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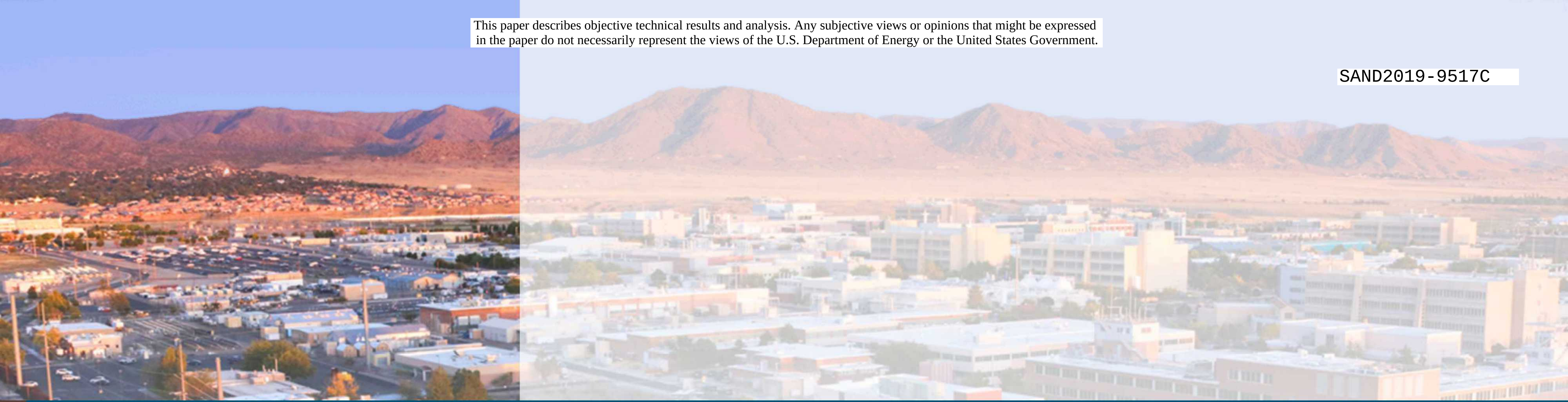

# Optical Beat Note Readout of a Magnetic Gradient

**Peter D. D. Schwindt**

Sandia National Laboratories

Quantum Sensing & Magnetometry: from the nanoscale up to geological explorations

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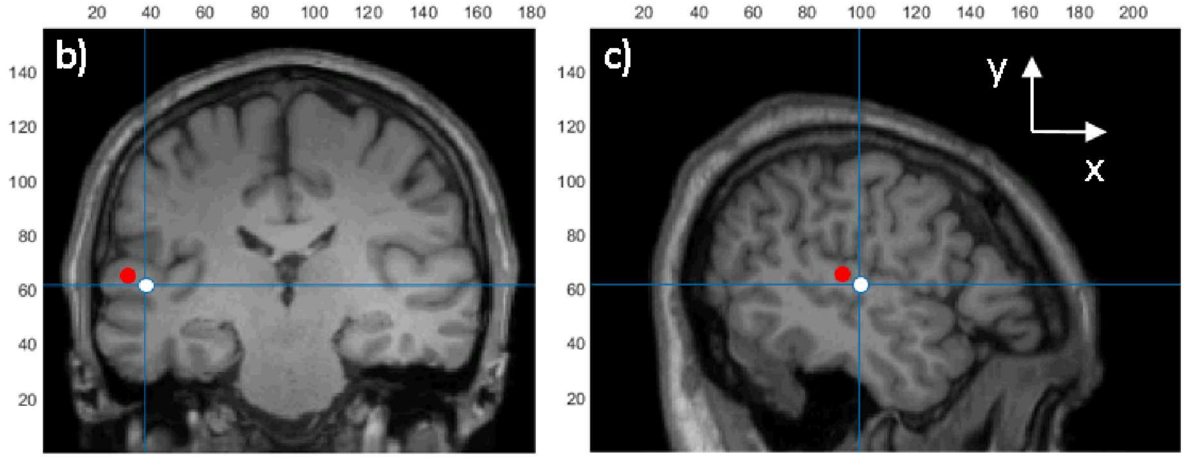
# Motivation

Direct optical measurement of a magnetic field gradient

High sensitivity in the Earth's magnetic field

- High common mode rejection

Application: magnetoencephalography and magnetocardiography

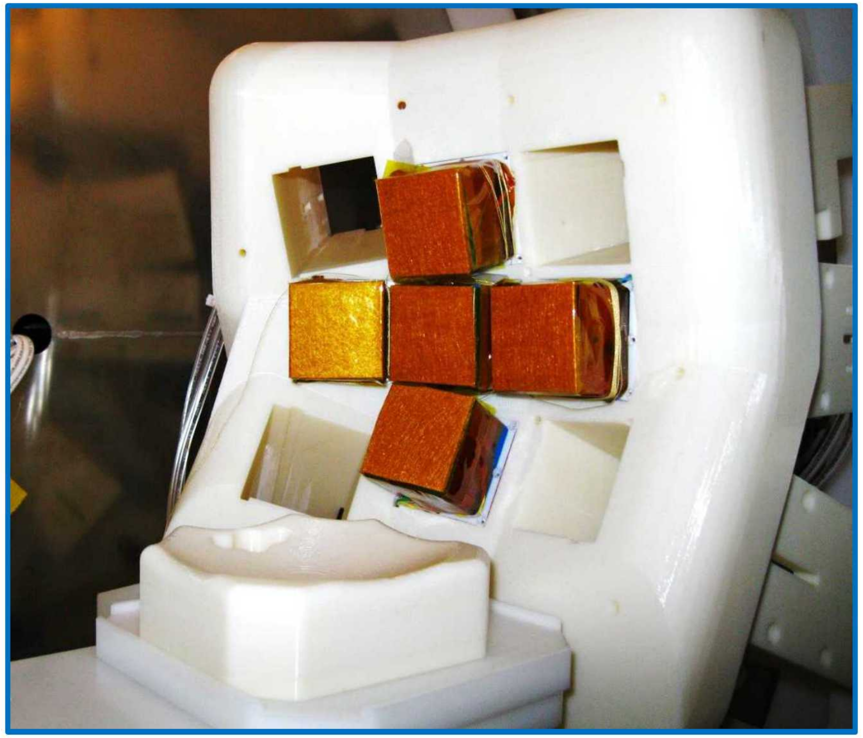


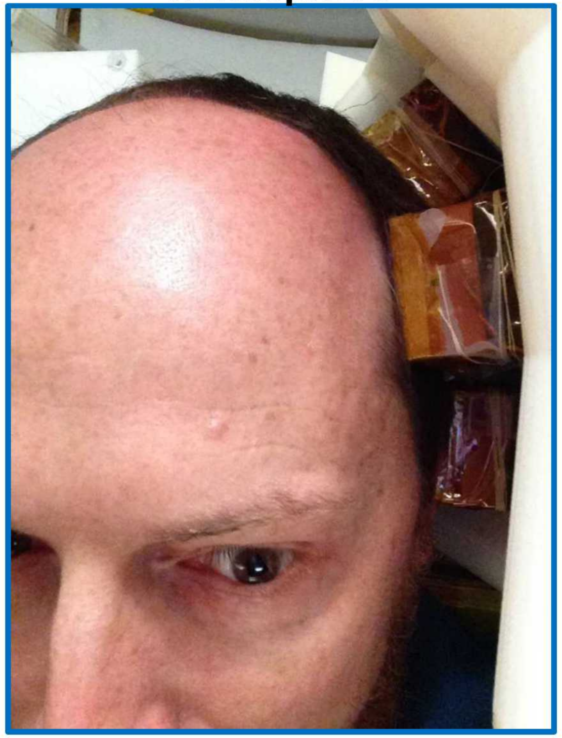

5-sensor, 20-channel array

Partially covers the left hemisphere

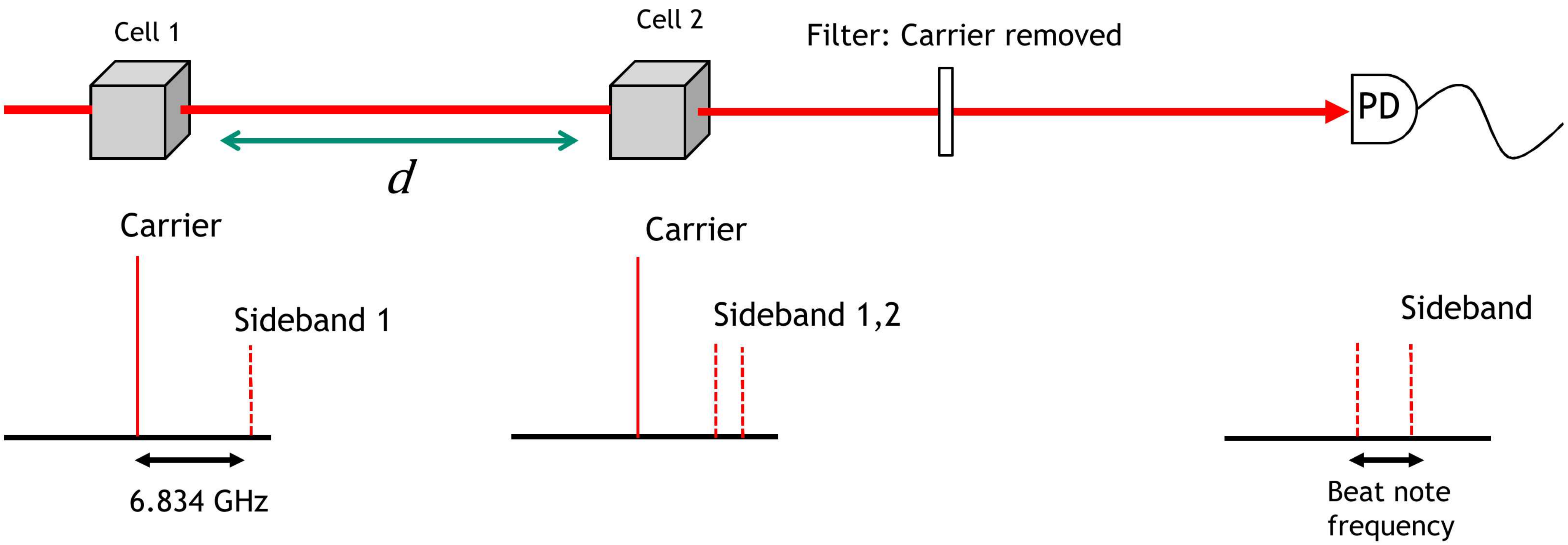
Person-Sized Magnetic Shield

Insert Person Here





# Basic Idea – Produce a beat note signal



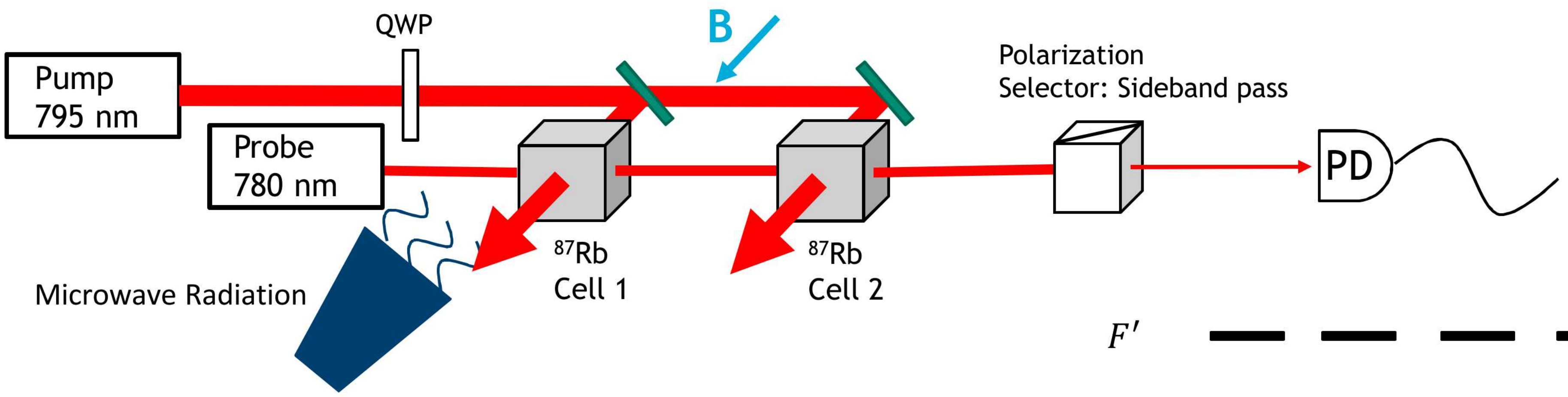

Sideband Produced in the first cell orthogonally polarized to the carrier

Sideband Produced in the second cell orthogonally polarized to the carrier

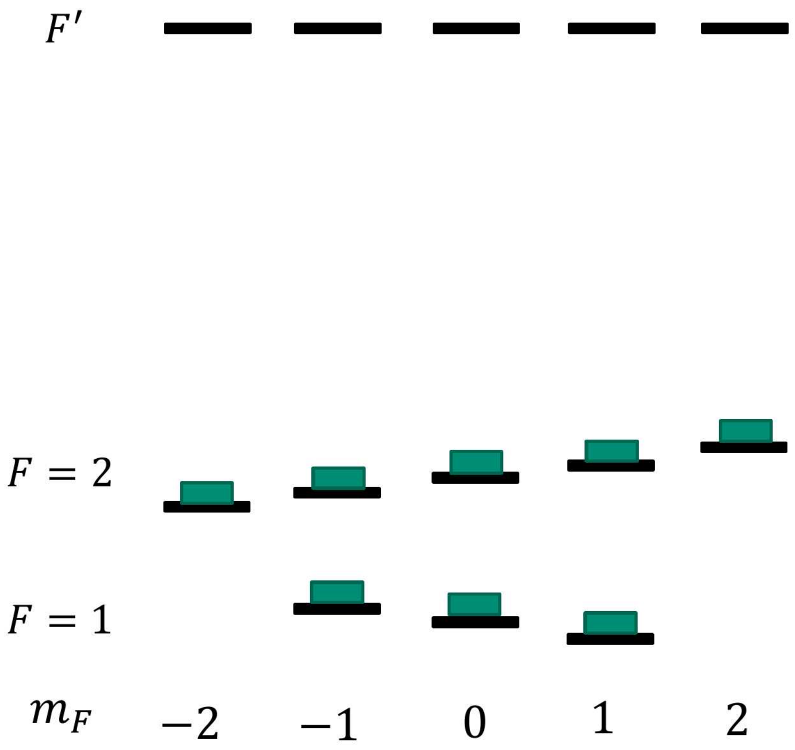
Carrier removed and sidebands beat together

