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Stray Field Imaging by Magnetic Field Sweep

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A novel variant on nuclear magnetic resonance stray field imaging (STRAFI) is presented in which an additional magnetic field sweep coil is used to sweep the region of resonant frequency through a stationary sample. Variants on this technique using an integral superconducting field sweep coil as part of a spectroscopy magnet and a room temperature field sweep coil mounted inside an imaging magnet are detailed. One-dimensional profiles of ''Perspex'' and polytetrafluoroethylene samples are presented. The results from both superconducting and room temperature field sweep coils compare favorably with ''conventional'' STRAFI. © 1998 Academic Press

Key Words: **NMR; STRAFI; stray field; imaging; solids.**

INTRODUCTION

It has previously been shown that the large magnetic field gradient available in the stray field of an NMR magnet can be used to image broad line materials (*1–3*). Gradient values are typically in the range 10–100 T m^{-1} and are therefore much larger than can be achieved using conventional gradient coils. These large gradients have also proved useful because of their inherent stability for the measurement of slow diffusion processes (*4, 5*).

In normal stray field imaging (STRAFI) the sample is moved through the sensitive imaging slice. The width of the slice depends on the field gradient and the bandwidth of the r.f. pulses, and if relaxation effects are neglected, the signal is proportional to the number of excited spins. By acquiring data as the sample is moved through the sensitive slice, a one-dimensional profile of the sample can be built up from the echo amplitudes. In this communication a novel and potentially more convenient field sweep variant of STRAFI (fs-STRAFI) is demonstrated in which the sensitive slice is moved through the sample rather than the sample being moved through the sensitive slice.

Two methods of field sweep are discussed. The techniques are shown in Figs. 1 and 2. Ideally a STRAFI experiment is carried out where the stray field gradient of the magnet is linear and where the contours of constant magnetic field strength are planar. In general this usually indicates a position near the end of the magnet where the field strength is approximately half its central value. Although it would be possible, in principle, to move the sensitive slice by increasing or decreasing the central field of the magnet, most superconducting NMR magnets operate in the persistent mode and great care is taken to ensure the stability of the central field. Thus it is generally not practical to change the field over the course of an experiment. The first technique relies upon varying the magnetic field generated at the center of the magnet by the addition of a superconducting field sweep coil within the windings of the magnet. At the University of Kent we are in possession of a vertical bore magnet with just such an integral sweep coil designed for the spectroscopy of very broad line materials. The current through the field sweep coil can be increased from zero to its maximum value in a period of a few minutes. A complication arises in that the field sweep coil and the main field coil have a significant mutual inductance. Thus as the current in the field sweep coil is increased, that in the main field coil is *reduced* and the stray field strength decreases. This means that the sensitive slice moves toward the center of the magnet as the sweep current is increased.

The second method does not require a specialized magnet design, but uses a room temperature coil, separate from the superconducting magnet. The sweep coil is a short solenoid coaxial with the main field coil and positioned such that its center is coincident with the sensitive plane. The sweep coil and the main field coil are only loosely coupled so that the central field of the magnet is virtually unaffected by current in the field sweep coil. This technique has two main advantages over the first, in that a conventional superconducting NMR magnet can be used and that, because of the small mutual inductance between the two coils, the sensitive plane can be moved more rapidly and by a greater amount.

RESULTS: METHOD I

Measurements were carried out on a Magnex 7.04-T (300-MHz), 89-mm vertical bore magnet with an internal superconducting field sweep coil capable of increasing the central field of the magnet by ~0.5 T. A Chemagnetics CMX Infinity spectrometer provided the transmitter and receiver electronics. The sample used consisted of a short square-section length of polymethylmethacrylate (PMMA—''Perspex'')

