Appendix A

Self-shielding Superconducting Solenoids

For high precision experiments, fluctuations in the ambient magnetic field must be shielded out or otherwise compensated to obtain a region with a strong magnetic field which is stable in time. Flux conservation in superconducting circuits makes it is possible to design superconducting solenoid systems which produce large magnetic fields and also react to shield the high-field region from ambient fluctuations [33]. This may be realized in many specific solenoid geometries and circuit configurations; the choices depend upon the desired field properties for particular applications. Shielding the fluctuations in the ambient field is crucial for achieving the highest precision measurements. However, even for less precise experiments, good shielding makes it possible to make measurements much nearer to sources of fluctuating magnetic fields.

We have demonstrated that an extra superconducting coil added to a standard, 6 Tesla solenoid results in a self-shielding solenoid system which utilizes flux conservation to passively shield an interior volume from changes in the ambient field, such as those from solar activities and from neighboring MBTA (cambridge) subways, particle accelerators, or elevators [38]. Such self-shielding solenoids could be very useful for mass spectroscopy of trapped particles, nuclear magnetic resonance experiments and magnetic resonance imaging. As an example, an antiproton ICR measurement with a fractional accuracy of 4×10^{-8} was recently done in a 6 T superconducting solenoid located near a large particle accelerator [36]. Without the shielding, the magnetic fluctuations in this environment would have limited the measurement accuracy to 1 ppm.

In this section, we discuss the general shielding principles and important considerations in the design and tests of self-shielding superconducting magnets. In the first trial, the large shielding factor of 156 for fluctuations of the uniform ambient magnetic field has been attained without compromising the spatial homogeneity of the field produced by the basic solenoid. Passive shielding using flux conservation applies in principle to external field fluctuations which are arbitrarily fast. High-field solenoids, however, are typically wound on copper or aluminum cylinders which readily support eddy currents, especially when cold. External field fluctuations more rapid than 1 Hz typically are already severely screened by the cylinder.

A.1 Ambient Fluctuations in the Magnetic Field

For precision mass spectroscopy, we are particularly concerned about spatially uniform fluctuations in the ambient field, the sources of which are frequently beyond the experimenter's control. For example, to compare the masses of a proton and antiproton to a desired precision of 1 part in 10^9 in a 6 Tesla magnet field requires a time stability better than 6 nT per hour. Unfortunately, depending upon location, variations of 10 nT (100 μG) to 100 nT (1 mG) are observed, and larger variations are possible during magnetic storms which are related to solar activity [75].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. Fig.A.1 shows the typical situation in our laboratory as measured with a fluxgate magnetometer. During a window of a few hours at night (Fig.A.1a), when the MBTA (Cambridge) subway is not running, the fluctuations are of order 1 nT (100 μG) with occasional steps of order 60 nT (600 μG). By day (Fig.A.1b), much larger fluctuations up to 300 nT (3 mG) are typical. Simultaneous measurements of the fluctuating ambient field, with probes separated by several meters, showed that the fluctuating ambient field is typically spatially uniform.

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 [24] , but there was trouble with flux jumps associated with the shield.

In typical NMR and ICR experiments, the superconducting solenoids do not and need not shield the components of the fluctuating, ambient field which are perpendicular to the strong field B_o. A fluctuating transverse field $B_\perp$ provides only a quadratic correction to the magnitude of the strong field:

$$B = B_o\sqrt{1 + \left(\frac{B_\perp}{B_o}\right)^2} \tag{A.1}$$

Even an extremely large transverse field $B_\perp = 6\mu T$ (60 mG) thus results in an extremely small fractional change in the field, $\delta B/B < 10^{-14}$. Only the z-components of the magnetic field contributions are relevant if we choose the z-axis to coincide with the axis of symmetry of the solenoid system.

