Next Generation Polarized He-3 Targets for Electron Scattering and Related Processes

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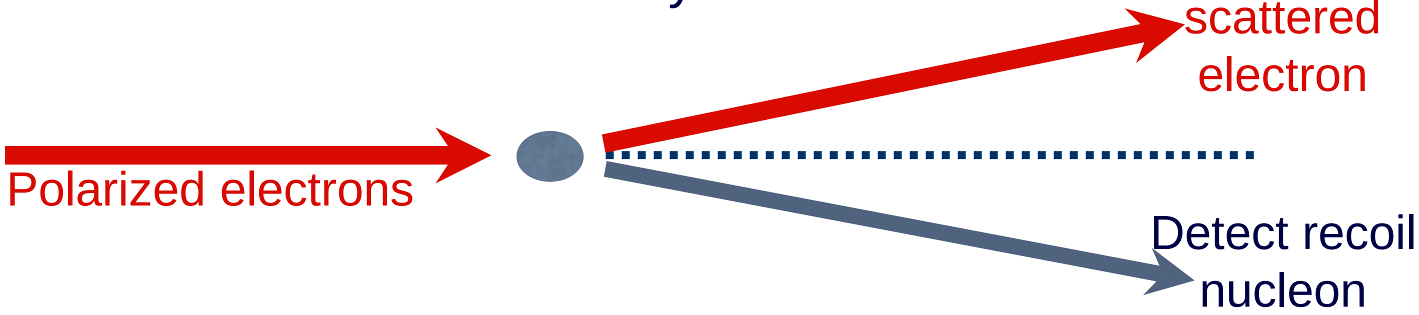
Outline

- Form factor studies at JLab and the need for high performance cell
- Techniques we use to study the cell
- Convection cell studies
- How magnetic field affects polarization (what we're currently working on)

Elastic Form Factor Studies at JLab

- JLab, with a high-current cw beam, has made it possible to study form factors with great accuracy at high Q^2 where count rates are very low.

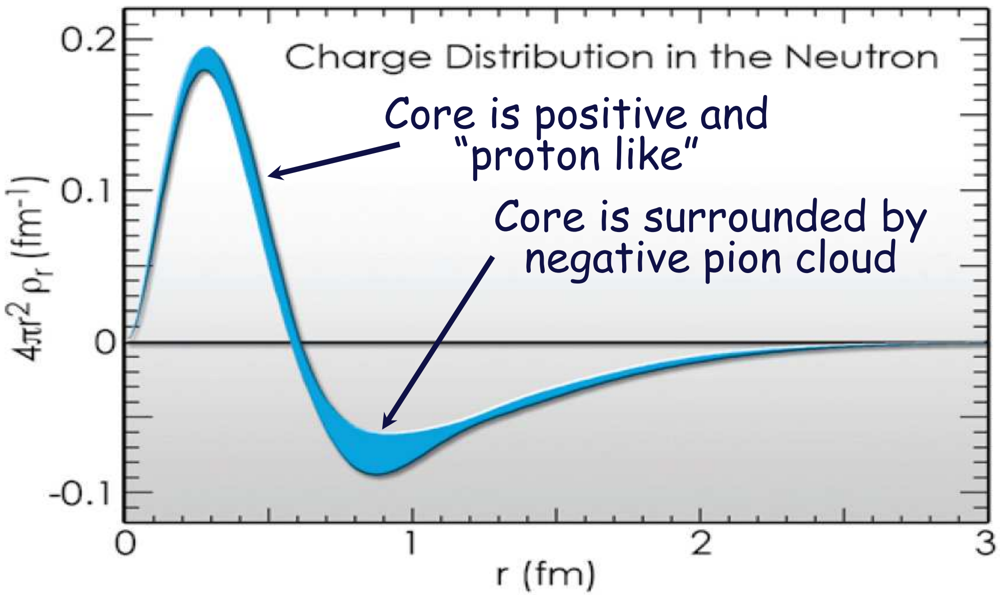


For a spinless target:

$$F(q^2) = \int \rho(\vec{\mathrm{R}}) e^{i\vec{q}\cdot\vec{R}} d^3\vec{R}$$

The neutron charge distribution in the non-relativistic picture

The Fourier transforms of neutron FF tells you the charge distribution within the neutron. This interpretation suffers, however, in that the momentum transfers are too large to ignore relativistic effects



Why is high polarization important?

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left\{ \frac{G_E^2 + \frac{q^2}{4M^2} G_M^2}{1 + \frac{q^2}{4M^2}} + \frac{q^2}{4M^2} \cdot 2G_M^2 \tan^2\theta \right\}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{Z^2 \left(e^2 / 4\pi\right)^2 \cos^2 \frac{1}{2}\theta}{r p_0^2 \sin^4 \frac{1}{2}\theta [1 + \left(2 p_0 / M\right) \sin^2 \frac{1}{2}\theta}$$

$$G\left(q^2\right) = \left(1 + \frac{q^2}{M_V^2}\right)^{-2} \text{ with } M_V^2 = \left(0.84 GeV\right)^2$$

Above equations show that high q^2 significantly reduces cross section. However, figure of merit is also proportional to P^2, so high polarization becomes increasingly important as we approach higher q^2.

Improvements of our cells

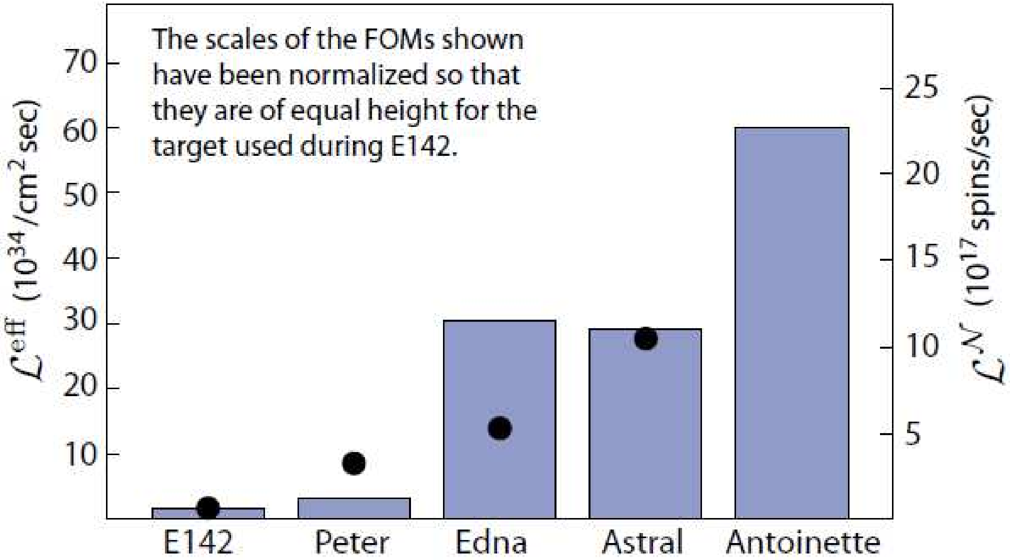
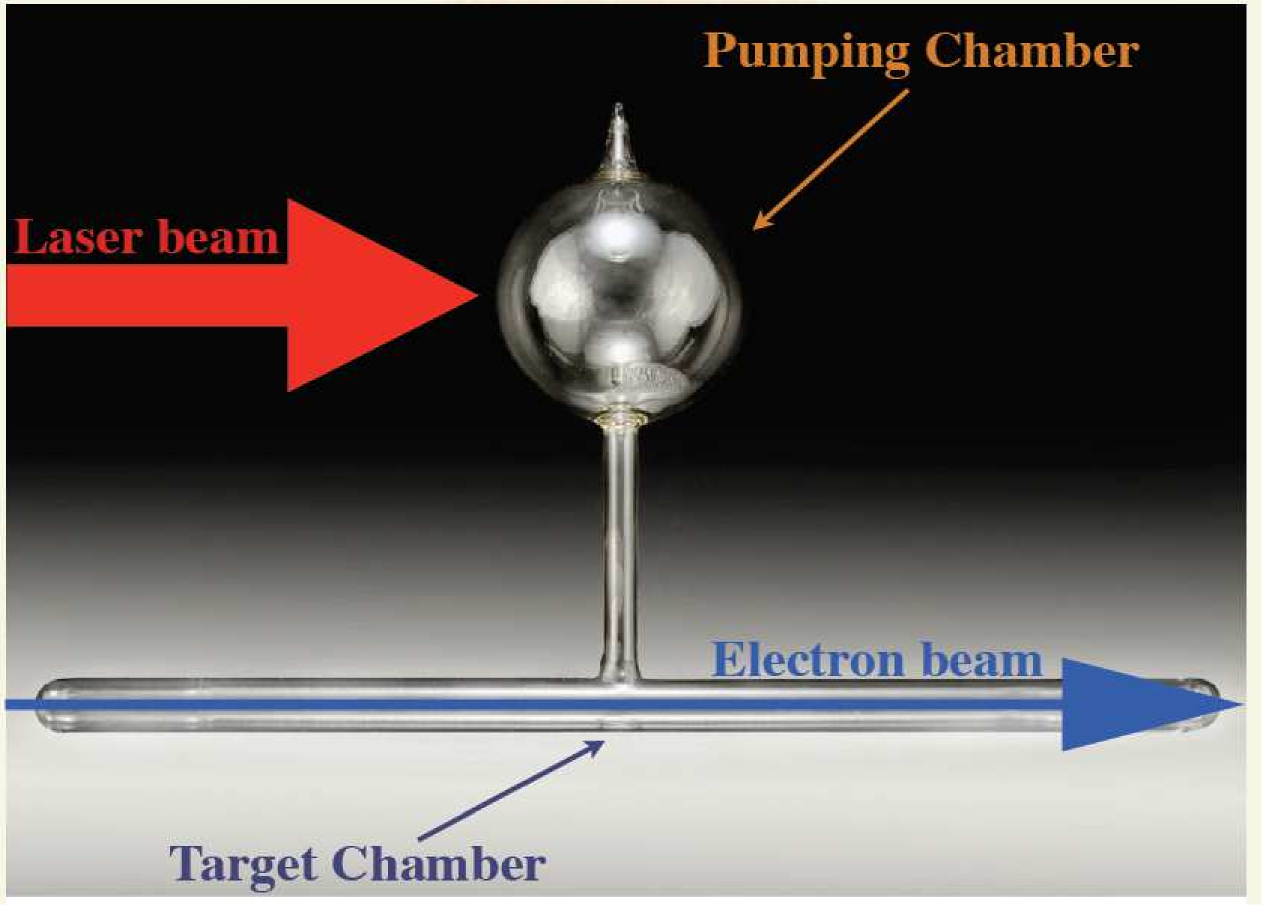