$$f_B \propto \frac{\Delta B}{d}$$

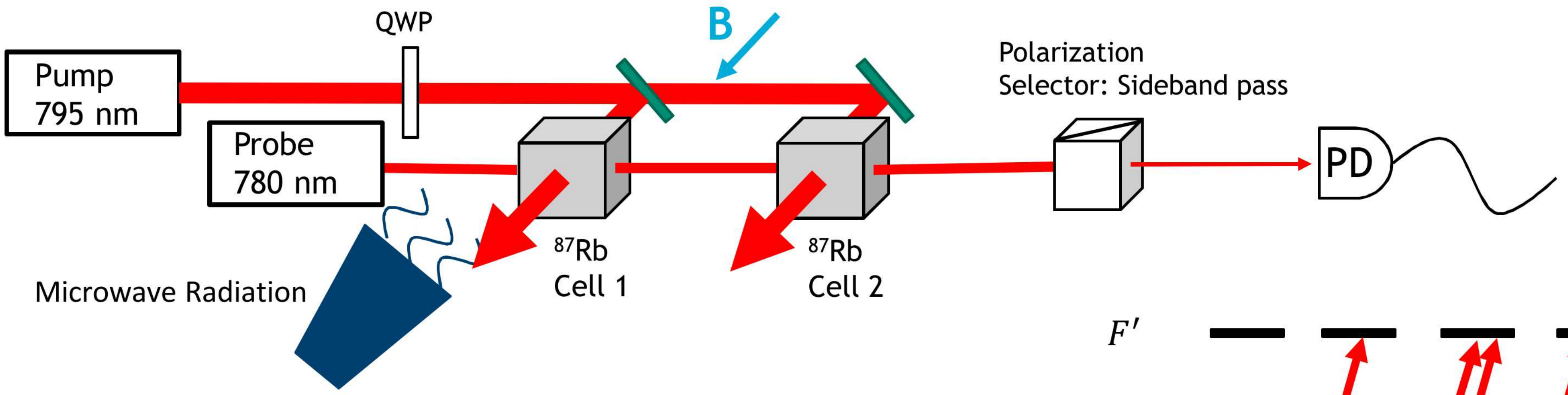
# More detailed description




Gradiometer Process

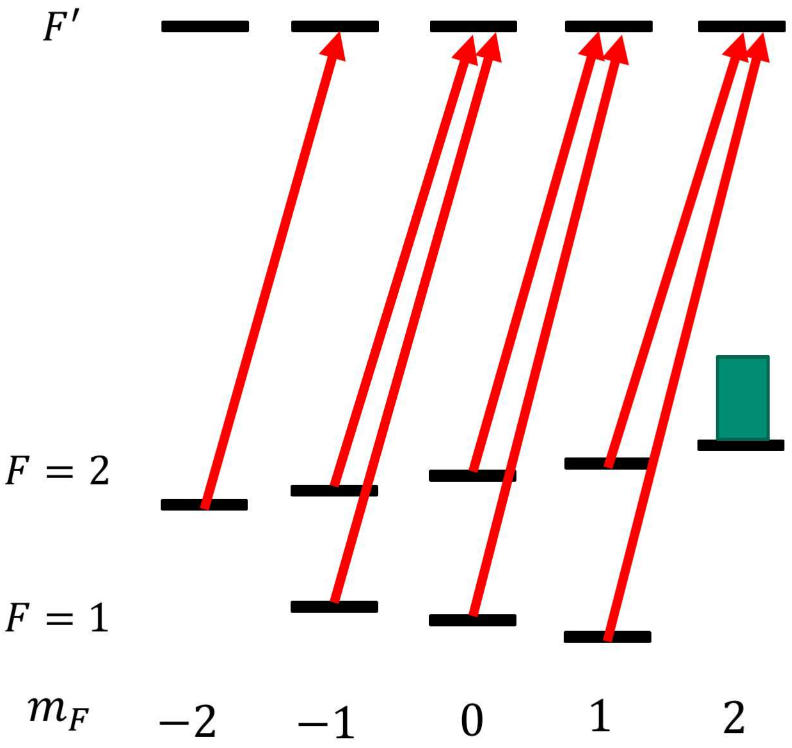


# More detailed description




## Gradiometer Process

1) Optically pump atoms to the end-state



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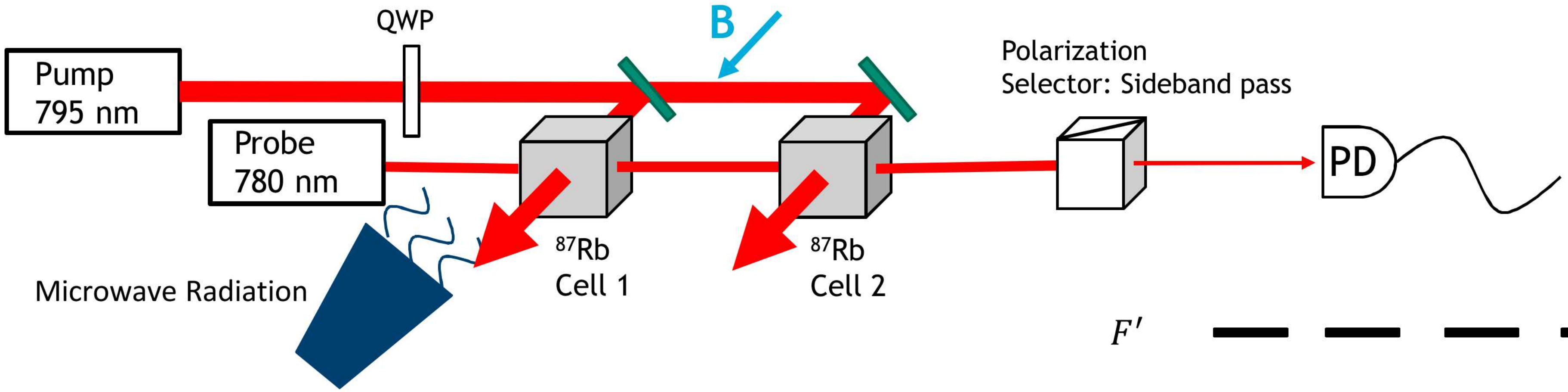
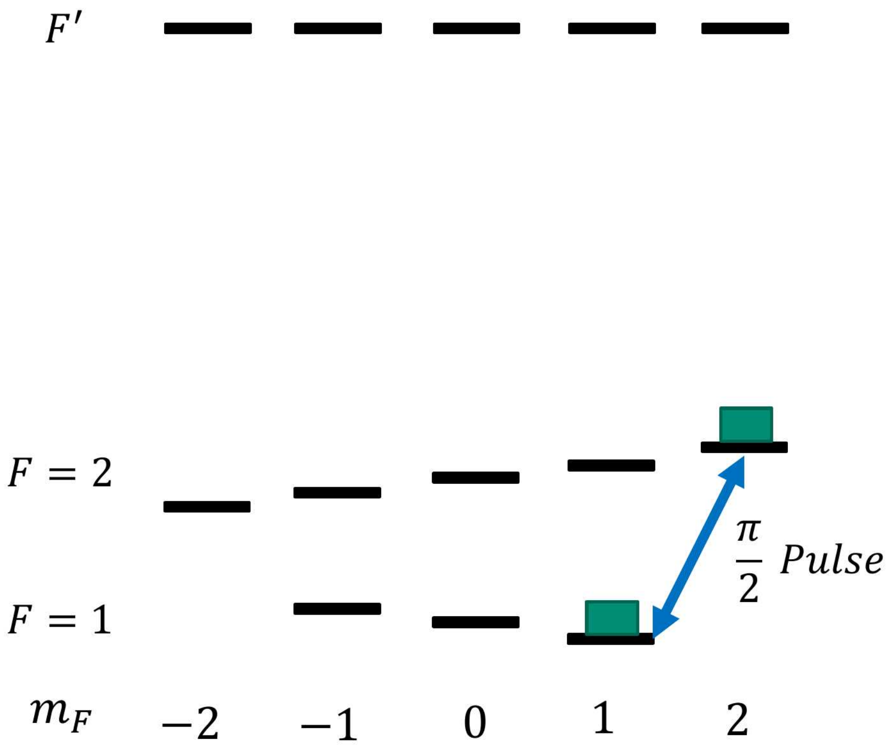


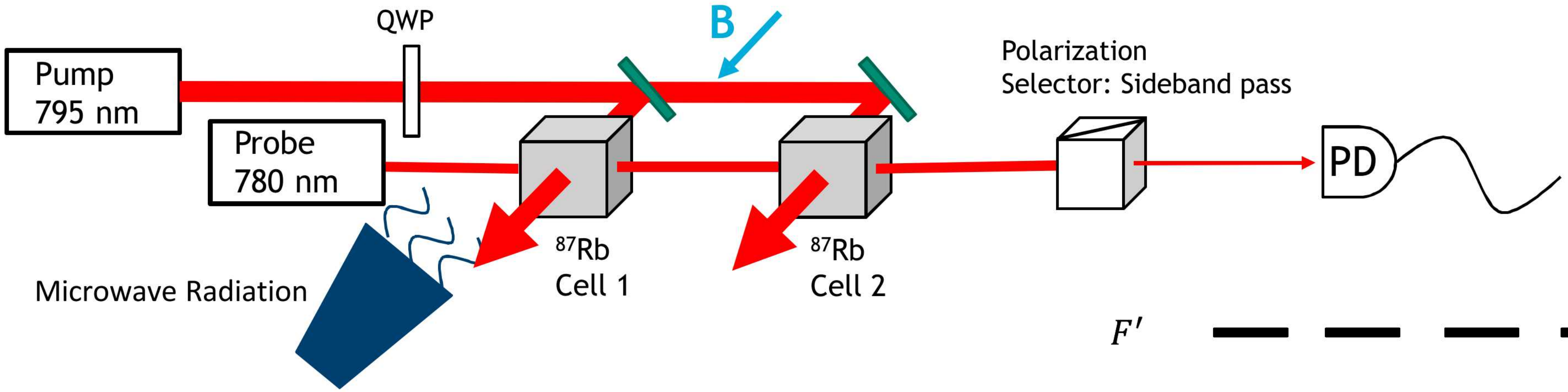



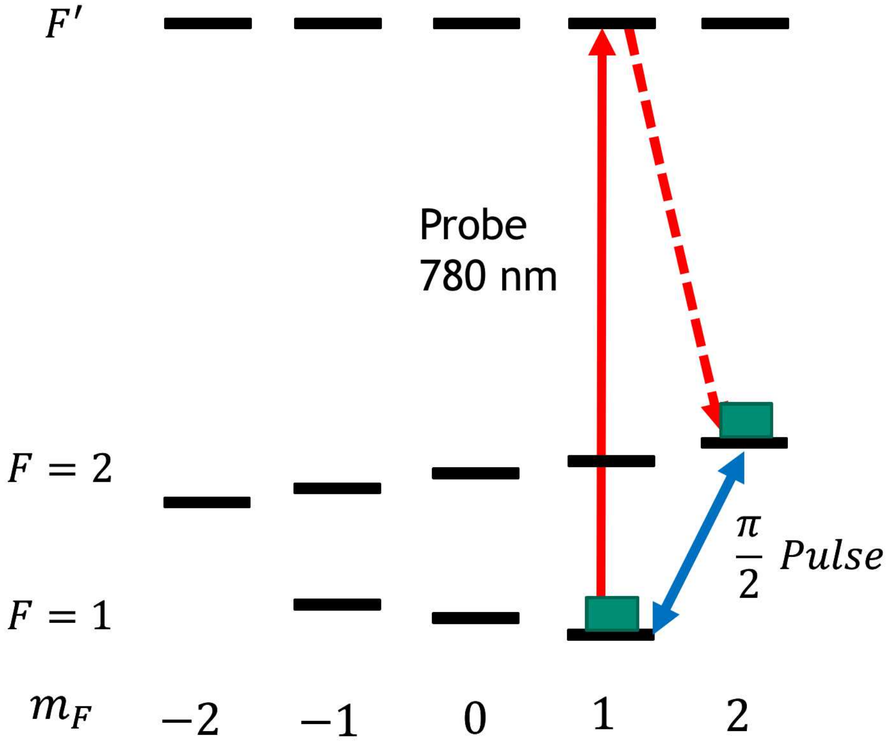

Gradiometer Process

1) Pump atoms to the end-state

2) Apply a $\frac{\pi}{2}$ pulse of magnetic energy to put the atoms in a coherent superposition

# More detailed description



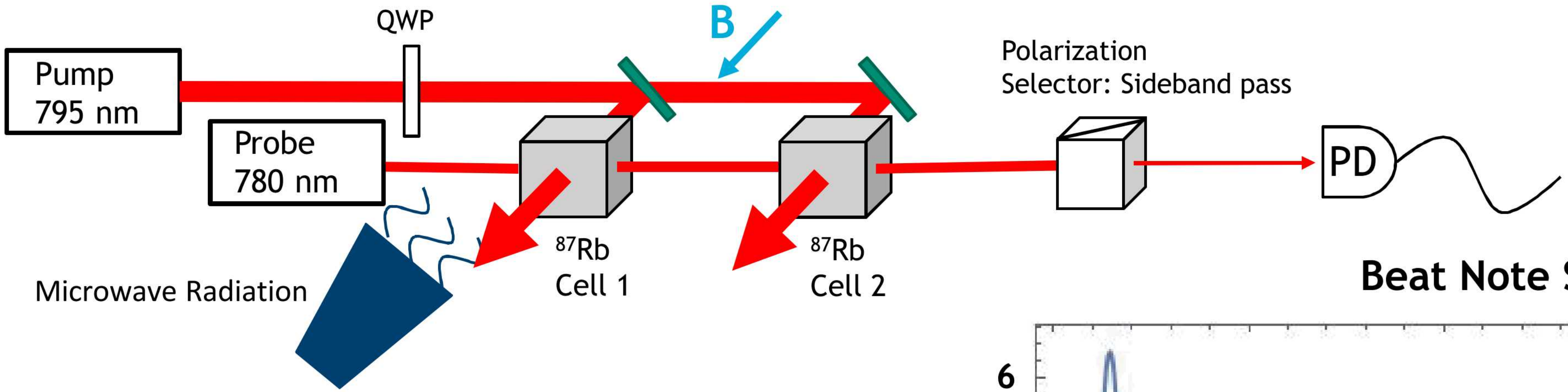

## Gradiometer Process

1) Pump atoms to the end-state

2) Apply a $\frac{\pi}{2}$ pulse of magnetic energy to put the atoms in a coherent superposition

3) Send in Probe light to generate a sideband in each cell

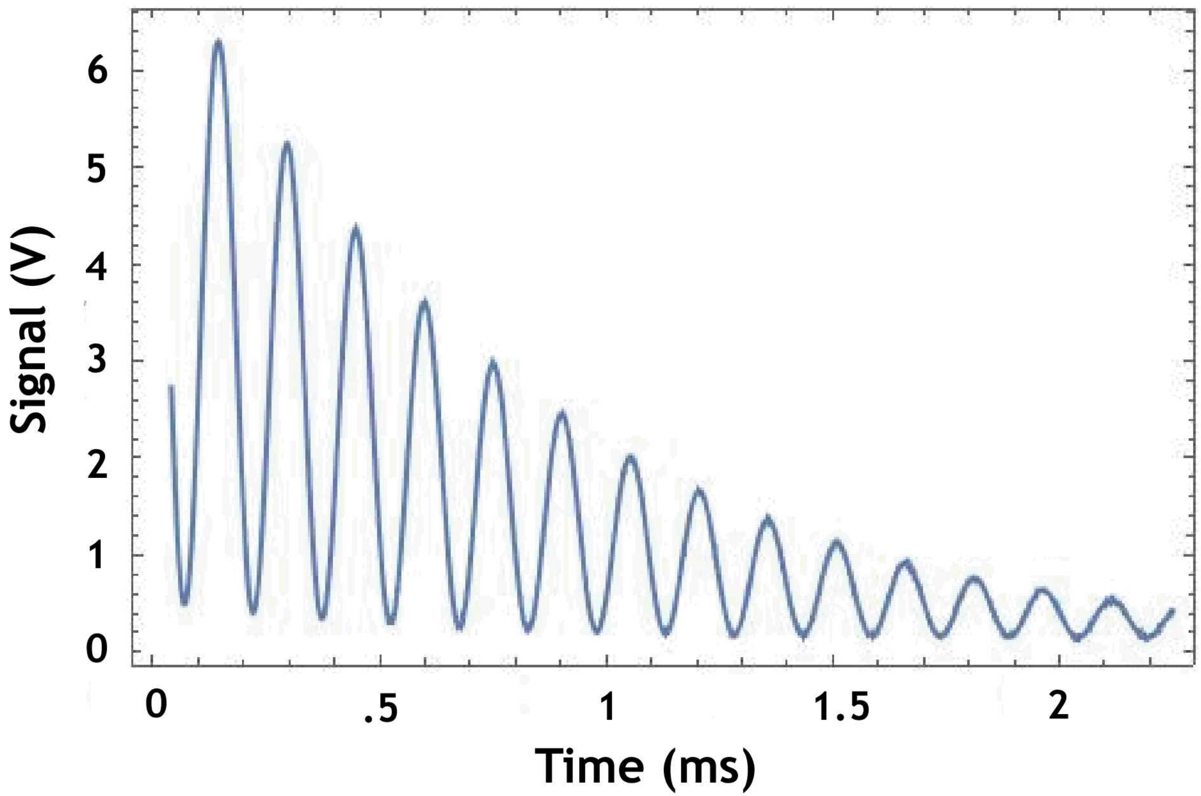
# More detailed description



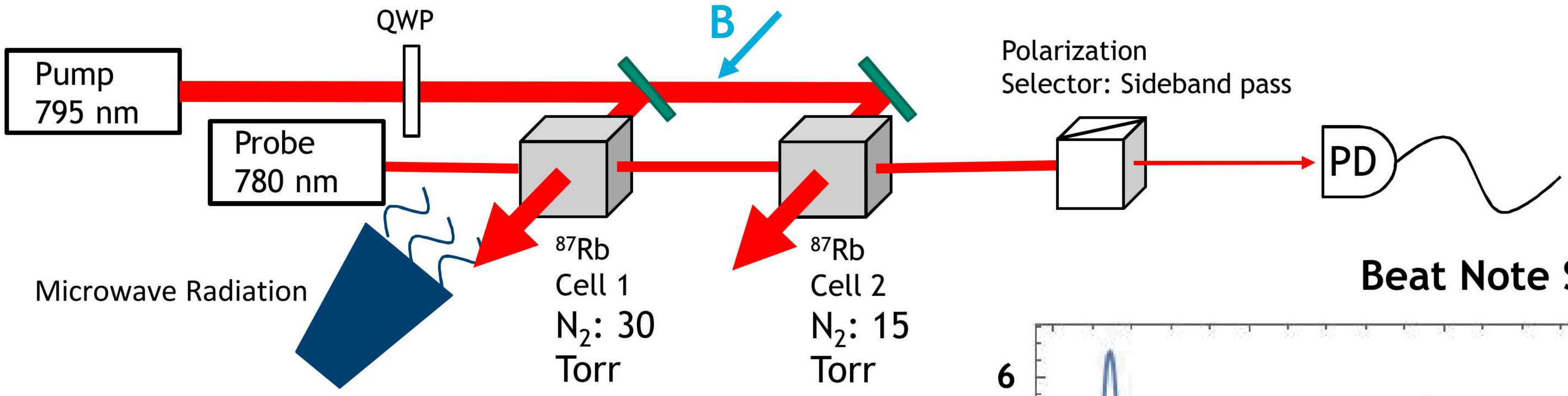

Gradiometer Process

1) Pump atoms to the end-state
2) Apply a $\frac{\pi}{2}$ pulse of magnetic energy to put the atoms in a coherent superposition
3) Send in Probe light to generate a sideband in each cell
4) Beat the sidebands together to produce a beat note

