Using the Resonant Faraday Effect to Probe External Magnetic Fields

Jiachen He, Wolfgang Korsch, Swejyoti Mitra

University of Kentucky

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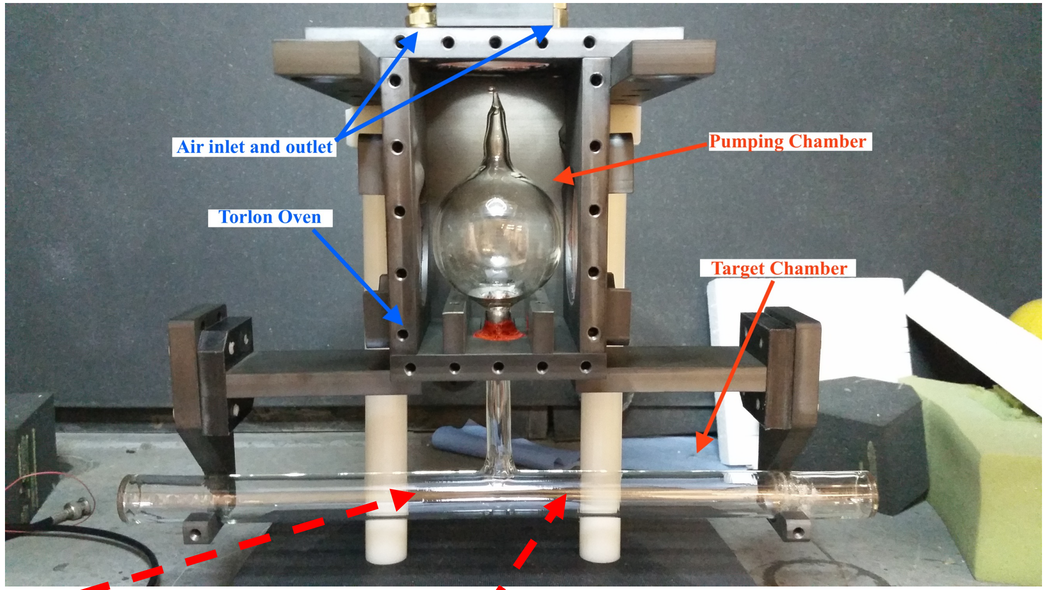
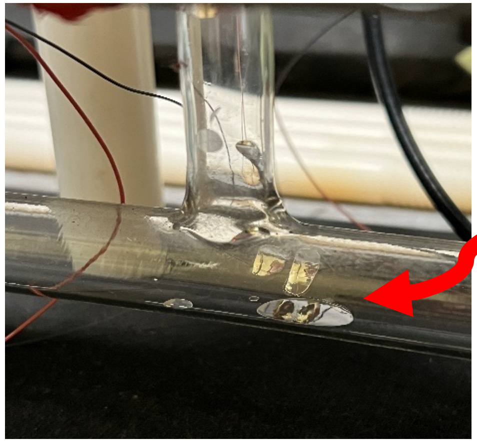
Motivation

- Helium-3 spin-exchange optical pumping cell is commonly used for electron scattering experiment at Jefferson Lab to study fundamental structures of neutrons.
- Measuring small change of magnetic field (~ 10 mG) due to polarized helium-3 atoms on top of a holding $\overrightarrow{B_0}$-field.
- Alkali metal residue diffusion in the target chamber due to temperature gradient over time.
- Exploring the application of the resonant Faraday effect on alkali metal D lines for real-time, continuous monitoring of the spin polarization state of helium-3 atoms.





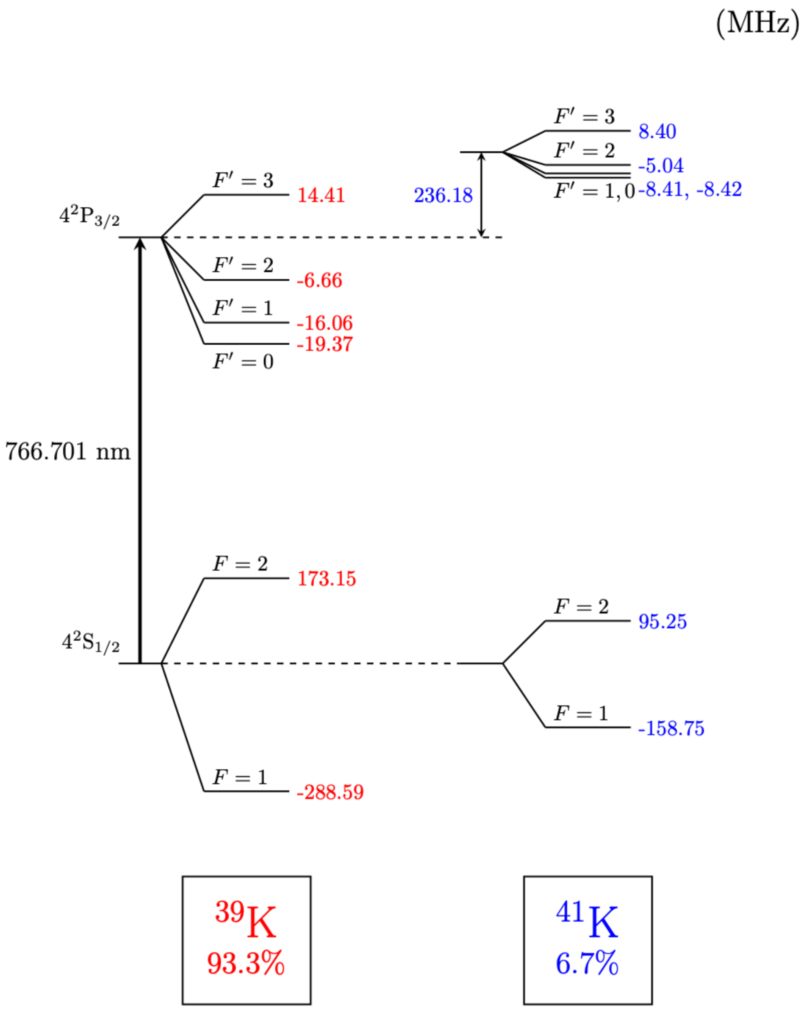
Observed alkali metal deposited from the pumping chamber to the target chamber over time.

The Resonant Faraday Effect

- The alkali atoms acquire circular anisotropy in the presence of longitudinal magnetic field.
- The resonant Faraday rotation at large detuning

$$\theta = \frac{r_e c}{6} l[\mathrm{K}] \left[\frac{\mu_B}{3h} \left(7 \frac{\Delta_{3/2}^2 - \gamma_{3/2}^2/4}{(\Delta_{3/2}^2 + \gamma_{3/2}^2/4)^2} + 4 \frac{\Delta_{1/2}^2 - \gamma_{1/2}^2/4}{(\Delta_{1/2}^2 + \gamma_{1/2}^2/4)^2} \right) B + \left(\frac{\Delta_{3/2}}{(\Delta_{3/2} - \delta_{3/2})^2 + \gamma_{3/2}^2/4} - \frac{\Delta_{1/2}}{(\Delta_{1/2} - \delta_{1/2})^2 + \gamma_{1/2}^2/4} \right) P \right]$$

  - l is the path length of the probe light.
  - $[\mathrm{K}]$ is the number density of the atomic medium.
  - Δ is the frequency detuning of the probe light from resonance.
  - δ is the resonance linewidth.
  - γ represents spontaneous decay and the effect of buffer gas collisions.
  - P is the electronic spin polarization.



