Parallel Imaging with SQUID Arrays

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Introduction:

In this paper we discuss and review the design of an imaging system which allows the direct observation of the very low frequency precession of nuclear spins at external fields as low as few nT. Since conventional "RF"-coils detect temporal magnetic flux changes only, these sensors are orders of magnitudes too insensitive to measure any signal from a slowly precessing nuclear spin system. However, SQUIDs (superconducting quantum interference devices) are native magnetic flux detectors with a sensitivity sufficient to detect magnetic fields as low as 1 fT at 1 Hz detection bandwidth (1). Nevertheless, the equilibrium nuclear spin magnetization at nT fields is too low for signal detection. To overcome these difficulties the magnetization has to be enhanced transiently either by prepolarization in mT fields or by hyperpolarization. Combining single SQUIDs to a detector array one may measure simultaneously magnetic field vectors and some spatial derivatives of magnetic field components at typical 30 to 100 positions. Those detector systems with some hundred detection channels are commonly used to record magnetic fields from the human brain in a magnetoencephalography (MEG) system (2). A first attempt to combine MEG and single channel SQUID detected nuclear spin precession was reported recently (3). In principle a MEG system may serve as a multi-channel detector for parallel imaging of the magnetic fields originating from precessing nuclear spins within brain tissue. A prerequisite for detecting free nuclear spin precession at nT fields is a magnetically shielded room with a shielding factor of at least 10000 at low frequencies to reduce ambient low frequency (1/f)-noise, static magnetic field gradients and the residual static magnetic field. An accessible magnetically shielded room with a shielding factor of 10^6 at 1 Hz and a residual field of about 100 pT is available now (4). At ultra-low fields and corresponding low proton Larmor frequencies of a few Hz only, one can easily manipulate the spin system non-adiabatically by switching "static" magnetic fields or magnetic field gradients. Since there is no need to apply any field resonantly we avoid the term "magnetic resonance" when dealing with freely precessing nuclear spins. As a matter of fact the B0-field and the gradient fields can be generated by the same coil system, e.g. by 3 pairs of Helmholtz coils. Furthermore, the direction of the B0-field can be changed during the measurement which enables the design of completely new "imaging sequences". Due to the non-resonant behavior during spin preparation together with the non-resonant SQUID detection the system described above allows a broadband operation and is an intrinsic multi-nuclear spin detector. Besides from spatial encoding in magnetic field gradients spatial information can be obtained from the initial preparation of the nuclear spin system which is done either by applying a magnetic field in the militesla range for some seconds (prepolarization) or by optical means (hyperpolarization). In this way various spatial encoding schemes are conceivable.

Nevertheless we focus our attention on imaging a freely precessing nuclear spin system by a SQUID array detector. Considering a single precessing dipole the signals detected by an array of SQUID detectors contain some spatial information with respect to the position and direction of the dipole and its time evolution (see Fig.1).

In contrast to high field MR there are no propagation effects of the electromagnetic fields, i.e. delays or phase distortions, affecting the reconstruction of the spatio-temporal information of the measured data. Actually, the measured (quasi-static) magnetic fields can be analyzed simply by assuming a set of dipoles evolving under the (classical) bloch equations. Due to motional narrowing one should observe rather T2-relaxation than T2*-relaxation making spin echo experiments unnecessary.

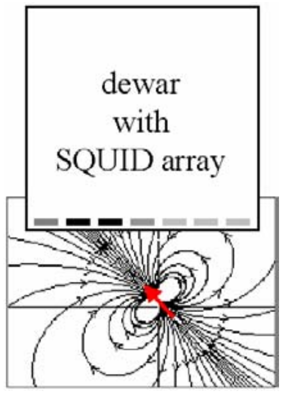


Fig.1

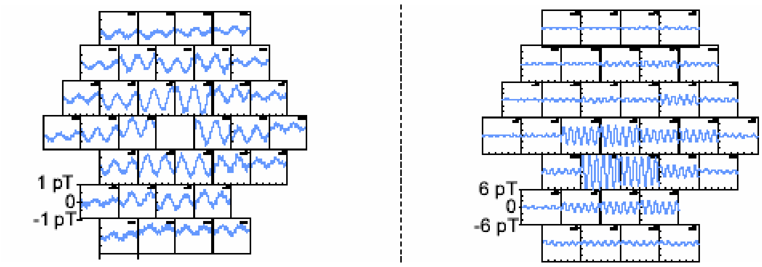
Methods:

