

# Design and Analysis of the Novel Test Tube Magnet for Portable NMR Device

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**Abstract**— The paper presents a novel test tube magnet (TTM) for Portable NMR device, which is composed of a dipole cylinder magnet and a hemi-cylinder or a hemi-sphere magnet. The hemi-cylinder or the hemi-sphere magnet is attached to one end of the dipole cylinder magnet, so that the whole magnet is shaped like a test tube. TTM generates a wide diameter spherical volume (DSV) with a high magnetic field homogeneity, which makes the device more applicable for portable NMR. The two configurations were simulated with three-dimensional finite-element methods. Flux density elements are effectively corrected in the DSV. The homogeneity increases, the magnet volumes and mass are markedly decreased, and the construction is very reasonable. Taken together the new designs have improved characteristics for portable NMR.

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## 1. INTRODUCTION

In the past few years, portable NMR devices have been rapidly developed, and several important applications have been suggested and realized. The main problem in designing portable NMR device is not so much the production of high magnetic fields, but rather high and homogeneous fields in a large and accessible volume at acceptable weights. Permanent magnets, because of their advantages in terms of cost and no maintenance, are receiving increased attention for the construction of portable NMR devices. Halbach arrays [1] of permanent magnets offer a unique and elegant solution to strong and homogenous magnets. A direct and simple solution is a Halbach arrangement of magnets on a cylinder magnet forming a dipolar magnetic field with the transverse fields direction along the cylinder axis.

For NMR in moderately homogeneous fields, only the inner dipole is of practical interest. This field is perfectly homogeneous for a perfect Halbach geometry and an infinitely long cylinder. However since in reality the cylinder must have a finite length, the strength of magnetic field gradually decreased from the center to the edge of the cylinder.

In order to get an enough homogeneous magnetic field region, axis length of the cylinder magnet must be long enough. In fact, the region is very small in the whole cylinder magnet, in which the homogeneity is satisfied.

A novel test tube magnet (TTM) has been designed for portable NMR device. TTM is composed of a dipole cylinder magnet and a hemi-sphere magnet or a hemi-cylinder magnet at one end, which gives the whole arrangement the shape of a test tube. Such a design compensates for the drop of magnetic field at the lower end of the magnet and also increases the homogeneous region. Furthermore, the size and weight of the whole magnet are decreased, which are relative to a cylinder with the same homogeneity. Therefore, the compensated magnetic field in TTM is much more suitable for measuring the sample in the test tube.

## 2. THEORY

Easy Axis Rotation Theorem is the theoretical foundation of Halbach magnets. If in a 2D, soft-steel free, system all easy axes are rotated by some degree, then all magnetic fields outside the system rotate by the same angle on the contra-side without a change in amplitude.

If the space between the two circles  $r_{ci}$  and  $r_{co}$ , inner and outer radii of cylinder, is filled with rare earth magnetic material, with a remanence of  $B_r$  and easy axis rotated with  $\beta(\varphi) = 2\varphi$ . Magnet field [1] in the space  $r_c < r_{ci}$  is

$$B(r_c, \varphi) = B_r \ln(r_{ci}/r_{co}) \quad (1)$$

$c$  being the cylinder magnet. The magnetic field outside the magnet is exactly zero.

If the space between the two spheres  $r_{si}$  and  $r_{so}$ , inner and outer radii of sphere, is filled with rare earth magnetic material, and the remnant field  $\vec{B}_r$  distribution can be expressed as  $\vec{B}_r = B_r (\vec{e}_r \cos \theta + \vec{e}_\theta \sin \theta)$  ( $\vec{e}_r$ ,  $\vec{e}_\varphi$ , and  $\vec{e}_\theta$  are the unit vectors of spherical coordinates, respectively.), the magnetic field inside the sphere magnet is

$$\vec{B}_s = \frac{4}{3} B_r \ln(r_{so}/r_{si}) \vec{k} \quad (2)$$

$s$  is the sphere magnet.