Kadlecek, Stephen John. *Spin relaxation in alkali vapors*. The University of Wisconsin-Madison, 1999.

Characterize the Performance of An Optical-Magnetometer

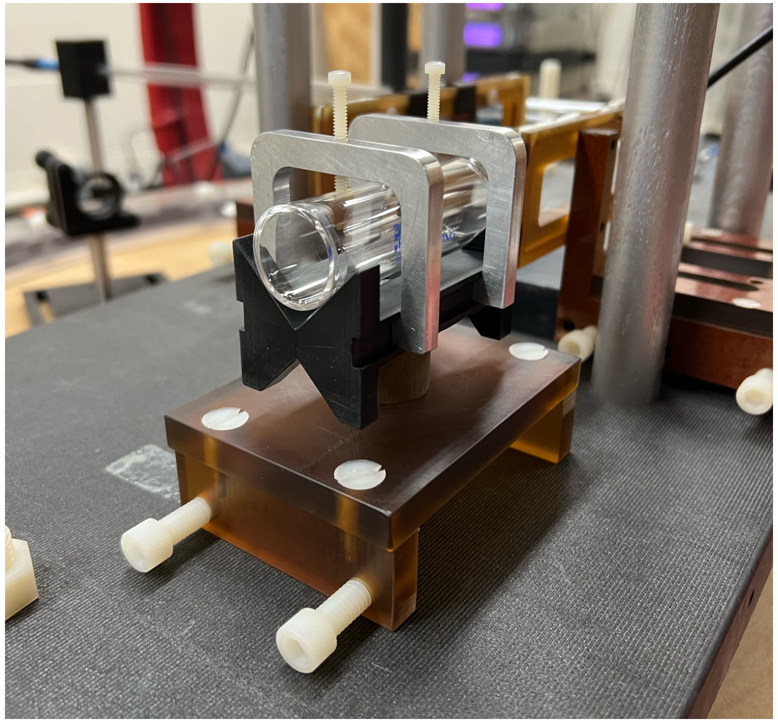
- The sensitivity δB_z to magnetic fields along the direction of light propagation ($\hat{z}$) is

$$\delta B_z = \left(\frac{\partial \theta}{\partial B_z}\right)^{-1} \delta\theta$$

  - $\delta\theta$ is the angular sensitivity of polarization rotation in units of $\mathrm{rad}/\sqrt{\mathrm{Hz}}$.
  - $\partial\theta/\partial B_z$ is the slope of the measured optical rotation with respect to a longitudinal magnetic field B_z.

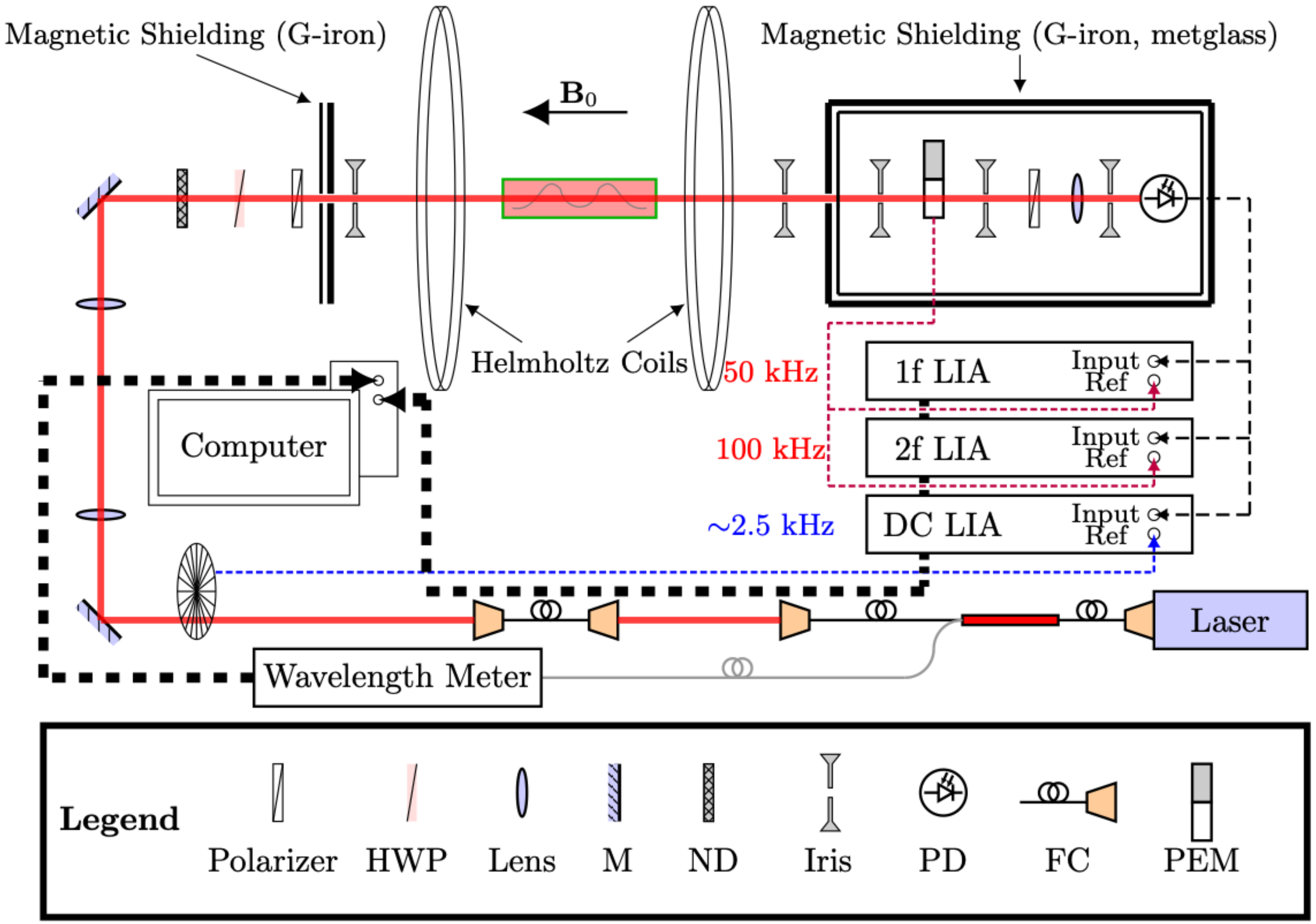
- The sensitivity of the optical magnetometer based on the resonant Faraday effect is

