Novel High Field Permanent Magnet Flux Sources

By Herbert A. Leupold and Ernest Potenziani II,
U.S. Army Electronics Technology and Devices Laboratory (ET&DL),
SICET-ES, IABCOM, Fort Monmouth, NJ 07703-5601

Abstract

Several compact permanent-magnet configurations are discussed which produce fields greater than the remanence of the magnetic material comprising them. For example, a field of 20 kG can be produced in a one-inch diameter spherical cavity by a NdFeB sphere of 12 kG remanence and 3.5 inch diameter. Field perturbation due to access holes in the structure are analyzed by finite element methods, and their effects on device utility are discussed.

Introduction

The advent of high-energy product magnet materials has made it possible to replace many dc flux sources that are presently driven by bulky electrical solenoids with relatively light, compact permanent magnet structures. Especially promising for such purposes are various configurations based on the hollow cylindrical flux source (HCFS) principle used by Halbach[1] in the design of a variety of devices.

A HCFS is a cylindrical permanent-magnet shell with its magnetization vector constant in magnitude and oriented according to the formula

$$\alpha = 2\phi + \frac{\pi}{2} \quad (1)$$

where Φ is the angular cylindrical coordinate, see Figure 1. Such a distribution gives rise to an interior field of:

$$H = B_r \ln\left(\frac{p_0}{p_i}\right) \quad (2)$$

where B_r is the remanence of the ring and p_i and p_o its inner and outer radius, respectively. Equation (2) shows that fields greater than the remanence can be generated, but since H varies only logarithmically with $R = p_o/p_i$, large values of R are needed to produce relatively small changes in H. Nevertheless, if the specified fields are restricted to less than twice the remanence, rings generating them are practical. For a field equal to the remanence, R need equal only 2.7, that is, a NdFeB ring only 2.7 cm in diameter would, by calculation, produce 12.0 kOe in a 1.0 cm cavity.

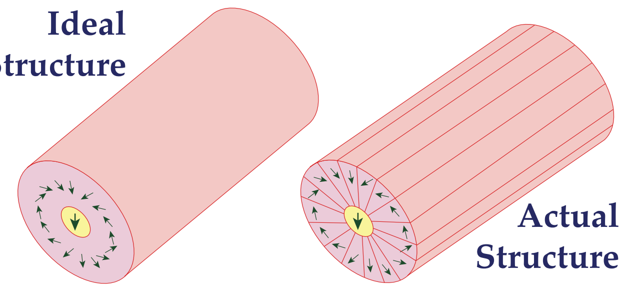

Figure 1 — The ideal and actual structure configurations for a HCFS are shown

The Hollow Spherical Flux Source

Equation (1) can also be applied to a spherical shell with the polar angle θ substituted for the cylindrical azimuthal angle Φ, see Figure 2.

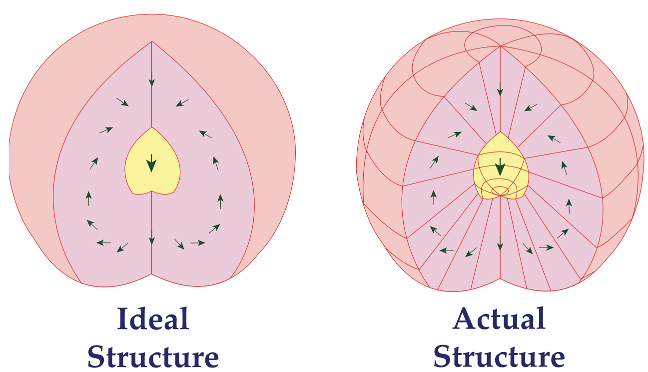

Figure 2 — The ideal and actual structure configurations for a HSFS are shown. A quarter of the structure has been removed for clarity.

The resulting hollow spherical flux source (HSFS) produces a field in its central cavity, given by:

$$H = \frac{4}{3} B_r \ln\left(\frac{r_0}{r_i}\right) \quad (3)$$

Thus, a HSFS produces a field 4/3 as great as a HCFS with the same radius. Also, the sphere has no field distortions due to end effects, as does a HCFS, but has the disadvantage of no open ends for access to the field.

