Measurements with dense alkali vapors

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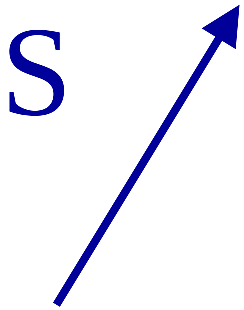
Spin Interactions



$$H = -\mu \vec{B} \cdot \frac{\vec{S}}{S} \qquad -\hbar \vec{\Omega} \cdot \vec{S}$$

Magnetic Field

Rotation

Beyond Standard Model:

$$-\boldsymbol{d}\,\vec{E} \cdot \frac{\vec{S}}{S} \qquad -\vec{b} \cdot \frac{\vec{S}}{S} \qquad g^2 \vec{S}_1 \cdot \vec{S}_2$$

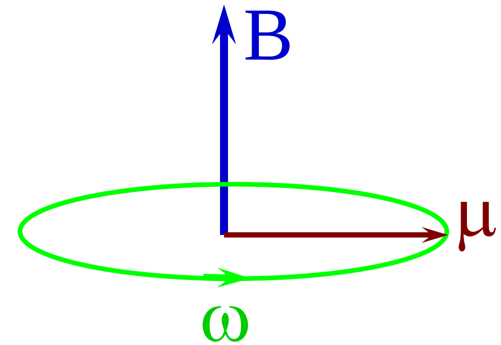
Electric Dipole Moment
CP, T violation

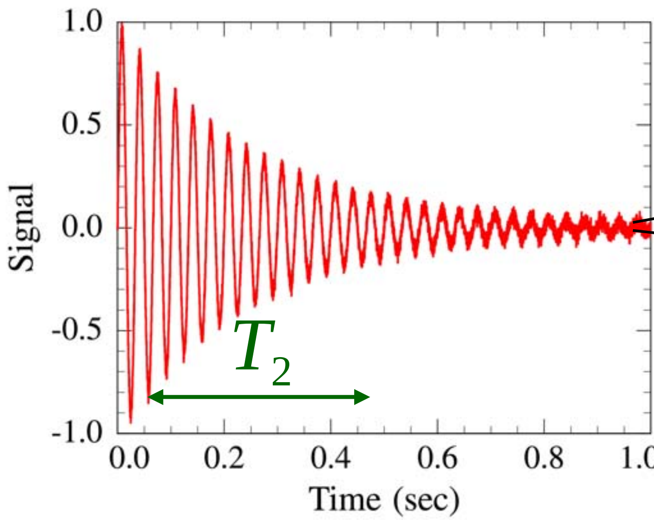
Background Vector Field
Lorentz, CPT violation

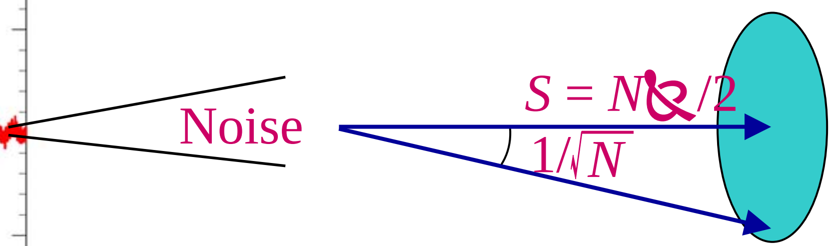
Spin Dependent Forces
Pseudoscalar Exchange

Spin Precession

$$\omega = \frac{2\mu B}{\hbar}$$







Quantum noise limit for N atoms:

$$\delta\omega = \frac{1}{\sqrt{T_2 N t}}$$

Need large number of atoms
long coherence time

Prefer small measurement volume:

Compact
High spatial resolution
Electric field application
Insensitivity to gradients

High-density spin ensembles
Strong interactions

1. High density alkali-metal magnetometer

⇒ Elimination of alkali-metal spin-exchange broadening

⇒ High sensitivity multi-channel magnetic field measurements

⇒ Application: Detection of brain magnetic field

⇒ Application: Detection of nuclear quadrupole resonance

2. Noble gas-alkali – alkali-metal co-magnetometer

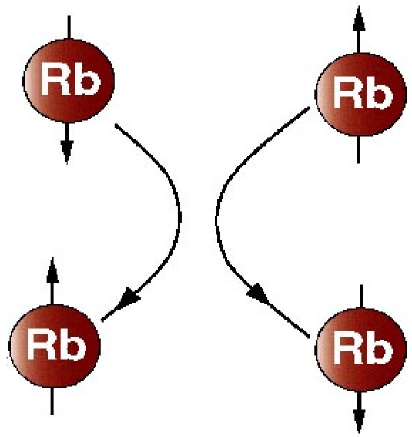
⇒ Automatic cancellation of magnetic fields