An infinite dipole magnet is cut by the  $x$ - $y$  plane at  $z = 0$  (see Fig. 1). If  $V_c^{z+}(x, y, z)$  is the scalar potential produced by the dipole magnet when  $z > 0$ , then the scalar potential produced by the dipole magnet at  $z < 0$  must be  $V_c^{z-}(x, y, z)$ . If  $V_c(x, y)$  is the scalar potential inside the infinite dipole, obviously, the following must hold:

$$V_c^{z+}(x, y, z) + V_c^{z-}(x, y, z) = V_c(x, y) \quad (3)$$

Applying the appropriate operator to (5), we get the field quantity  $B_c(x, y, z)$  of interest,

$$B_c^{z+}(x, y, z) + B_c^{z-}(x, y, z) = B_c(x, y) \quad (4)$$

One obtains

$$By_c^{z+}(x, y, 0) = By_c^{z-}(x, y, 0) \quad (5)$$

### 3. DESIGN AND ANALYSIS

Many designs and application of cylindrical magnets [2–4] with Halbach arrays have been done. For the compensation of the transverse field along the cylinder axis, some design principles [4, 5] have been given.

For portable NMR, the sample is always measured in a test tube. Typically, the diameter of a test tube is about one inch. Therefore, the field of the cylinder magnet, with  $r_{ci} = 30$  mm and  $r_{co} = 35$  mm, is simulated by three-dimensional finite-element methods.

There are two methods to get enough DSV of the homogeneous magnetic field region for portable NMR, which are prolonging cylinder magnet axis length and compensating the field on the end.

Table 1: Homogeneity and DSV/L of the Halbach Cylinder.

L(mm)	45	67.5	90	135	180
Homogeneity (ppm)	7150	4064	1928	418	108
DSV/L	0.4	0.27	1928	0.13	0.10

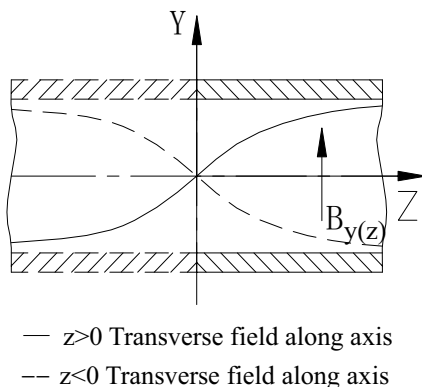


Figure 1: Along axis, the magnetic field distribution of Halbach magnet.

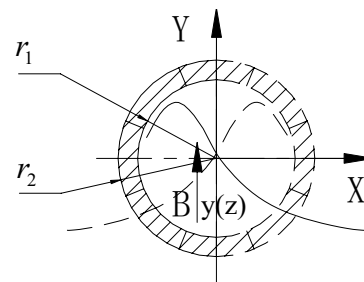


Figure 2: Along  $X$  coordinate the magnetic field distribution of Halbach magnet.

Prolonging the length of the cylinder magnet ( $L$ ) along its axis is one of the traditional methods. In the conditions of DSV=18 mm and  $Br = 1.23$  T, Table 1 lists the homogeneity and DSV/ $L$  produced by some different length cylinders.

One can see from Table 1 that the homogeneity is better, but DSV/ $L$  ratio is worse with prolonging the length of the magnet. We can found out the method exhausted more magnet size and weight to obtain more DSV, so that prolonging the magnet axis length is not acceptable for portable NMR.

Next, we consider the method of compensating the field on the end. Based on the field distribution as described in Fig. 1 and the requirement of design and manufacture, two structures are proposed. Hemi-cylinder and hemi-sphere respectively to compensate the decay of the field towards one end of such a cylindrical magnet and hence increase the DSV.

Figure 2 shows a transverse cut through the infinite dipolar magnet in the  $y$ - $z$  plane at  $x = 0$ . The direction of magnetic field parallels  $Y$  coordinate. If  $B_c^{x+}(x, y, z)$  is the field quantity of interest by the dipole magnet at  $x > 0$ , then the field quantity of interest at  $x < 0$  must be  $B_c^{x-}(x, y, z)$ . We get the field quantity  $B_c(y, z)$  of interest,

$$B_c^{x+}(x, y, z) + B_c^{x-}(x, y, z) = B_c(y, z) \quad (6)$$

$$By_c^{x+}(0, y, z) = By_c^{x-}(0, y, z) \quad (7)$$

Being the same radius  $r_{ci}$  and  $r_{co}$ , the flux density on the edge of cylinder magnet equals to the field on the section of hemi-cylinder magnet, and both directions are the same on the axis.