Hyperpolarized 129Xe was produced off-line by spin-exchange optical pumping using circularly polarized laser radiation to pump the D1 transition of Rb (5). At 16 W laser power we achieved 129Xe nuclear spin polarizations between 10 %–20 % within few minutes. Subsequently the spin polarized xenon gas was expanded into an evacuated spherical glass bulb (o.d. 5 cm). Free precession of the 129Xe magnetization in ultra-low magnetic fields was recorded inside a magnetically shielded room (MSR, $2.2\times2.2\times2.3 m^3$, shielding factor >10000), using a 37-channel DC SQUID magnetometer with the low-Tc DC SQUIDs arranged in a horizontal plane (white noise level 8 fT/sqrt(Hz), sampling rate 250Hz). When entering the MSR the strength of the ambient magnetic field drops within 50 cm from earth field (50 µT) to several nT. Carrying the bulb sufficiently fast for the nuclear magnetization not to adiabatically follow the changing direction of the local ambient field, free precession of the nuclear magnetization around the axis of the ambient magnetic field was initiated. Inside the MSR the residual magnetic field was about 5 nT and oriented approximately vertically. A pair of Helmholtz coils (diameter 1 m) allowed to apply additional magnetic fields of some tens of nT along a horizontal axis.

Results:

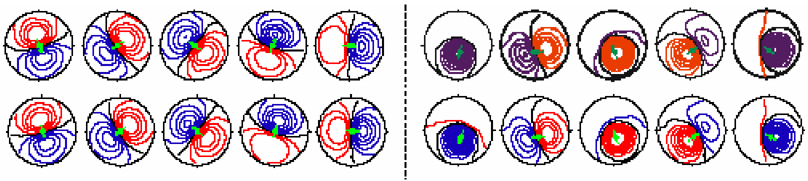
From FIDs recorded with a single channel SQUID gradiometer we deduced Larmor frequencies as low as 55 mHz and T2 values of up to 8000 s depending on the gas pressure within the bulb. In Fig.2 the output signal of all 37 channels of the planar SQUID magnetometer array versus observation time is shown for two different values of B0. The vertical magnetic field components arising from the bulb with the free precessing 129Xe nuclear spins are of the order of 1 pT to 10 pT. The observation time was 10 minutes typically. No averaging was applied.

Fig.2:
Spatially resolved spin precession measured with 37-element SQUID system
left: ambient magnetic field (B0 = 12nT)
right: additional field (B0 = 32nT)



For data analysis the average of the signals of all SQUID detectors was subtracted from each channel at each instant to reduce noise due to drifts of the ambient magnetic field. The angular precession frequency was derived from the signal of one of the SQUID detectors. Subsequently the signal of each channel was filtered by fitting it to a damped sinusoid. Fig.3a (Fig.3b) illustrates the spatial distribution of the oscillating vertical magnetic field component in the plane of detectors precessing at the Larmor frequency of 0.142 Hz (0.374 Hz) corresponding to an ambient field of 12 nT (32 nT) at phase increments during a precession periode of 72 deg.

Fig.3



The magnetic field patterns shown in Fig.3c,d were obtained assuming a precessing magnetic dipole at the center of the sphere perpendicular to the average B0-field and by fitting simulated dipolar fields to the data (a) and (b) derived from experiment. Excellent agreement between theory and experiment was achieved. In this way the location of the center of the spherical glass bulb with respect to the position of the central SQUID, the orientation of the B0- field, the precessing magnetic moment and its initial phase were obtained.

Conclusions:

Using a 37 channel planar SQUID detector we demonstrated the feasibility of parallel imaging of an extremly slowly precessing nuclear spin system which consisted of hyperpolarized 129Xe gas in a glass bulb exposed to B0-fields of few nT. Similar results should be attainable when using water protons and proper signal averaging techniques. Although the signal expected from prepolarized (in mT fields) water protons is about 3 orders of magnitude lower than the signal of the same volume of hyperpolarized 129Xe, the SNR of the SQUIDS should be sufficient for signal detection. SQUID array based parallel imaging of freely precessing nuclear spins in ultra-low B0-fields will offer some new possibilities and advantages over conventional MRI, particular its natural combination with MEG and/or near infrared spectroscopy techniques.

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