Toward a Free Precession Hg-Cs Co-magnetometer for Measurements of Long-Range Spin-Spin Interactions

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Introduction

We are preparing a Hg-Cs co-magnetometer to search for anomalous long-range spin-spin interactions (LRSSIs). These interactions could be indicative of a fifth fundamental force mediated by undiscovered low mass or massless bosons, or the existence of torsion gravity. The co-magnetometer consist of two ^{133}Cs magnetometers used to monitor the ambient magnetic field and a single ^{199}Hg magnetometer which is sensitive to LRSSI.

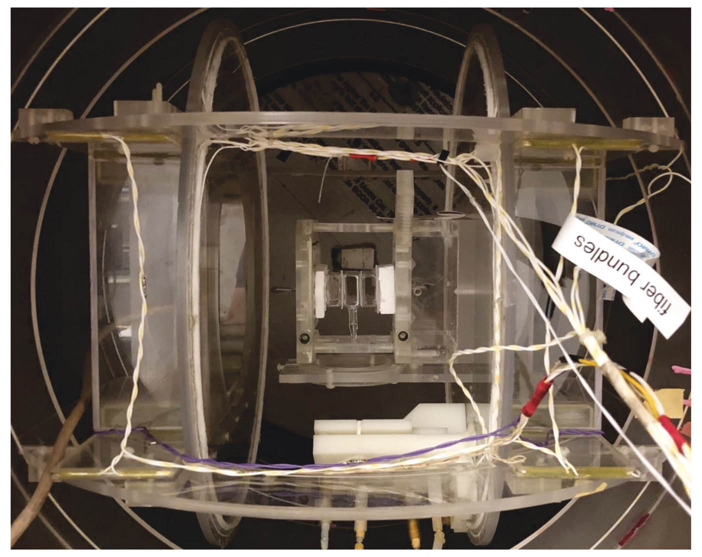

Figure 1. *Three mounted atomic vapor cells and supporting rings housing Helmholtz coils.*

Background

Our previous experiment established bounds on all twelve possible terms that can produce interaction via the exchange of a light vector boson [1], including the best bounds in the long range limit on all the velocity dependent LRSSI terms. One example of such a potential is:

$$V_2(r) = -\frac{g_A^X g_A^Y \hbar c}{4\pi\hbar c}\frac{\hbar c}{r}\hat{\boldsymbol{\sigma}}_1 \cdot \hat{\boldsymbol{\sigma}}_2 e^{-\frac{r}{\lambda}}.$$

$\hbar$ = reduced Planck constant
c = speed of light
r = distance between fermions
$\hat{\boldsymbol{\sigma}}_i$ = unit vector in the spin direction
g_A^i = axial vector coupling constants
$\lambda = \hbar/Mc$
M = exchange boson mass

Here the potential decays as $1/r$ with the exponential factor suppressing the interaction at scales longer than the boson's Compton wavelength [2].

This work hopes to improve the sensitivity of our LRSSI experiment by an order of magnitude, ultimately achieving a sensitivity of 70 nHz (90 pG) for a week of integration. To accomplish this we have investigated a new optical magnetometer configuration that is more immune to the AC light shifts that limited the sensitivity of our earlier experiment.

Geoelectrons

In the experiment we record the precession frequencies of the magnetometers at different orientations of an applied magnetic field with respect to the Earth's surface. By reversing the direction of the applied magnetic field, B_{app}, we are able to isolate the spin-spin interaction between geoelectrons in the mantle of the earth and ^{199}Hg. The geoelectron source allows for searches for spin-spin interactions with ranges larger than a kilometer.

