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a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 303-492-5956

RPPR Final Report
as of 23-Sep-2021

Agency Code: 21XD

Proposal Number: 75189PHDRP
INVESTIGATOR(S):

Agreement Number: W911NF-19-1-0330

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DUNS Number: 007431505

EIN: 846000555

Report Date: 17-Aug-2021

Date Received: 21-Sep-2021

Final Report for Period Beginning 18-May-2019 and Ending 17-May-2021

Title: Towards Practical Self-calibrating Vector Magnetometry in an Atomic Vapor Cell

Begin Performance Period: 18-May-2019

End Performance Period: 17-May-2021

Report Term: 0-Other

Submitted By: Ph.D. Cindy Regal

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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 1

STEM Participants: 3

Major Goals: The goal of this project is to self-calibrate vector magnetic fields using atomic spectroscopy on a microwave polarization ellipse. To accomplish this our goal is to show that Rabi oscillations can be used to extract self-consistent information in a hot atomic vapor cell of Rb. The method consists of two stages: First, the mapping of an applied microwave field polarization using atomic transitions. Second, the microwave polarization ellipse can be used for calibrated vector magnetometry. Our goal is to characterize both the sensitivity and accuracy of the vector and scalar measurements extracted from Rabi measurements.

Accomplishments: Please see enclosed description and graphics.

Training Opportunities: We have trained both graduate and undergraduate students in atomic physics, magnetometry, and technical design. Dan Wagner graduated Summa Cum Laude with his undergraduate thesis work at the University of Colorado based upon this project.

Results Dissemination: Chris Kiehl: Poster Heraeus Seminar Magnetometry 2019, Contributed talk DAMOP 2020 //

Tobias Thiele: Invited talk Gordon Research Seminar 2018 //

Two manuscripts in progress - see technical pdf

Honors and Awards: Cindy Regal gave the Manne Siegbahn Memorial Lecture in Experiment physics // Cindy Regal received the Baur-SPIE endowed chair in optics and photonics

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI

Participant: Cindy Regal

Person Months Worked: 1.00

Project Contribution:

National Academy Member: N

Funding Support:

RPPR Final Report
as of 23-Sep-2021

Participant Type: Co PD/PI

Participant: Toobias Thiele

Person Months Worked: 4.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Chris Kiehl

Person Months Worked: 7.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Ting-Wei Hsu

Person Months Worked: 1.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Undergraduate Student

Participant: Daniel Wagner

Person Months Worked: 3.00

Project Contribution:

National Academy Member: N

Funding Support:

Partners

,

RPPR Final Report
as of 23-Sep-2021

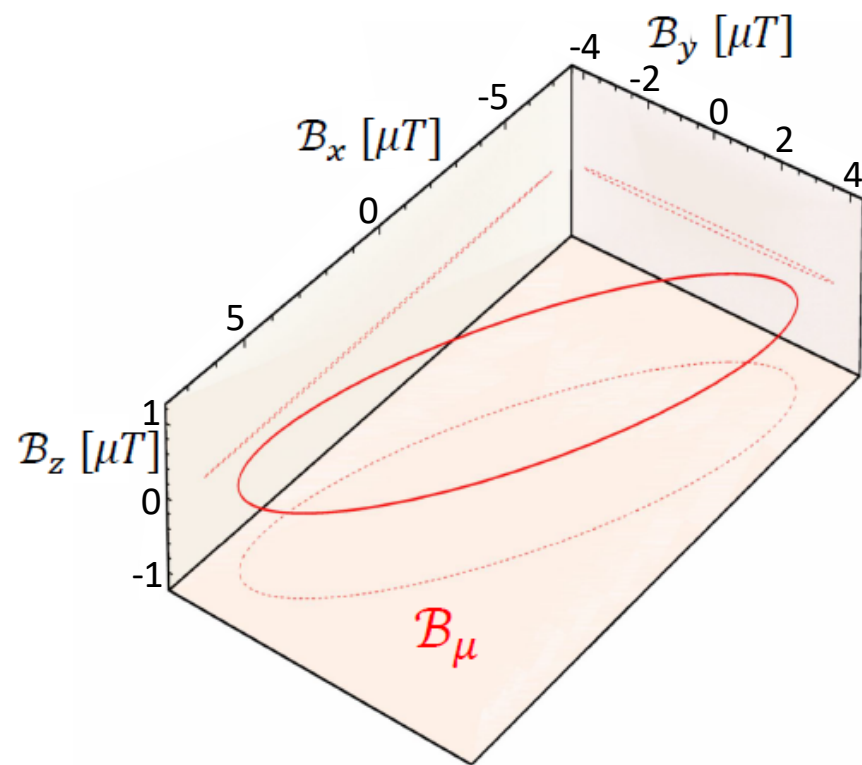
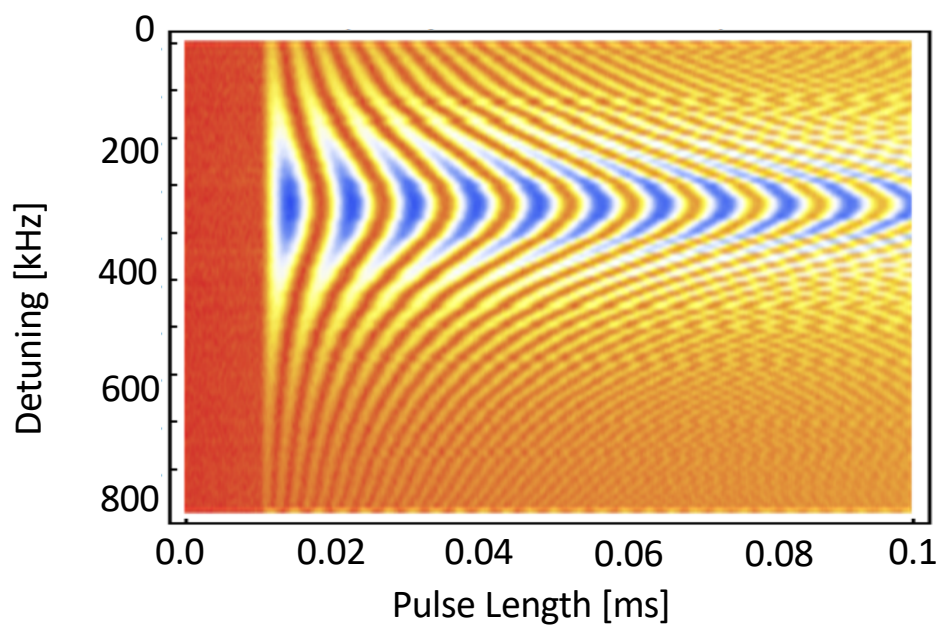
I certify that the information in the report is complete and accurate:

Signature: Cindy A Regal

Signature Date: 9/21/21 5:27PM

Towards Practical Self-calibrating Vector Magnetometry in an Atomic Vapor Cell

January 2021



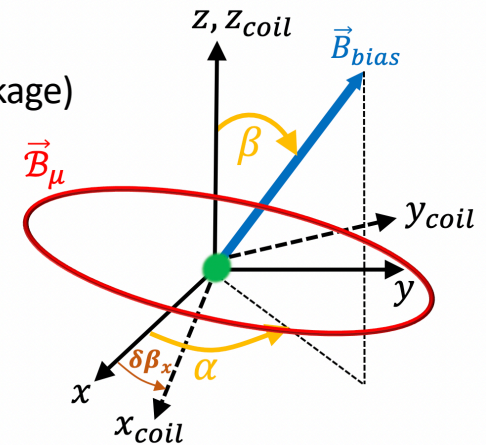
Overview

what we have been doing on the experiment:

- fixing microwave source (main goal from June: power monitor, switch to limit channel leakage)
- theoretical understanding of expected Rabi coherence from spin-exchange (QND measure in vapor cell for Rabi is a first)
- full long data set; conclusions

good/what has worked:

- made a vector magnetometer with a mm atomic vapor cell with single laser path and no coil modulation
- ability to calibrate: convergence rate of non-orthogonality parameters similar to rotated scalar mags, e.g. SWARM
- sensitivity consistent with PE structure and noise in Rabi measurement - very close to proposed values
 - Larmor: $S_{|B|} = 16 \text{ pT}/\sqrt{\text{Hz}}$ ($2 \text{ pT}/\sqrt{\text{Hz}}$)* (dominated by coil noise, gradients) *single shot
 - vector: $S_{\alpha} = 35 \text{ } \mu\text{Rad}/\sqrt{\text{Hz}}$ $S_{\beta} = 17 \text{ } \mu\text{Rad}/\sqrt{\text{Hz}}$ (in optimal angular regions)
 - Rabi component noise: $90 \text{ pT}/\sqrt{\text{Hz}}$ ($7 \text{ pT}/\sqrt{\text{Hz}}$)* (dominated by microwave noise)
 - Rabi scalar: $S_{|B|} = 340 \text{ pT}/\sqrt{\text{Hz}}$ (affected by noise in Rabi and indirect measure)
- vector accuracy proven to mrad level – comparing combined PE measurements with prediction of calibrated model, compare multiple PEs, compare scalar measurements for multiple PEs



