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A compact permanent magnet array with a remote homogeneous field

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Abstract

We present the design and construction of a single sided magnet array generating a homogeneous field in a remote volume. The compact array measures 11.5 cm by 10 cm by 6 cm and weights ∼5 kg. It produces a B_0 field with a 'sweet spot' at a point 1 cm above its surface, where its first and second spatial derivatives are approximately zero. Unlike other sweet spot magnets of this general type, our array has B_0 oriented parallel to its surface. This allows an ordinary surface coil to be used for unilateral measurements, giving the potential for dramatic SNR improvement.

Keywords: Unilateral magnetic resonance; Inhomogeneous fields; Saddle point; Permanent magnets

1. Introduction

Beginning with early experiments and apparatus designed for nuclear magnetic resonance (NMR) well logging [1–4], there has been a continued interest in unilateral NMR (UMR) [5–19]. UMR refers to NMR signal transduction, performed in such a way that the sample volume is external to the measurement apparatus and has the obvious advantage of allowing arbitrarily large samples to be investigated. In modern UMR hardware, permanent magnets are employed to produce the B_0 field in some remote region. Several recent designs generate a field with a controlled spatial distribution for experiments such as profiling [5,6], diffusion [7], and spectroscopy [8]. However, most applications still rely on bulk measurements of the magnetization in a 'sensitive volume' defined by the inhomogeneities of B_0 and B_1 [3,4,9–17].

In the case where a sensitive volume is desired, two distinct classes of instrument exist. While many designs exist producing symmetrical 3D external sensitive volumes, for example a toroid [2], we limit the discussion here to magnets with a sensitive spot above one face. In the first class [9–12], a grossly inhomogeneous B_0 field is generated by one or more magnets, and a RF coil is oriented such that B_1 and B_0 are orthogonal within some region. The B_0 gradient along with the excitation bandwidth will define a sensitive volume. The advantages of this method include more compact magnet arrays, stronger B_0 fields, and strong gradients which can sensitize measurements to slow molecular motions. Furthermore, many of these designs have B_0 directed parallel to the magnet face allowing an ordinary surface coil to be used for excitation and detection, affording both simplicity and sensitivity. Drawbacks include a small spot size, and pronounced diffusive attenuation in liquid samples, both due to the high gradient. By 'ordinary surface coil', we mean a coil made from a simple loop of wire, generating a B_1 field directed along the axis of the loop.

The second class of instrument generates a 'sweet spot' at which B_0 contains a saddle point and is therefore locally homogeneous [3,4,13–17]. This creates a larger spot for a given excitation bandwidth; the reduced gradient limits diffusive attenuation, facilitating the measurement of liquid samples. The tradeoff is that these designs generally operate at a lower field as the saddle point is obtained by field cancellation.

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Most sweet spot magnets reported in the literature have a B_0 field directed orthogonal to the magnet face [3,4,13,16,17]. In a 2D plane, two magnets with the same orientation can be arranged to give a saddle point; a third magnet placed between them can zero the second spatial derivative of the field in the depth direction, creating a relatively homogeneous spot. This is typified by designs such as Kleinberg's well logging magnet [4] and Fukushima's barrel magnet [14], and is illustrated schematically in Fig. 1a. While this leads to a compact, simple design, the drawback is that an ordinary surface coil cannot be used as its field will be parallel to B_0. Instead, more elaborate, and generally less sensitive coils must be employed [18]. It was recently noted [19] that the advantages of the improved B_0 homogeneity of a sweet spot magnet compared to a high-gradient design such as the NMR-MOUSE [9] are negated by the elimination of an ordinary surface coil from the measurement.

There have been sweet spot magnets designed with B_0 parallel to their surface to allow the use of an ordinary surface coil [8,15]. In these cases, four magnets, arranged in alternating orientations as shown in Fig. 1b have been used, the net effect being a cancellation of the inhomogeneity of the outer pair with that of the inner pair. The disadvantage of this configuration is that the magnet array must in general be large relative to the sensitive volume, in order to give the B_0 field the space necessary to reorient itself from vertical (over the magnets) to horizontal (in the sweet spot). Furthermore, we have found in practice that although it is straightforward to generate a saddle point with this design, zeroing the second spatial derivative of B_0 will incur severe array size and field strength penalties. The field from previously reported designs of this type rapidly becomes inhomogeneous away from the saddle point.