FIG. 1: Shown are two figures of merit (FOM) for five polarized ^{3}He targets. The solid circles (left-hand scale) indicate the luminosity weighted by ^{3}He polarization squared ($P^2_{\rm He}$) achieved in beam. The shaded columns (right-hand scale) show a FOM proportional to the total number of spins polarized per second, again weighted by $P^2_{\rm He}$.

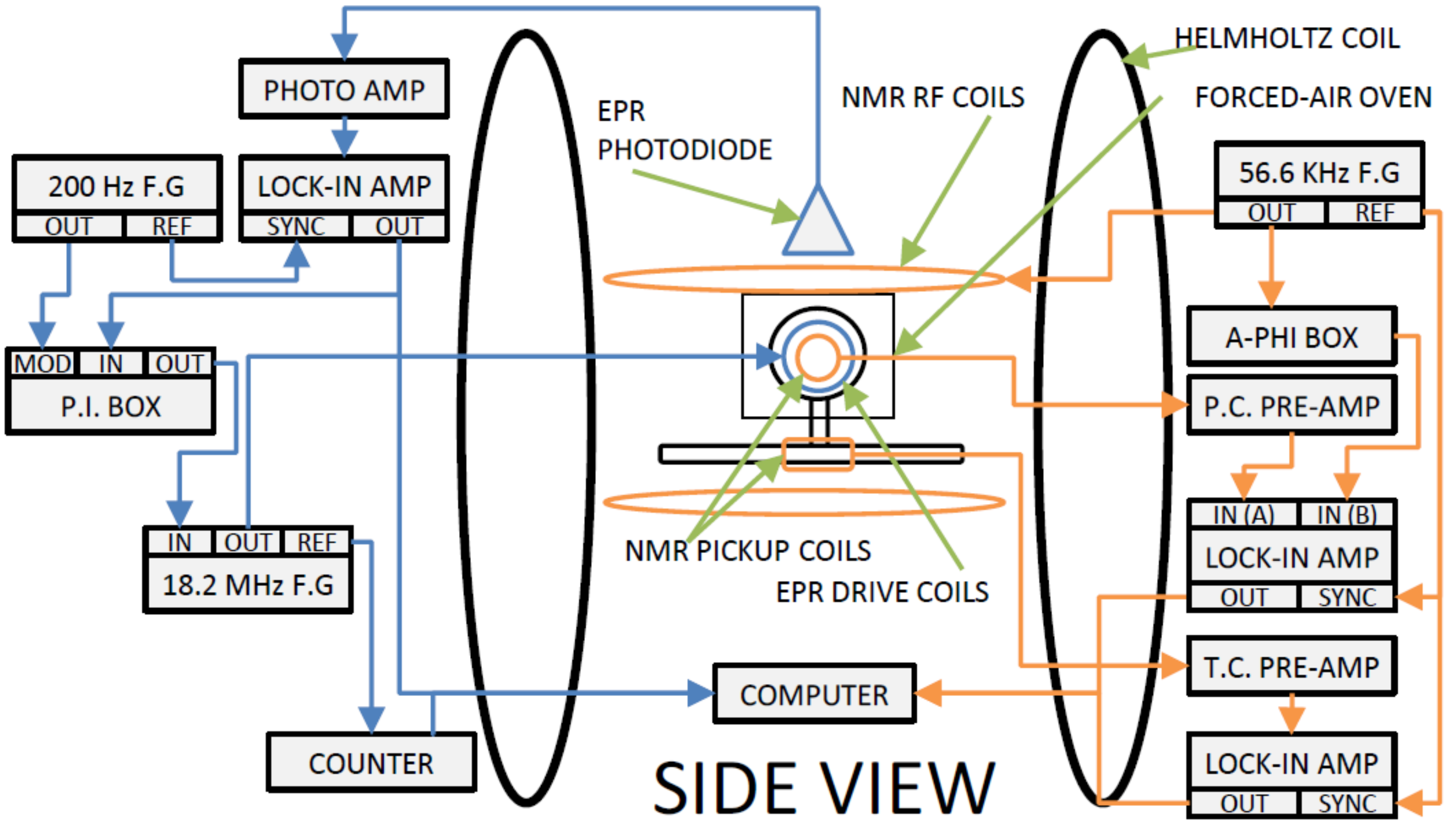
How do we study the cell?

- NMR and EPR technique
- Faraday Rotation technique
- SEOP simulation

A target cell



NMR and EPR setup



NMR Polarimetry

- Adiabatic Fast Passage (AFP) Sweep

Slow enough, adiabatic condition:

$$\frac{\dot{B}}{B_1} << \omega$$

Fast enough,

$$D\frac{|\nabla B_z|^2}{B_1^2} << \frac{\dot{B}}{B_1}$$

Combining the above equations:

$$\underset{1.5mHz}{D\frac{|\nabla B_z|^2}{B_1^2}} \quad << \quad \underset{13Hz}{\frac{\dot{B}}{B_1}} \quad << \quad \underset{56.6kHz}{\omega}$$

Rotating frame

- Co-Rotating Frame of Reference

In the rotating frame,

$$\hbar\frac{\partial I}{\partial t} = \gamma\hbar I \times [(B_0 - w/\gamma)\hat{z} + B_1\hat{y}'] = \gamma\hbar I \times B_{eff}$$