Overview

non-ideal inaccuracy detected:

- at 1 mrad scale we measure systematics (but again important we have self-assessment)
- conclusion: have ideas for origin; next generation apparatus required to improve

main expected risks from proposal: stability of microwave system -> sensitivity says on fast scale this is reasonable

things addressed to get where we are: Stark shifts, microwave stability and monitoring, cavity Q

additional non-ideal effects discovered over time and recently:

facts from data studying sensitivity that could be linked to accuracy:

- changing (α, β) results in more noise than leaving fixed -> points to DC coils (Eddy currents, coil drifts)
- static magnetic gradients affect Rabi rates and corresponding fitting model error
- cannot rule out that microwave fluctuations or frequency dependence do not also cause inaccuracy



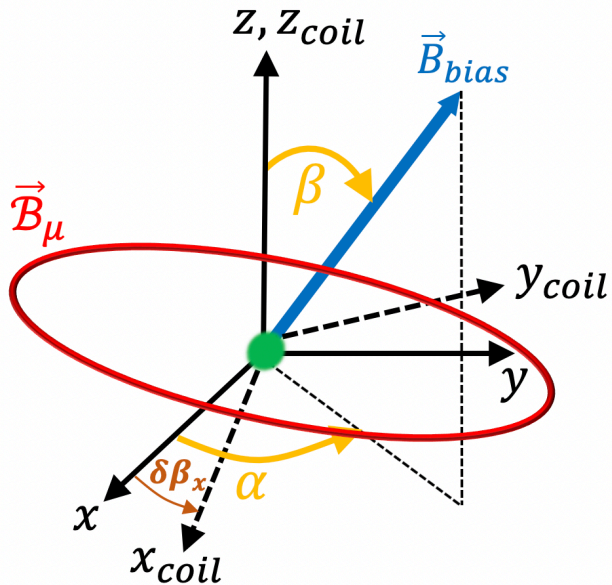
Artifacts of the proof-of principle apparatus:

- Eddy currents in microwave cavity
 - limit time between measurements in calibration, and cavity heating procedure (measurement time = 1 – 30 ms, wait time = 500 ms)
 - deadtime limits – ability to measure faster than microwave drifts
- magnetic gradients hard to get rid of with current coil configuration
- large DC coil system subject to thermal shifting, especially with large dead time
- large microwave cavity and launching strategy

to solve technical challenges may combine with ideas from other vector sensor calibrations:

- scalar calibration of vector magnetometers
- sensor and field rotations

Review: idea of polarization ellipse reference



$$(\alpha, \beta) = f(\delta\beta_x, \dots, \alpha_c, \beta_c)$$

- P.E. described by:

$$\vec{B}_\mu = \frac{1}{2} \sum_{j \in \{x, y, z\}} B_j e^{-i(\phi_j + \omega t)} + c.c. \Rightarrow 5 \text{ P.E. parameters: } B_x, B_y, B_z, \phi_x, \phi_y (\phi_z = 0)$$

- P.E. parameters determined by solving system of (>5) equations

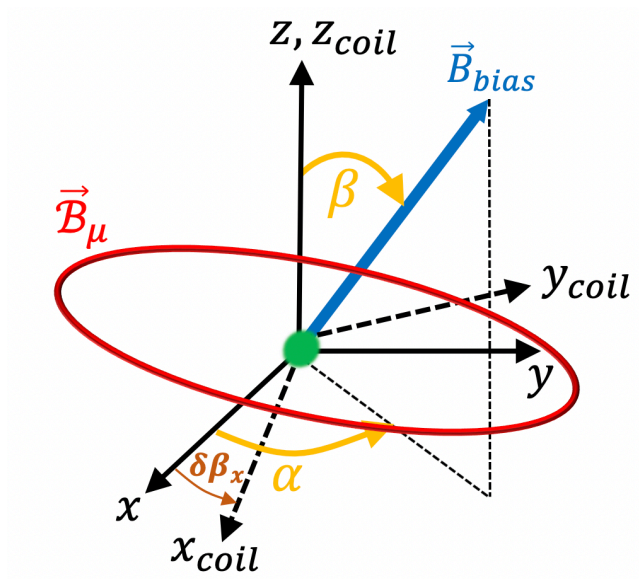
$$\begin{aligned} \left(B_{\pi}^{(\alpha_c, \beta_c)} \right)^2 &= f_{\pi}(B_x, B_y, B_z, \phi_x, \phi_y, \delta\beta_x, \dots, \alpha_c, \beta_c) \\ \left(B_{\sigma_{\pm}}^{(\alpha_c, \beta_c)} \right)^2 &= f_{\pm}(B_x, B_y, B_z, \phi_x, \phi_y, \delta\beta_x, \dots, \alpha_c, \beta_c) \end{aligned}$$

Measure
Solve For Parameters
Model Correction Variables
Set Parameter

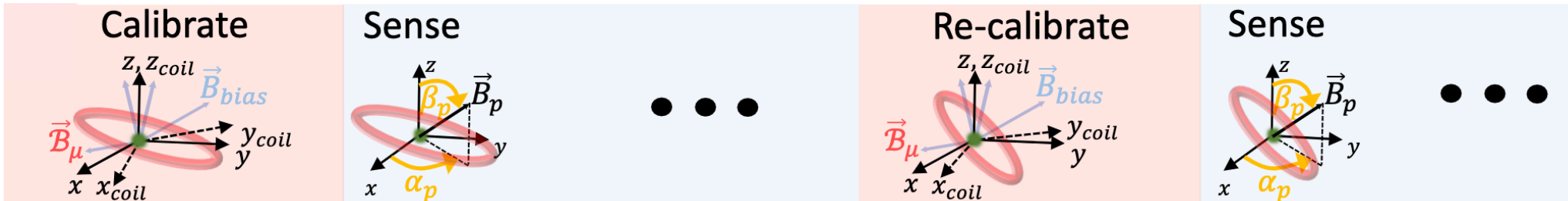
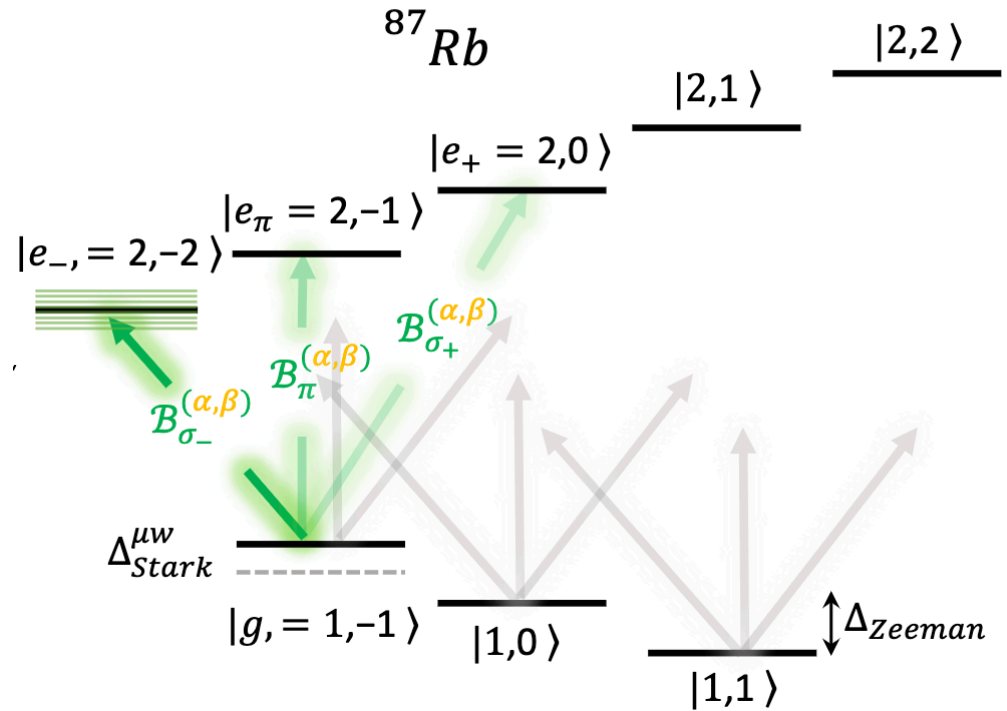
Orthogonal Frame (Lab)
Model Correction Variables
Non-orthogonal Frame (Coils)