$$\delta B_z \propto \left(\frac{[\mathrm{K}]}{\Delta^2}\right)^{-1}$$



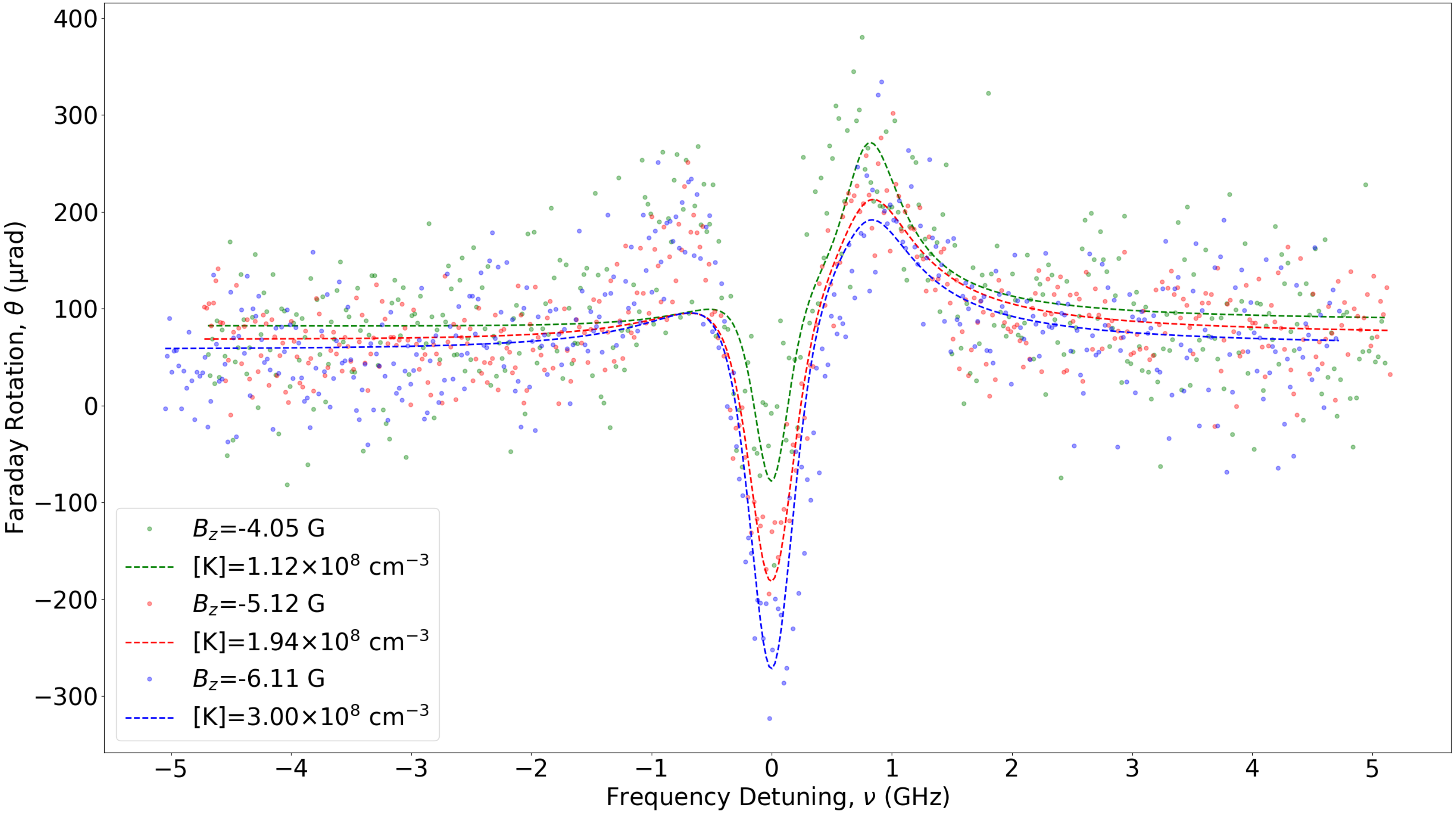
Budker, D., D. F. Kimball, S. M. Rochester, V. V. Yashchuk, and M. Zolotorev. "Sensitive magnetometry based on nonlinear magneto-optical rotation." *Physical Review A* 62, no. 4 (2000): 043403.

Experimental Setup of Faraday Rotation Measurements Using Polarization Modulation Ellipsometer



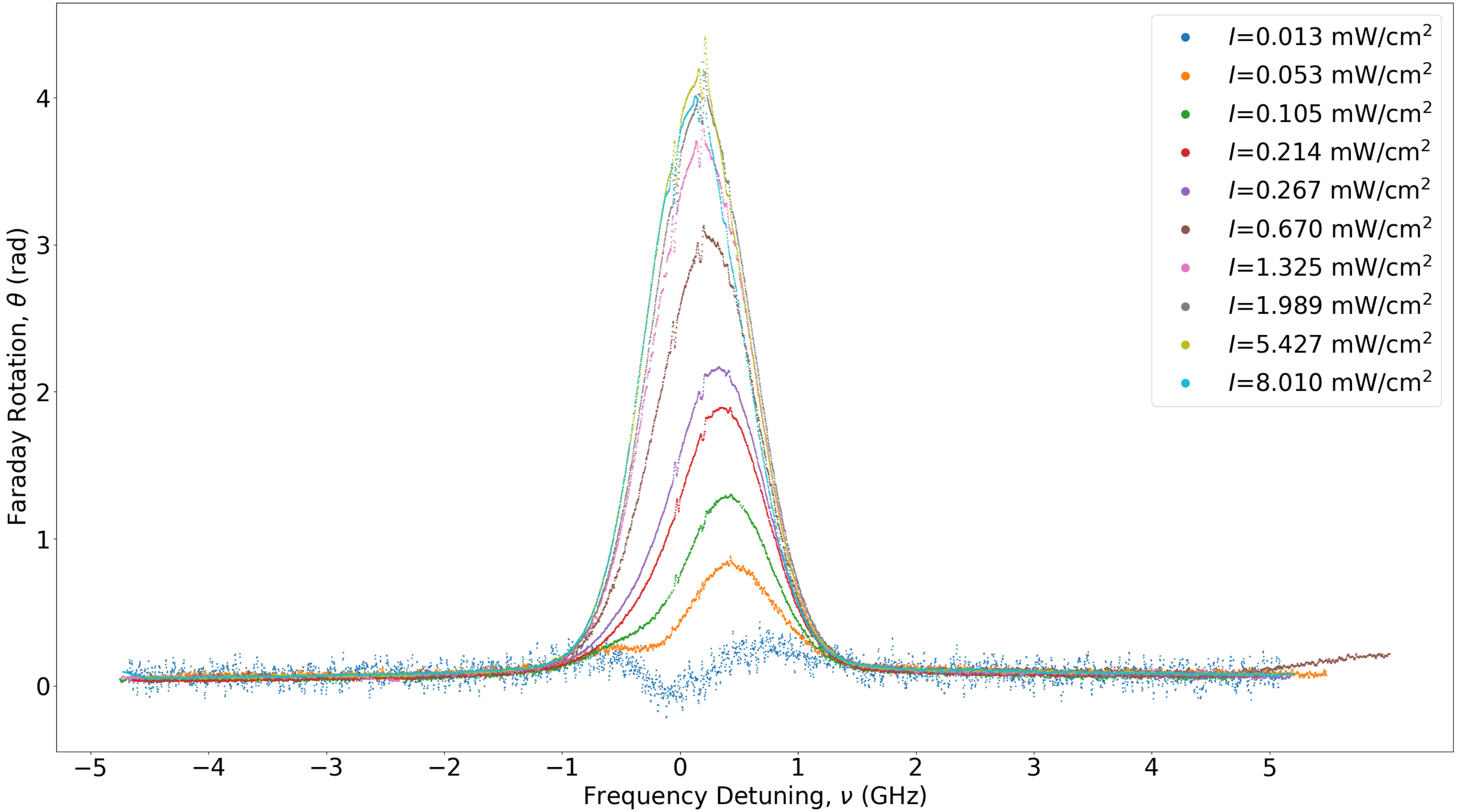
- An external cavity diode laser (ECDL) is scanned over a range of ~10 GHz for Faraday rotation measurements, centered on the potassium D2 ($4^2S_{1/2} \rightarrow 4^2P_{3/2}$) line, at a scanning speed of ~24 MHz/s.
- Incorporated a photoelastic modulator (PEM) for polarization modulation, with two lock-in amplifiers (LIAs) used to measure voltages V_{1f} and V_{2f} referenced to the PEM modulation frequency f. The laser intensity is modulated by an optical chopper, with another LIA measuring the PEM-modulated signal V_{dc}. An avalanche photodiode detector is used to measure the optical signal to a voltage signal at low light intensity levels (< 0.4 mW/cm^2), beam diameter ≈ 2.2 mm.
- Data acquisition is managed by a synchronous system (SDAQ) controlled by a computer, ensuring precise time synchronization across multiple instruments via TTL-level pulses.
- Measurements, each lasting 400 s, are conducted sequentially with and without the cell, isolating Faraday rotation induced by the potassium vapor.

