Continuous-Wave MRI of Short-T_2 Solid Materials

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Introduction:

Rigid solid materials typically exhibit very short T_2 relaxation times, as short as 10-20 μs in some cases. As a result, many of these materials cannot be studied by conventional "liquid-state" MRI. A number of strategies for imaging solids have been developed over the years, perhaps the most successful (in terms of applications) being Stray-Field Imaging (STRAFI) [1] and Single-Point Ramped Imaging with T_1 Enhancement (SPRITE) [2]. STRAFI uses pulsed acquisition typically in the very strong, static field gradient located in a superconducting magnet's fringe field, with stepped motion of the sample providing a one-dimensional projection of the spin density. SPRITE is a pure phase-encoding method, again using pulsed acquisition. Despite their success at imaging a range of materials, neither technique can readily image in 3 dimensions solids exhibiting the shortest T_2 values. We have developed Continuous-Wave MRI (CW-MRI) in order to address this problem. Instead of employing pulsed RF excitation followed by signal detection (with an inevitable dead-time, which prevents the study of ultra-short T_2 samples), CW-MRI employs continuously-applied RF in the presence of a strong, quasi-continuous field gradient. Signals are produced by sweeping the magnetic field through resonance, yielding a one-dimensional projection of the sample. Images are produced by back-projection reconstruction following step-wise rotation of the applied gradient in 2 or 3 dimensions.

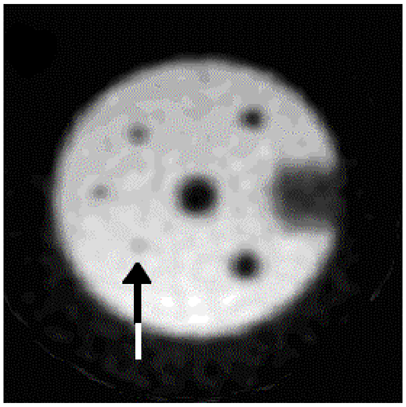
Apparatus:

Our system is built around a 183-mm horizontal bore, 7-tesla superconducting magnet (Oxford Instruments Ltd., UK), giving a proton frequency of 300 MHz. Detection is by a home-built CW homodyne reflection bridge. A birdcage resonator is used to apply continuous low-power (1-10 mW) RF to the sample. RF is applied to the resonator via a hybrid junction, through which changes in the electrical characteristics of the resonator as the magnetic field is swept through resonance are recorded. As is ubiquitous in CW magnetic resonance, sensitivity is improved by employing magnetic field modulation and lock-in detection. Here an audio-frequency amplitude-modulation is superimposed on the magnetic field during the field sweep. As resonance is approached the sample goes in and out of resonance at the modulation frequency, causing the reflected signal to have the same modulation, which is detected by a phase-sensitive detector (a "lock-in amplifier") connected after the RF detection circuit. The lock-in amplifier is also the source of the field-modulating signal, and is set up to record only input signals at that frequency, within a narrow band. The CW-NMR spectrum is recorded as the output of the lock-in amplifier as a function of the swept magnetic field. Due to the nature of the lock-in detection process, it is actually the first derivative of the absorption NMR spectrum; the latter can easily be recovered by integration.

Our system incorporates a coil assembly (Laplacian Ltd., UK) containing 3 gradient coils and 2 solenoidal coils (one for field sweep and the other for field modulation). The maximum gradient strength is 300 mT/m on each axis, while the solenoids produce a magnetic field sweep of ± 16 mT and a modulation field of up to ± 800 μT at frequencies up to 10 kHz.

Results and Conclusions:

We have used our system to image a variety of materials, including polymethyl methacrylate (PMMA, "Plexiglass" or "Perspex" polymer), which exhibits multi-exponential transverse relaxation (corresponding to different phases of the polymer), with the strongest component having a T_2 of ~16 μs. The figure on the right shows an image of a 30-mm diameter, 10-mm thick PMMA test object. 180 projections over 180° were obtained, using a gradient strength of 300 mT/m. Holes were drilled through the disc in order to determine spatial resolution; the smallest hole (0.75 mm diameter) can just be discerned at the position indicated by the arrow. We have also performed CW-MRI experiments of samples containing nuclei other than protons, including ^{7}Li, ^{23}Na, ^{27}Al and ^{13}C, using birdcage resonators at appropriate frequencies [3]. In the bio-medical field CW-MRI is likely to be of use in the study of implants made of ceramic or polymer materials. It should also be possible to image bone using ^{31}P CW-MRI.



References

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