⇒ Application: Nuclear spin gyroscope

⇒ Application: Search for a Lorentz-violating background field

3. Resonance narrowing in optically dense vapor

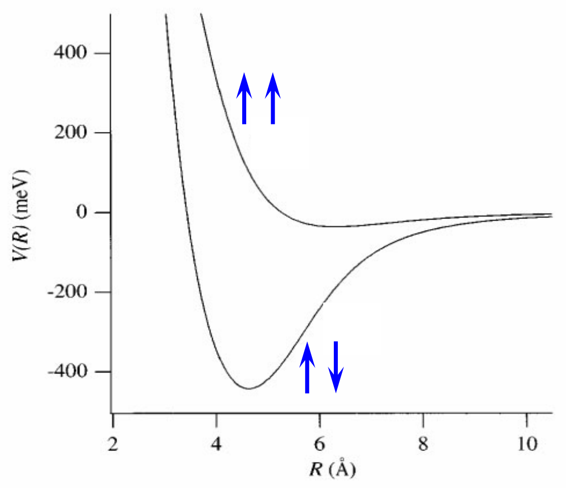
Alkali-metal spin-exchange collisions



$$T_2^{-1} = \sigma_{se}\, \bar{v}\, n$$

$$\sigma_{se} = 2 \times 10^{-14} \mathrm{cm}^2$$

$$\text{Other } \sigma \sim 10^{-18}\, \mathrm{cm}^2$$



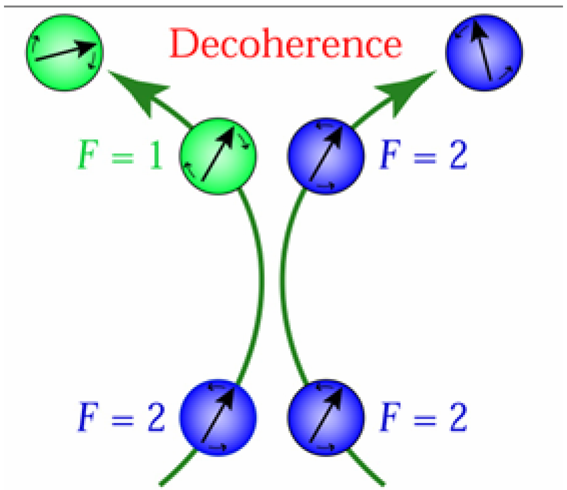
⇒ Increasing density of atoms decreases spin relaxation time: $T_2 N = \sigma_{se}\bar{v}V$

⇒ Under ideal conditions: $\delta B \simeq 1\mathrm{fT}\sqrt{\dfrac{\mathrm{cm}^3}{\mathrm{Hz}}}$

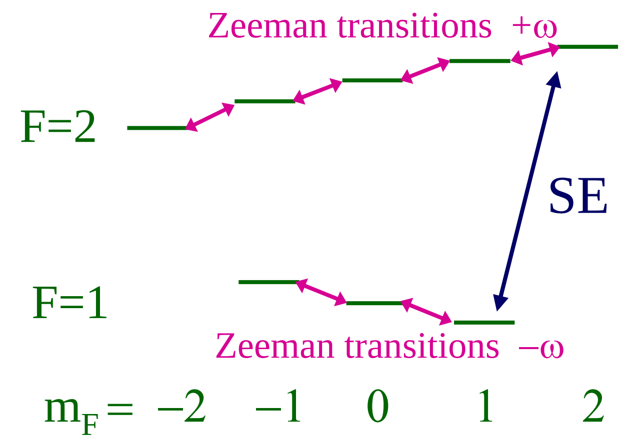
⇒ One solution: use large cells with low density (Budker, Alexandrov)

Why do spin-exchange collisions cause relaxation?

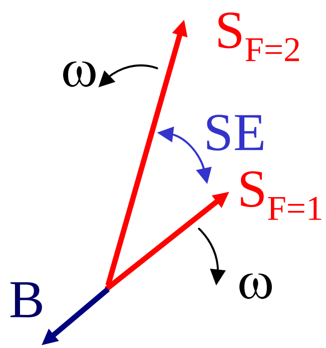
- Spin exchange collisions preserve total angular momentum
- They change the hyperfine states of alkali atoms
- Cause atoms to precess in the opposite direction around the magnetic field

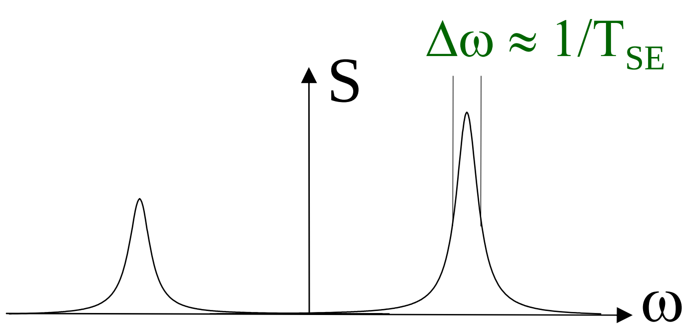


Ground state Zeeman and hyperfine levels



$$\omega_{F=I\pm 1/2} = \pm \frac{g\mu_B B}{\hbar(2I+1)}$$



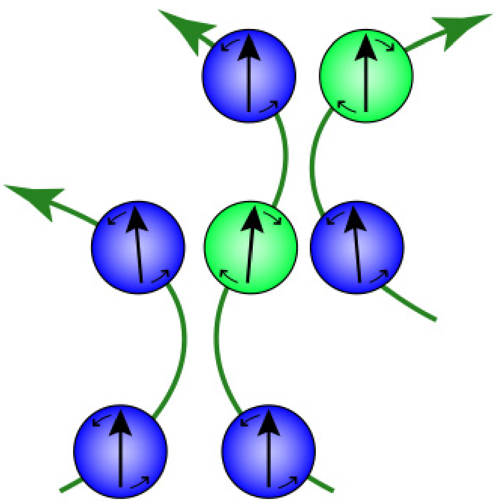


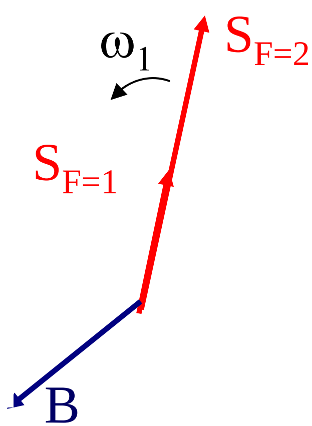
Eliminating spin-exchange relaxation

1. Increase alkali-metal density
2. Reduce magnetic field

$$\omega \ll 1/T_{SE}$$

Atoms undergo spin-exchange collisions faster than the two hyperfine states can precess apart



