SAND2020-11313C

Pulsed gradiometry in Earth's field

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA). The views, opinions and/or findings expressed are those of the authors and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government

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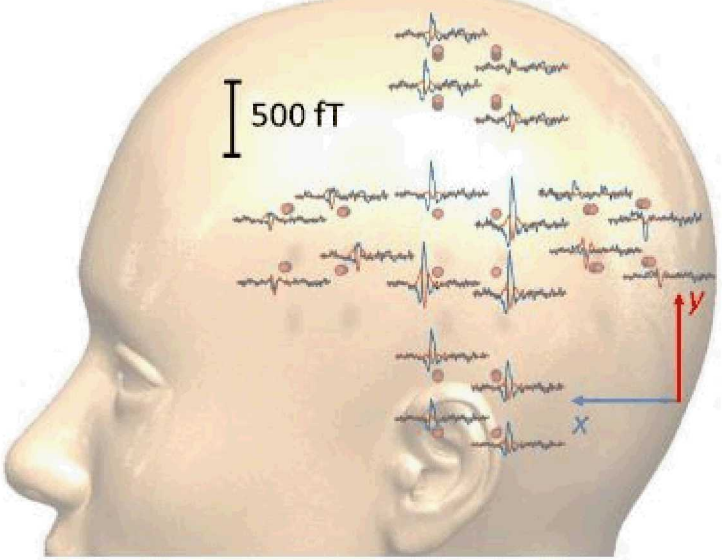
Kaleb Campbell

Sandia National Labs, University of New Mexico Department of Physics and Astronomy

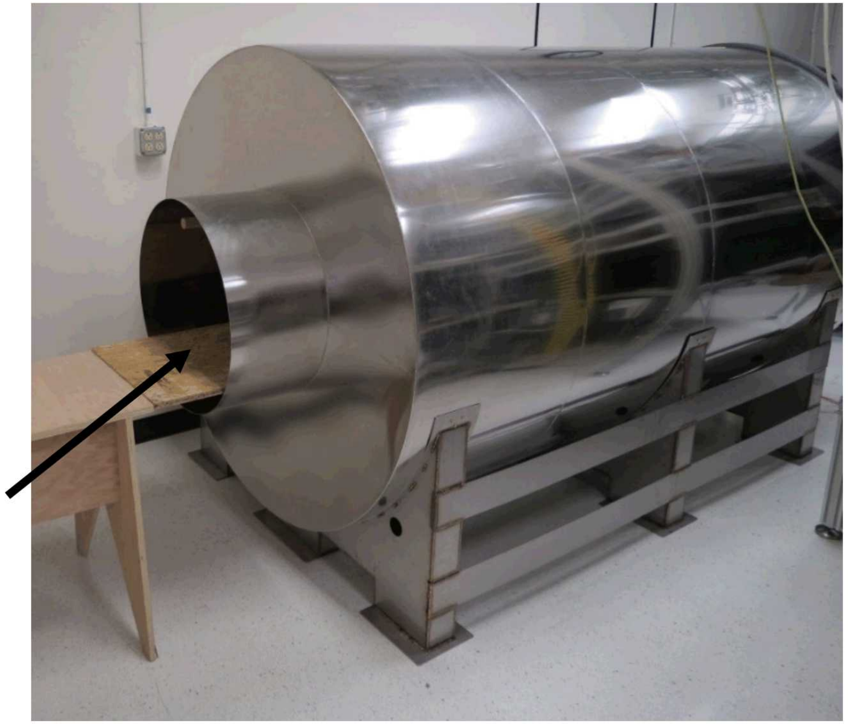
Applications of OPM's



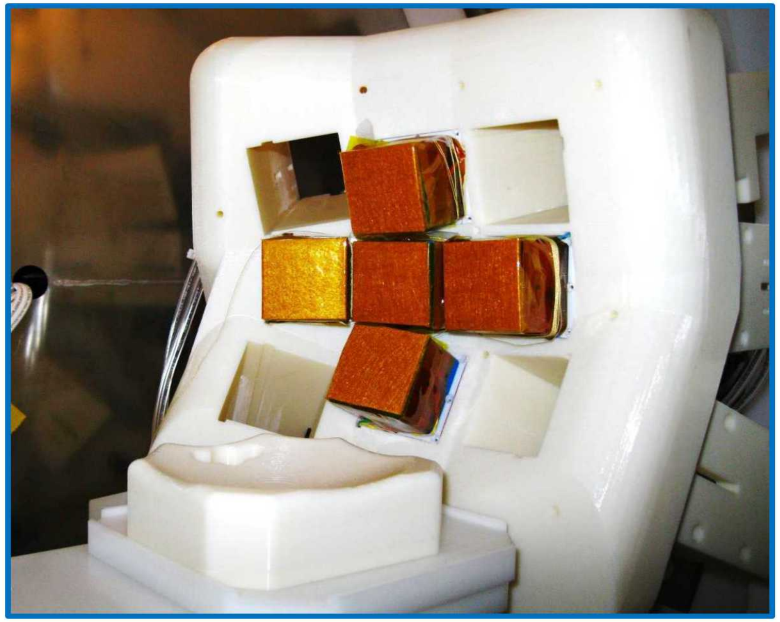
Magnetoencephalography (MEG)

- Magnetic fields generated from neuronal activity in the brain
- Fields in the femto-tesla to pico-tesla range – requires very sensitive magnetometers
- SERF magnetometers are most sensitive – require magnetic shielding or field cancelation coils

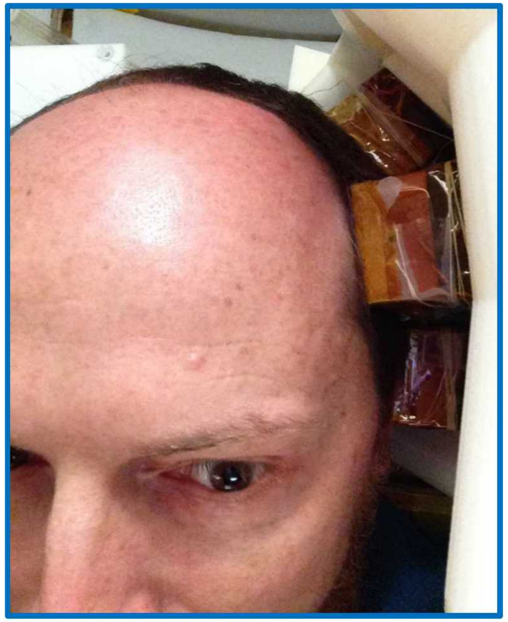
Insert Person Here



5-sensor array

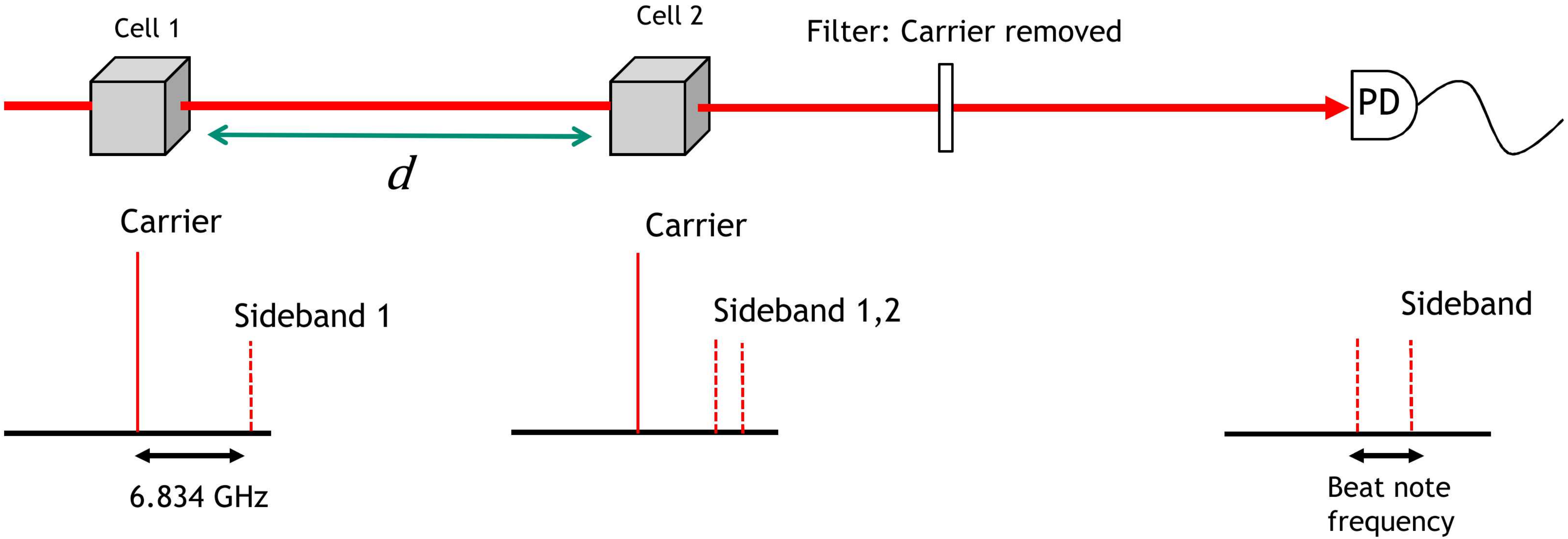


Partially covers the left hemisphere



Borna, A., et al, Physics in Medicine and Biology (2017)

Basic Idea – Magnetic Gradiometer



Sideband Produced in the first cell orthogonally polarized to the carrier

Sideband Produced in the second cell orthogonally polarized to the carrier

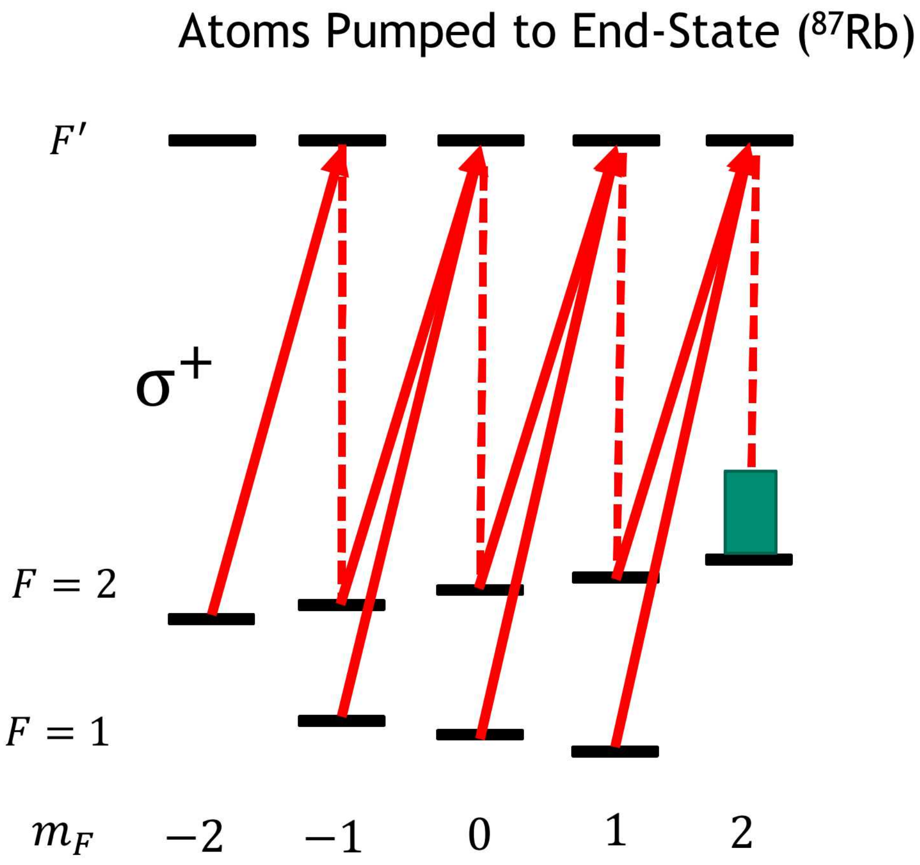
Carrier removed and sidebands beat together

$$f_B \propto \Delta B$$

*__Henry Tang__, *Parametric Frequency Conversion of Resonance Radiation in Optically Pumped* ^{87}*Rb Vapor*. Phys. *Rev. A* **7**, 2010 (1973).