A.2 Single Superconducting Solenoid Circuit

We now present an alternative approach, whereby the geometry of the superconducting solenoids that produce the large magnetic field is chosen so that external fluctuations are canceled at the location of the experiment by extra currents induced in the solenoids. As is well known, magnetic flux through a closed superconducting circuit is conserved. We discuss how to configure coupled superconducting circuits so that this flux conservation insures that external field

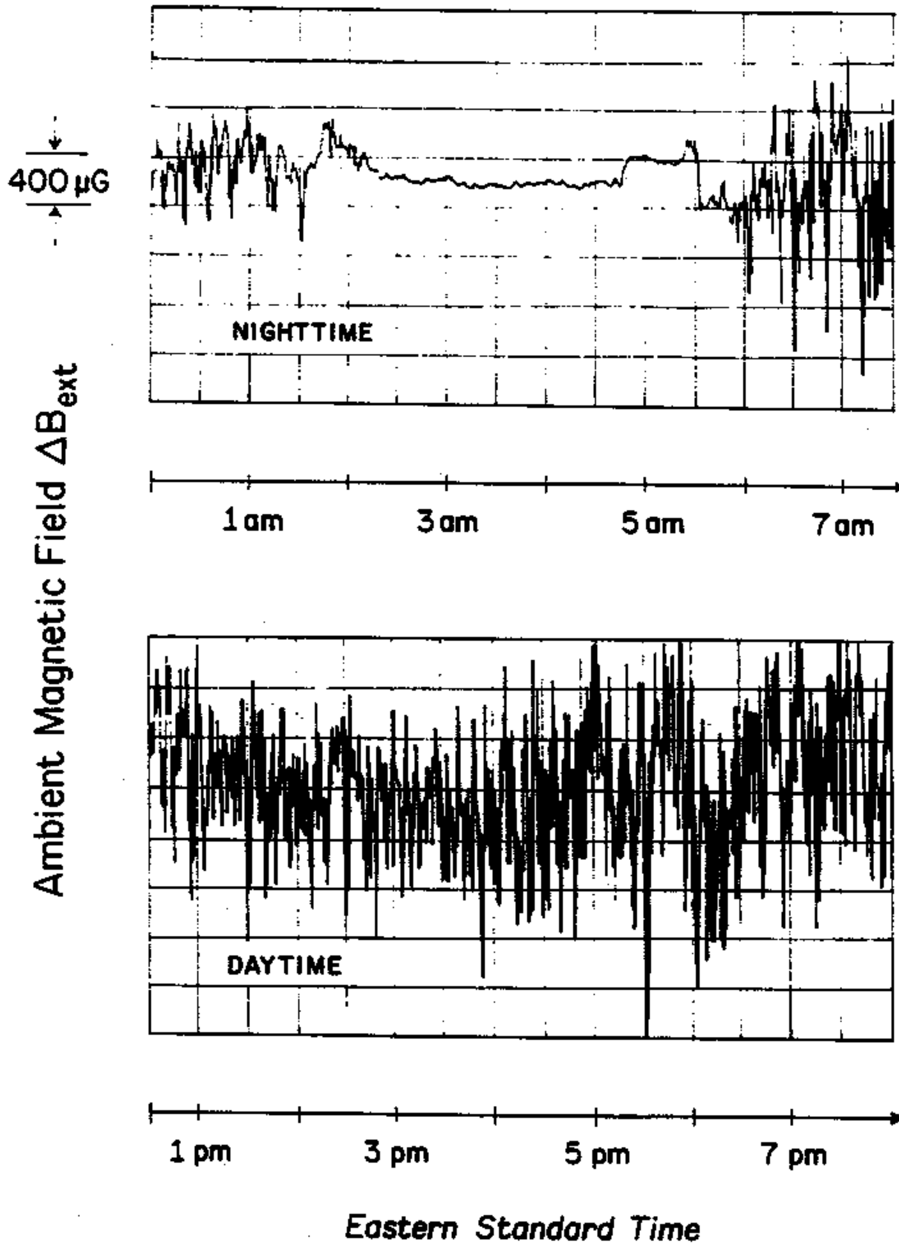

Figure A.1: Typical fluctuations in the magnetic field in our laboratory as measured using a fluxgate magnetometer and a detection bandwidth of 0.01 Hz. The quiet window during the night occurs when the MBTA (Cambridge) subway is shut down.

fluctuations are screened from a selected region of interest. For simplicity, the focus here is on superconducting circuits composed of solenoids which are axially symmetric about a z axis. 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 of interest. We thus choose our examples of self-shielding solenoid systems to suggest ways that these can be designed with minimal distortions of the field homogeneity. Real solenoid systems are more complicated than our examples, but may be analyzed in the same way.

