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Communication

A low-field, low-cost Halbach magnet array for open-access NMR

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Abstract

A working prototype of a novel low-cost Halbach-array-based NMR system is described. The new design provides open access to the sample relative to conventional NMR magnet designs and this facilitates the simultaneous use of multi-sensor techniques on the same sample, in which NMR/MRI can potentially be combined with other spectroscopies such as impedance spectroscopy, laser scattering and rheological experiments.

Keywords: Open-access NMR; Low-field NMR; Halbach magnet array; Multi-sensor

1. Overview

In conventional NMR spectrometers the sample is enclosed by the magnet, shim and RF coils which typically prevent the sample from being readily studied by other, non-NMR spectroscopic, and/or mechanical probes. In many situations, such as food processing, the sample undergoes rapid and irreversible changes and it would be advantageous to be able to monitor these changes with a variety of complementary spectroscopic methods. Of course, one-sided magnet systems, such as the NMR-MOUSE offer easy access to the sample by other non-NMR probes, but the NMR signal itself arises only from the surface of the sample and not the bulk, which is inadequate for many applications. In this communication we report our efforts to overcome these limitations by exploiting a Halbach array of four permanent magnets.

Halbach dipole magnets, originally proposed by Klaus Halbach as focusing magnets for particle accelerators [1], are permanent magnets consisting of segments joined together in such a way as to create a dipole magnet with the dipole transverse to the long axis of the magnet. A number of Halbach dipoles can be combined in an array so as to create a homogeneous magnetic field transverse to the long axis of the array, an arrangement which is convenient for NMR because a solenoid can more easily be used for the NMR RF coil rather than a saddle coil. Halbach arrays have previously been used in a number of NMR applications (see for example [2–6]). Typically in NMR one wants to homogenize the field, by combining as many Halbach dipoles as possible in a polygonal or circular array. We consider here the alternative advantages of reducing the number of dipoles to a bare minimum, sacrificing homogeneity in favour of a more open magnet design.

A rectangular Halbach magnet array may be constructed with just four dipole magnets sufficiently far apart, relative to the NMR-sensitive region close to the field centre, that the arrangement may legitimately be described as open-access. By this, we mean that there is an open space surrounding the RF coil, which is larger (relative to the magnet gap) than in conventional magnet/probe designs. In fact in our prototype 74.5% of a circle in the horizontal (yz) plane and centred on the

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sample is unobstructed ("open"), the remainder is blocked by the four magnets. This open-access arrangement allows for larger samples or the introduction of other equipment for manipulating or observing the sample.

Unfortunately, there is a price to pay for this open-access arrangement. By moving the magnets away from the sample and using permanent magnets, B_0 is low, and inhomogeneous (although the confinement of flux in a properly symmetrised Halbach configuration does help to optimize the homogeneity as much as possible under the circumstances, and spin echo experiments can be used to refocus the dephasing effects of the remaining field inhomogeneity). Nevertheless, the lower field means lower sensitivity and signal/noise ratio. Fortunately these disadvantages are offset, for certain applications, by three advantages. First, the relative ease of construction and low cost of the magnet array. Second, the portability of the magnet, which does not require a heavy steel yoke to carry the flux lines. Third, and most significant, the open-access nature of the Halbach array which allows for several lines of further development, namely,

1. Multi-sensor technology—the combination of NMR/MRI with other spectroscopies (EPR, NIR, microwave reflectance, etc), scattering techniques (X-rays, neutrons, and lasers), ultrasonics, and/or electrochemical measurements including impedance spectroscopy and voltammetry. Multi-spectral domains can be scanned independently or combined by means of multi-dimensional correlation spectroscopy techniques [7]. Our preliminary experiments with a Halbach array have already succeeded in combining NMR with impedance spectroscopy on a gel sample.
2. Easy access to the samples allows for mechanical micro-manipulation of samples during NMR or other spectroscopic investigation, facilitating a variety of NMR-rheology experiments.
3. There is more available space (relative to a conventional design) to introduce the means to subject the sample to extremes of temperature and/or pressure. Samples might be physically moved through the magnet space by pipes, conveyors etc.
4. In principle the size of the array can be scaled up or down. A sufficiently large array might allow NMR or even low-resolution MRI of large intact samples such as foodstuffs and human limbs.