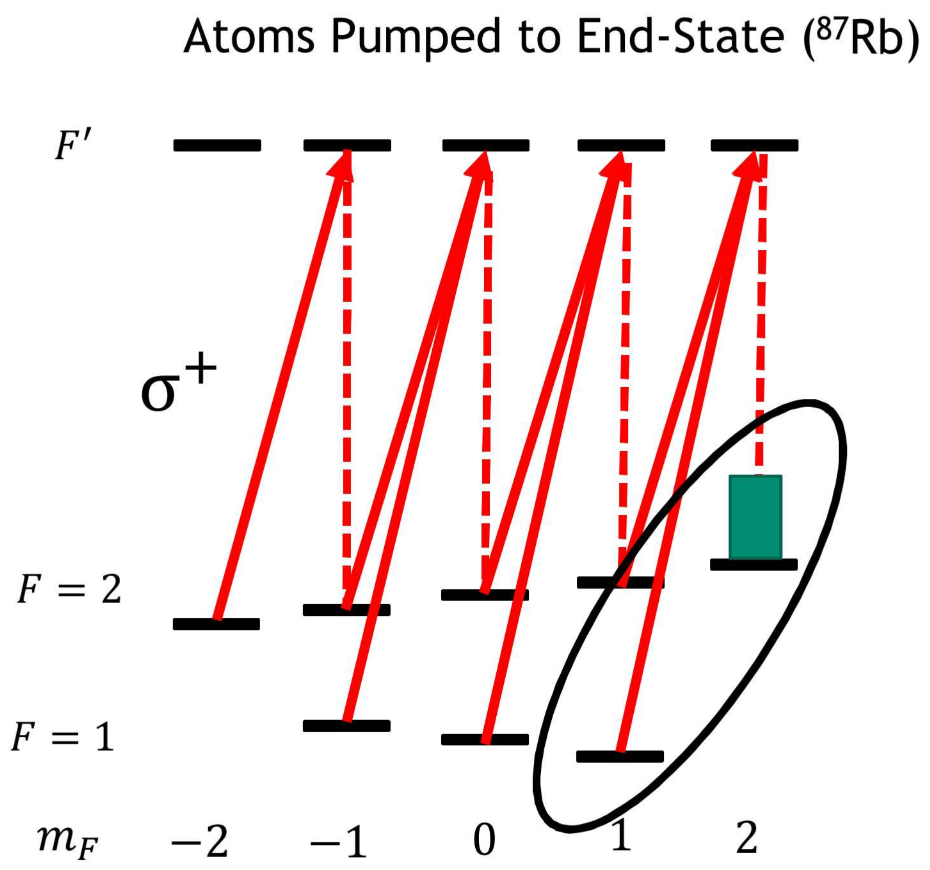
*Vishal Shah, *System and Method for Measuring a Magnetic Gradient Field*. Patent. US10088535 (2018)

How Sidebands are produced



- Atoms absorb angular momenta from σ^+ light
- Make $\Delta m_F = +1$ transitions to excited state

How Sidebands are produced



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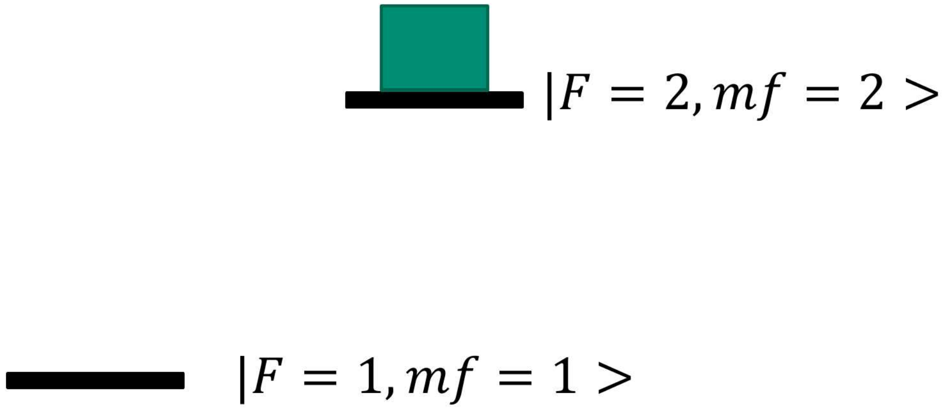

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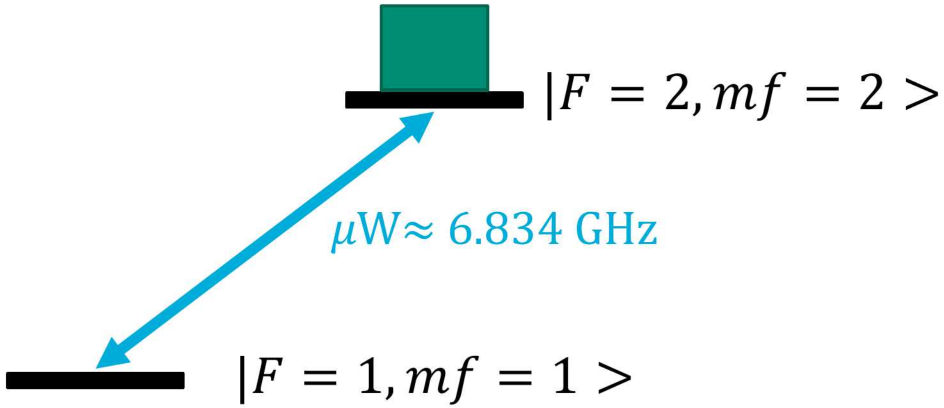
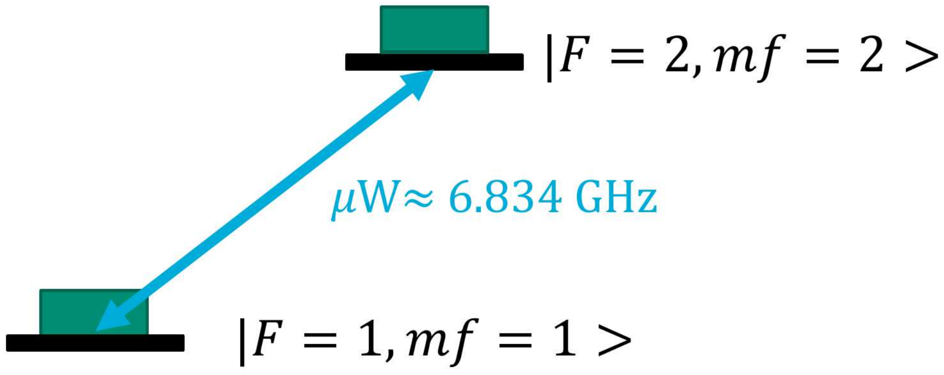


- μW field Induces Rabi oscillations between levels
- Rabi frequency $\Omega = \frac{\mu B}{\hbar}$
- Ωt = $\pi/2$ known as $\pi/2$ Pulse

How Sidebands are produced



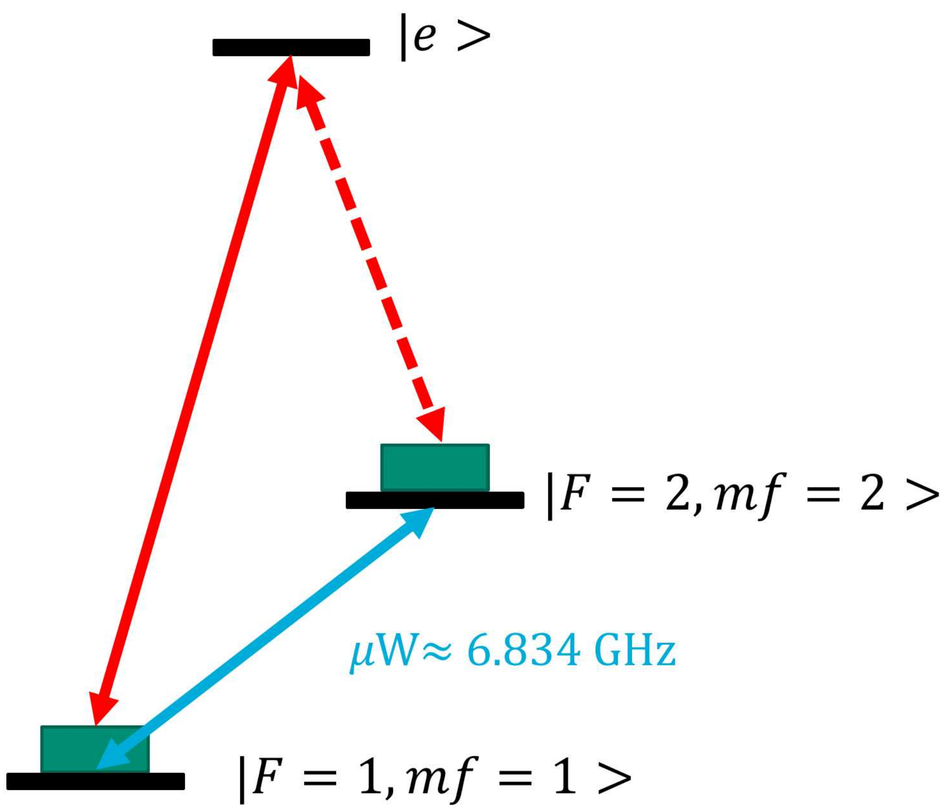
- Atoms are in a coherent superposition of both states

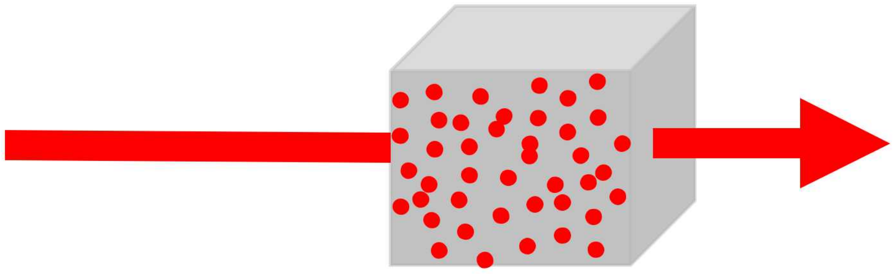
- Coherences are maximized

$$\rho = \begin{bmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{bmatrix} = \begin{bmatrix} 1/2 & 1/2 \\ 1/2 & 1/2 \end{bmatrix}$$

- Atoms oscillate at the ground state hyperfine frequency (6.834 GHz for Rb^{87})
  - Nuclear spin and Electronic spin tumbling around each other in phase

