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Inside-out NMR probe for portable spectrometry

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Abstract—**Nuclear Magnetic Resonance (NMR) measurements in grossly inhomogeneous static magnetic fields are possible if the inhomogeneity is inferior to a theoretical limit. A design is proposed for a single-sided inside-out NMR probe with static and radiofrequency (RF) magnetic fields perpendicular and correlated on a large volume. This probe was constructed with ferrite material. It can found application as a portable scanner for local NMR spectrometry.**

***Keywords*—Portable NMR, magnetic field homogeneity, perpendicular magnetic fields.**

I. INTRODUCTION

Measuring Nuclear Magnetic Resonance (NMR) relaxation parameters outside a magnet may be useful in many applications. Inside-out NMR has been developped in the 80's for petroleum applications [1]: a complete NMR system, including magnets, coil and electronics is dropped in a borehole. Two opposite magnets create a relatively homogeneous magnetic field, and spin echo sequences [2] are used to refocus the phase dispersion due to the static field inhomogeneity. In the last decade, the NMR MOUSE [3] was developped by Blumich *et al.* This portable NMR apparatus can probe any proton-containing material.

Recent advances in NMR sequence design [4] shown that high resolution NMR is possible with a single-sided probe, if the static and the RF magnetic fields are perpendicular and strongly correlated in the measurement volume.

In this paper, we give design consideration to built an inside-out NMR probe with a minimal magnet size. In the first part, we discus the acceptable static field inhomogeneity. Then, a coil and magnet configuration is described, and magnetic materials are discussed.

This probe is positioned manually on the object and an image can be obtained by moving the apparatus.

II. THEORY

A. Static field inhomogeneity

One can ask which inhomogeneity is acceptable in NMR. In standard NMR systems shimming coils are used to attein a 10E-6 relative inhomogeneity: this is necessary to observe the chemical shifts with classical NMR sequences.

Taking into account of the recent advances in portable NMR systems and in sequence design, the acceptable inhomogeneity depends on the available RF power. After a RF pulse, the nutation angle is

$$\theta = \tau\gamma B_1 \qquad (1)$$

where τ is the pulse length, γ is the gyromagnetic ratio and B_1 is the RF magnetic field. If the static magnetic field is not homogeneous, the nutation angle becomes

$$\theta + \Delta\theta = \tau\sqrt{\Delta\omega_{RF}{}^2 + (\gamma B_1)^2} \qquad (2)$$

where $\Delta\omega_{RF} = \gamma\Delta B_0$ is the offset of the RF frequency from the local Larmor frequency.

To ensure a correct excitation (ie $\Delta\theta \ll \theta$) the excitation system must fullfil the condition

$$\Delta\omega_{RF} \ll \gamma B_1 \qquad (3)$$

The minimum value of τ is the inverse of the Larmor frequency. For a $\pi/2$ pulse, a Taylor development of Eq. (2) gives

$$\frac{\Delta B_0}{B_0} = \frac{1}{2}\sqrt{\frac{\Delta\theta}{\pi}} \qquad (4)$$

For a accepted error of 10 degrees, this gives a accepted inhomogeneity $\Delta B_0 / B_0 \approx 0.1$. This is a theoretical limit for static field inhomogeneity. However, it is difficult to generate such strong and short RF pulses and most of the inside-out NMR devices operates with an inhomogeneity $\Delta B_0 / B_0 \approx 0.01$.

B. Perpendicular magnetic fields

In NMR systems, the static and the RF magnetic fields must be perpendicular. It is classically done using a solenoid or a bird-cage coil which produce a RF magnetic field homogeneous in a large volume. In inside-out NMR application, the presence of strong field gradients complicates the matching of the RF and the static magnetic fields. In the NMR MOUSE [3], a solenoidal coil positioned in the gap between two Neodymium-Iron-Borum (Nd-Fe-B) magnets ensure RF field approximately orthogonal to the static field.

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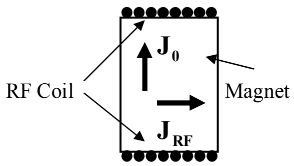


Fig. 1. In this basis 2D configuration, the static magnetic field created by the magnet (polarized verticaly) is perpendicular to the RF magnetic field produced by the coil. This property is true everywhere in the space. Moreover, the static field strength varies with the RF field strength.

In 2D systems, it is possible to create two magnetic fields which are exactly orthogonal everywhere in space [5]. A typical configuration is shown on Fig. 1: the static magnetic field is created by a permanent magnet having a magnetisation $\mathbf{J_0}$. The two current sheets covering the upper and the lower faces of the magnet are equivalent to a magnet with a magnetisation $\mathbf{J_{RF}}$. From the *easy-axis* rotation theorem [6]-[7], the RF and the static magnetic fields are perpendicular.

