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The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

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

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RPPR Final Report
as of 23-Sep-2021

Agency Code: 21XD

Proposal Number: 75189PHDRP
Agreement Number: W911NF-19-1-0330

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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 Summar 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
Funding Support:
Project Contribution:
National Academy Member: N

Participant Type: Co PD/PI
Participant: Toobias Thiele
Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Chris Kiehl
Person Months Worked: 7.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Ting-Wei Hsu
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Undergraduate Student
Participant: Daniel Wagner
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Partners

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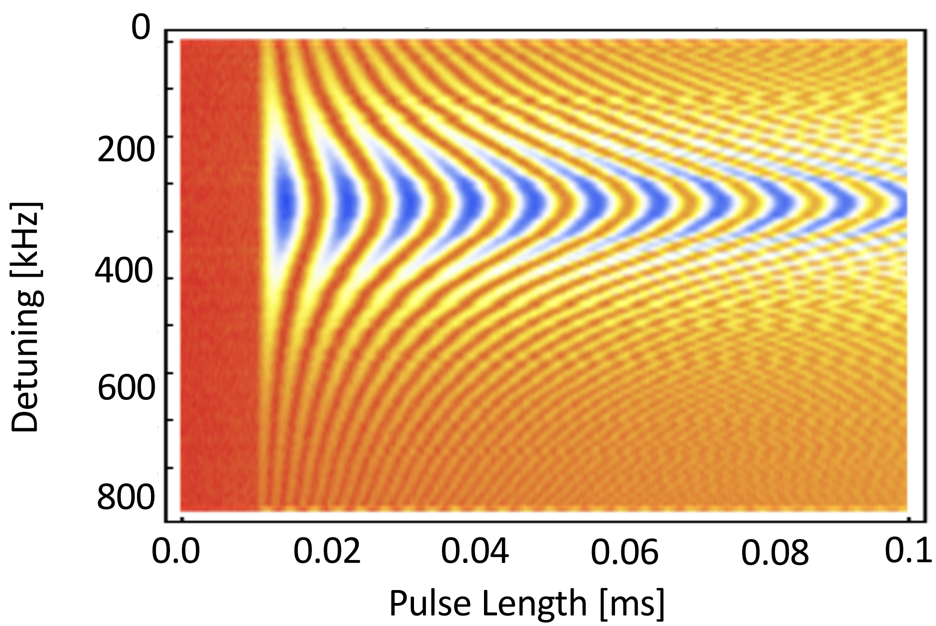
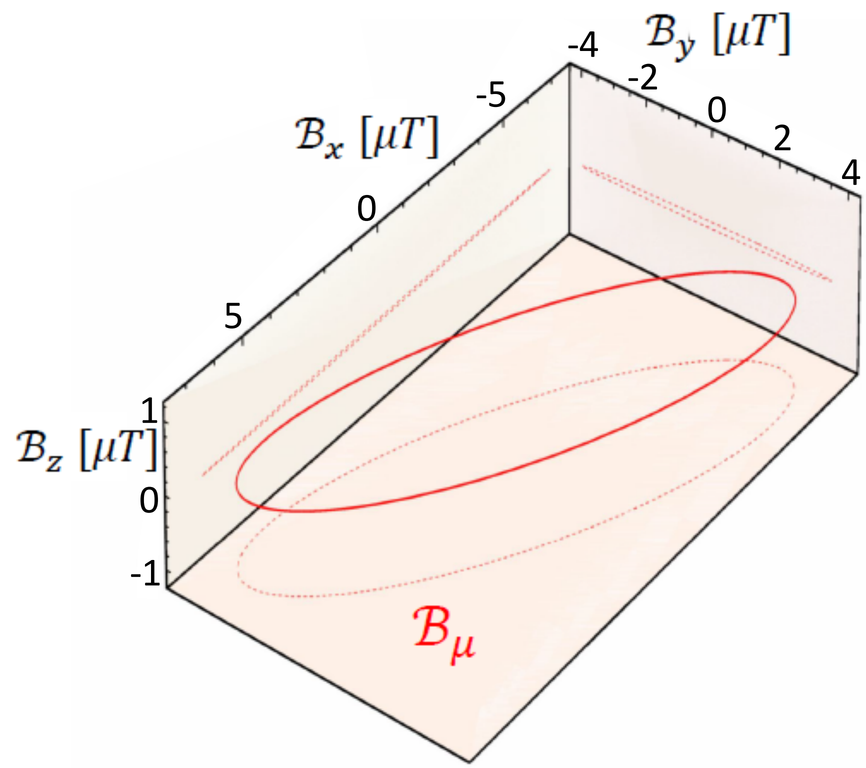
RPPR Final Report
as of 23-Sep-2021

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

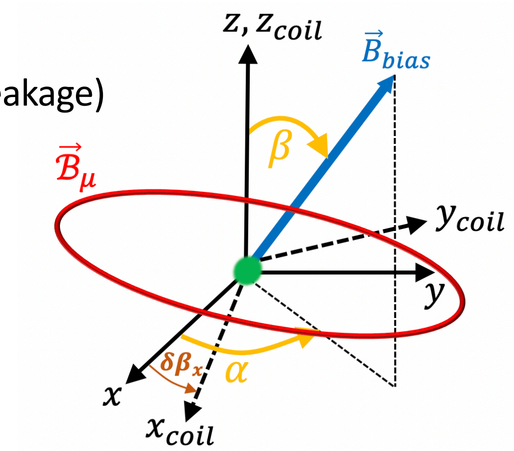




Overview

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: $S_{|B|} = 16\, pT/\sqrt{Hz}$ $(2\, pT/\sqrt{Hz})$* (dominated by coil noise, gradients) *single shot
  - vector: $S_{\alpha} = 35\, \mu Rad/\sqrt{Hz}$ $S_{\beta} = 17\, \mu Rad/\sqrt{Hz}$ (in optimal angular regions)
  - Rabi component noise: $90\, pT/\sqrt{Hz}$ $(7\, pT/\sqrt{Hz})$* (dominated by microwave noise)
  - Rabi scalar: $S_{|B|} = 340\, pT/\sqrt{Hz}$ (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

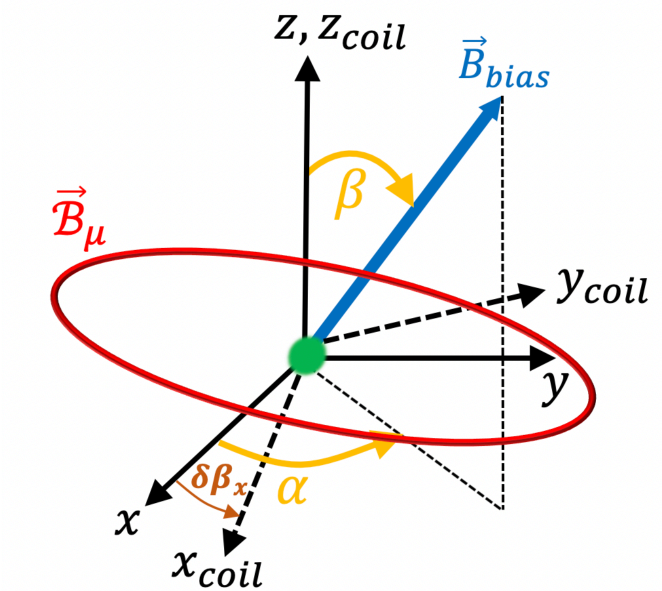
additional non-ideal effects discovered over time and recently:

<u>facts from data studying sensitivity</u> 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