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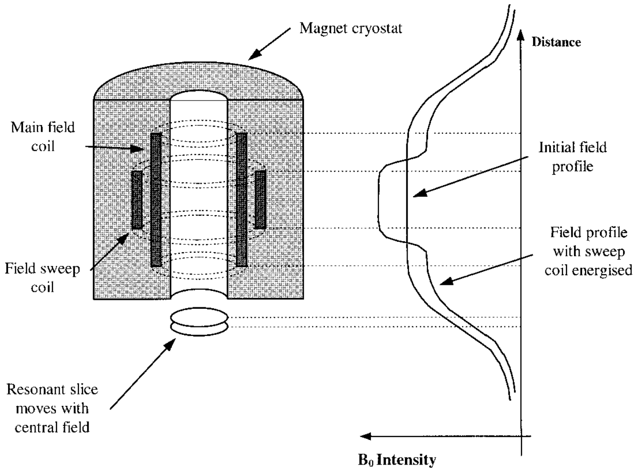

FIG. 1. Imaging by field sweep method I. In a ‘‘conventional’’ STRAFI experiment the sample is moved through the sensitive slice, whereas in this method the resonance condition is moved through the sample by varying the central field of the magnetic through its interaction with the field sweep coil.

of dimensions 3.5 × 3.5 × 8.5 mm. It was machined to fit within one of the 7.5-mm sample tubes of the probe. The sample was then placed within the probe such that the long axis of the sample was at a known angle (∼50°) to the main field (Fig. 3a). The sample was placed at a distance of 27 cm from the center of the magnet where the resonant frequency for protons was found to be 120 MHz. In the first part of the experiment the whole probe assembly was moved manually through the sensitive slice at 1 mm increments as in a ‘‘conventional’’ STRAFI experiment. A $90_x - \tau - 90_y$ solid echo pulse sequence was used with an r.f. pulse length of 5 μs and an interpulse spacing of 30 μs. The echo was acquired at a sampling rate of 5 MHz with 256 sample points. The echo data were used to construct a one-dimensional profile of the sample as shown in Fig. 3b. Allowing for the noise level, and the background fluorine signal from the probe body, there is good agreement between the theoretical and experimental profiles of the sample (Figs. 3a and 3b).

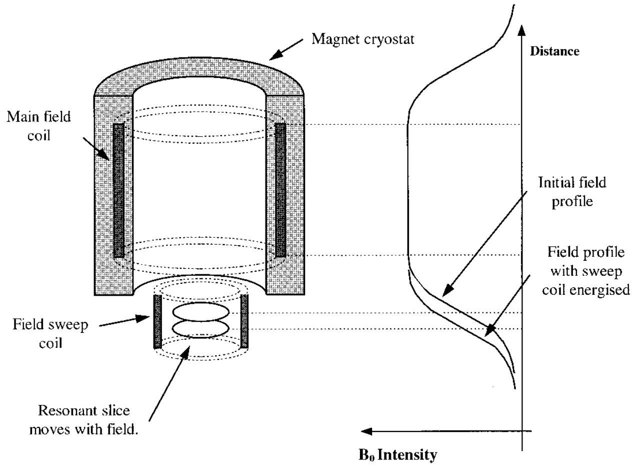

FIG. 2. Imaging by field sweep method II. The field sweep coil is offset from the center of the magnet and is loosely coupled to the main field coil. The resonance position can be moved by energizing the field sweep coil. The loose coupling between the coils allows the magnetic field to be modified local to the sample without gross changes of the central field strength.