Determine the Atomic Density at Room Temperature



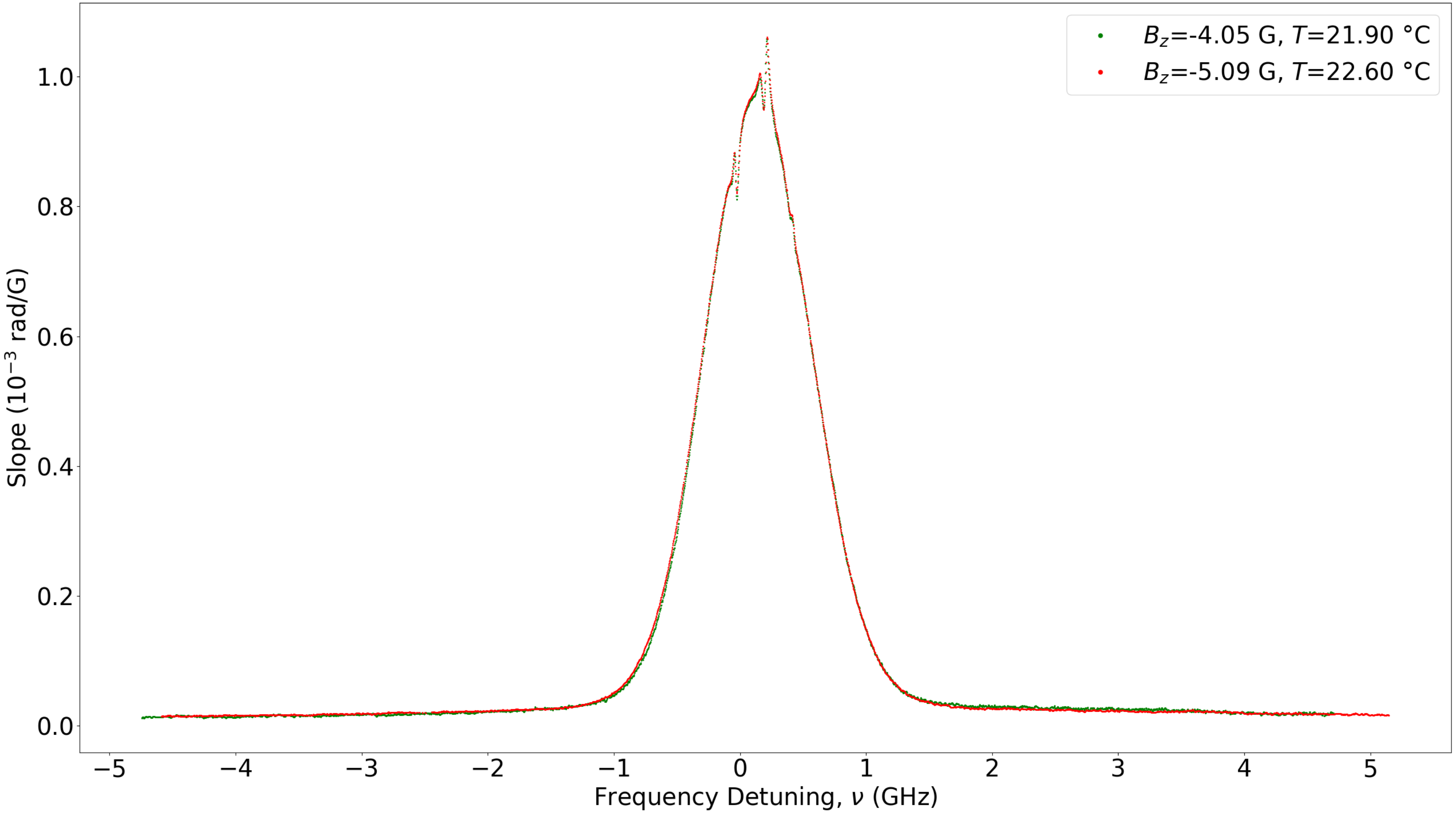
The atomic density are determined by fits (dashed lines) to the measured Faraday rotations (circles) at low light intensity $I = 1.3{\times}10^{-2}\ \mathrm{mW/cm^2}$.

Measured Faraday Rotation Spectrums at Various Laser Intensities



The power dependence of the resonant Faraday rotations at a constant magnetic field $B_z = 4$ G and temperature $T = 22 \pm 0.2$ °C.

Slope $\partial\theta/\partial B_z$ As a Function of Laser Detuning of the K D2 Line



Slope $\partial\theta/\partial B_z$ as a function of laser frequency detuning of the K D2 line, light intensity is $8\ \mathrm{mW/cm^2}$.

