci. Instrum., Volume 58, No. 4, Issued April 1987, A. Dutta et al., "High Field Nuclear Magnetometer" see pages 628-631	-
A	US,N, Rev. Sci. Instrum., Volume 57, No. 4, Issued April 1986, R.S. Van Dyck, Jr. et al., "Variable Magnetic Bottle for Precision Geonium Experiments" see pages 593-597	-

* Special categories of cited documents: [10]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
28 April 1989	06 JUL 1989
International Searching Authority	**Signature of Authorized Officer**
ISA/US	David M. Gray