To illustrate the basic shielding scheme, consider a single, axially symmetric solenoid i. The solenoid shown in Fig.A.2 is made of superconducting wire and its ends are connected to make a closed circuit. The potential difference around the shorted solenoid is zero. 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, ie.

$$\int_i [B_e + B_i] dA = 0. \tag{A.2}$$

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 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 $B_e(0,0) + B_i(0,0)$

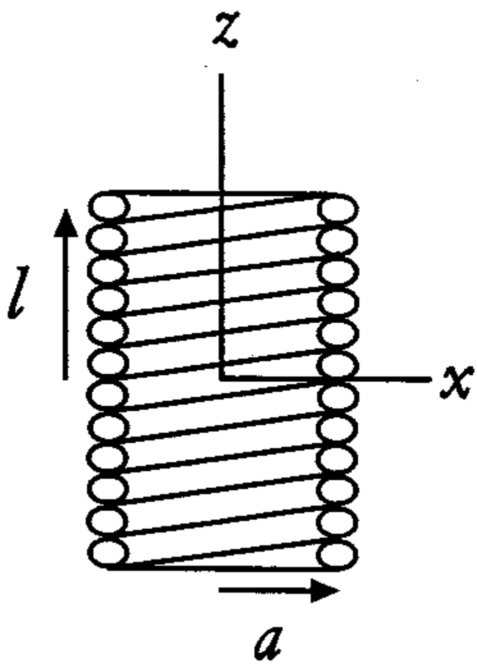

Figure A.2: Simple, single-layer solenoid.

can be written in terms of the shielding factor S as $B_e(0,0)/S$ so that

$$S^{-1} = 1 + \frac{B_i(0,0)}{B_e(0,0)}. \tag{A.3}$$

In light of the flux conservation criterion Eq.(A.2), this can be written

$$S^{-1} = 1 - \frac{\int_i B_e dA / B_e(0,0)}{\int_i B_i(\rho,z) dA / B_i(0,0)} \tag{A.4}$$

To aid intuitive interpretation, we note that S^{-1} is linear in the ratio of two averaged fields

$$S^{-1} = 1 - \frac{\overline{b_e}}{\overline{b_i}} \tag{A.5}$$

defined by

$$\overline{b_e} = \frac{\int_i B_e dA}{B_e(0,0) \int_i dA} \tag{A.6}$$

$$\overline{b_i} = \frac{\int_i B_i(\rho, z)dA}{B_i(0,0)\int_i dA}. \tag{A.7}$$

Here $\int_i dA$ 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, $\overline{b_e} = \overline{b_i}$.

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 $\overline{b_e} = 1$ and the shielding is given by

$$S^{-1} = 1 - \frac{1}{\overline{b_i}}. \tag{A.8}$$

For a short solenoid, the magnetic field near the windings is larger than the magnetic field near the center. The average value in the bore $\overline{b_i}$ is thus greater than 1 so that S^{-1} is positive. For a long solenoid, the volume average of the magnetic field produced by the solenoid within the bore is slightly less than the field at the center because of the fringing field at its ends. Thus, $\overline{b_i}$ increases to a value of 1 with increasing length. This corresponds to S^{-1} increasing to a limit of 0. 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

$$B_i(0,0) = g_i\, I_i, \tag{A.9}$$

as is the flux through the solenoid

$$\int_i B_i(\rho, z)dA = L_{ii}\, I_i. \tag{A.10}$$

The latter proportionality factor L_{ii} is the self-inductance for solenoid i. Substituting these two expressions in Eq. (A.4) yields

$$S^{-1} = 1 - \frac{g_i A_i}{L_{ii}}. \tag{A.11}$$

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

$$A_i = \frac{\int_i B_e dA}{B_e(0,0)}, \tag{A.12}$$

which depends on the spatial distribution of B_e.

In Fig. A.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 [41] and efficient calculation techniques have been discussed [39]. The qualitative features discussed above are readily apparent. The self-shielding is complete (i.e. $S^{-1} = 0$) at the aspect ratio [13]

$$l/a = 0.88 \tag{A.13}$$

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 represented in Fig. A.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 A.1. 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. 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. A.4. More practical modifications involve two or more coupled superconducting circuits, which will be discussed next.