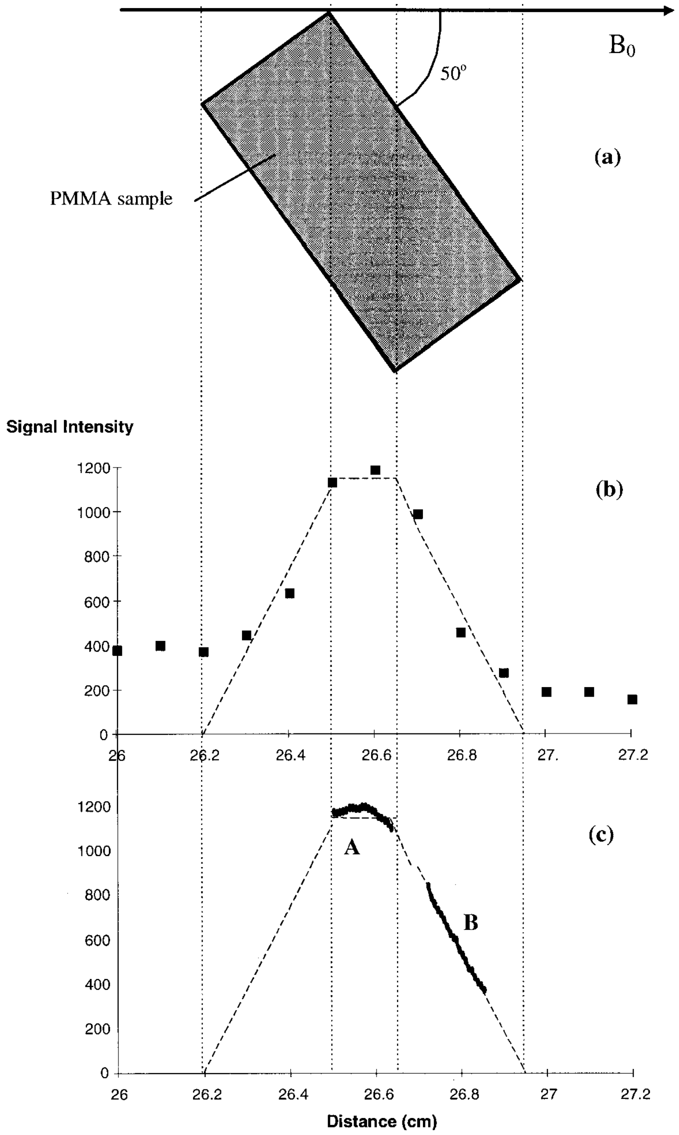

FIG. 3. (a) The sample geometry of the Perspex block used in method I. (b) Profile measured by a conventional STRAFI type experiment (black squares). (c) Profiles obtained using method I in the regions A and B of the sample (bold lines). Note: Profiles expected from the known sample geometry are shown as dashed lines.

In the second part of the experiment using the field sweep coil, one-dimensional profiles of the sample were acquired at two separate points (26.5 and 26.7 cm from the magnet center). The sweep coil was ramped from 0 to 18 A in 1-A steps. At full current, the sweep coil was calculated to shift the sensitive slice by approximately 1 mm, so that only part of the sample projection could be measured. The first measurement was taken over a uniform section of the sample, Fig. 3c region A, to ensure the technique gave the expected constant echo signal intensity. The second measurement was taken at one end of the sample, Fig. 3c region B, where the sample profile would result in a predictable decrease in signal intensity. The measured sample profile indicated a total sweep distance of (0.7 ± 0.1) mm, which compares well with the range calculated from theoretical considerations (*6*) of the magnetic field change in the two coils of 0.9 mm. Although the range is limited, it is clear that the field sweep method can give excellent results, comparable to ‘‘conventional’’ STRAFI.

RESULTS: METHOD II

In this method an additional room temperature z coil was used to sweep the field. Measurements were carried out on a Magnex 4.7 T (200 MHz) 20 cm bore imaging magnet. A Bruker CXP spectrometer with the Aspect computer replaced by a PC equipped with SMIS (*7*) hardware and software was used to control the experiments. The sample used was a cylindrical polytetrafluoroethylene (PTFE) block 31 mm long by 21.5 mm in diameter placed inside a birdcage r.f. coil. A circular notch 3 mm in width was milled into the block to a depth of 7.5 mm approximately halfway along its length, Fig. 4a. The field sweep coil was produced by using one of the Maxwell pair of coils used to provide the normal z imaging gradient. Current for the coil was provided by a Techron 7700 power amplifier governed by a 12-bit digital-to-analogue converter in the PC. The r.f. birdcage coil was tuned to a fluorine frequency of 109.13 MHz, which was the resonance condition of the center of the region of interest. A current varying from −100 to +100 A was run through the field sweep coil in steps of 4 A. At each current step a two pulse solid echo was acquired as in method 1. A total of 128 averages for each current setting were recorded. At each echo center 20 points were acquired at a sampling rate of 5 MHz and the points were averaged to improve signal-to-noise. It was arranged so that as the sweep coil current was increased, the resonant slice moved further away from the magnet center. As can be seen from Fig. 4b, the echo data convincingly reproduce the central waist of the PTFE sample.