If a field of 20 kOe is needed in a spherical space of 1.0 cm diameter, and if a B_r of 12 kG is used, the outer diameter need be only 3.49 cm. The structure would weigh about 0.145 kg, an extraordinarily small mass for so great a field in that volume.

Since it is not feasible to construct an ideal HSFS, in practice, a segmented approximation such as that of Figure 2B must be used. In such a configuration the magnetization is constant in both magnitude and direction within anyone segment. Fortunately, even with as few as eight segments per great circle of longitude, more than 90 percent of the field of the ideal structure is obtainable. This greatly facilitates construction of a practical device and would reduce costs considerably. All calculations in this paper are for such an approximation. Azimuthal field dependence is assumed to be continuous.

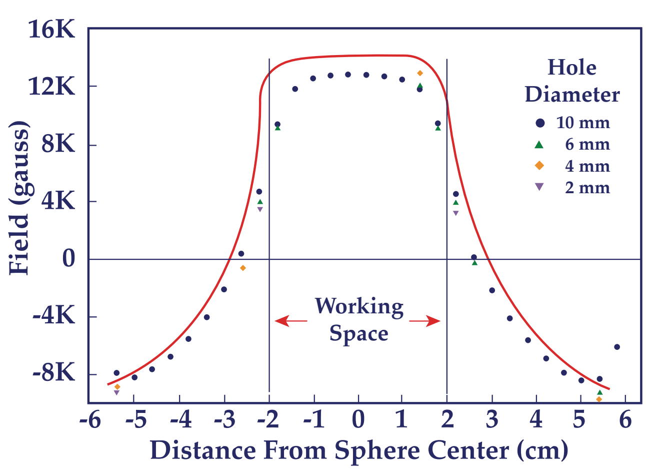

Figure 3 — The on-axis field of a single HSFS for various polar hole diameters. The magnet shell thickness is 4 cm, the inner radius is 2 cm and the magnet remanence is 10 kG.

For the field in the cavity to be useful, accessibility to electrical leads, waveguides, and/or other conduits is required. Figure 3 shows the calculated effect of cylindrical holes drilled axially through the poles. Fortunately, even holes as large as 1.0 cm in diameter reduce the field by only five percent, so that conduits of one-fourth the diameter of the working space are practical. Such geometrical insensitivity greatly enhances the general utility of the HSFS.

Another attractive feature of the HSFS is the axial field uniformity in its interior. as shown in Figure 3. For polar holes of up to 4 mm, fraction-of-a-percent uniformity extends over 70 percent of the axial diameter of the spherical working spaces. Such a wide extension of essentially peak fields results in a large magneto-motive force (mmf) between the ends of the axial diameter; about 50 kilo-gilberts for the sphere of Figure 3 with 4 mm holes. This is of great potential importance for Faraday rotators at optical frequencies in which short optical paths are desirable to avoid unnecessary losses.

The Hollow Hemispherical Flux Source

Also of considerable potential usefulness are the hemispheres and semi-cylinders formed by halving a sphere and a cylinder through their equators at $\theta = 0$ and $\Phi = 0$, respectively. With either structure, one can produce a field by merely laying its flat side on a slab of a flux conductor such as iron. The anti-mirror image of the hemisphere in the iron effectively completes the HSFS. A field of 20 kOe can thus be produced in a 2.54 cm diameter space with a 1.3 kg magnet mass. Access holes for electrical leads can be drilled through the iron slab, rather than through the expensive magnets, as would be necessary for the full HSFS.