Dimensions	Calculated parameters
$a_1 = 7.62 \ cm$	$L_1 = 232.3 \ H$
$a_2 = 12.70 \ cm$	$A_1 = 2219 \ m^2$
$l_1 = 25.40 \ cm$	$g_1 = 0.1469 \ T/A$
$n_1 = 64000$	$S = -2.95$

Table A.1: Basic solenoid

A.3 Coupled Superconducting Circuits

Practical solenoid systems typically contain several circuits, one to produce the large field and the others as shims to make the field near the center as homogenous

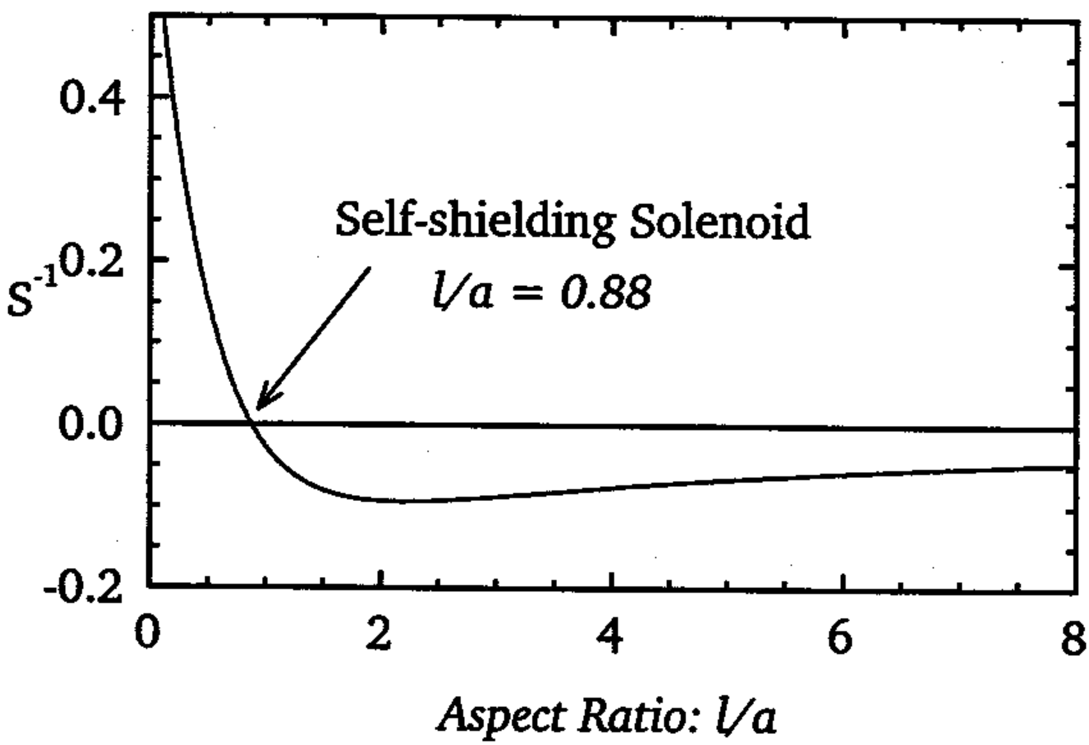

Figure A.3: Shielding of a densely would, single-layer solenoid as a function of its aspect ratio, the ratio of its half length l to its radius a.

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 $\mathbf{I}$ and a related column vector $\mathbf{g}$ relates the field at the center to the currents with components defined by

$$B_i(0,0) = g_i\ I_i. \tag{A.14}$$

The areas of the circuits are represented by column vector $\mathbf{A}$ with components

