^{3}He-^{129}Xe Gyro with ^{87}Rb decoupled SERF detection

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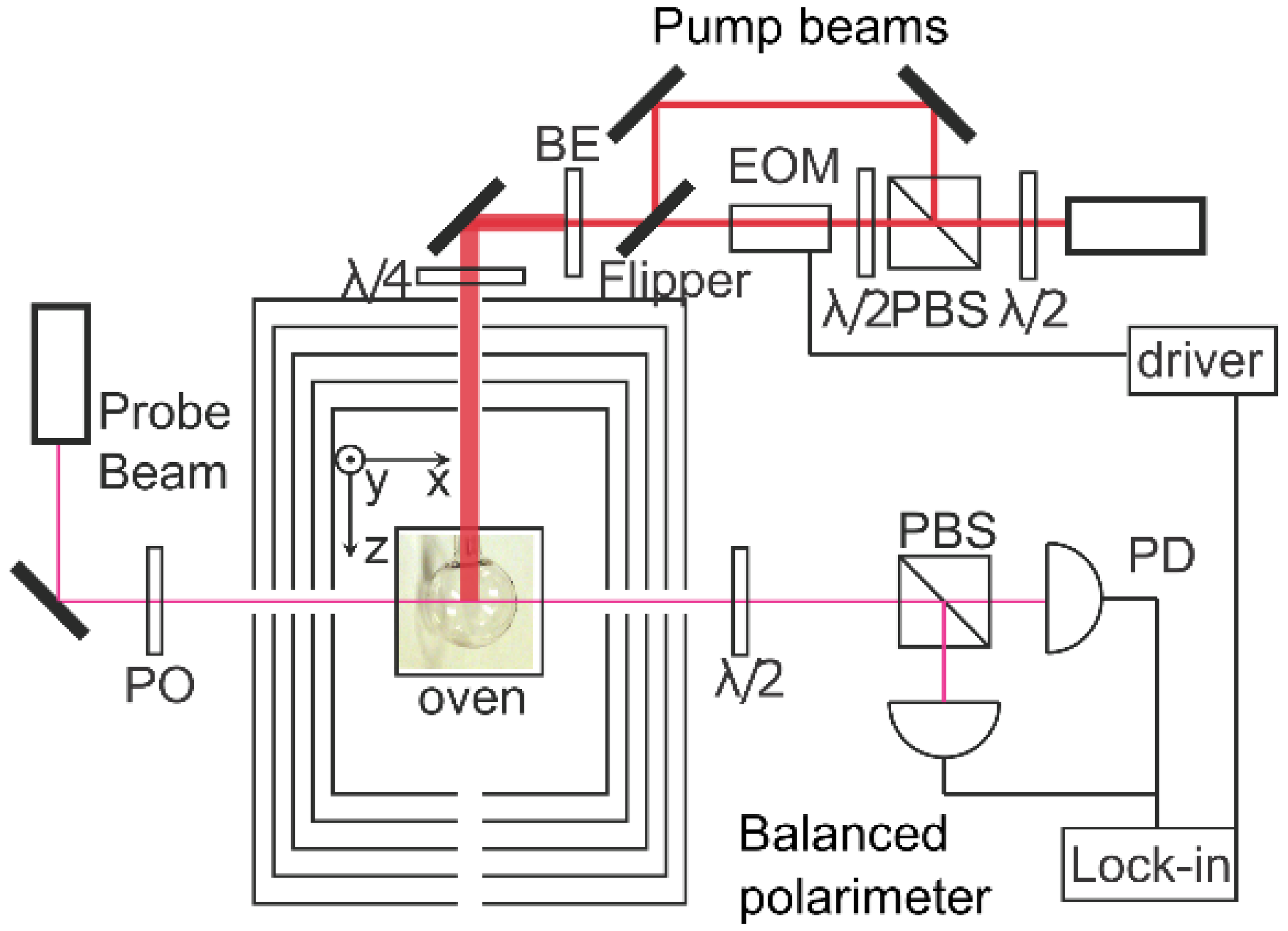
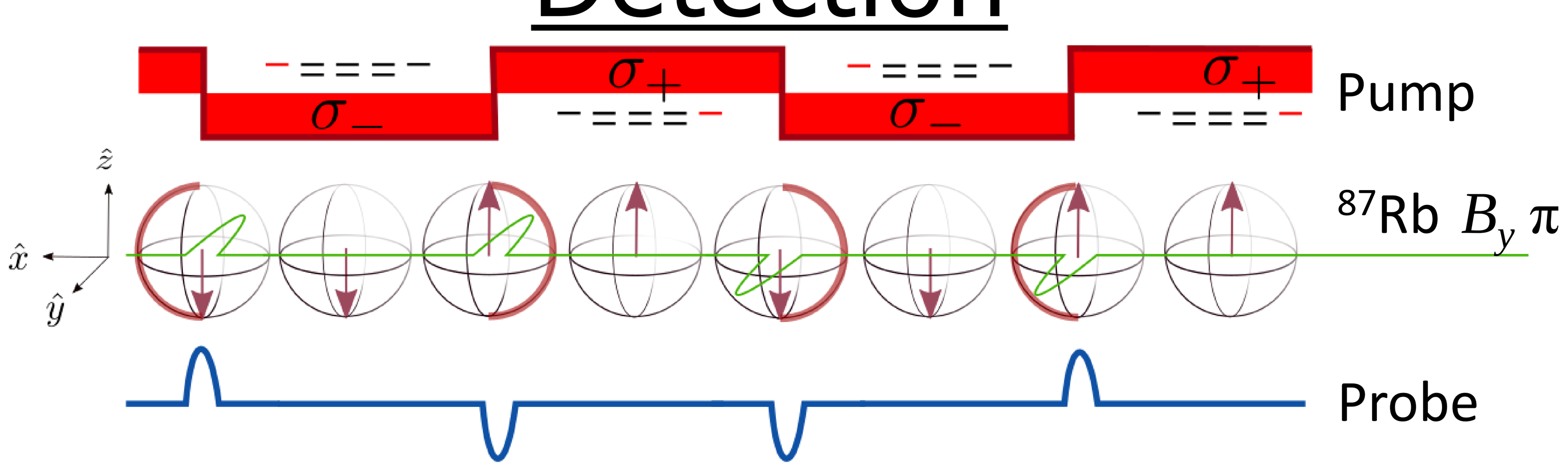
Apparatus