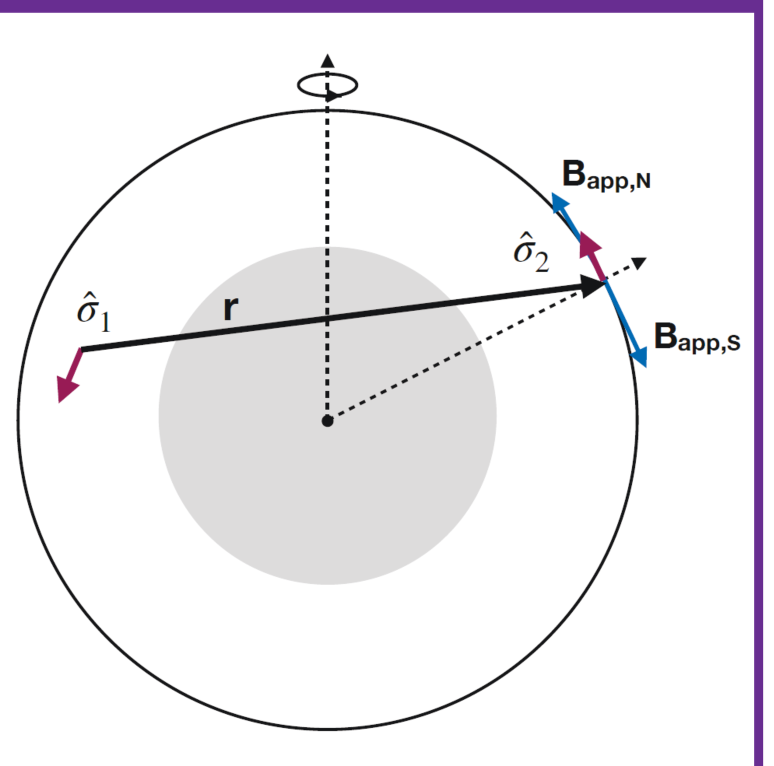

Figure 2. *Schematic depiction of the experiment.*

Magnetometer Configuration

The previous experiment used an M_x configuration in which the pump and probe beams were the same. This required a significant component of circularly polarized light along the magnetic field direction, giving rise to first-order AC light shifts. Our new pump-then-probe geometry is only second-order sensitive. This work investigated the new scheme's systematics.

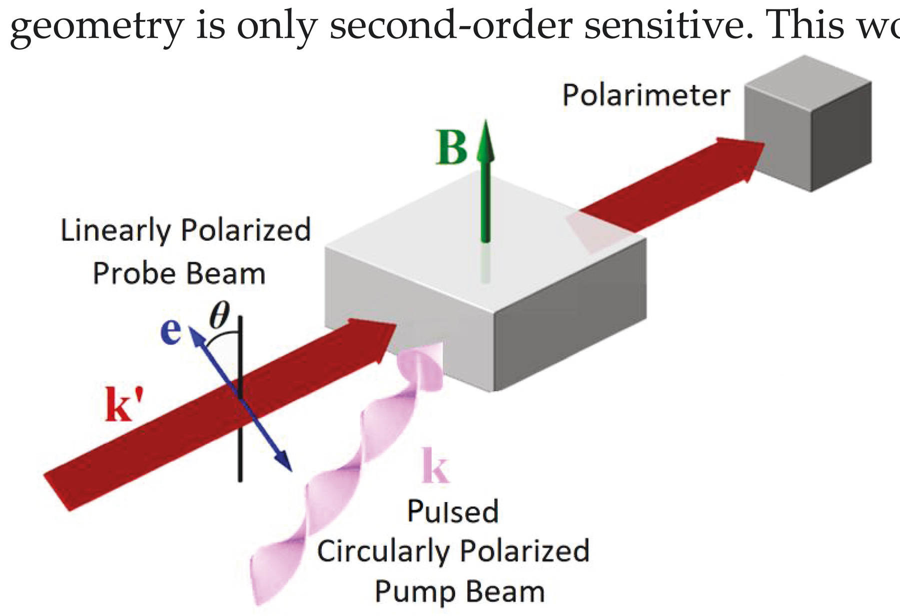

Figure 3. *Pump-then-probe geometry in which the pump and probe are orthogonal to the B-field, the pump is off during probing, and the probe is off resonance.*