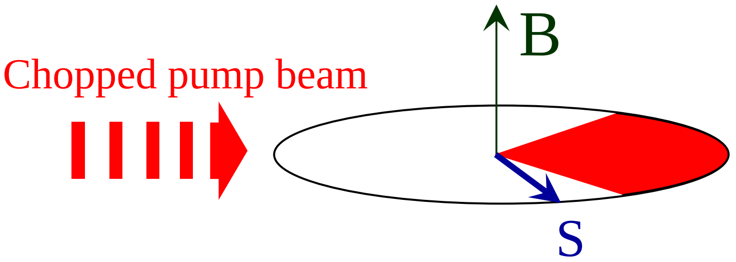


$$\omega_1 = \frac{3(2I+1)}{3+4I(I+1)}\omega = \frac{2}{3}\omega$$

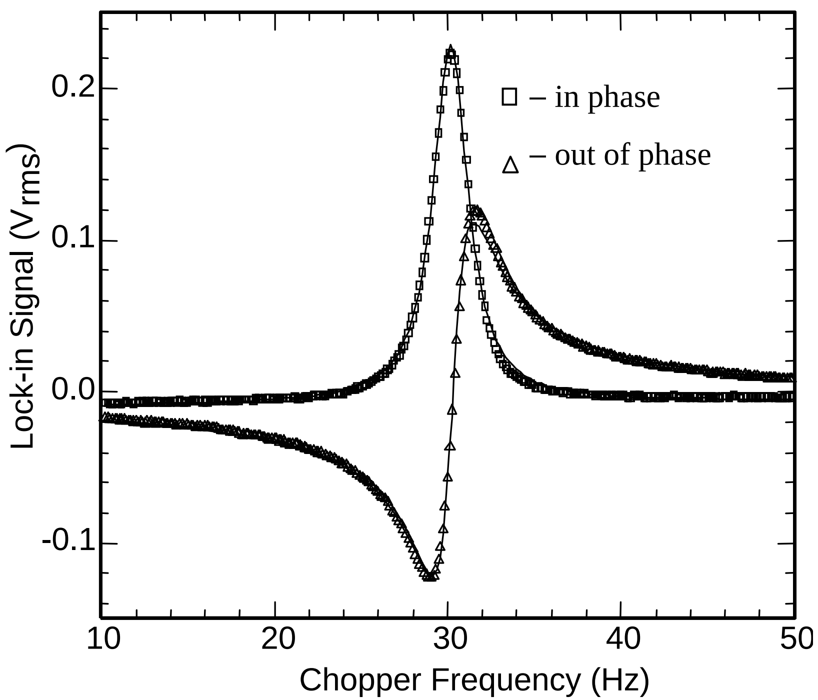
- No relaxation due to spin exchange

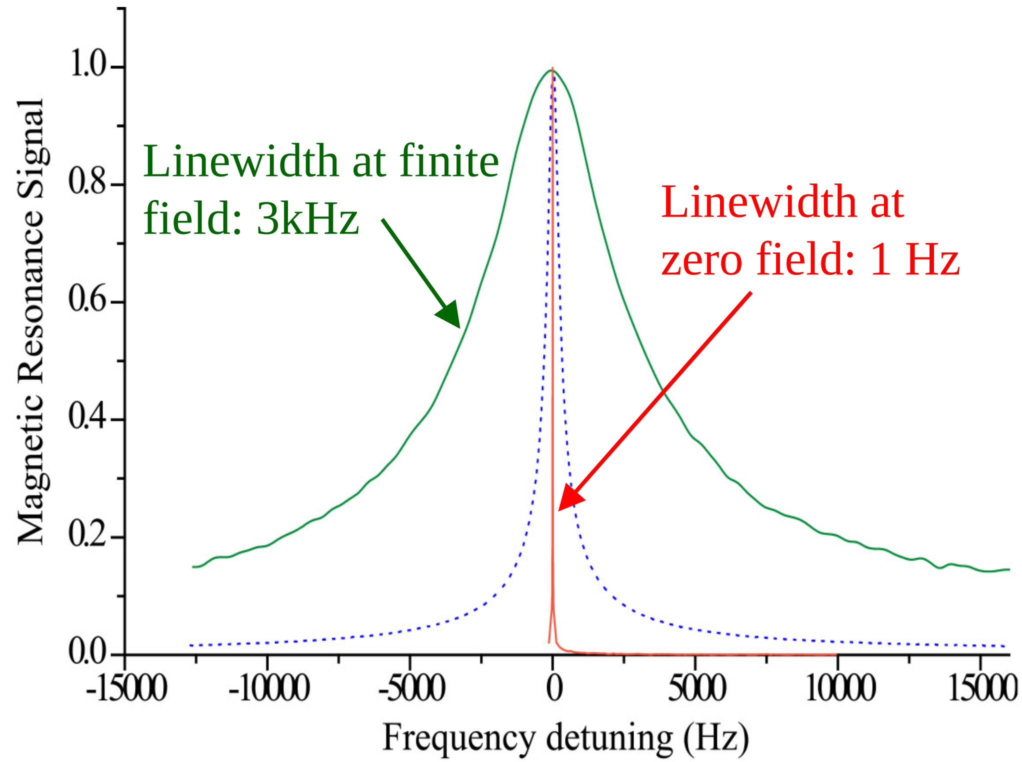
W. Happer and H. Tang, PRL **31**, 273 (1973)