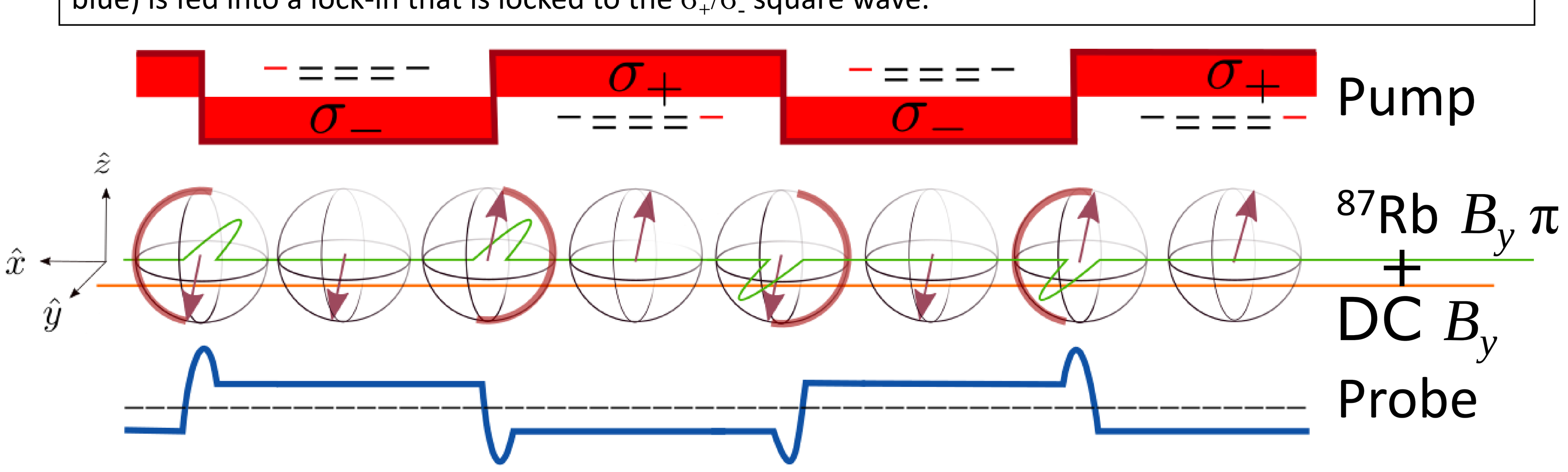


Our NMR gyro uses a vapor cell containing ^{3}He, ^{129}Xe, and ^{87}Rb, and sits inside five shields, where the spins are manipulated using a ^{87}Rb pump laser and magnetic field coils. The ^{3}He and ^{129}Xe precess in a $B_z \approx 0.5\ \mu$T bias field, and are read out by probing the polarized ^{87}Rb by Faraday rotation, i.e., a ^{87}Rb magnetometer detecting a ^{3}He-^{129}Xe comagnetometer.