It is interesting to compare the open-access Halbach array with other magnet/probe designs which may be regarded as being of open-access type. These include surface coils and the NMR-MOUSE ([8,9]) which is simply applied to the exterior of the subject under study, and there is no enclosing magnet. Using a locally applied magnetic field, one-sided NMR systems suffer from poor field homogeneity. Application of such designs is typically limited to relaxation measurements, lineshape analysis and MRI. Signal is only obtained from a thin surface layer (a few millimetres) of the subject. It is thus very difficult to do simultaneous spectroscopy at other wavelengths, scattering experiments, rheology, etc of the same region of the sample which is undergoing NMR excitation.

The open-access Halbach array may be regarded as being, in a sense intermediate between the NMR-MOUSE and its cousins, and more conventional designs [10]. The subject is enclosed inside the magnet array in a moderately homogeneous field, but is not tightly confined between the pole pieces. The flat solenoid RF coil employed in the current design resembles a surface coil in that large samples can be placed on or near it to get a signal, but better B_0 homogeneity should allow excitation of a larger sample volume.

In this paper, we briefly report the successful design and testing of a simple open-access Halbach magnet array and RF coil system capable of low-field, low-resolution NMR. This represents a first step towards building the kind of hybrid NMR technologies suggested above.

2. Magnet and RF coil design

The Halbach array was composed of a set of four strong composite permanent magnets. These were neodymium-ferrite-boron, type NdFeB N38H, 200 mm long by 18×18 mm square, fabricated by Magnet Sales and Service Ltd of Highworth, UK. The magnetic axis of each magnet runs parallel to one of the 18 mm dimensions. An aluminium frame held the magnets in a square array 200 mm long by 74 mm square, in such a way that they could be rotated about their long axes, and then locked in position with their short sides at angles of 45° with respect to the frame (Fig. 1). This gave rise to the magnetic field pattern shown schematically in Fig. 2, with the B_0 field running diagonally across the frame. The RF coil was located in the horizontal plane halfway up the frame, with B_1 running vertically up the long central axis (x) of the frame and therefore perpendicular to B_0. Total cost of such a system is ~£1500.

Numerical modelling of the field due to the four magnets in the above arrangement predicted a total field at the centre of 888 ±2 gauss in a 1 cm^3 volume, corresponding to a ^1H resonance frequency of 3.78 MHz ± 8.5 kHz. This implies the field homogeneity is about ±0.23% or 2300 ppm.

After experimenting with several RF coil designs, a good workable arrangement was found to be a simple short eight-turn solenoid coil, of diameter 4 cm and length 5 mm. The inductance of the coil was measured to be 9.6 μH from $\nu = 0$–6 MHz. The coil was coupled through a conventional tuning and matching circuit,

