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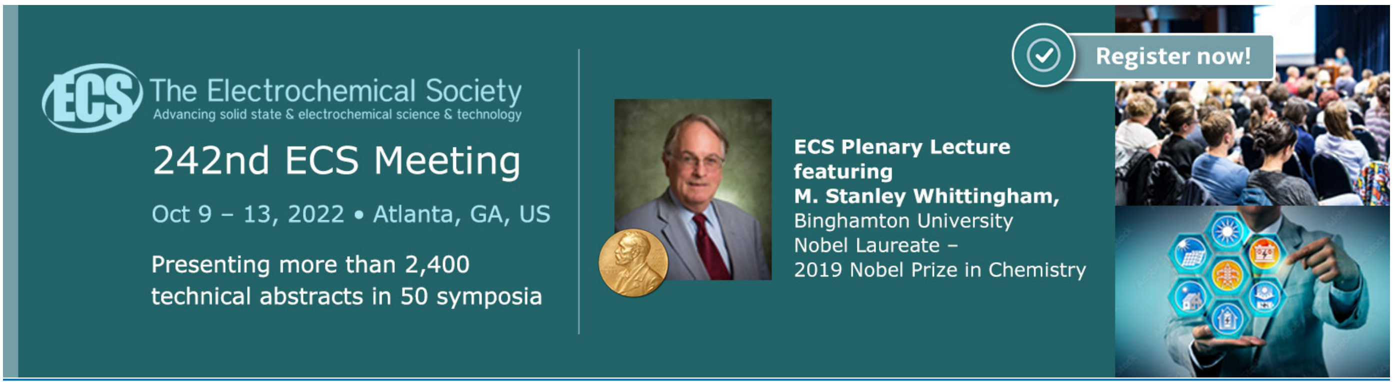

Development of Halbach magnet for portable NMR device

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Abstract: Nuclear magnetic resonance (NMR) has enormous potential for various applications in industry as the on-line or at-line test/control device of process environments. Advantage of NMR is its non-destructive nature, because it does not require the measurement probe to have a contact with the tested media. Despite of the recent progress in this direction, application of NMR in industry is still very limited. This is related to the technical and analytical complications of NMR as a method, and high cost of NMR analyzers available at the market. However in many applications, NMR is a very useful technique to test various products and to monitor quantitatively industrial processes. Fortunately usually there is no need in a high-field superconducting magnets to obtain the high-resolution spectra with the detailed information on chemical shifts and coupling-constant. NMR analyzers are designed to obtain the relaxation parameters by measuring the NMR spectra in the time domain rather than in frequency domain. Therefore it is possible to use small magnetic field (and low frequency of 2-60 MHz) in NMR systems, based on permanent magnet technology, which are specially designed for specific at-line and on-line process applications. In this work we present the permanent magnet system developed to use in the portative NMR devices. We discuss the experimental parameters of the designed Halbach magnet system and compare them with results of theoretical modelling.

Keyword: NMR analyzer, Halbach magnet

1. Introduction

Nuclear magnetic resonance (NMR) is a general technique which is widely used in various areas of basic research, in industry for testing broad range of products and to control manufacturing processes [1], in diagnostic medical imaging [2] and analytical chemical spectroscopy [3]. Usually, for good spectroscopic resolution a superconducting magnet is used to produce the high magnetic fields (9-20 T) with homogeneity of the sample volume as high as possible ($\Delta B_0/B_0 < 10^{-7}$) [4]. Inhomogeneous magnetic fields had been avoided in the previous 50 years because of the understanding that chemical-shifts cannot be resolved in a polarization field B_0 that is inhomogeneous across the sample (see Ref. [5]). Today, however, the ideas of multi-dimensional NMR [3,6] are extensively explored with mobile sensors and *inhomogeneous fields* (see, for instance, Ref. [7]). In multidimensional NMR techniques the correlations of the parameters other than the resonance frequencies or space coordinates in images are utilized to increase resolution and to make the NMR data more informative. Now it is commonly accepted that NMR in inhomogeneous fields inside and outside the magnet is very useful instrument of characterization and research. Especially the mobile

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NMR devices equipped with light-weight magnets with homogeneous fields and simple field profiles have very high potential to use in various applications. To realize these devices the Halbach magnet design is considered as the most prospective magnet system (see Ref. [7-9]). This design is a quasi-cylinder magnet constructed from many magnet blocks in such a way that the magnetic field is largely homogeneous inside the cylinder, transverse to the cylinder axis, and zero outside [10]. Nearly homogeneous fields for applications in the one-sided NMR are conventionally generated by the classical C-shaped magnet geometry[11].