 Calibrate out systematics

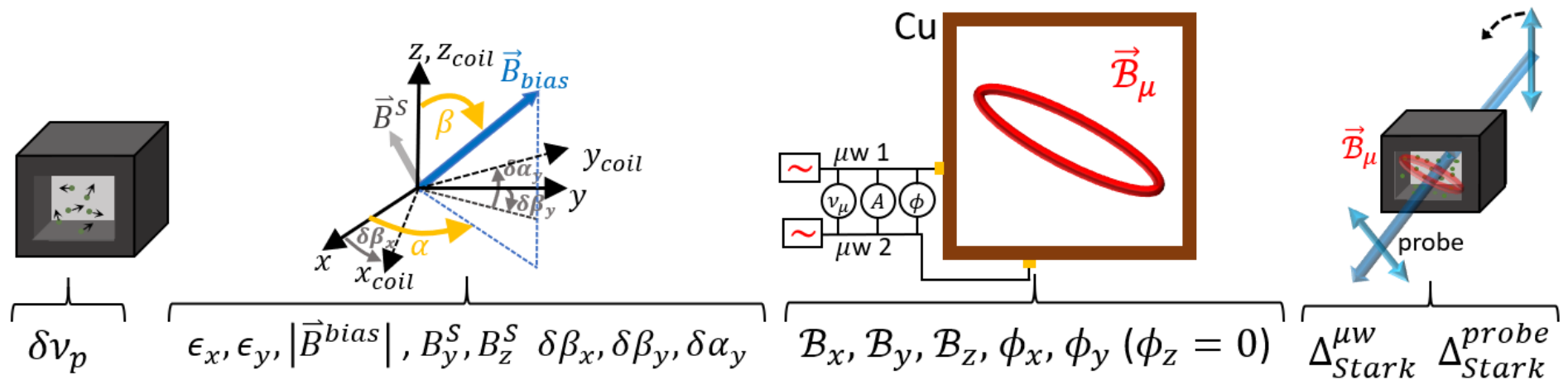
Review: idea of polarization ellipse reference



0.5 s of deadtime between each measurement!

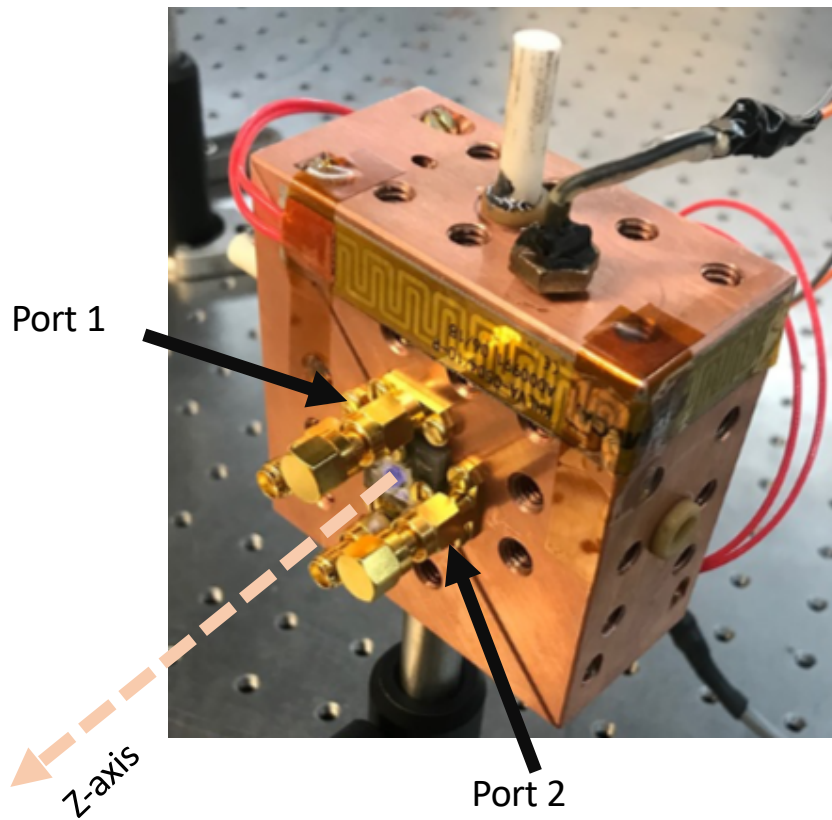


Review: expansion of parameters our algorithm calibrates



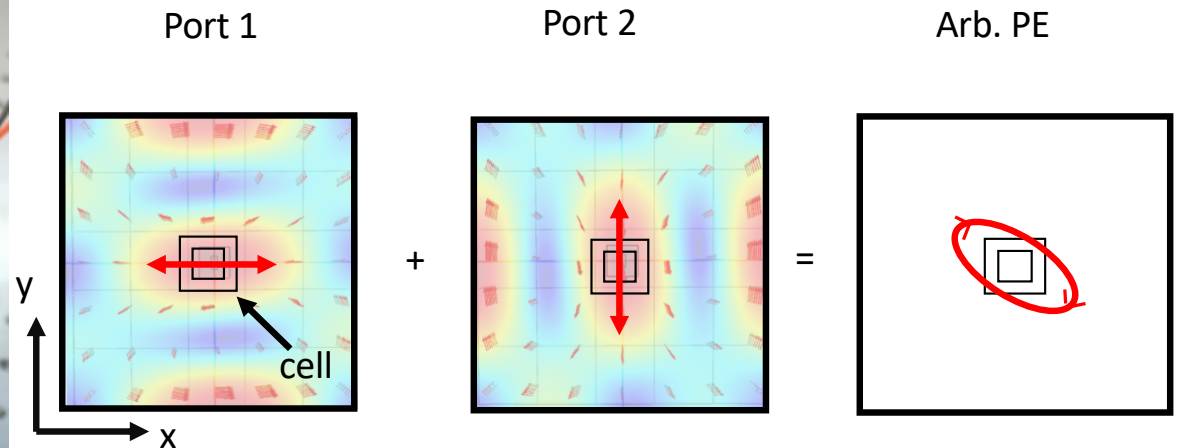
- we think of our algorithm now as both a scalar and vector measure
- but can also get scalar from typical Larmor

Review: microwave source – arbitrary polarization control



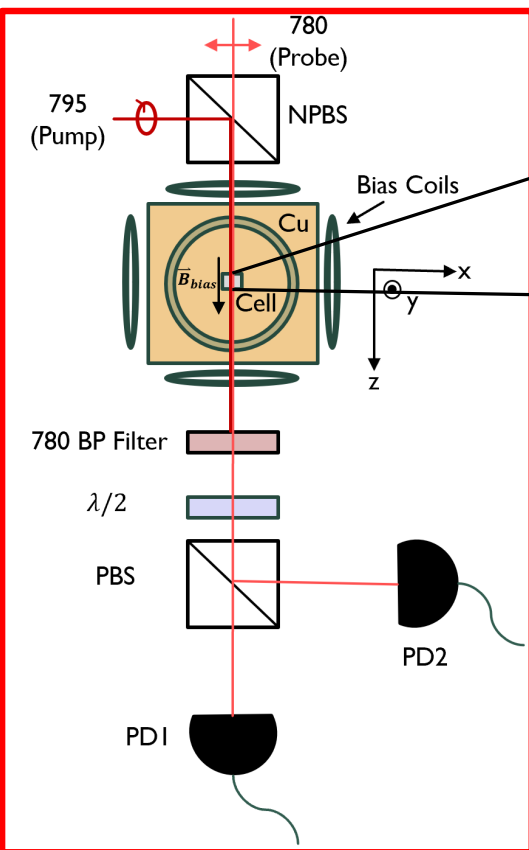
$$\omega_{mn} \approx 6.8 \text{ GHz} \approx \Delta \nu_{\text{clock}}^{\text{Rb}}$$

Cavity Modes
 $(n_x, n_y, n_z) = (2,1,0)$ and $(1,2,0)$



frequency-dependent amp and phase of cavity
(including an accidental detuning) causes
differential effects for transitions

Review: experiment setup

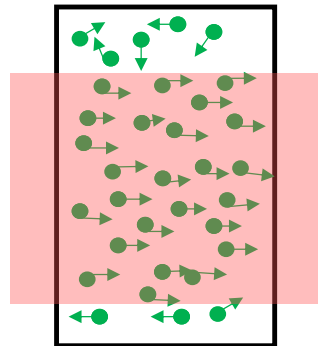


Microfabricated Cell

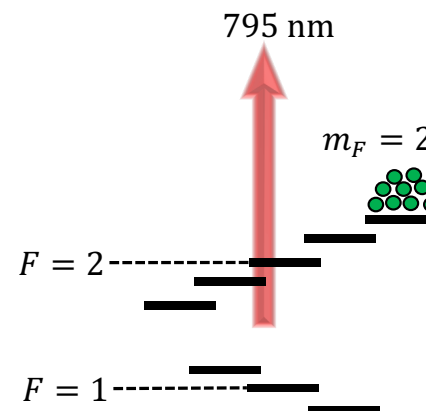
100°C

500 torr $\text{N}_2 + {}^{87}\text{Rb}$

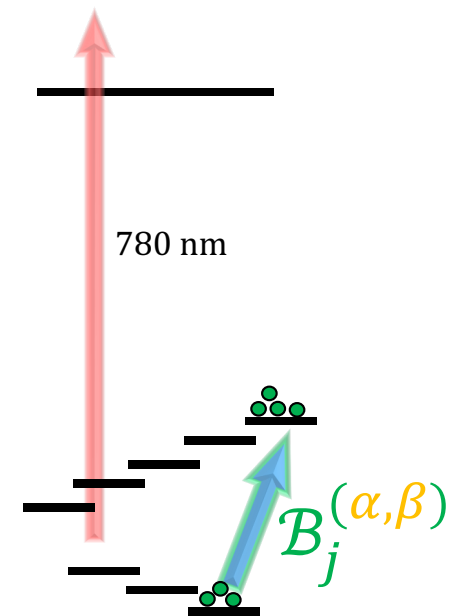
Side View



pump to stretch
($>90\%$ in $200\ \mu\text{s}$)