Complete elimination of spin-exchange broadening



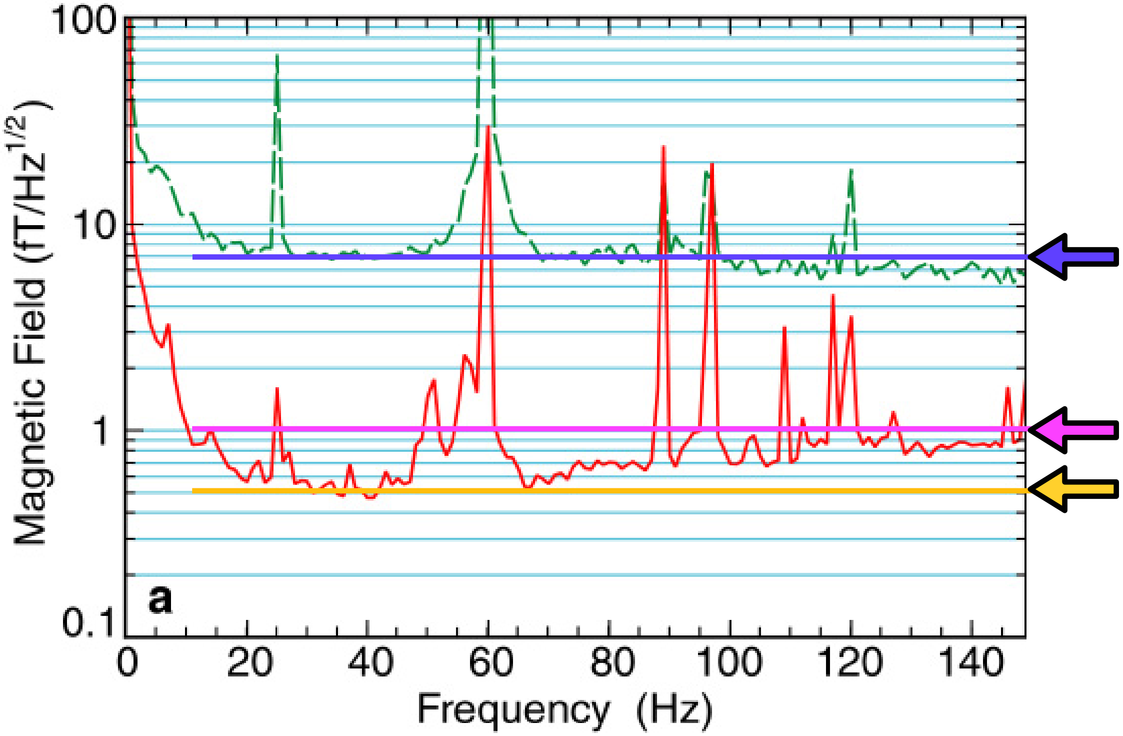
K density: 10^{14} cm^{-3}
Temperature: 185°C





J. C. Allred, R. N. Lyman, T. W. Kornack, and MVR, Phys. Rev. Lett. **89**, 130801 (2002)

Magnetometer Performance



Magnetic shield noise
7 fT/Hz$^{1/2}$

Best SQUID

Gradiometer Sensitivity
0.5 fT/Hz$^{1/2}$

- limited by magnetic shield gradient noise

- Fundamental sensitive limit $\delta B = \dfrac{1}{\gamma\sqrt{T_2 N t}}$

T_2 = 0.16 sec
n =10^{14} cm^{-3}
V_{cell}=10 cm^3

N ~ 10^{15} atoms

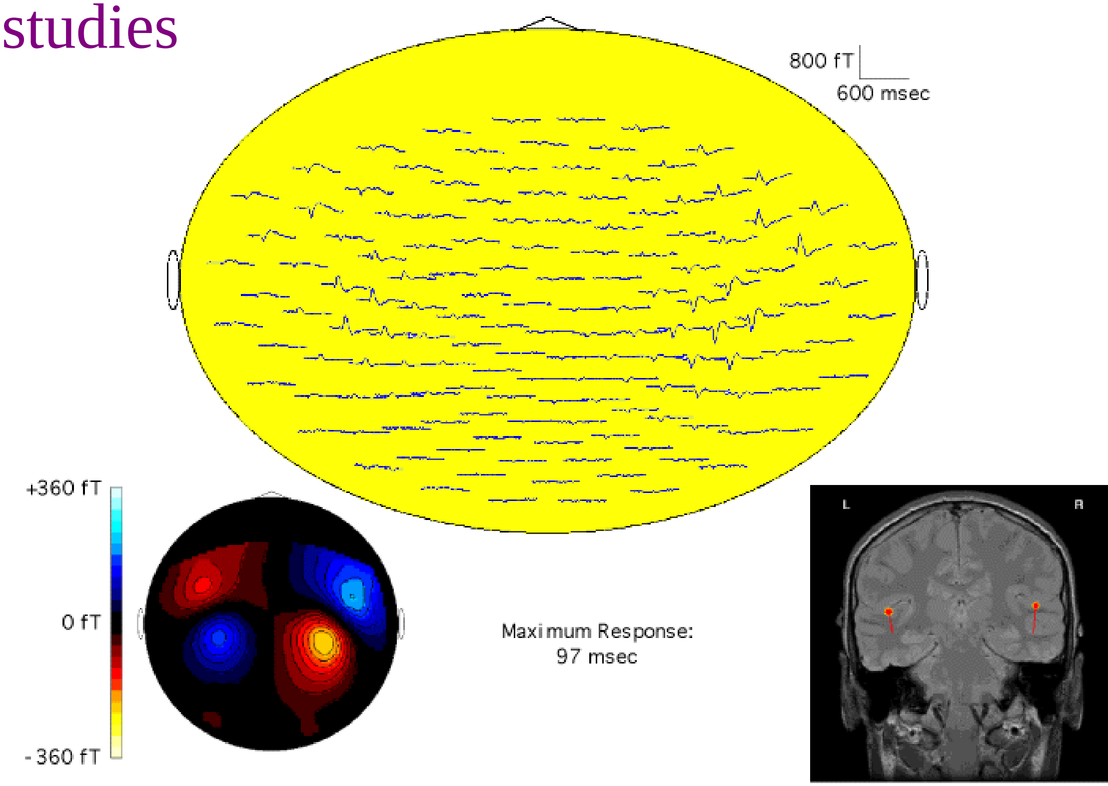
$$\delta B = 2\times10^{-18}\ \mathrm{T\ Hz^{-1/2}}$$