In last years, low-field NMR devices (NMR analyzers) have found very wide applications in different industrial and agricultural fields, such as food products, medicine and petrochemical industry. Widespread application fields of low-field NMR include determining moisture, oil, and hydrogen and flour amount. For instance, manufacturers of eatable oils prefer to buy raw products according to the oil content in a substance. However, most of the NMR analyzers commercially available today are not portable. There are table-top versions to be used at the laboratory conditions (at-line NMR devices). Besides, some NMR devices are specially designed heavy (not portable) constructions to use in the specific on-line processes (on-line devices). On the other hand, some prototypes of the portable devices have already been developed but not found yet a wide application area. The main problem in developing portable NMR devices is to produce light-weighting magnet system that could provide a magnetic field with desirable homogeneity rather than to create a high magnetic field. Therefore, the compact and light magnet designs for homogeneous magnetic field, such as Halbach design, have attracted a special attention of researchers [7-16].

Ideal Halbach magnet is formed from the bar magnets with equal magnetization that are oriented and positioned with analytic equations [10]. This design has the following advantages which are important for NMR applications [10]:

- High homogeneity of the static magnetic field
- Optimal use of the material magnetization
- Transverse field direction (allows using the solenoidal coils for NMR)
- Very small stray fields
- Simple, compact and robust construction consisting of identical magnets
- Easy and cheap production process

Several researchers have recently applied Halbach magnets to build NMR magnets for using in a tabletop NMR [17], a mobile NMR for measuring drilled rock [12, 18] and pre-polarized samples in the earth-field NMR experiments [19]. A Halbach magnet generates a highly homogeneous static magnetic flux density near its center and a moderately homogeneous static magnetic flux density near its top; it can also be built to be very compact. It has been demonstrated that the field homogeneity of the Halbach magnet is high enough to be used in various versions of portable devices (see Refs. [10-14, 20]).

The above mentioned motivated us to construct and to study the magnetic properties of most simple version of Halbach magnet design with aim to check its potential for application in the mobile NMR devices.

2. Theory of Halbach magnet construction

Theory predicts that the circular structure with magnetization direction rotating as shown in Fig. 1 will produce homogeneous magnetic field. However, it is hardly possible to realize practically such rotation through a continuous media, while it is easy to assemble a discrete structure having individually polarized parts. Therefore, the real Halbach design consists of the permanent magnets with equal magnetization that are oriented and positioned with analytic equations [7,18] (see below).

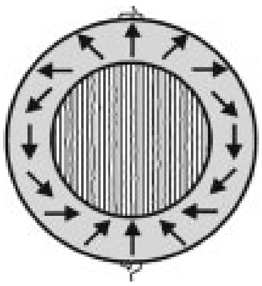

Figure 1. Ideal Halbach magnet, producing strong, homogeneous field inside and low stray field outside.

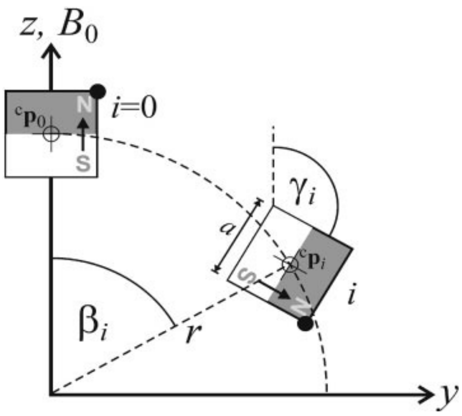

Figure 2. Infinitely long array for perfect magnetic homogeneity [10].

For the calculation of the exact geometry of the magnet arrangement, two parameters are predetermined: the radius of the ring, *r*, and the number of magnets, *n.* Each magnet is positioned such, that its center (vector ${}^{c}p_i$) has the same distance *r* from the origin. The coordinates of each magnet center are then represented with matrix representation:

$$ {}^{c}p_i = \begin{pmatrix} {}^{c}y_i \\ {}^{c}z_i \end{pmatrix} = r \begin{pmatrix} \sin\beta_i \\ \cos\beta_i \end{pmatrix} \qquad \text{where} \quad \beta_i = i\alpha \quad \text{with} \;\; i = 0,1,...,n-1 \,. $$