How Sidebands are produced





- Introduce Carrier (probe) light to the experiment

From Maxwell’s equations (No current source, magnetic susceptibility, or spatial charge)

$$\nabla^2 E + \nabla(\nabla \cdot E) = \frac{-1}{c^2}\frac{\partial^2 D_e}{\partial^2 t}$$

where

$$D_e = E + 4\pi P$$

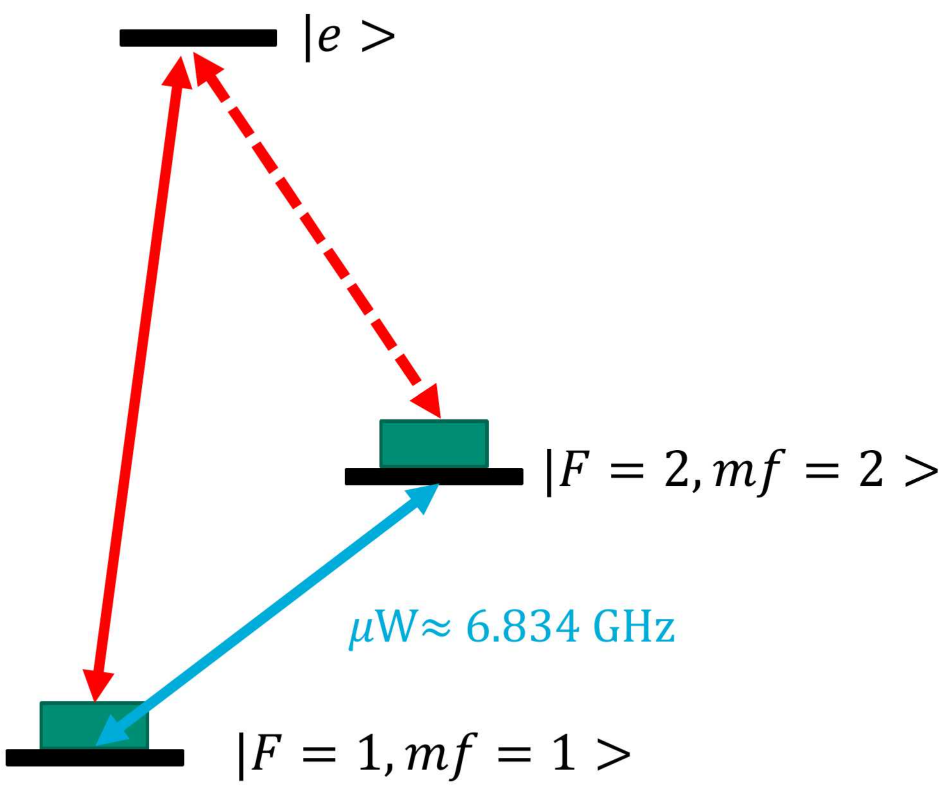
The electric displacement is related to the electric dipole moment of the atoms

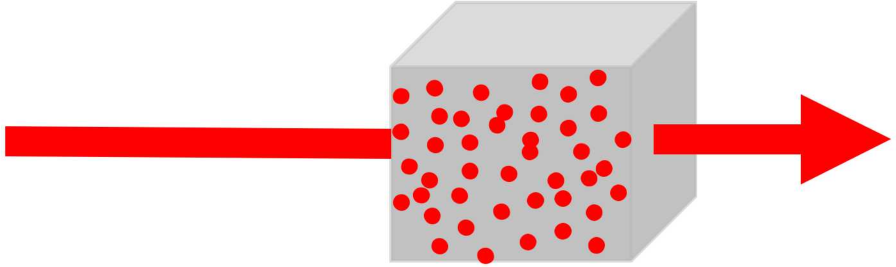
$$D_e = E + 4\pi N < D >$$

Or

$$D_e = (1 + 4\pi\chi)E$$

How Sidebands are produced





$$\nabla^2\widetilde{\mathbf{E}} - \nabla(\nabla\cdot\widetilde{\mathbf{E}}) = -\frac{\omega^2}{c^2}\left(\widetilde{\mathbf{E}} + 4\pi n_a\langle\widetilde{\mathbf{D}}\rangle\right)$$

- For a one-dimensional plane wave

$$\left(\frac{\partial}{\partial z} \pm i\frac{\mathbf{W}}{c}\cdot(1+\boldsymbol{\chi}/2)\right)\cdot\widetilde{\mathbf{E}}_\pm$$

$$\langle\omega'|\boldsymbol{\chi}|\omega\rangle = 4\pi n_a \sum_{\mu,\nu} \boldsymbol{\alpha}_{\mu\nu}\tilde{\rho}_{\mu\nu}\delta_{(\omega'-\omega),\Omega_{\mu\nu}} e^{\frac{i}{c}(\omega'-\omega)z}.$$

•Sidebands are produced offset from the carrier beam by the hyperfine frequency (frequency of modulation)

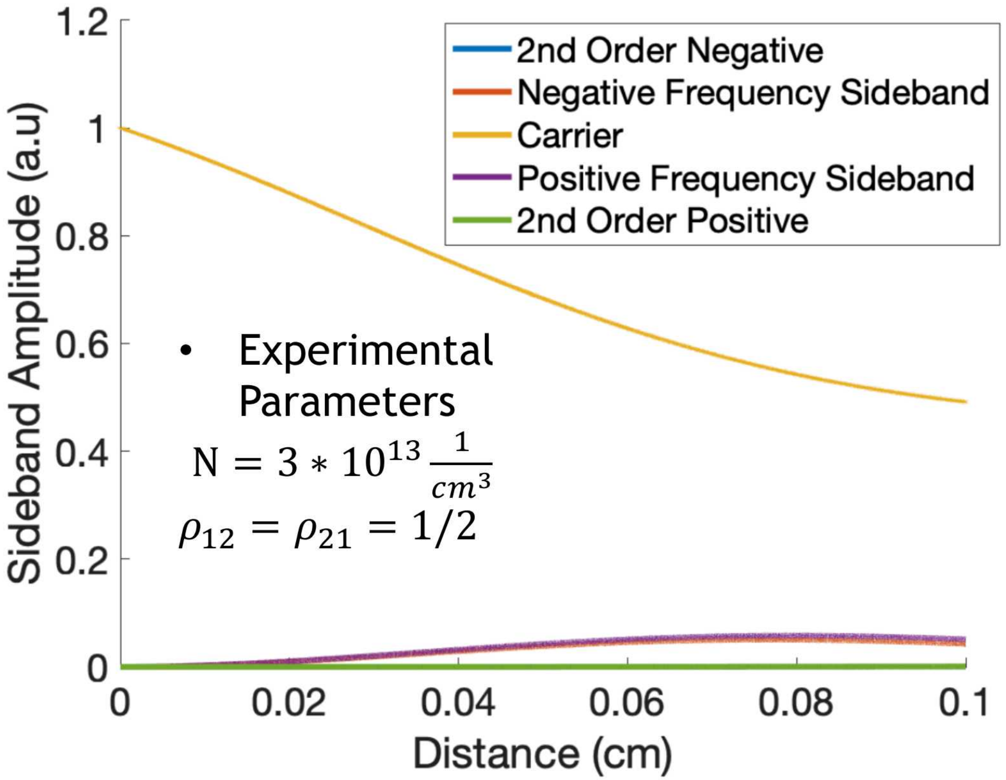
$$\omega_+ = \omega_0 + \mu W$$

$$\omega_- = \omega_0 - \mu W$$

ω_0 = Carrier frequency

•Similiar to an Electro-optic modulator (EOM)

