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Detection of NMR signals with a radio-frequency atomic magnetometer

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Abstract

We demonstrate detection of proton NMR signals with a radio-frequency (rf) atomic magnetometer tuned to the NMR frequency of 62 kHz. High-frequency operation of the atomic magnetometer makes it relatively insensitive to ambient magnetic field noise. We obtain magnetic field sensitivity of 7 $fT/Hz^{1/2}$ using only a thin aluminum shield. We also derive an expression for the fundamental sensitivity limit of a surface inductive pick-up coil as a function of frequency and find that an atomic rf magnetometer is intrinsically more sensitive than a coil of comparable size for frequencies below about 50 MHz.

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Keywords: NMR; Atomic magnetometer; Radio-frequency; Pick-up coil; Sensitivity

Nuclear magnetic resonance (NMR) signals are commonly detected with inductive radio-frequency (rf) pick-up coils. Recently, alternative detection methods using SQUID magnetometers [1–3] or atomic magnetometers [4,5] have been explored. These techniques can achieve higher sensitivity at low NMR frequencies and offer other advantages in specific applications. In particular, atomic magnetometers [6,7] eliminate the need for cryogenic cooling and allow simple multi-channel measurements [8]. However, most atomic magnetometers are designed to detect quasi-static magnetic fields and are sensitive to oscillating fields only in a limited frequency range. Previous NMR and MRI experiments with atomic magnetometers detected either static nuclear magnetization [4,9–11] or nuclear precession at a very low frequency (~20 Hz) [5].

Recently we developed an rf atomic magnetometer that can be tuned to detect magnetic fields at any frequency in the kHz to MHz range [12] and demonstrated detection of NQR signals at 423 kHz using this device [13]. Another technique for detection of rf fields with atoms is presented in [14]. Here, we describe detection of NMR signals from water at 62 kHz and discuss issues specific to NMR detection, such as application of a uniform static magnetic field. The rf magnetometer offers a number of advantages over traditional quasi-static atomic magnetometers. It can detect NMR signals in a wide range of magnetic fields and can allow measurements of chemical shifts as has been demonstrated with SQUID magnetometers [15]. Operation at high frequency reduces the magnetic noise produced by Johnson electrical currents in nearby conductors [16]. In magnetic resonance imaging applications it increases the available bandwidth and eliminates the effects of transverse magnetic field gradients [17]. The rf magnetometer also has a number of practical advantages. It is relatively insensitive to changes in DC magnetic field allowing it to operate in an unshielded or lightly shielded environment. Unlike previous setups, we did not use μ-metal magnetic shields in this experiment, relying only on a thin aluminum rf shield. The magnetometer is also relatively insensitive to vibrations and laser noise because it detects alkali-metal spin precession signals at high frequency. We used inexpensive multi-mode diode lasers mounted on an aluminum plate without vibration isolation. We identified several technical

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issues that need further research, such as improvement in the uniformity of the static magnetic field and reduction of the magnetometer dead time after the rf excitation pulse.

We also compare the fundamental limits on the magnetic field sensitivity for an rf magnetometer and a traditional inductive pick-up coil. There has been much interest recently in conducting NMR measurements with pick-up coils in low magnetic fields (1–1000 mT) where superconducting magnets are unnecessary [18–21]. We derive an estimate for the sensitivity of a surface pick-up coil over a wide frequency range and compare its optimal performance with that of an atomic rf magnetometer of similar size. We find that the fundamental sensitivity of an atomic magnetometer is higher than fundamental sensitivity of a surface pick-up coil for frequencies below about 50 MHz.