$$A_i = \int_i dA \tag{A.15}$$

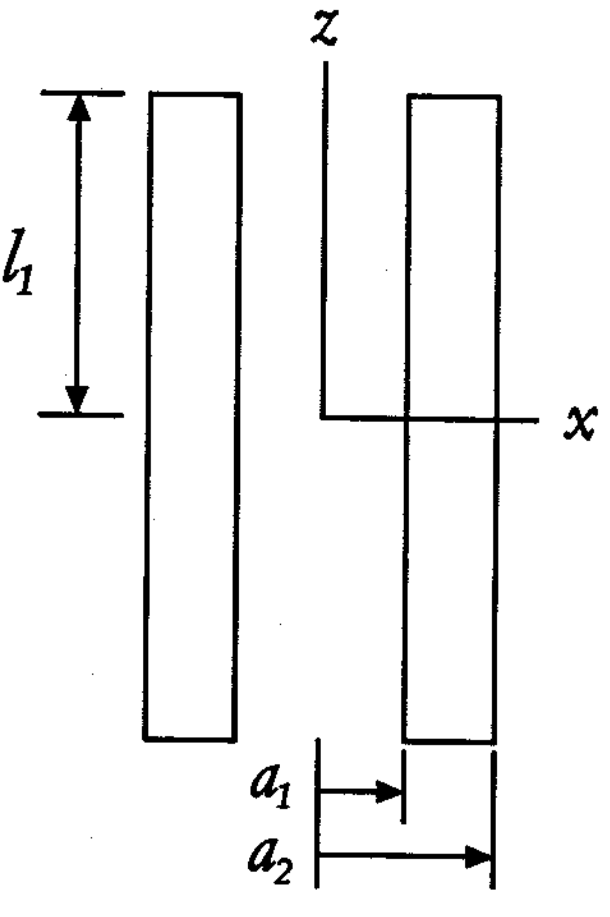

Figure A.4: Large solenoid to illustrate typical properties of high-field persistent solenoids.

which may be generalized for the case of non-uniform B_e as was done in Eq.(A.12). The familiar symmetric inductance matrix L has components given by

$$\int_i B_j(\rho, z) dA = L_{ij} \; I_j. \tag{A.16}$$

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

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

with the superscript T indicating transposition so that $\mathbf{g}^T$ is a row vector. For a single circuit Eq. (A.17) reduces immediately to Eq. (A.11). Complete shielding occurs when

$$\mathbf{g}^T \mathbf{L}^{-1} \mathbf{A} = 1. \tag{A.18}$$

This is the condition for a self-shielding solenoid system.

As an illustration, consider a system of 2 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 the 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 Eq. (A.17), the shielding factor is

$$S^{-1} = 1 - \left[\frac{g_1 A_1}{L_1} + \frac{g_2 A_2}{L_2} - \frac{M}{L_1 L_2}(g_2 A_1 + g_1 A_2)\right] \left[1 - \frac{M^2}{L_1 L_2}\right]^{-1}. \tag{A.19}$$

For $M \to 0$, comparison with Eq. (A.11) 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

$$V_2 = -L_2 \frac{dI_2}{dt}. \tag{A.20}$$

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

$$MI_1 + L_2 I_2 = 0 \tag{A.21}$$

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.

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. [86] 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 occured 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.

A.4 Commercial Solenoid Circuits

In practical solenoid systems, the closed superconducting circuits are generally composed of individual solenoids connected in series. It is convenient to relate the column vectors $\mathbf{g}$ and $\mathbf{A}$ and the inductance matrix $\mathbf{L}$ for the circuits to the analogous quantities for the solenoids $\tilde{\mathbf{g}}$, $\tilde{\mathbf{A}}$ and $\tilde{\mathbf{L}}$. We define the $N \times \tilde{N}$ matrix $\mathbf{\Omega}$ such that the currents in the solenoids $\tilde{\mathbf{I}}$ are given by

$$\tilde{\mathbf{I}}^T = \mathbf{I}^T \mathbf{\Omega}. \tag{A.22}$$

For N circuits there are $\tilde{N}$ solenoids with $\tilde{N} \geq N$ since at least one solenoid is in given circuit. In simple cases wherein 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 transformation rules are

$$\mathbf{g} = \mathbf{\Omega}\tilde{\mathbf{g}}, \tag{A.23}$$

$$\mathbf{A} = \mathbf{\Omega}\tilde{\mathbf{A}}, \tag{A.24}$$

and

$$\mathbf{L} = \mathbf{\Omega}\tilde{\mathbf{L}}\mathbf{\Omega}^T. \tag{A.25}$$

We have found that it is convenient to set up the computation in terms of the solenoid quantities, since each solenoid typically has a different geometry, and then carry out the contractions as above using $\mathbf{\Omega}$ to get the circuit parameters needed to evaluate the screening.

Simple geometries and dimensions which seemed theoretically promising were described in [33]. However, high-field NMR solenoids with state-of-the-art spatial homogeneity are generally constructed commercially, with complicated geometries which vary from manufacturer to manufacturer. 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. For the first trial, Nalorac Cryogenics provided us with the (proprietary) internal dimensions of their standard, high-homogeneity solenoid made for NMR applications. This system has a calculated shielding factor of

$$S = -4.45 \pm 0.10 \tag{A.26}$$

which agrees with the measured value. Other calculated properties of this system are given in Table A.2. (This comparison is discussed further towards the end of