Building a numerical model

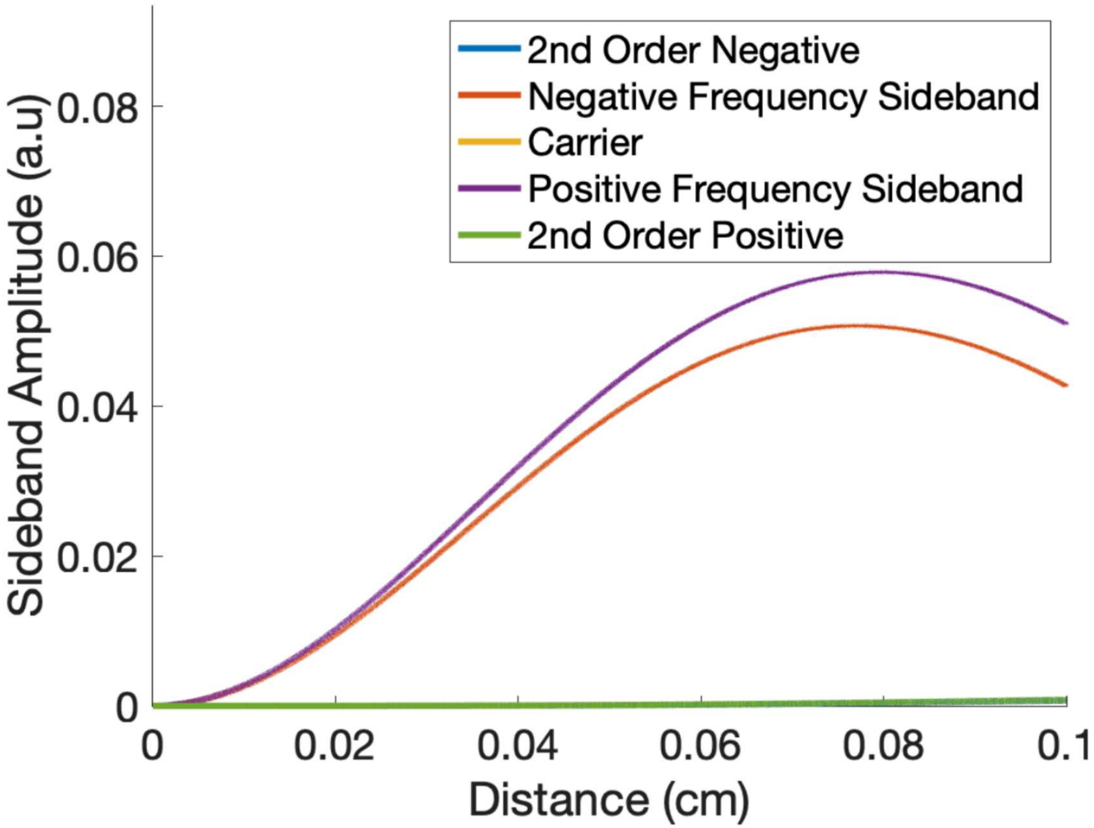


- Experimental Parameters

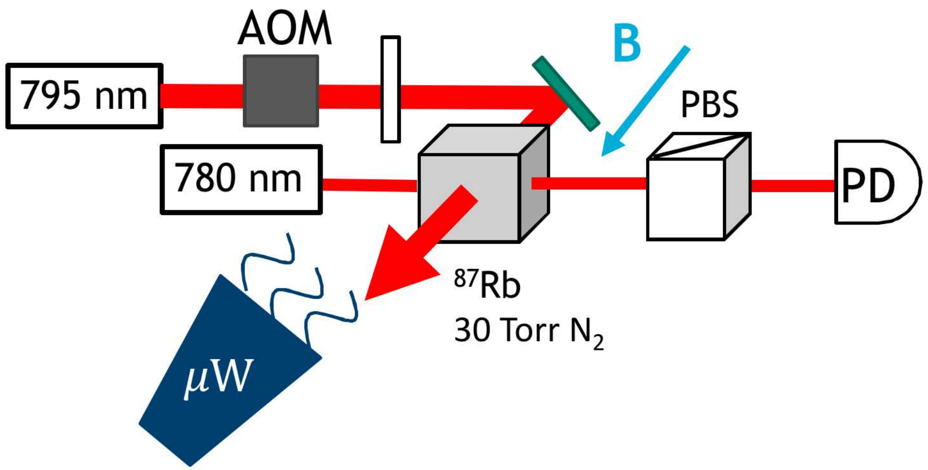
$N = 3 * 10^{13} \frac{1}{cm^3}$

$\rho_{12} = \rho_{21} = 1/2$

Zoomed In On Sidebands

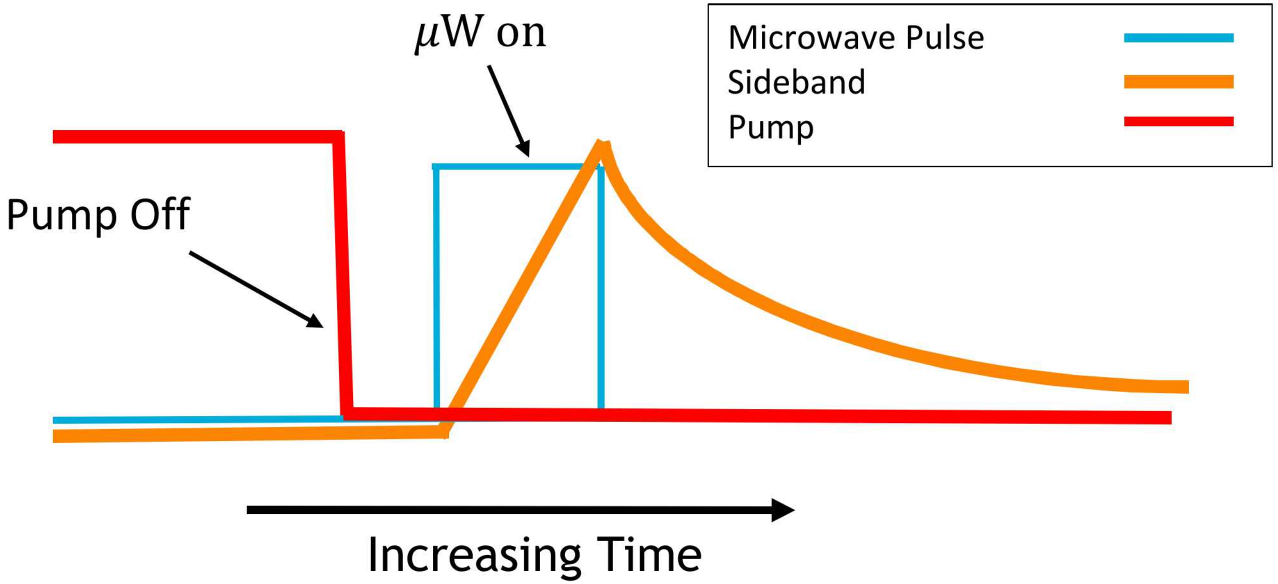


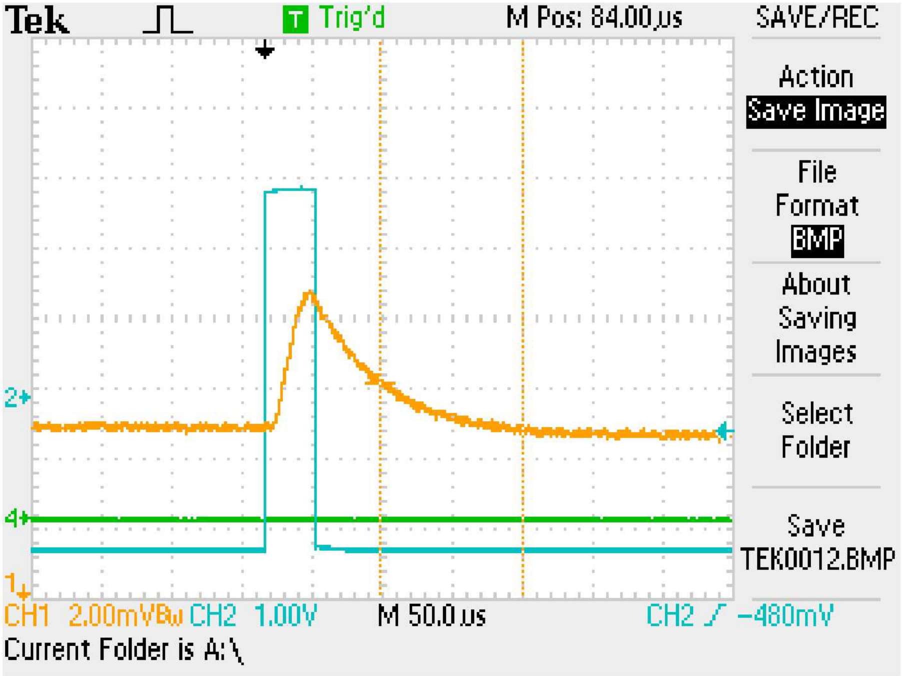
Pulsed Experiment



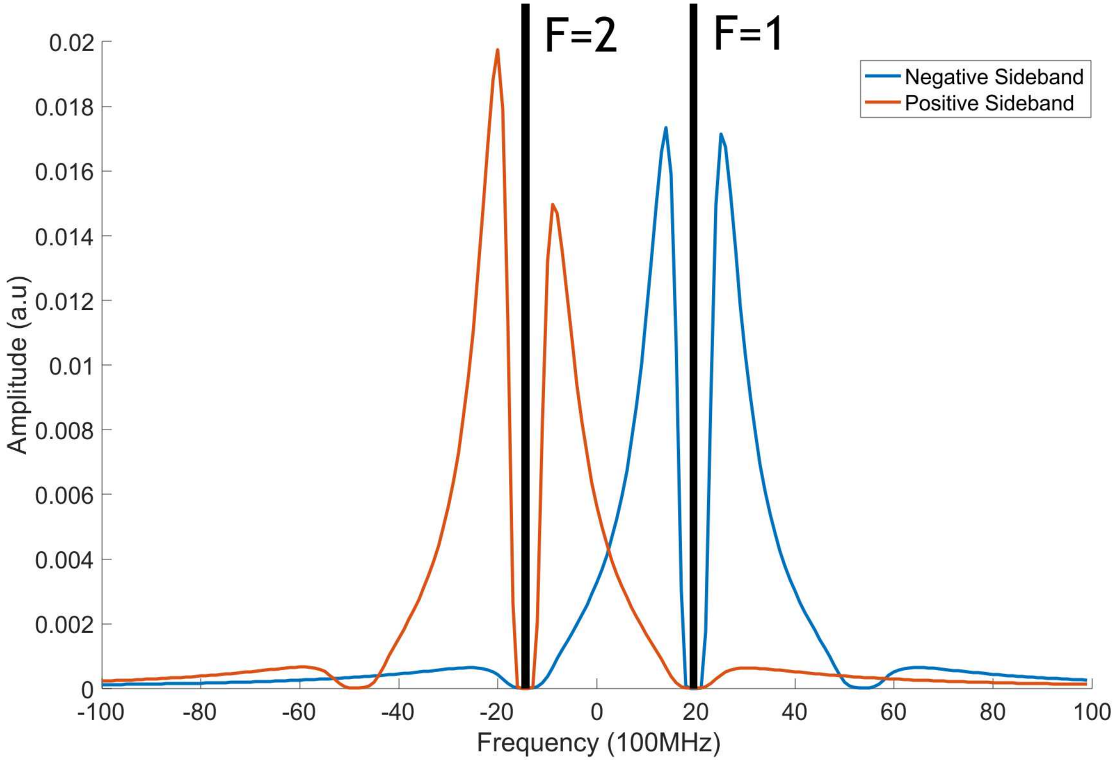
Use an AOM as a switch on Pump

Pump is off when making measurement
- Pump doesn't degrade coherence
- Stronger pump can be used (better pumping)

