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Profiles with microscopic resolution by single-sided NMR

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Abstract

A single-sided NMR sensor to produce depth profiles with microscopic spatial resolution is presented. It uses a novel permanent magnet geometry that generates a highly flat sensitive volume parallel to the scanner surface. By repositioning the sensitive slice across the object one-dimensional profiles of the sample structure can be produced with a space resolution better than 5 μm. The open geometry of the sensor results in a powerful testing tool to characterize arbitrarily sized objects in a non-destructive way.

Keywords: MRI; Single-sided NMR; Mobile probes; Microscopic resolution profiling; NMR-MOUSE

1. Introduction

Single-sided NMR sensors offer access to study arbitrarily sized objects non-invasively. They combine open magnets and surface RF coils to generate a sensitive volume external to the sensor and inside the object under investigation [1–5]. The price paid to gain in access is the impossibility of generating homogeneous magnetic fields. Nevertheless, this natural gradient can be exploited to obtain depth resolution into the material. The procedure is fully equivalent to the one used by the STRAFI technique [6], where the strong stray field gradient of superconducting magnets is used to measure profiles with high spatial resolution (in such a set-up, the superconducting magnets are used as large single-sided sensors). Although the strength of the static gradient generated by single-sided magnets is comparable to that in STRAFI experiments, the lateral gradients from small magnets results in rather poor depth resolution. Several attempts have been made to increase the gradient uniformity by tailoring the magnet geometry, but spatial resolution better than half a millimeter is hard to achieve [7–10]. Complicated magnet arrays have been the result of optimization procedures where the field profile is improved by playing with the position and orientation of a large number of permanent block magnets [9,10]. The philosophy adopted in previous designs requested the magnet to generate planes of constant field strength in large depth ranges. Such a profile is convenient because it allows selecting slices at different depths into the object simply by electronically switching the tuning frequency. Although the retuning procedure is simple and fast, we have detected deficiencies in this approach. Density profiles are contrasted by relaxation times or self-diffusion to improve the discrimination of heterogeneities in the material, but when the depth is changed the values of these parameters vary, introducing systematic changes in the contrast. For example, considering that the static field has a gradient of some T/m the resonance frequency changes by several MHz in a few millimeters. This poses a restriction to the use of T_1 contrast in samples with frequency dependent T_1. Moreover, the transverse relaxation time ($T_{2\mathrm{eff}}$) measured by a CPMG sequence in inhomogeneous fields, which is a mixture of T_1 and T_2 [11], changes with the depth due to the variation of the B_0 and B_1 field profiles. Even the contrast by

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diffusion is distorted as a consequence of the variation of the static gradient as a function of the depth.

During the last year, we have changed the scanning strategy going back to the original one used by the STRAFI technique, where the sample profiling is performed just by changing the relative position of the sample with respect to the sensitive slice keeping the excitation frequency constant [6]. Besides being a distortion free procedure, it only requires the generation of a flat sensitive slice at a single depth. This important reduction in constraints to the optimization procedure is exploited to produce higher depth resolution.

In this work, a single-sided NMR sensor intended for high resolution sample profiling is described. With it, microscopic depth resolution is achieved in situ for the first time with an open NMR sensor. By repositioning the sensor with respect to the sample, 1D profiles with a spatial resolution better than 5 μm are obtained. An important fact is that the magnet is of extremely simple construction and inexpensive to manufacture, which is important factor when such a tools are intended for quality control.

2. Sensor design

Magnets optimized to generate a uniform gradient in a large depth range are mainly based on the U-shape geometry, which uses two block magnets with antiparallel polarization placed on an iron yoke [3]. The important advantage of this magnet geometry relies on the fact that the static field is parallel to its surface, allowing its combination with simple and efficient surface RF coils. Recently, sensors based on simpler magnets like single solid bars or hollow cylinders [12,13] have been employed to generate near their pole faces a much more uniform magnetic gradient. But as the magnetic field generated by these geometries points along the depth direction, special planar RF coils are required to provide a B_1 field parallel to the magnet surface. Coil geometries, like figure-8 [12], are generally used in combination with these magnets, but they have two main disadvantages. First, the strong gradient of the B_1 field makes these coils inefficient for measurements at large depths. Second, they offer poor lateral selection, which is a critical issue when high depth resolution is required. The lateral dimensions of the plane where the magnets generate a constant magnetic field are finite and the selective excitation of this region is primarily determined by the design of the RF coil. On account of these facts, we decided for a magnet geometry with the static field parallel to the surface.

2.1. Magnet system

The poor depth resolution characteristic of the U-shaped geometry (Fig. 1 with $d_S = 0$) is fully determined by the lateral variation of the static field. Fig. 2 shows the spatial dependence of the magnetic field magnitude at different depths along the x and z directions. Although the field depends on the spatial coordinates in a complicated way, it can be approximated well by

$$|B_0(r)| = B_0(y) + \alpha(y)z^2 + \beta(y)x^2, \quad (1)$$

where $B_0(y)$ takes into account the main spatial variation along the depth, and α and β account for the lateral deviations at each depth. Since α and β have opposite signs, a sensitive volume with the shape of a horse saddle is defined. Although at the surface $|\alpha| > |\beta|$, the relationship is inverted $|\beta| > |\alpha|$ for large enough depth of the order of the magnet gap d_B.Therefore, for increasing depths, the sensitive volume becomes rather flat along z, and it is the curvature along x which determines the resolution.

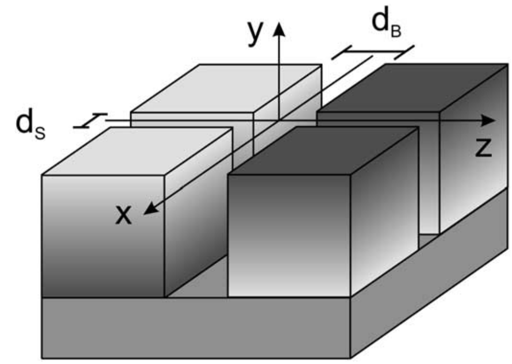

Fig. 1. The new magnet geometry used to generate a highly flat sensitive volume. It consists of four permanent magnet blocks positioned on an iron yoke. The direction of polarization of the magnets is indicated by the gray scale. Two magnets are polarized along y and two along $-y$. Magnets with the same polarization are separated by a small gap d_S (2 mm) while magnets with opposite polarization are separated by a gap d_B (14 mm). At 10 mm depth, the magnetic field points along z and has a magnitude of about 0.4 T, while the gradient is about 20 T/m and points along y.

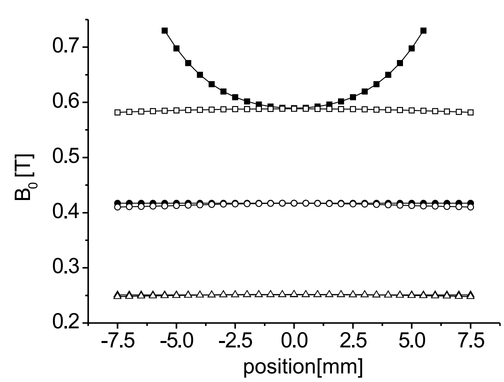

Fig. 2. Magnitude of the magnetic field along z (filled points) and x (empty points) at $y = 0$ (squares), 10 (circles), and 20 mm (triangles). The field magnitude was computed from the three field components scanned with a hall probe. It can be observed that the value of both $|\alpha|$ and $|\beta|$ in Eq. (1) becomes smaller with the increasing depth. They keep their sign, but α clearly goes to zero much faster than β.