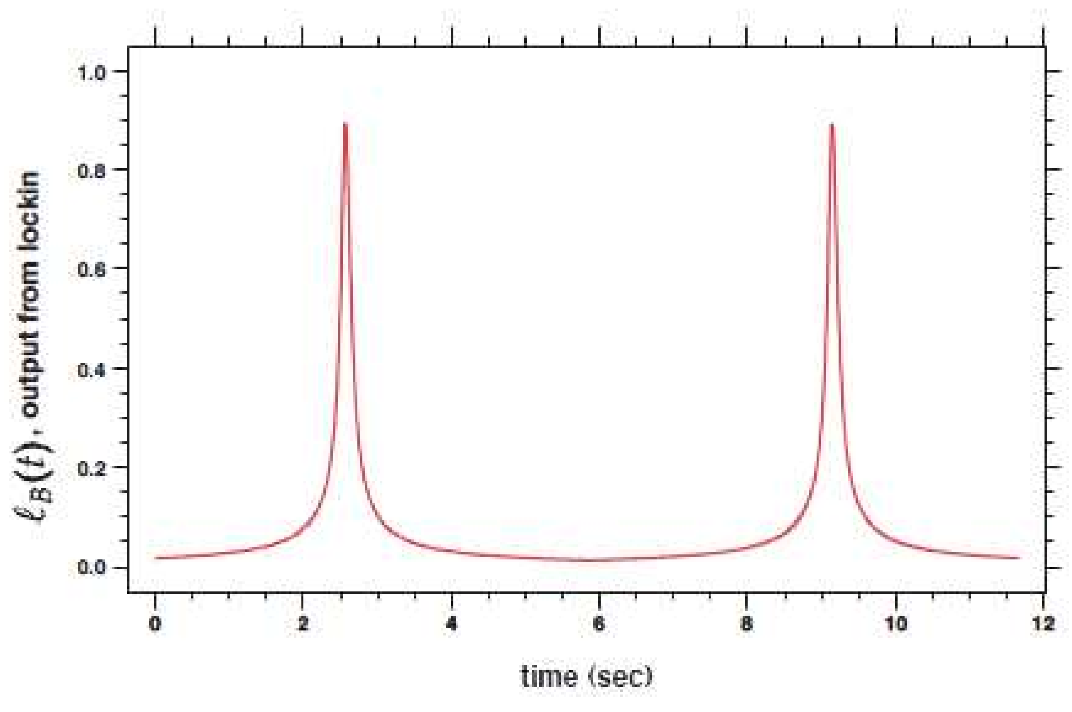
B_0 from 12.6G to 20.4G

$B_1 \approx 0.1G$

Pickup coils are perpendicular to holding field and RF field, resonance is at

$$B_0 = \omega / \gamma$$

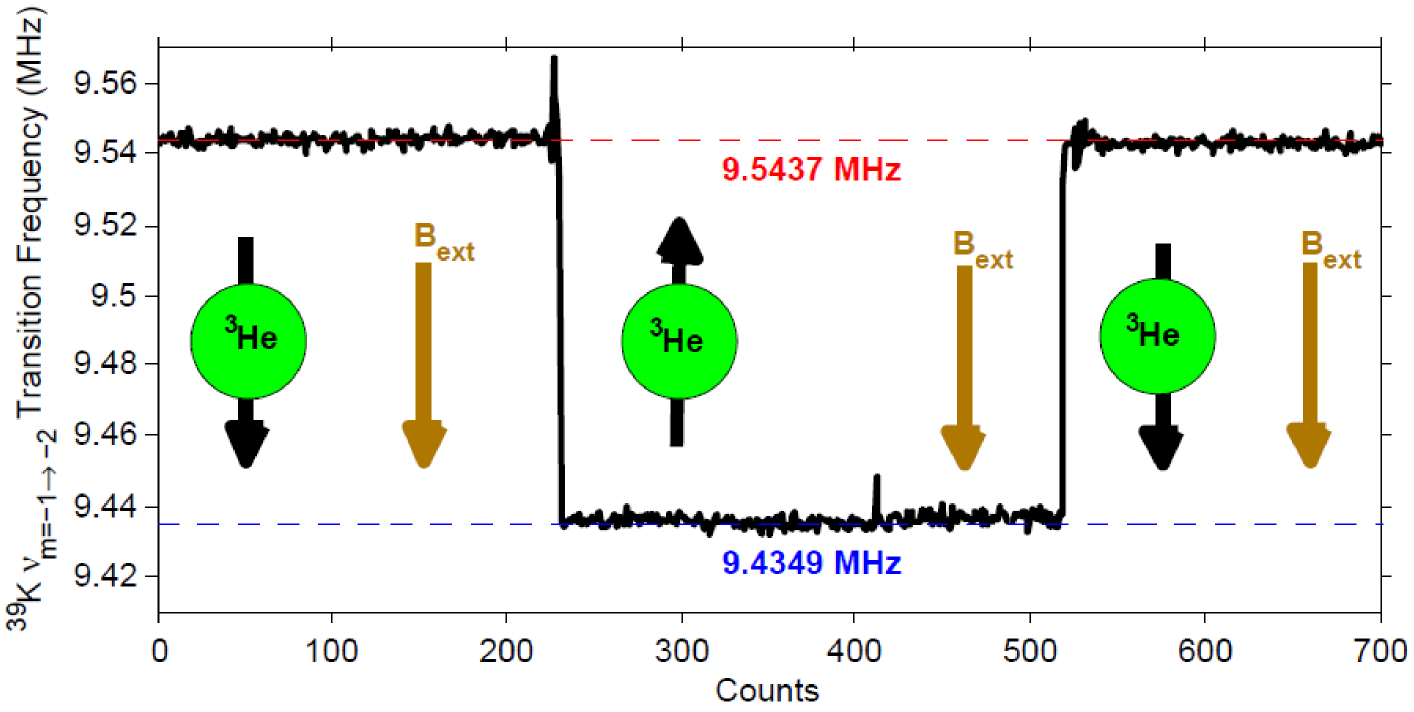
Typical AFP signal



EPR Polarimetry

- EPR method uses the shift of Rb Zeeman resonance due to the small "effective" field created by polarized ^{3}He gas.
- The average EPR transition frequency is located by exciting the EPR transitions with EPR RF coils and observing the resulting change in the intensity of D2 fluorescence.
- To isolate the effect of ^{3}He gas, we perform a frequency sweep AFP spin flip (keeping the holding field B_0 constant).

Typical EPR measurement



Quote from Peter Dolph’s thesis

Calculate He-3 polarization

- Field produced by a uniformly magnetized sphere

$$\Delta B = \frac{\mu_0 (\gamma / 2\pi) h}{3} P[He]$$

- Additional field due to spin-exchange interaction that is traditionally treated as an enhancement to the He-3 magnetization

$$\Delta B = \frac{\mu_0 (\gamma / 2\pi) h}{3} \kappa_0 P[He]$$

$$\kappa_0^{K-He} = 5.99 + 0.0086\left[T - 200^\circ C\right]$$

$$\kappa_0^{Rb-He} = 6.39 + 0.00914\left[T - 200^\circ C\right]$$

Quote from Babcock, E., Nelson, I. A., Kadlecek, S., and Walker, T. G. Phys. Rev. A 71(1), 013414 Jan (2005)