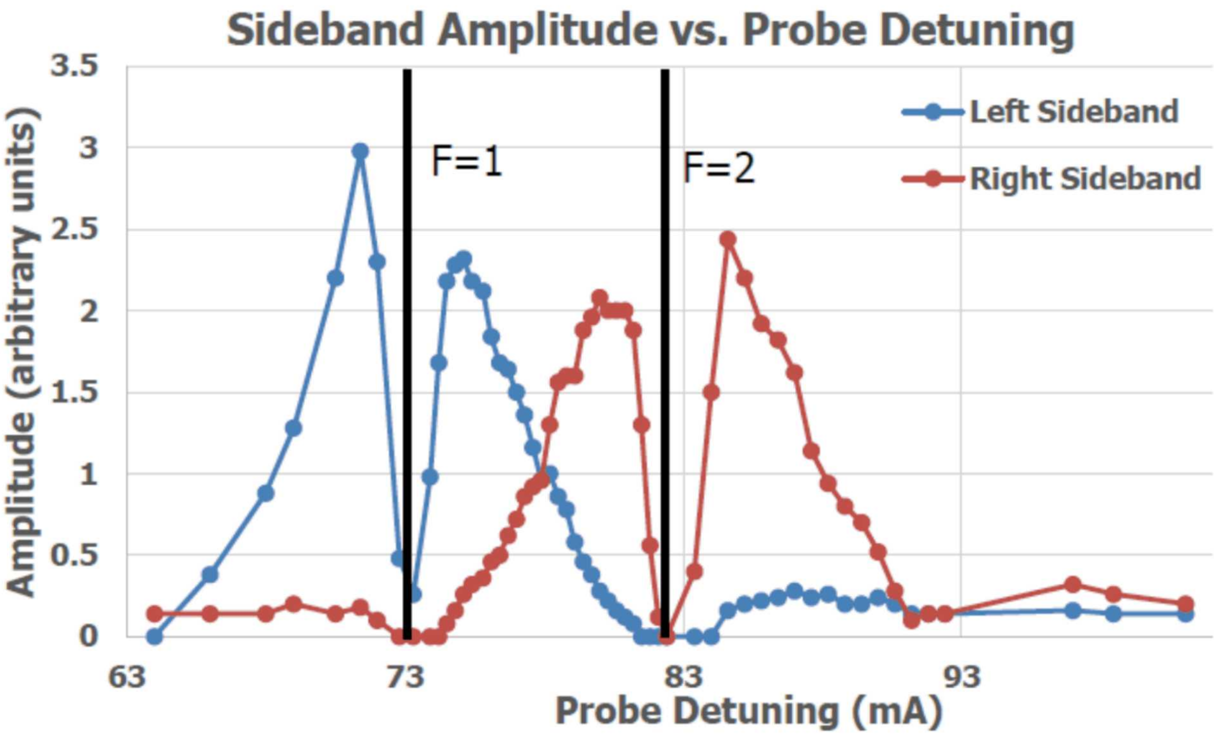




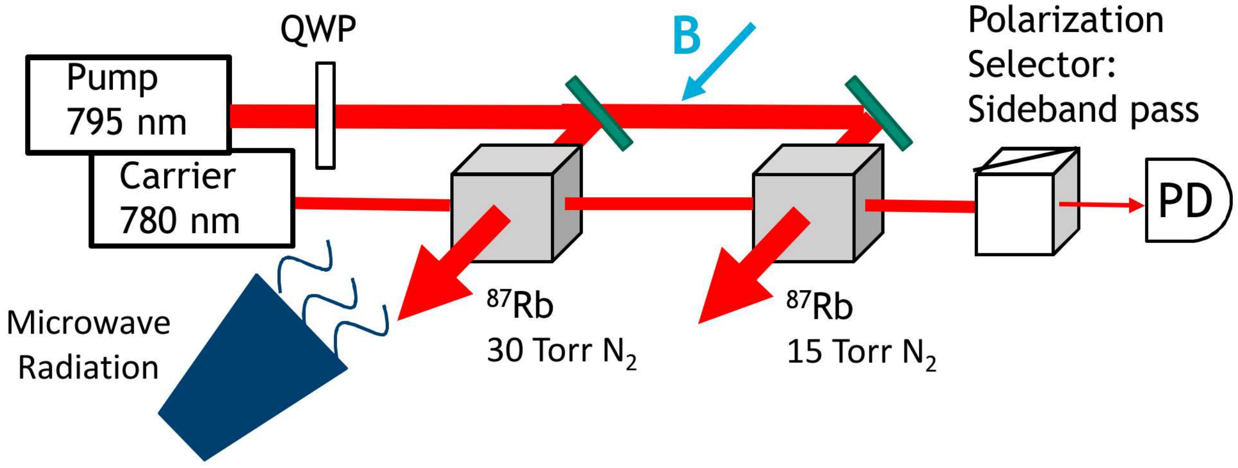
Building a numerical model

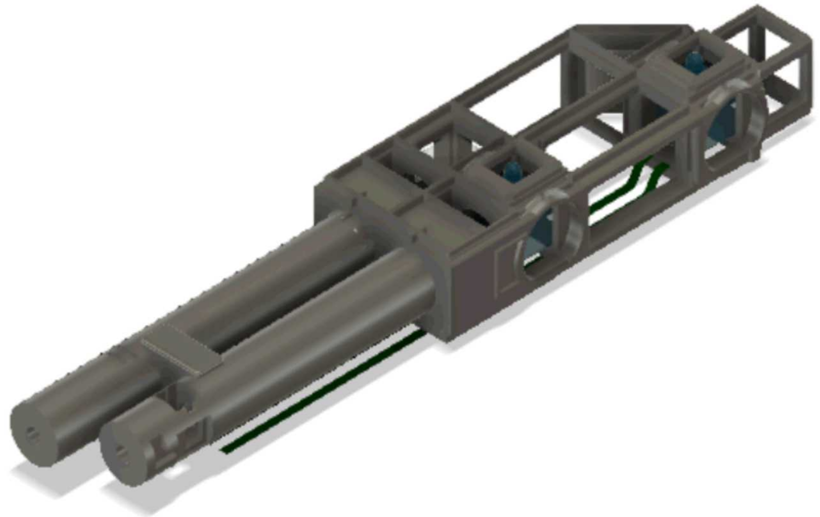


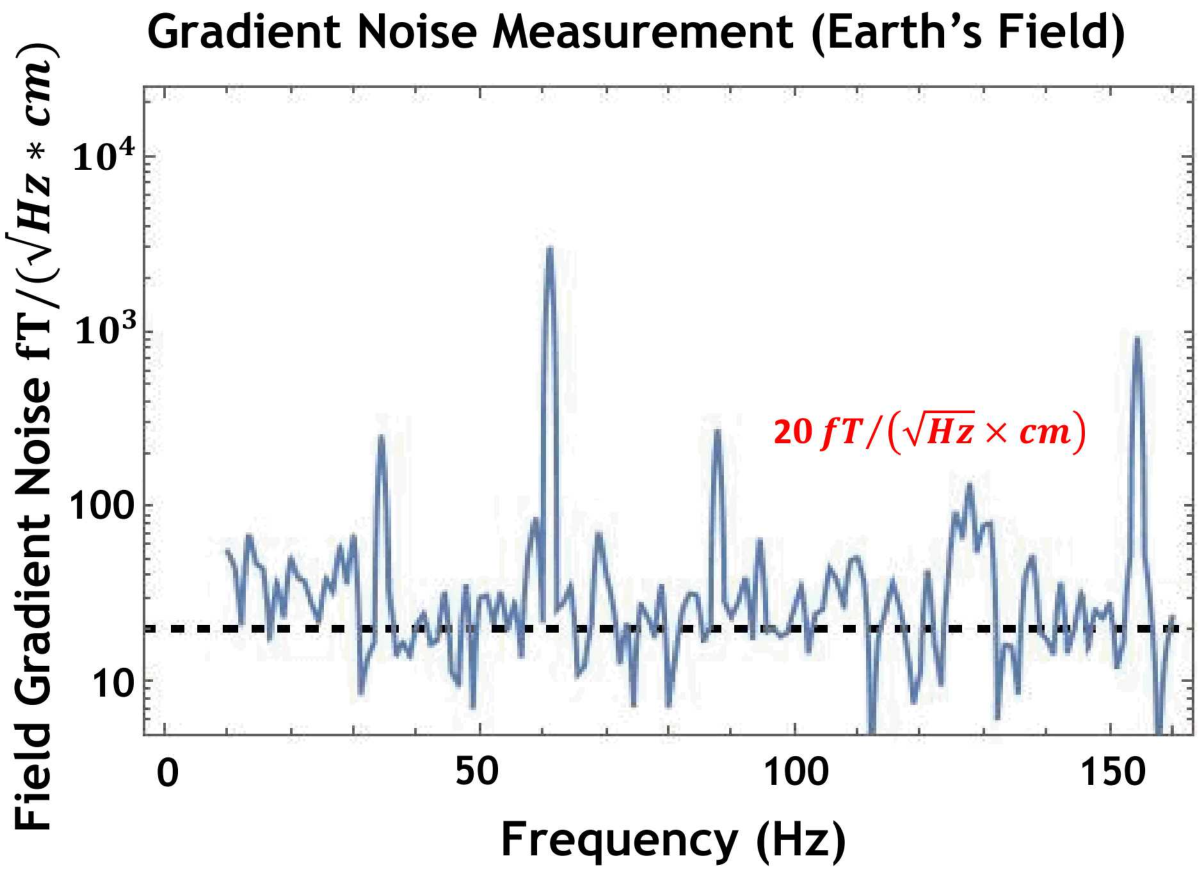
Data taken at Sandia a while ago



QuSpin Physics Package Results



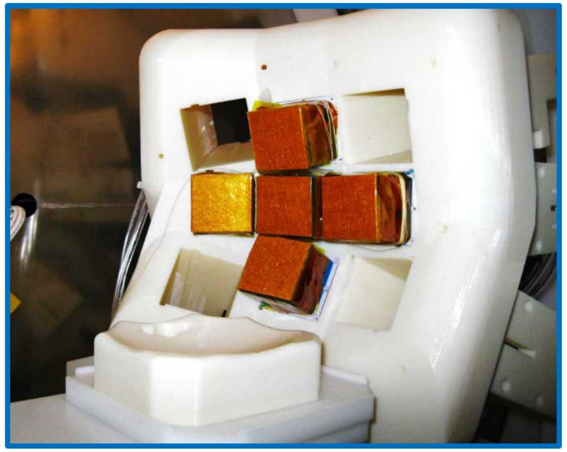




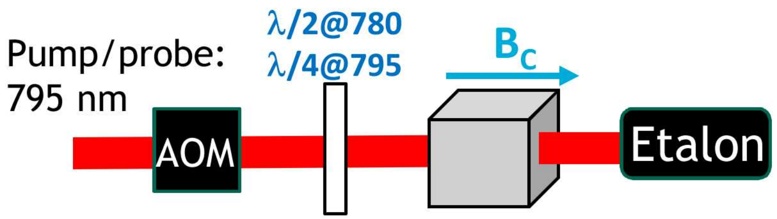
Photon Shot Noise: ~6 fT/cm/rt-Hz

Data and photo courtesy of QuSpin

Compact single 795nm laser setup

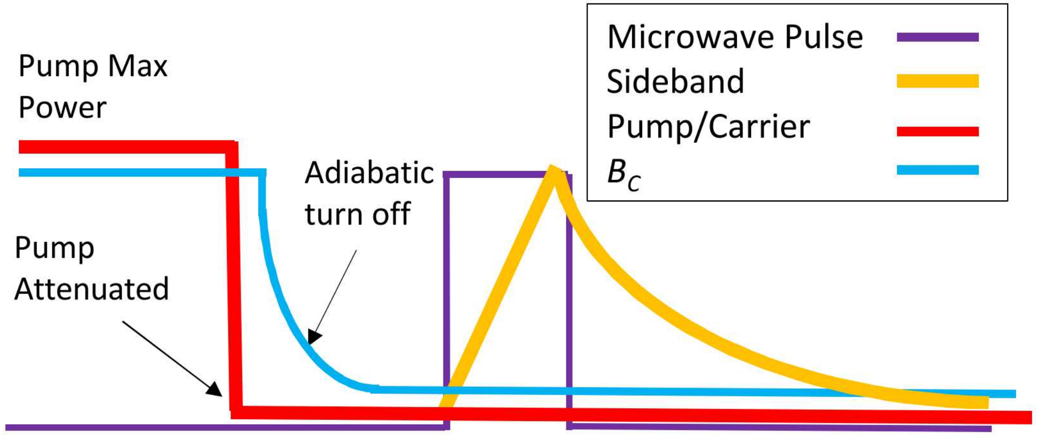


- Potentially Halve number of lasers needed
- Simpler experimental Setup



How we do it

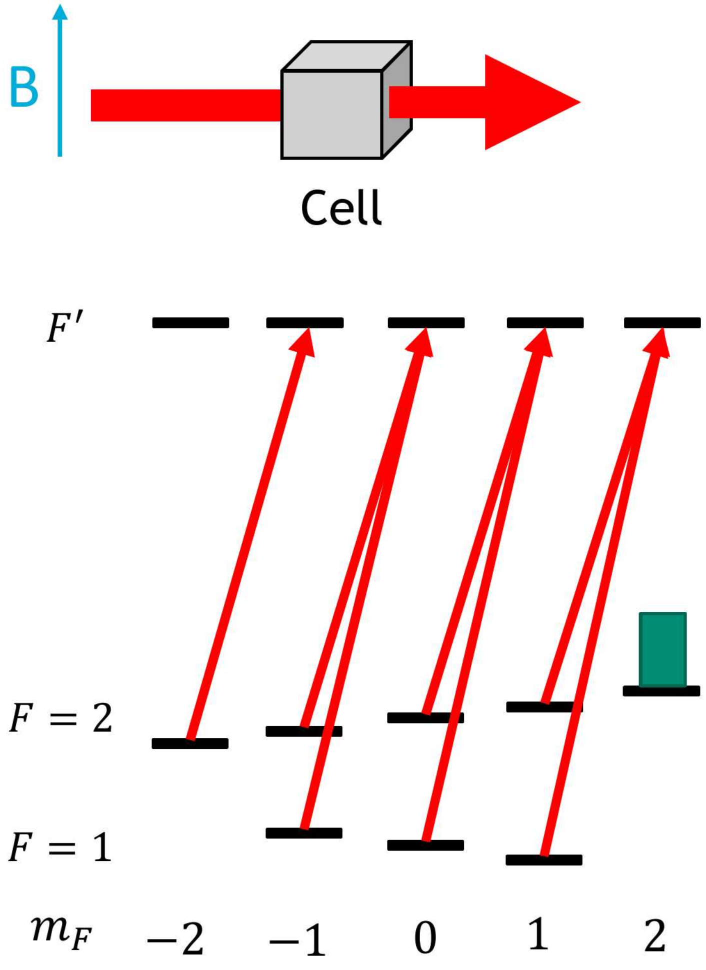
- Replace the 780nm probe with an attenuated pump
- Use an etalon to distinguish between carrier and sidebands
- Temperature/angle tune the etalon to the sideband mode



Can we make the sensor dead-zone free?