Here, β_i is angle between the magnet centre and direction of the magnetic field B_0. Orientation of each magnet relative to the *z* axis is determined with $\gamma_i = 2\beta_i$ angle. Once the *n* magnets are spatially arranged (calculating *n*/8 magnets or one octant is sufficient due to symmetry), their size, *a*, is usually scaled such that the most dense arrangement results. This gives the following coordinates of each corner of the i^{th} bar-magnet:

$$^{1}p_i = \begin{pmatrix} ^{1}y_i \\ ^{1}z_i \end{pmatrix} = {}^{c}p_i + \frac{a}{\sqrt{2}} \begin{pmatrix} \cos\xi_i \\ \sin\xi_i \end{pmatrix}$$

$$^{2}p_i = \begin{pmatrix} ^{2}y_i \\ ^{2}z_i \end{pmatrix} = {}^{c}p_i + \frac{a}{\sqrt{2}} \begin{pmatrix} -\sin\xi_i \\ \cos\xi_i \end{pmatrix}$$

$$^{3}p_i = \begin{pmatrix} ^{3}y_i \\ ^{3}z_i \end{pmatrix} = {}^{c}p_i + \frac{a}{\sqrt{2}} \begin{pmatrix} -\cos\xi_i \\ -\sin\xi_i \end{pmatrix}$$

$$^{4}p_i = \begin{pmatrix} ^{4}y_i \\ ^{4}z_i \end{pmatrix} = {}^{c}p_i + \frac{a}{\sqrt{2}} \begin{pmatrix} \sin\xi_i \\ -\cos\xi_i \end{pmatrix}$$

$$\text{with } \xi_i = \frac{\pi}{4} - 2\beta_i$$

These matrix representations give coordinates of corners of each magnet.

Here each corner is represented by a vector $^{j}p_i$, where the index i identifies the magnet and j denotes the corner, numbered in the sense of quadrants as shown in Fig. 3.

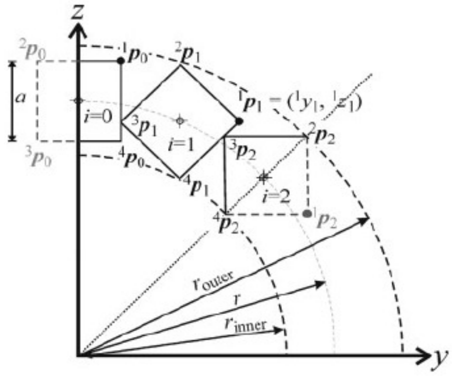

Figure 3. Symbolic representation of magnet coordinates [9].

The length of a magnet's side, a, is found by solving

$$^{4}p_{(n/8)\text{-}1} + \lambda\,(^{1}p_{(n/8)\text{-}1} - {}^{4}p_{(n/8)\text{-}1}) = {}^{3}p_{n/8} \ ,$$

which gives $a = 2r\Xi(\alpha)$ with:

Hence, the area, A, occupied by the n magnets is

$$A = na^2 = 4nr^2\Xi(\alpha)^2 .$$

The inner radius (accessible for experiments) is then given by

$$r_{inner} = r(1-\sqrt{2}\Xi(\alpha)) ,$$

and the outer radius is

$$r_{outer} = r(1+\sqrt{2}\Xi(\alpha)) .$$

Homogeneity of the magnetic field depends on the number bar magnets used in the Halbach magnet design. Each magnet should have the same magnetization and sizes to produce homogeneous magnetic field for NMR devices. A best compromise between homogeneity and field strength is obtained at high magnet numbers. However, n=4 will also results in a good homogeneity but not maximal magnetic field. To hold the magnets in the correct orientation and fixed position, the supporting structure withstanding mutual magnetic forces of these magnets is needed (see Ref. [10,18]).

3. Experimental results and their discussion.

In this work we have constructed the simplest Halbach magnet design having 4 permanent magnets with square cross section (Fig. 4). It uses the minimal number of permanent magnets providing at the same time enough high homogeneity of the magnetic field of the target volume. Magnetic field depends on the distance between the sample and the magnets as well as on the magnetization of the magnets.

At room temperature NdFeB (Neodymium-Iron-Boron) type permanent magnets have very suitable magnetic properties comparing with other permanent magnet compounds. Therefore, we use grade N45 of NdFeB magnets and the dimensions of these permanent blocks were 50×50×50 mm^3. Magnetic properties of the magnets were as follows: remanence B_r=1320-1380 mT, coercivity H_c=923 kA/m and maximum energy product $(BH)_{max}$=43-46 MGOe.