This result is not true for realistic 3D systems, but correct orthogonality and field correlation are obtained using relatively long (80x10x15 mm) permanent magnets. To decrease the peak RF power, the static field homogeneity is increased using two anti-parallel permanent magnets: this design is shown on figure 2. Compared to the existing inside-out NMR systems, this probe ensures enhanced RF and static field perpendicularity and similar homogeneity performances. Moreover, the static and the RF magnetic fields are strongly correlated (i.e. the RF field strength varies with the static field strength): this founds applications in high resolution inside-out NMR.

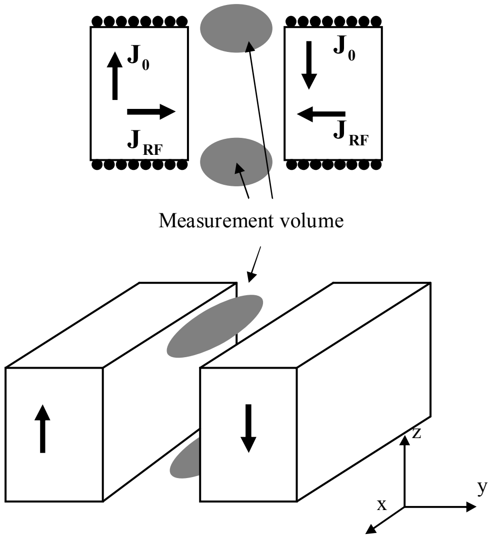


Fig. 2. A two magnet configuration is used to increase the grossly homogeneous volume.

The homogeneity, the perpendicularity and the correlation of the RF and static magnetic fields were simulated with the Mathcad software: results are shown on figure 3 for a $80 \times 30 \times 15$ mm probe. These simulations prove the interest of this design in term of correlation and perpendicularity of the magnetic fields.