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

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

⬇

Calibrate out systematics

- P.E. described by:

$$\vec{\mathcal{B}}_\mu = \frac{1}{2} \sum_{j \in \{x,y,z\}} \mathcal{B}_j e^{-i(\phi_j + \omega t)} + c.c. \quad \Rightarrow \quad \text{5 P.E. parameters:}$$

$$\mathcal{B}_x, \mathcal{B}_y, \mathcal{B}_z, \phi_x, \phi_y \ (\phi_z = 0)$$

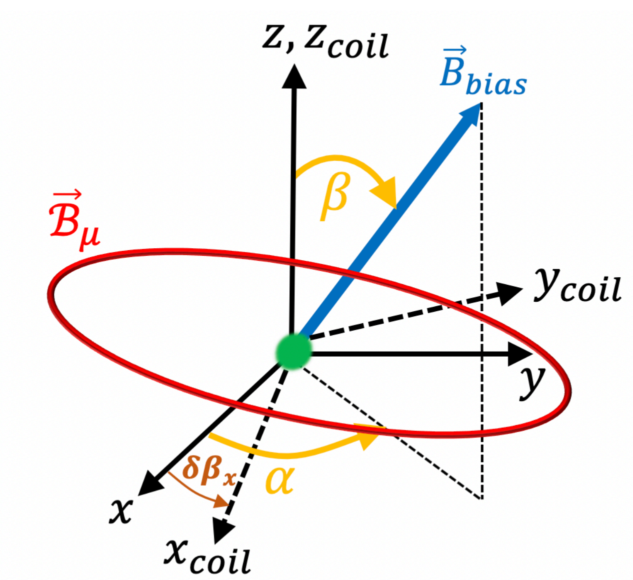
- P.E. parameters determined by solving system of (>5) equations

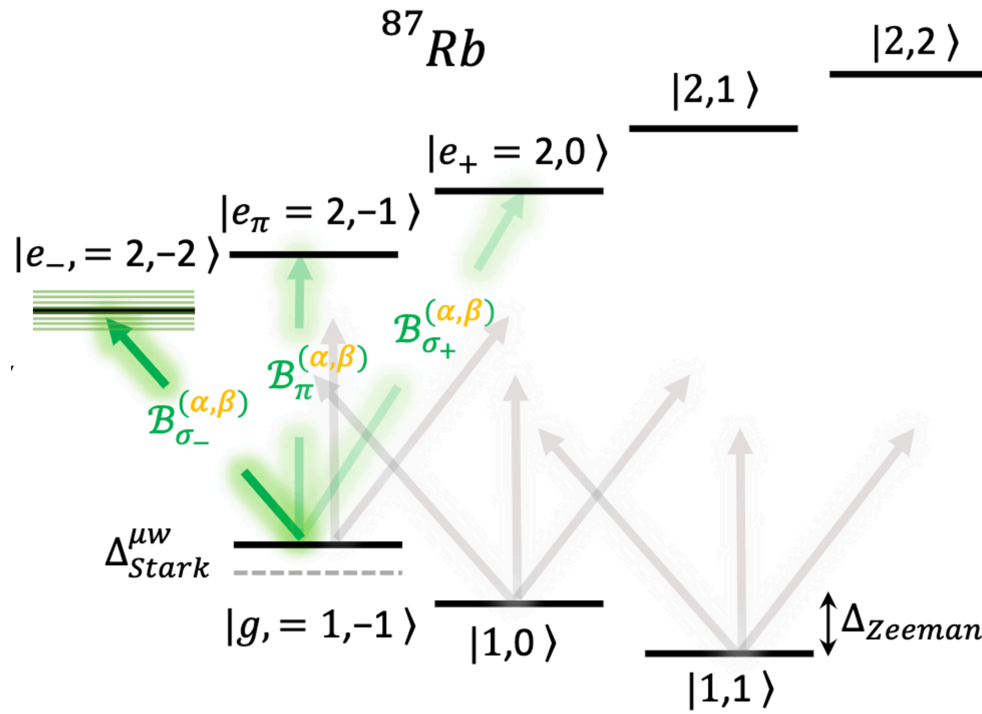
$$\left(\boxed{B_\pi^{(\alpha_c,\beta_c)}}\right)^2 = f_\pi\left(\boxed{\mathcal{B}_x, \mathcal{B}_y, \mathcal{B}_z, \phi_x, \phi_y, \delta\beta_x, \dots}, \boxed{\alpha_c, \beta_c}\right)$$

$$\left(\boxed{B_{\sigma_\pm}^{(\alpha_c,\beta_c)}}\right)^2 = f_\pm\left(\boxed{\mathcal{B}_x, \mathcal{B}_y, \mathcal{B}_z, \phi_x, \phi_y, \delta\beta_x, \dots}, \boxed{\alpha_c, \beta_c}\right)$$

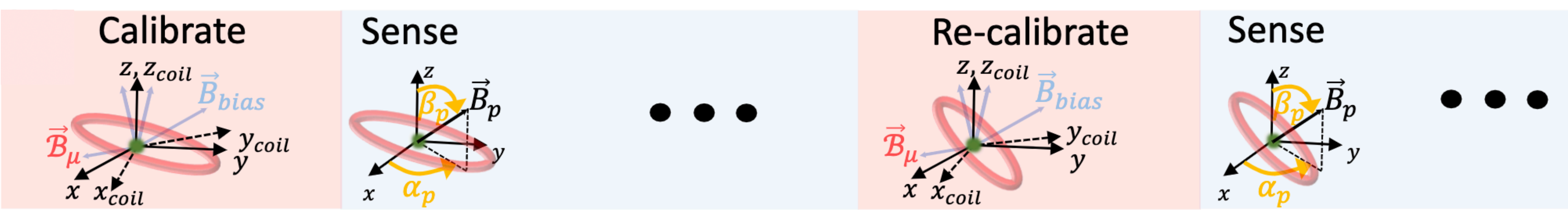
Measure **Solve For Parameters** **Model Correction Variables** **Set Parameter**

Review: idea of polarization ellipse reference

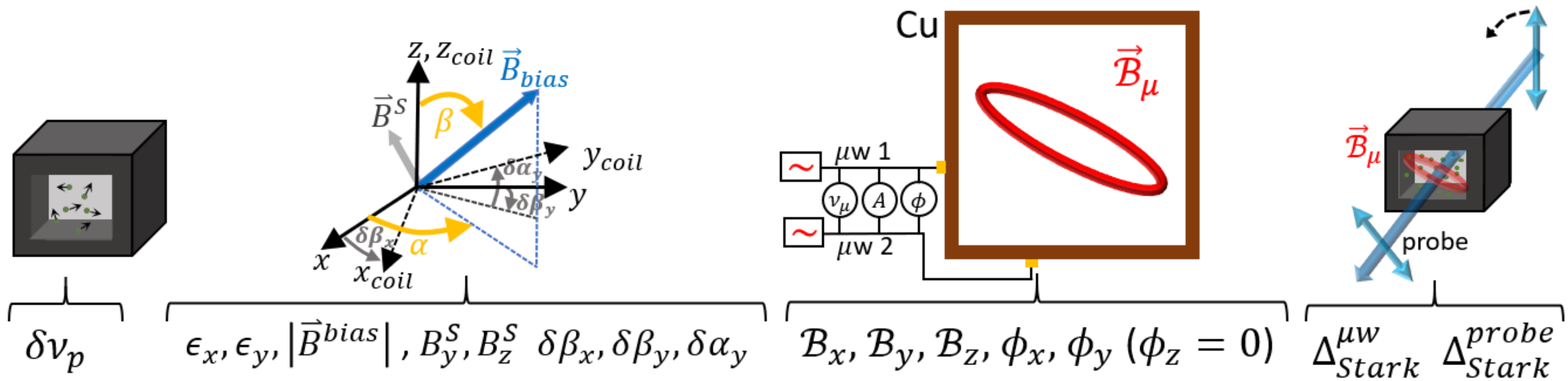




0.5 s of deadtime between each measurement!