Antoinette results

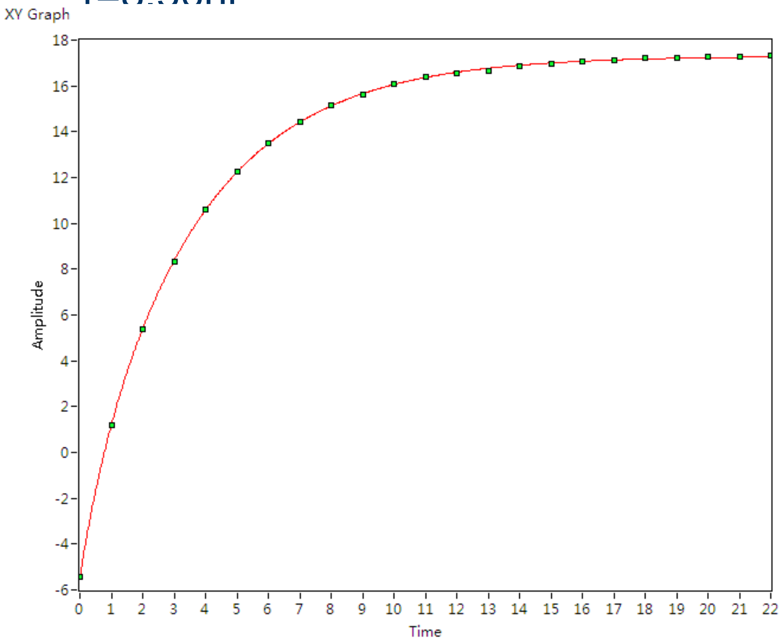
- Spinup curve at oven temperature 235℃

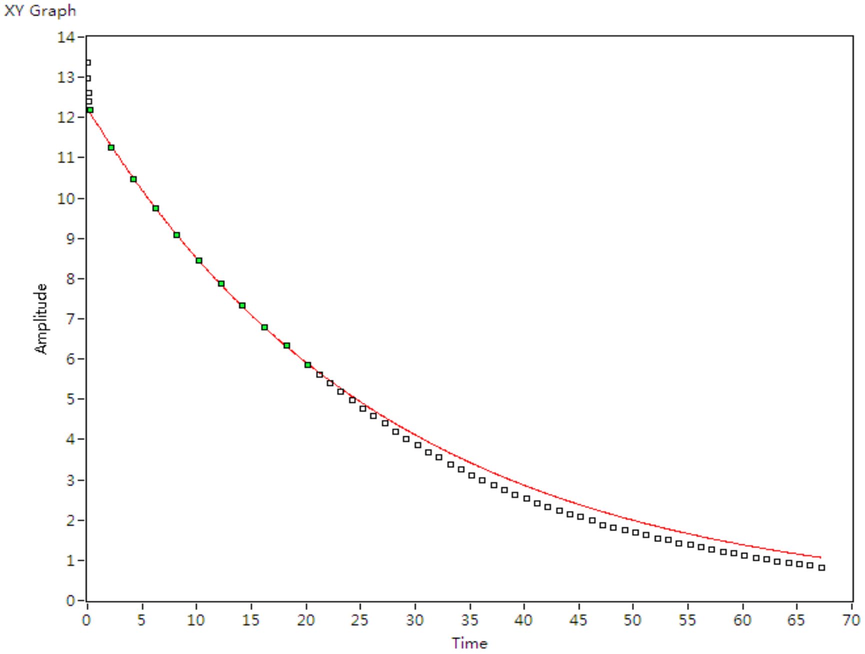
  PHe=61.3%,

  τ=3.56hr

- Room temperature spindown curve

  τ=27.56hr





Faraday Rotation

- Faraday Effect describes how a weak(~1mW) linearly polarized probe beam “rotates” in the presence of a polarized alkali vapor.
- The amount of the rotation depends on the product of alkali density with the distance that the laser travels through the pumping chamber (this distance is called “path length”).

Progression of Probe Beam through a Polarized Alkali Vapor

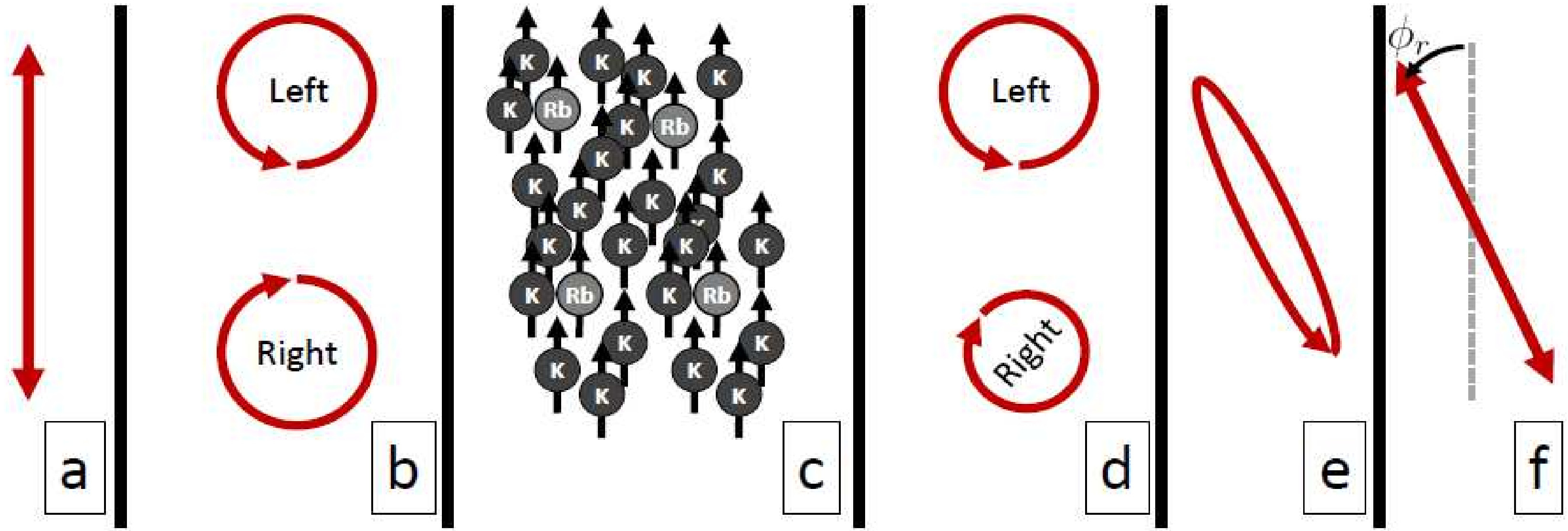


Figure 4.1 from Peter Dolph's thesis

Difference/Sum ratio

- Using a polarizing beam splitting cube and a photoelastic modulator

$$\frac{\Delta}{\Sigma}=\frac{\left|\tilde{E}_x\right|^2-\left|\tilde{E}_y\right|^2}{\left|\tilde{E}_x\right|^2+\left|\tilde{E}_y\right|^2}=\frac{P\sin(\Gamma_0\sin(\gamma t))\cos 2\Phi}{\cosh 2\beta+\cos(\Gamma_0\sin(\gamma t))\sinh 2\beta}$$

expand in terms of Bessel functions, use a lockin amplifier to pick one term to increase signal to noise ratio.

$$\frac{\Delta}{\Sigma}=\frac{2PJ_1(\Gamma_0)\cos 2\Phi}{\cosh 2\beta+J_0(\Gamma_0)\sinh 2\beta}$$

Faraday Rotation

- Extracting Number Density Ratio D

Faraday Rotation angle can be written as:

$$\phi_r = -\left(\frac{e^2}{12mc\varepsilon_0}\right)P[K]l\omega([f_1^{Rb} - f_2^{Rb}]/D + [f_1^{K} - f_2^{K}])$$