$$By_c^{x+}(0, y, z) = By_c^{z+}(x, y, 0) \quad (8)$$

One obtains

$$By_c^{x-}(x, y, z) + By_c^{z+}(x, y, z) = By_c(x, y, z) \quad (9)$$

According to the same principle,

$$By_s(x, y, 0) = By_c(0, y, z) \quad (10)$$

Using (1), (2) in (10), one obtains

$$\frac{4}{3} \cdot Br \ln(r_{so}/r_{si}) = Br \ln(r_{co}/r_{ci}) \quad (11)$$

$$(r_{so}/r_{si})^{4\beta} = r_{co}/r_{ci} \quad (12)$$

We get,

$$By_s^{x+}(x, y, z) + By_c^{z-}(x, y, z) = By_c(x, y, z) \quad (13)$$

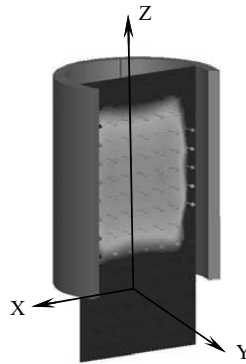


Figure 3: The 3D magnetic field distribution of Halbach magnet.

From the (9), (13), we know that the hemi-cylinder and hemi-sphere can compensate the flux density at the end of cylindrical magnet. The field distribution of a cylindrical magnet is simulated with three-dimensional finite-element methods, as described in Fig. 3. The field distribution of hemi-cylinder magnet and hemi-spherical magnet is simulated, as described in Figs. 4(a), (b).

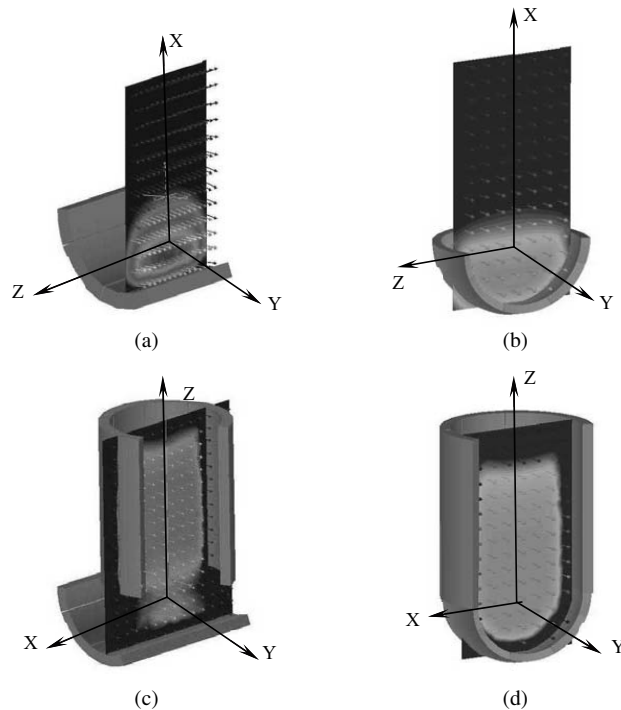


Figure 4: The 3D magnetic field distribution (a) Hemi-cylinder magnet, (b) hemi-sphere magnet, (c) Hemi-cylinder TTM, (d) hemi-sphere TTM.

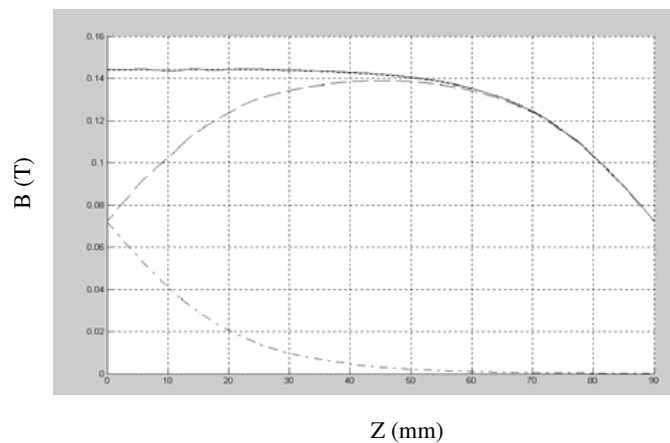


Figure 5: Along the axis, the field distributions of cylinder magnet (dashed line), hemi-cylinder or hemi-sphere magnet (center line), hemi-cylinder TTM (solid line), hemi-sphere TTM (point line).

Along  $Z$ -coordinate, the flux density distribution of cylinder magnet can be seen as in Fig. 5 (dashed line) on  $z > 0$ . The field is relatively uniform in the center of cylinder magnet, in which the samples are detected. Along  $X$ -coordinate, on  $x > 0$  the flux density distribution of Hemi-cylinder or hemi-sphere magnet can be seen as in Fig. 5 (center line).