Challenges From the Helium-3 Spin-Exchange Optical Pumping Cell

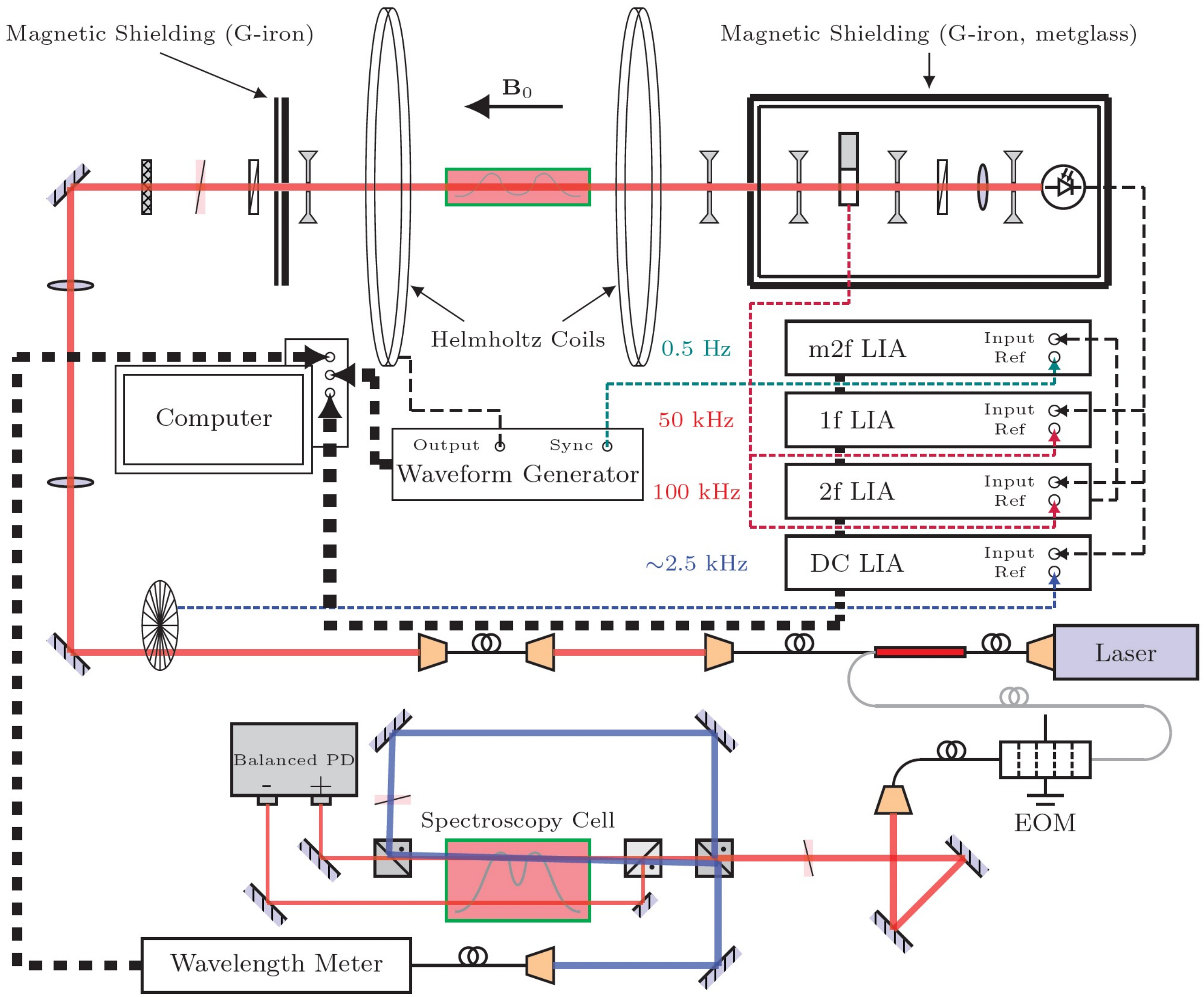
- Alkali metal atomic transitions experience significant pressure broadening and frequency shift due to high helium-3 fill density.
- The resonance linewidths (γ) and frequency shifts (δ) are modeled as a function of density ρ and temperature T.
- We estimate the linewidth and frequency shift of the potassium D2 line in the target chamber are

$$\gamma_{\mathrm{K\ D2}}(4.4\ \mathrm{amg}, 513\ \mathrm{K}) \approx 99.8\ \mathrm{GHz}$$
$$\delta_{\mathrm{K\ D2}}(4.4\ \mathrm{amg}, 513\ \mathrm{K}) \approx 1.4\ \mathrm{GHz}$$

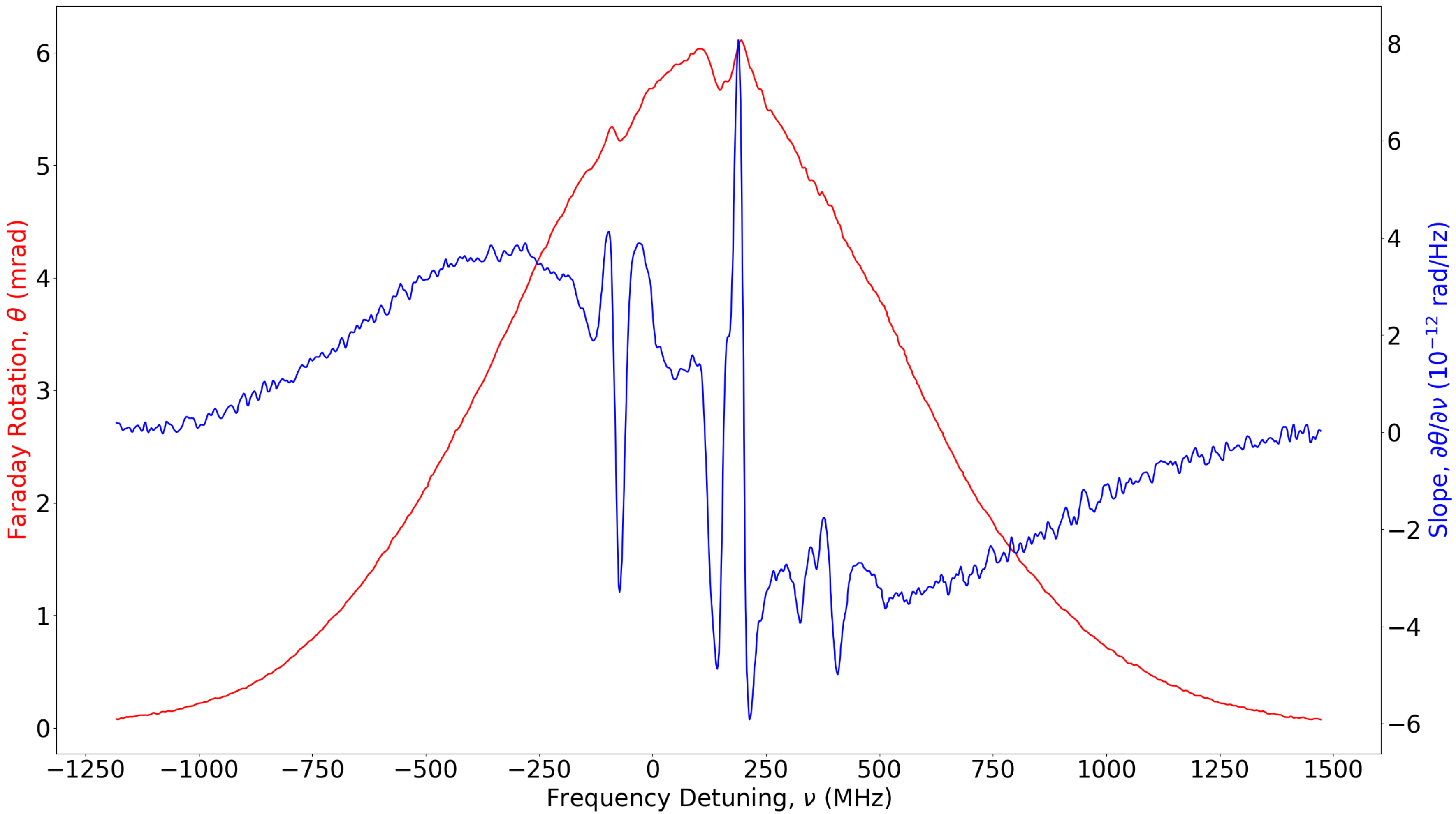
K. A. Kluttz, T. D. Averett, and B. A. Wolin, "Pressure broadening and frequency shift of the D1 and D2 lines of Rb and K in the presence of ^3He and N_2," Phys. Rev. A **87**, 032516 (2013).

