

# Synchronously Pumped NMR Gyro

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**Abstract**—We are implementing a new design for spin-exchange-pumped NMR gyros that addresses the key systematic errors as compared to previous implementations. The key concept is to drive magnetic resonance using spin-exchange collisions in a reference frame rotating about a bias magnetic field. The resulting purely transverse polarization is predicted to be insensitive to spin-exchange field shifts and quadrupole interactions, both of which are prominent in designs based on conventional magnetic resonance. Preliminary studies have identified a novel type of spin-exchange broadening that can be compensated to allow the system to reach T1-limited line width.

## I. INTRODUCTION

A practical spin-exchange-pumped gyro was recently reported by Larsen and Bulatowicz [1] at Northrop-Grumman Corp (NGC). The NGC gyro has demonstrated an ARW < 0.004 deg/rt(hr) and a bias instability < 0.02 deg/hr with a physics package volume of just 6 cc. Such an approach has favorable scalings for high performance in a small package.

Of substantial interest are the systematic errors that may or may not be present in such a device. A recent collaboration between NGC, Indiana University, and the University of Wisconsin [2] used an NMR gyro-like apparatus to reveal the nature of important systematic effects, namely differential NMR frequency shifts for the two isotopes due to nuclear quadrupole interactions and differential spin-exchange field shifts whose variation likely contribute to bias instability.

To address these issues we have begun investigating a new type of NMR gyro, the synchronously pumped gyro, whose purely transverse noble gas precession moves alkali field shifts off of DC and eliminates first-order quadrupole interactions. In addition, the absence of electromagnetic drives and longitudinal polarization removes a key contribution to ARW. This paper will briefly summarize these ideas and present some early experimental studies.

## II. SYSTEMATIC ERRORS IN NMR OSCILLATORS

The basic concept of an NMR gyro is to drive magnetic resonance of two nuclei at the same time. One serves as a co-magnetometer and is used to stabilize the magnetic field. Then any precessions of the second set of nuclei that do not scale with the ratio  $\gamma_1/\gamma_2$  of gyromagnetic ratios appears as a signal. The desired precessions are of course rotations, but other sources of NMR frequency shift can appear as false rotations. The prominent systematic errors in using two Xe species can be summarized in two equations from Ref. [2]:

$$f_{2i} = |\gamma_2 B_2| - \hat{z} \cdot \hat{B} X_2 + 2i|Q_{\parallel}| + \frac{3Q_{\perp}^2 \delta_{i0}}{4f_2} \quad (1)$$

This equation represents the 3 fundamental precession frequencies  $f_{2i}$  of the 131-Xe nuclei in magnetic field  $B$ . The three frequencies arise from quadrupolar interactions of the spin-3/2 nuclei with electric fields on the container walls. These quadrupolar interactions are characterized in terms of parameters  $Q_{\parallel}$  and  $Q_{\perp}$ , and in an NMR gyro the frequency of the quadrupolar interaction contribution to the total precession frequency is a weighted average of these parameters.  $X_2$  is, in the case of an NMR gyro, the inertial rotation rate. The effective frequency is in the microHz to milliHz regime and must be rigorously stabilized in order not to contribute to bias instability.

The second primary systematic error is the differential alkali field shift, whose significance is reflected in the ratio of the (quadrupole-corrected) NMR frequencies of 129-Xe ( $f_1$ ) and 131-Xe ( $f_2$ ):

$$\frac{f_1}{f_2} = \frac{\gamma_1}{\gamma_2} \left( 1 + \delta B_A \frac{P B_A}{B_0} \right) + \hat{z} \cdot \hat{B} \frac{X_1 + \gamma_1 X_2 \gamma_2}{f_2} \quad (2)$$

The first term, featuring the ratio of gyromagnetic ratios of the two species, would be a fundamental constant of nature were it not for the fact that the alkali atoms that produce and sense the noble-gas precession also produce a false differential magnetic field  $\delta B_A$  that is not precisely the same for the two species. The reader is referred to Ref. [2] for a full discussion of this point.

In order to address both the quadrupole and differential alkali field effects, a future Synchronously Pumped NMR Gyro uses only spin-1/2 nuclei 3-He and 129-Xe. (The rest of this paper will concentrate on an initial demonstration with a single isotope.) This combination of nuclear species would cause a large ( $\delta B_A \approx B_A$ ) differential alkali field in a conventional NMR gyro. Synchronous pumping however, makes the alkali field perpendicular to the bias field and parallel to the nuclear spins, thereby eliminating torque from the alkali field, and makes the alkali field AC so that its time-averaged effect is zero.