Detection

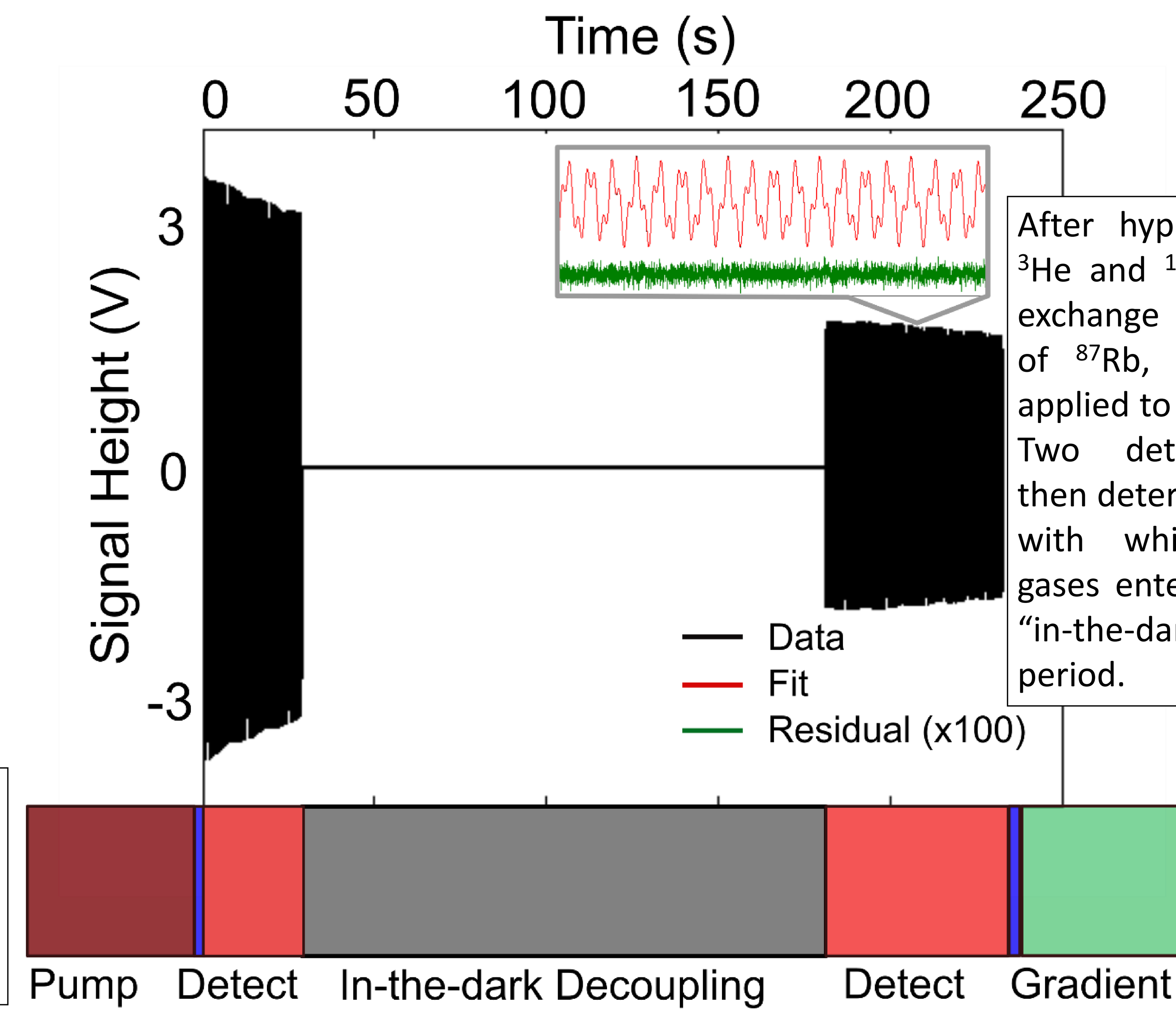


^{87}Rb (shown with a red arrow) is optically pumped using σ_+/σ_- 795 nm light, and driven back and forth using B_y π pulses (in green) at a repetition rate that exceeds the Larmor precession rate of the ^{87}Rb (>4 kHz) in the bias field $B_z \approx 0.5\ \mu$T. We probe the projection of the ^{87}Rb polarization along the x axis with a linearly polarized beam (detuned from 795 nm) that is detected with a balanced polarimeter. The probe signal (in blue) is fed into a lock-in that is locked to the σ_+/σ_- square wave.