Experimental Setup of a Triple Modulated Polarization Modulation Ellipsometer

- The magnetic field ($\vec{B}_0$) generated by a pair of Helmholtz coils ($r = 1.67$ m) is modulated by a voltage-controlled power supply.
- A cascaded LIA (m2f LIA) referenced to the modulation frequency of the magnetic field is added to measure the change of Faraday rotation ($\Delta\theta$) associated with the longitudinal magnetic field modulation (ΔB_z).
- The laser is frequency shifted through sideband laser locking with an electro-optic phase modulator ($\mathrm{BW} = 6$ GHz) and stabilized via Doppler-free saturated absorption spectroscopy.
- Measurements, each lasting 1 hour with a 200 s sampling interval during the triple modulation experiment, are conducted sequentially for 5 continuous measurements.

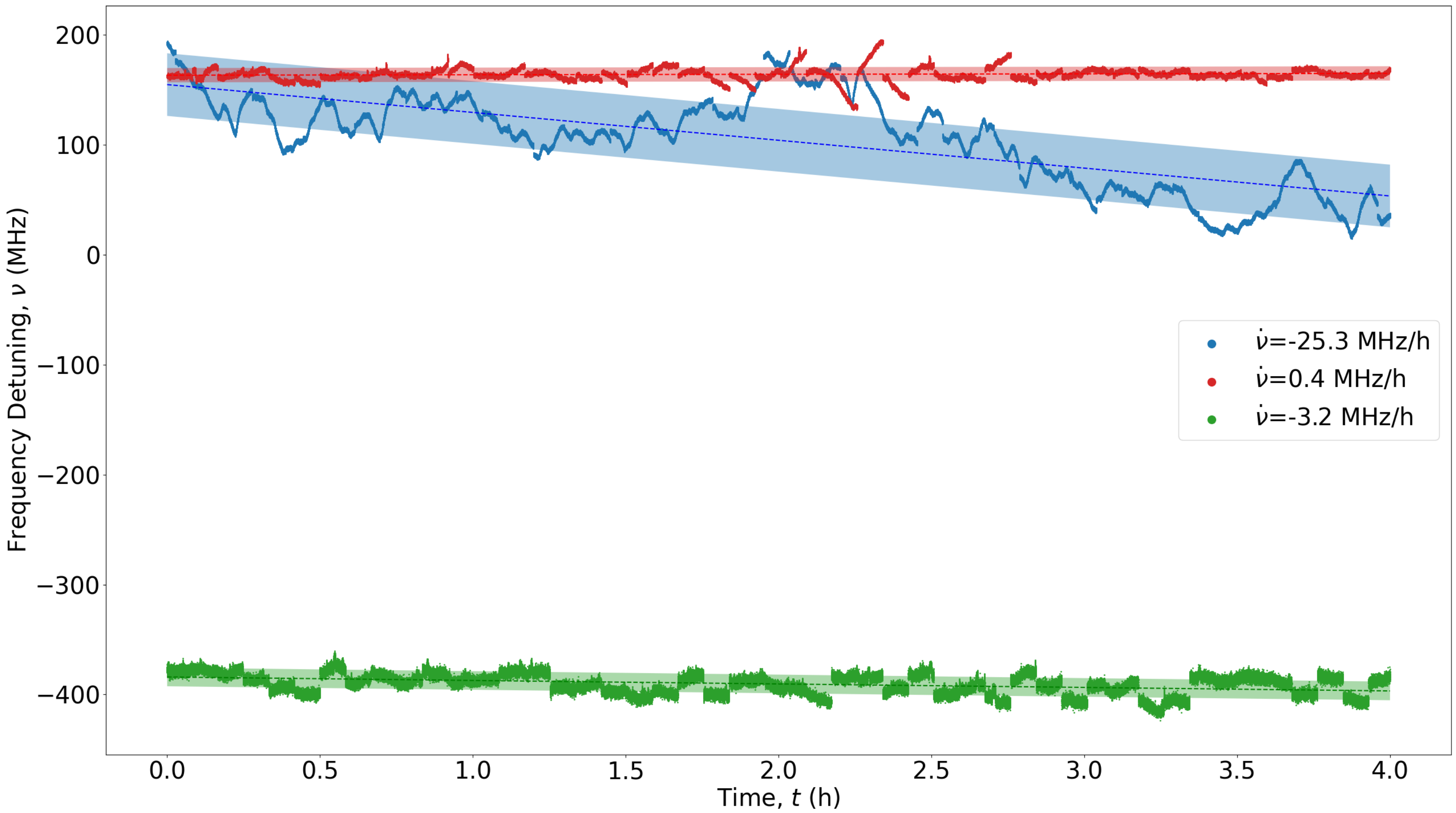


Slope $\partial\theta/\partial\nu$ As a Function of Frequency Detuning



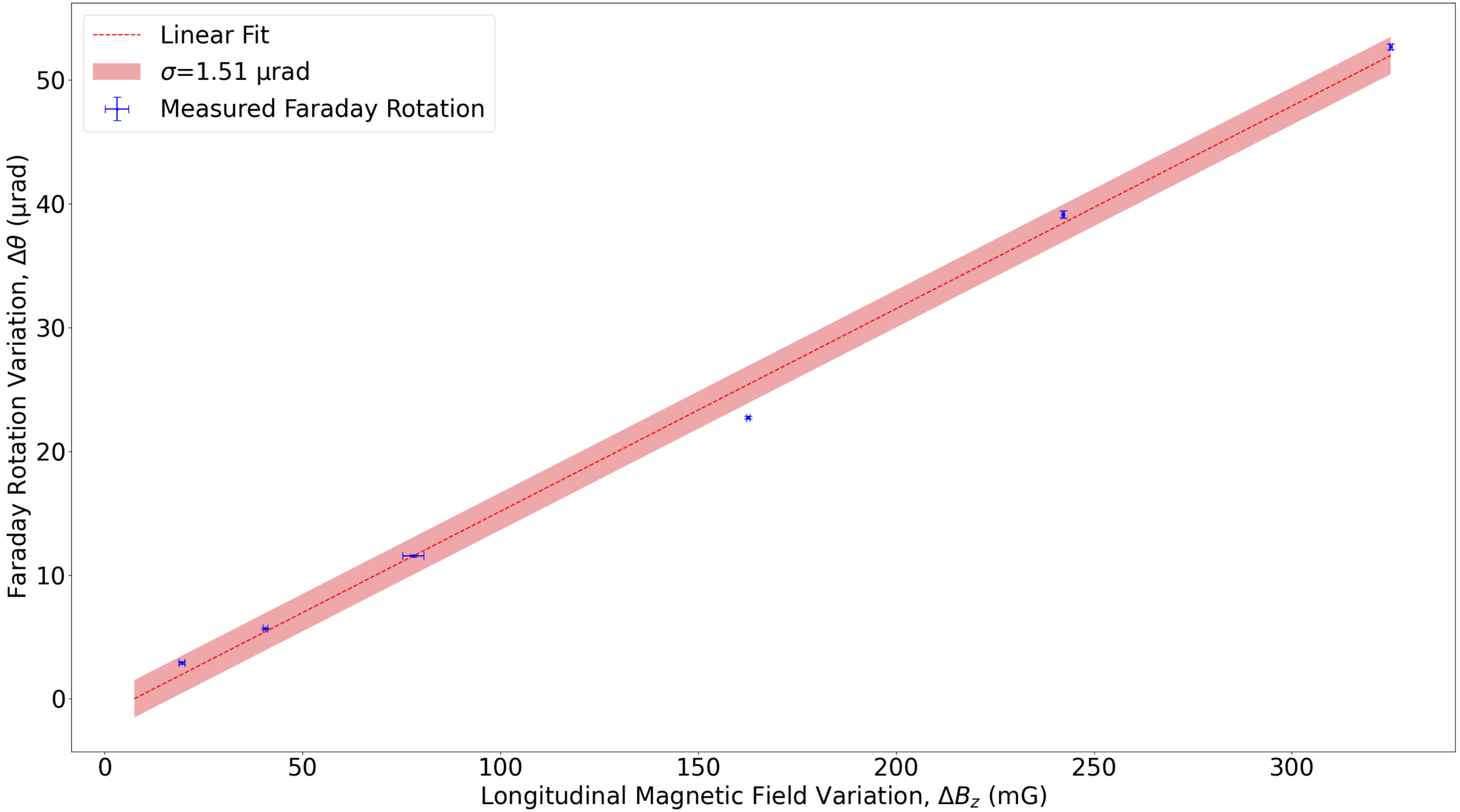
Faraday rotation (θ) and slope ($\partial\theta/\partial\nu$) measured with a 16 MHz amplitude modulation.

Laser Frequency Stability Over Time



Frequency stability of top fringe laser locking without EOM (red) and with EOM (green) using Doppler-free saturated absorption spectroscopy, in comparison with a free running laser (blue).

System Sensitivity with Modulated Longitudinal Magnetic Field