Position of the magnets is very important to obtain good homogeneity at the centre of the structure. Four magnet blocks were positioned in aluminium frame with diameter of 18 cm and depth of 5 cm (Fig.5). In order to fix the magnets, 5×5 cm aluminium block with 3.4 cm hole was placed in the middle of the magnets. Aluminium disks with thickness of 5 mm were used to cover construction from the bottom and the top. Four brass screws were used to fix the overall structure consisting of the frame, central blocks, top and bottom disk and permanent magnet blocks (Figs. 4-5). The weight of overall construction was about 6 kg.

The static magnetic flux density profile of the magnet was measured using a Hall-probe gaussmeter (Hirst GM05 Gaussmeter with TP002 Hall Probe). Measurements with aid of Hall-effect gaussmeter using a home-made 2D position fixture revealed rather high magnetic field (nearly 5.60 kG) in the center of the magnet construction. Dependence of the magnetic field in the central lateral plane showed good homogeneity for the radial direction perpendicular to magnetic lines (the horizontal direction in Fig. 4): the magnetic field deviation is very close the measurement error of the gaussmeter of about % 0.5. However, the homogeneity in the radial direction parallel to magnetic lines (it is vertical in Fig. 4) reveal rather large magnetic inhomogeneity through the hole (>1%)..

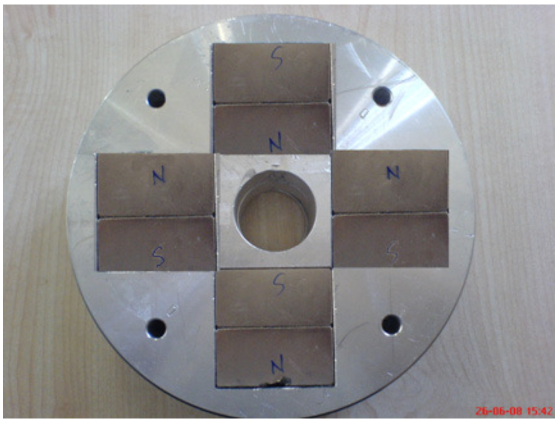

Fig. 4. Permanent magnets installed in the aluminium frame.

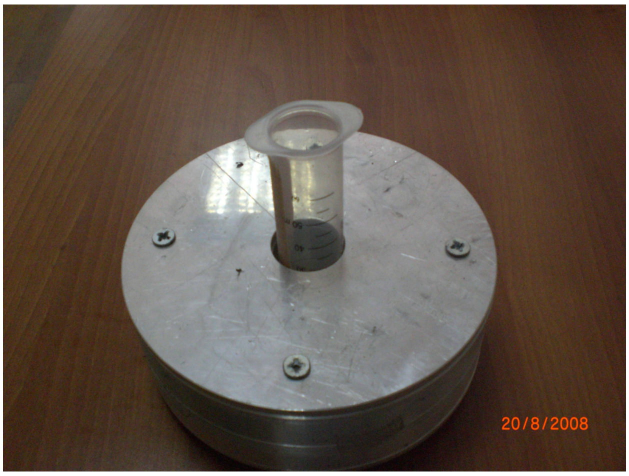

Fig. 5. Magnet construction as a whole.

To compare the experimentally measured magnetic fields with theoretically expected profiles FEMLAB software packet has been used. The calculated magnetic field profiles in the directions perpendicular (x-axis) and parallel (y-axis) to the magnetic lines are shown in Fig. 6 and Fig. 7, respectively. The theoretical calculations have revealed the magnetic field changes along x of nearly the same magnitude as in experiment, while the magnetic inhomogeneity along the field lines (y-axis) is expected to be much smaller than observed in our Hall-probe measurements. This discrepancy is attributed to the tolerances of the construction and in the magnetic parameters of the permanent magnets used. Thus the results of our theoretical modelling shows that an improvement of the construction is still possible and it will be the subject of further work.

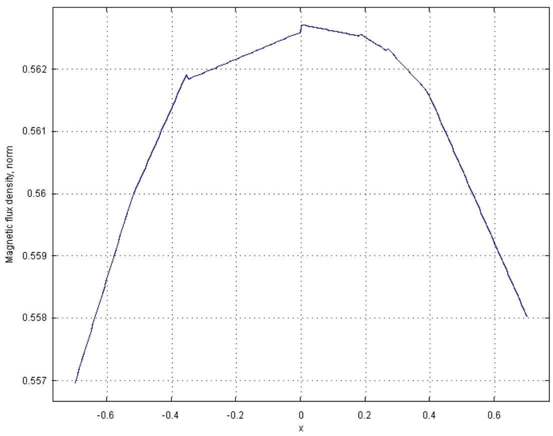

Fig. 6. The calculated magnetic field profile the central z-plane of the construction in the direction ***perpendicular*** to the magnetic lines.