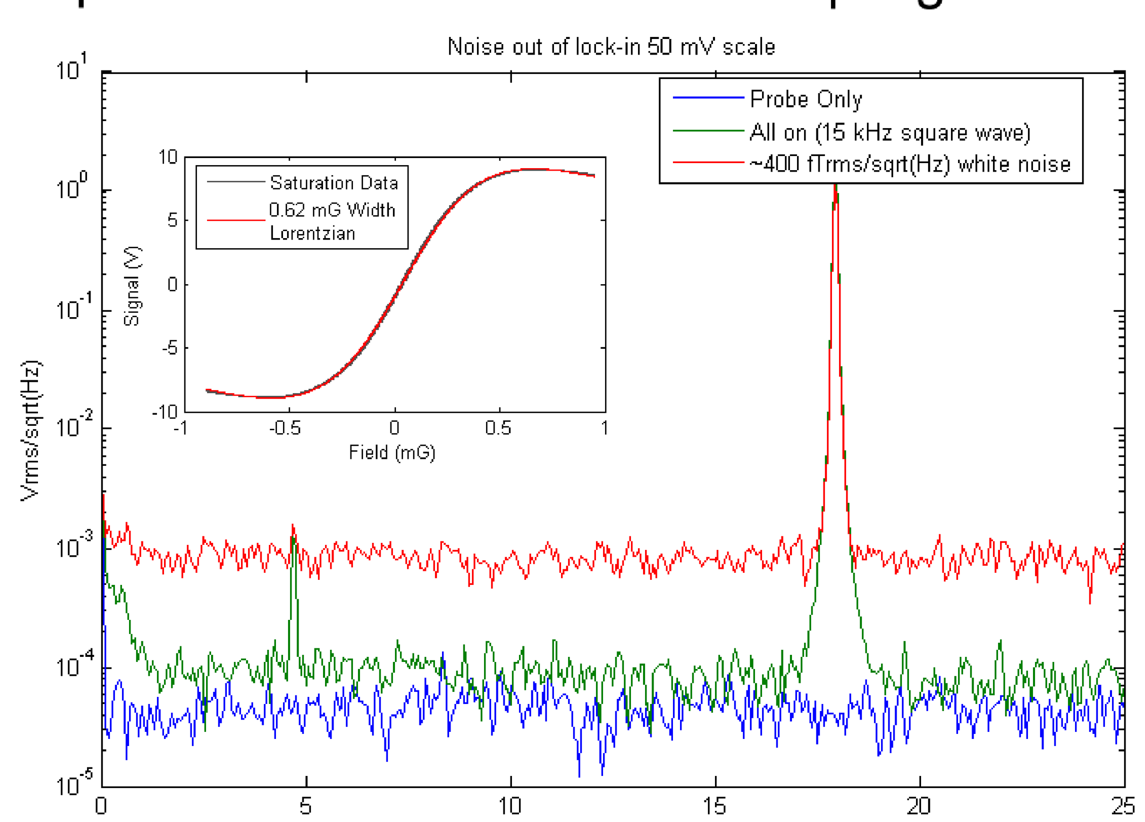


Here, the steady-state result of a DC field (in orange) along the magnetometer's sensitive y axis is shown. The ^{87}Rb magnetization vector precesses in the additional B_y DC field, with the phase accumulation being gradually erased by relaxation and pumping/probing of ^{87}Rb. The resulting projections of the ^{87}Rb onto the x axis lead to Faraday rotations of the probe beam, and a DC signal out of the lock-in.