## III. SYNCHRONOUSLY PUMPED NMR GYRO

A schematic of the new approach is shown in Figure 1. A key novel component is the use of a sequence of short pulses [3] to produce a bias magnetic field that sets the sensitive rotation axis. The pulse areas correspond to  $2\pi$  pulses for the Rb atoms, and repeat at the Rb Larmor precession frequency  $f_0$ . The pulse chain timing is derived from an atomic clock. The Rb atoms have essentially no magnetic interactions with the  $2\pi$  pulse chain, and therefore their time-averaged behavior is as if they are at zero field. They can therefore be optically pumped in any desired direction, in particular orthogonal to

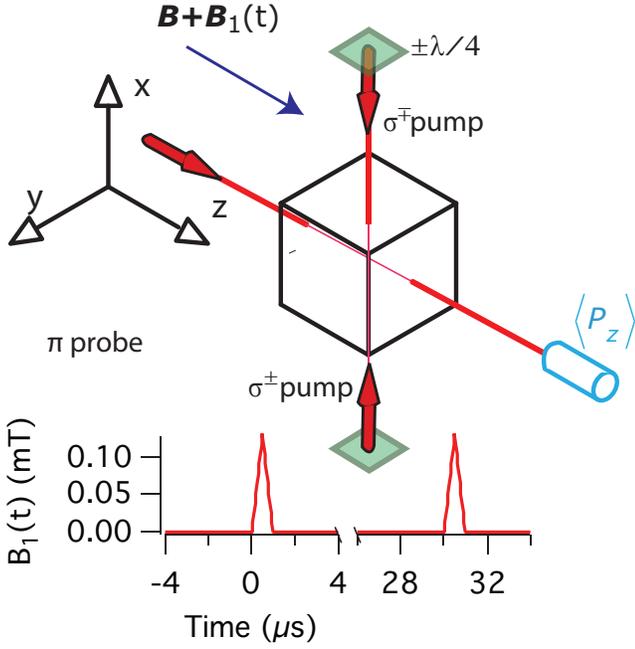


Fig. 1. Transverse optical pumping with pulsed parametric resonance. A modulating field  $B_1$  consists of a series of short  $2\pi$  pulses separated in time by the DC Larmor precession period  $1/\gamma B$ . The atoms become polarized along the  $\hat{x}$ -direction, and the time-averaged  $\hat{y}$  polarization is sensitive to any differences between the pulse repetition frequency and the DC Larmor frequency.

the bias field. The NMR precession is produced from the same sequence of  $2\pi$  pulses, but the net precession of the noble gas is much smaller;  $f_i = \gamma_i f_0 / \gamma_{Rb} = \gamma_i B \rightarrow B = f_0 / \gamma_{Rb}$ ; the magnetic field strength is thus directly derived from the atomic clock. Thus while the alkali atoms do not precess (in a time averaged sense), the noble gas nuclei do. Circularly polarized light, which propagates transverse to the bias field, optically polarizes the Rb atoms. This polarization is optically reversed at a frequency that corresponds to the NMR frequency of the Xe nuclei in the bias field; therefore, through spin-exchange collisions between the Rb and Xe, a rotating Xe nuclear polarization is created. Feedback synchronizes the Rb polarization to the rotating Xe polarization, with the Xe precession frequency being a precise sum of its Larmor precession and inertial rotation about the bias field axis.

Since the short  $2\pi$  pulses produce the same net rotation as a  $0\pi$  pulse, the time averaged response of the Rb atoms is nearly the same as in zero field, even though the time-averaged magnetic field is a fraction of a gauss. Thus the Rb atoms also serve as a spin-exchange relaxation free magnetometer for the NMR precession. The NMR detection is performed by this ultra-sensitive Rb magnetometer through a novel form of ultrasensitive magnetic detection, leading to predicted signal-to-noise ratios that support far below 0.001 deg/rt(hr) ARW.

