Resonant Faraday rotation measurements in a potassium vapor cell

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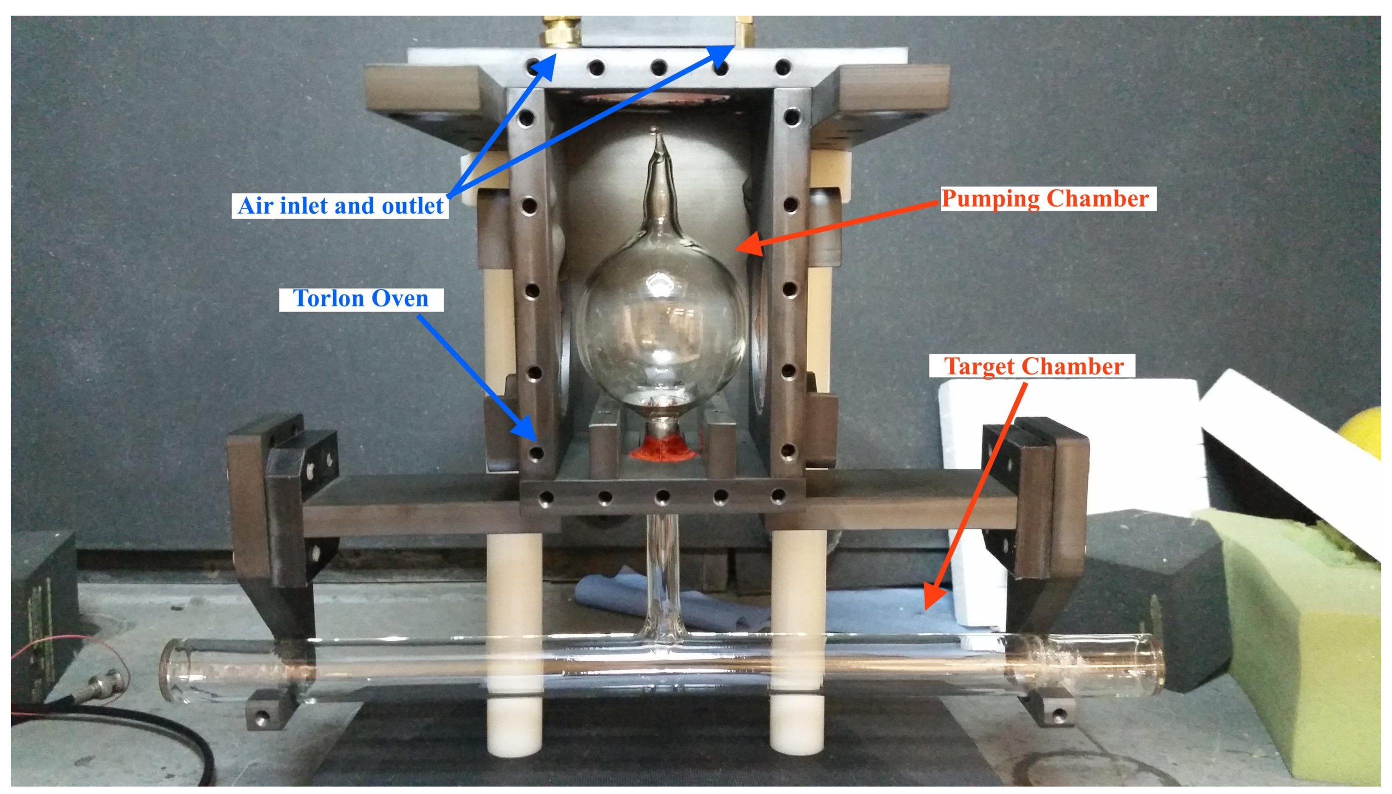
Motivation

At Jefferson Lab, Spin Exchange Optical Pumping (SEOP) cells are commonly used in electron scattering experiments to probe internal structures of neutron. These cells, contain Rb, K, helium-3, and nitrogen gases, require precise determination of helium-3 polarization at the target cell. Traditional methods like EPR and NMR can only measure this polarization when the electron beam is off, requiring a repetitive process of measuring polarization, turning on the beam for scattering, and then remeasuring polarization. To address this limitation, we are exploring the resonant Faraday effect, which utilizes linearly polarized light resonant with Rb or K to continuously monitor helium-3 polarization. My research focuses on evaluating the sensitivity and accuracy of this technique for real-time polarization monitoring.