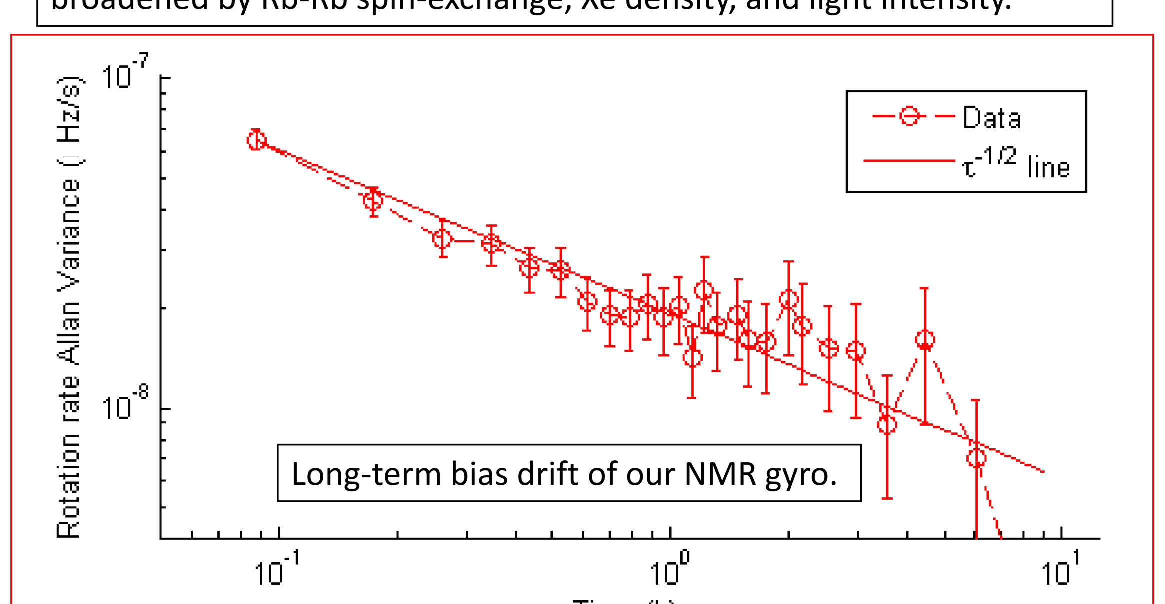
Measurement



After hyperpolarizing the ^{3}He and ^{129}Xe using spin-exchange optical pumping of ^{87}Rb, a $\pi/2$ pulse is applied to the noble gases. Two detection periods then determine the phases with which the noble gases enter and leave the "in-the-dark" decoupling period.



The ^{87}Rb magnetometer using π pulse detection has shown a sensitivity of 40 fT/sqrt(Hz). Inset: A typical magnetometer linewidth, which can be broadened by Rb-Rb spin-exchange, Xe density, and light intensity.