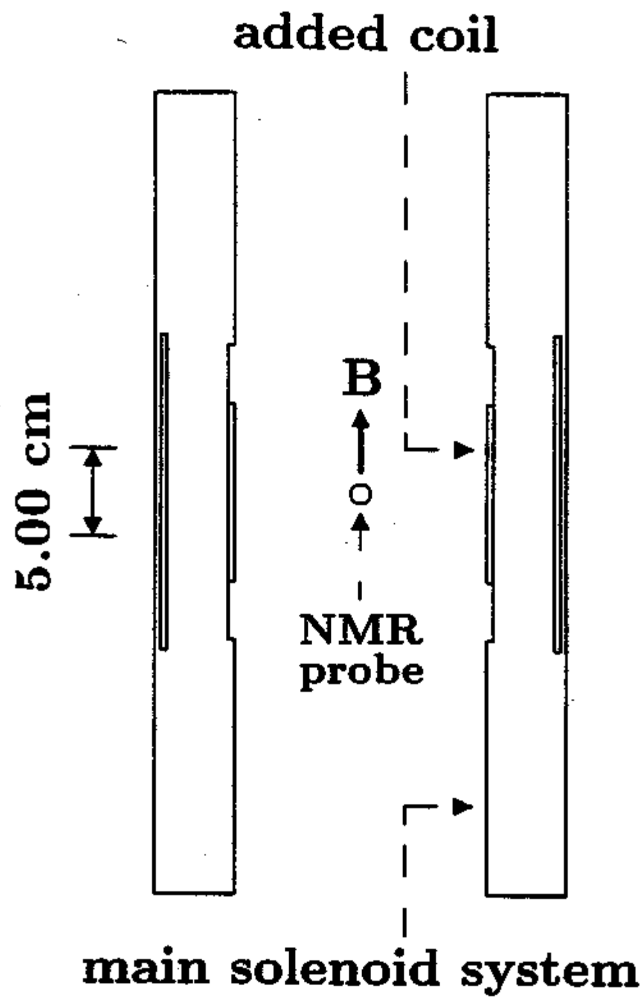

Figure A.5: Cross section of the windings of the high-field solenoid which produces a vertical magnetic field. The innermost solenoid was added to make the solenoid system cancel external fluctuations.

the next section.) The uncertainty reflects some imprecision in our knowledge of the location of the windings and inaccuracy in our inductance calculation. Our detailed calculations for finding a practical geometry which satisfies the shielding condition in Eq.(A.18) indicated that a small, persistent, interior solenoid could be added to make a solenoid system which cancels external fluctuations. No other modification of the standard system was needed to preserve the high degree of spatial homogeneity ($\delta B/B < 10^{-8}$ over a sphere 1 cm in diameter). A cross section of the solenoid and the added interior coil (to scale) is shown in Fig. A.5. The strong field produced within the solenoid is along the symmetry axis of the solenoid. The large outer coil produces the large magnetic field and contains shaped correction coils to obtain a high degree of spatial homogeneity. Without the added interior solenoid, this cross section is typical of a high-field NMR solenoid. The inductance matrix for this system is calculated to be

$$\mathbf{L} = \begin{pmatrix} 0.1310 & 0.2508 & 2.3434 \\ 0.2508 & 2.4161 & 16.1924 \\ 2.3434 & 16.1924 & 173.4107 \end{pmatrix} \mathrm{H} \,, \qquad \text{(A.27)}$$

where the smallest diagonal element is the inductance of the added interior solenoid and the remaining diagonal elements are the inductances of the two solenoids forming the standard system. Table A.3 includes other calculated properties of the first system designed and constructed to be self-shielding.

A.5 Measured Shielding

To measure the shielding, we insert an NMR probe with an acetone sample into the high-field region. The sample is a sphere with a diameter of 1 cm. We apply an external magnetic field to the solenoid using large square Helmholtz coils,which are 2.81 m on a side and are separated by 1.53 m. These coils produce a magnetic field which varies over the solenoid by less than 0.3 % .

By opening the circuit of the inner shielding coil, we measure a shielding which is typical of a high-homogeneity, high-field NMR solenoid. Fig. A.6a shows the

Parameter	Value	Unit
A_1	135.88	m^2
A_2	1662.01	m^2
L_1	2.386	H
L_2	177.5	H
M	16.25	H
$L = L_1 + L_2 + 2M$	212 H	H
g_1	14.483	mT/A
g_2	134.910	mT/A
$(e/m)(g_1 + g_2)/2\pi$	4.182(3)	GHz/A
S	-4.45 ± 0.10	—

Table A.2: Calculated properties of a Nalorac superconductive magnet (JOB43).