Resonant Faraday Effect

To validate our system, we used a potassium vapor cell to measure Faraday rotation. The Faraday effect, discovered by Michael Faraday in 1845, involves the rotation of light polarization in the presence of a magnetic field due to differences in refractive indices for different light helicities. This rotation is particularly enhanced near resonances and is directly linked to the electron polarization of potassium atoms. Although typically small in gases, this effect can be amplified by inducing a non-equilibrium population distribution between Zeeman sublevels through optical pumping.

Paramagnetic Faraday rotation:

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

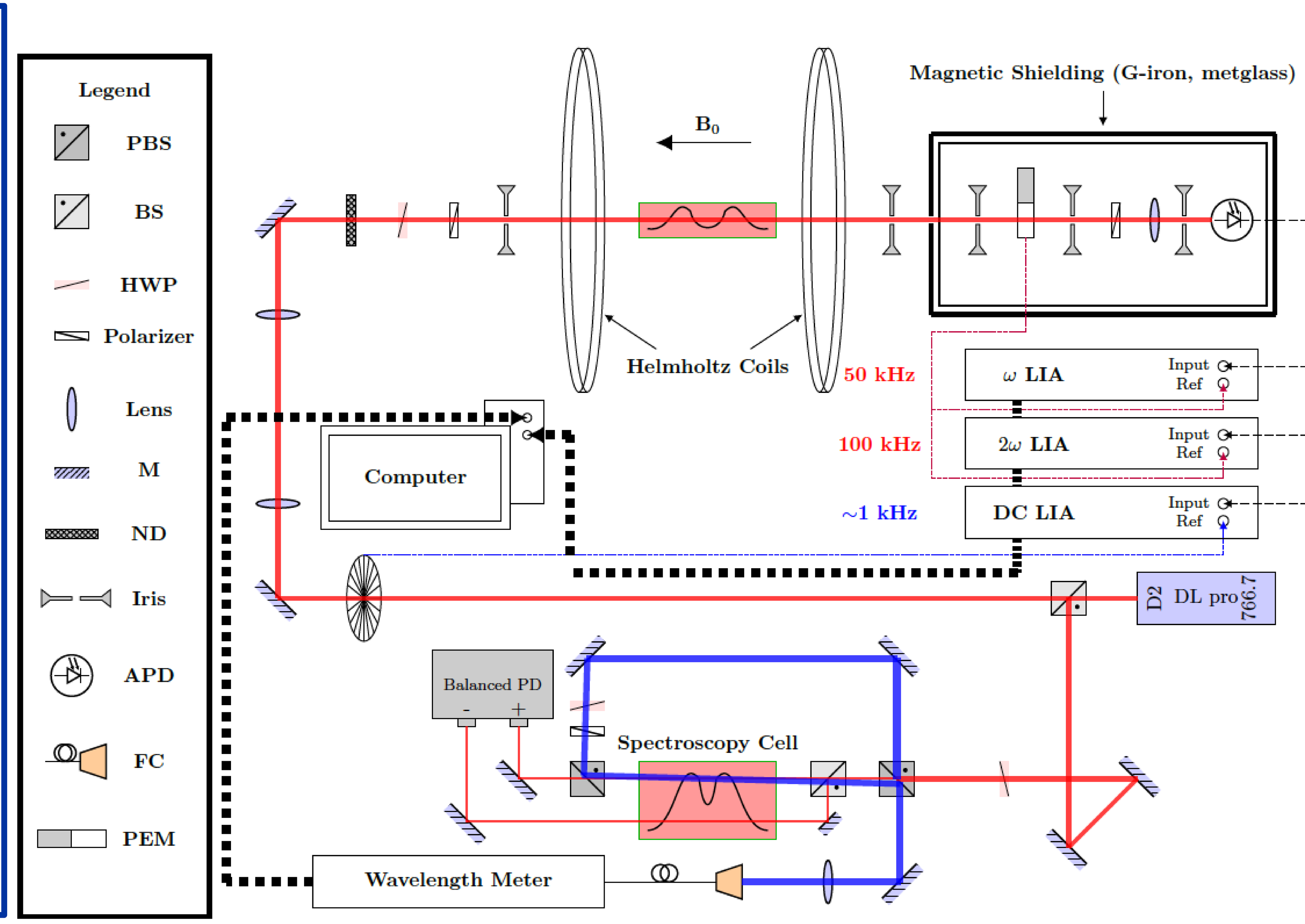
Diamagnetic Faraday rotation:

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

Note: l is the path length of the probe light, [K] is the number density of the medium, Δ is the 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.