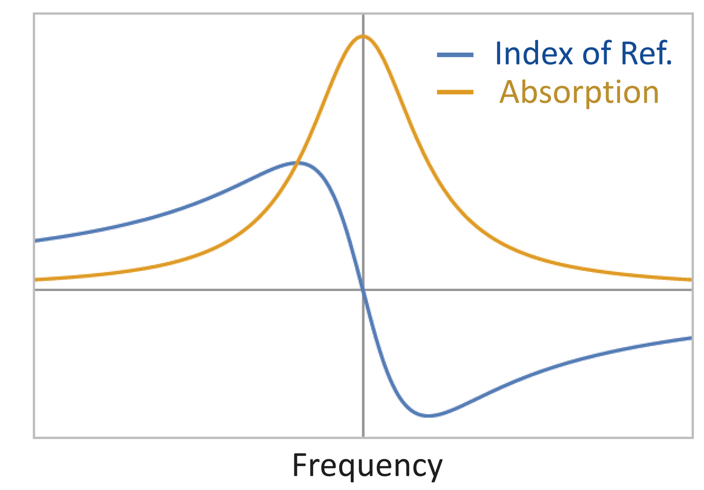

Figure 4. *Optical probing takes advantage of the slow fall-off of the index of refraction as the laser is tuned off resonance.*