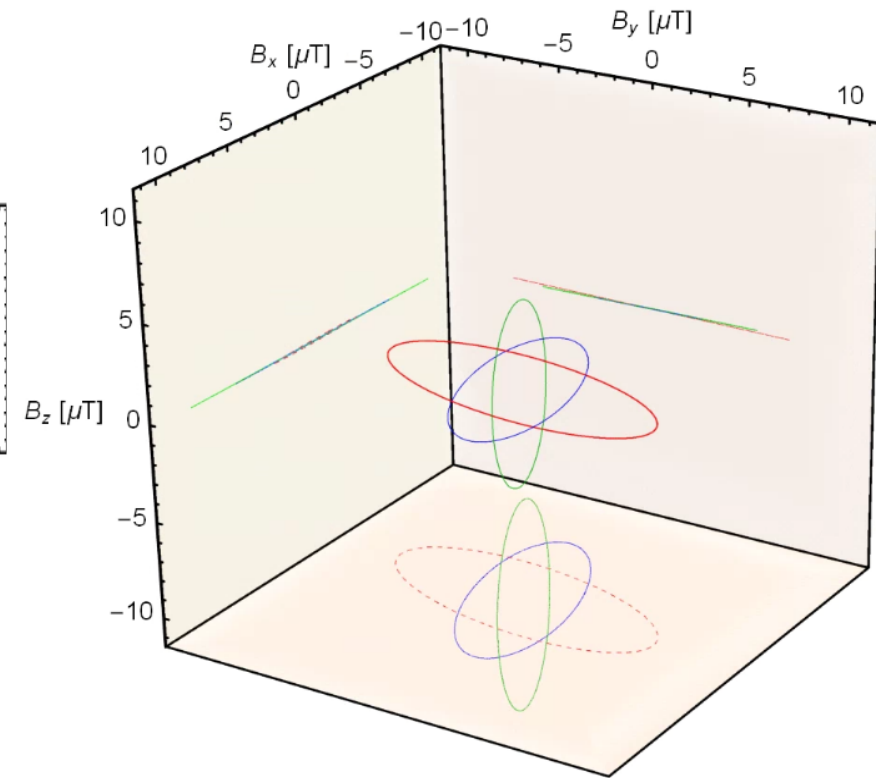
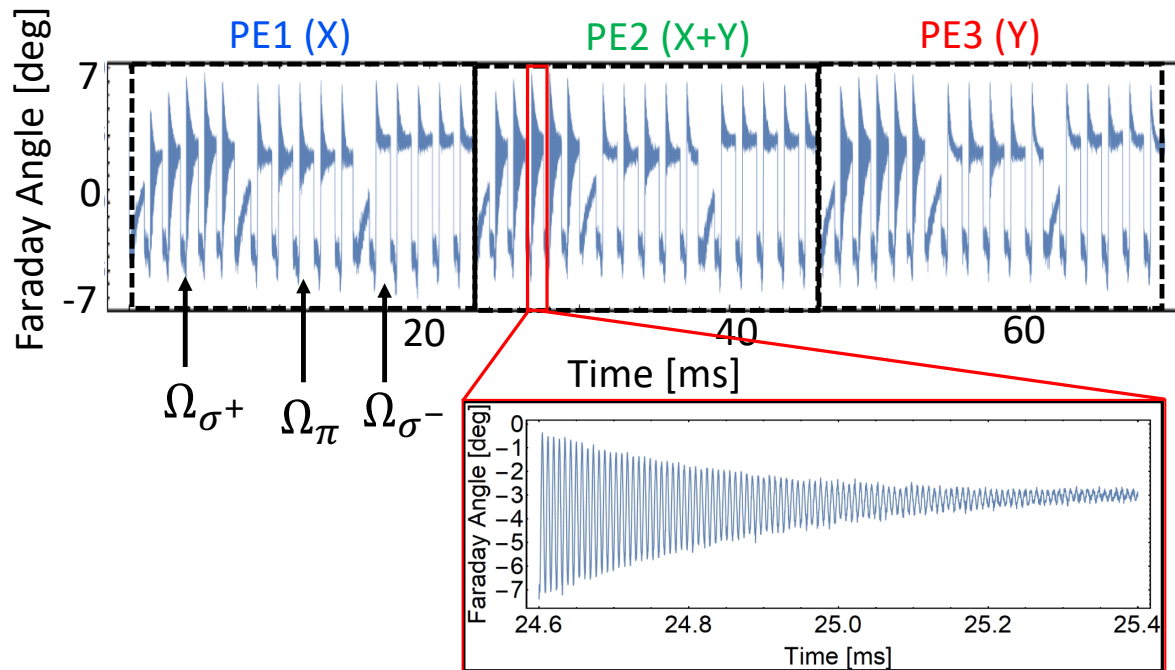
non-destructive measurement
with detuned probe



Review: sequential Rabi measurements for PE calibration

Vary static field $\vec{B}_s$ to calibrate $\vec{B}_\mu$

Real-Time Rabi Measurements for PE Calibration



Outline of supporting information on systematics

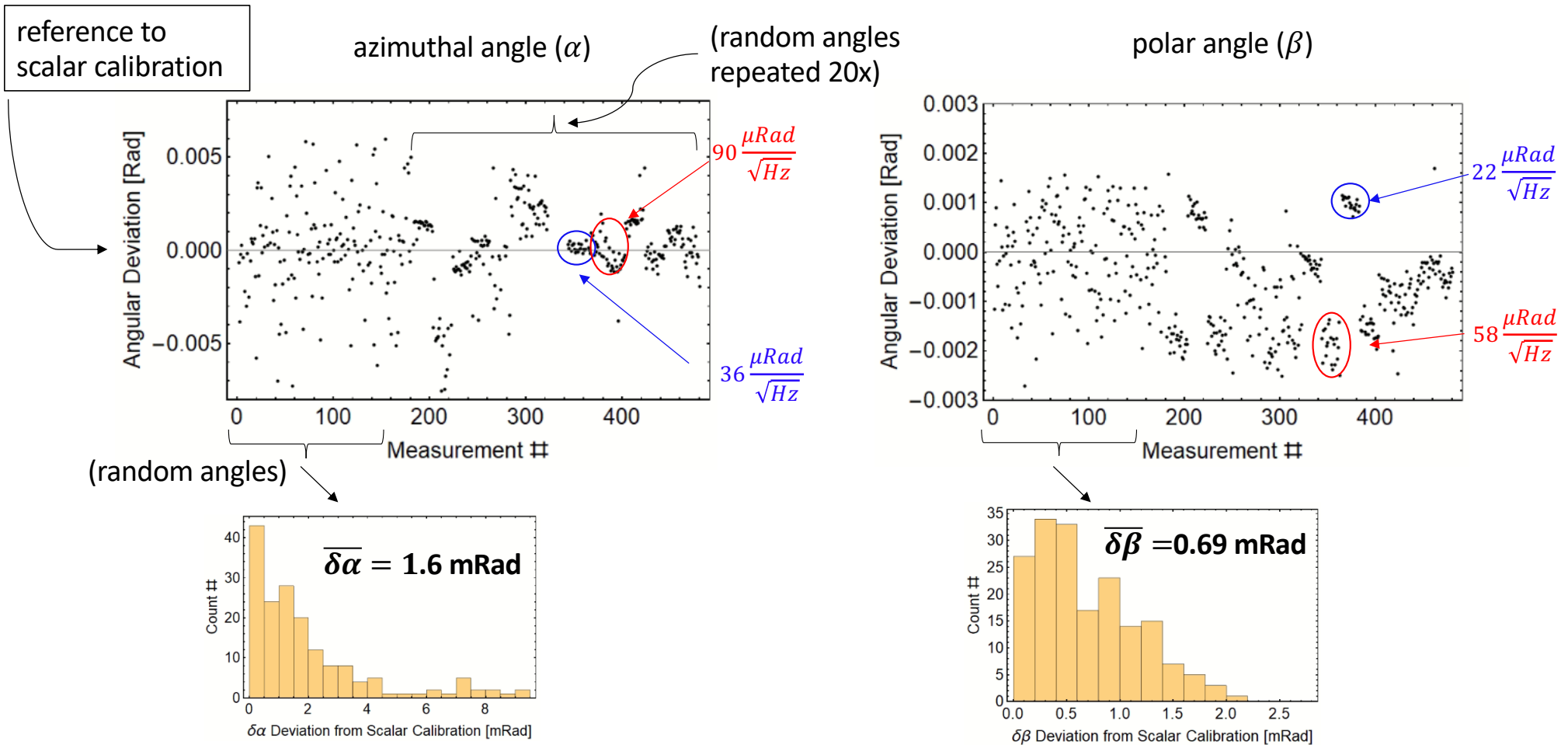
presentation of two key sets of information about systematics

elaborate on related system component analyses

- **DC coils:** changing (α, β) results in more noise than leaving fixed
 - in both scalar and Rabi modes
 - can study some aspects of this behavior
- **microwave** amplitude fluctuations or frequency dependence
 - fixed a number of problems to first order, but potentially residual concerns
- static **magnetic gradients** affect Rabi rates and corresponding fitting model error