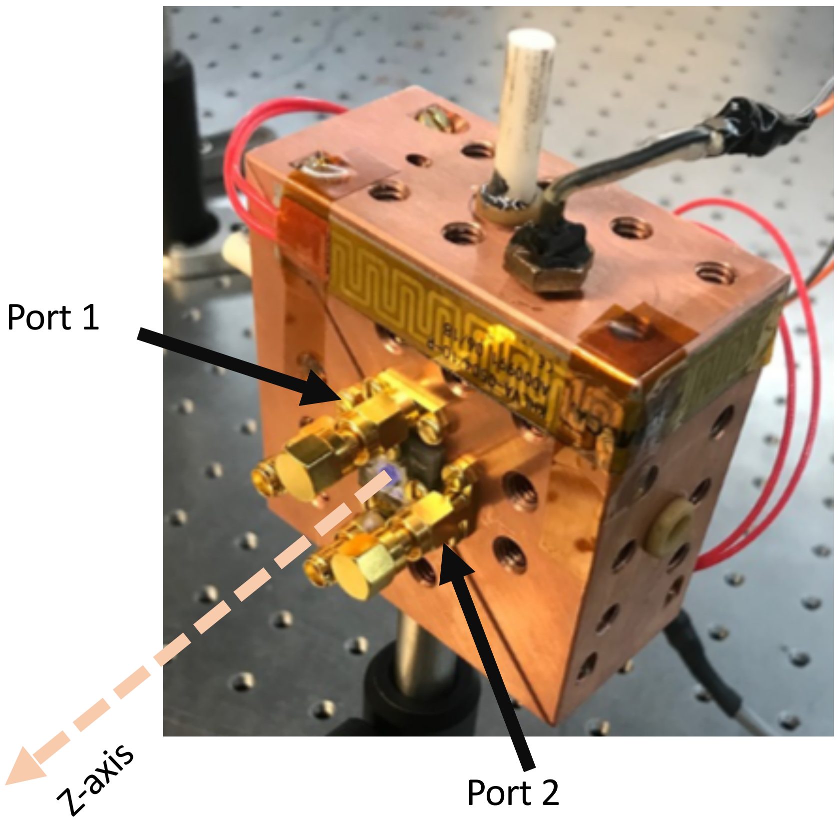


Review: expansion of parameters our algorithm calibrates



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

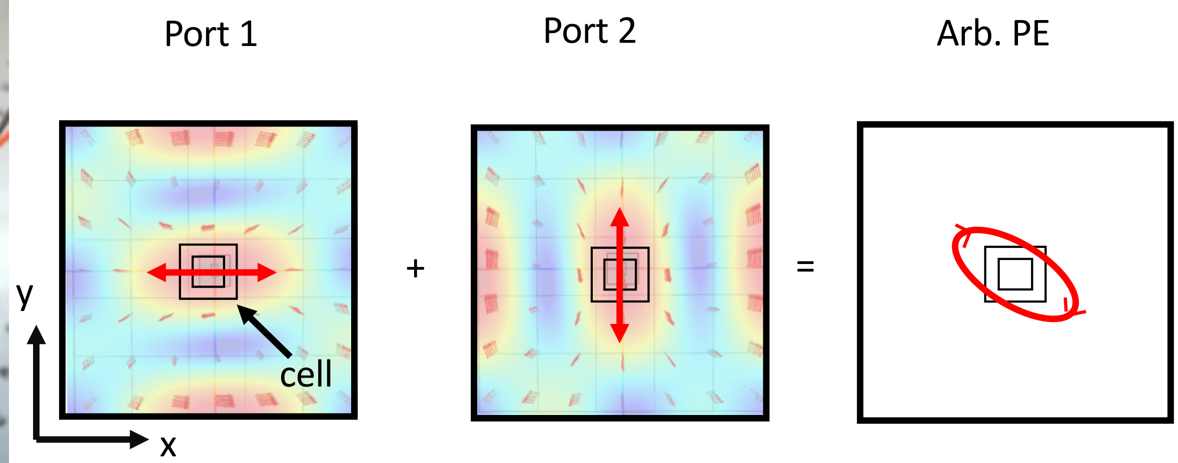
Review: microwave source – arbitrary polarization control