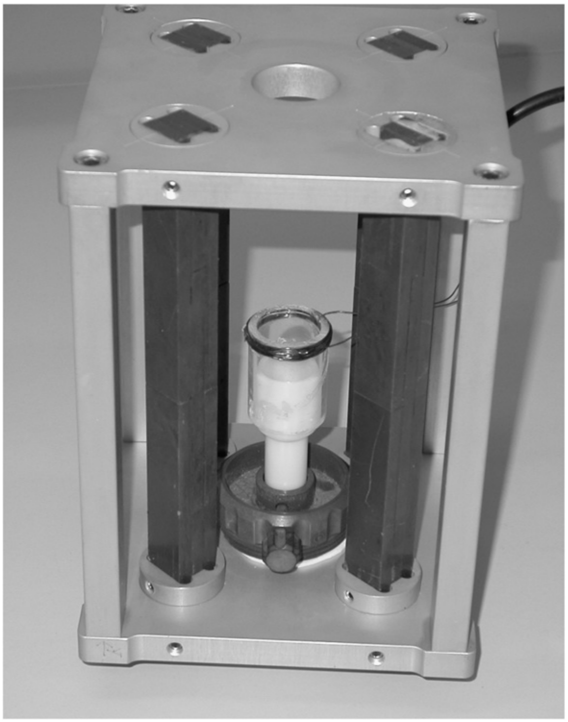

Fig. 1. Side view of a simple rectangular open-access Halbach magnet array with RF coil. The position of the coil can be mechanically adjusted to locate the field centre.

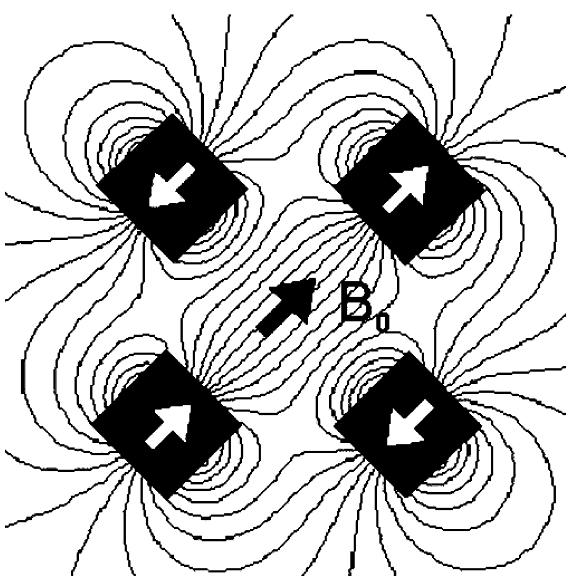

Fig. 2. Schematic of the magnetic field in the horizontal plane (yz) through the centre of the Halbach magnet array shown in Fig. 1. The central arrow shows the homogenous region of the total field B_0 due to the four dipoles at the corners. (Not to scale.)

crossed diodes and a $\lambda/4$-equivalent network to a Resonance Instruments UltraMaran spectrometer (400W output). A ^{1}H signal was obtained from doped water when the coil was tuned and matched at 3.87 MHz. The probe dead time was $<\sim 30$ μs and the best obtainable 90° RF pulse was 4.1 μs.

To alleviate potential problems with external RF noise interference, two counter-wound but otherwise identical RF coils, connected in series, were used. The sample was placed in the primary coil, while the second coil was placed at the top of the Halbach cage, well away from the sample, but still within the magnetic field. In this way any external interference would induce equal and opposite currents in the two coils which would be cancelled at the receiver. Only genuine NMR signal from the sample would thereby be observed. (A similar concept is used in SQUID gradiometers.) In extremely RF-noisy environments it may be necessary to resort to shielding by enclosing the entire magnet and coil system as well as tuning/matching box in an earthed Faraday cage of thin copper mesh. We found one such environment when operating the equipment in different laboratories; a Faraday cage ($\sim$50 cm along each side) eliminated the problem. Clearly a Faraday cage should be avoided if possible because it may also limit access to the sample by other spectroscopic techniques.

In some applications it may be desirable to control the temperature of the permanent magnets independently of the sample. The neodymium–ferrite–boron magnets in the prototype have good thermal stability (the temperature coefficient of the remanence being only ca. $-0.1\%/°C$). Nevertheless for extreme applications where the sample may be subjected to high temperatures it will be necessary to thermostat each of the four magnets by placing them in a cooling jacket. This will not seriously compromise the accessibility because the jacket need only be a few millimetres wider than the magnet.