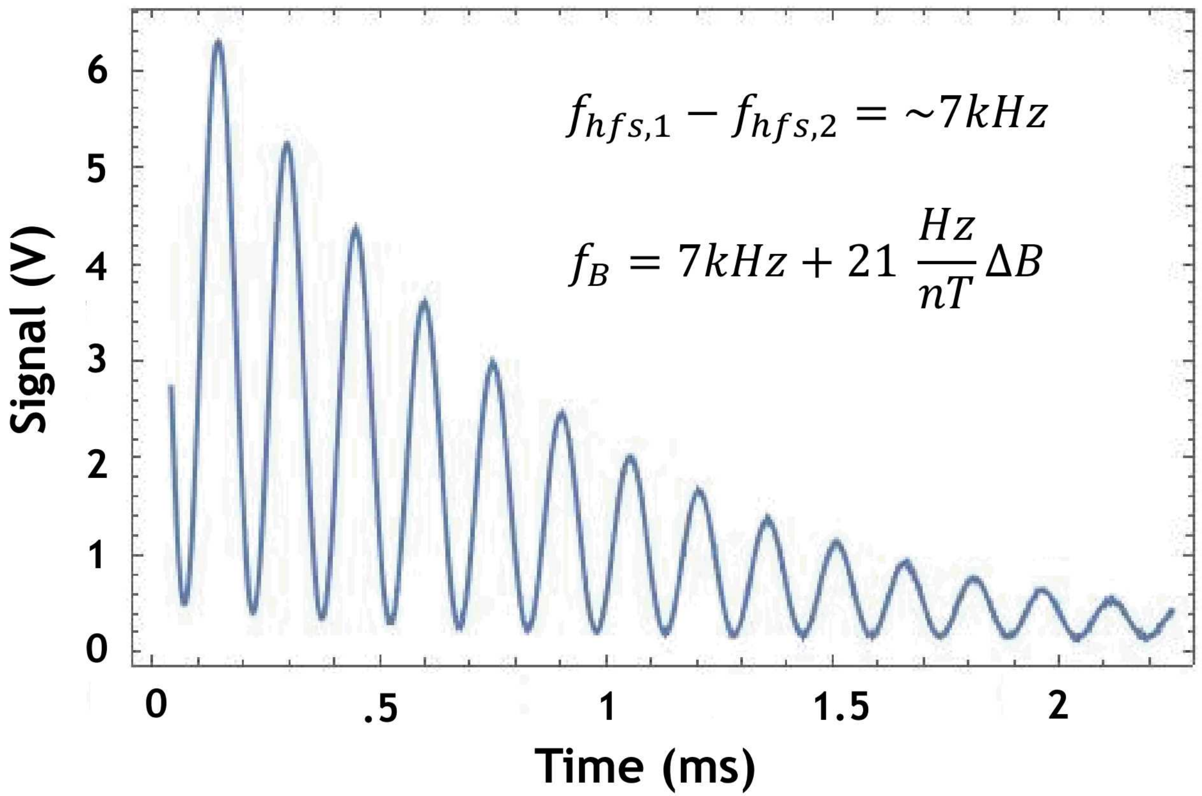
**Beat Note Signal**



# More detailed description




## Beat Note Signal



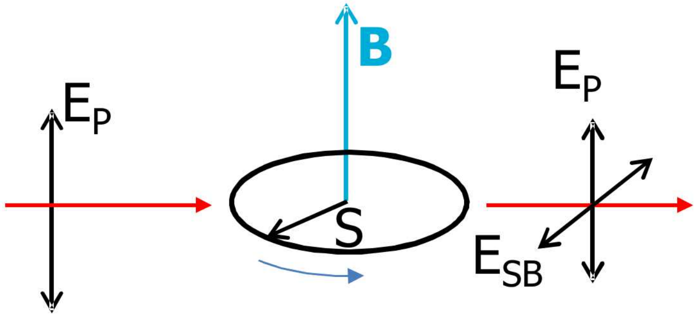

## Gradiometer Process

1) Pump atoms to the end-state
2) Apply a $\frac{\pi}{2}$ pulse of magnetic energy to put the atoms in a coherent superposition
3) Send in Probe light to generate a sideband in each cell
4) Beat the sidebands together to produce a beat note
5) Measure the frequency of the beat note to determine the magnetic gradient between the cells

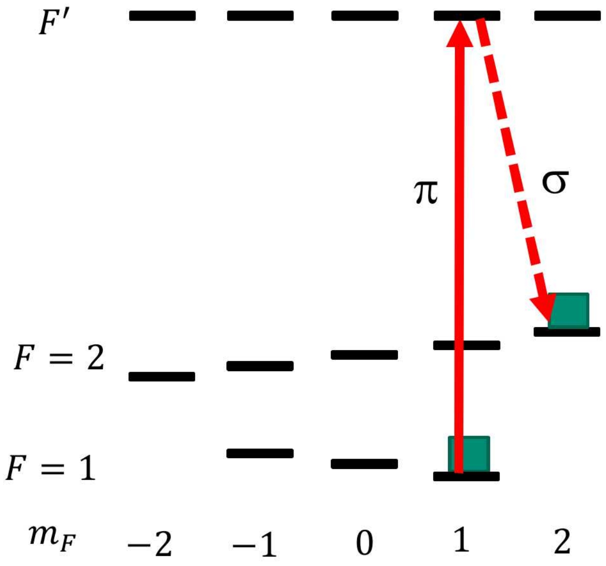
# Sideband Generation

## Modulation of the index of refraction

- Polarization rotation at the hyperfine frequency

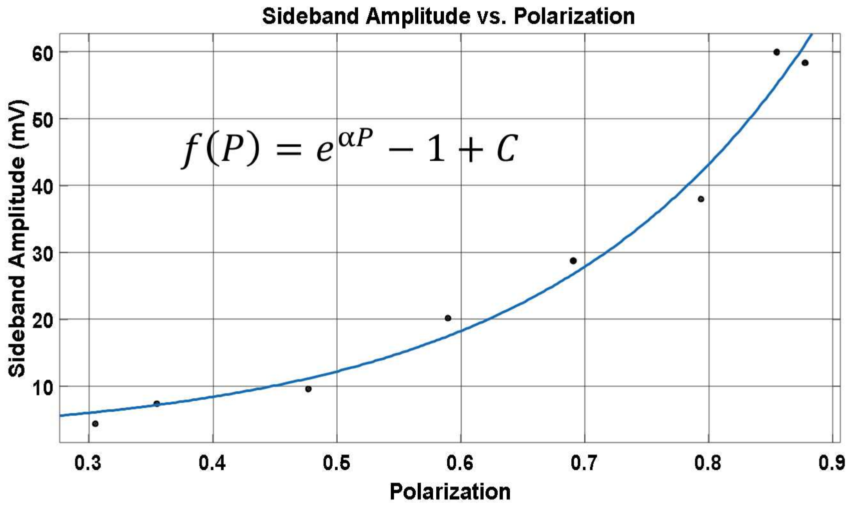



## Stimulated Raman Transitions




$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] + R,$$

$$\frac{d\Omega_i}{dz} = -\alpha_i \times Im[\rho_{i3}],$$



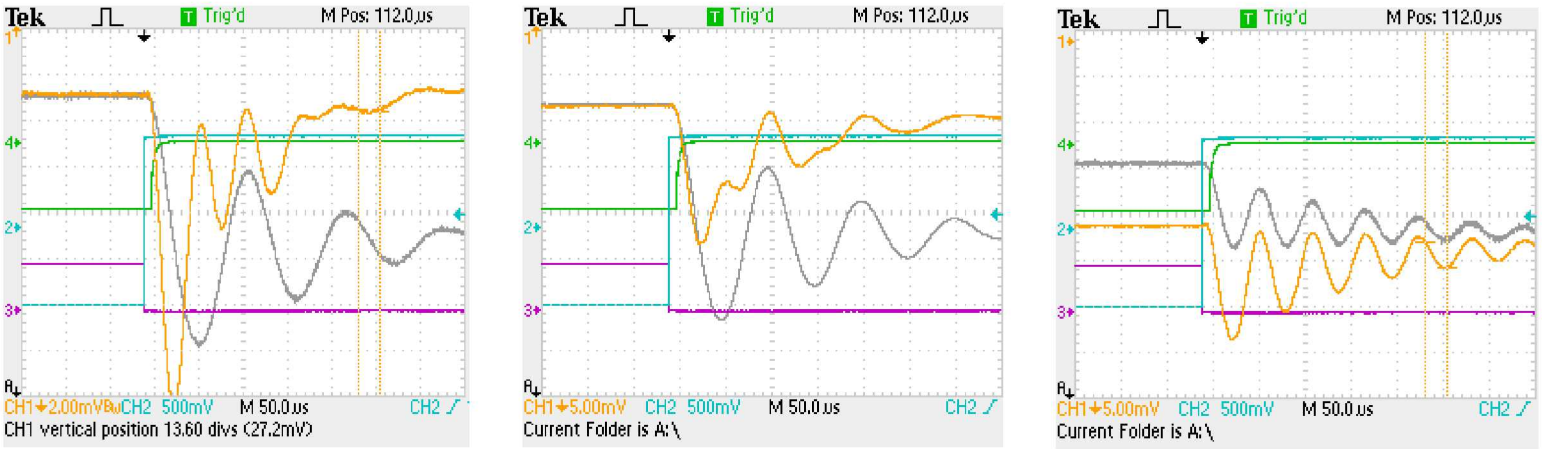


H. Tang and W. Happer, "Parametric Frequency Conversion of Resonance Radiation in Optically Pumped Rubidium-87 Vapor," *Phys. Rev. Lett.* **24**, 551 (1970).
Henry Tang, "Parametric Frequency Conversion of Resonance Radiation in Optically Pumped $Rb^{87}$ Vapor," *Phys. Rev. A* **7**, 2010 (1973).
Vishal Shah, *System and Method for Measuring a Magnetic Gradient Field*. Patent. US10088535 (2018).

# Sideband generation from coherence

- Microwave optical double resonance (MODR) signal oscillates at the Rabi frequency, Ω.
- Sideband signal oscillates at 2 Ω on resonance.
- Sidebands maximized when coherence is maximized.

Detuning: 0 kHz | 3 kHz | 14 kHz



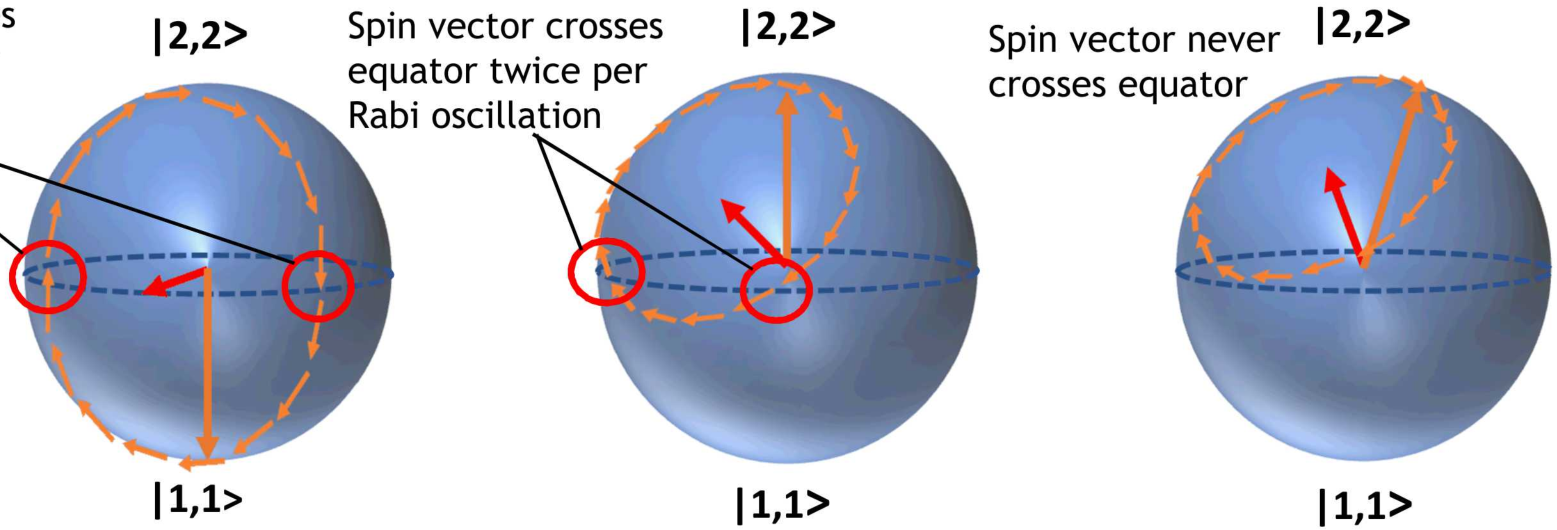

Gray: MODR signal/parallel polarizers

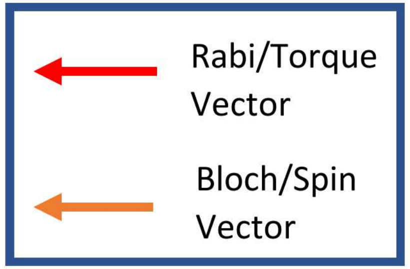
Orange: Sideband signal (inverted)/ crossed polarizers

Spin vector crosses equator twice per Rabi oscillation

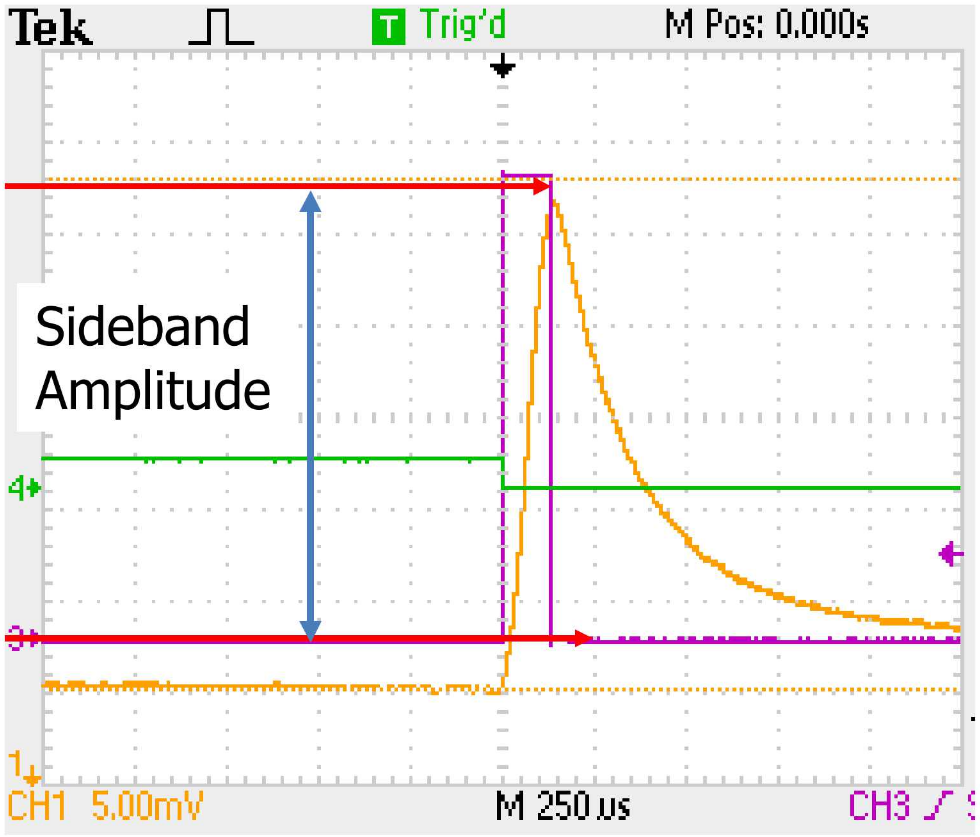
Spin vector crosses equator twice per Rabi oscillation