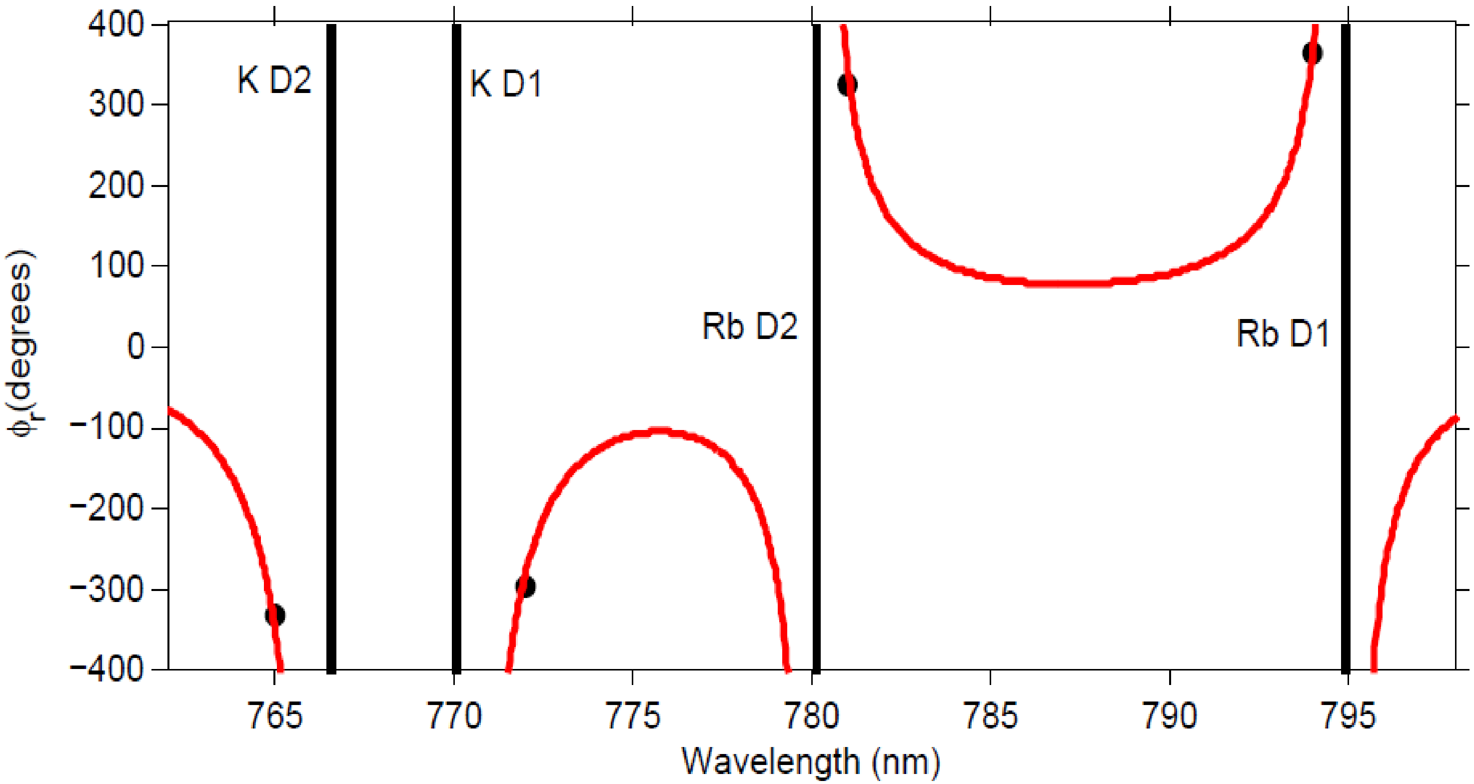
where

$$D = [K]/[Rb]$$

$$f = \frac{1}{\omega_D}\frac{\Delta_D}{\Delta_D^2 + \frac{\gamma_D^2}{4}}$$

Faraday Rotation

- Extracting Number Density Ratio D



Alkali polarimetry

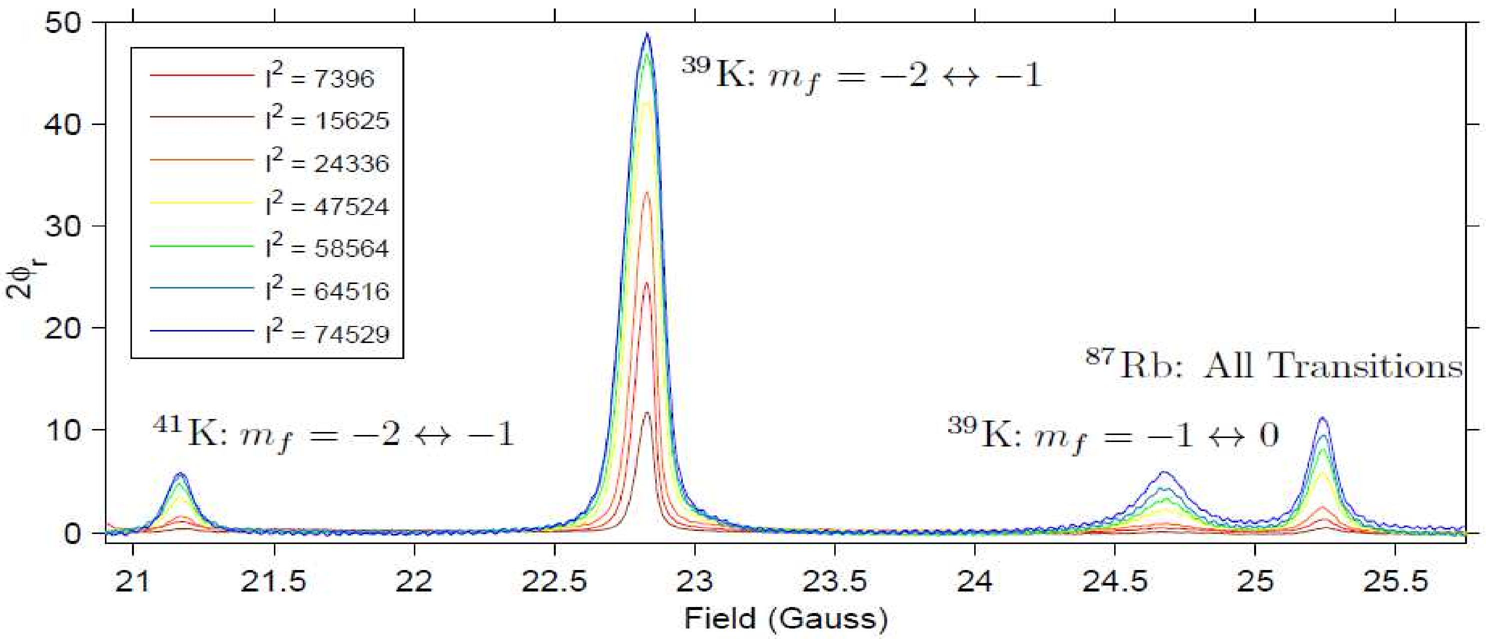
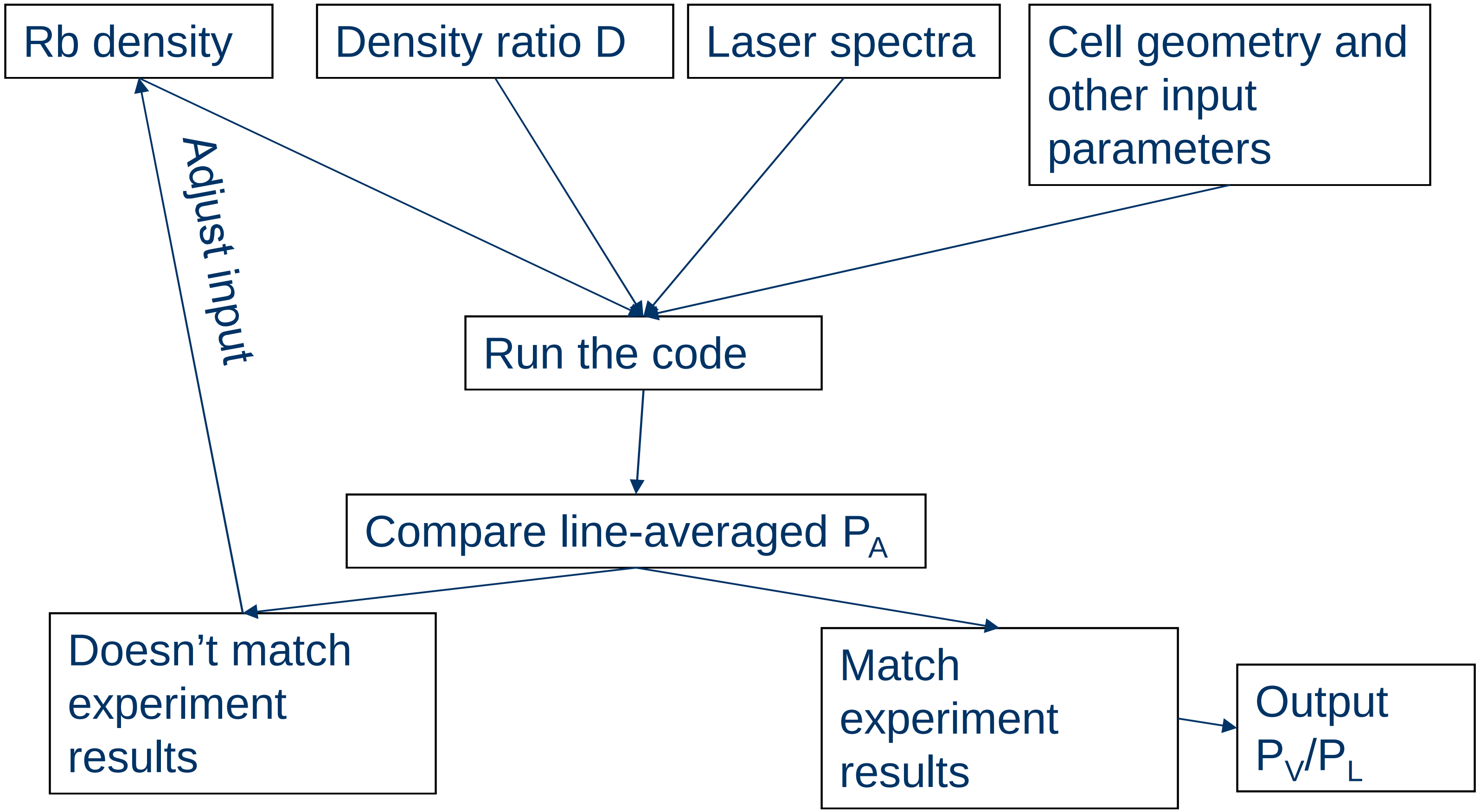


Figure 4.6: Alkali Polarization Scan for Target Cell Brady at Probe Wavelength 785nm with 1 Comet Laser.