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

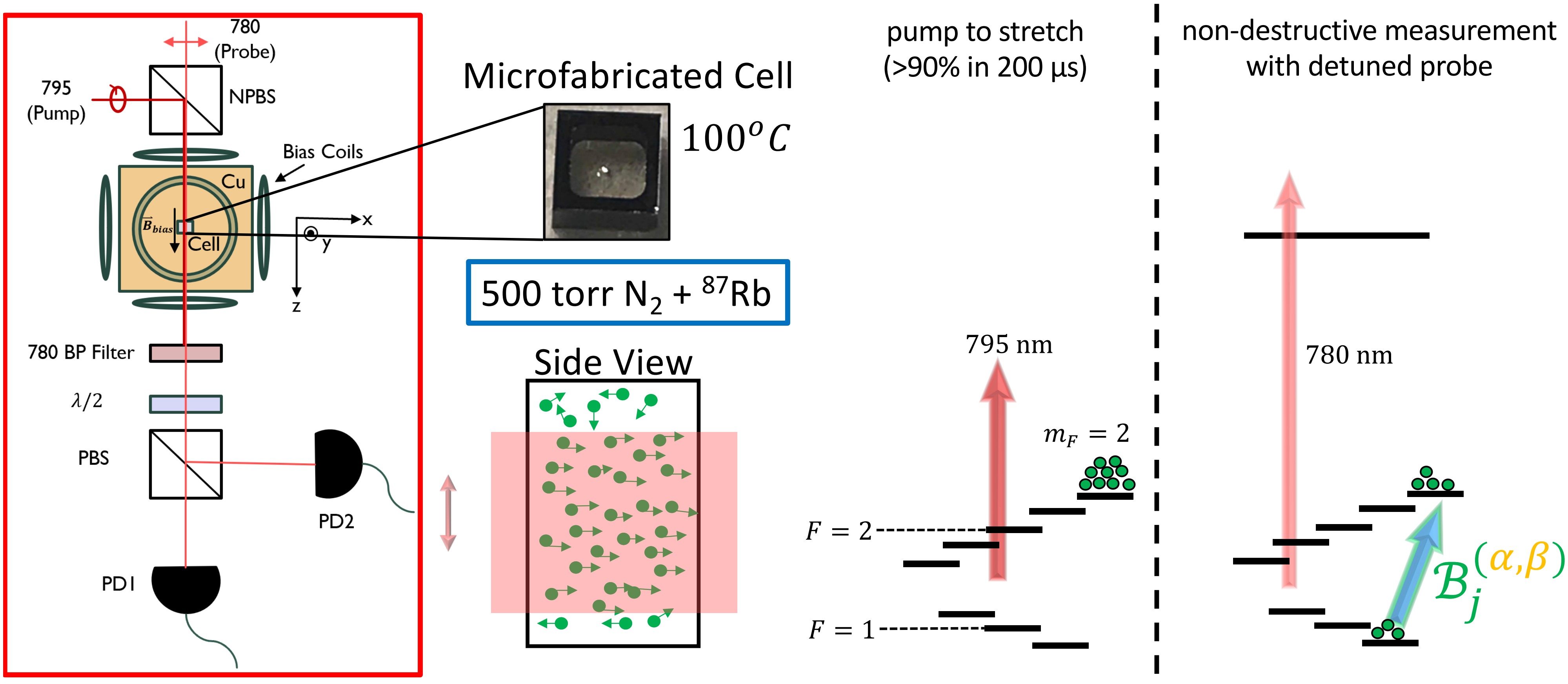
Cavity Modes

$(n_x, n_y, n_z) = (2{,}1{,}0)$ and $(1{,}2{,}0)$



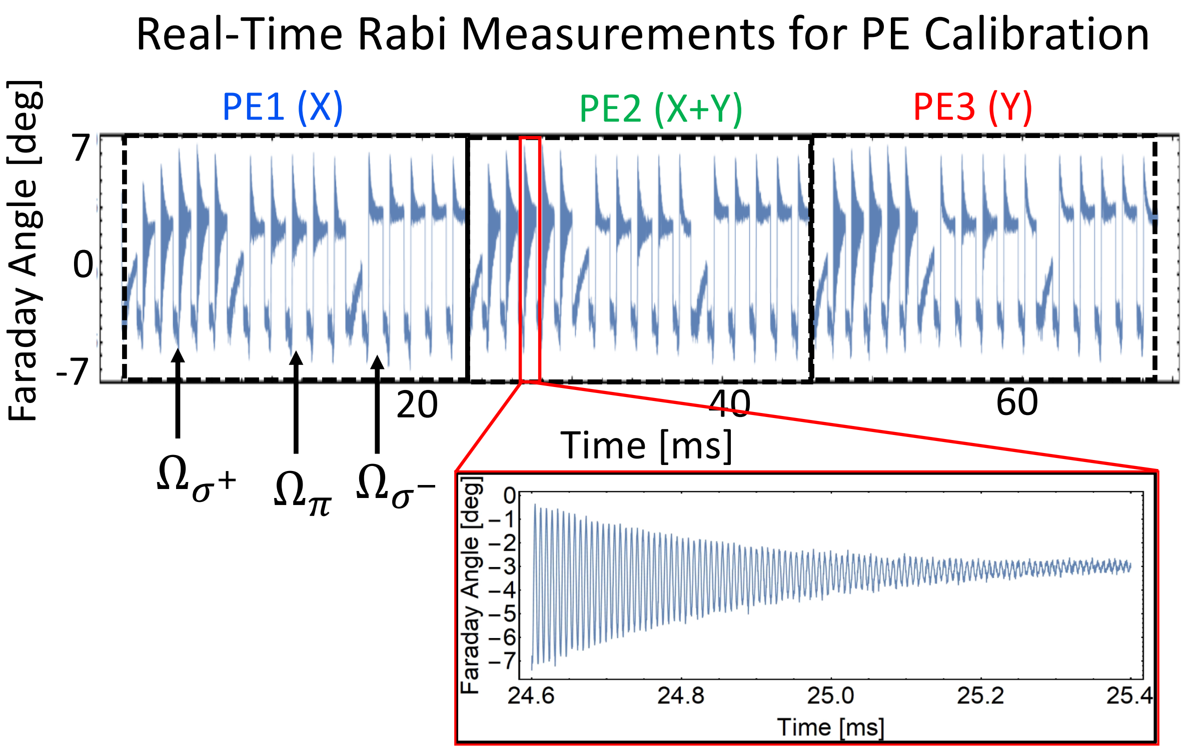
frequency-dependent amp and phase of cavity (including an accidental detuning) causes differential effects for transitions

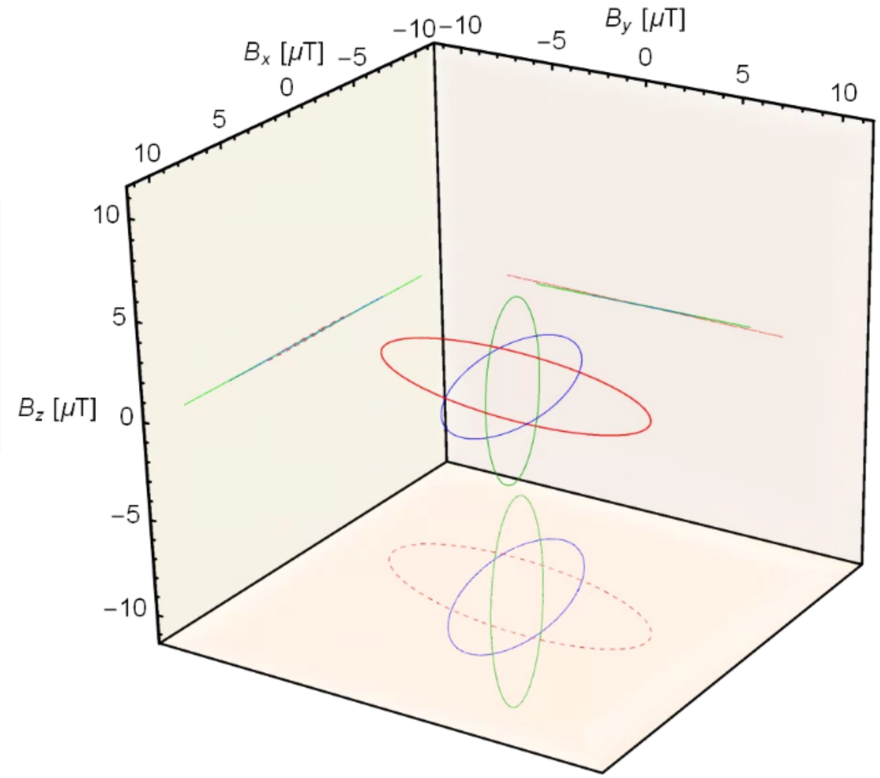
Review: experiment setup



Review: sequential Rabi measurements for PE calibration

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





Outline of supporting information on systematics

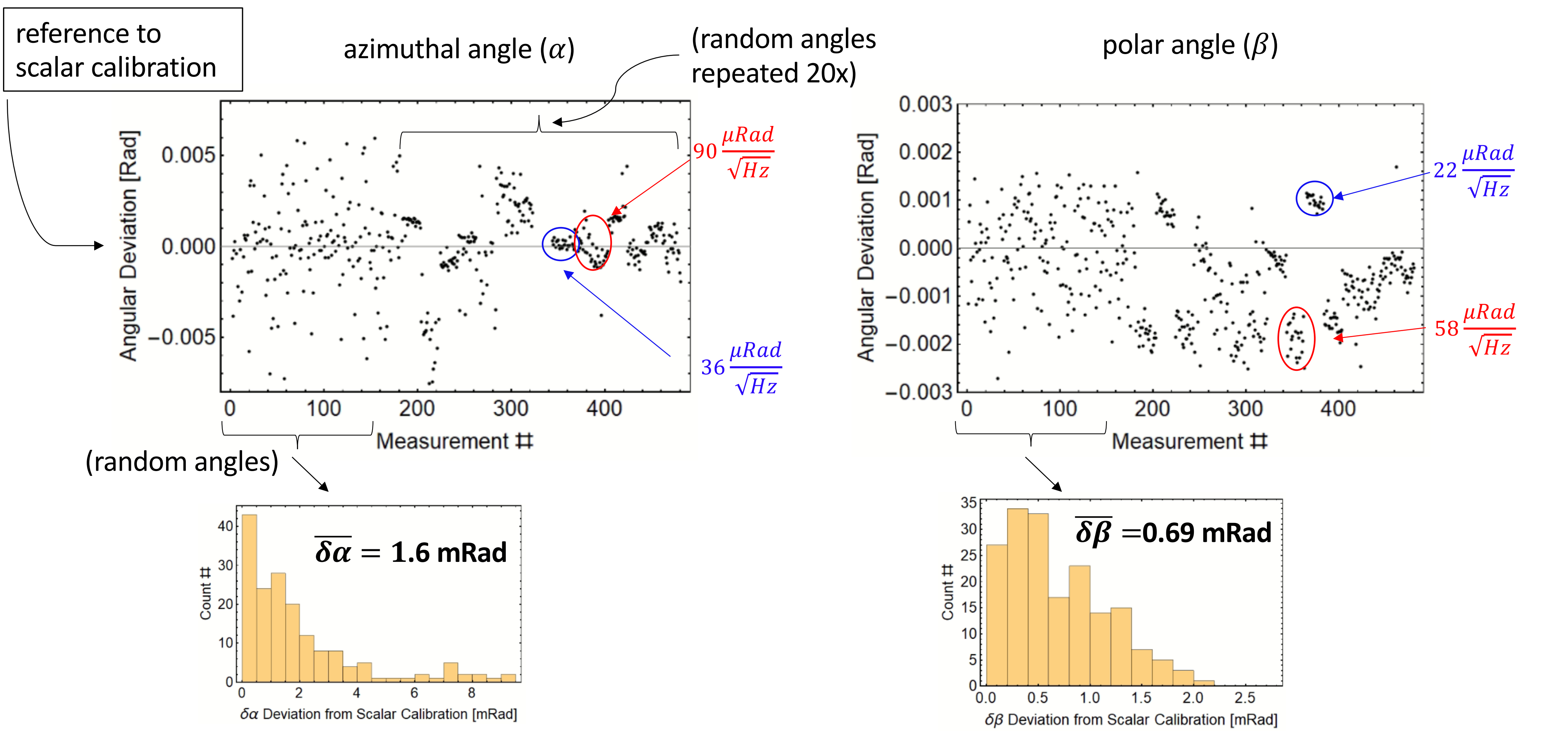
presentation of two key sets of information about systematics

