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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.
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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.

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.

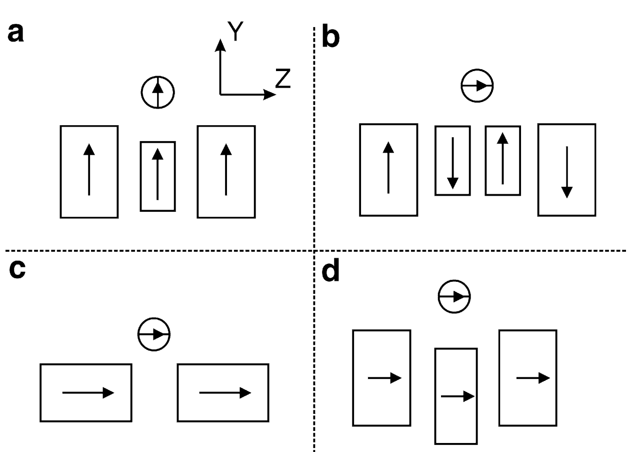

Fig. 1. Illustrations of previously reported magnet arrays (a)–(c), along with the new design considered here (d). Rectangles denote permanent magnets with their magnetization direction indicated by the arrows. Circles indicate approximate location of the sensitive spot, with the arrows showing the magnetic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

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

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