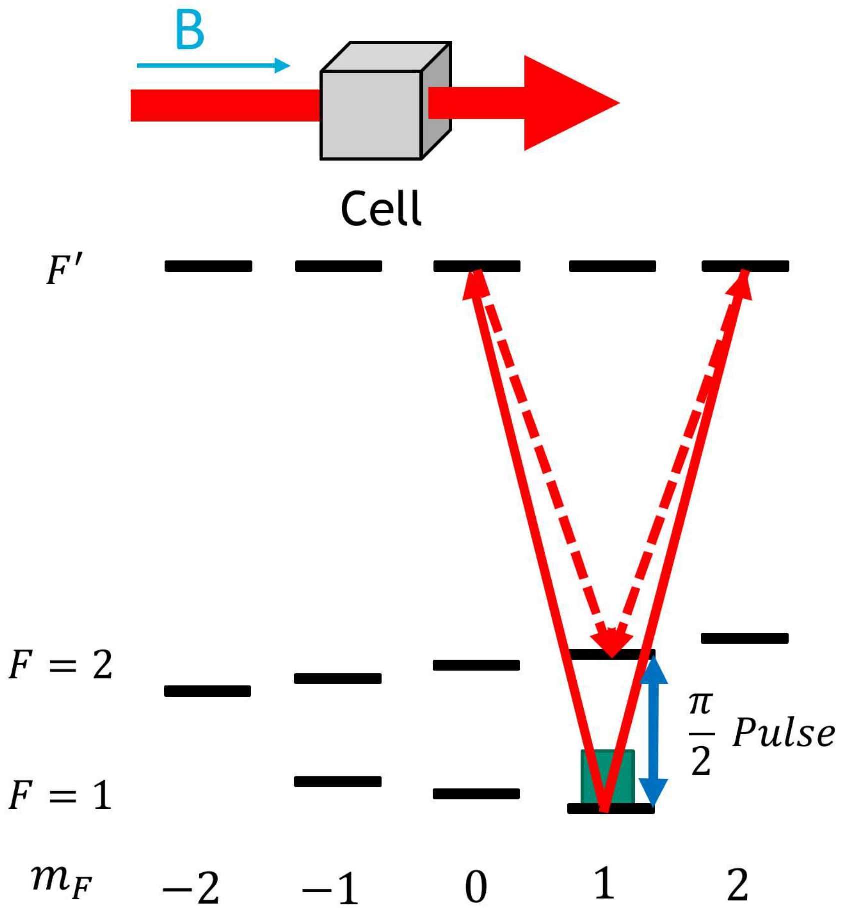
Case 1: Perpendicular field

- How can we optically pump to the end state?



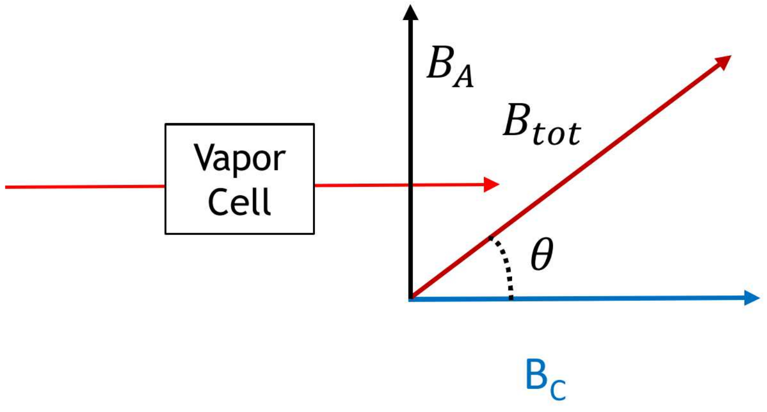
Case 2: Parallel field

- Only σ optical transitions allowed
- Requires $\Delta m_F = 0$ microwave transition
- How to prepare in the $|F=1, m_f = 1>$ state?