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

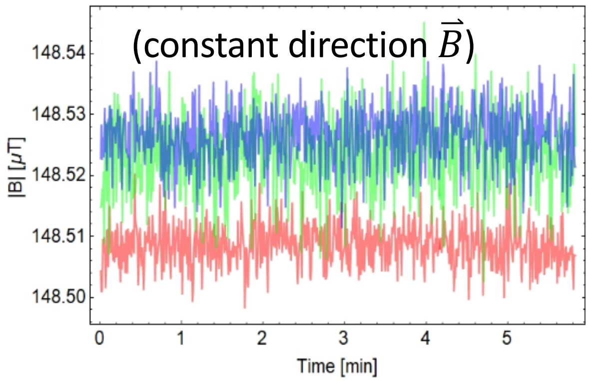
Vector accuracy report: Rabi deviation from scalar calibration

- 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,

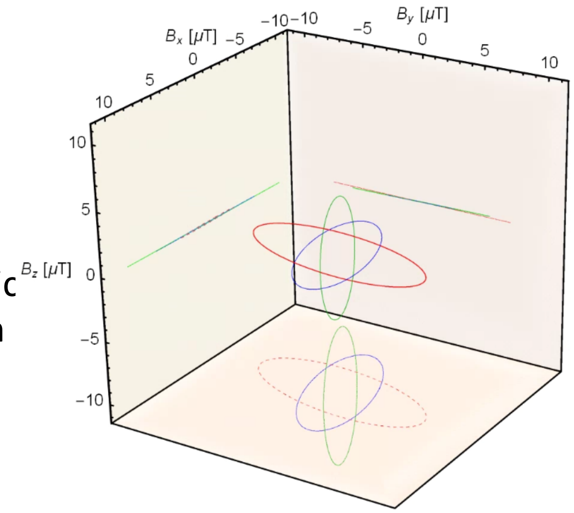


PE3 = Blue

PE2 = Green

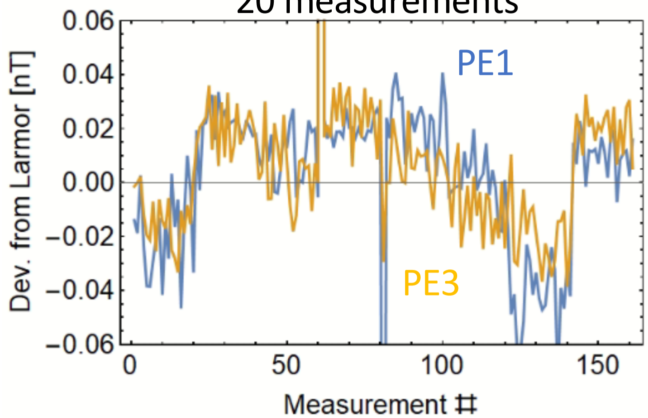
PE1 = Red

Systematic Between PE's

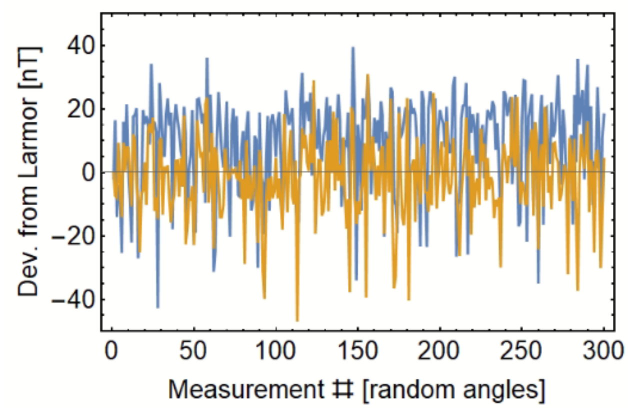


Recent data run:

direction held constant every 20 measurements



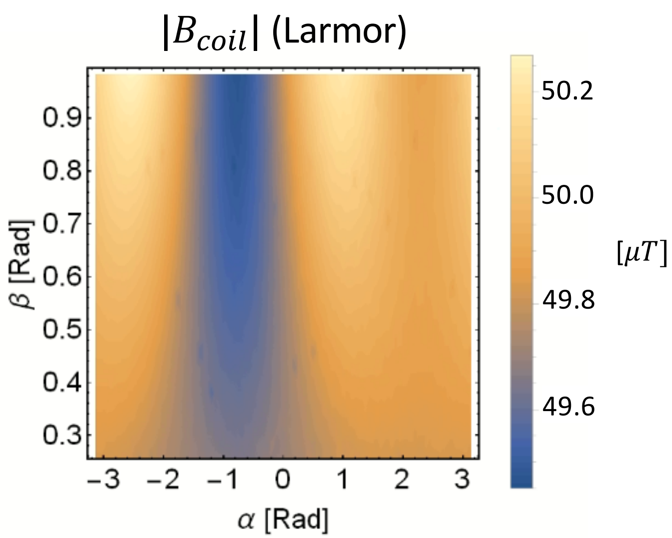
random direction every shot



~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.



scalar calibration of coil system parameters

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

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

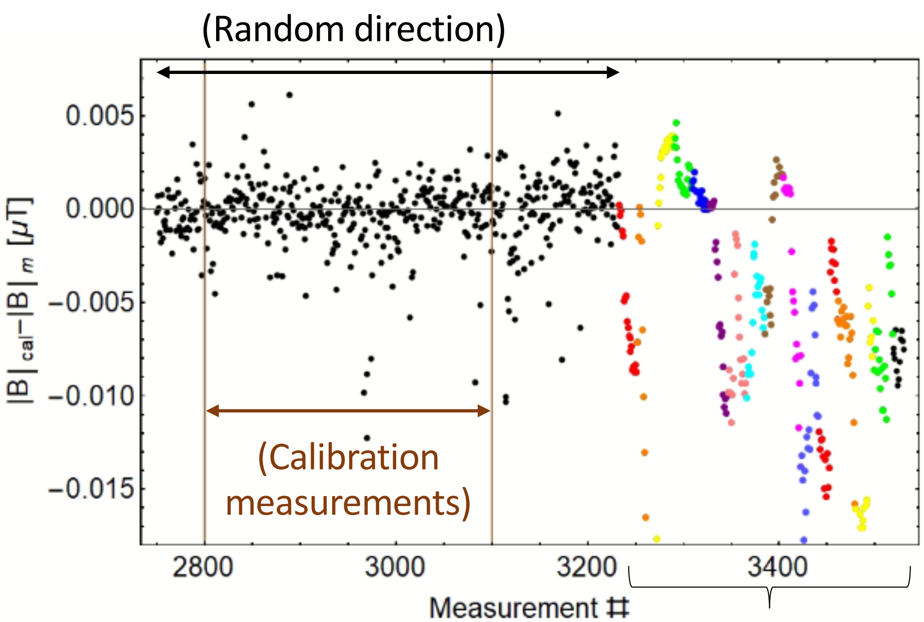
   a) How well does data agree with coil system model?