This method of optical pumping has many advantages. These include the ability to optically pump the Rb atoms perpendicular to the bias field, which in turn makes the alkali

field perpendicular to the bias field. The Rb atoms can also have their direction reversed by simply reversing the direction of the circular polarization of the optical pumping light (we use a liquid crystal variable retarder to accomplish this). Thus the Rb spins can be made to reverse direction synchronously with the precession of the noble gas nuclei. Spin-exchange collisions [4] with the oscillating Rb spins thus drive the noble gas magnetic resonance; there is no electromagnetic drive field. Two other advantages of the pulsed field arrangement were explicitly demonstrated in Ref. [3]. Since the Rb atoms experience essentially zero magnetic field, spin-exchange collisions do not dephase the Rb atoms and the sensitivity of the Rb atoms as a magnetometer is (mostly) preserved, even though the average net magnetic field is  $\sim 0.1$  Gauss. Thus the Rb atoms also serve as a spin-exchange relaxation free magnetometer for the NMR precession.

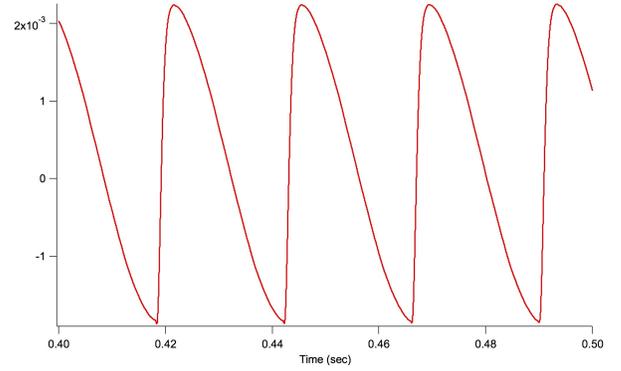


Fig. 2. Synchronously pumped Xe NMR signal.

Returning to the effective NMR drive, the noble gas nuclei undergo spin-exchange collisions with the oscillating Rb spins. The Bloch equation for the transverse spin components is

$$d_t K_+ = -(i\Omega + \Gamma)K_+ + \Gamma_{SE} S_{\perp} \text{sign}[\cos(\omega t)] \quad (3)$$

The last term represents spin-exchange collisions with the electrons of polarization  $S_{\perp} \text{sign}[\cos(\omega t)]$ . The fundamental Fourier component of the oscillating Rb spin thus drives magnetic resonance with a steady-state response

$$K_+ = \frac{2\Gamma_{SE} S_{\perp} / \pi}{\Gamma + i(\Omega - \omega)} e^{-i\omega t} = |K_+| e^{-i\phi} \quad (4)$$

The phase shift between the nuclear precession and the drive phase is

$$\delta\phi = \phi - \omega t = -\tan^{-1} \left( \frac{\omega - \Omega}{\Gamma} \right) \quad (5)$$

Rearranging,

$$\omega = \Omega - \Gamma \tan(\delta\phi) \quad (6)$$

so if the drive frequency is servoed to hold  $\delta\phi = 0$ , the drive frequency is precisely equal to the Larmor frequency. The absence of other contributors to this fundamental gyro equation that gives promise for this configuration having excellent performance as regards to bias instability.

Since the alkali field is perpendicular to the bias field, it does not contribute to  $\Omega$  and the only contributions to the Larmor frequency are from the magnetic field and rotation.

With a dual species operation, the magnetic field dependence can be removed, leaving sensitivity only to inertial rotation.

The NMR is detected using the Rb atoms as an ultra sensitive magnetometer. The signal is the magnetic field produced by the Xe nuclei, modulated by the reversing Rb polarization, as illustrated in Fig. 2.

The potential statistical sensitivity of the device can be estimated from Eq. 6. The ARW is dominated by the noise on the detection of the phase difference  $\delta\phi$ . Thus the angle random walk is

$$\text{ARW} = \frac{1}{2\pi T_2 \text{SNR}} = \frac{\delta B}{2\pi T_2 B_{Xe}} \quad (7)$$

where  $\delta B$  is the transverse magnetic field noise,  $B_{Xe}$  is the magnetic field from the polarized Xe, and  $T_2$  the transverse relaxation time of the Xe. Currently, we have  $\delta B = 5 \times 10^{-10}$  G/ $\sqrt{\text{Hz}}$  from our magnetic shields,  $B_{Xe} = 300 \mu\text{G}$ ,  $T_2 = 16$  sec, giving a potential ARW = 0.0004 deg/ $\sqrt{\text{hr}}$ .