The hemi-cylinder or the hemi-sphere magnet is attached to one end of the cylindrical magnet to construct the TTM. If cylinder magnet and hemi-cylinder magnet both have same  $r_{ci}$  and  $r_{co}$ , and the radius  $r_{si}$  and  $r_{so}$  of the hemi-sphere magnet is according to (12), the field distribution in the TTM is simulated with three-dimensional finite-element methods, as described in Figs. 4(c), (d).

The distribution of the flux components  $B_x$ ,  $B_y$ , and  $B_z$  as in Figs. 6 (a), (b), (c). The  $B_x$ ,  $B_y$ , and  $B_z$  components of the hemi-cylindrical magnet and hemi-spherical magnet just compensate the  $B_x$ ,  $B_y$ , and  $B_z$  elements of cylinder magnet, so that the  $B_x$  and  $B_z$  component of TTM are almost zero and  $B_y$  is very uniform in the central space of the TTM.

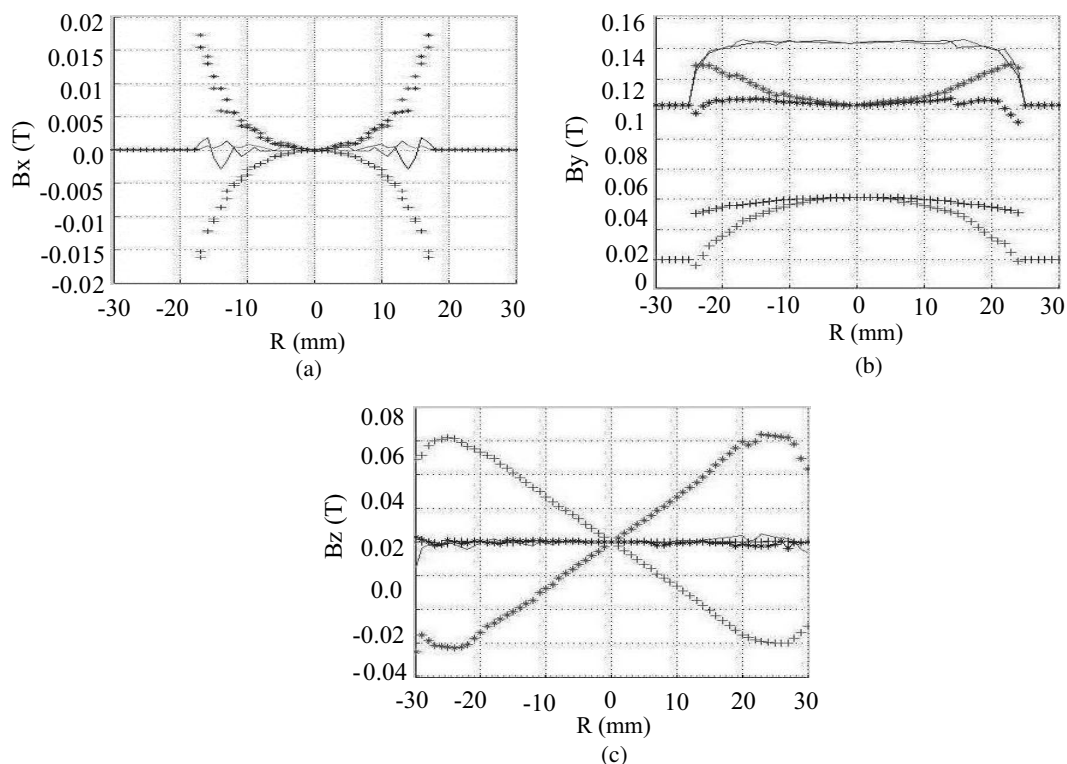


Figure 6: At  $Z=10$  mm, on  $x$ -coordinate as gray and  $y$ -coordinate as black, the distribution of  $B_x$ ,  $B_y$ , and  $B_z$  in the Cylinder magnet as “+”, hemi-cylinder or hemi-sphere magnet as “\*”, and TTM as “-”. (a)  $B_x$  element, (b)  $B_y$  element, (c)  $B_z$  element.

#### 4. CONCLUSIONS

The obtained results are available in the project discussion of the TTM for a portable NMR device.

- The components are effectively corrected in the region of homogeneous magnetic field.
- As the homogeneity increases markedly, the magnet volumes and mass decreased accordingly, which make their construction more desirable for sample measurement in the test tube.

Taken together the new designs have improved characteristics for portable NMR.

#### ACKNOWLEDGMENT

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