Pulyer and Patz [17] have proposed a design in which two axially magnetized and axially oriented magnets are spaced in such a way as to generate a saddle point in the field above them. A diagram of this configuration is given in Fig. 1c. The advantage of this design is that a saddle point can be generated from a relatively compact array (as the field is already oriented in the correct direction over the magnets) and an ordinary surface coil may be employed for the measurement. In this arrangement, only the first field derivative can in general be made zero.

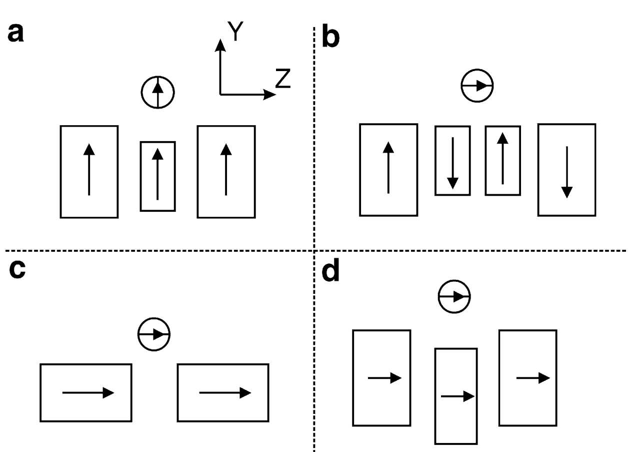

Fig. 1. Illustrations of previously reported magnet arrays (a)–(c), along with the new design considered here (d). Rectangles denote permanent magnets with their magnetization direction indicated by the arrows. Circles indicate approximate location of the sensitive spot, with the arrows showing the magnetic field direction.

In this paper, we exploit the benefits of Pulyer's design and the configuration of Fig. 1a to develop a simple magnet arrangement in which the first and second spatial derivatives of B_0 can be zeroed to give a large, homogeneous spot, with the field oriented parallel to the magnet surface. This provides all of the advantages of previous sweet spot designs with the sensitivity and simplicity offered by an ordinary surface coil. The arrangement is presented in Fig. 1d. Because the field above the magnets is already parallel to their surface, the design is naturally more compact. The design has the added advantage that all the magnets are oriented along the same axis, a safe, low energy configuration. In the design shown in Fig. 1a, strong repulsive forces exist between the magnets, creating a potential safety problem. In subsequent sections, we briefly outline the design process for this magnet, and show field plots from a fabricated device. Sample experimental results are presented to give an idea of the sensitivity of this design.

2. Theory

2.1. Magnetic field calculation

We begin by deriving a simple equation for the magnetic field due to a bar magnet. While this calculation can be found in the literature [20], it is somewhat obscure, and may be of interest to those designing UMR arrays with permanent magnets. The magnet is magnetized along $\hat{z}$ and positioned with its upper surface at the origin as illustrated in Fig. 2a. The width of the magnet is w, and its thickness, t. If the magnet is assumed to be infinitely long in the depth (x) direction, is can be represented by two sheets of current I located at its upper and lower surfaces. From the right hand rule, the current flows out of the page on the top surface and into the page on the bottom. These sheets of current can be divided into infinitesimal line current elements of width dz', as in Fig. 2b. The magnetic field due to such a current is well known

$$\vec{B}' = \frac{\mu_0 i}{2\pi r'}\hat{\theta}' \tag{1}$$

where $i = I dz'$ is the current in each wire, r' is the distance from the wire to the observation point and $\hat{\theta}' = -\sin\theta'\hat{z}' + \cos\theta'\hat{y}'$ is the unit normal in polar coordinates. Converting to Cartesian coordinates, the total field due to the current in the upper sheet can be calculated by integration giving