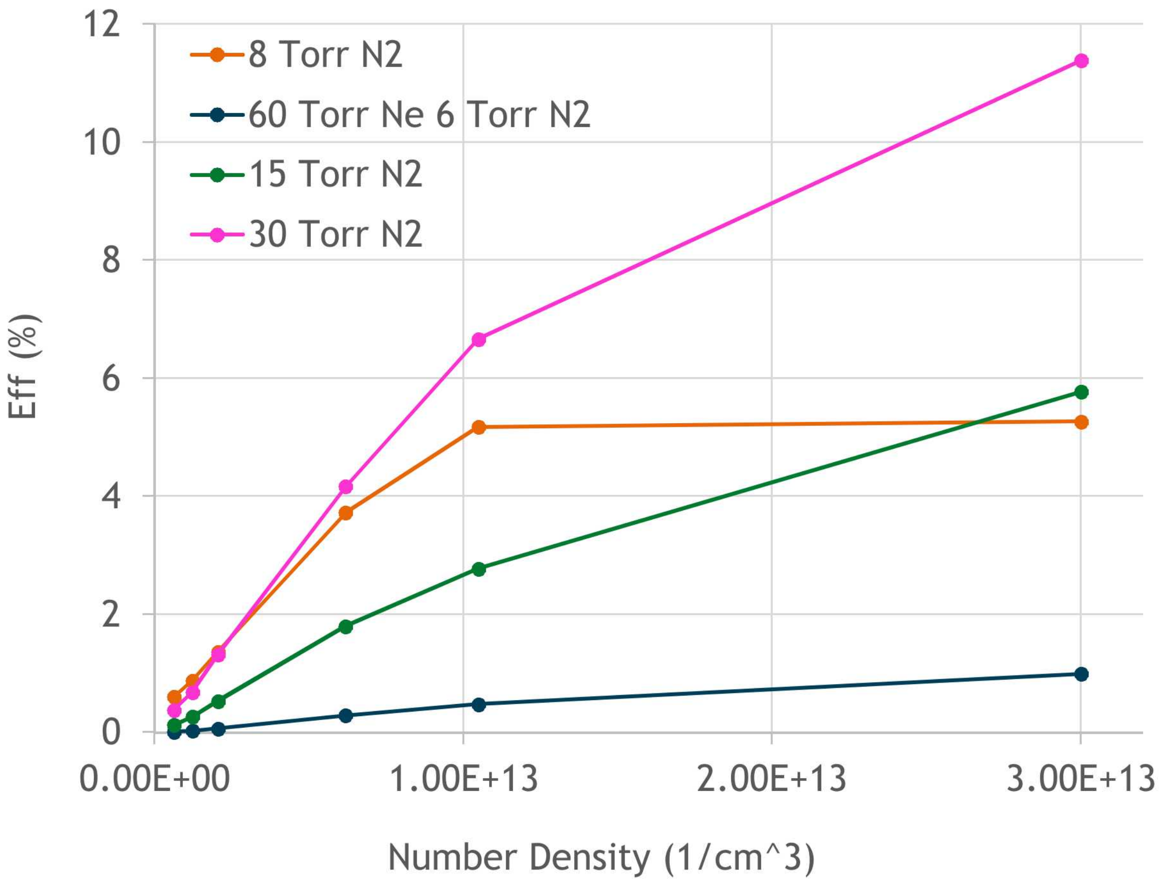
Spin vector never crosses equator



# Sideband Optimization: Buffer Gas Pressure




$$Eff = \frac{Sideband\ Amplitude\ (\mu W)}{Input\ Probe\ Power\ (\mu W)}$$

- Percentage of probe power being converted to sideband by the vapor cell.
- Input power = 12 μW

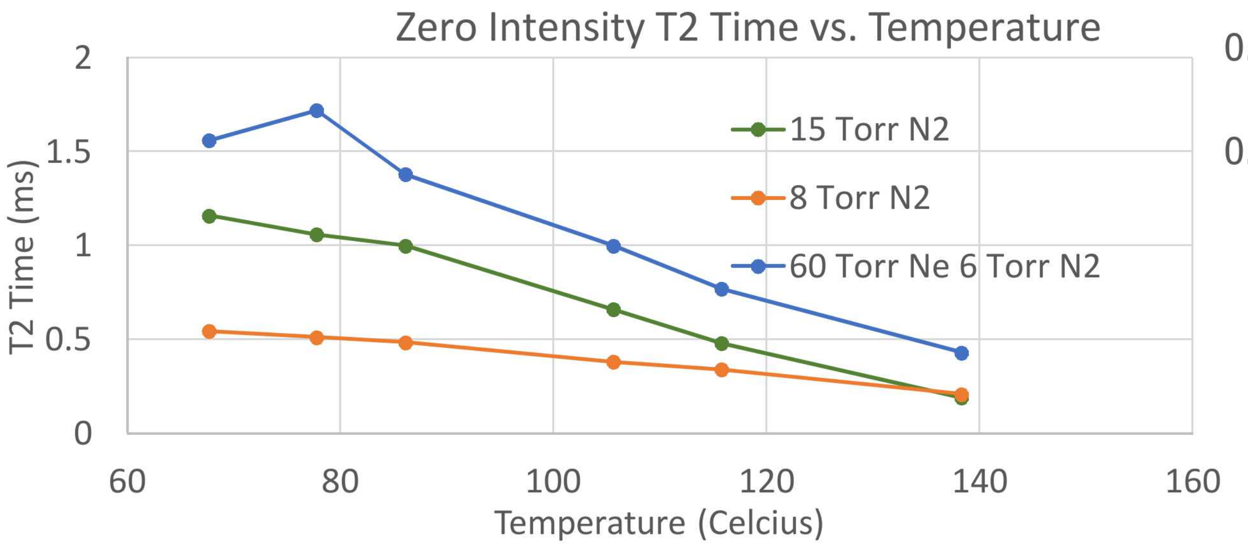
# Figure of Merit

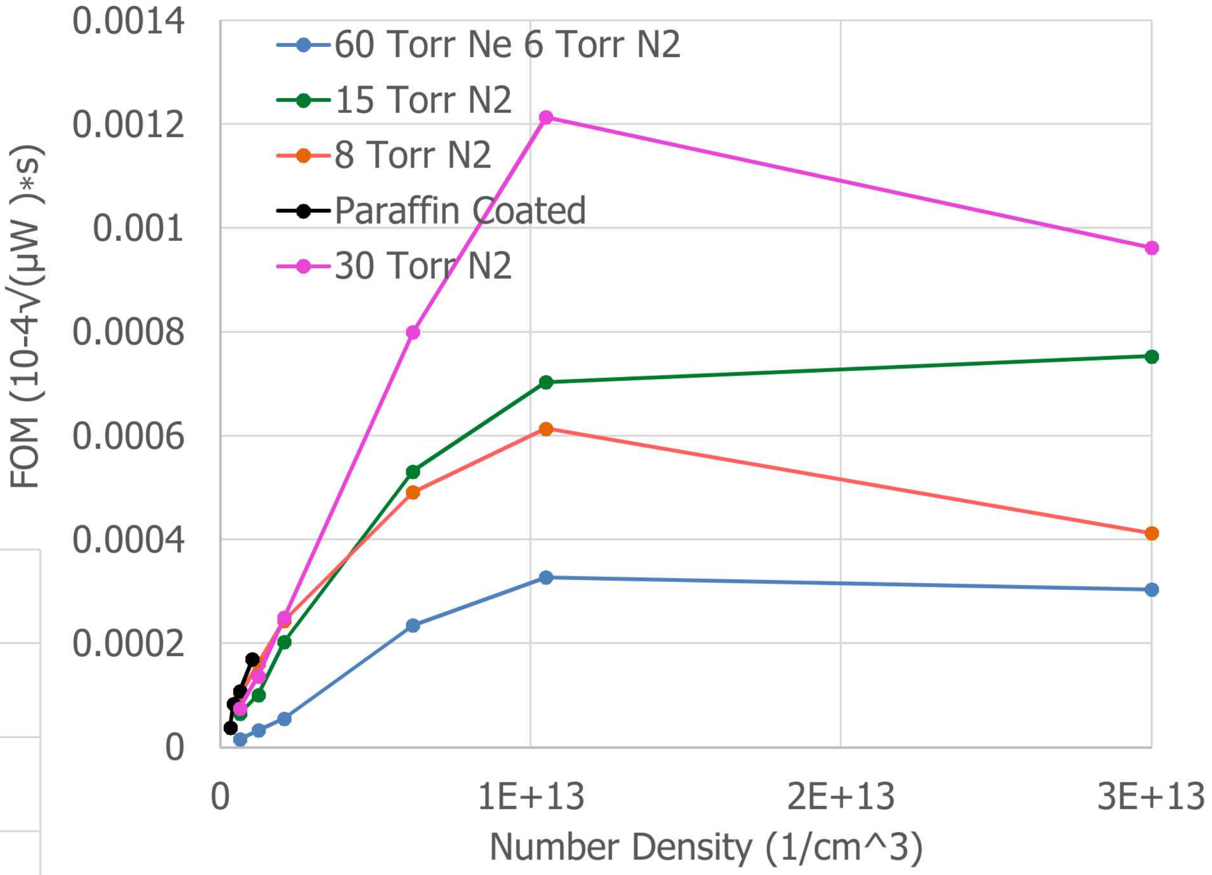
Figure of merit

- Reflects the performance of the gradiometer
- $FOM = \sqrt{S}/w_2$
- $S$ = sideband signal amplitude
- The linewidth $w_2 = 1/(\pi\, T_2)$.

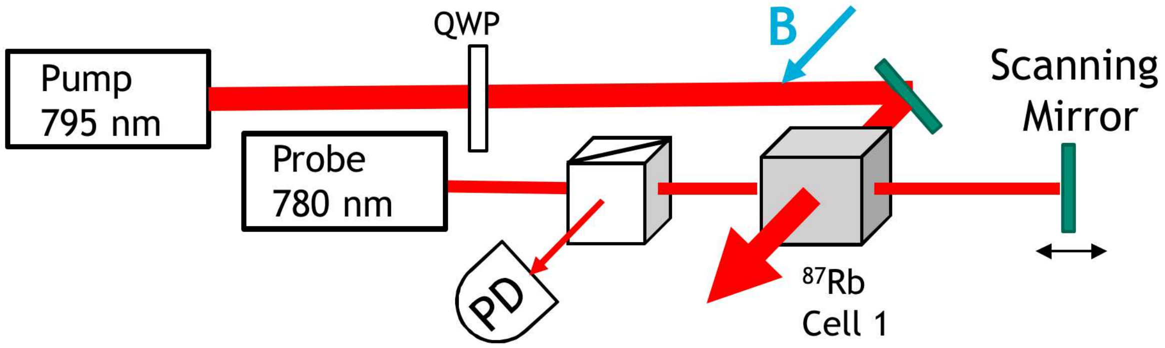
Probe on continuously throughout the measurement.

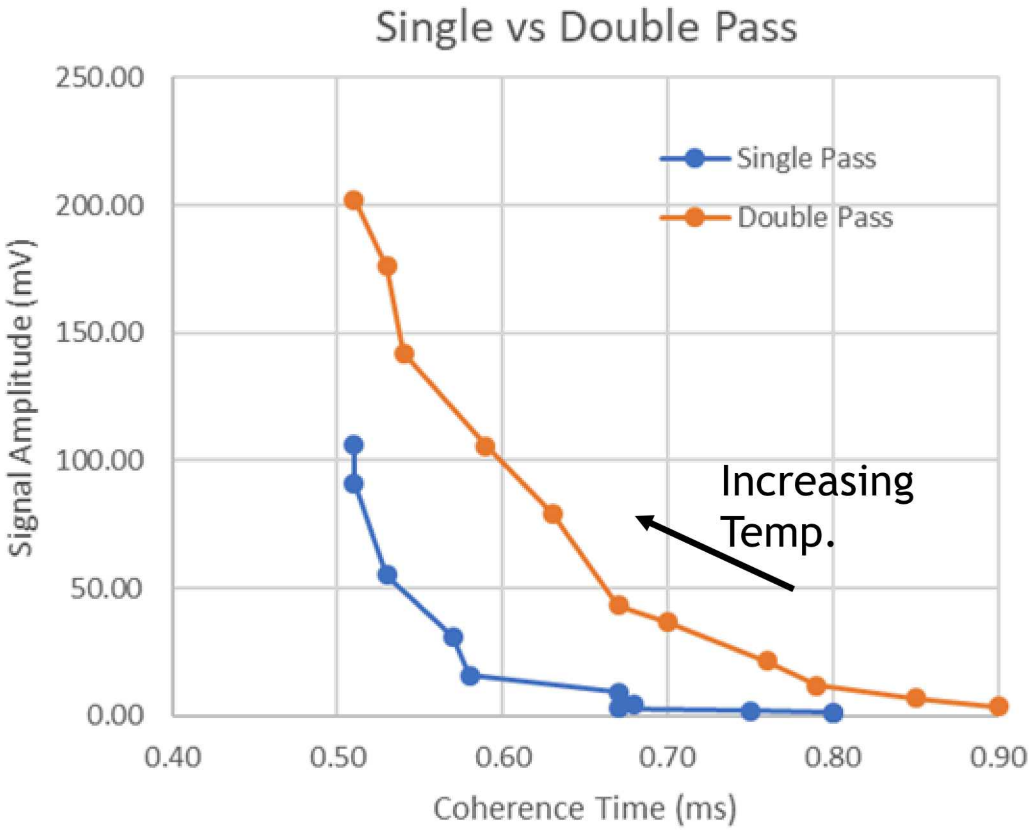
- The probe power is 12 uW.