I. K. Kominis, T. W. Kornack, J. C. Allred and MVR, Nature **422**, 596 (2003)

Magnetoencephalography

- Low-temperature SQUIDs in LHe
- 100 – 300 channels, 5fT/Hz$^{1/2}$, 2 – 3 cm channel spacing
- Cost ~ $2-3m
- Clinical and functional studies

Auditory response



H. Weinberg, Simon Fraser University

Atomic magnetometer advantages

- **Potentially higher sensitivity than SQUID (fundamental noise limitation below 0.01 $fT/Hz^{1/2}$)**
- **Does not require cryogenic cooling :**

  $\Rightarrow$ ***Smaller magnetic shields with better shielding***

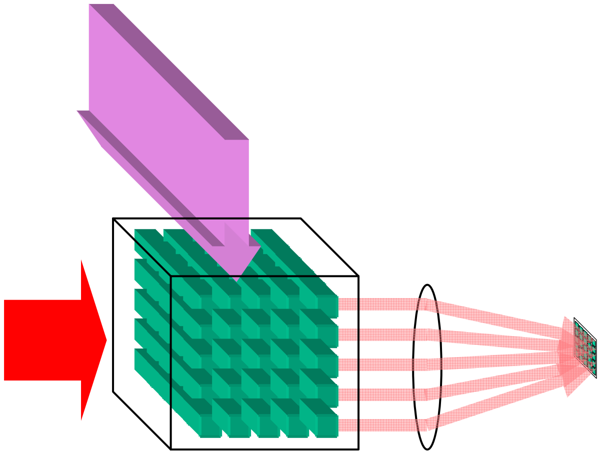
  $\Rightarrow$ ***No magnetic dewar noise***

  $\Rightarrow$ ***Accommodates variations in head size***

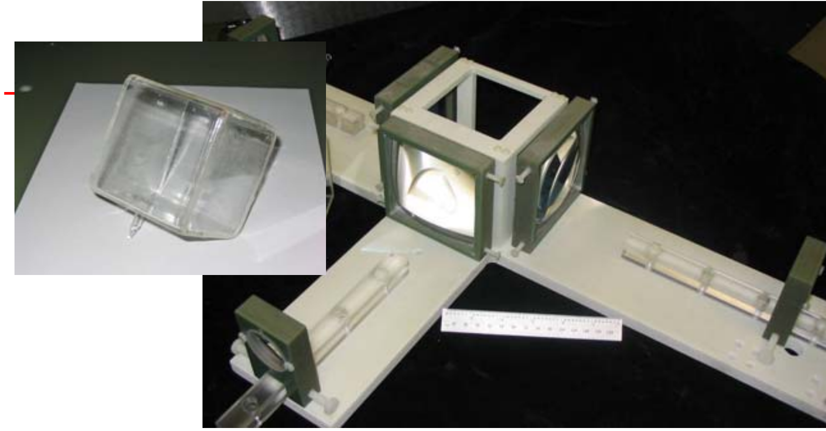
  $\Rightarrow$ ***Lower construction cost***

  $\Rightarrow$ ***No cryogenic maintenance***

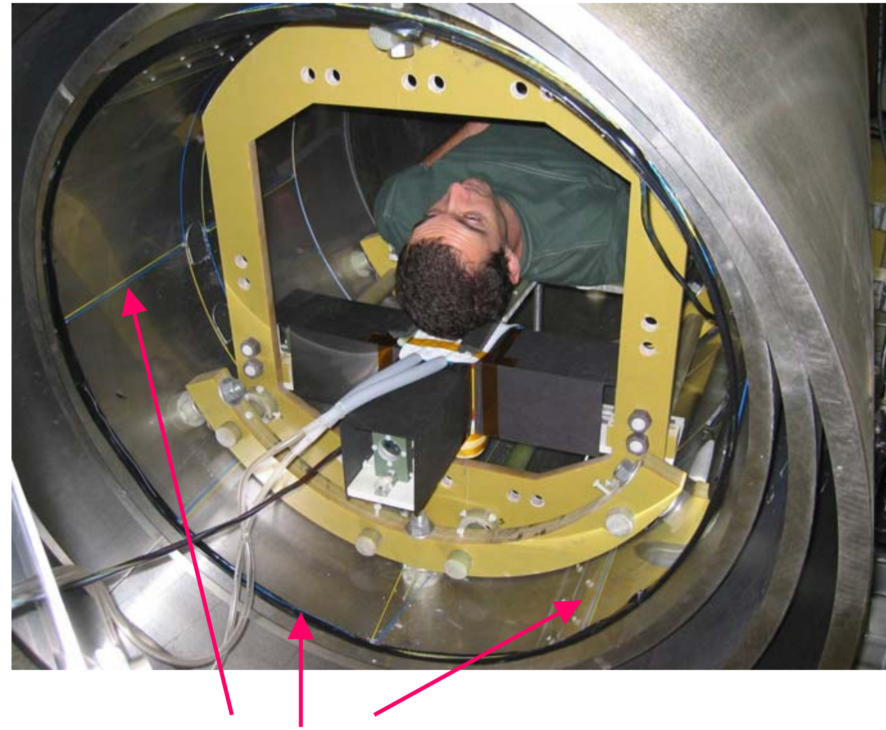
- **Multi-channel photodetector technology well developed and inexpensive**
- **Higher detector density**
- **Allows independent and simultaneous measurement of all 3 components of the magnetic field**