The principle of operation of the rf alkali-metal magnetometer is discussed in [12]. Briefly, it uses a bias magnetic field to tune the Zeeman resonance frequency of alkali atoms $\omega_0 = \gamma B$ (potassium with nuclear spin $I = 3/2$ has $\gamma = g\mu_B/\hbar(2I+1) = 2\pi \times 700$ kHz/Gauss) to the frequency of the oscillating magnetic field. The alkali atoms are optically pumped along the bias field and their transverse spin precession excited by the weak rf field is detected with an orthogonal probe laser. The experimental setup for the magnetometer is shown in Fig. 1. Helmholtz coils are used to cancel the Earth field and generate the bias field. The alkali metal is contained in a glass cell that is heated to about 180 °C with flowing hot air. The cell contains about 2.5 atm of buffer gas to slow diffusion of alkali atoms to the cell walls. The sensitivity of the magnetometer near its resonance frequency is shown in Fig. 2. The broad peak in the spectral density of the magnetometer signal is due to transverse spin oscillations excited by magnetic field noise and other sources of fluctuations. The width of the peak is equal to the bandwidth of the magnetometer, which is on the order of 1 kHz, substantially larger than the bandwidth of NMR signals in liquid samples. The height of the peak indicates the level of magnetic noise. In Fig. 2, we compare the noise levels of the rf magnetometer operating in an unshielded environment, with simple eddy-current shielding using thin aluminum sheets, and inside multi-layer magnetic μ-metal shields. For comparison, with a quasi-static magnetometer operating in an unshielded environment we observed noise of several pT/Hz$^{1/2}$ [22]. The

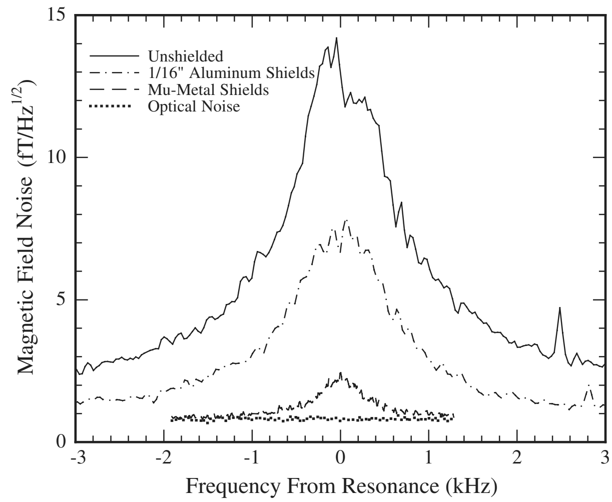

Fig. 2. Comparison of sensitivities of high-frequency atomic magnetometer: (1) unshielded (solid line), at 75 kHz; (2) with 1/16″ aluminum shield (dash-dotted line), at 75 kHz; (3) μ-metal shielded (dashed line), at 99 kHz; (4) optical noise (dotted line). The NMR signals were detected using the aluminum shield.

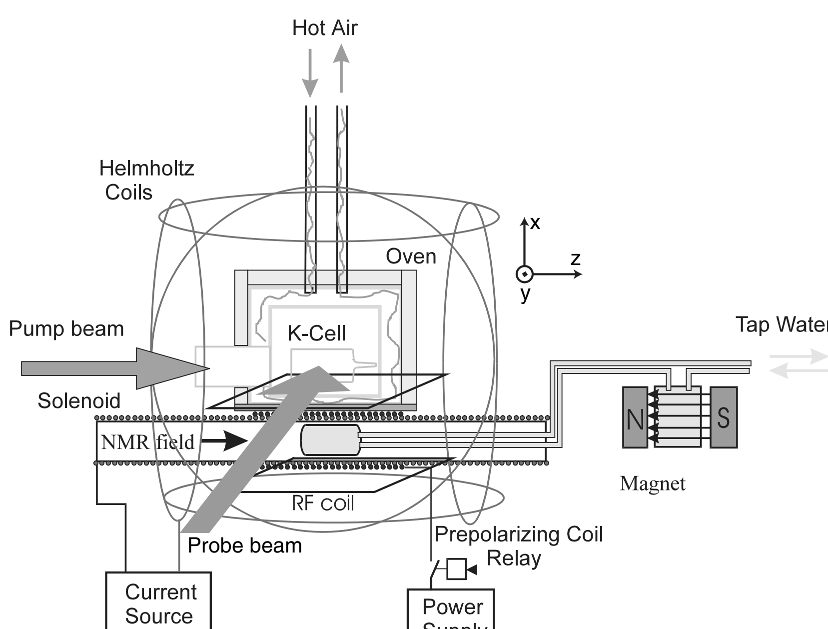

Fig. 1. Experimental setup for the observation of water NMR with a radio-frequency atomic magnetometer.