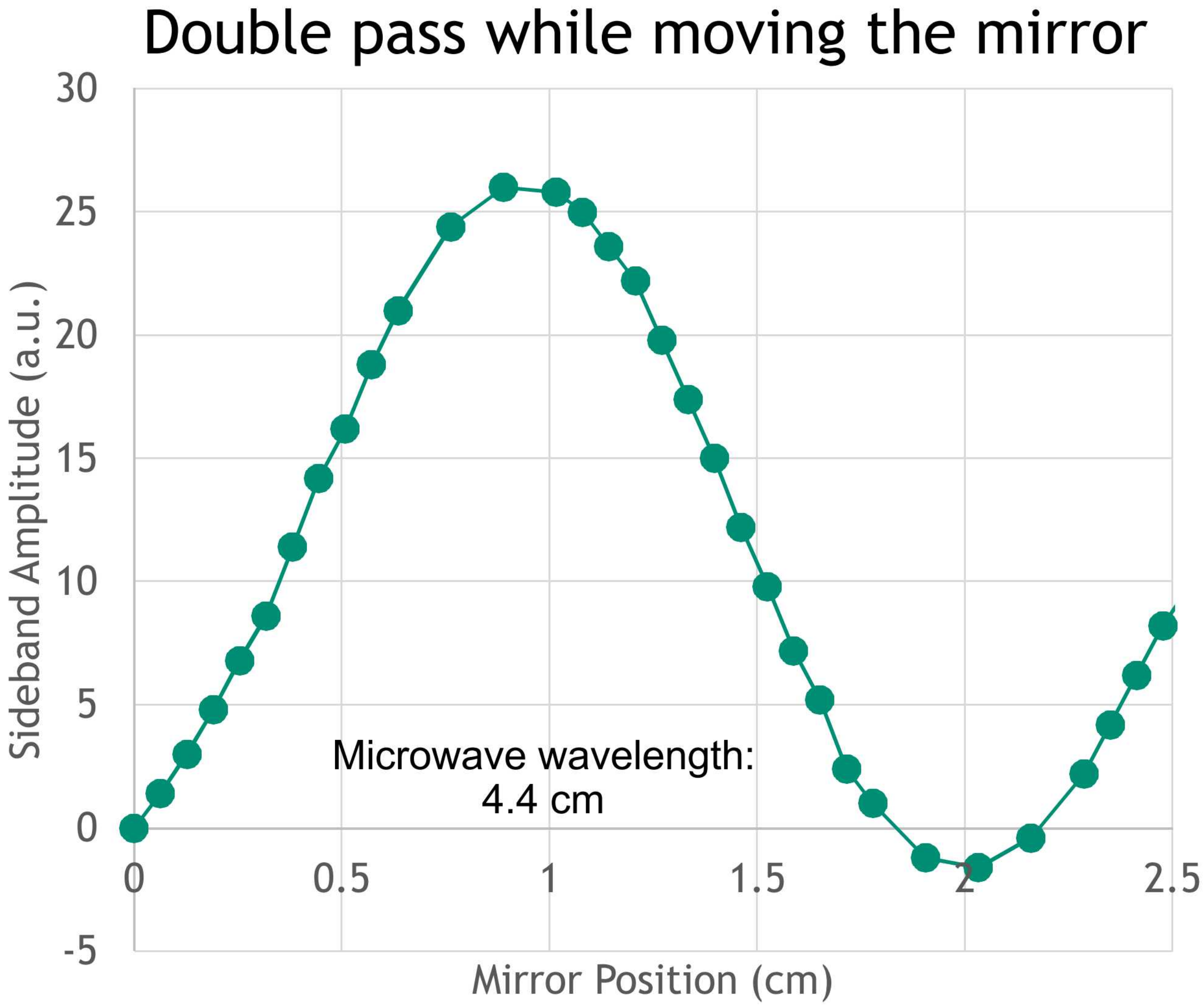


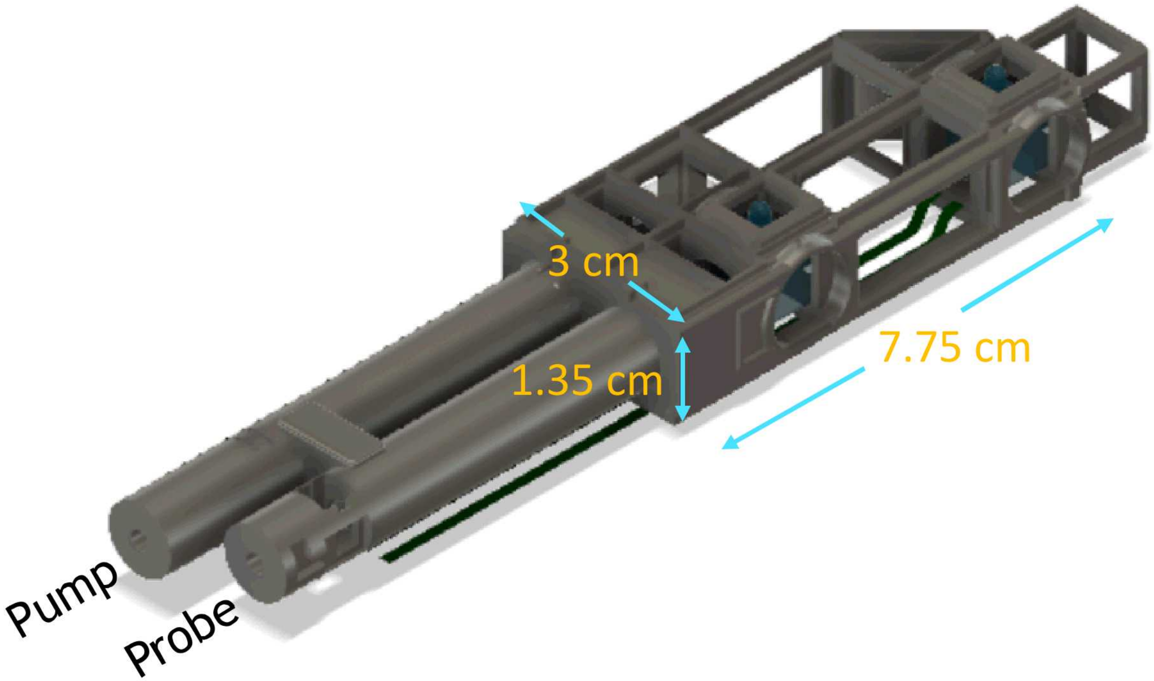
# Sideband enhancement: Retroreflected probe laser

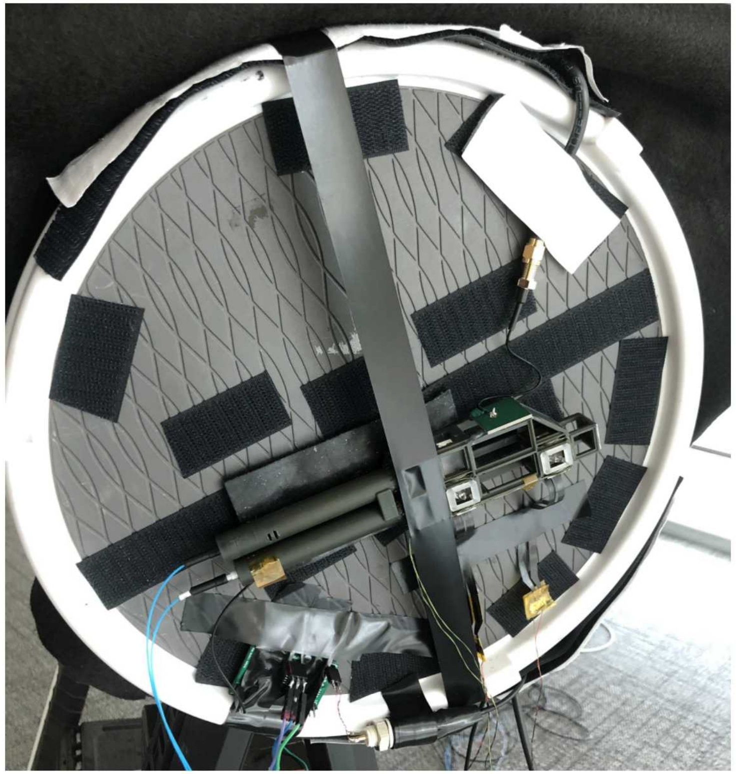


# Prototype Design

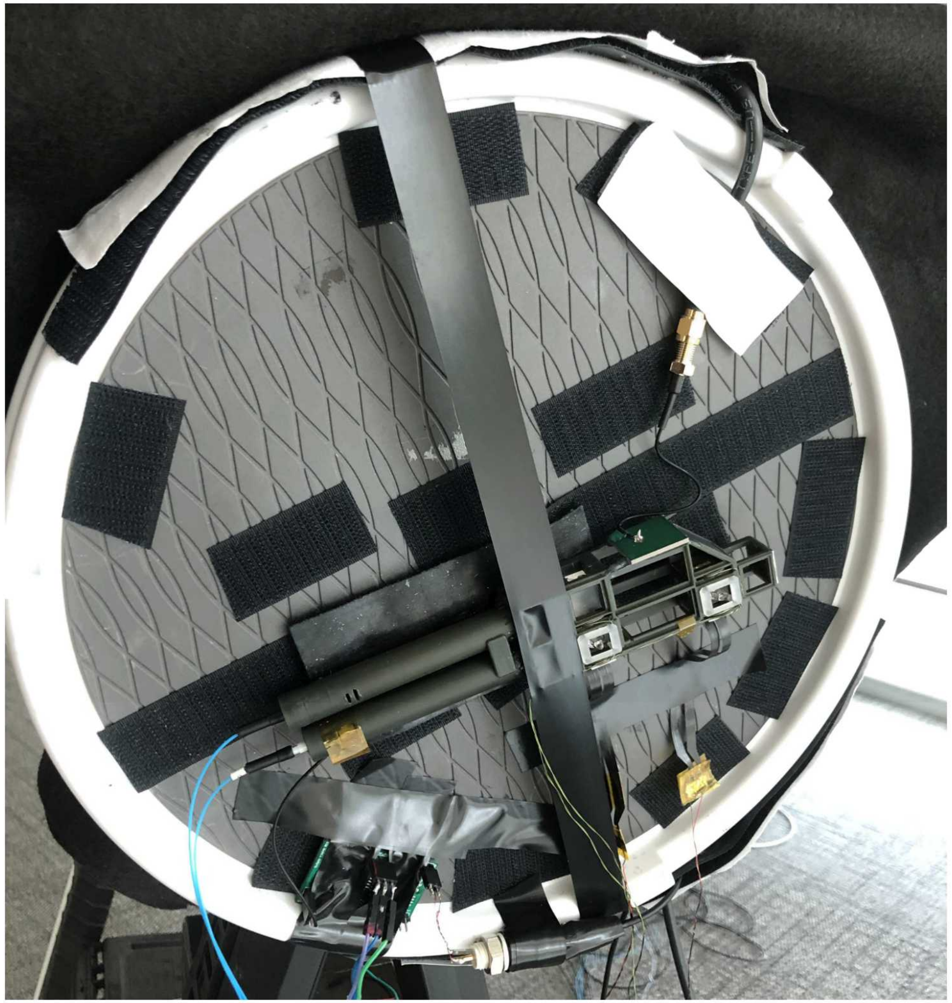


- All components are dropped-in design. Requires minimum alignment.
- Improved gradient cancellation coil design.

# Results

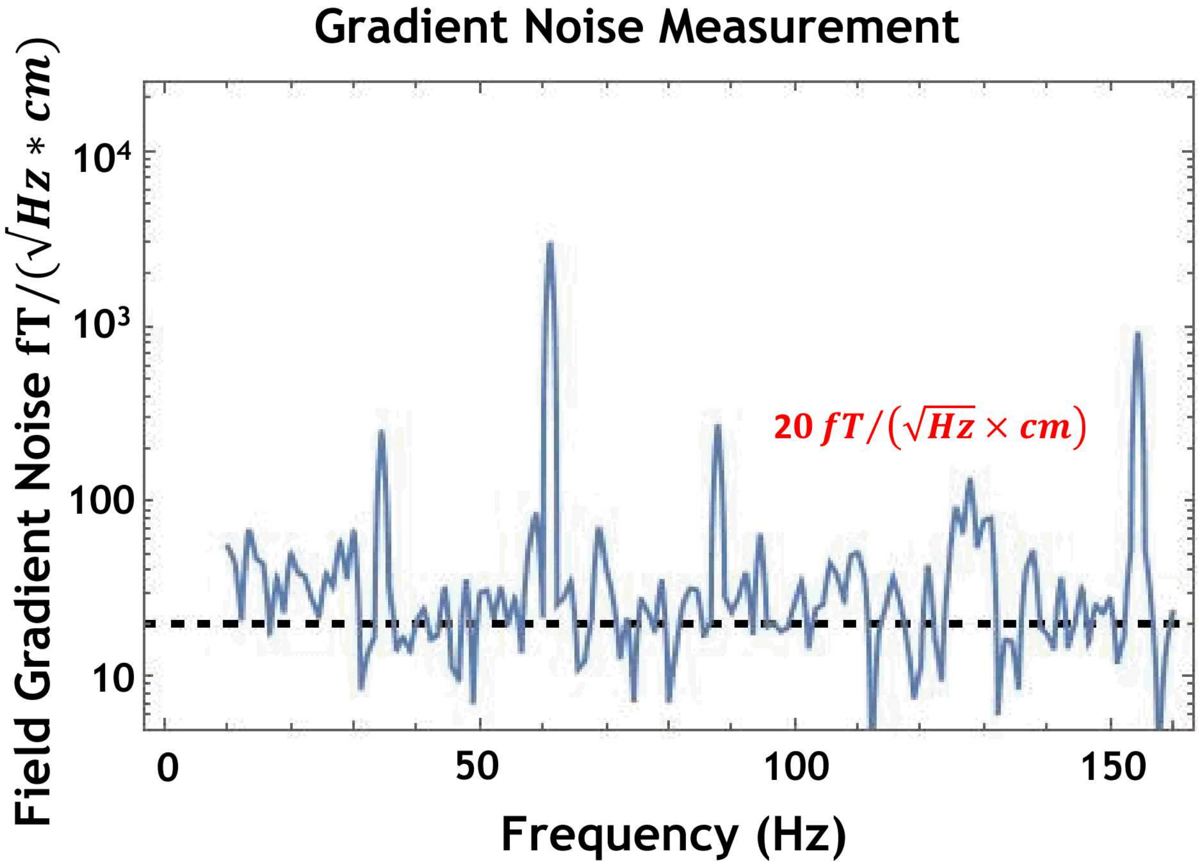
In Earth's Field



$^{87}$***Rb cells with 30 torr $N_2$ and 15 torr $N_2$***

***Separation: 4.4 cm***

Data and photo courtesy of QuSpin



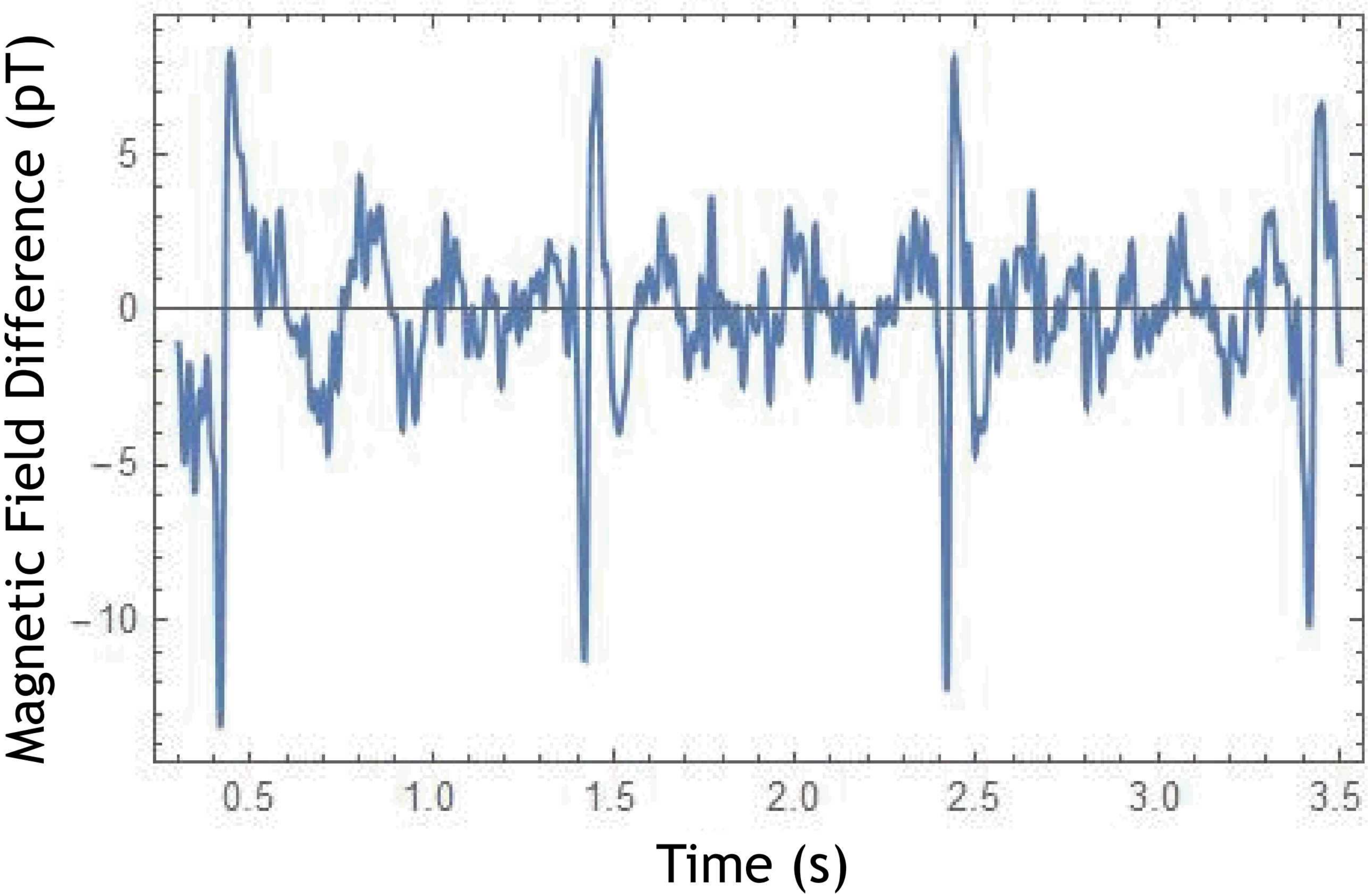

Data rate: 320 Hz

Photon Shot Noise: ~6 fT/cm/rt-Hz

# Heartbeat Measurement

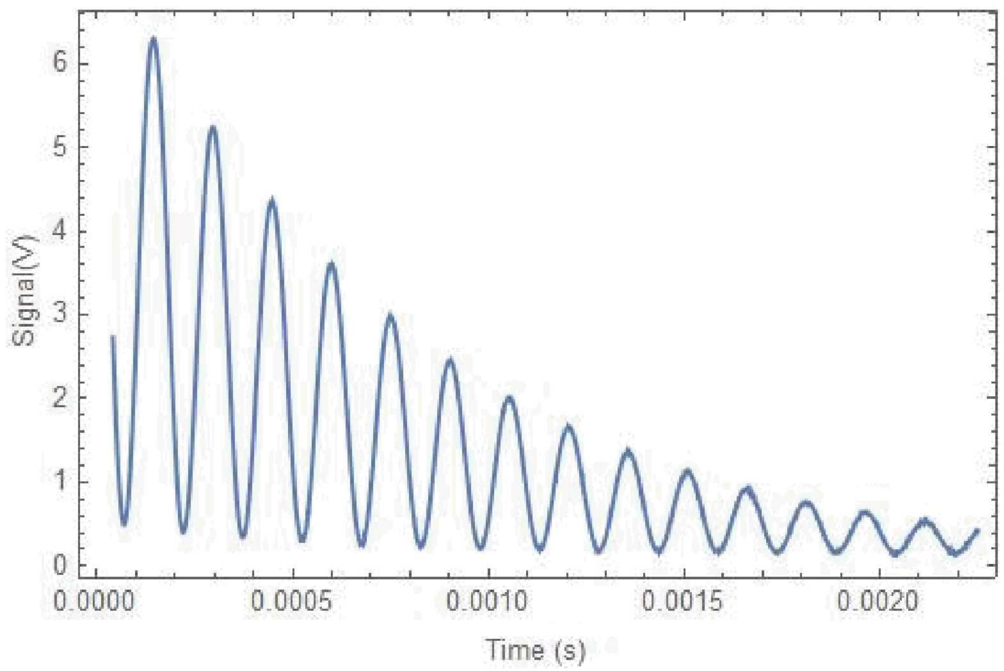
Heartbeat measurement of an adult male

Bandpass: 3-45 Hz



# Conclusion

- Demonstrated beat note detection of a gradient
  - Use hyperfine structure
- Optimized sensitivity versus buffer gas pressure and temperature
- Earth's field sensitivity as low as $\frac{20\ fT}{\sqrt{Hz}*cm}$ .
- Next steps:
  - Make more compact
  - Dead-zone free