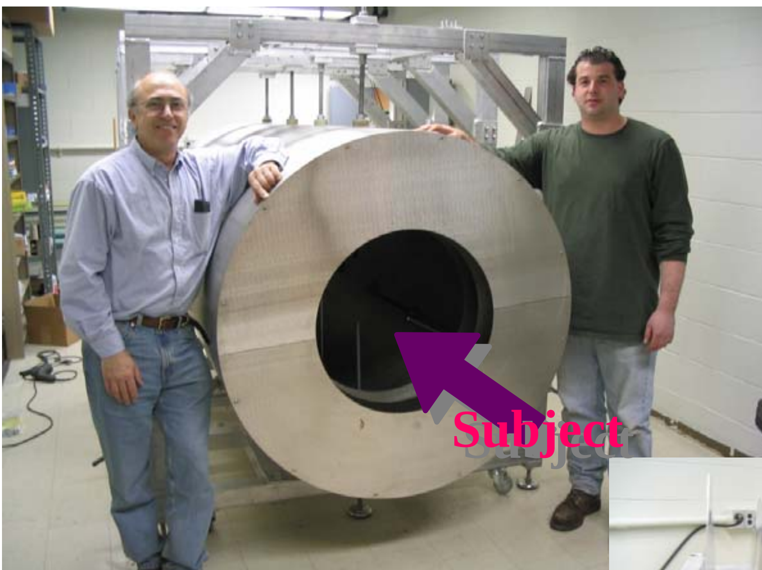
The Dream Capsule



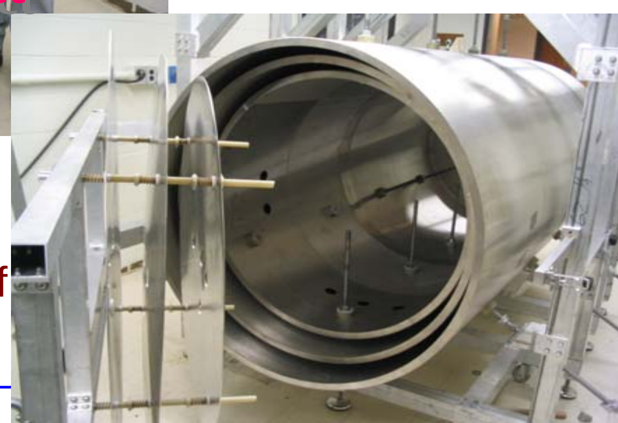
- Pyrex cell 75X75X75 mm @ 1 atm
- Hot air oven @ 160-180 deg. C

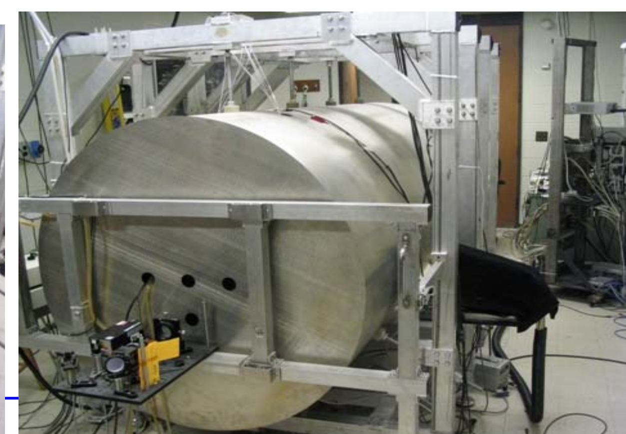


•18 computer-controlled coils to compensate residual fields

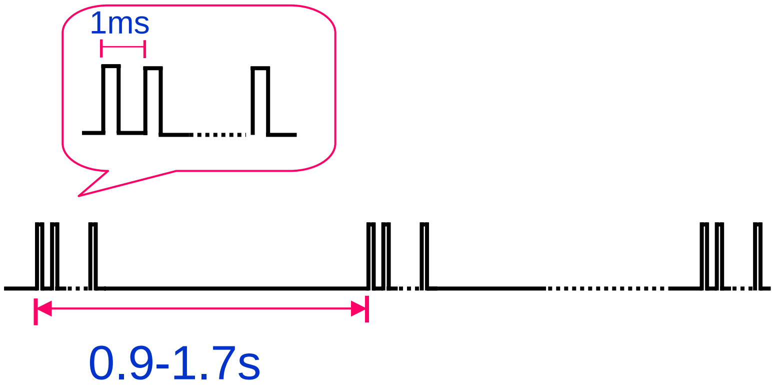


•3-layer μ-metal shields with transverse shielding factor of 7000 and longitudinal factor of 1000 at low frequency.