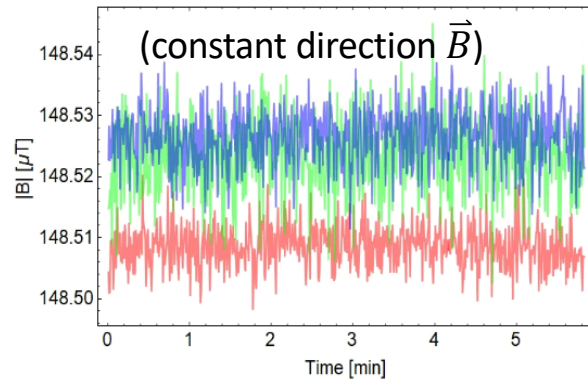
Vector accuracy report: Rabi deviation from scalar calibration

- whenever measuring Rabi found that fixed alpha and beta is less noisy
- using data from two PEs for vector measurement



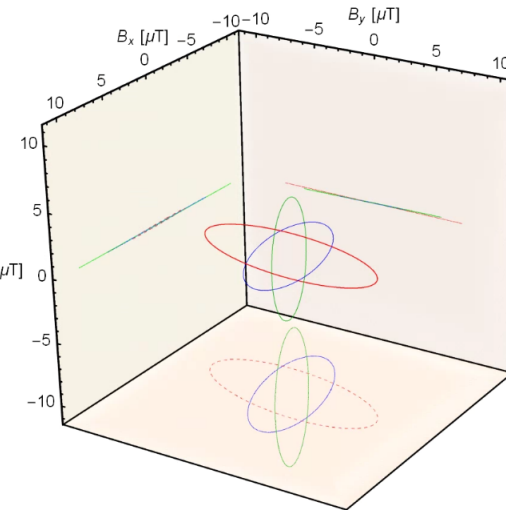
Scalar accuracy report

In March 2020,



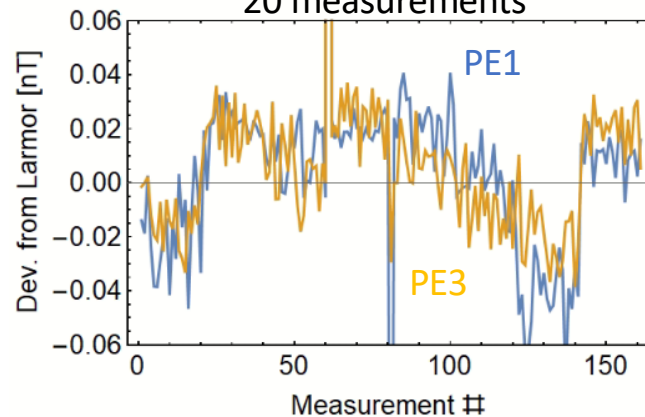
PE3 = Blue
PE2 = Green
PE1 = Red

Systematic
Between
PE's

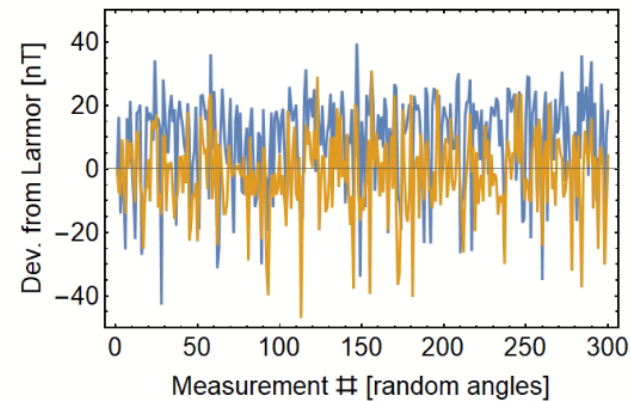


Recent data run:

direction held constant every
20 measurements



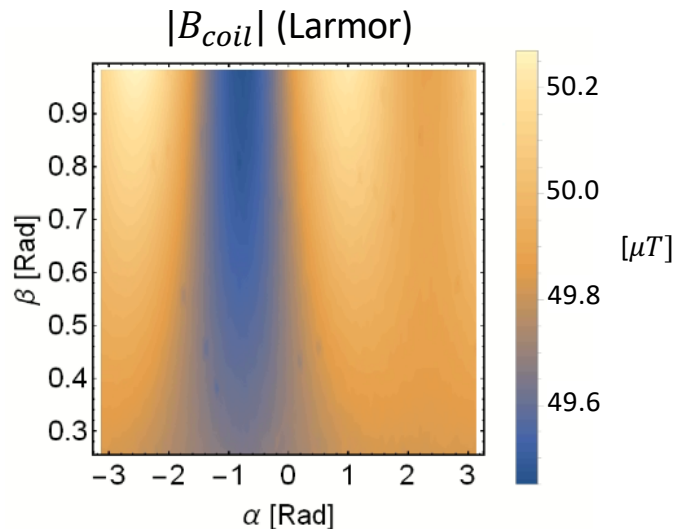
random direction every shot



~10 nT systematic on
average

Coil system benchmarking

Scalar measurements from Larmor precession are a useful tool to benchmark systematics related to our coil system.



1) scalar measurements serve as a benchmark of stability of coil system

a) How well does data agree with coil system model?

2) residuals of scalar calibration + statistical model benchmark vector accuracy

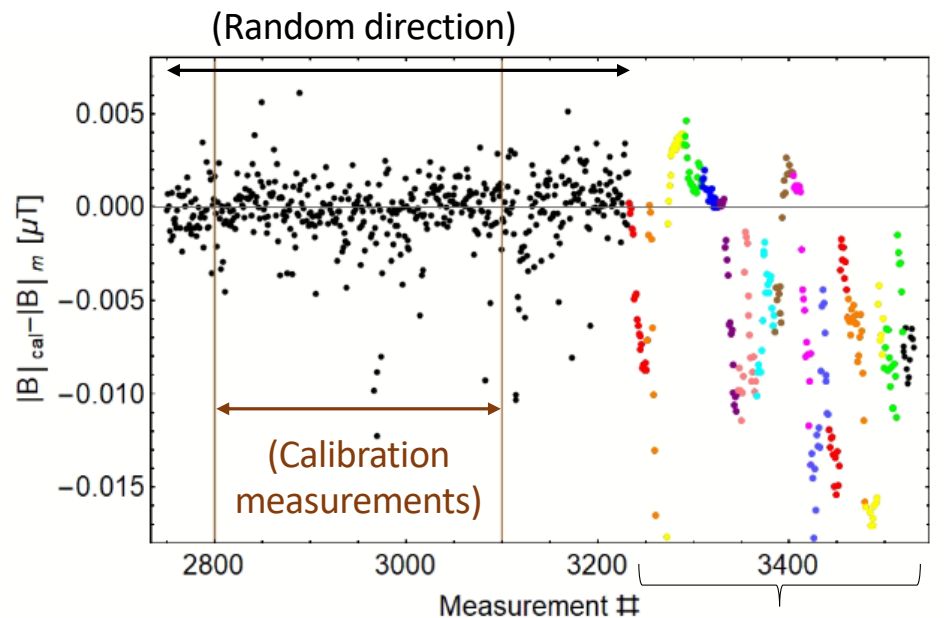
a) What is the vector accuracy from using finite calibration?

scalar calibration of
coil system parameters

$$d\beta_x, d\beta_y, d\alpha_y, |B_{bias}|, \epsilon_x, \epsilon_y, B_x, B_y, B_z$$

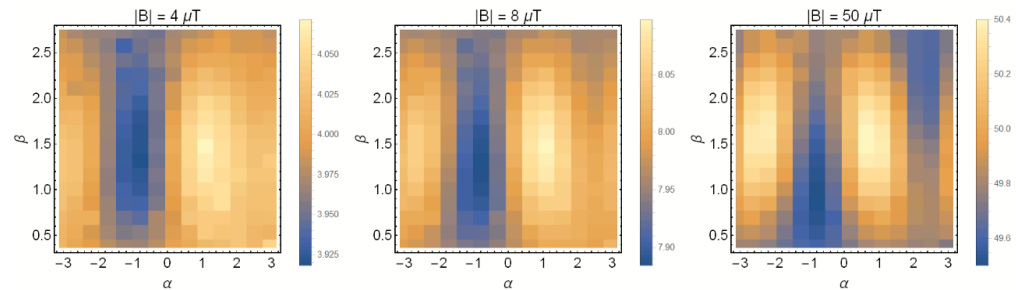
Coil system benchmark: observing instability

