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Design of a large-scale vertical open-structure cylindrical shield employing magnetic shaking

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The shield developed consists of four concentric magnetic shells positioned on the outer surfaces of paper pipes of ~2.7 m length, ~1 cm thickness, and with outer diameters of 67, 72, 82.2, and 97.4 cm, respectively. The first (innermost) shell is a Permalloy shell of 2.1 mm thickness and 1.8 m length. The second, third, and fourth shells are made of ~50 mm wide, ~22 μm thick Metglas 2705M amorphous ribbons. The second shell, which is a 2.2 m long helical structure, consists of 48 layers of Metglas ribbon divided into four equal sections by ~1 cm thick flexible Styrofoam sheets. The third shell, 2.43 m in length, and fourth shell, 2.7 m in length, consist of 26 and 30 layers, respectively. A thin polyethylene film is tightly wound on each section of the second shell as well as on the third and fourth shells. It increases the friction between the Metglas ribbons and prevents them from sliding down; there is no foreign material in between the layers of the ribbon. All shells are enclosed by toroidal coils which are used to demagnetize the Permalloy shell and to apply magnetic shaking to the amorphous magnetic shells. The gross weight of the shield is ~400 kg including ~65 kg of Permalloy and ~110 kg of Metglas. An ~10^5 transverse shielding factor and a relatively large ~380 axial shielding factor, despite the effect of the openings, are achieved for a 10 μT external field in the extremely low frequency region. The measured shaking leakage and magnetic noise field strengths at the shield's center are less than 1 nT. As these low field strengths, it is possible to operate highly sensitive SQUID magnetometers for biomagnetic measurements. © *2000 American Institute of Physics.* [S0021-8979(00)82108-8]

I. INTRODUCTION

A relatively compact, vertically structured shield (Fig. 1) is potentially more effective at accommodating a SQUID (superconducting quantum interference device) magnetometer used for magnetoencephalography applications compared to that of a horizontal structure. The shield's diameter can be made smaller in this case and greater axial and transverse attenuation ratios (shielding factors) can be achieved. Considering the compactness of the shield, it is important to keep both ends of the shield open and they provide easy access and prevent claustrophobia. It is also much easier to supply an open-ended shield with toroidal coils and to apply magnetic shaking to increase the permeability and shielding performance of the magnetic material.[1,2]

A vertical shield is exposed to a vertical component of the earth's magnetic field unless it is located near the equator. This field component acts along the axial direction and seriously reduces the shielding performance, especially if the shield's ends are open.

The present work focuses on overcoming the above difficulty as well as overcoming new technical difficulty associated with the design of this new type of shield.

II. CONCEPT

The principal objective of this research was to achieve residual magnetic field strength less than 1 nT in the extremely low frequency region at the shield's center. This frequency range corresponds to the operating range of modern highly sensitive SQUID magnetometers.

The strategy of the design was aimed first of all to achieve a large transverse shielding factor (TSF). According to Ref. 3, we expected that four active, to which magnetic shaking[1,2] is applied, narrowly spaced Metglas 2705M shells can provide transverse shielding factor larger than 4000. Reference 3 suggests the use of a helical structure consisting of Metglas ribbons in the shells' construction.

Considering the axial performance of the shield, the goal was to achieve an axial shielding factor (ASF) of a 100 or more. It should decrease the ambient low frequency noise field strength to below 1 nT, which is a rough estimation of the saturation level of SQUID magnetometers. Reference 4 shows that the casting direction of Metglas ribbons should be aligned with the ambient field in order to make magnetic shaking efficient. In other words, applying magnetic shaking to the above helical structure provides effective shielding in the transverse direction. Hence, axial shells[4] should be included in the shield to improve its axial shielding performance.