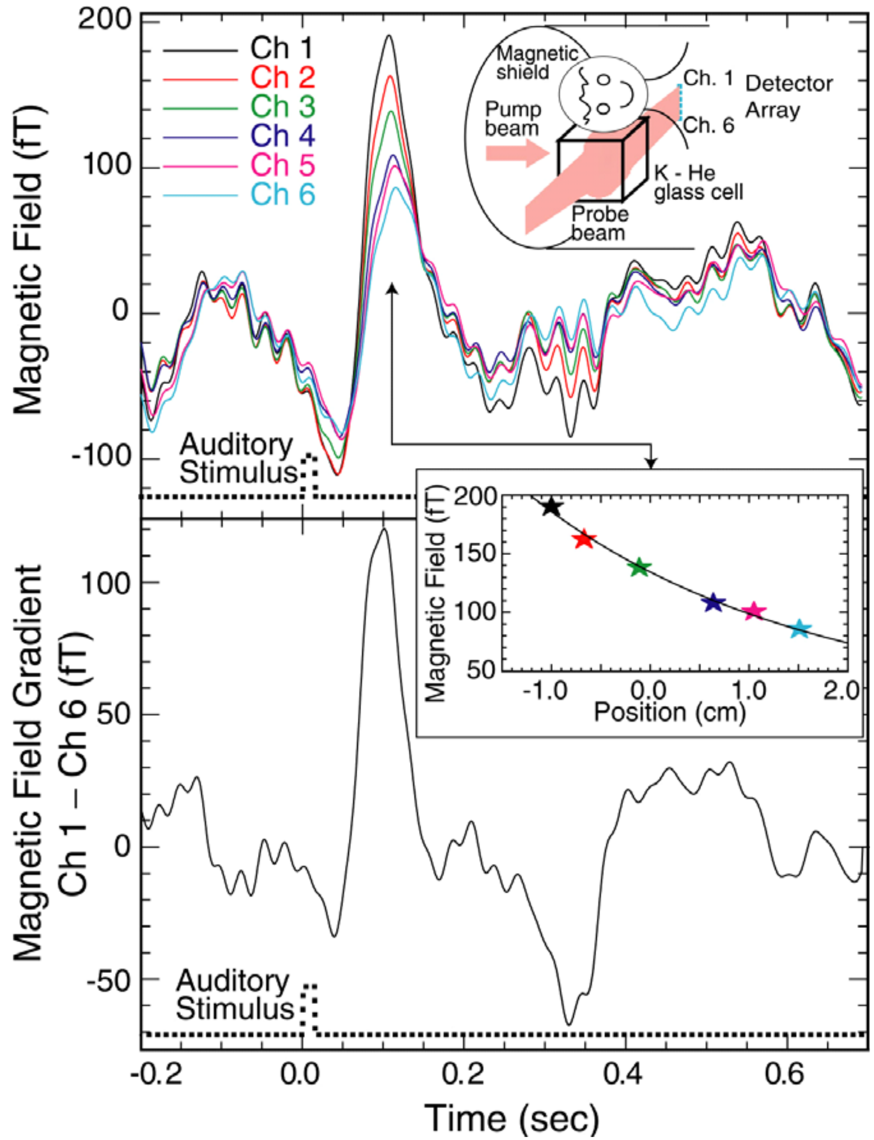
First brain signals detected with non-cryogenic magnetometer



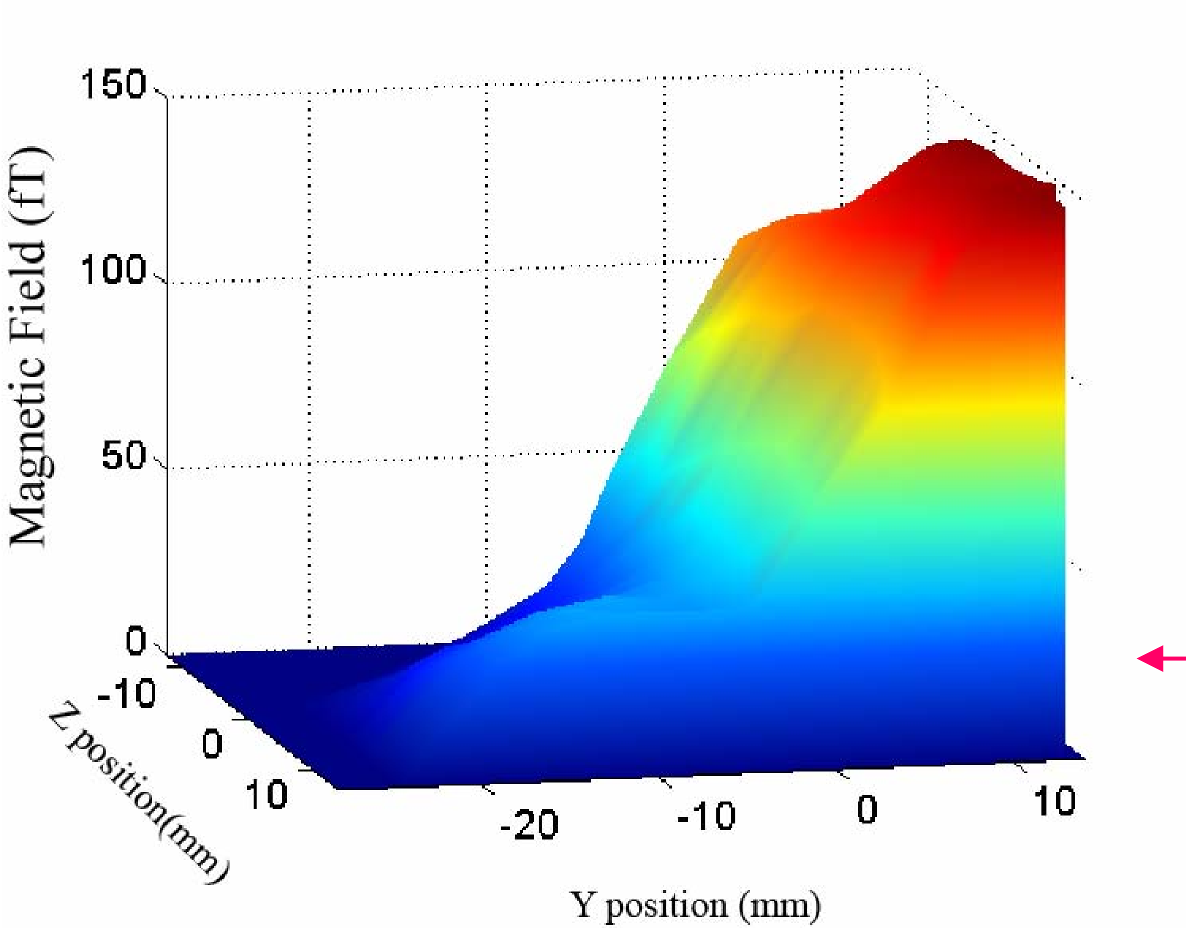
- Auditory stimuli delivered to opposite ear with pneumatic earphone; each stimulus is a train of clicks lasting 16ms; stimuli interval varying randomly between 0.9~1.7sec