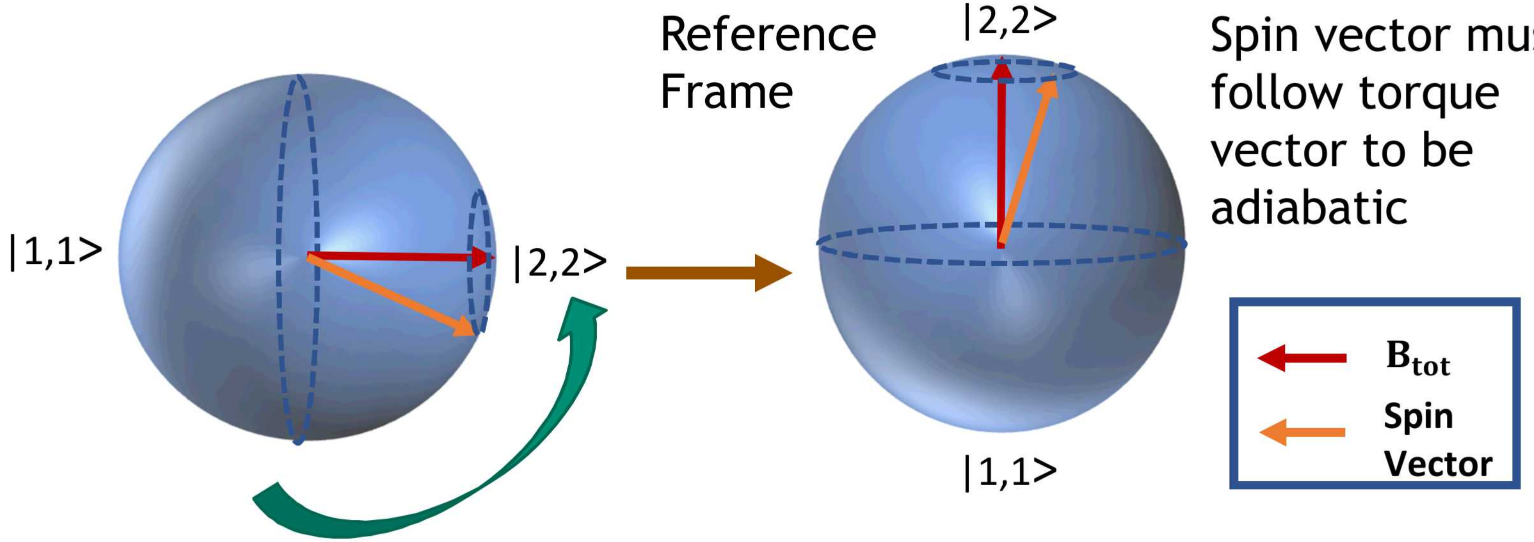


Case 1: Ambient field perpendicular to the laser axis

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

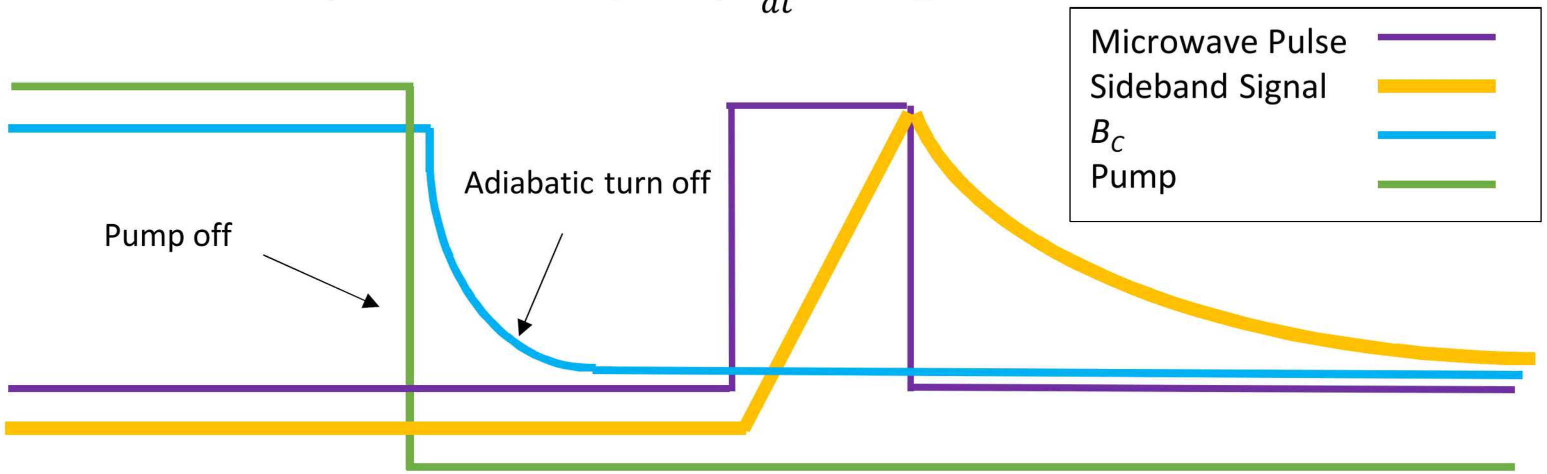


Rotate Reference Frame

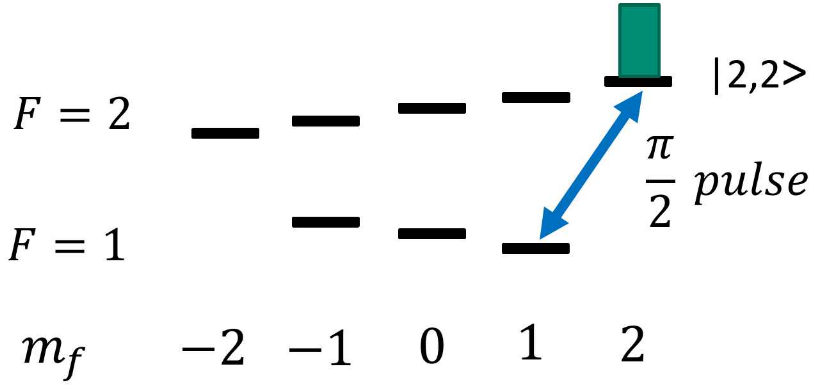


Spin vector must follow torque vector to be adiabatic

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

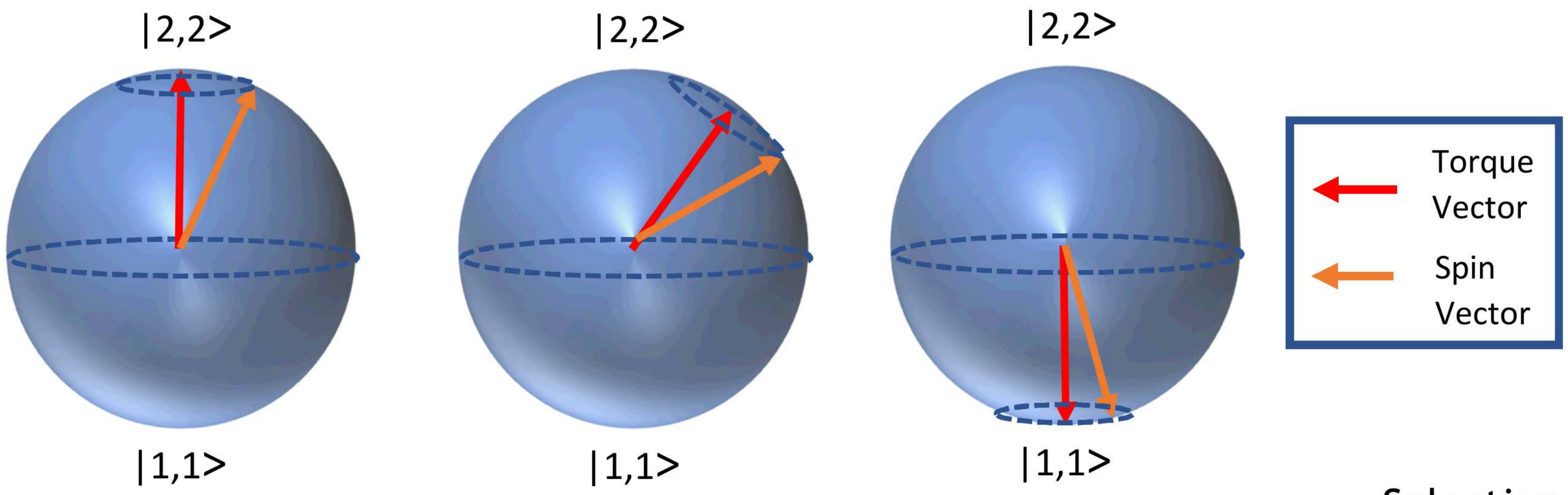


Selection rules now allow Δm_F = 1 transitions

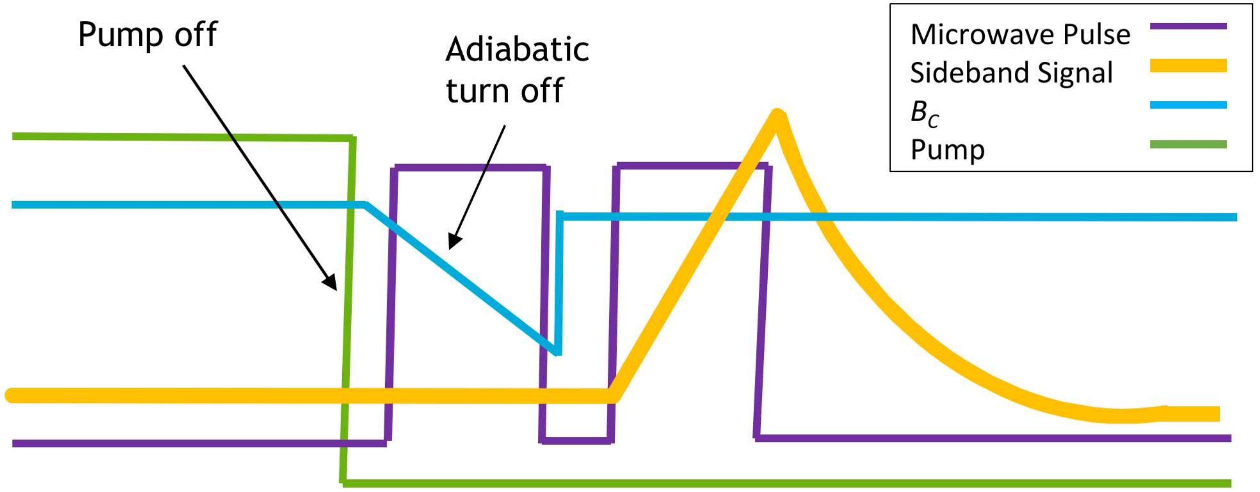


Case 2: Ambient field parallel to the laser axis

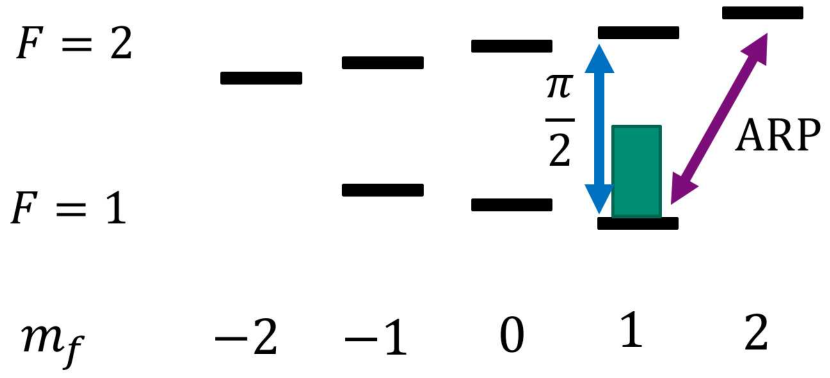
- We perform adiabatic rapid passage to transfer the population from the|2,2> state to the|1,1> state.
- We use a magnetic field ramp to simplify microwave and cover both cells.



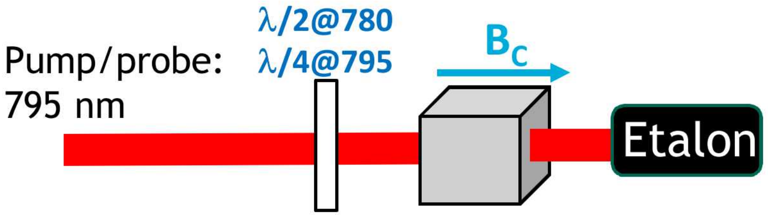
Magnetic field must be ramped slow enough that the Spin vector follows the Torque vector



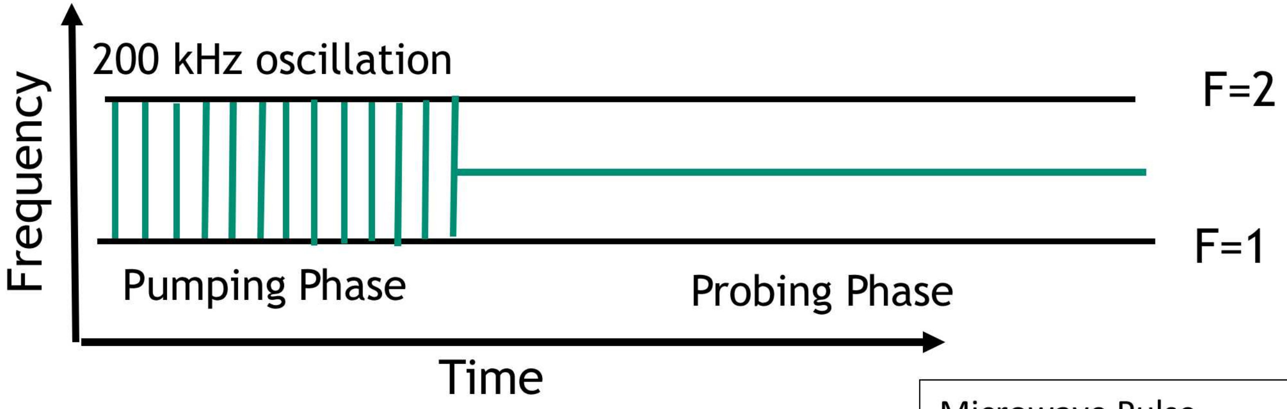
Selection rules allow Δm_F = 0 transitions



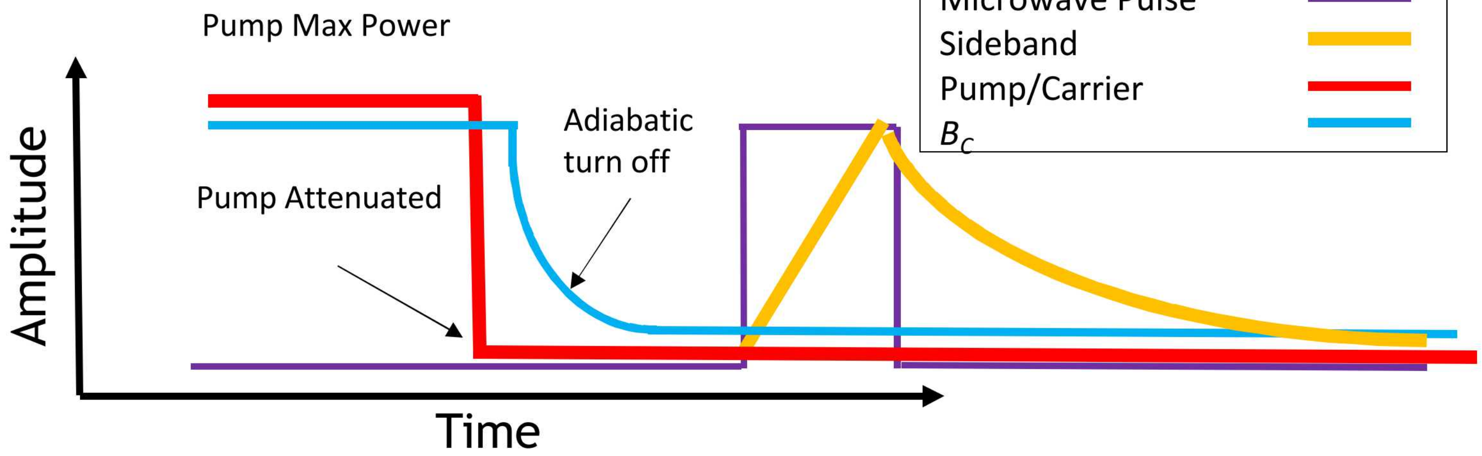
First Single Laser Experiment



Scan the probe frequency Between the F=1 and F=2 resonances



Scan the frequency between F=1 and F=2 during probe phase



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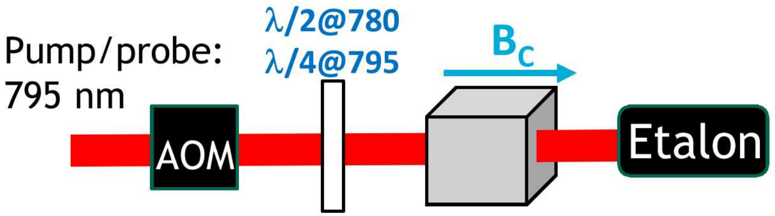

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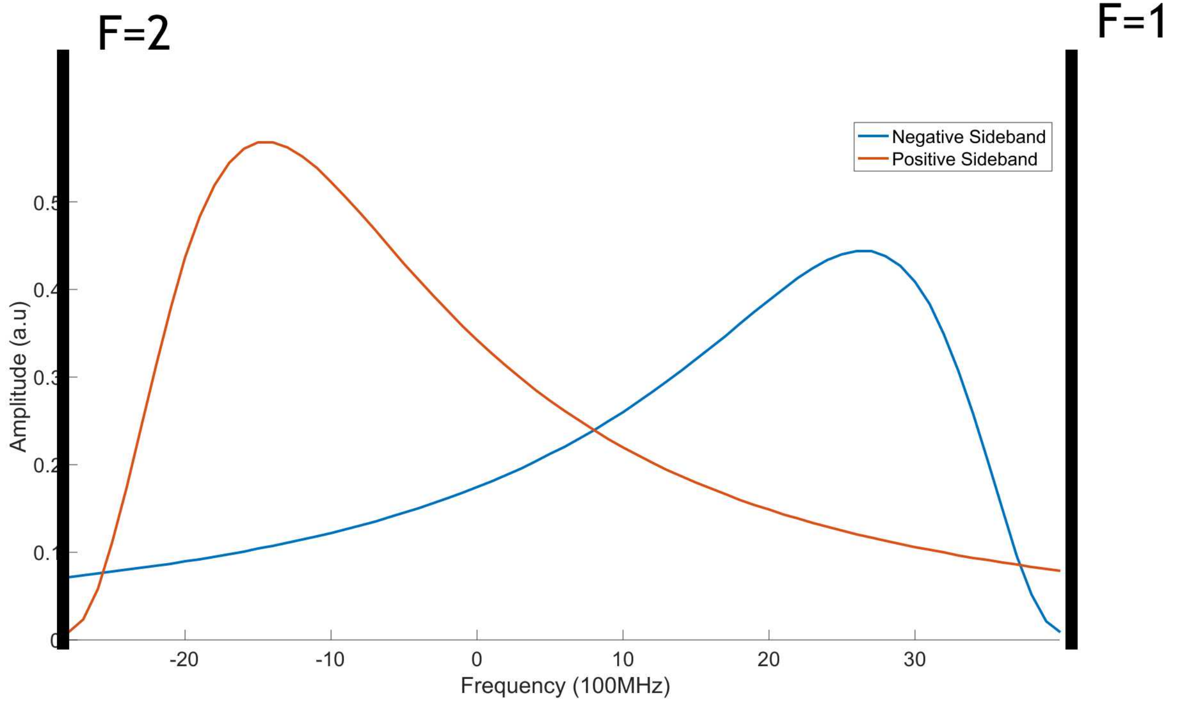