Scalar calibration residuals ($|B_{meas}| - |B_{cal}|$)



Directions held fixed
for 20 measurements

Varying $|B_{coil}|$ and observe drift in coil system parameters

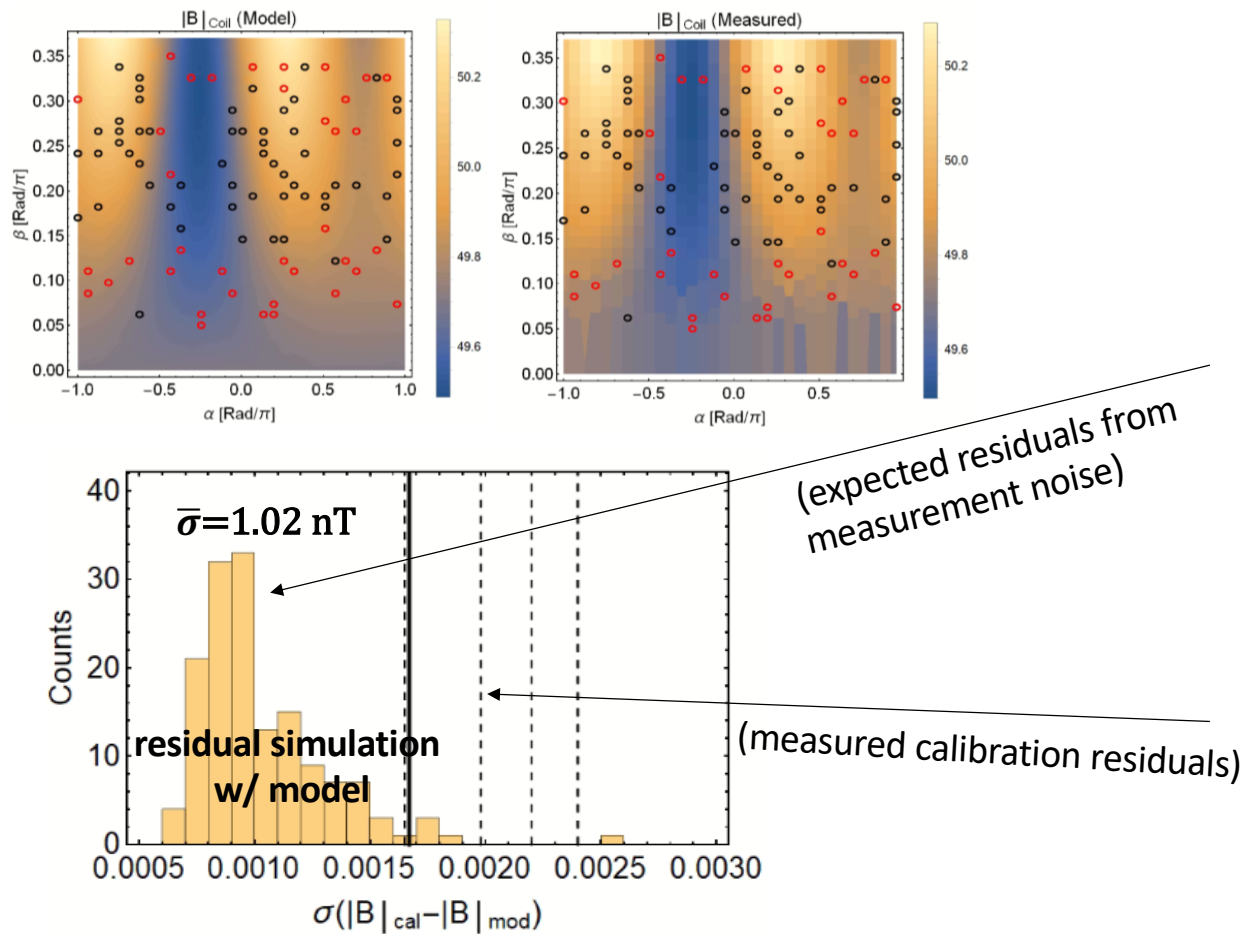


hypothesis: eddy currents + thermal
drifts from coil currents cause
instability

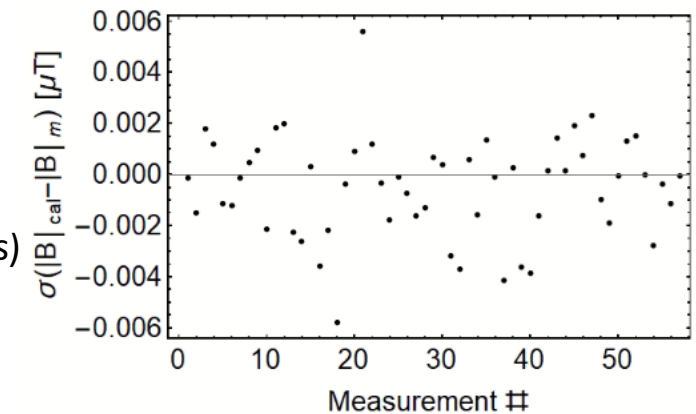
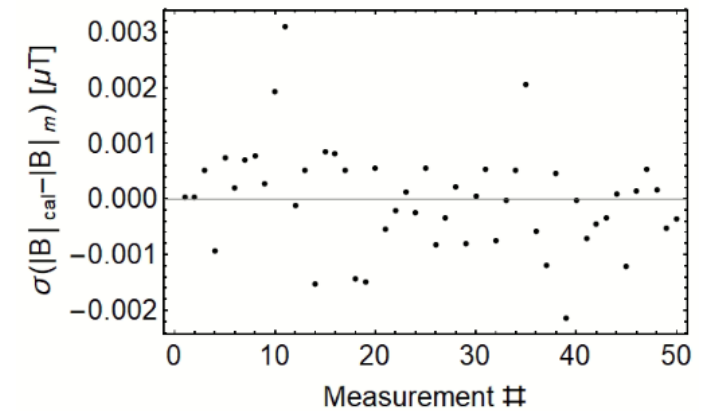
limit accuracy of calibration for vector
magnetometry

Coil system benchmark: vector accuracy bound from calib. residuals

Finite calibration time can limit accuracy (we now have a more quantitative analysis of this)