#### IV. ALKALI FIELD BROADENING

The in-phase and quadrature components of the Xe NMR signal are shown in Fig. 3. The in-phase signal is broader than expected from the T1 time, but we also observe a substantially smaller quadrature signal than would be expected from Eq. 4. Studies of this effect indicate that it originates in the alkali

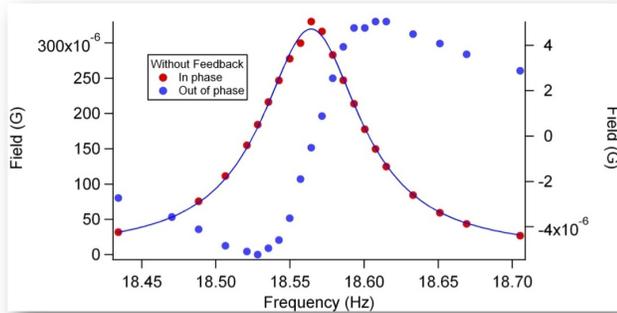


Fig. 3. In-phase (left axis) and quadrature (right axis) Xe NMR signals without the compensating field. Note the dramatic difference in scales.

field  $B_A$ . When the driven Rb polarization oscillation is off resonance, the oscillating alkali field has a phase shift that produces a DC longitudinal Xe polarization:

$$K_z = \frac{-2\gamma B_A}{\pi\Gamma} K_\perp \sin(\delta\phi) = K_\perp \tan \alpha \quad (8)$$

The parameter  $\tan \alpha \gg 1$  measures the relative size of the Larmor precession about the alkali field as compared to the noble gas relaxation rate. This effect alters Eq. 6 to

$$\omega = \Omega - \Gamma \sec^2 \alpha \sin(\phi - \theta) \quad (9)$$

so that

$$\delta\phi = \frac{\omega - \omega_0}{\Gamma \sec^2 \alpha} \quad (10)$$

Note that the alkali field does not shift the resonance frequency, but it does broaden the line and suppress the quadrature response.

These observations lead to the following prediction. If we apply a real oscillating field in phase with the Rb polarization, but in the opposite direction to the alkali field, the line shape should narrow and the quadrature signal increase in amplitude. Figure 4 shows that the application of the compensating field indeed narrows the NMR width by a factor of 7. The minimum line width is consistent with the measured 15 second T1 limit. Likewise, the quadrature response increases by a factor of 37, shown in Fig. 5.

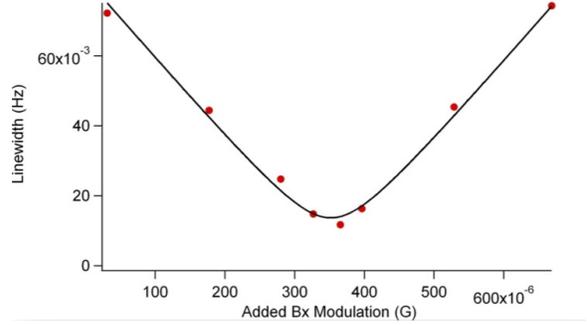


Fig. 4. Xe NMR line width as a function of compensating field amplitude.

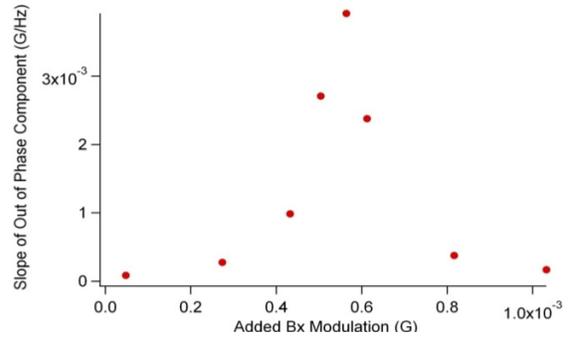


Fig. 5. Xe NMR line width as a function of compensating field amplitude.

#### V. CONCLUSION

We have demonstrated a new method, Synchronous Spin-Exchange Optical pumping, which has promising application to making a compact yet sensitive NMR gyro that potentially eliminates the dominant known sources of bias instability in the usual NMR gyro approach. Our first demonstrations, with a single isotope, have concentrated on understanding the basic physics of this approach. We identified and compensated for a new type of spin-exchange broadening and have demonstrated line widths consistent with the T1 limit. Using the signal sizes and known base field noise levels gives optimism for developing a new low-noise and high stability NMR gyro sensor.

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