# Acknowledgements


## Experiment

Sandia National Laboratories

-Kaleb Campbell
-Peter D.D Schwindt

QUSPIN

-Ying-Ju Wang
-Vishal Shah-PI

## Theory

Los Alamos National Laboratory

-Igor Savukov

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# Optical Beat Note Readout of a Magnetic Gradient

P.D.D. Schwindt,[1] K. Campbell[1], Igor Savukov[3], Y.J. Wang[2], and V. Shah[2]

[1] *Sandia National Laboratories, Albuquerque, NM, USA*
[2] *QuSpin Inc., Louisville, CO, USA*
[3] *Los Alamos National Laboratories, Los Alamos, NM, USA*

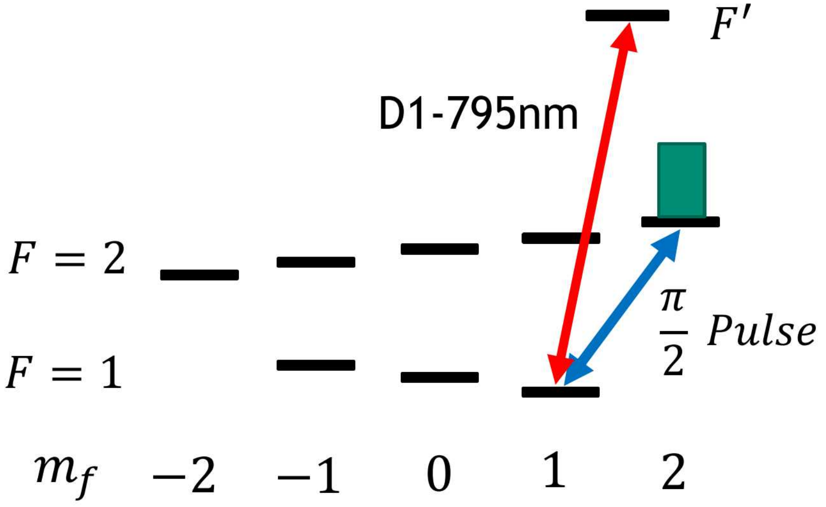
Typical gradient measurements using optically pumped magnetometers consist of making two independent measurements and then subtracting the results electronically. We present a technique where the gradient of the magnetic field is derived directly from the optical signal [1]. Using two $^{87}$Rb vapor cells, the atoms are pumped into the |$F$ = 2, $m_F$ = 2> stretched state. Then, a resonant microwave pulse is applied to make a superposition between the |2,2> and |1,1> levels, and a resonant 780-nm probe beam is passed through the two vapor cells. With the atomic superposition precessing at the hyperfine splitting frequency, the probe laser will be modulated, parametrically generating an optical sideband [2]. If there is a magnetic field gradient between the two vapor cells, the sidebands will have a frequency difference and generate a beat note. Thus, the beat note frequency will be proportional the magnetic gradient. We will present an experimental implementation of this technique and describe efforts to improve the sensitivity and to eliminate dead zones of the gradiometer.

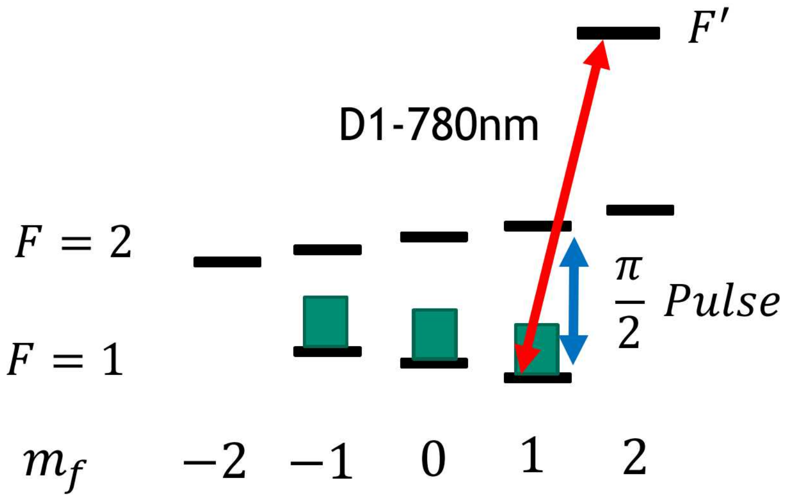
## References

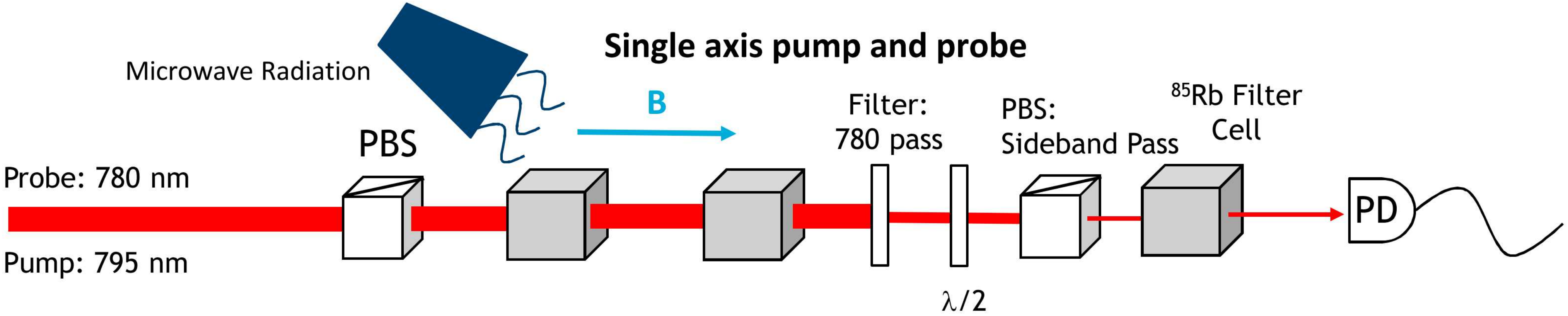
1. Vishal Shah, System and Method for Measuring a Magnetic Gradient Field. Patent. US10088535 (2018).
2. Tang, H. Parametric Frequency Conversion of Resonance Radiation in Optically Pumped $Rb^{87}$ Vapor. Phys. Rev. A, **7**, 2010–2032 (1973).

# Can we make the sensor more compact?

- Pump and Carrier along the same axis?
- Selection rules prohibit sideband generation on the |F=1, $m_f$ = 1> to |F=2, $m_f$ = 2> transition.
- Selection rules allow only $\Delta m_F = 0$ transitions.



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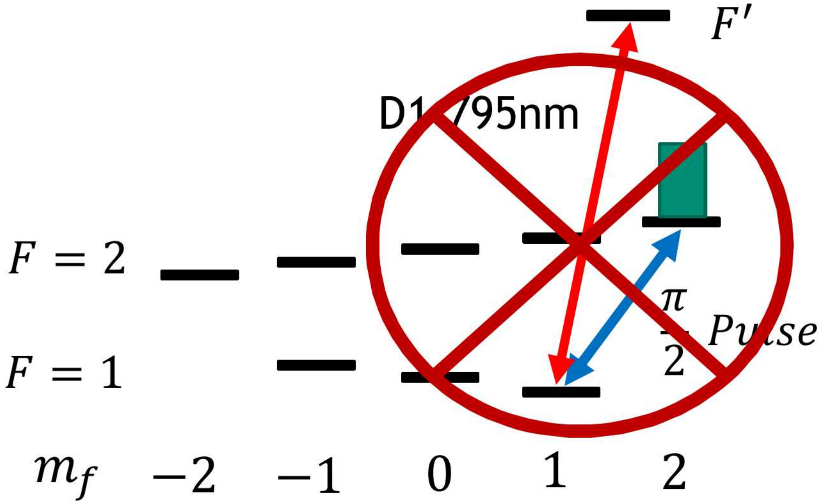


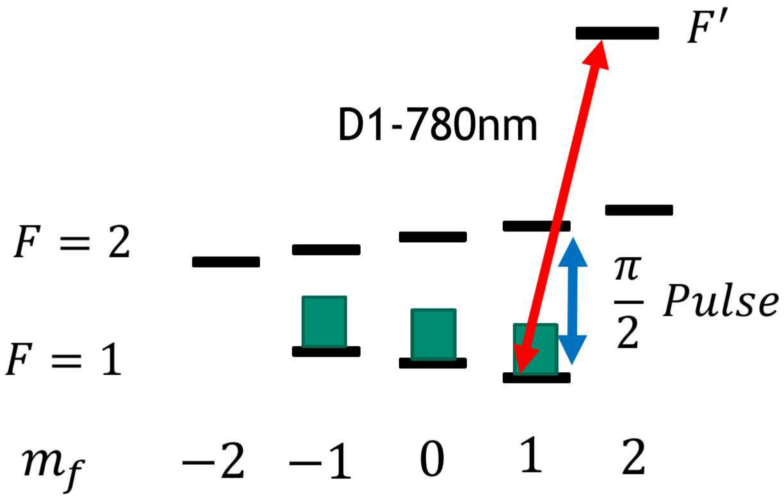


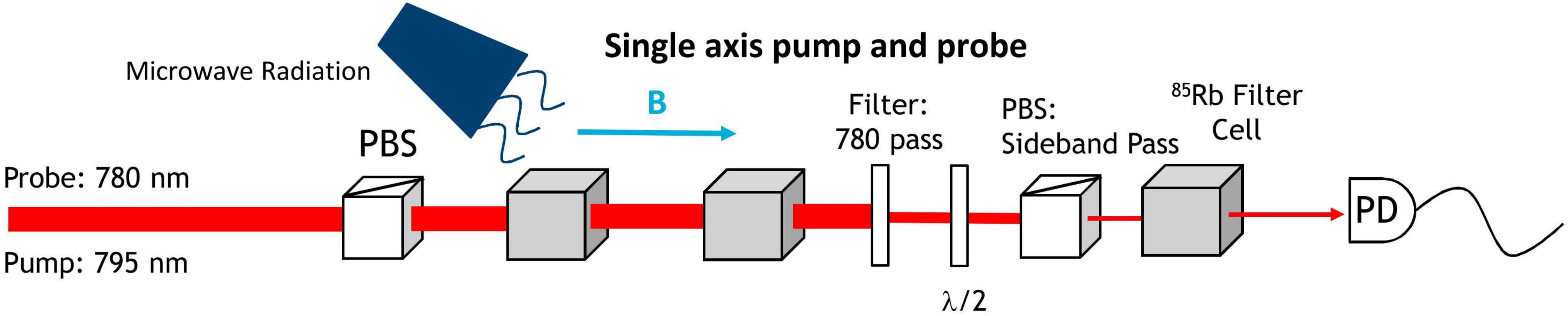

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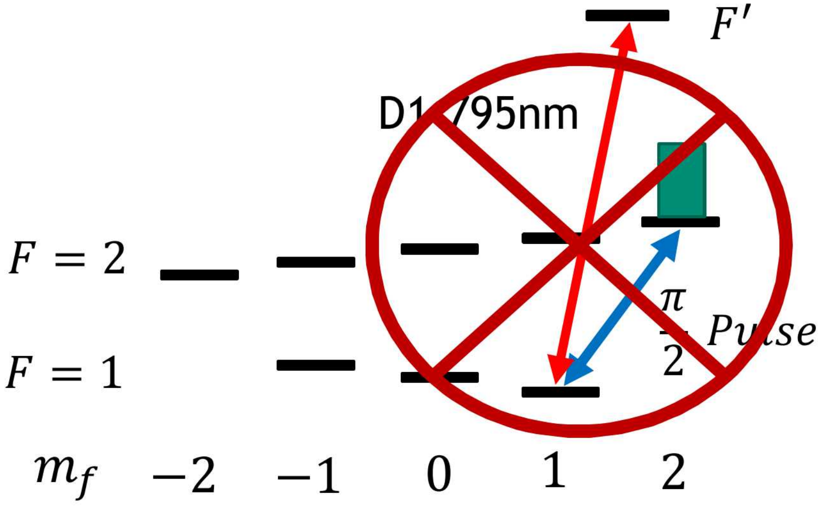
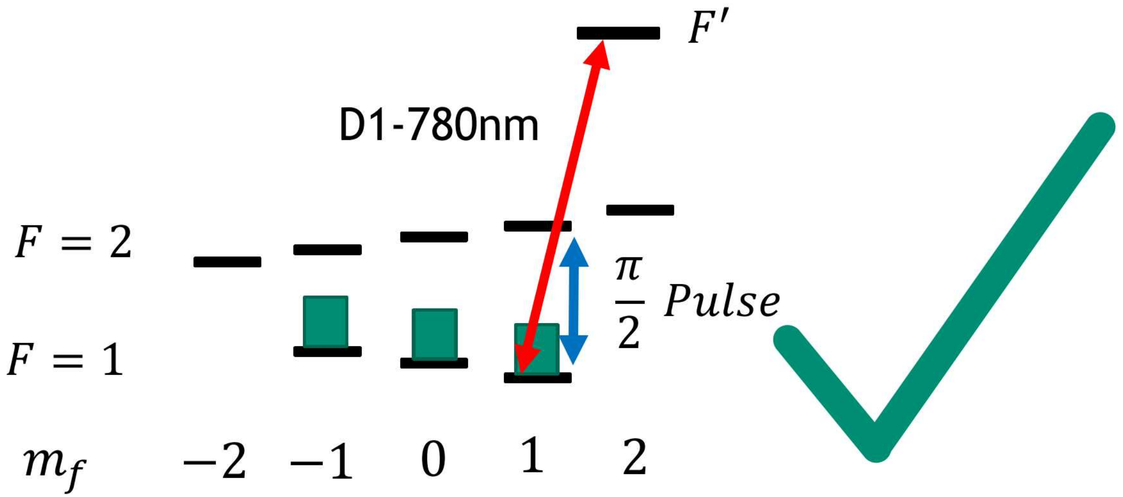
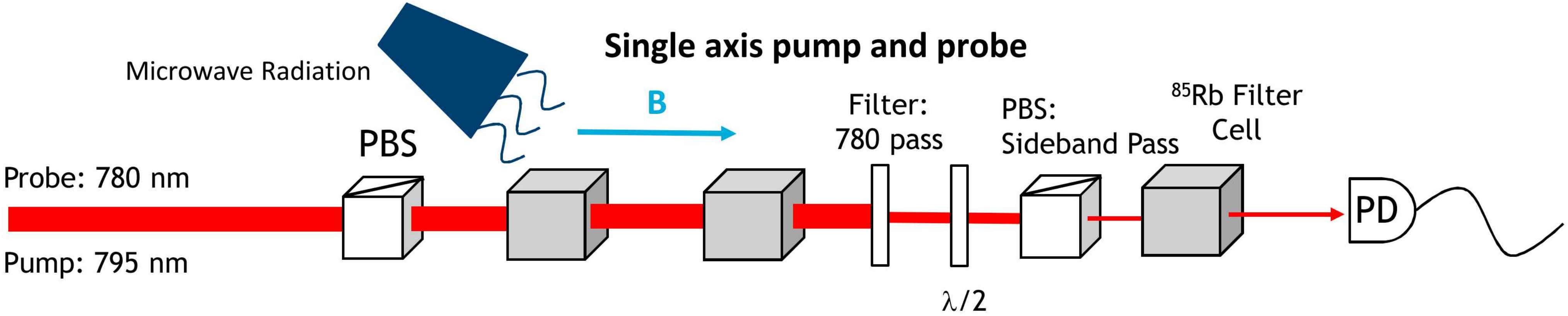
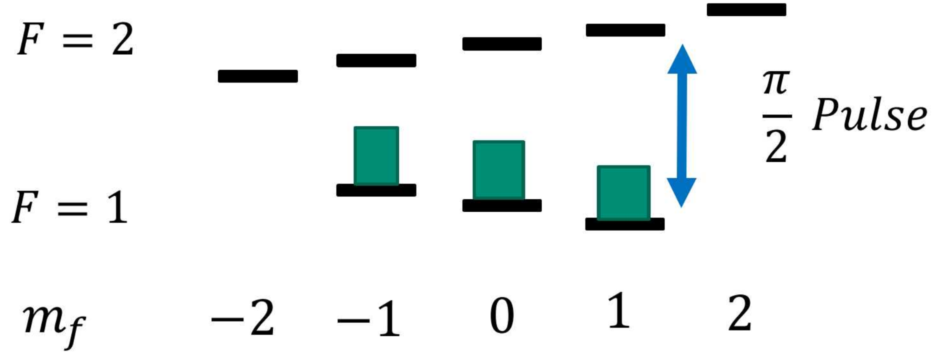