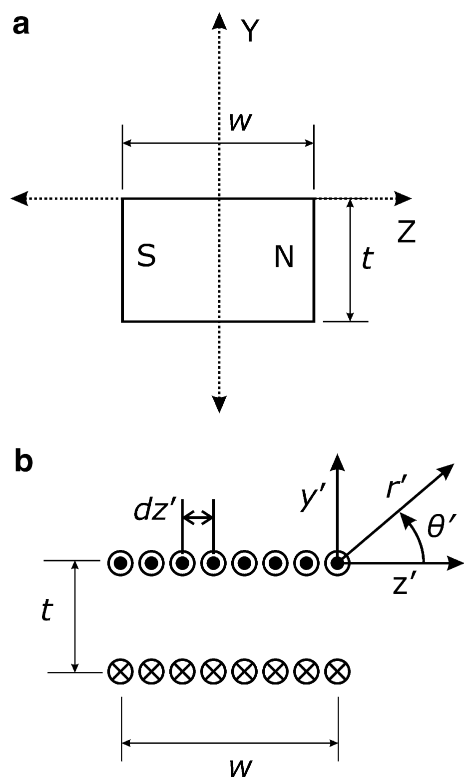

Fig. 2. Magnet positioning and orientation for calculations (a) and approximation of a permanent magnet as two sheets of thin wires (b).

$$\vec{B}_{\mathrm{top}}(z,y) = K\left[-\int_{-w/2}^{w/2} \frac{y}{(z-z')^2+y^2}\,\mathrm{d}z'\hat{z} + \int_{-w/2}^{w/2} \frac{z-z'}{(z-z')^2+y^2}\,\mathrm{d}z'\hat{y}\right] \tag{2}$$

where $K = \mu_0 I/(2\pi)$. Integrating and adding $\vec{B}_{\mathrm{bottom}} = -\vec{B}_{\mathrm{top}}(z, y+t)$ to represent the bottom sheet gives the total field from the magnet

$$\begin{aligned}\vec{B}(z,y) = K\bigg[&-\tan^{-1}\left(\frac{z-w/2}{y}\right)+\tan^{-1}\left(\frac{z+w/2}{y}\right)\\ &+\tan^{-1}\left(\frac{z-w/2}{y+t}\right)-\tan^{-1}\left(\frac{z+w/2}{y+t}\right)\bigg]\hat{z}\\ &+\frac{K}{2}\bigg[\log\left(\frac{y^2+(z+w/2)^2}{y^2+(z-w/2)^2}\right)\\ &-\log\left(\frac{(y+t)^2+(z+w/2)^2}{(y+t)^2+(z-w/2)^2}\right)\bigg]\hat{y}.\end{aligned} \tag{3}$$

We have found that this expression agrees almost exactly with 2D finite element simulations of a single, uniformly magnetized permanent magnet. The field from many permanent magnets can be calculated by superposition. This calculation assumes infinitely long magnets, and does not take into account inhomogeneities in the magnetization, or saturation effects from magnets in close proximity. As such, it will never be able to exactly calculate the field from a real magnet array. However, we have found that it can serve as a simple and reasonably accurate guideline for magnet array design.

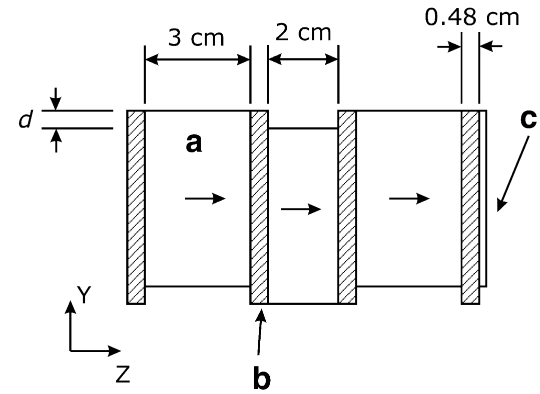

Fig. 3. Diagram of the magnet array. The magnets (a), with sizes and direction of magnetization shown, are spaced apart with aluminum spacers (b). A piece of steel (c) is used to compensate for the lower magnetization of the rightmost magnet.