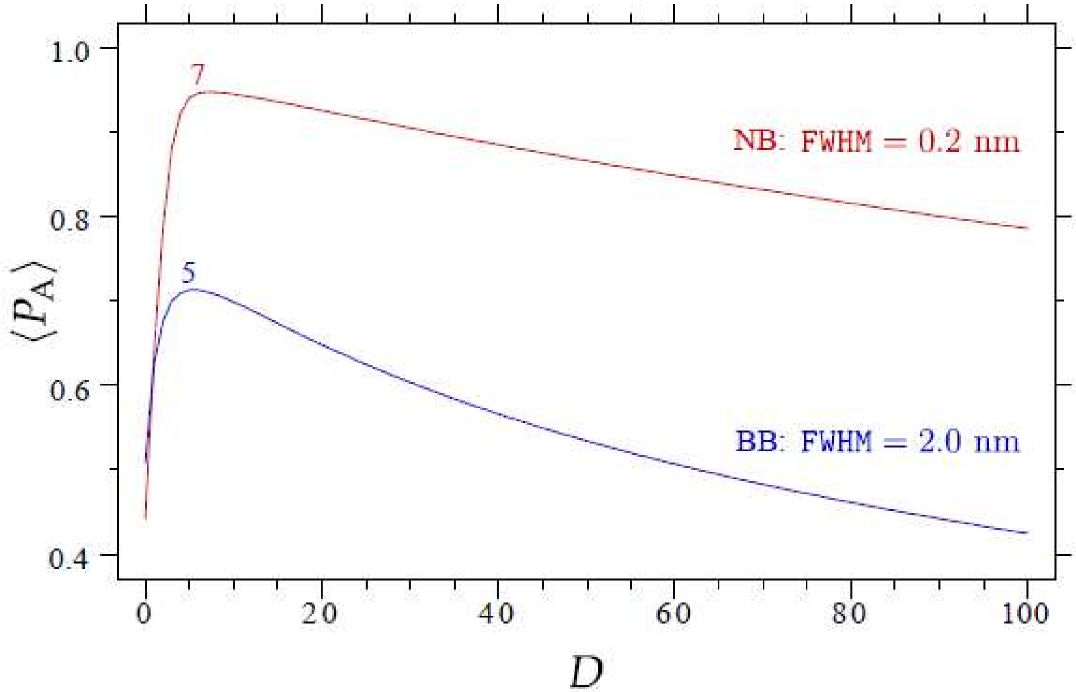
$P_{line} \neq P_{volume}$

- All information faraday rotation gives is line-averaged
- We use a simulation combined with faraday rotation results to compute volume-averaged alkali density and polarization

Fine tuning inputs for simulation

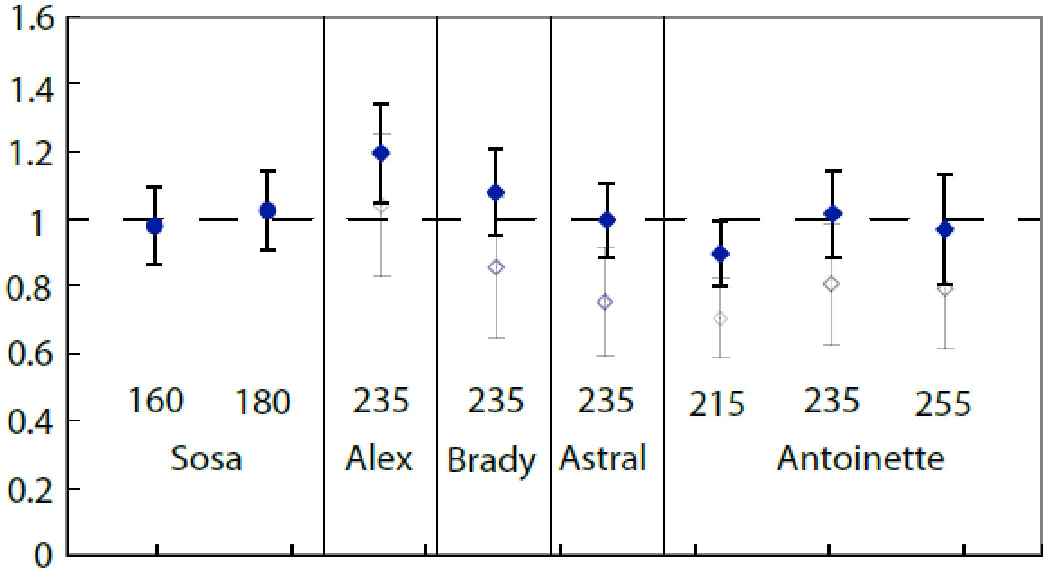


Alkali polarization vs. density ratio D



NB (BB) refers to a narrowband laser with 0.2 nm (2.0 nm) linewidth. The optimal ratio for the NB (BB) laser considered is approximately 7 (5).

Fit for kse^K



Plotted is the ratio m^F/m^s for eight separate measurements, where m^s is the slope measured at the beginning of a spinup, and m^F is calculated using faraday rotation results combined with volume-averaged correction from the simulation, and the spin-exchange coefficients for Rb and K. For all but the Sosa (Rb only) measurements, kse^K was treated as a free parameter, while fitting m^F/m^s to unity, yielding the results:

$kse^K=(7.4\pm0.7) \times 10^{-20}$ cm^3/s.

Babcock reported in his thesis: $kse^K=(5.5\pm0.4) \times 10^{-20}$ cm^3/s

X factor

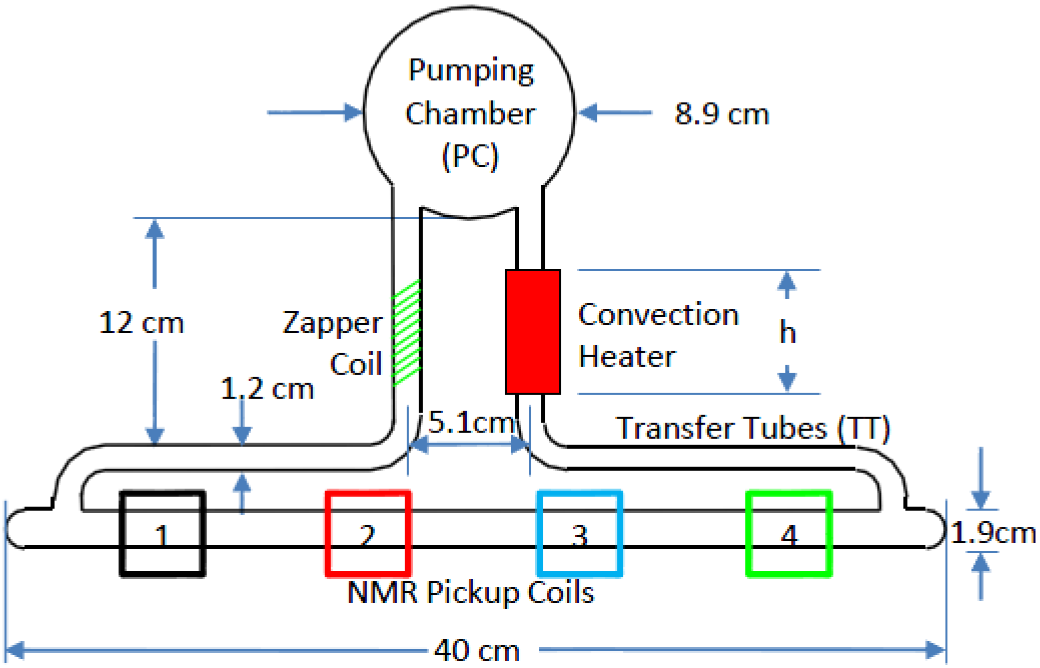
- E. Babcock et al., Phys.Rev.Lett. 96,083003(2006)

$$P_{He} = \frac{\langle P_A \rangle_{pc} f_{pc} \gamma'_{se}}{f_{pc} \gamma'_{se} (1 + X) + \langle \Gamma_{He} \rangle}$$