Experimental Setup

- 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_ω and $V_{2\omega}$ referenced to the PEM modulation frequency ω. The laser intensity is modulated by an optical chopper, with another LIA measuring the PEM-modulated signal V_{dc}. An avalanche photodiode detector (APD) is used to measure the optical signal to a voltage signal at low power levels (<15 μW).
- 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.
- Absorption: $\epsilon = \frac{V_\omega}{2\pi J_1(A) V_{dc}}$ (3)
- Rotation: $\theta = \frac{V_{2\omega}}{2\pi J_2(A) V_{dc}\sqrt{1-4\epsilon^2}}$ (4)

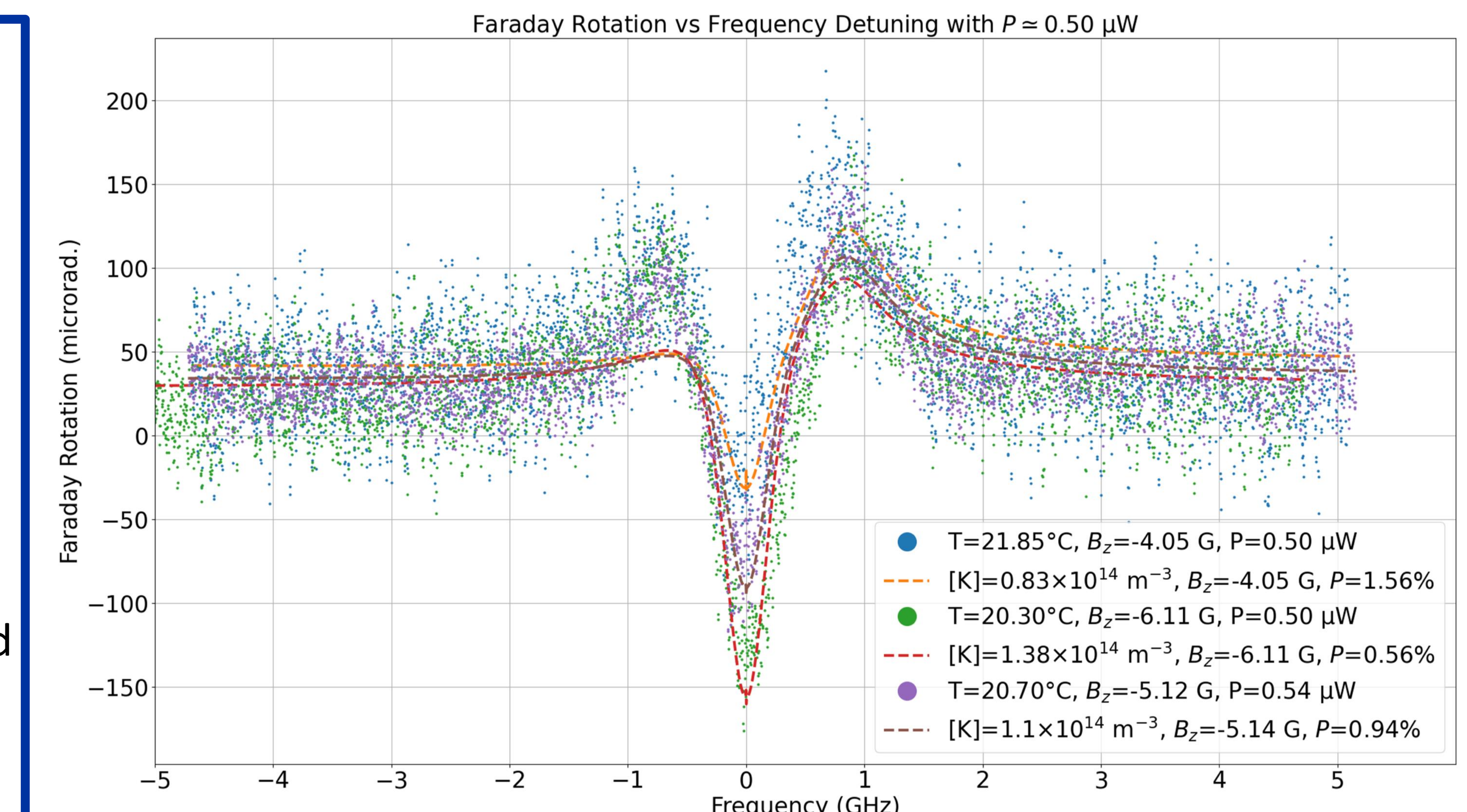


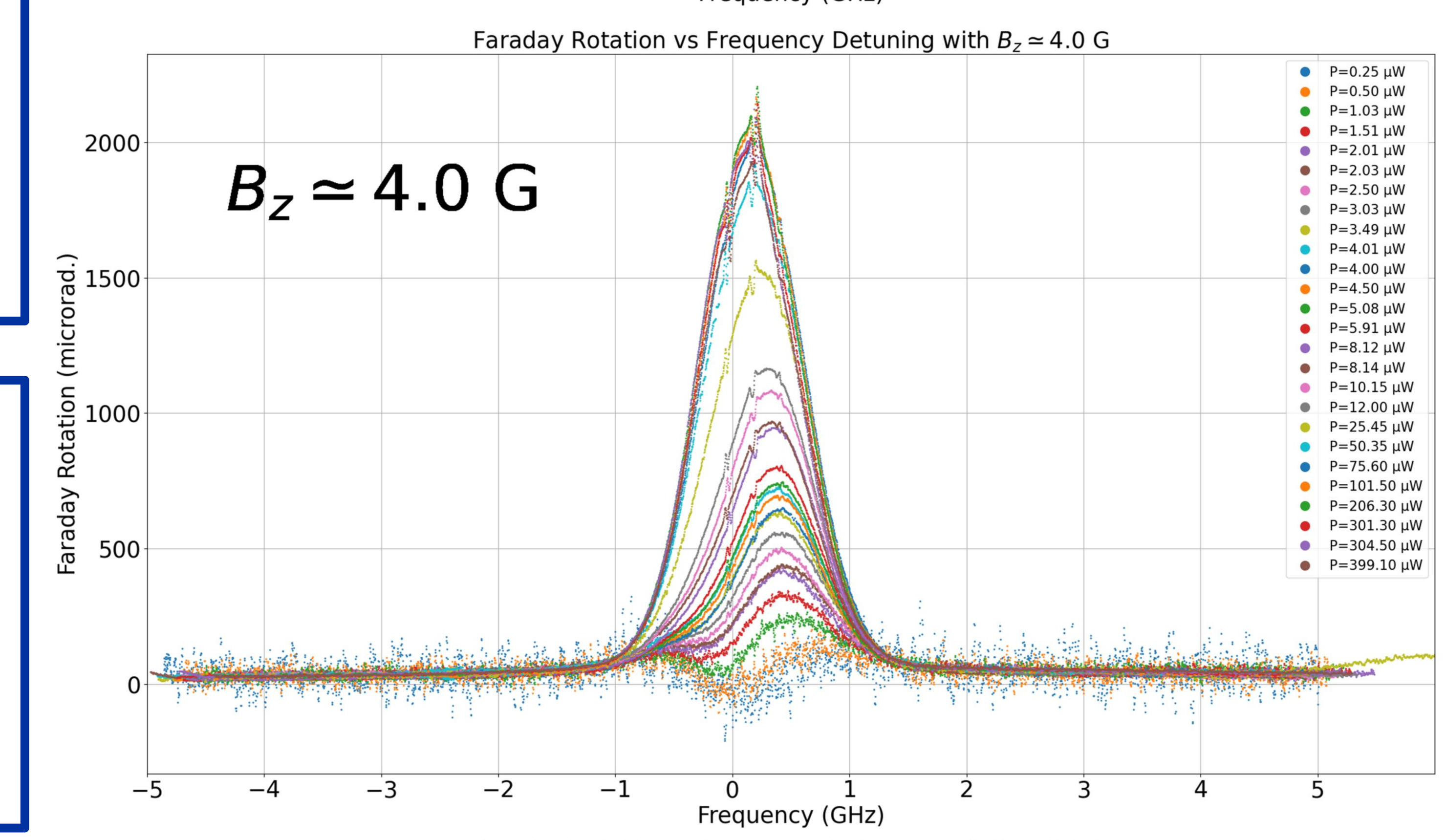
Results