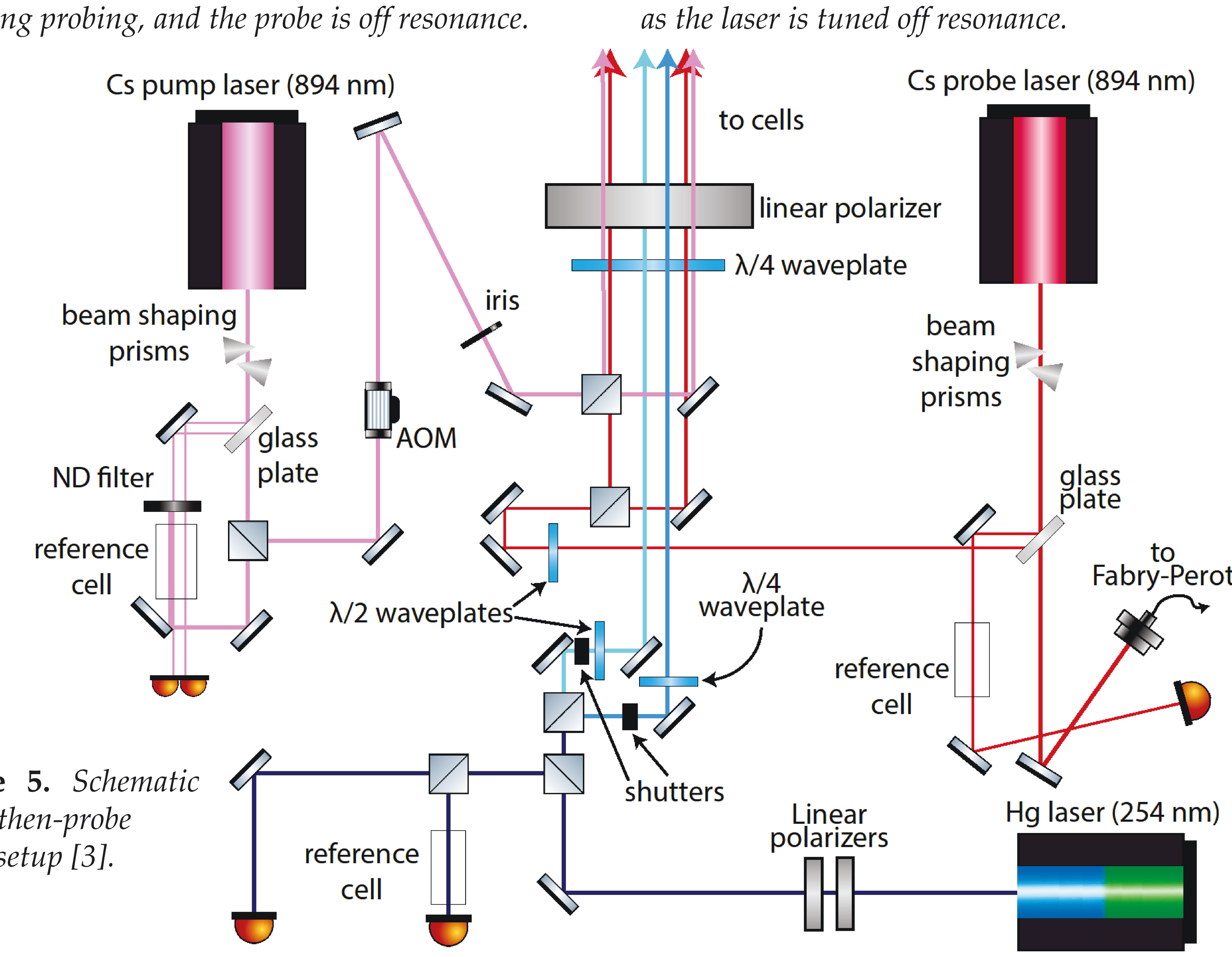

Figure 5. *Schematic pump-then-probe optics setup [3].*

Optical Pumping and Probing

Three magnetically shielded atomic vapor cells are exposed to an applied magnetic field, B. Each cell is first illuminated by a circularly polarized optical pump beam pulsed at the Larmor frequency to induce spin polarization. After blocking the pump beam, the free precession of the spins induces optical rotation of the linear polarization of a weak, off resonance, probe beam. Polarimeters monitor this rotation, which appears as a decaying sine wave. We fit this function to determine the precession frequency in each of the three cells.

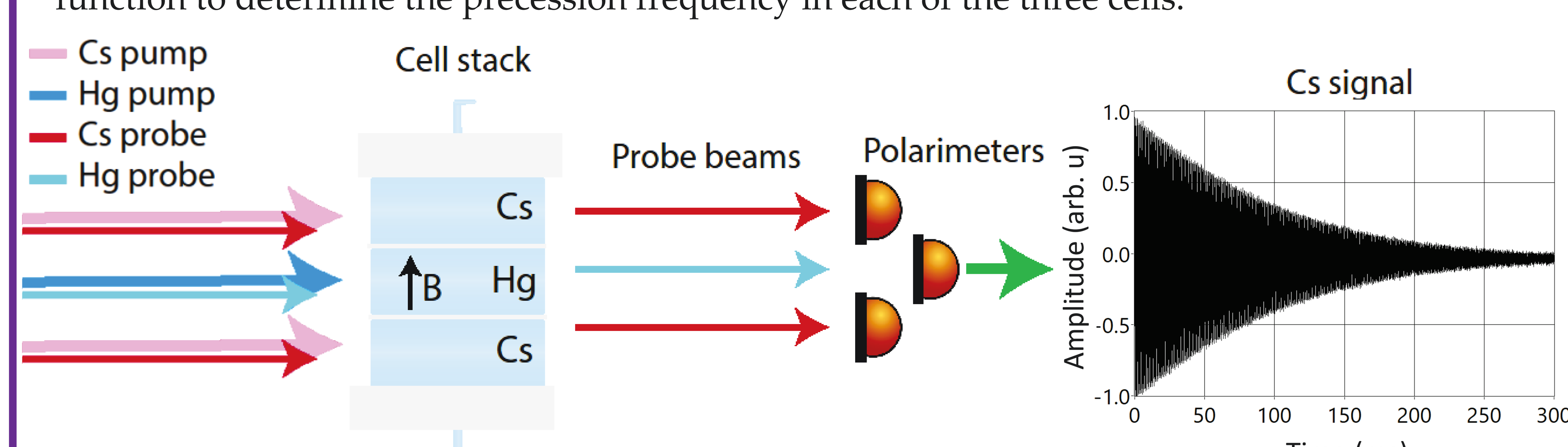

Figure 6. *Optical pumping and optical probing schematic.*

If spin-spin interactions between geoelectrons and ^{199}Hg atoms do exist, they will modify the spin precession frequency of our Hg atoms. We use the two Cs atomic vapor cells to monitor the ambient field, allowing us to isolate our signal from magnetic field drifts.