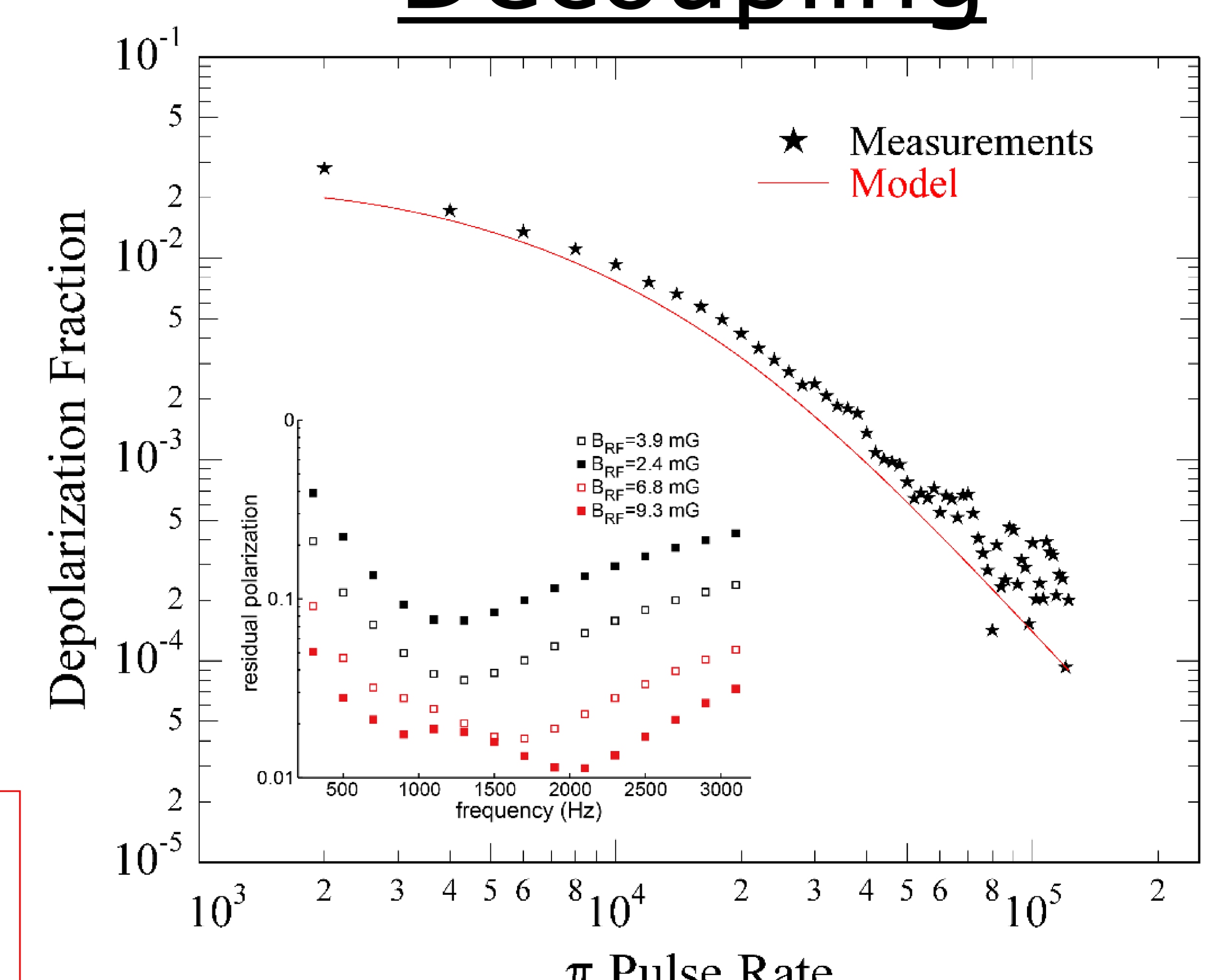
Long-term bias drift of our NMR gyro.

The premise of an NMR gyro is a comagnetometer measurement that is insensitive to bias field drift. We are developing this technology for use in a chip-scale inertial navigation system, and spin-gravity searches. In our NMR gyro, we detect the precession of spin-1/2 ^{3}He-^{129}Xe using ^{87}Rb. Spin-exchange optical pumping occurs via a Fermi-contact interaction $H = \alpha S \cdot K$, where S and K are the operators for the alkali electron and noble-gas nuclear spins. This interaction also causes the spins to experience magnetic fields that are enhanced by a factor κ_0 over the classical dipolar field, where κ_0 is 6 for Rb-^{3}He and 490 for Rb-^{129}Xe. Thus, ^{87}Rb detection allows us to approach nuclear spin shot-noise sensitivity. In turn, however, polarized ^{87}Rb is a source of instability in the ratio of the ^{3}He and ^{129}Xe precession frequencies, ω_{He}/ω_{Xe}, in a $B_z \approx 0.5\ \mu$T field.

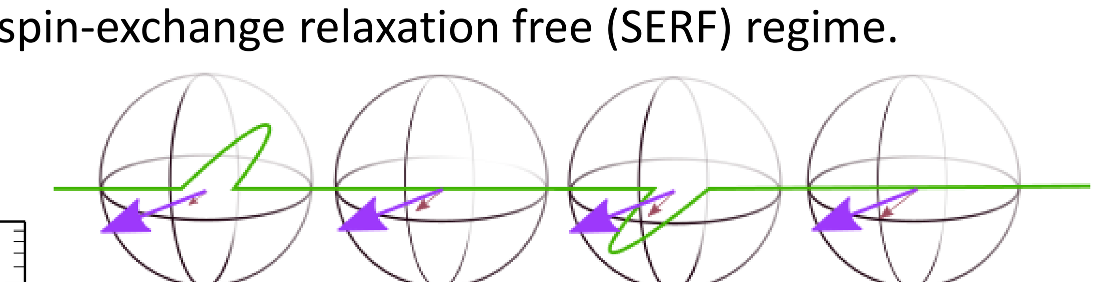
Gyroscopic detection of a rotation rate Ω along B_z shows up in the frequency ratio as $(\omega_{He} \pm \Omega)/(\omega_{Xe} \pm \Omega)$, so any instability in the ratio of precession frequencies degrades the NMR gyro performance. Our method of decoupling the noble gas spins from their interaction with ^{87}Rb at very low field requires three-axis averaging of any ^{87}Rb that is backpolarized from ^{129}Xe, along with "in-the-dark" ^{3}He-^{129}Xe evolution.