The field sweep coil produced a change in field ~±0.1 T at ±100 A. Since the field gradient of the main field coil at the region of interest was 18 ± 0.5 T m^{-1}, the theoretical sweep width of the experiment should be ~1 cm. If we assume a linear gradient and that the magnetic field generated by the sweep coil is linear over the region of interest, the measured results indicate a maximum sweep width of ~9 mm. This agrees well with the theoretical value.

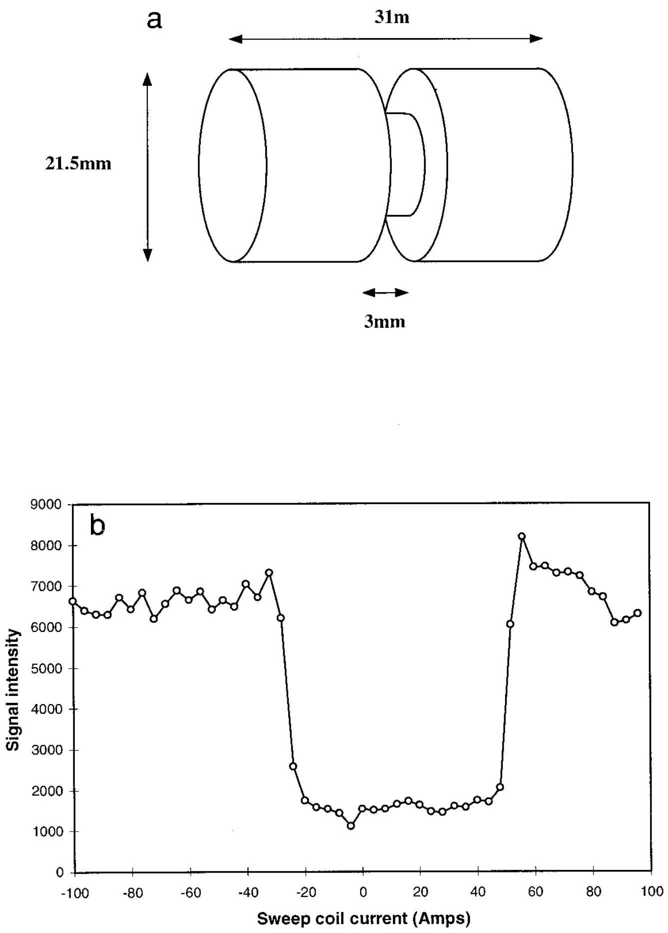

FIG. 4. (a) Cylindrical PTFE phantom with central milled region used for method II. (b) Signal intensity as a function of sweep coil current (method II) showing the distinctive shape of the central region of the phantom. The region of lower signal intensity between −30 and +50A represents a distance of 3 mm of the sample. The complete current sweep represents a field of view of approximately 9 mm.

CONCLUSIONS

By adding a field sweep facility to the main z field of an NMR magnet it has been shown that it is possible to perform stray field imaging without having to physically move the sample. The fs-STRAFI method has the advantage that there are no problems associated with positional reproducibility, backlash, or misalignment in the sample travel. It should be noted that stray field imaging is usually undertaken at a position in the field gradient where the B_0 field is planar. The addition of a secondary magnetic field should therefore be accomplished in such a way that the contours of magnetic field intensity in this region of interest remain flat. The field sweep technique would appear to be highly suited to experiments where it is impractical to move the sample during the time scale of the experiment and/or where the region of interest is of the order of a few millimeters or less, e.g., thin films, surface effects, or boundary layers.

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