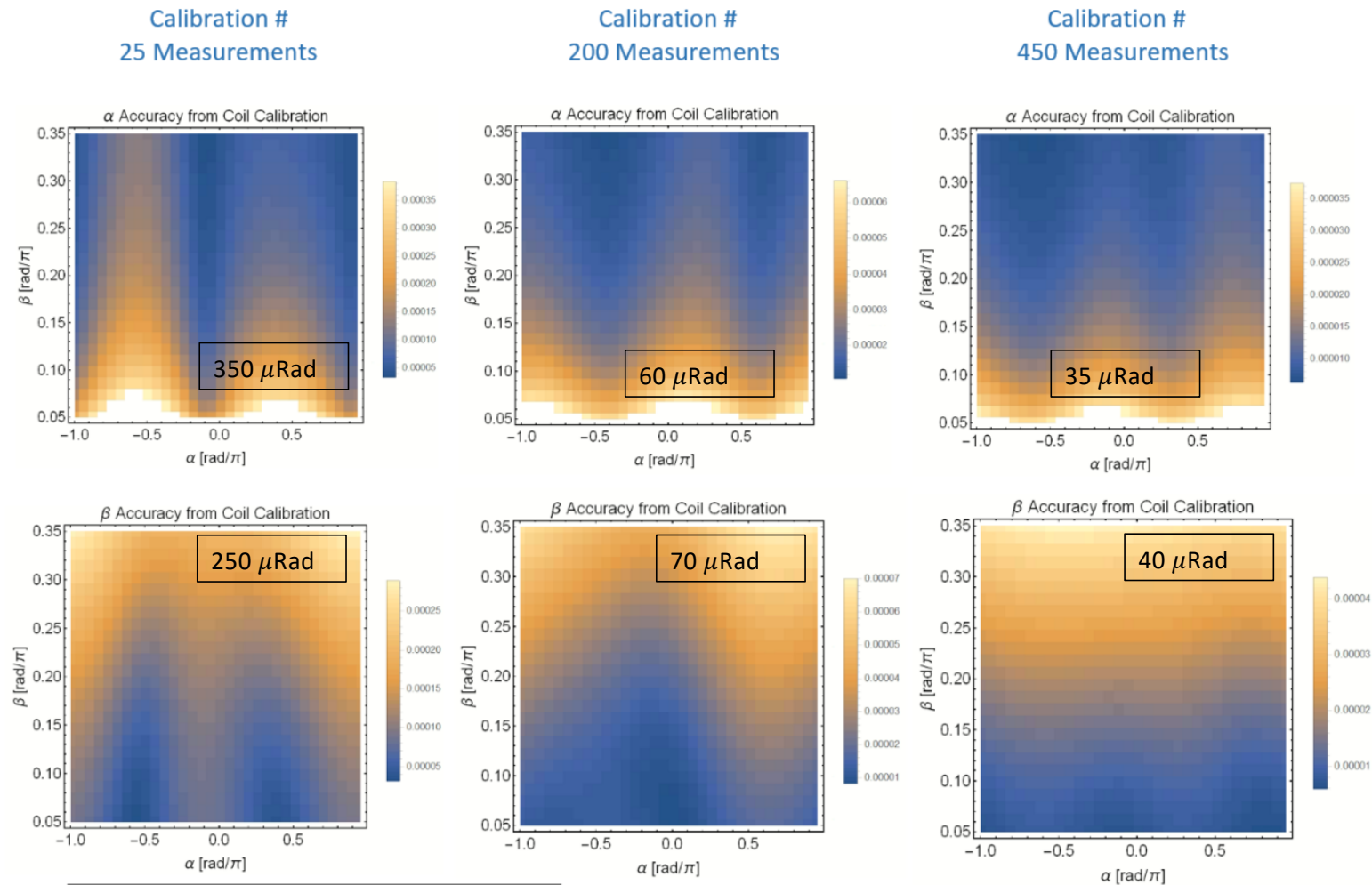


Calibration Residuals



Coil system benchmark: vector accuracy bound from calib. residuals

Finite calibration time can limit accuracy (we now have a more quantitative analysis of this)



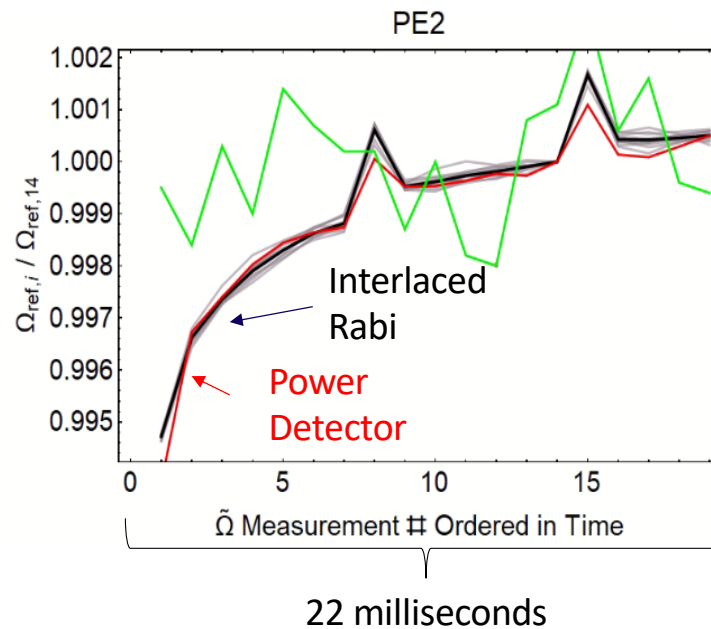
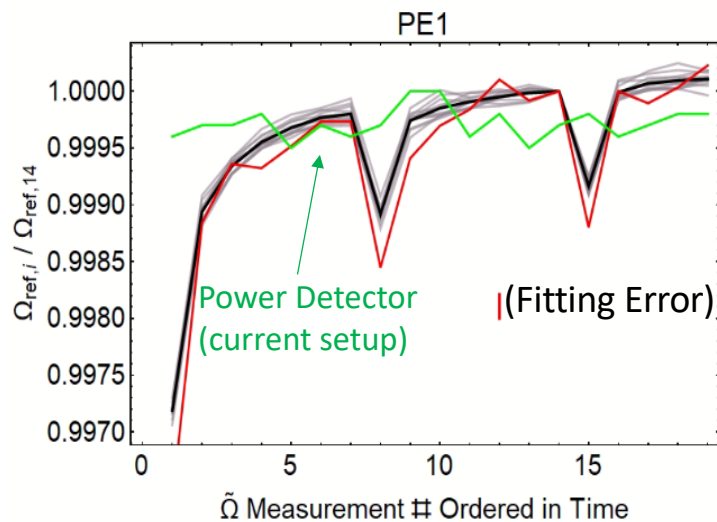
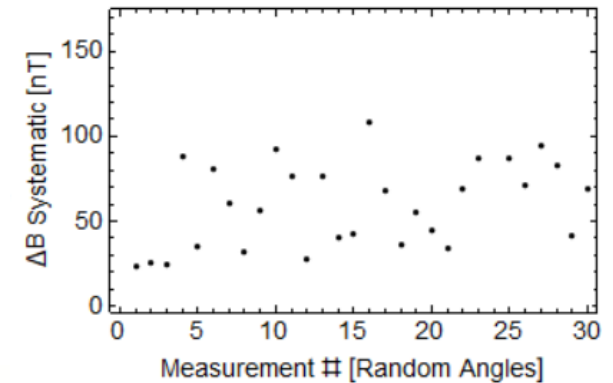
Microwave system: microwave power drifts

We observe fast microwave power drifts on the millisecond timescale.

- improved microwave turn on/off sequence for better stability
- incorporated microwave power detectors for monitoring

From
resonance
of Rabi
frequencies

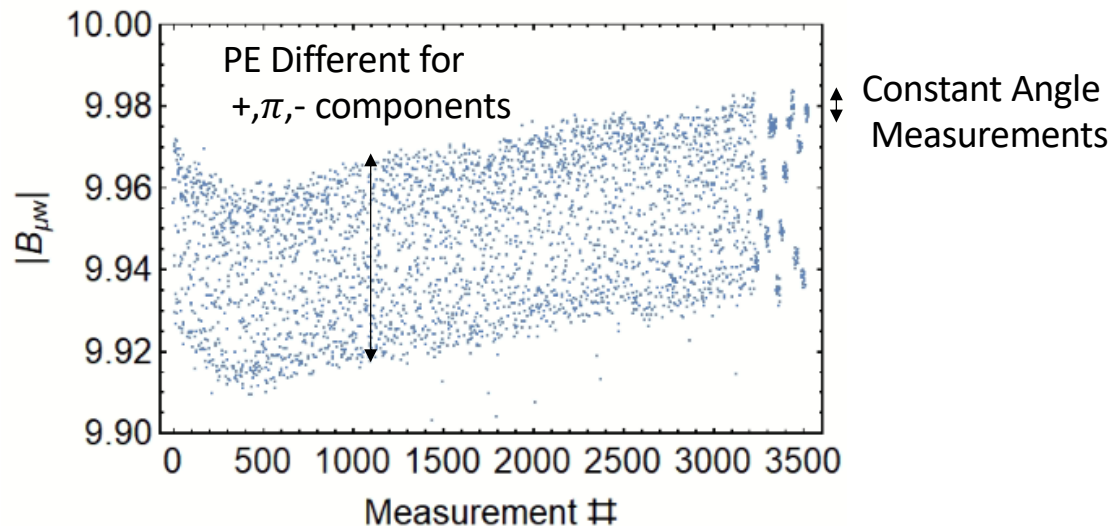
|B| Differences w/wo Drift Compensation



5%
Amplitude
Drift

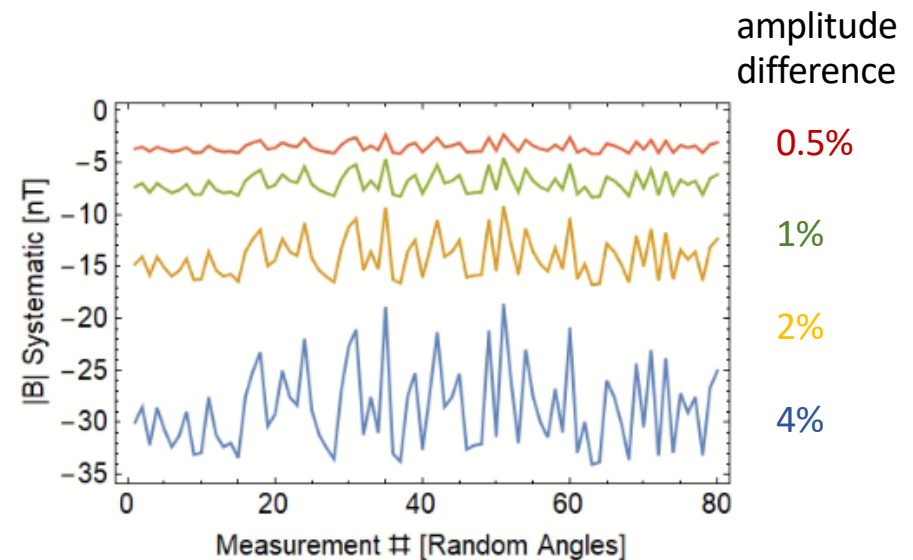
Microwave system: PE frequency dependence

norm of microwave field shows frequency dependence



- In June 2020: Broadened microwave cavity Q to minimize frequency dependence from cavity
 - Still see some frequency dependence
- appears to not affect current mRad inaccuracies in vector magnetometry
- can cause a few 10s of nT systematic in $|B|$ Rabi measurement