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

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

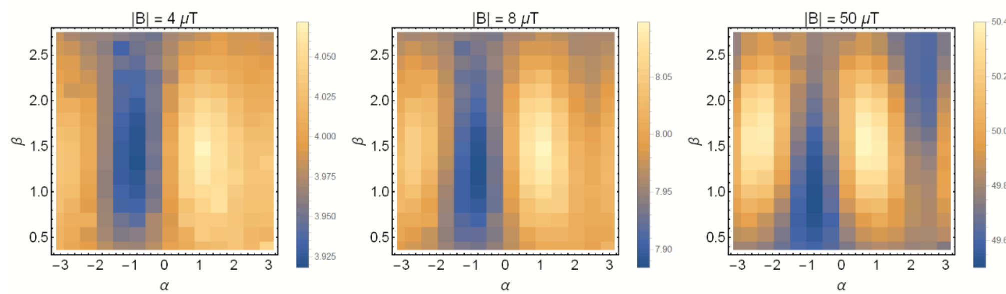
Coil system benchmark: observing instability

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



Directions held fixed for 20 measurements

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

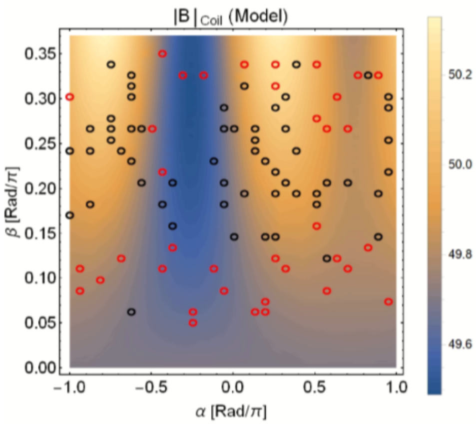


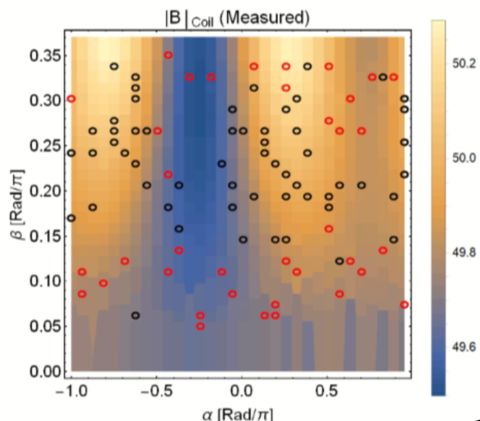
hypothesis: eddy currents + thermal drifts from coil currents cause instability

limit accuracy of calibration for vector magnetometry

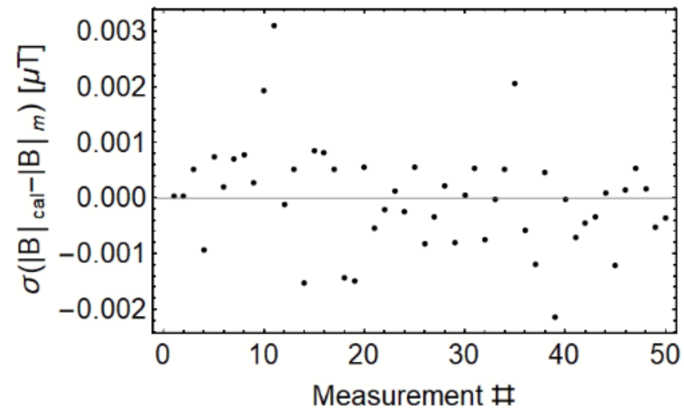
Coil system benchmark: vector accuracy bound from calib. residuals

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

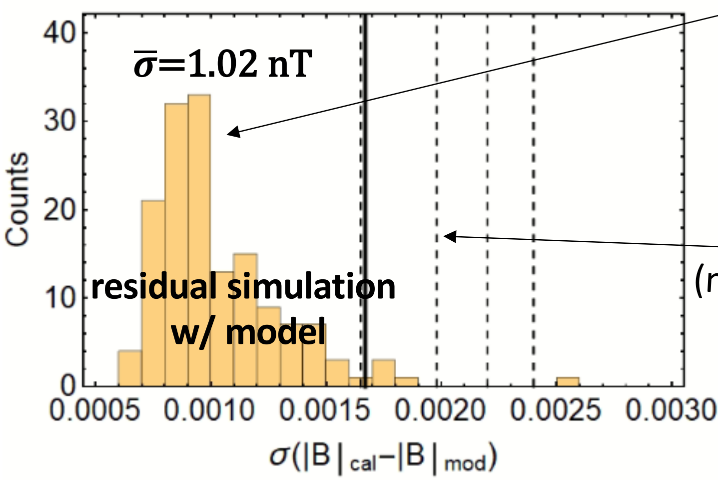




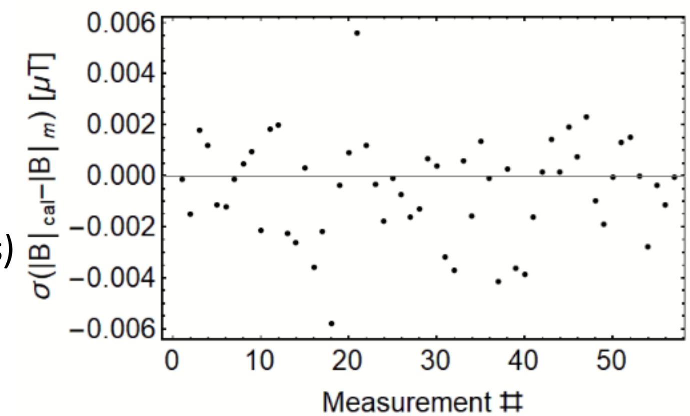
Calibration Residuals



(expected residuals from measurement noise)

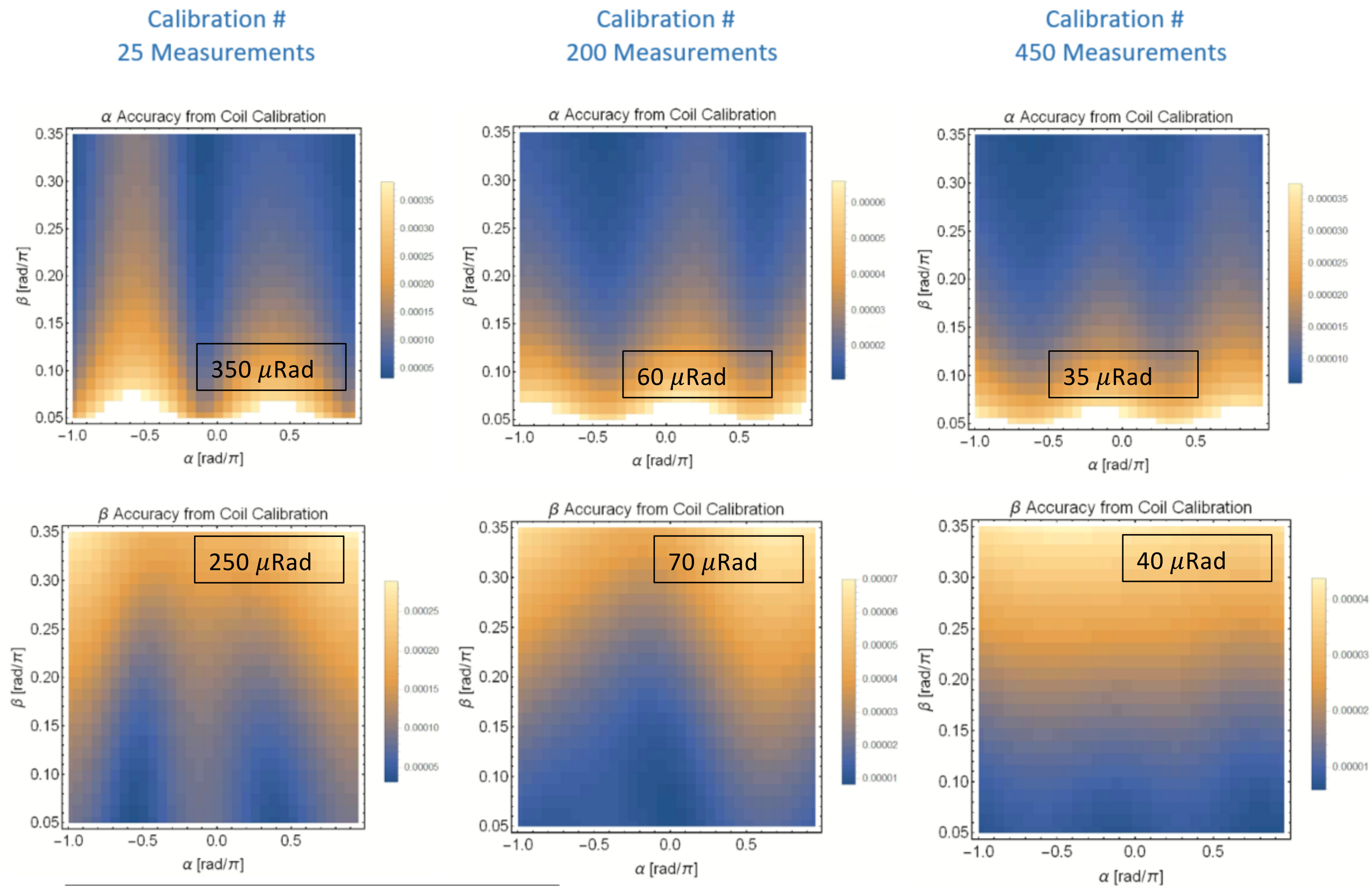


(measured calibration residuals)