2.2. Three magnet configuration

As pointed out by Fukushima and Jackson [14], two separated magnets, magnetized along the same direction will produce a field with a local maximum centered above and between them. The position of a third magnet centered between the first two can be adjusted such that its field, which decays with distance, adds to the increasing field below the saddle point in order to generate a field which has its first and second spatial derivatives with respect to y equal to zero. It is also possible to introduce a controlled y-gradient in the field by varying the position of the central magnet. While previous designs rely on the field above the poles of the magnets, we use the field along the sides of the magnets, an idea which although simple has been neglected in the literature.

Our magnet design, shown in Fig. 3, consists of three magnets, all magnetized along z. The magnets all have $t = 5$ cm, the outer pair of magnets have $w = 3$ cm while the inner magnet has $w = 2$ cm. The spacing between each magnet was set to 4.76 mm (3/16″) in order to accommodate stock aluminum as a spacer. The inner magnet is offset a distance d below the outer magnets in order to give the appropriate field. Using Eq. (3), it was calculated that for a central magnet offset by $d = 4.8$ mm, the first and second field derivatives would be zero at a point 1.08 cm above the outer magnets.

3. Results

3.1. Field measurements

Magnets of the sizes given above, and 10 cm long in the ‘infinite’ direction, were purchased from the Yuxiang Magnetic Materials Ind. Co. Ltd. (Xiamen, China). The magnets were NdFeB with a specified remanence of ~1.3 T. Due to manufacturing tolerances, the purchased magnets had a variation in surface field of ~8% between the pair of outer magnets. The field of the central magnet was somewhere in between the two values of the outer magnets. A variation on this scale was anticipated, and a frame was designed for the magnets such that the offset d of the center magnet could be varied in order to achieve the desired field. To assist in correcting the field, two pieces of scrap steel, each measuring 5 cm by 10 cm and ~1 mm thick were placed side by side outside the frame next to the magnet with the lower field. These have the effect of shifting the magnetic flux lines to that side and can reduce the asymmetry in the field. It was found that with this configuration, the first and second derivatives of the field can be approximately zeroed at a point about 1.05 cm above the face of the magnets with the offset d of the central magnet equal to 5 mm. These numbers correspond very well with the calculated magnet positions.

Magnetic field measurements were made with a Lakeshore 460 3-axis Hall probe and a computer controlled 3-axis position system. Fig. 4 shows a contour plot of the magnetic field magnitude over the array. The position $y = 0$ corresponds to the upper surface of the outer magnets. A slight asymmetry is noted for larger values of $|z|$ due to the unequal magnetizations of the outer magnets, however the field over the center is reasonably symmetric. A saddle point is observed in the central region over the magnet. Fig. 5 plots the field magnitude as a function of z over the center of the magnets. The approximately flat region occurring around 1 cm from the magnet surface corresponds to the sensitive volume. There is a slight upward trend in the field strength at the center of the sensitive spot, but the field, which is nominally 0.109 T, remains within a .25 mT range over a region more than 5 mm deep.

3.2. NMR measurements

We present several measurements here in order to demonstrate the sensitivity of the instrument. Measurements used an inductively coupled ordinary surface coil, 1.5 cm in diameter, and tuned to 4.646 MHz. The coil was positioned ~5 mm above the surface of the outer magnets. Experiments were conducted with a Bruker Minispec console, modified to include an external Mitec preamplifier and lumped element duplexer. The sample was a bottle of

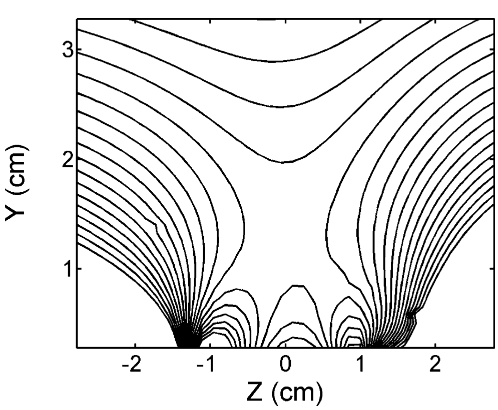

Fig. 4. Contour plot of the measured magnetic field magnitude in the zy plane, centered over the magnet. The field is characterized by a saddle point over the center of the magnet. The contour interval is 6.8 mT.