PE simulation assuming different $+, \pi, -$ components



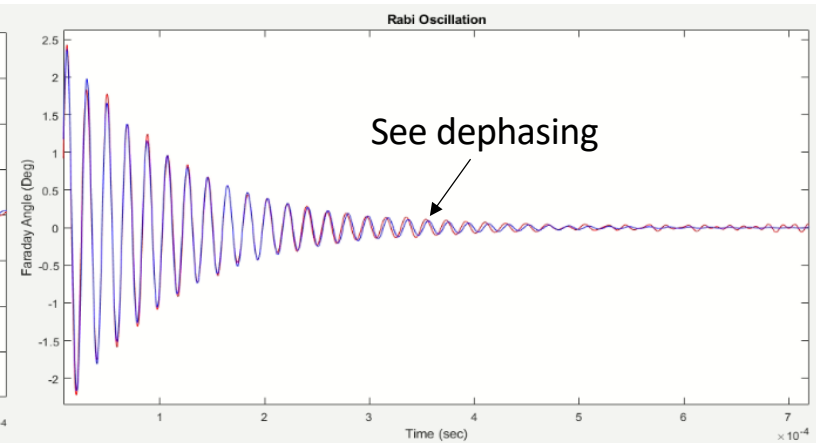
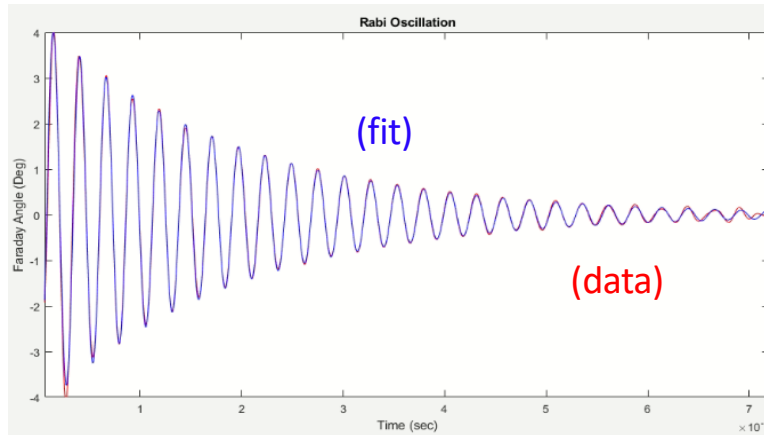
calibration fits give $\sim 6\%$ amplitude variation across the three transitions.

Magnetic gradients

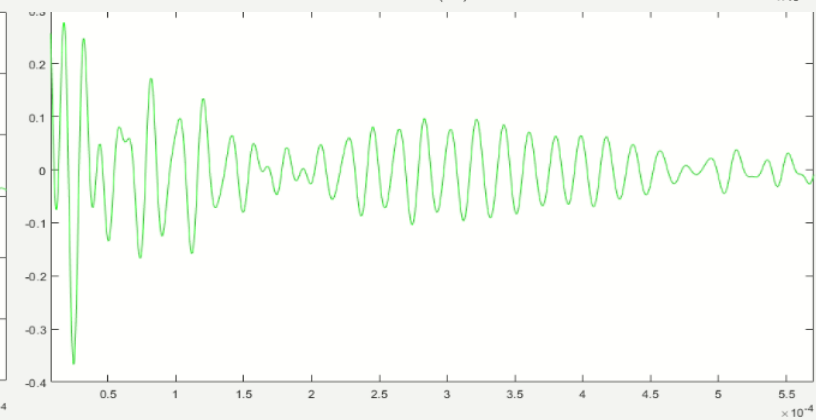
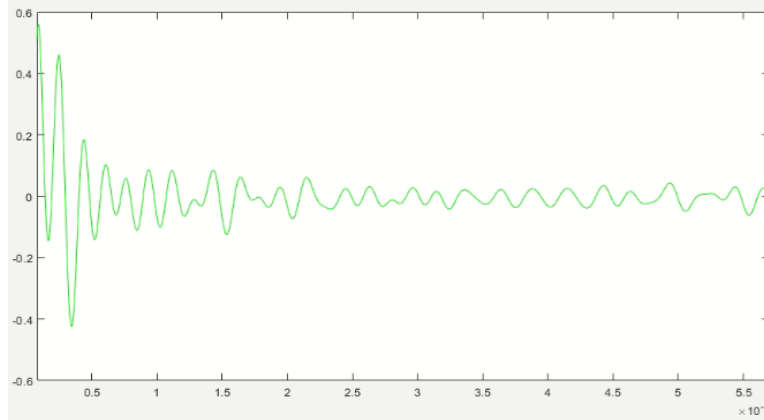
near-resonance

further-detuned

Rabi-oscillation



fit residual



Theoretical understanding of spin-exchange and Rabi FID

model [1]:

$$i\hbar \frac{d\rho}{dt} = \underbrace{A_{hf}[\mathbf{I} \cdot \mathbf{S}, \rho] + \mu_B[\mathbf{B} \cdot (g_s \mathbf{S} + g_I \mathbf{I}), \rho]}_{\text{Atomic Structure, Magnetic + Microwave}} + \underbrace{i\hbar \frac{\phi(1+4\langle S \rangle \cdot S) - \rho}{T_{ex}} + i\hbar \frac{\phi - \rho}{T_{sd}}}_{\text{Spin-exchange decoherence, Buffer Gas and Rb-Rb SD collisions}}$$

- Atomic Structure
- Magnetic + Microwave

- Spin-exchange decoherence
- Buffer Gas and Rb-Rb SD collisions

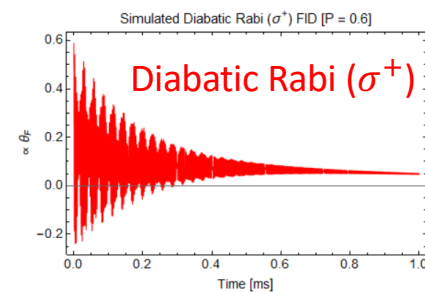
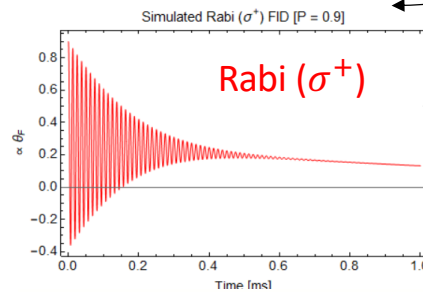
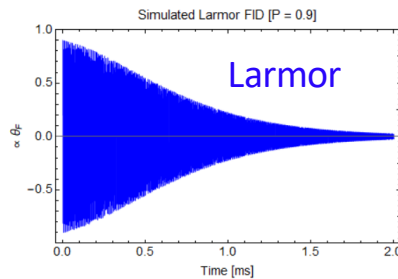
estimated decoherence
from cell parameters
($T_{cell} = 100^\circ C$,
500 Torr N_2 Buffer Gas):

$$1/T_{sd,buffer} = 156 \text{ Hz}$$

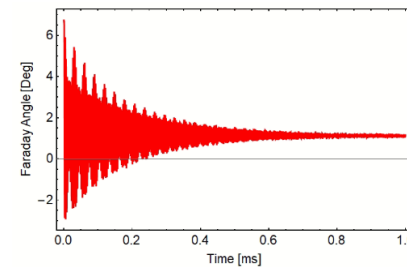
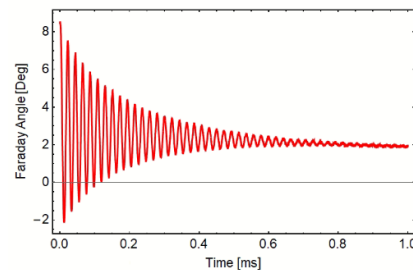
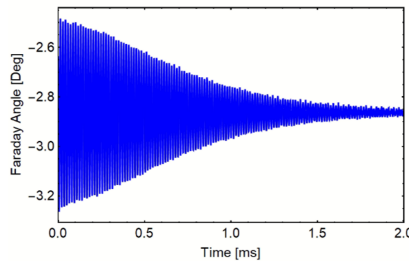
$$1/T_{sd,Rb-Rb} = 4 \text{ Hz}$$

$$1/T_{ex} = 2.2 \text{ kHz}$$

numerical
solution



experiment



[1] <https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.89.130801>

Manuscripts in progress

- Manuscripts in progress
 - 1) Coherence of Rabi oscillations with spin-exchange
 - 2) Atomic vapor vector Rabi magnetometry