Coil system benchmark: vector accuracy bound from calib. residuals

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



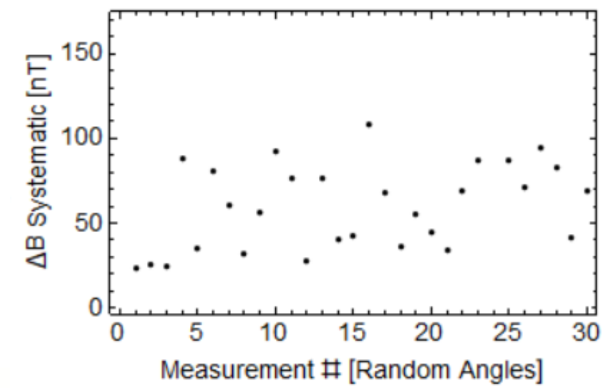
Microwave system: microwave power drifts

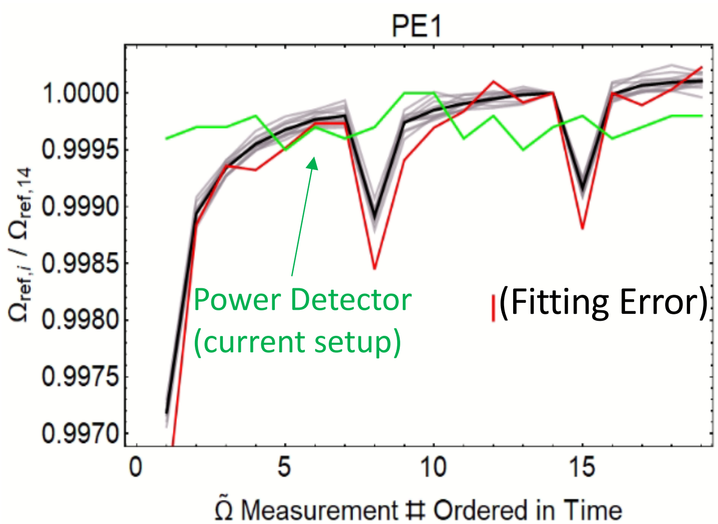
We observe fast microwave power drifts on the millisecond timescale.

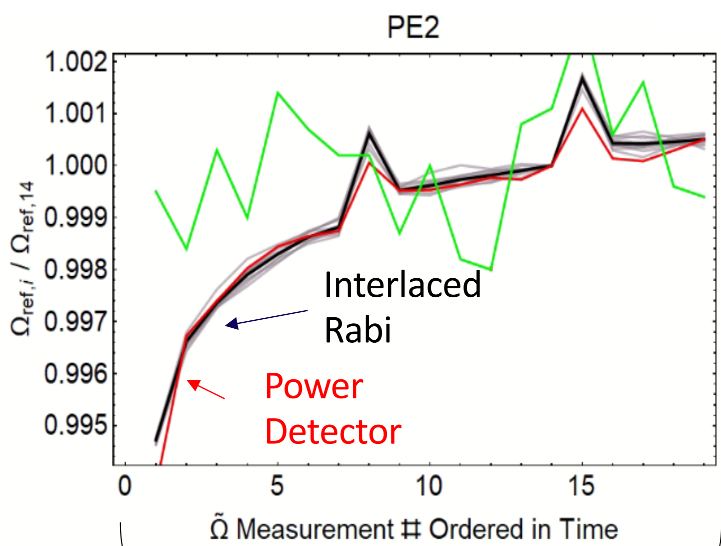
- improved microwave turn on/off sequence for better stability
- incorporated microwave power detectors for monitoring

From resonance of Rabi frequencies

|B| Differences w/wo Drift Compensation





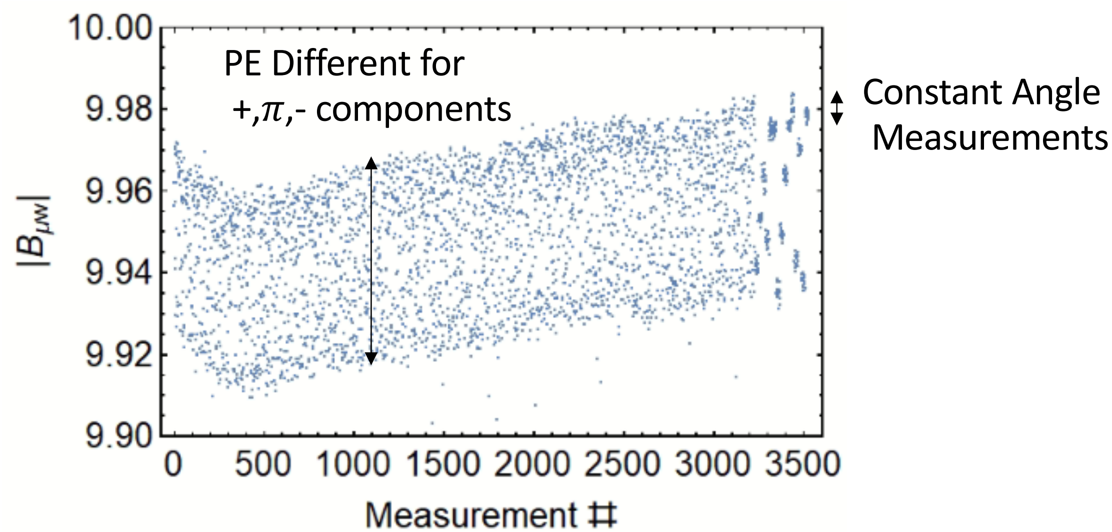


5% Amplitude Drift

22 milliseconds

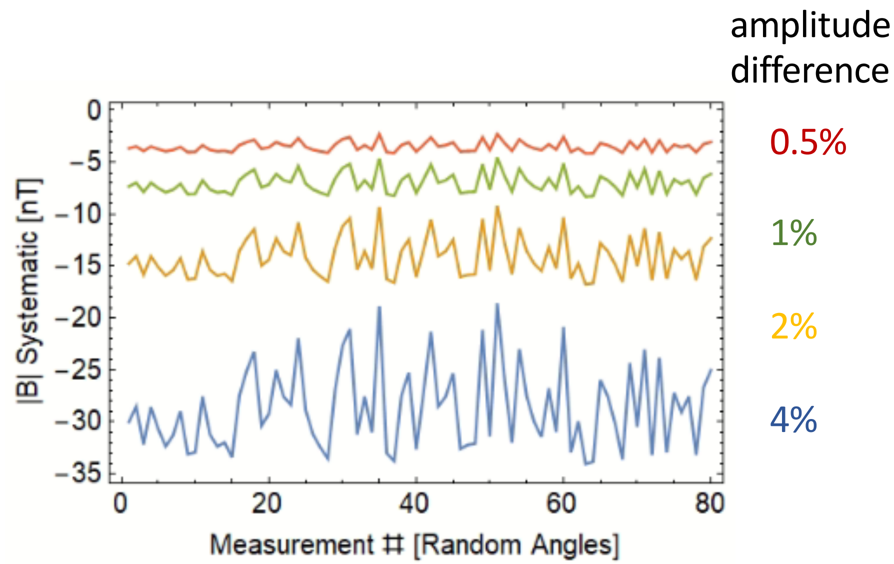
Microwave system: PE frequency dependence