Parameter	Value	Unit
A_s	17.53	m^2
A_1	136.72	m^2
A_2	1644.02	m^2
L_1	2.416	H
L_2	173.4	H
M	16.19	H
$L = L_1 + L_2 + 2M$	208 H	H
g_s	7.231	mT/A
g_1	14.565	mT/A
g_2	133.109	mT/A
$(e/m)(g_1 + g_2)/2\pi$	4.134(3)	GHz/A

Table A.3: Calculated properties of a new Nalorac superconductive magnet designed to be self-shielding (JOB51). Subscript s indicates the added interior solenoid.

field change within the central volume of the solenoid (from the measured shift in NMR frequency) as a function of the external field applied with the Helmholtz coils. The measured shielding factor is

$$S = -4.27 \pm 0.07 \ . \tag{A.28}$$

This means that external field fluctuations are reduced by this factor, and we expect that this number is rather typical of high-field solenoids of reasonable geometry since it is rather insensitive to the details of the geometry. The negative sign is also typical. It indicates that the solenoid overcompensates the external fluctuation, so that the fluctuation experienced in the center region is actually oppositely directed to the applied external field. The measured value compares well with the calculated value $S = -4.5 \pm 0.1$ given above.

When the inner solenoid is allowed to go persistent, the shielding improves dramatically, as indicated in Fig.A.6b. The measured shielding factor is

$$S = -156 \pm 6 \ . \tag{A.29}$$

We interpret this as the shielding for a spatially uniform field, after increasing the uncertainty from 3 (the measurement precision) to 6 to include effects of possible inhomogeneities in our applied field. We observe the same linewidth in the NMR signal with the shielding coil as without, indicating that the spatial homogeneity is not compromised over the 1 cm diameter of the spherical NMR probe.

A.6 Field Homogeneity of Shielded Region

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 Eq. (A.18) allows for many possible self-shielding configurations. The approach taken in Fig.A.5 has minimal effect on field homogeneity. The basic solenoid, optimized to provide the desired level of homogeneity,

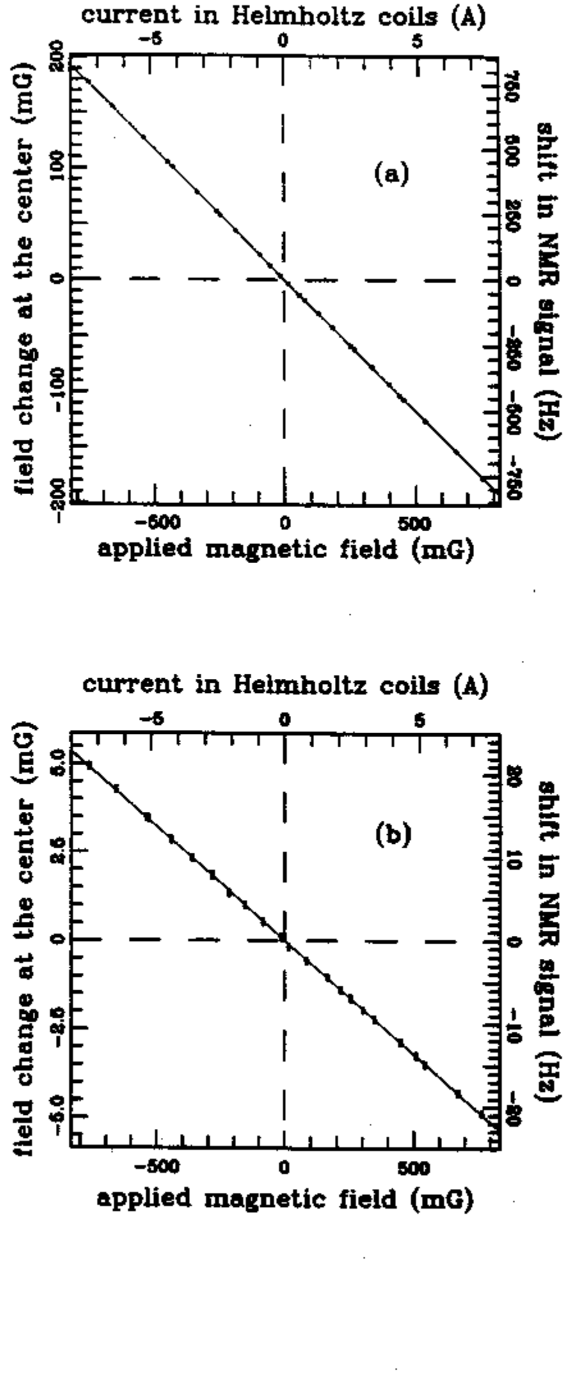

Figure A.6: Change in the magnetic field measured within the solenoid (deduced from the change in NMR frequency of an acetone sample) as a function of the external magnetic field applied over the solenoid, without (a) and with (b) the added inner solenoid.