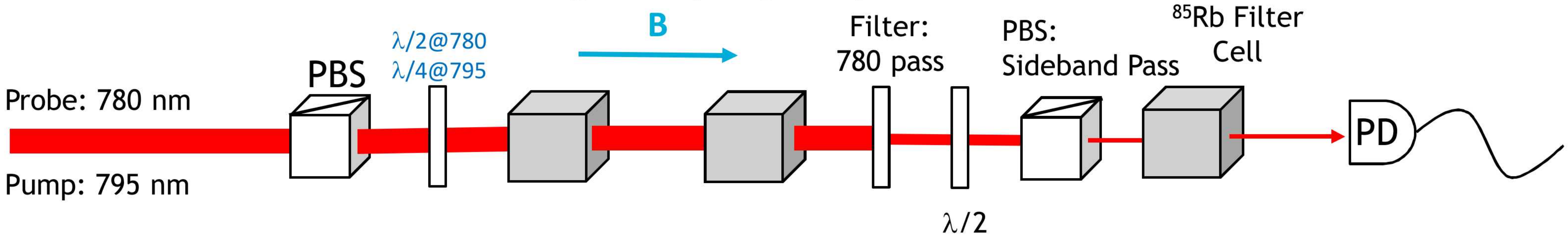
# Problems with this orientation

- We can only pump the atoms to a single ground state, not an individual Zeeman sublevel
- Reduced sideband amplitude

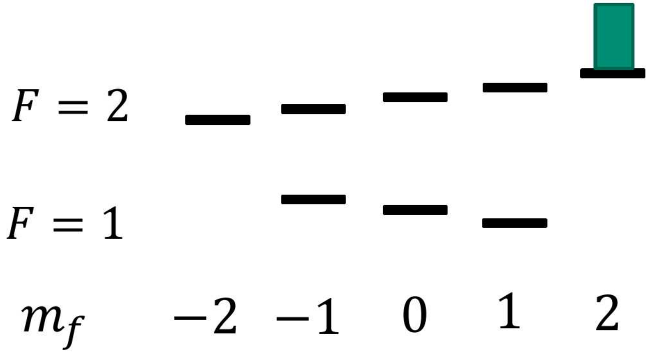


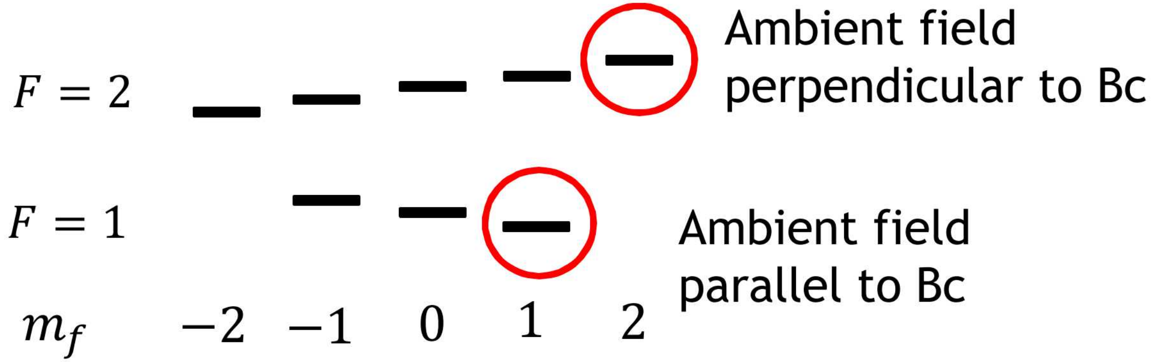

## Solutions?

**Single axis pump and probe**



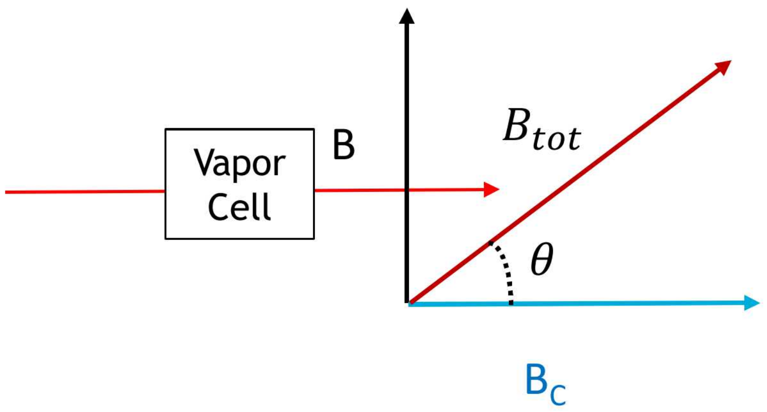

Atoms optically pumped to the end-state

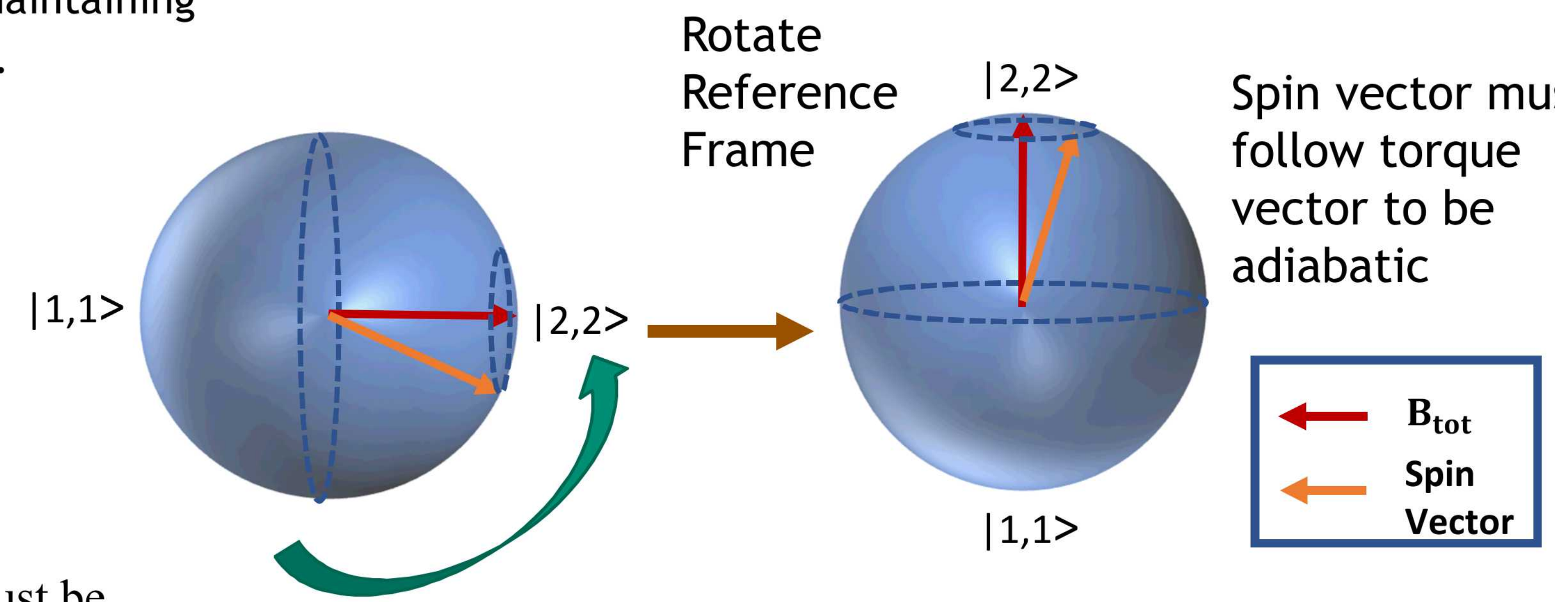


# Case 1: Ambient field perpendicular to the laser axis

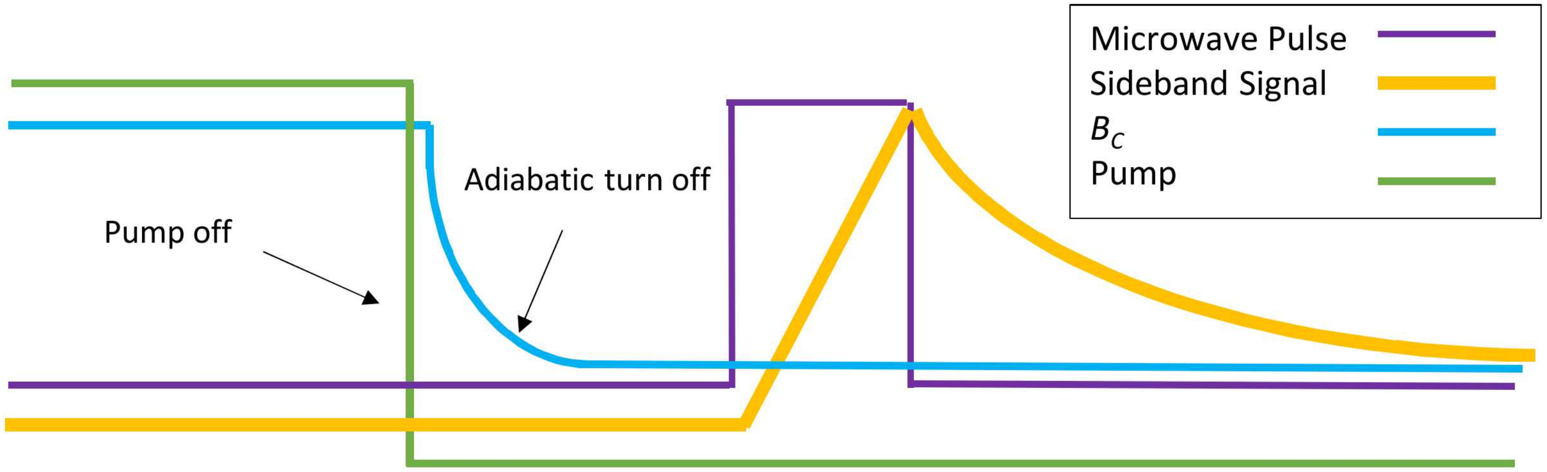
We rotate the quantization axis, while maintaining the atomic population in the |2,2> state.



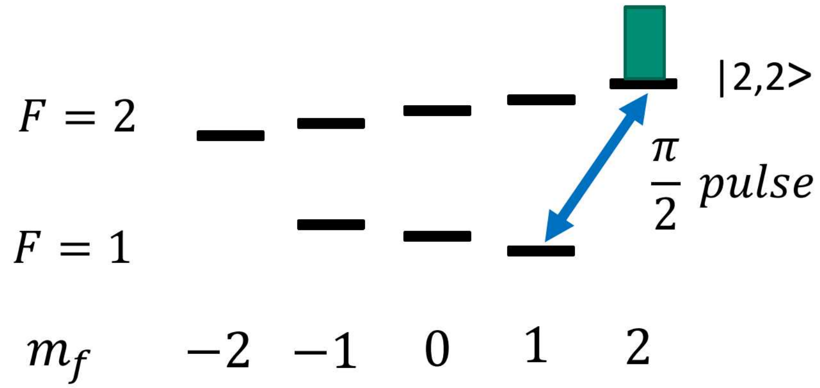




Spin vector must follow torque vector to be adiabatic

To be adiabatic, the rotation rate of the field must be less than the Larmor precession frequency $\frac{d\theta}{dt} << \omega_L$.



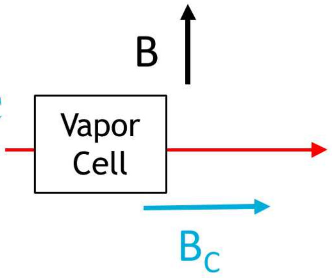

Selection rules now allow $\Delta m_F$ = 1 transitions

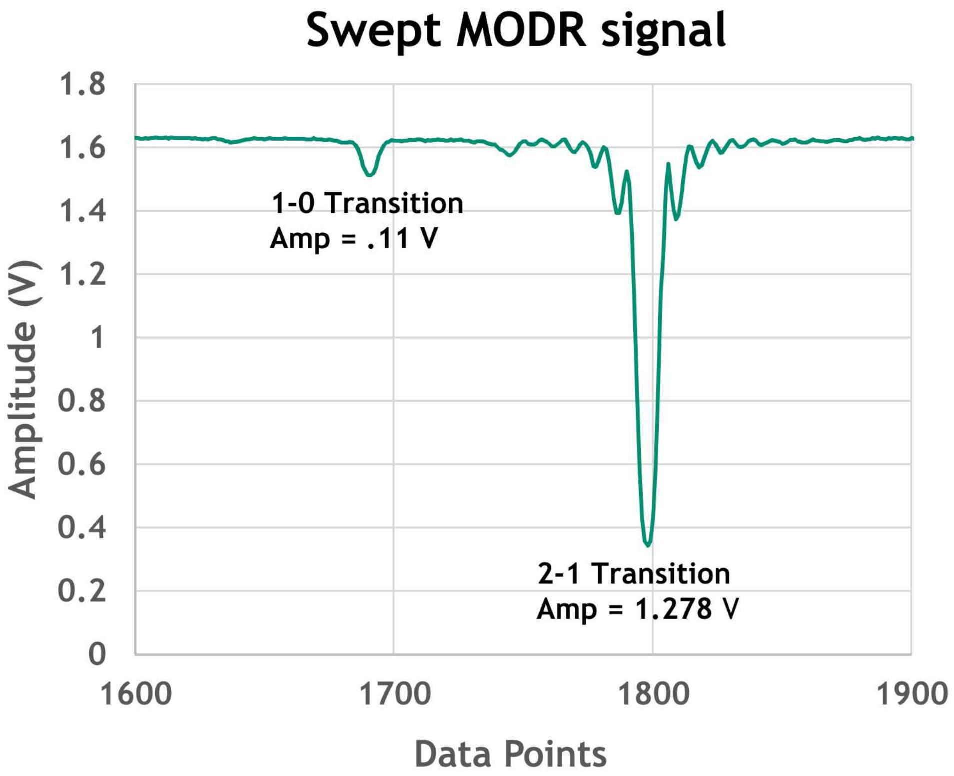


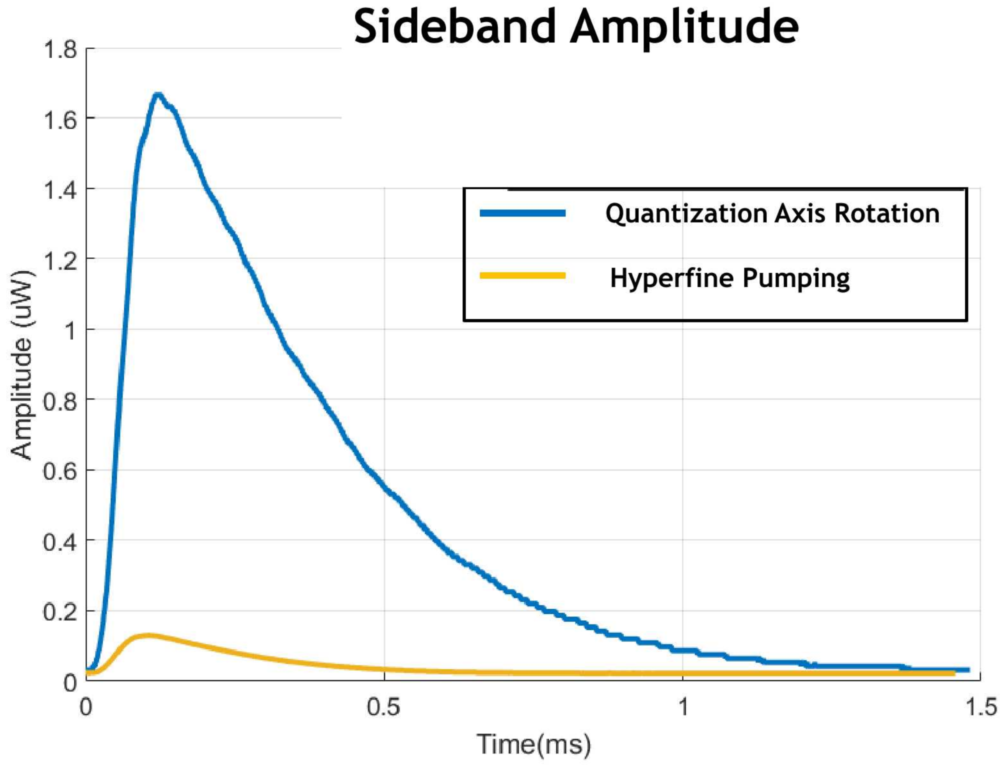
# Case 1: Results

Compare adiabatic field switching to the old method of hyperfine pumping.