Data (circles) are fit to a linear model $y = ax + b$, yielding a slope $a = 1.6{\times}10^{-4}$ rad/G, the laser is frequency stabilized at $\Delta = 569.35 \pm 3.39$ MHz.

Summary and Outlook

- Optically determined the atomic density ($10^8\ \mathrm{cm}^{-3}$) of potassium vapor atoms under room temperature ($\sim 22\ ^\circ\mathrm{C}$), in good agreement with previously published data.
- Established a sensitive triple modulated PME setup for the resonant Faraday rotation measurement, enabling precise optical magnetometry in alkali vapor (potassium D2 line).
- Incorporated an EOM with spectroscopic laser locking technique for precise frequency control.
- Preliminary results have concluded an optical magnetometer setup achieved the sensitivity to probe a $20\ \mathrm{mG}$ magnetic field variation on top of a $4.9\ \mathrm{G}$ longitudinal holding field under room temperature.
- Conducted a systematic study of an optical magnetometer based on the resonant Faraday effect with respect to light intensity, and light frequency.

❖ **Numerical simulation of dynamic substate populations in alkali vapors**, Swejyoti Mitra, 10:12 am – 10:24 am

References

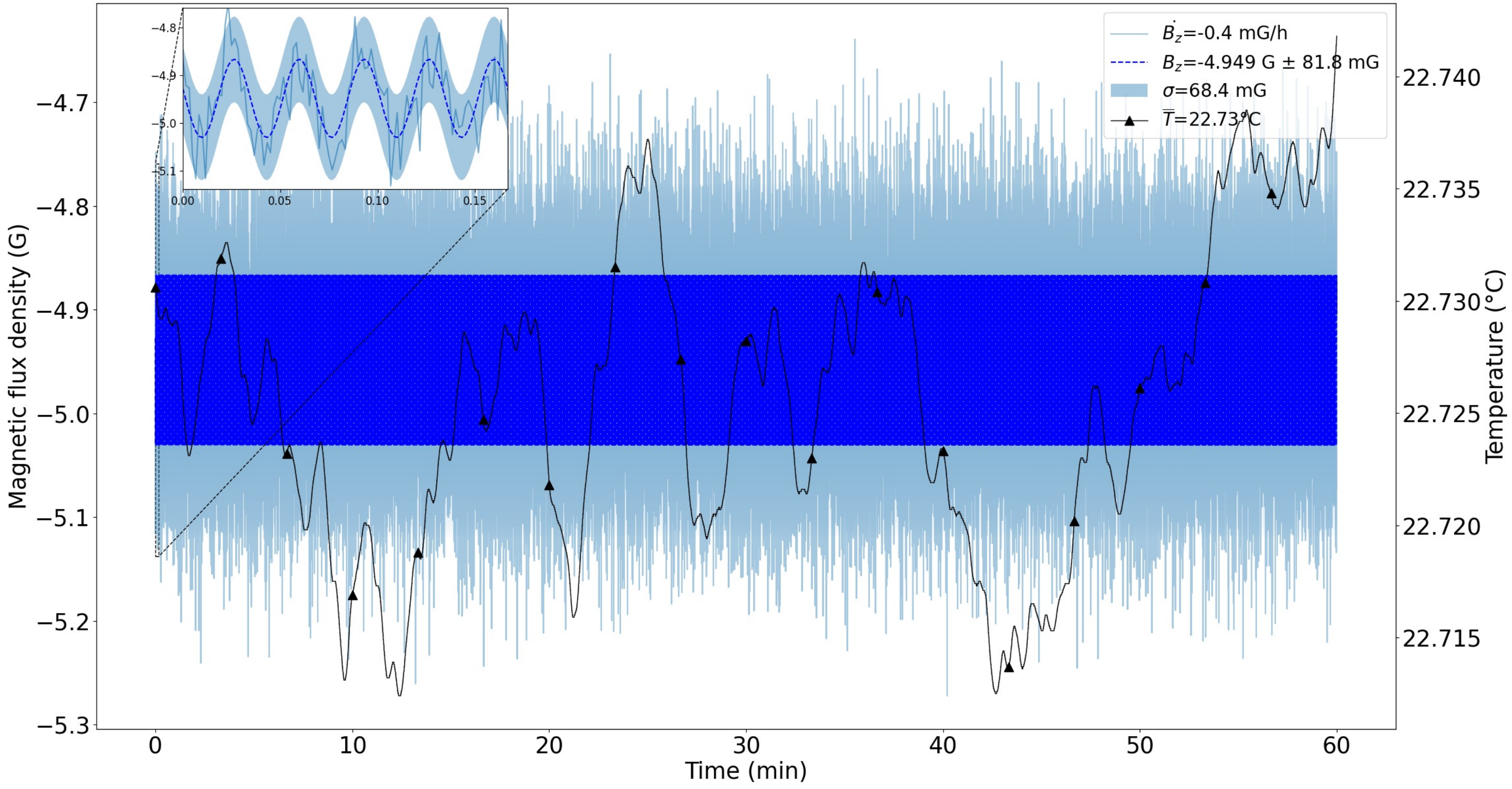
[1] Williamson III, R. S., and T. Walker. "Magneto-optical trapping and ultracold collisions of potassium atoms." *Journal of the Optical Society of America B* 12, no. 8 (1995): 1393-1397.