The following was taken into account while optimizing the dimensions of the shield. Reference 5 suggests a maximum possible length-to-diameter ratio for the shield in order to increase both the ASF and TSF. Reference 6 shows that at least two shells are needed in order to obtain an ASF of 100 or more. The latter reference also suggests the use of inner shells which are shorter than the outer shell in order to screen them to a certain extent from the external field. Numerical simulations showed, however, that an extensive shortening

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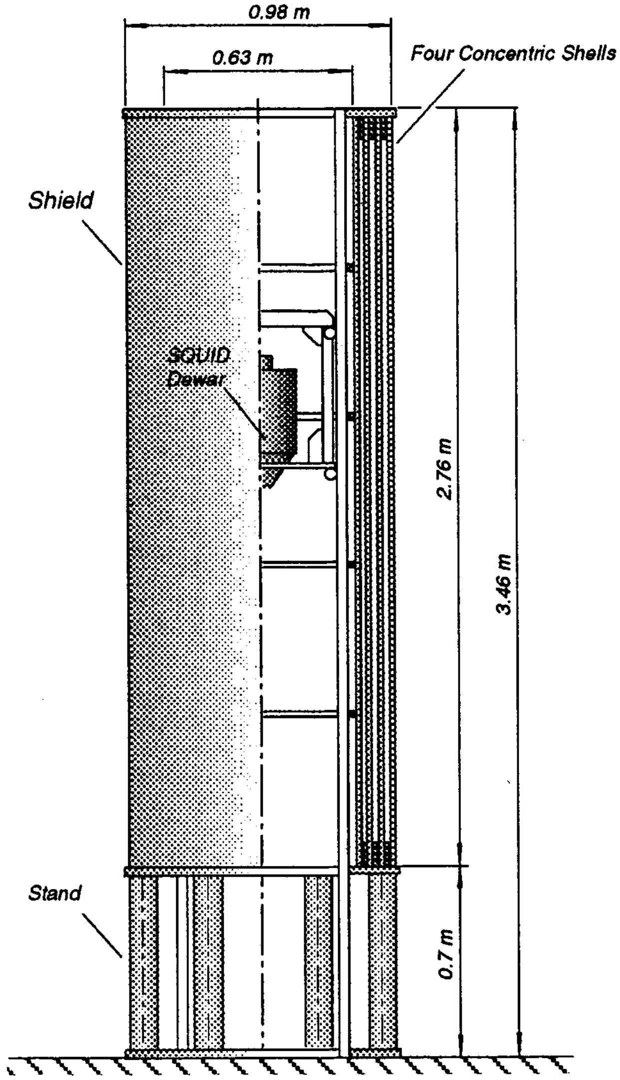


FIG. 1. Drawing of a vertical open-structure cylindrical magnetic shield.

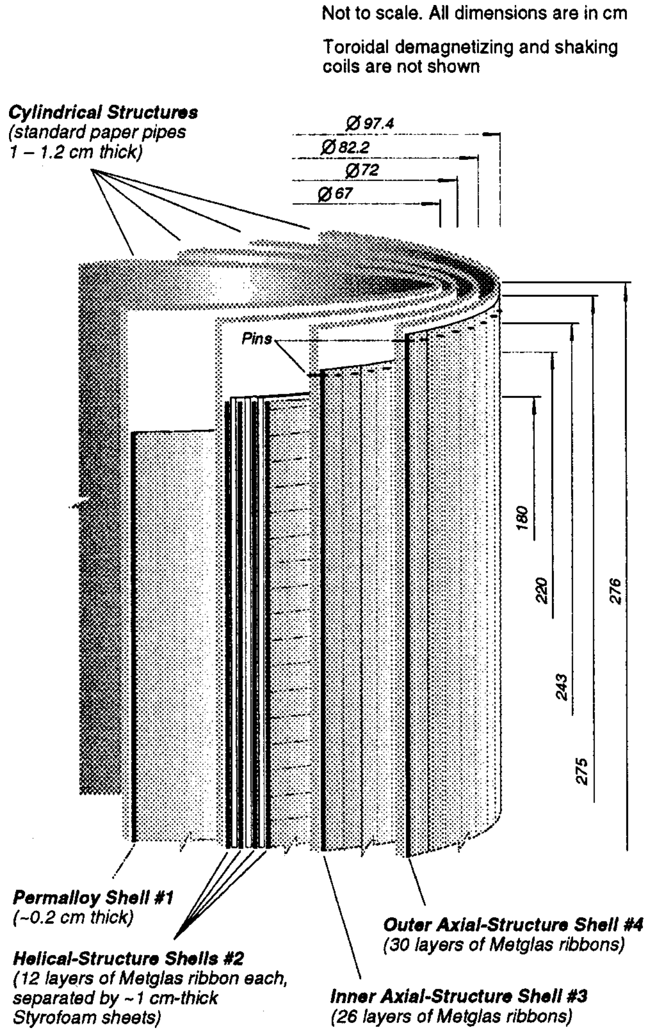


FIG. 2. The simplified structure of the shield.