The limiting He polarization is given by:

$$f_{pc} \gamma'_{se} >> \langle \Gamma_{He} \rangle \rightarrow P_{He} \approx \frac{\langle P_A \rangle_{pc}}{1 + X}$$

Convection cell



Dolph, Singh, et al., PRC v84, pg 065201 (2011)

Why we need convection cell?

- Reduces polarization gradients between pumping chamber and target chamber while using higher current
- We may want to physically locate pumping chamber further from target chamber to provide radiation shielding

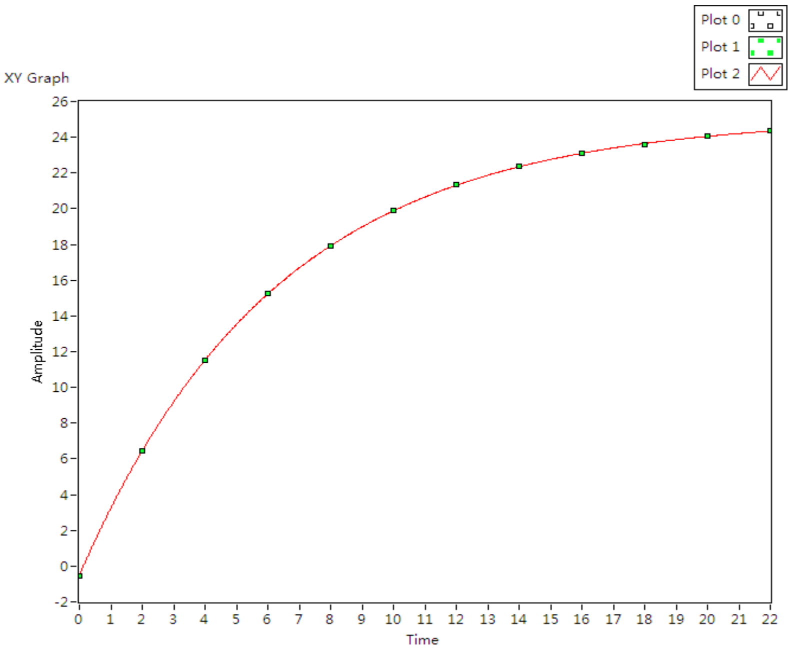
Results from Protovec-I

- Spinup curve

main oven temperature=235 ℃

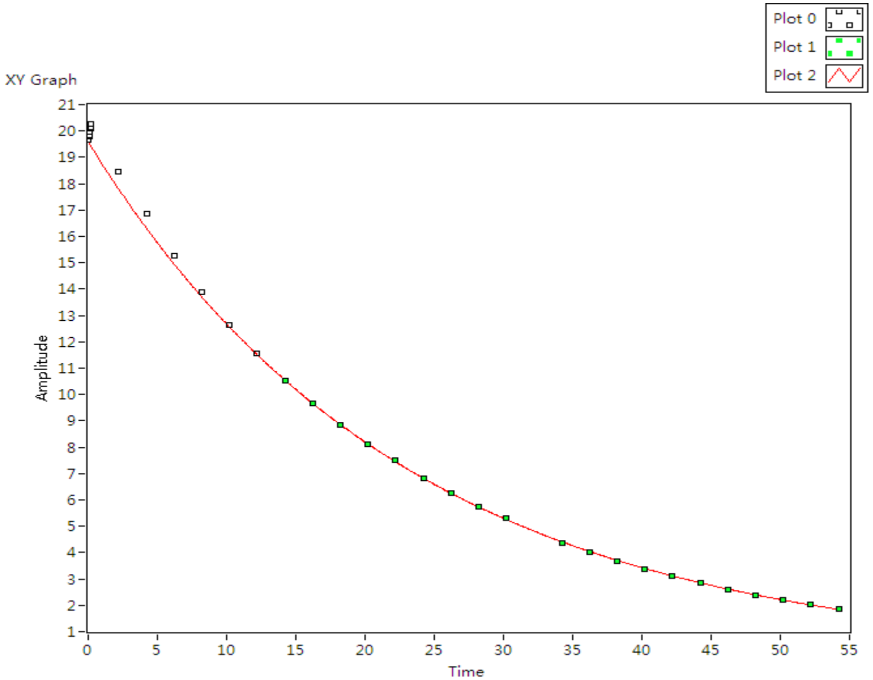
convection oven temperature=80 ℃

PHe=57.15%, τ=6.29hr



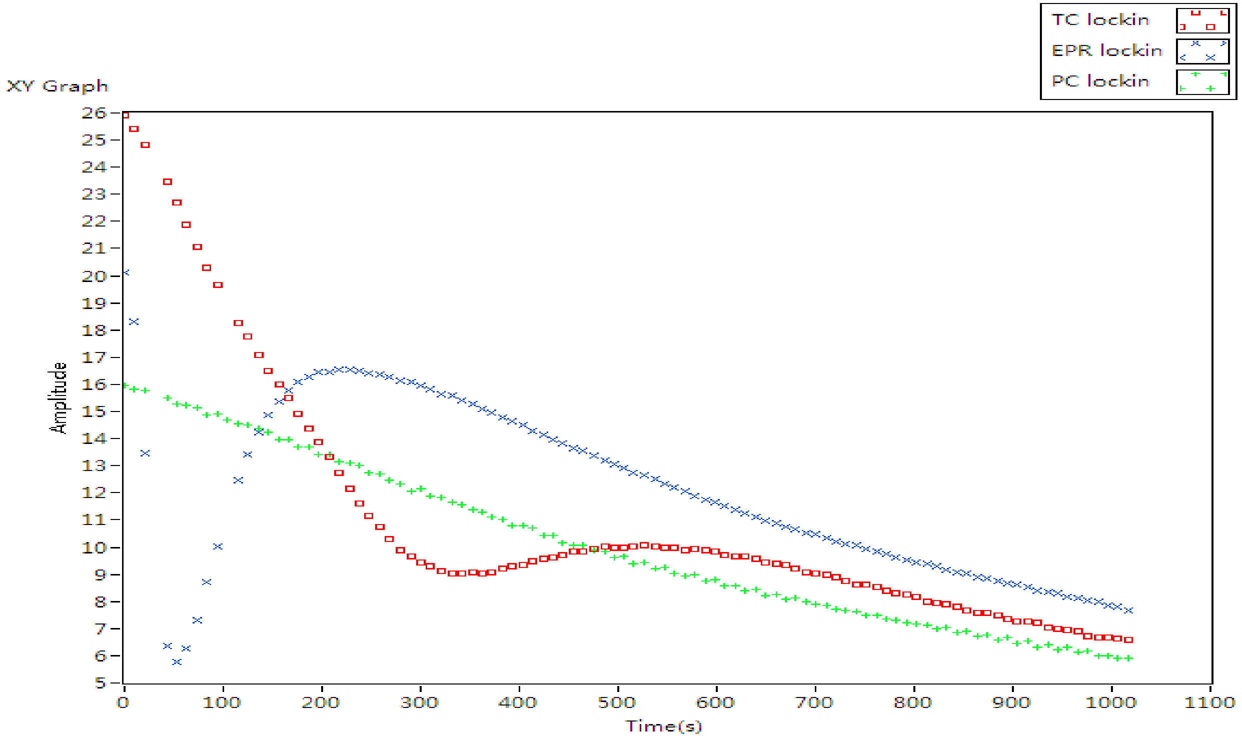
- Room temperature sphindown

τ=22.95hr(18.76hr)