Parameter Optimization

The parameter's of Table 1 have been determined to reasonably maximize our sensitivity while minimizing the UV exposure of our cell. As an example, if Hg probing occurs too near resonance then significant absorption occurs and the probe signal will be attenuated, and the spin-precession time decreases. Too far off resonance, the signal amplitude diminishes because the incident light is unable to interact efficiently with the atoms.

Hg parameter	Variation
Probe power	2 μW
Pump power	20 μW
Probe frequency	8120 MHz above transition line center
Pump frequency	on transition line center
(Probe duration)	30 s (or lifetime dependent)
Pump duration	30 s

Table 1. *Hg magnetometer parameters resulting in projected sensitivity below 70 nHz (90 pG).*

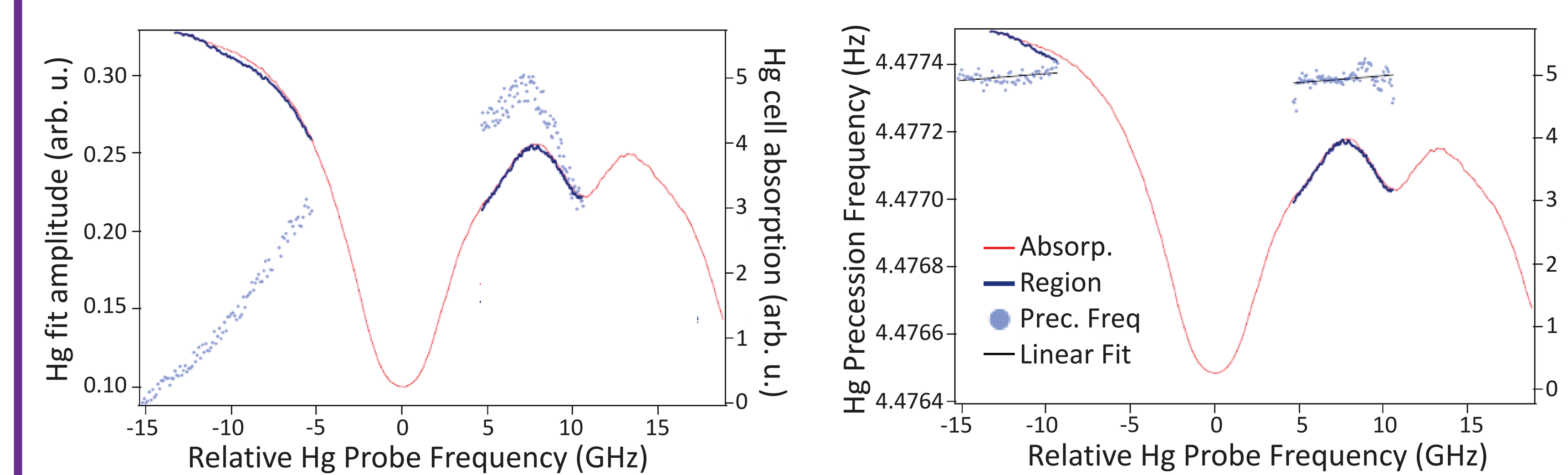

Figure 7. *Precession frequency and amplitude for varrious Hg probe frequencies.*

Systematic Optimization

The intensity and frequency of each laser is systematically varied and the resulting precession frequency is recorded. The resulting slope, s, relates changes in the parameter to changes in the precession frequency. The variation, v, in a given parameter over the course of the data collection cycle is then determined. The statistical limit can found by multiplying those quantities $(|s|+1\sigma)\times v$.