Our magnetometer operation uses a ^{87}Rb π pulse train in conjunction with σ_+/σ_- pump light, which retains sufficient ^{87}Rb polarization for Faraday detection while mitigating the effect of polarized ^{87}Rb on the precessing ^{3}He and ^{129}Xe. If the repetition rate of the ^{87}Rb π pulses exceeds the Larmor precession frequency of ^{87}Rb, this scheme refocuses the Rb-Rb spin exchange that causes Rb polarization loss. Hence, the Rb is decoupled from a (relatively) larger bias field than previous experiments done in a spin-exchange relaxation free (SERF) regime.

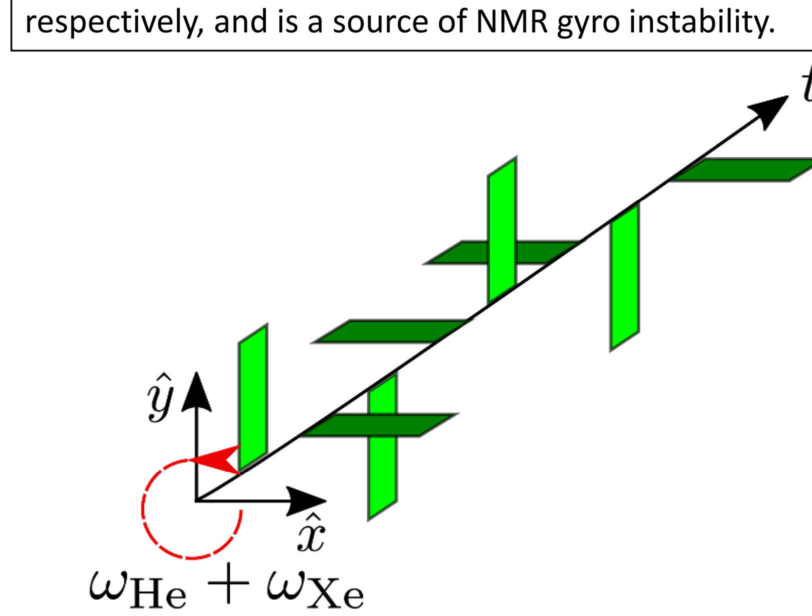
Decoupling



Decoupling of the Rb-Xe Fermi-contact interaction along a single axis by a factor approaching 10^4 using Rb π pulses, a factor of 10^2 better than standard sine-wave depolarization schemes [1] (inset).



The y-only π pulses only average the ^{87}Rb polarization along the z and x axes. When polarized ^{129}Xe (shown in purple), has a projection along the y axis, it "backpolarizes" the ^{87}Rb (shown in red). This leads to an additional field due to the ^{87}Rb affecting ^{3}He and ^{129}Xe, scaled by the κ_0 enhancement of 6 and 490, respectively, and is a source of NMR gyro instability.



Our "in-the-dark" decoupling pulse scheme averages the ^{87}Rb polarization along three axes, introduces no net helicity of the field pulses, and can be rotated to null the effect of the sequence on the ratio of the precession frequencies.

References:
[1] New Classes of Systematic Effects in Gas Spin Comagnetometers, D. Sheng, A. Kabcenell, M. V. Romalis, Phys. Rev. Lett. **113**, 163002 (2014).
[2] Nuclear spin gyroscope based on an atomic comagnetometer, T. W. Kornack, R.K. Ghosh, M. V. Romalis, Phys. Rev. Lett. **95**, 230801 (2005).
[3] NMR Detection with an Atomic Magnetometer. I. M. Savukov and M. V. Romalis, Phys. Rev. Lett. **94**, 123001 (2005).