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.A.5, 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.

A.7 Shielding for Nonhomogeneous Fields

Spatial homogeneity of applied field is important in measuring shielding factors. Larger than expected shielding factors were obtained by applying an external field using a single loop around the solenoid, for example, or using Helmholtz coils which are too small (Fig. A.7). An early measurement used a pair of square coils (side length of 2m) to apply an external magnetic field to an unmodified, Nalorac solenoid system. Although the coils were separated by 2 meters, we calculated that the spatial inhomogeneity in the applied external field over the volume of the solenoid system reduces the shielding from $S = -4.45$ in Eq. (A.26) to $S = -4.10$ which is what agrees with our measurements. To calculate the modified shielding factors, the generalized definition of effective areas in Eq. (A.12) must be used, taking B_e to be the nonuniform field of the external coils.

Field fluctuations due to distant sources typically are spatially uniform. The system which has been tested was specifically designed to shield out fluctuating fields which are spatially uniform. There are cases, however, wherein the high-field region can be shielded from nonhomogeneous ambient fluctuations. For example, a linear gradient in the applied field averages to zero over the solenoid, making no contribution to $\bar{b}_e$ and to the shielding factor. As another 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 is then suitably chosen to compensate the drift in the field.

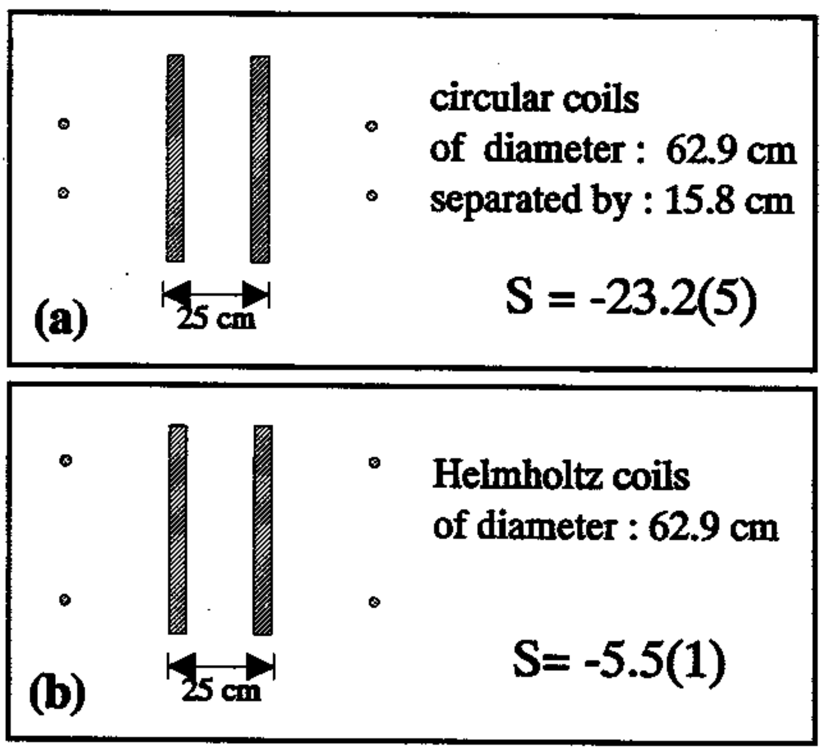

Figure A.7: Examples of larger than expected shielding factors due to gradients in the applied magnetic field.

Nearby magnetic materials distort the fluctuating ambient (otherwise uniform) field and significantly modify the shielding. For example, steel reinforcements in concrete blocks located beside the solenoid at CERN distort the fluctuating field from the nearby storage rings. For the CERN PS, we observe a shielding factor of $S = -100$. The field from the closer LEAR magnets is shielded by a factor of $S = -50$. These shielding factors are significantly lower than the shielding factor of $S = -156$ observed for uniform magnetic fields, but are still large reductions in the fluctuations of the magnetic field in the volume within the solenoid where experiments are located.