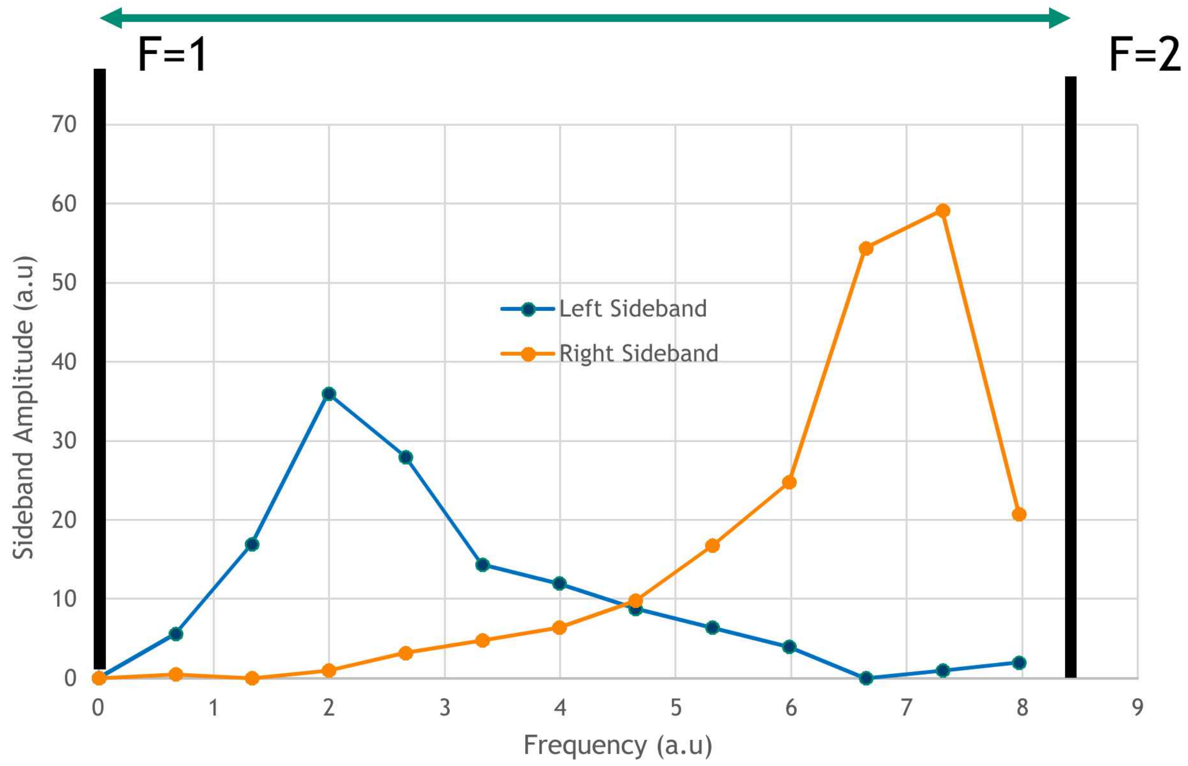

Acknowledgements

QUSPIN

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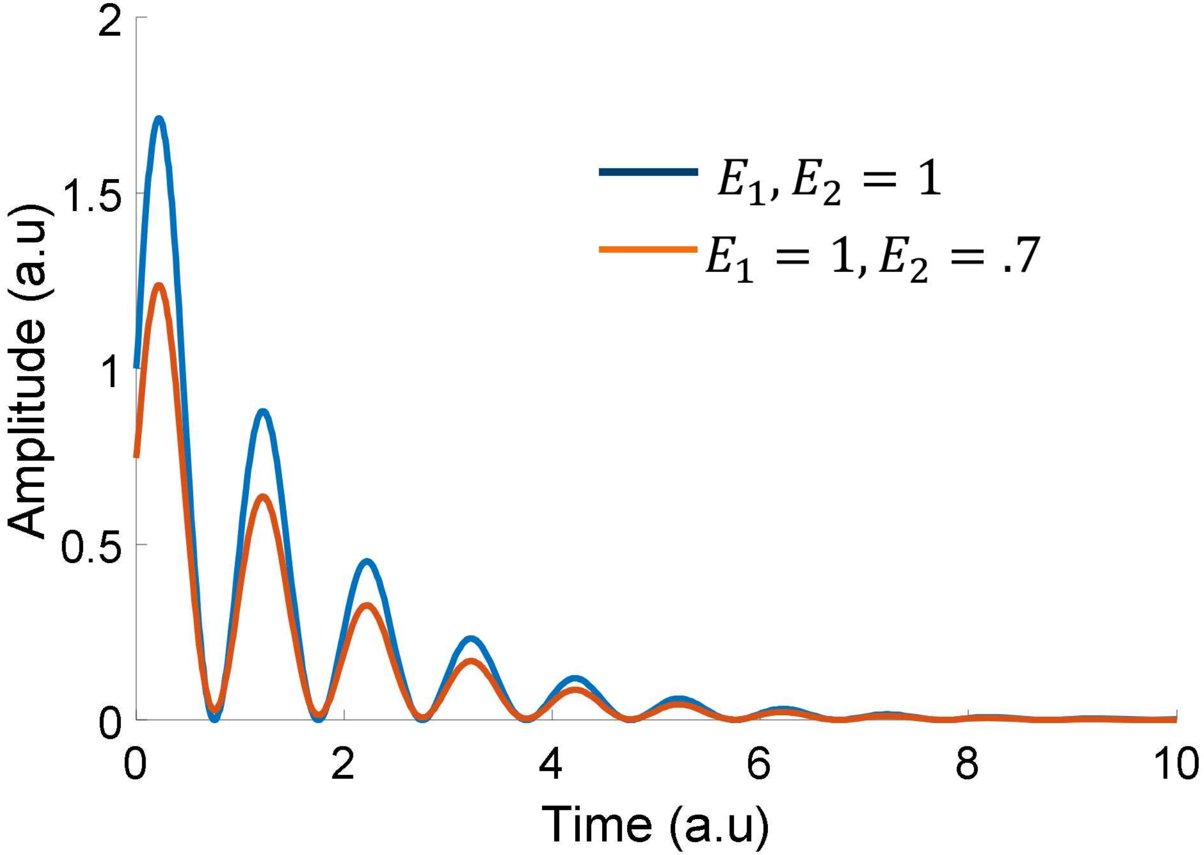
Thank You!

How bad will this be?

Beatnote Function

$$S(t) = \frac{E_1^2}{2} e^{-2t/T_1} + \frac{E_2^2}{2} e^{-2t/T_2} + E_1 E_2 e^{-t\left(\frac{1}{T_1}+\frac{1}{T_2}\right)} \sin(2\pi f t + \varphi)$$



- $FOM = \sqrt{S}/w_2$
- Need to test this out with experimentally
- Square root dependence on amplitude
- This method is more efficient than ARP for small B-field gradients

Dead-zone free operation

Minimum field

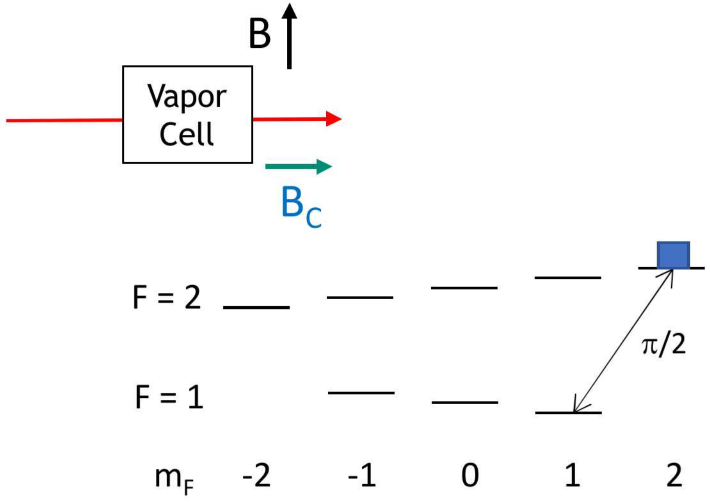
- $f_{1\to 2} - f_{1\to 1} \gg \frac{1}{2\pi\, T_{\pi/2}}$
- For $T_{\pi/2}$ = 0.1 ms, $B_{min} \gg$ 230 nT

How to switch between the two schemes

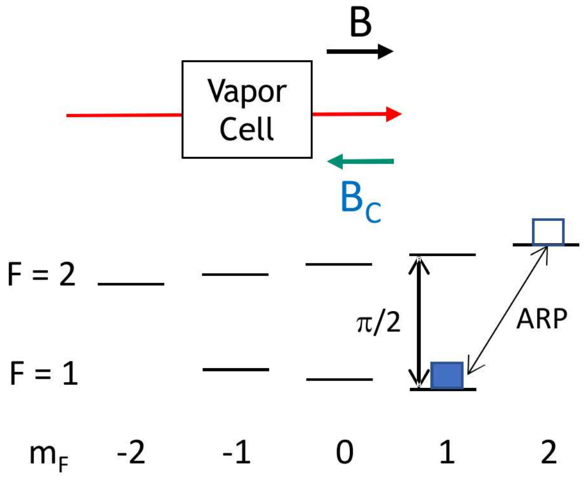
- Start up:
  1. Determine ambient field and direction using a field zeroing scheme
  2. Select scheme, microwave frequency, and direction of B_C
  3. Begin operation.
- Continuous operation:
  1. Monitor signal size
  2. If signal size drops below threshold, switch scheme.
     1. If this fails, re-zero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

Need to understand better how to ramp Bc for ARP

Quantization axis rotation



ARP with longitudinal field



Atom shot noise limit

$$\delta B = \frac{1}{\gamma\sqrt{NT_2\tau}}$$

γ = gyromagnetic ratio
T_2 = transverse coherence time
N = number of atoms
τ = measurement time

Decoherence limits noise to $1/N^{1/2}$ scaling

Sensitivity improved by increasing T_2 or N

Most AMs do not operate at this limit.

Photon shot noise limit

$$\delta B = \frac{\sqrt{2N_{ph}}}{dS(N_{ph})/dB} \propto \frac{1}{\sqrt{N_{ph}}}$$

Most AMs operate at or near the photon shot noise limit

Probe intensity contributes to T_2 so N_{ph} cannot be made arbitrarily high.

Ground State Hamiltonian:

Spin angular momentum $\mathbf{S}$

Nuclear angular momentum $\mathbf{I}$

Total angular momentum $\mathbf{F} = J + \mathbf{I}$

$$H_{HF} = \mu_B g_S \mathbf{S} \cdot \mathbf{B} + \mu_B g_I \mathbf{I} \cdot \mathbf{B} + A_{HF} \mathbf{I} \cdot \mathbf{S}$$

$g_S = 2.002,\ g_I = -0.000995$ (^{87}Rb), -0.000399 (^{133}Cs)

$$E_{HF} = \frac{1}{2} A_{HF} \big(F(F+1) - I(I+1) - S(S+1) \big)$$

^{87}Rb : $\Delta E_{HF}/h = 6.835$GHz, $I = 3/2$

^{133}Cs: $\Delta E_{HF}/h = 9.192$GHz, $I = 7/2$

At low field the nuclear and electron spins are combined,

$H_B = \mu_B g_F \mathbf{F} \cdot \mathbf{B},\ \ \Delta E_{mF} = g_F m_F \mu_B B$

$g_F \approx \pm \frac{1}{2F_{max}},\ -F \le m_F \le F$

$\frac{g_s \mu_B}{h} = 2.8$ MHz/G or 28 Hz/nT (gyromagnetic ratio)

^{87}Rb: $g_F = \pm \frac{1}{4},\ \frac{g_F \mu_B}{h} = 700$ kHz/G or 7 Hz/nT

^{133}Cs: $g_F = \pm \frac{1}{8},\ \frac{g_F \mu_B}{h} = 350$ kHz/G or 3.5 Hz/nT