- Observe ~90% in the |2,2> state with optical pumping: expect improvement with lager $B_C$
- Adiabatic switch does not degrade populations
- See a 10x improvement in sideband size



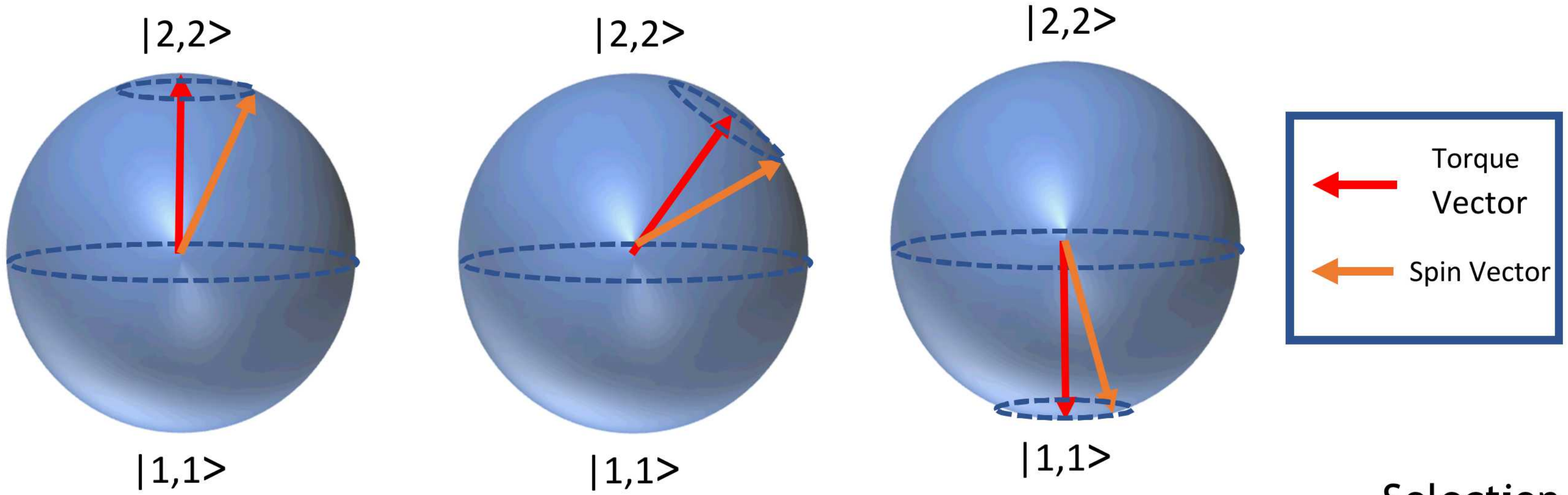



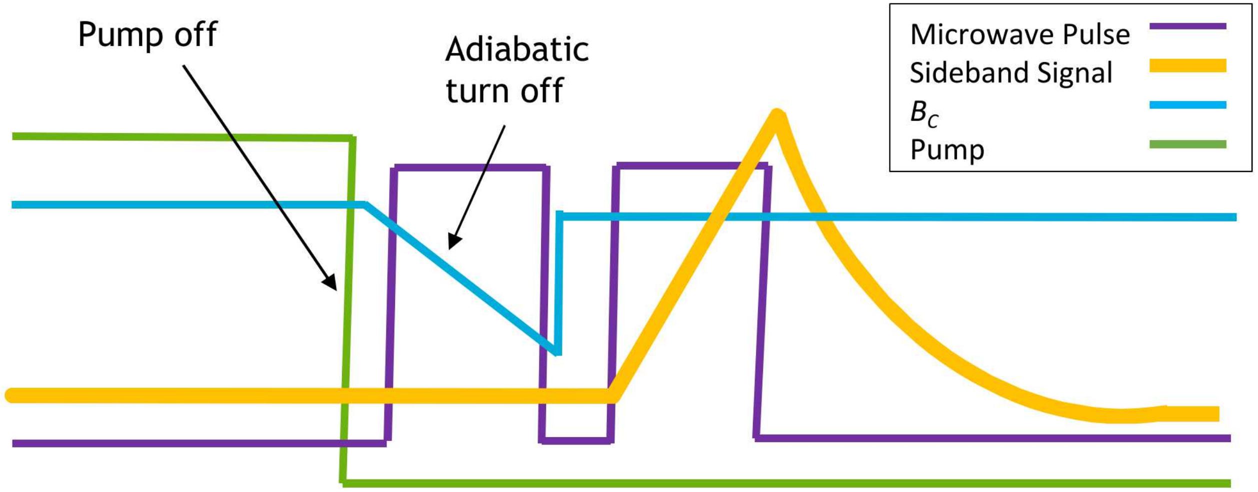

**Probe Power = ~20 μW; Detuning near F = 1; Useing Rb-85 filter cell; Buffer gas: 30 Torr N2; Cell Temp = 98 °C;**

# Case 2: Ambient field parallel to the laser axis

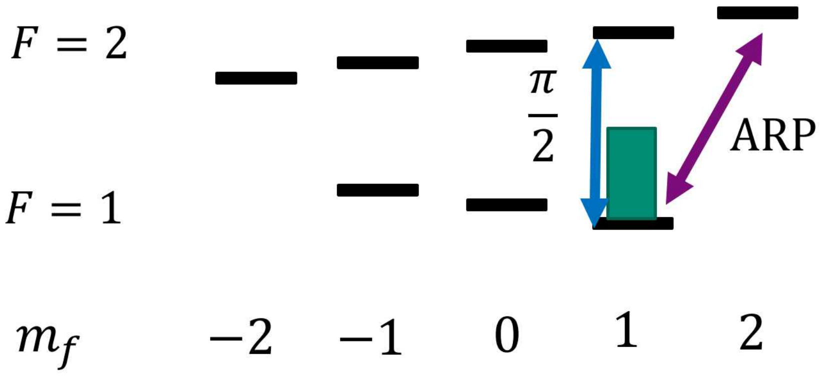
- We perform adiabatic rapid passage to transfer the population from the |2,2> state to the |1,1> state.
- We use a magnetic field ramp to simplify microwave and cover both cells.




Magnetic field must be ramped slow enough that the Spin vector follows the Torque vector



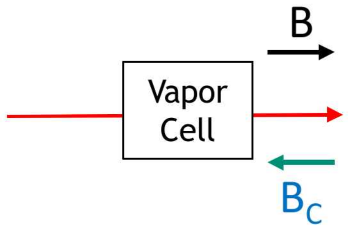

Selection rules allow $\Delta m_F = 0$ transitions

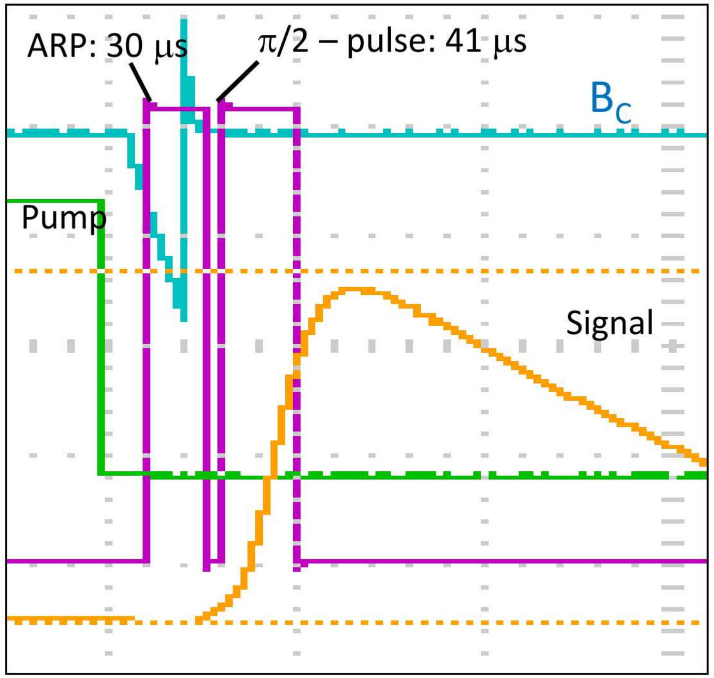


# Field parallel to the laser axis

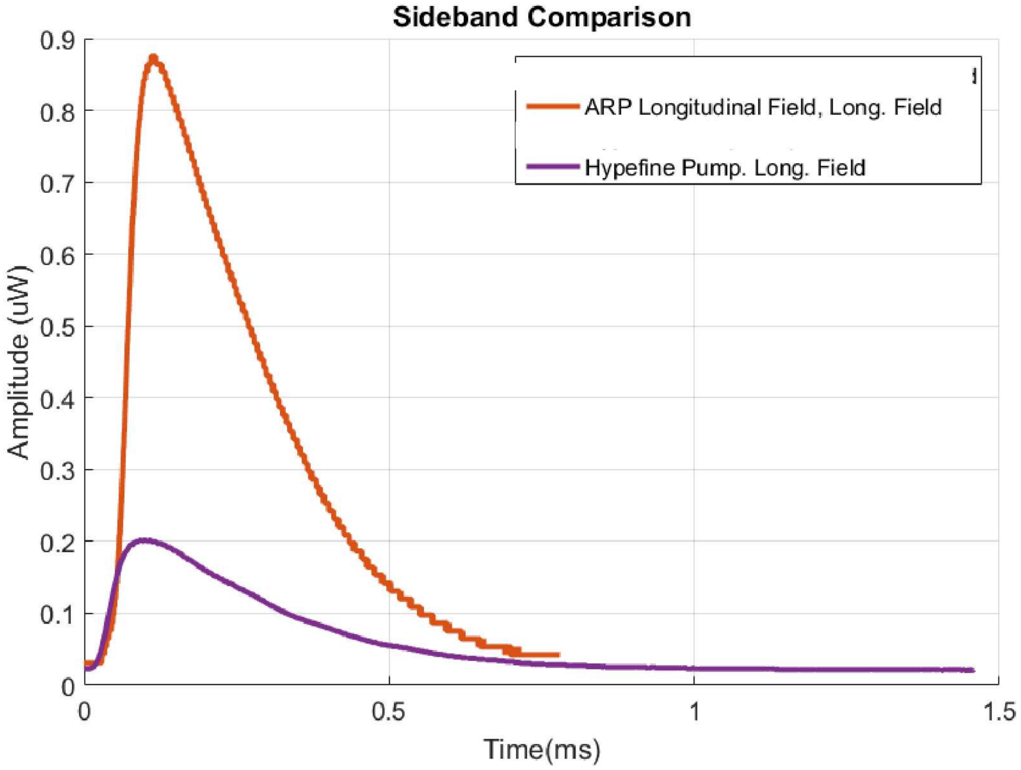
Compare adiabatic field switching to the old method of hyperfine pumping.

- Observe ARP from |2,2> to |1,1>
  - Use a single microwave synthesizer
  - The percentage of the transfer uncertain
- See a 4x improvement in sideband size on the |1,1> to |2,1> transition.



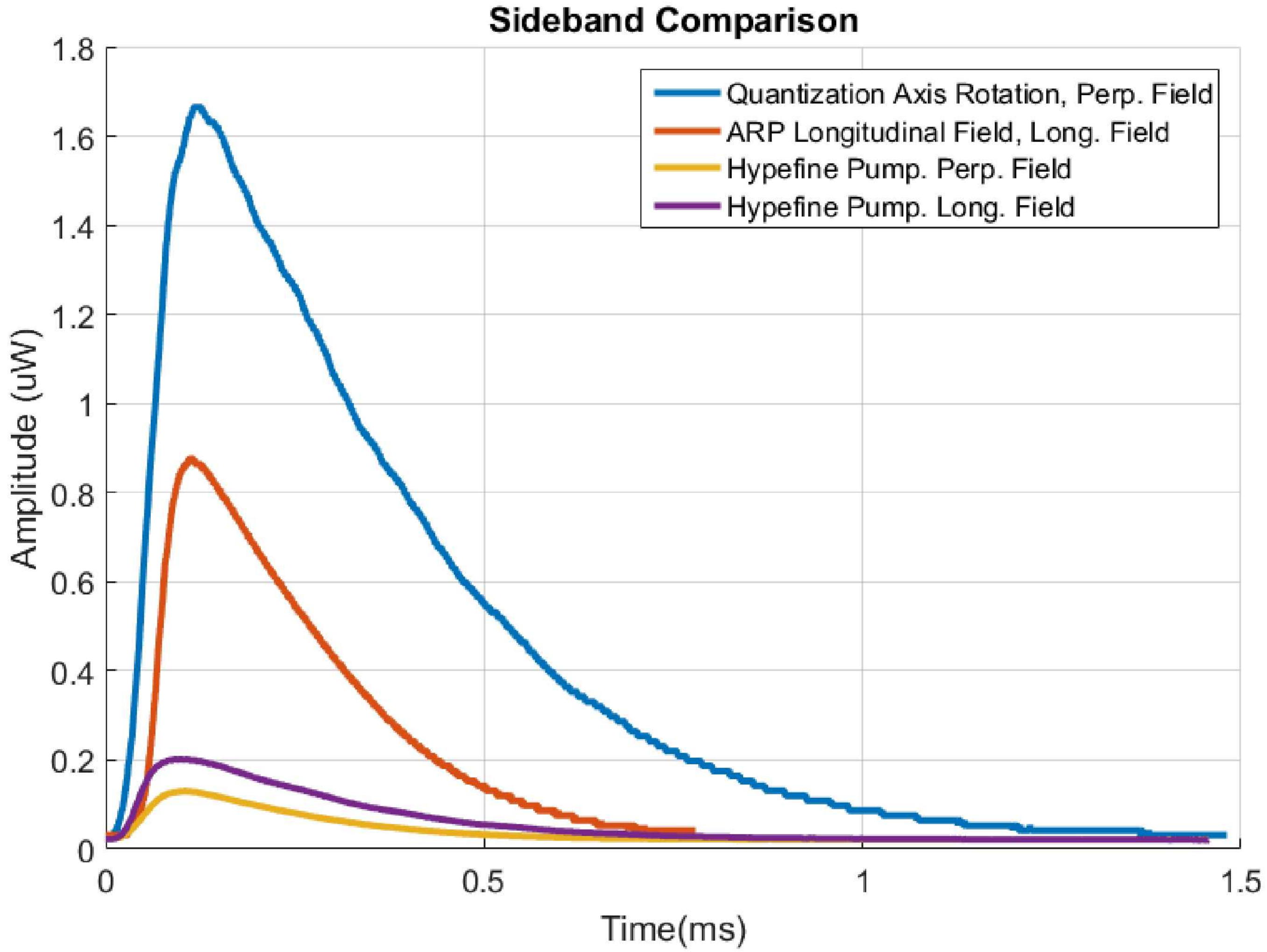

0.1 ms/div



# Comparison of four experiments

Quantization axis rotation currently working better than microwave ARP

- Why is this?



# Can we work towards dead-zone free operation?

Minimum field

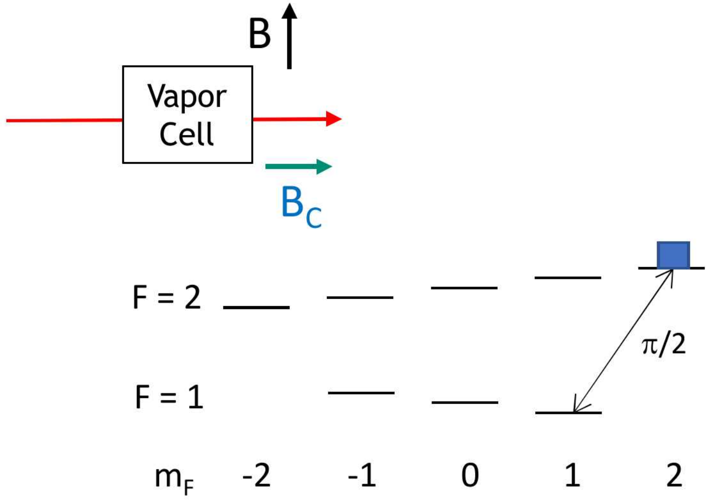
- $f_{1\to2} - f_{1\to1} \gg \frac{1}{2\pi\, T_{\pi/2}}$
- For $T_{\pi/2}$ = 0.1 ms, $B_{min} \gg$ 230 nT

How to switch between the two schemes

- Start up:
  1. Determine ambient field and direction using a field zeroing scheme
  2. Select scheme, microwave frequency, and direction of $B_C$
  3. Begin operation.
- Continuous operation:
  1. Monitor signal size
  2. If signal size drops below threshold, switch scheme.
     1. If this fails, re-zero field.

Need to understand better how to ramp Bc for ARP

Quantization axis rotation




ARP with longitudinal field