3. Results and conclusion

Experiments were performed using Hahn echo or CPMG pulse sequences on samples in conventional NMR tubes ranging over 5–18 mm diameter. To illustrate the open-access aspect of the instrument, whole fruit and eggs were also scanned by simply resting them on the RF coil, as well as a human finger (inserted through the coil) and a gel sample in a 2 cm diameter impedance cell. Considering the limitations of the design, especially low S/N ratio, the results were considered satisfactory and capable of yielding useful information such as T_2 and T_1 distributions and M_0 ratios in solid/liquid mixtures as would be expected of any low-field NMR instrument (see Fig. 3 below).

To investigate the sensitivity of the RF coil the relative integrated spin echo intensity for a 2 mM $MnCl_2/H_2O$ doped water sample was measured as a function

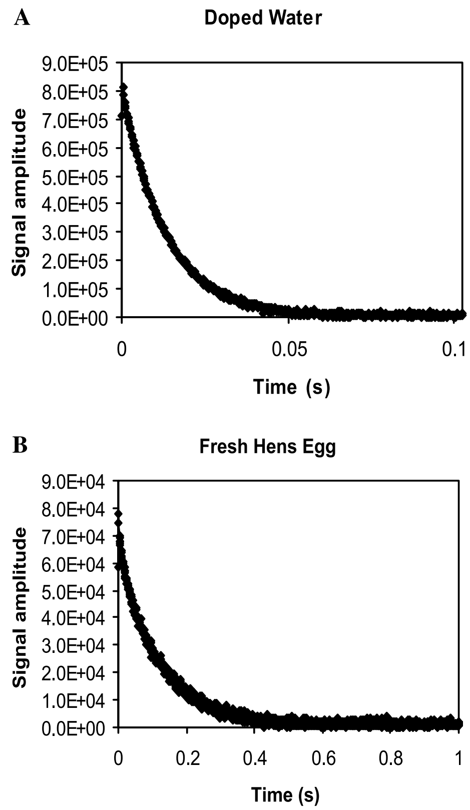

Fig. 3. CPMG decays (echo maxima) for doped water (2 mM $MnCl_2$/H_2O) and fresh chicken egg. (A) Water with $\tau = 100$ μs, 500 scans, single exponential decay with $T_2 = 13$ ms. (B) Egg with $\tau = 400$ μs, 32 scans, double exponential decay, 89% component with $T_2 = 123$ ms, 11% with $T_2 = 10$ ms.

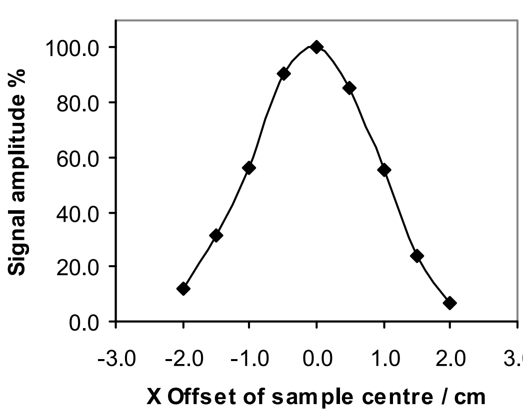

Fig. 4. Relative sensitivity of the RF coil for a 1 cm diameter × 2 cm deep sample of doped water as a function of position along the coil axis.

of sample position inside the coil. Fig. 4 shows the variation along the coil axis. There was a variation of no more than ∼10% as a function of radial position in the plane of the coil. Most of the signal comes from a region within ∼2 cm above and below the coil. This permits a crude form of volume selectivity when large samples such as fruit are examined.

In conclusion, we have established that an open-access rectangular Halbach magnet array is quite capable of being used for conventional low-field NMR. In conjunction with suitable shim and gradient coils the NMR capability of the system could be improved and extended. Above all, the open-access nature of the array allows us to envisage a wide-variety of experimental scenarios in which NMR is coupled with other techniques, as outlined above. Many of these scenarios would be more difficult or impossible with a conventional magnet/probe design.

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