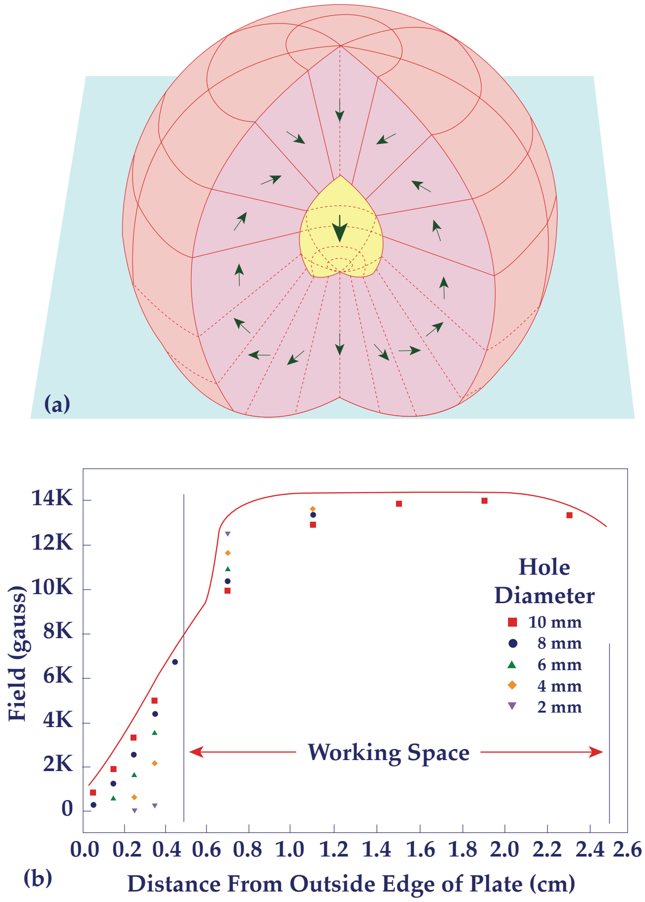

Figure 4 — The actual structure configuration for a HHFS is shown in (a). A quarter of the structure has been removed for clarity. In (b) we show the on-axis fields of a HHFS with a hole in the iron plate only. All dimensions are the same as in Figure 3 with a 0.5 cm plate thickness.

Figure 4 shows such a hemispherical structure, or hollow hemispherical flux source (HHFS), together with its axial field variation with the diameter of an access hole through the center of the iron slab. Again, the structure shows itself to be forgiving as the hole size affects the axial field significantly near the plate only.

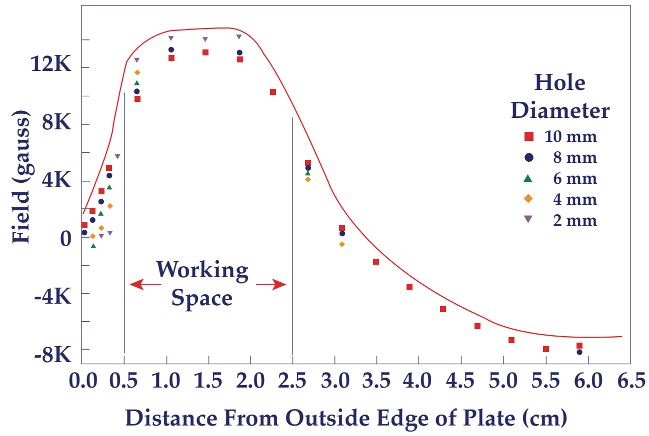

Figure 5 — The on-axis fields of a HHFS for various hole diameters (through both the pole and iron plate). All dimensions are the same as in Figure 4.

Figure 5 shows the effect of axial holes of equal size through both the pole and the iron. In this case, sensitivity of the axial field profile to hole size is greater: enough to diminish its utility for some purposes, but not enough to reduce the peak field by more than five percent.

Conclusion

Though presently difficult to fabricate, HCFS's, HSFS's, HHFS's, and their derivatives have a wide range of potential use. Possible applications are in optical rotators, millimeter-wave filters, easily portable laboratory field sources, and, when placed in tandem, periodic permanent magnet stacks for traveling wave tubes. These and other potential applications are under current investigation.

Publishing History

First published September 1987. Reformatted and color illustrations added June 2009 by Mark Duncan.

References

[1] Klaus Halbach, "Permanent Magnets for Production and Use of High Energy Particle Beams," Proceedings of the Eighth International Workshop on Rare Earth Cobalt Permanent Magnets and Their Applications, University of Dayton, Dayton, OH, 1985, Paper No. 11-2, p. 123.