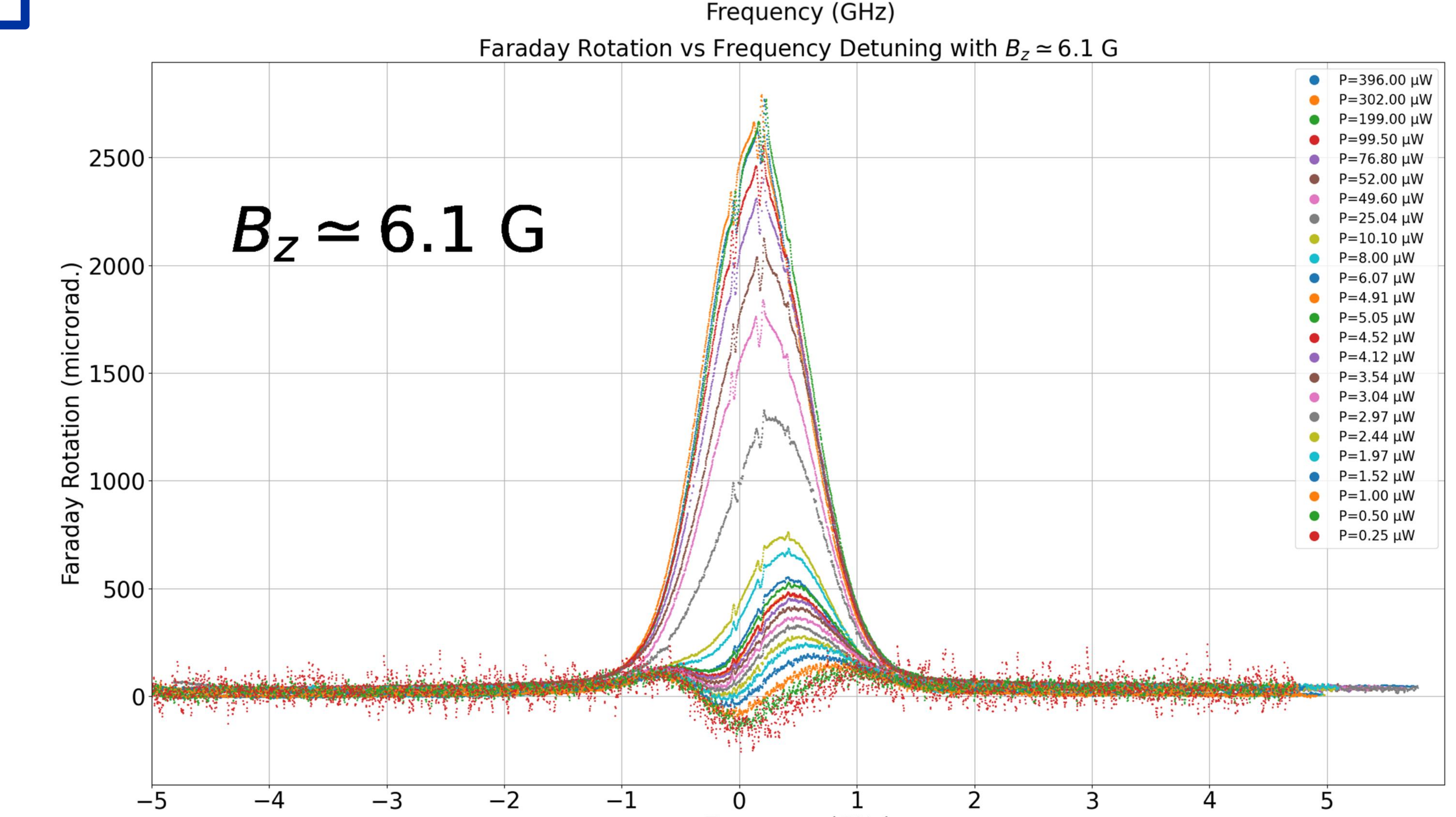
- The measurements were performed at various constant magnetic fields (**4, 5,** and **6 G**) while varying laser power from **250 nW** to **400 μW**.
- The laboratory temperature varies uncontrollably at a range of **21.7±1°C**.
- Measurements at **500 nW and below** showed agreement with theoretical predictions, with negligible paramagnetic Faraday rotation contribution.
- The potassium vapor **number density** is derived through fit functions.
- Identified the probe beam's **saturation power**, where Faraday rotation becomes insensitive of laser power variations.
- At laser power above 200 μW, **Bennett structure effects** in nonlinear magneto-optical rotation (NMOR) were observed.

Conclusions

- Reproducible measurements achieved.
- Vapor densities can be accurately extracted at low laser powers.
- At zero detuning, 500 nW measurements for magnetic fields of 4, 5, and 6 G resulted in polarization rotations of ~25, 75, and 130 μrad, indicating a sensitivity of ~50 nrad/mG.







References

[1] Stephen John Kadlecek. "Spin Relaxation in Alkali Vapors". PhD thesis. UNIVERSITY OF WISCONSIN MADISON, 1999.

[2] Kelley, M., and R. T. Branca. "A simple setup for in situ alkali metal electronic spin polarimetry." AIP advances 12.9 (2022).

Acknowledgments

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