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 +,π,- components



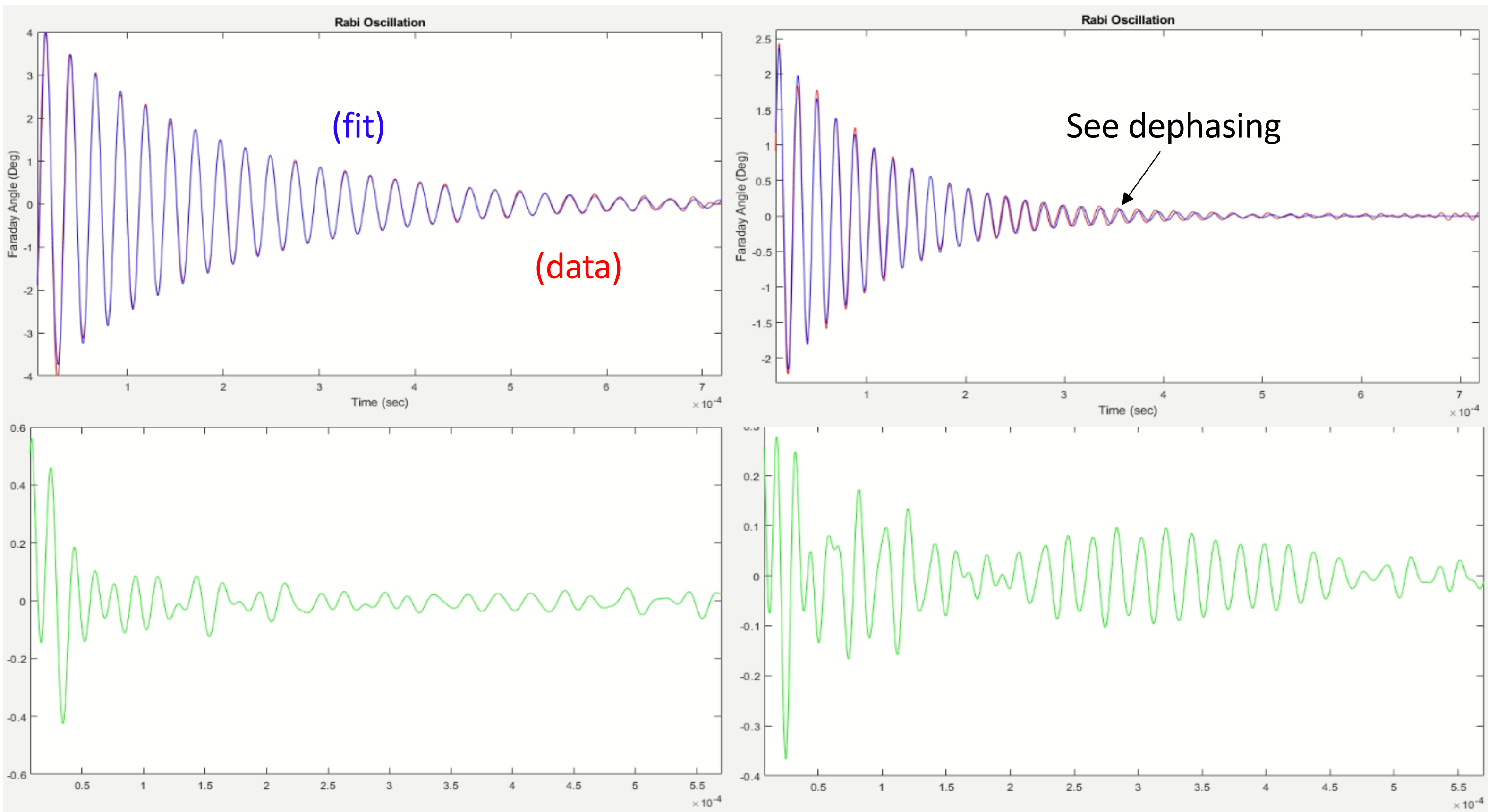
calibration fits give ~6% amplitude variation across the three transitions.

Magnetic gradients

near-resonance **further-detuned**

Rabi-oscillation

fit residual



Theoretical understanding of spin-exchange and Rabi FID

model [1]:

$$i\hbar\frac{d\rho}{dt} = \underbrace{A_{hf}[\boldsymbol{I}\cdot\boldsymbol{S},\rho] + \mu_B[\boldsymbol{B}\cdot(g_s\boldsymbol{S}+g_I\boldsymbol{I}),\rho]} + \underbrace{i\hbar\frac{\phi(1+4\langle\boldsymbol{S}\rangle\cdot\boldsymbol{S})-\rho}{T_{ex}} + i\hbar\frac{\phi-\rho}{T_{sd}}},$$

- Atomic Structure
- Magnetic +Microwave

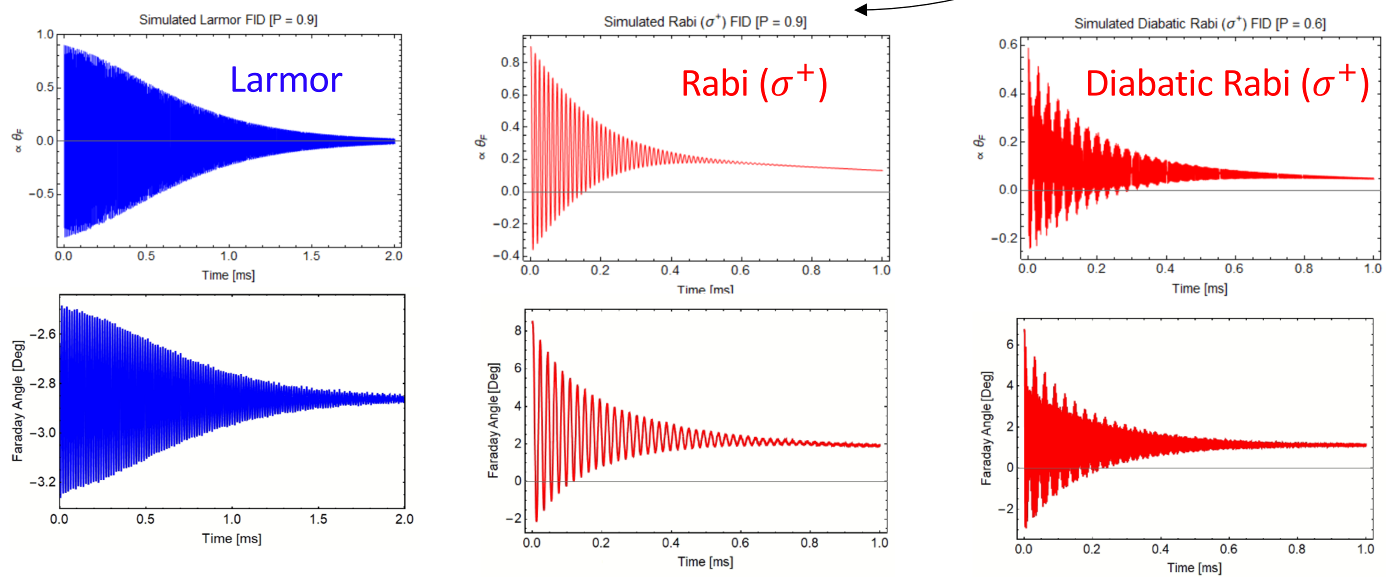
- Spin-exchange decoherence
- Buffer Gas and Rb-Rb SD collisions

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

$$\boxed{\begin{aligned} 1/T_{sd,buffer} &= 156\text{ Hz} \\ 1/T_{sd,Rb-Rb} &= 4\text{ Hz} \\ 1/T_{ex} &= 2.2\text{ kHz} \end{aligned}}$$

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