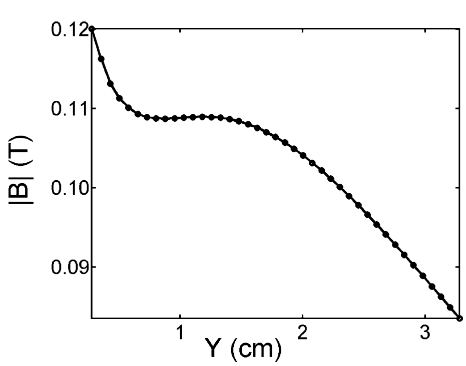

Fig. 5. Plot of field magnitude as a function of depth over the center of the instrument. The field profile is approximately flat 1 cm above the outer magnets, with a strength of ~0.11 T.

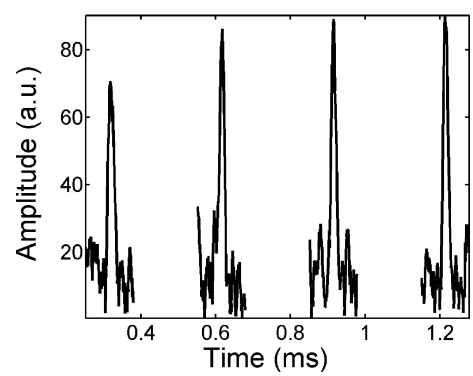

Fig. 6. Four echoes from an oil sample obtained in a single scan CPMG experiment. The 90° and 180° pulse widths were both 9.8 μs, the NMR frequency was 4.646 MHz, and the echo time was 0.3 ms. Signal was not recorded for a period between each echo to allow for RF pulse application and instrument dead time.

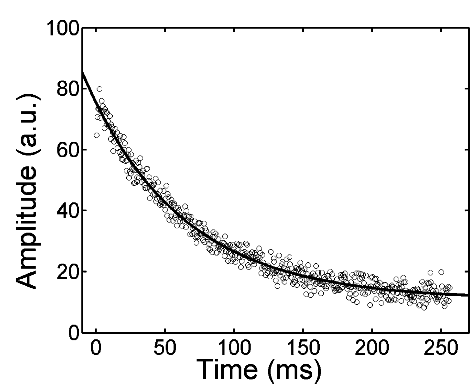

Fig. 7. T_2 decay measured using a CPMG sequence for an oil sample in 8 scans. The 90° and 180° pulse widths were both 9.8 μs with an echo time of 0.5 ms. The repetition time was 0.3 s, giving a total measurement time of <5 s. Circles indicate the experimentally measured echo maxima and the solid line indicates a least squares fit. The measured T_2 is 71 ± 2 ms. As the magnitude signal of the echoes was detected, a baseline offset is observed in the data.

commercially available fish oil, larger than the sensitive volume of the instrument.

Fig. 6 illustrates four echoes, acquired using a CPMG sequence in a single scan. As is common practice when working with inhomogeneous fields, the lengths of the 90° and 180° pulses were kept equal, and the flip angle adjusted by changing the pulse power; this ensures that the excitation bandwidth remains constant. The echoes are clearly resolved. The experimental time of just over 1 ms is much shorter than the sample T_2 and no attenuation is observed. The magnitude of the first echo is lower than that of subsequent echoes, a common phenomenon in inhomogeneous fields [4]. Fig. 7 shows a CPMG decay, measured with 8 signal averages. In both Figs. 6 and 7, relatively high quality data is obtained in a minimal experimental time, a feature that is important for on-line measurements.

4. Conclusions

We have presented the design and construction of a single sided magnet array generating a homogeneous field in an external volume. While designs with this characteristic are commonplace, our magnet has B_0 oriented parallel to its face, allowing a simple circular surface coil to be used for signal transduction. This feature increases the sensitivity of the instrument dramatically compared to designs that require special surface coils to produce a z-directed RF field.

The fabricated magnet measures 10 cm by 11.5 cm by 6 cm, and weighs ∼5 kg. Despite being much smaller than our previous 4-magnet designs with B_0 oriented along z, [15], the optimized field makes the instrument far more sensitive.

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