of the inner shells is not desirable because it decreases the residual field uniformity. A nonuniform residual magnetic field in the shield may cause low frequency noise in the output of magnetometers associated with mechanical vibration. Uniformity in the residual magnetic field is more important for the case of SQUID gradiometers, where magnetic field noises are, in principle, canceled out if they distributed uniformly. It is not easy to reduce a strongly nonuniform residual field by employing active compensation methods.[7] Another reason not to make inner shells too short is a likely increase in the leakage of the magnetic shaking field into the shielded area. To reduce the total leakage, axial shells that require larger shaking currents[4] are positioned outside the helical shell. Finally, an innermost passive Permalloy shell is included in the structure of the shield to further reduce the total leakage field from the other active shells.

III. STRUCTURE OF THE SHIELD

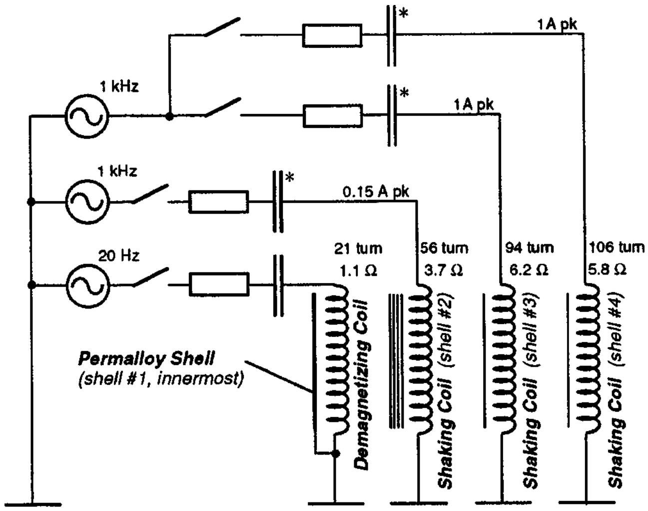
The configuration of the shield is shown in Figs. 1 and 2. Material and structural details are shown in Table I. The shield consists of four cylindrical structures, and standard large-diameter paper pipes, supporting the shield's four shells. The pipes are ~1 cm in thickness, 2.76 m in length, and have outer diameters of 67, 72, 82.2, and 97.4 cm, respectively. The inner diameter of the innermost pipe (65 cm) was chosen to allow an ordinary person to avoid a state of claustrophobia. The total length of the shield, 3.46 m (see Fig. 1), was made slightly shorter than the height of the ceiling, 3.6 m, in our experimental facilities.

TABLE I. Structure of the shield.

	No. and structure of shell	D_i[a] (cm)	t_i (mm)	L_i (cm)	L_i/D_i	L_i/L_{i+1}	Weight (kg)
1.	Permalloy	67	2.10	180	2.7	0.68	75.0
2/1.	Helical	72	0.27	220	3.1	0.91	9.4
2/2.	Helical	73	0.27	220	3.0	0.91	9.6
2/3.	Helical	74	0.27	220	3.0	0.91	9.7
2/4.	Helical	75	0.27	220	2.9	0.91	9.8
3.	Axial	82.2	0.57	243	3.0	0.88	29.9
4.	Axial	97.4	0.66	275	2.8	[b]	39.0

[a] D_i is the inner diameter, L_i is the length, and t_i is the thickness of shell No. i.

[b] There is no other shell outside of the No. 4 shell.



Resistors, 1 Ω, are used to monitor currents through the coils.
Capacitors, 0.68–0.1μF, eliminate dc and* adjust the phase of the currents.