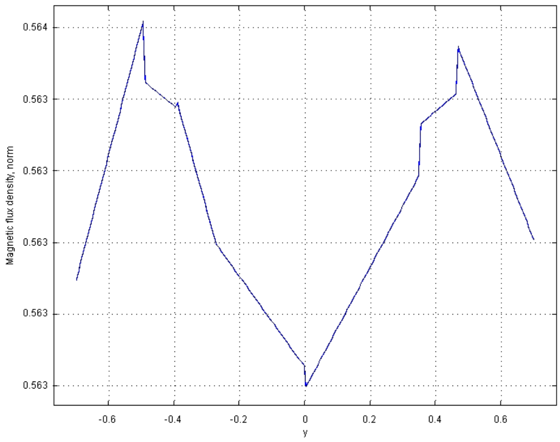

Fig. 7. The calculated magnetic field profile the central z-plane of the construction in the direction ***parallel*** to the magnetic lines.

4. Conclusions

Halbach magnet design has a number of advantages for using in the portable NMR analyser as a system to produce homogeneous magnetic field. Our results reveal that even a simple construction consisting of four permanent magnets provide magnetic parameters which are suitable for possible applications. There is some potential to improve homogeneity using the shim magnets in the bore region (see Refs. [21,22]). Their orientation, size and vertical position can be adjusted to control the field homogeneity or to make field gradients if needed. Depending on the application planned higher number of individual magnets or another approach, where differently shaped individual magnets are employed, may be used to increase the horizontal field strength or homogeneity. Besides, doubling of magnet construction can be considered as another way to improve the field homogeneity along the z-axis. Further research is planned to improve the magnetic field homogeneity of the Halbach construction to use in portable NMR devices.

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References.

[1] Nordon A, McGill C A and Littlejohn D, 2001 *Analyst* **126** 260
[2] Haacke E M, Brown R W, Thompson M R and Venkatesan R 1999 *Physical Principles and Sequence Design* (New York: Wiley)
[3] Ernst R R, Bodenhausen G and Wokaun A 1987 *Principles of Nuclear Magnetic Resonance in One and Two Dimensions* (Oxford: Clarendon Press)
[4] Blümich B 2000 *NMR Imaging of Materials* (Oxford: Clarendon Press)
[5] Meriles C A, Sakellariou D, Heise H, Moulé A J and Pines A 2001 *Science* **293** 82
[6] Aue W P, Bartholdi E and Ernst R R 1976 *Journal Chem. Phys.* **64** 2229
[7] Blümich B, Perlo J and Casanova F 2008 *Progress in Nuclear Magnetic Resonance Spectroscopy* **52** 197
[8] Halbach K 1980 *Nuclear Instrum. Methods* **169** 1
[9] Halbach K 1979 *IEEE Trans. Nucl. Sci. NS*-**26** 3882
[10] Raich H and Blümler P 2004 *Concepts Magnetic Resonance B* **23** 16

[11] Perlo J, Casanova F, Blumich B, 2007 *Science* **315** 110
[12] Anferova S, Anferov V, Arnold J, Talnishnikh E, Voda M A, Kupferschla¨ger K, Blumler P, Clauser C, Blumich B, 2007 *Magnetic Resonance Imaging* **25** 474
[13] Leupold H A, Potenziani II E and Abele M G 1988 *Journal Applied Physics* **64** 5994
[14] Leupold H A, McLane G F 1994 *Journal Applied Physics* **76** 6253
[15] Podol'skii A 2002 *IEEE Trans. Magn.* **38** 2
[16] Xu X N, Lu D W, Yuan Q, Han Y S and Jin X 2004 *Journal Applied Physics* **95** 6302
[17] Moresi G and Magin R 2003 *Concept Magnetic Resonance* **B19** 35
[18] Anferova S, Anferov V, Rata DG, Blumich B, Arnold J, Clauser C, et al. 2004 *Concept Magnetic Resonance* **B23** 26
[19] Appelt S 2005 NMR goes mobile in the Earth's magnetic field. *Book of abstracts:* 5th colloquium on mobile NMR. p. L03.
[20] Perlo J, Demas V, Casanova F, Meriles C A, Reimer J, Pines A, et al. 2005 *Science* **308** 1279
[21] Bertora F, Trequattrini A, Abele M G and Rusinek H 1993 *Journal Appl Physics* **73** 68641102
[22] Chang W H, et al. 2006 *Magnetic Resonance Imaging* **24** 1095