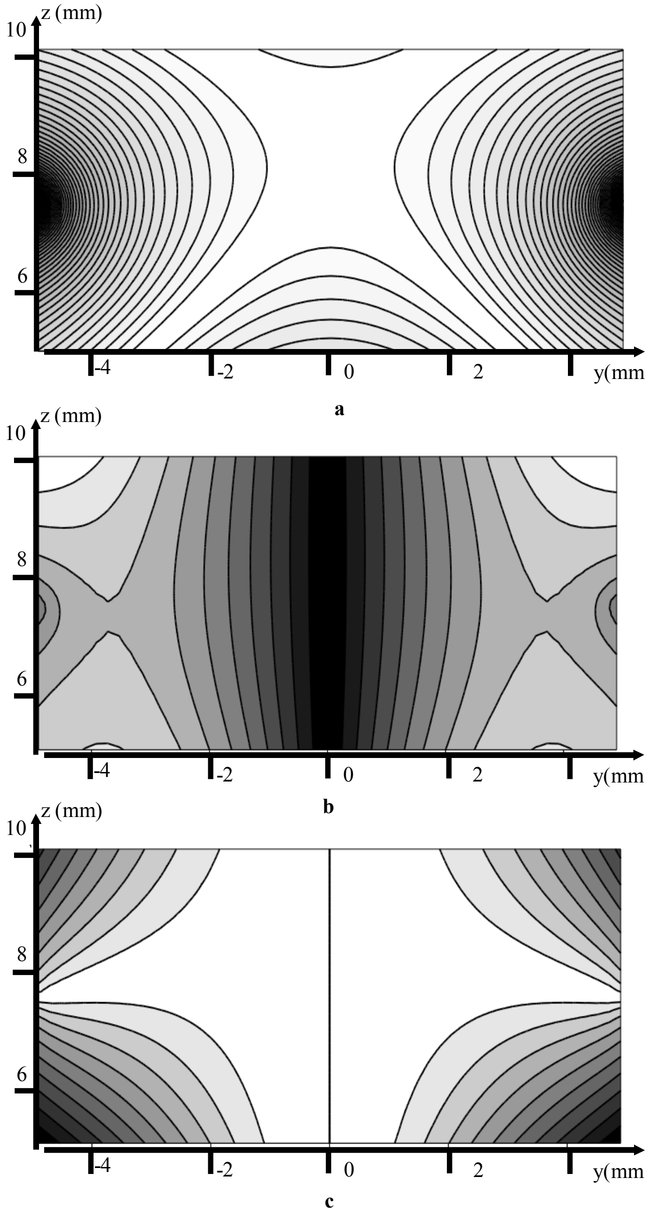


Fig. 3. Magnetic field simulation performed with Mathcad. The reference is at the center of the probe: the plotted area is the measurement volume at the top of the probe. For these simulations, x=0. **a** : static field homogeneity. The central contour plot corresponds to an inhomogeneity $\Delta B_0 / B_0 < 0.02$. **b** : the perpendicularity is evaluated by the product $\mathbf{B_0} \bullet \mathbf{B_1} / \|\mathbf{B_0}\| \|\mathbf{B_1}\|$. This product is inferior to $5\,\mathrm{E}-5$ at the centre and inferior to $5\,\mathrm{E}-4$ everywhere. **c** : map of the differences between the static and the RF fields, calculated with $\varepsilon = |1 - J_0 B_{RF} / J_{RF} B_0|$. In the contour plot at the centre, $\varepsilon < 3\,\mathrm{E}-5$.

C. *Magnetic material*

The RF field $\mathbf{B}_1$ generates eddy currents. These currents depend on the resistivity ρ of the magnet. An important power should be dissipated in the magnet, resulting a loss in the coil quality factor. Moreover, eddy currents oppose the main RF field and the coil sensitivity vanishes. Also, the field $\mathbf{B}_1$ penetrates in the magnet in a depth of

$$\delta = \sqrt{\frac{\rho}{2\pi f \mu_0 \mu_r}} \tag{5}$$

where f is the RF frequency, μ_0 is the vacuum permeability and μ_r is the relative permeability of the material; for magnets with high coercitive field $\mu_r \approx 1$. The skin effect should dramatically affect the RF field $\mathbf{B}_1$ and ruin the perpendicularity between $\mathbf{B}_1$ and $\mathbf{B}_0$.

Simulation with different magnetic material (Table I) proves the interest of ferrite magnets for this application. In this case, the coil's equivalent resistance R_{COIL} is not affected by the proximity of the magnet. Moreover, the eddy currents are negligible and does not oppose the coil magnetic field : that is why the coil's equivalent inductance L_{COIL} is maximum for ferrite magnets. Neodymium-Iron-Borum (Nd-Fe-B) and Samarium-Cobalt (Sm-Co) magnets are not suitable for this application.

III. REALIZATION AND EXPERIMENT

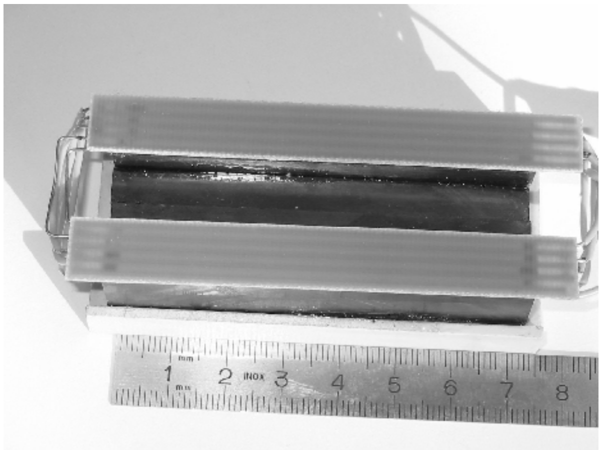
TABLE I

COIL EQUIVALENT RESISTANCE AND INDUCTANCE

Magnetic material	Resistivity Ω.m	Coil resistance Arbitrary unit	Coil inductance Arbitrary units
Sm-Co	10^{-7}	0.27	0.013
Nd-Fe-B	10^{-6}	1	0.029
Ferrite	10^{4}	$7.8\ 10^{-7}$	1

A single-sided inside-out NMR system was made with ferrite magnets and a printed circuit board coil. In the measurement volume, the static field strength is 0.1 T. The probe measures only $75 \times 30 \times 15$ mm and it weights 210 g. It is actually tested with a home built NMR spectrometer, based on a digital direct synthesizer and a software-radio receiver [8], as shown on figure 4. Currently, we are developing an RF amplifier suitable for strong and very short RF pulses.

IV. CONCLUSION



A theoretical limit for static magnetic field homogeneity is calculated for inside-out NMR applications. This shows that NMR measurement are possible in grossly inhomogeneous static magnetic fields if the sample is excited by short and strong RF pulses.

A new inside-out NMR probe design is proposed. The static and the RF magnetic fields of this probe are perpendicular and correlated in a large volume, and fields are relatively homogeneous, with respect to the homogeneity limit described above.

This probe can be used for portable spectrometry and imaging applications.

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