[2] Guzman, J. S., Adam Wojciechowski, J. E. Stalnaker, K. Tsigutkin, V. V. Yashchuk, and D. Budker. "Nonlinear magneto-optical rotation and Zeeman and hyperfine relaxation of potassium atoms in a paraffin-coated cell." *Physical Review A—Atomic, Molecular, and Optical Physics* 74, no. 5 (2006): 053415.

[3] Sargsyan, Armen, Rodolphe Momier, Claude Leroy, and David Sarkisyan. "Saturated absorption technique used in potassium microcells for magnetic field sensing." *Laser Physics* 32, no. 10 (2022): 105701.

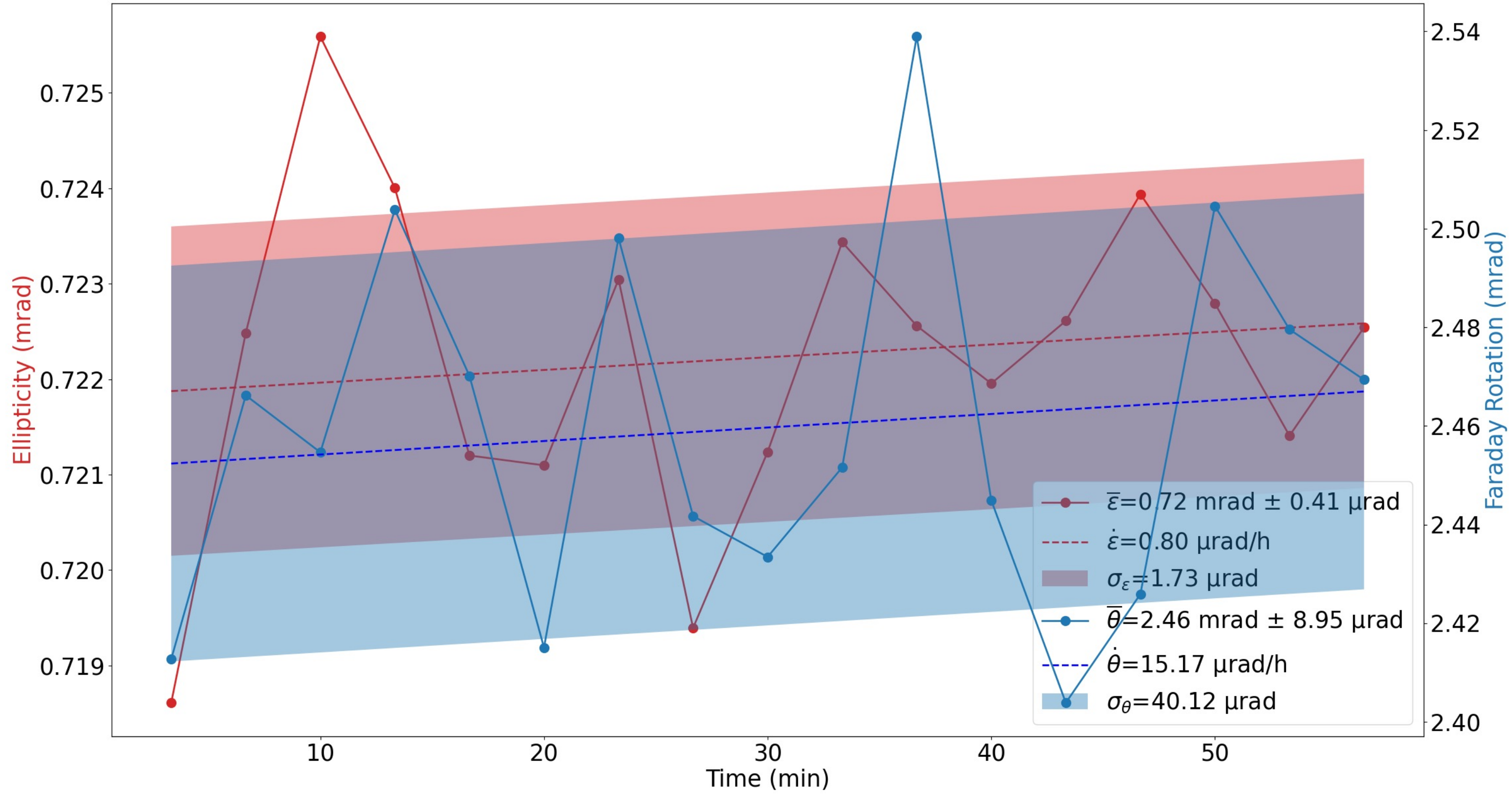
Backup Slides

Measured Modulated Longitudinal Magnetic Field with Fit



Measured through a transverse hall probe, the magnetic field modulation amplitude is determined through a fit with known waveform (sine).

Measured Ellipticity and Faraday rotations



Our experiment enables simultaneous measurements of ellipticity and polarization rotation through the readings from 1f and 2f LIAs.

Allan deviation Analysis