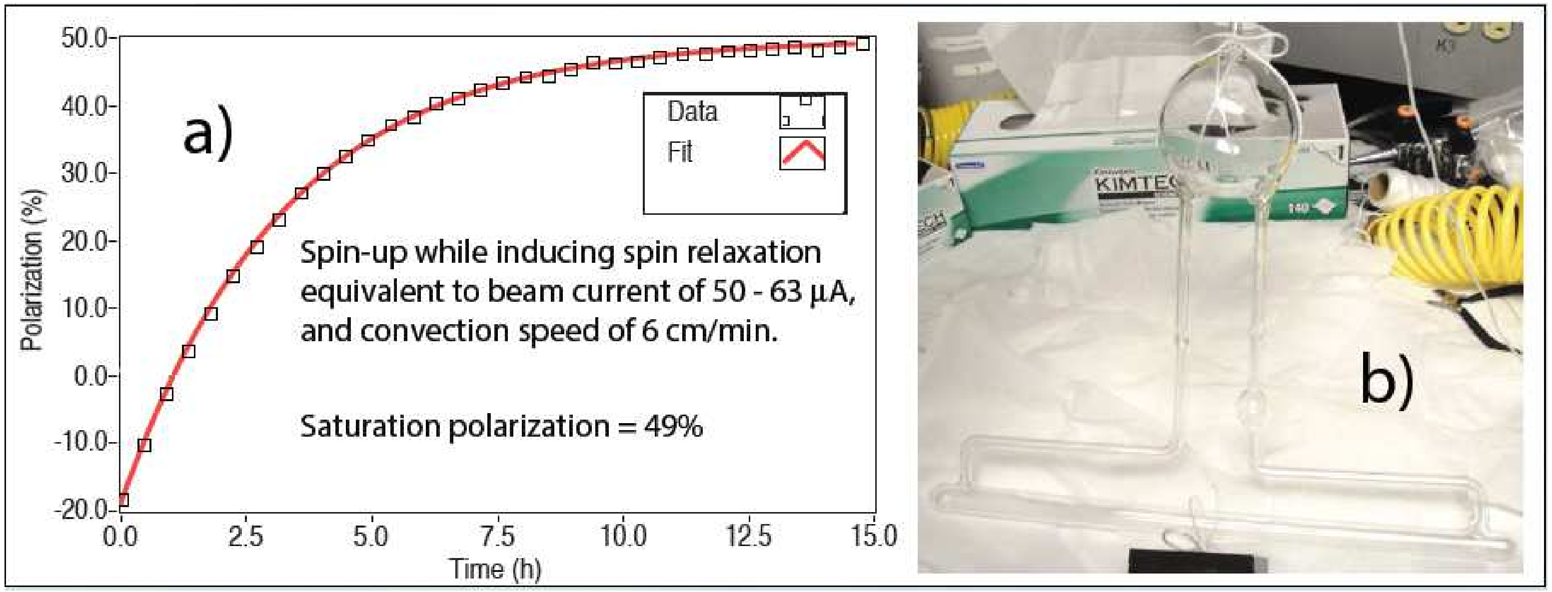


Convection speed measurement

convection speed=6.31cm/min, convection oven temperature=80 ℃



Expected performance of Protovec-I



Our simulated beam test suggests that the Protovec-I design will deliver at least 50%.

What about the effect of the magnetic field on performance and polarimetry?

- Longitudinal spin-relaxation rate caused by magnetic field inhomogeneities.

$$\frac{1}{T_1} = \frac{\left|\vec{\nabla} B_x\right|^2 + \left|\vec{\nabla} B_y\right|^2}{B_z^2} D$$

For a 10 amagat sample of ^{3}He, $1/T^1 \sim 1/56$hrs

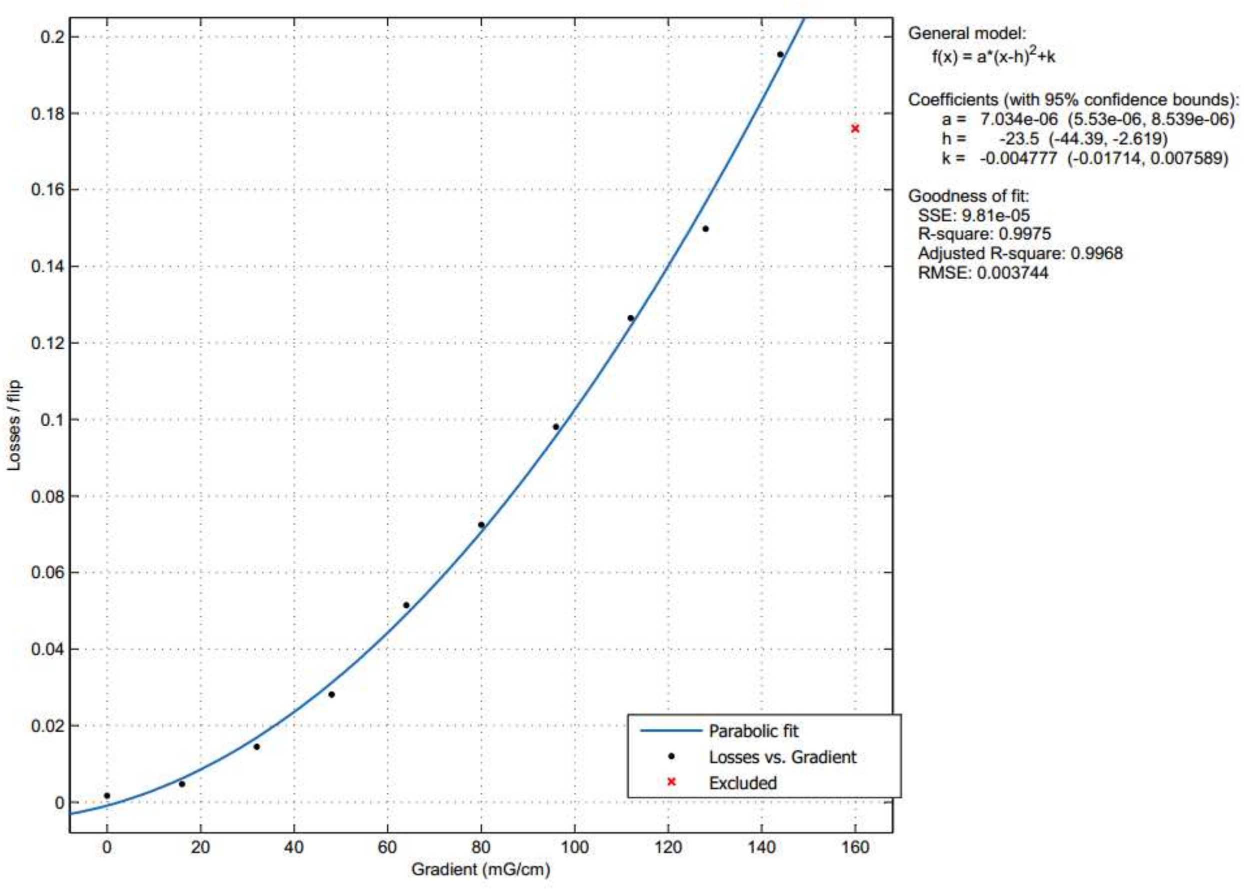
- AFP loss. On resonance, the longitudinal spin-relaxation rate in a frame that is rotating about the z axis at the Larmor frequency $1/T_{1\rho}$ is :

$$\frac{1}{T_{1\rho}} = \frac{\left|\vec{\nabla} B_z\right|^2}{B_1^2} D$$

The fractional relaxation that occurs during an AFP flip is approximately:

$$\text{fractional relaxation} = \frac{1}{T_{1\rho}} \frac{\pi B_1}{\left(\partial B_z / \partial t\right)}$$

AFP loss(one flip) vs. gradient of Bz



Currently working on

- Further study how static inhomogeneities affect AFP loss
- Compare experimental results with predictions
- Study the significance of the inhomogeneities of RF field