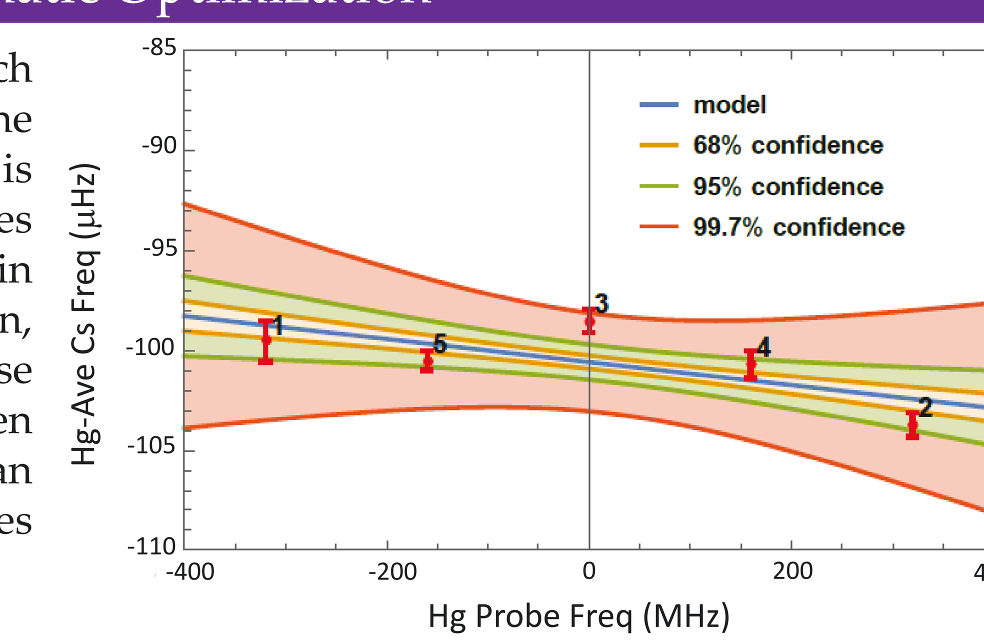

Figure 8. *Precession frequency, after subtracting common-mode noise using the Cs cells, as the Hg probe frequency is varied.*

Hg parameter	Variation	Slope+1σ	Stat. limit (nHz)
Probe power	0.005 μW	(0.3+0.9) μHz/μW	6
Pump power	0.04 μW	(0.08+0.12) μHz/μW	8
Probe frequency	0.3 MHz	(0.006+0.001) μHz/MHz	2
Pump frequency	0.3 MHz	(0.004+0.001) μHz/MHz	2
Cs Parameters			
Probe power	0.06 μW	(0.10+0.09) μHz/μW	10
Pump power	0.25 μW	(0.05+0.04) mHz/μW	50
Probe frequency	1 MHz	(0.0011+0.0012) mHz/MHz	5
Pump frequency	0.005 MHz	(0.139+0.003) mHz/MHz	2

Table 2. *Characterization of the co-magnetometer by examining the contribution of various parameters to our statistical error.*

Conclusion

Using the optimized parameters of Table 1 we were able reach our desired projected sensitivity goal. Table 2 also allows determination of the necessary control required on each parameter in order to maintain this sensitivity as we transfer our co-magnetometer from our test apparatus to the rotating apparatus. That effort is now underway.

Reference and Acknowledgements

[1] L. Hunter, J. Gordon, S. Peck, D. Ang, J.-F. Lin, Science **339** 928 (2013)
[2] P. Fadeev, Y. V. Stadnik, F. Ficek, M. G. Kozlov, V. V. Flambaum, and D. Budker, Phys. Rev. A **99**, 022113 (2019).
[3] Constructed with ComponentLibrary by Alexander Franzen
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