FIG. 3. Experimental setup.

The first (innermost) shell is made of Permalloy. Three other shells are made of $\sim$50 mm wide, $\sim$22 μm thick Metglas 2705M ribbons. The second, helical structure shell is separated into four identical sections by $\sim$1 cm thick flexible Styrofoam sheets. Each section consists of 12 layers of Metglas ribbon. The ribbons are wound helically, edge-to-edge and under some tension. The direction of winding was alternated section by section. A thin polyethylene film was tightly wound around each section. This increases the static friction between the Metglas ribbons and prevents them from sliding down; there is no foreign material in-between the layers of the ribbon.

The third and fourth axial shells are composed of 26 and 30 layers, respectively. To assemble these two shells, Metglas ribbons were cut to a desirable length and a 6 mm diameter hole was punched in each piece. Plastic pins were inserted into the two outer pipes (see Fig. 2), and 1222 pieces of the ribbon for shell no. 3 and 1590 pieces of the ribbon for shell no. 4 were hung on the pins all around the pipes. A thin polyethylene film was tightly wound around each axial shell in order to put the Metglas ribbons in better mechanical and magnetic contact with each other.

All shells of the shield are enclosed by toroidal coils. These coils are used to demagnetize the Permalloy shell and to apply magnetic shaking to the Metglas shells. Approximately 1.8 mm deep grooves were cut on the outer surface of each pipe to accommodate the inner layer of the coils' winding. Parameters of the coils are shown in Fig. 3.

IV. PERFORMANCE OF THE SHIELD

The performance of the three inner shells was measured (see Fig. 3 and Table II) by applying a transverse magnetic field with a pair of large $(2\times4\,\mathrm{m}^2)$ rectangular coils separated by a distance of 1.5 m and by applying axial field with three rectangular $(1.68\times1.68\,\mathrm{m}^2)$ coils separated by a distance of 1.1 m. The Permalloy shell was demagnetized before the experiment. Each of the three inner shells was tested alone (see Table II). Active shells were tested with and without magnetic shaking. The shaking efficiency is not a strong function of the shaking frequency. In this experiment, 1 kHz was chosen for it considering power consumption and shielding effectiveness of the Permalloy shell against leak magnetic fields from the shaking coil. The parallel connection in the shaking circuit is simply to share one power amplifier with two shaking coils.

TABLE II. Performance of the shield.

Combination of shells	TSF[a] without shaking	ASF without shaking	TSF with shaking	ASF with shaking	Leakage[b] field (nT, rms)
1	100	25	[c]	[c]	[c]
2	280	9	16 000	13	65.0
3	140	15	140	56	60.0
4[d]	140	12	140	50	60.0
1, 2, 3	2900	45	57 700	111	0.4
1, 2, 3, 4	−5000	−180	−100 000	−380	0–0.4[e]

[a] All parameters are measured at the center of the shield at 2 Hz.
[b] Measured along axis.
[c] Shaking is not applied to the Permalloy shell.
[d] Parameters are estimated.
[e] Can be adjusted by choosing a proper phase difference for shaking currents.

After the test, the three inner shells were assembled on a stand (see Fig. 1) and tested again (see Table II). The fourth (outermost) Metglas shell was assembled around the other three shells after they were placed on the stand (the pipe supporting the fourth shell was cut along the axis into two halves in order to install it on the stand). The completely assembled shield was tested by applying a transverse field with a dipole source and by applying an axial field with the three large rectangular coils.

Shield tests have shown the effectiveness of the design. A transverse shielding factor as high as 10^5 and a relatively large $\sim$380 axial shielding factor despite the effect of the openings are achieved for a 10 μT external field in the extremely low frequency region. The shaking leakage and magnetic noise field strengths at the shield's center were less than 1 nT. As these low field strengths, it is possible to operate highly sensitive SQUID magnetometers for biomagnetic measurements. It was also found that the leakage field can be further reduced if the phase differences among shaking currents in all three shaking coils are properly adjusted. A residual dc field was reduced below 1 nT by applying a dc current to a pair of ring coils installed inside the innermost pipe at the end of the cylindrical shell.

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