- Averaged over 600 stimuli

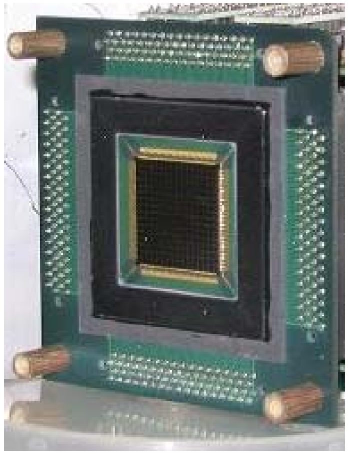
- N100m peak clearly seen; P300m also observed

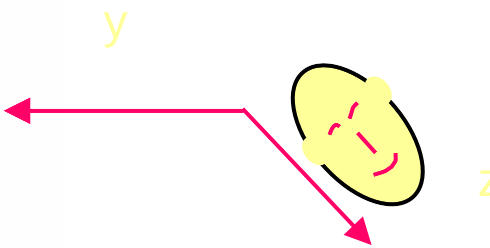


N100m peak recorded by 16x16 image array



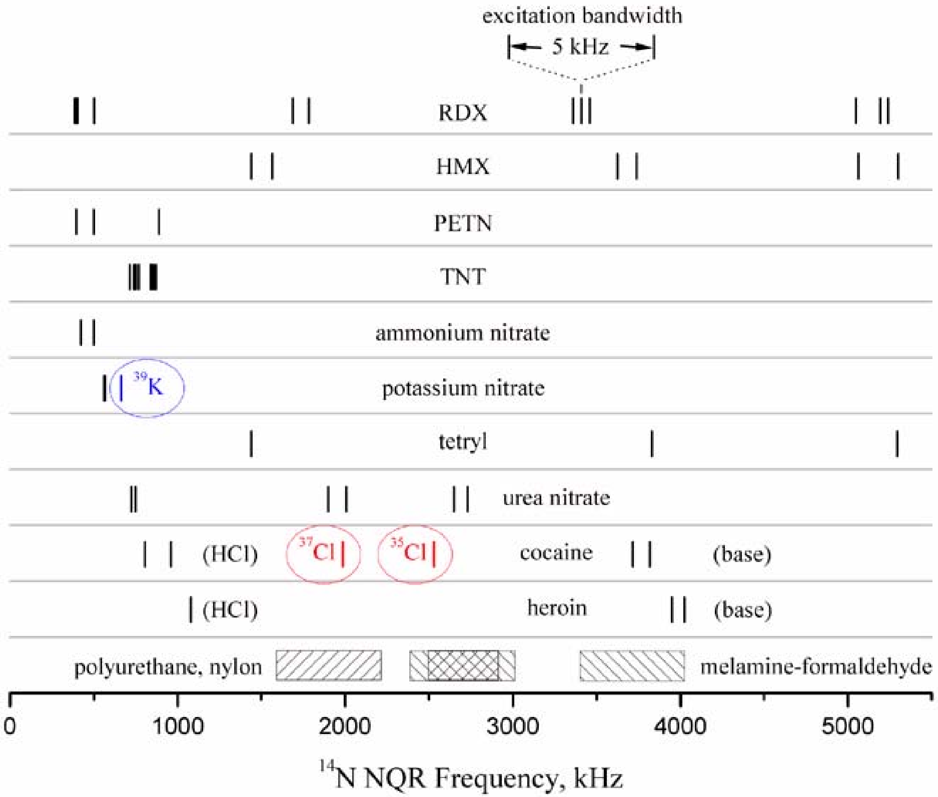
Photodetector





Detection of Explosives with Nuclear Quadruple Resonance

- Most explosives contain ^{14}N which has a large quadrupole moment
- NQR frequency is determined by interaction with electric field gradient in a crystal
- Each material has a very specific resonance frequency, linewidth ~1 kHz
- Very low rate of false alarms.
- Main problem – low signal/noise



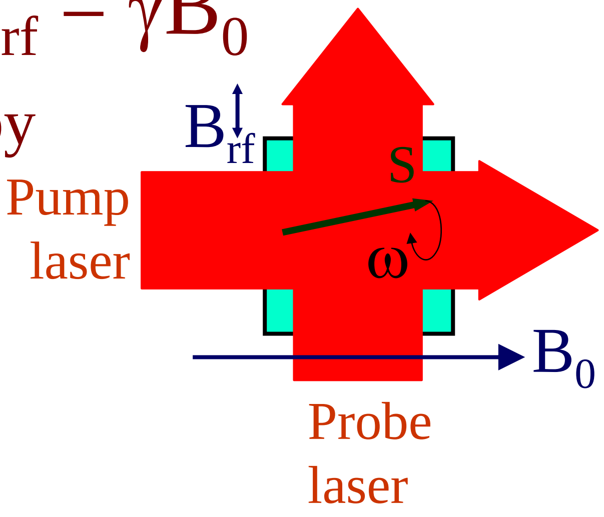
100 g of TNT located 10 cm away gives a 4 fT signal with a bandwidth of ~ 1 kHz.

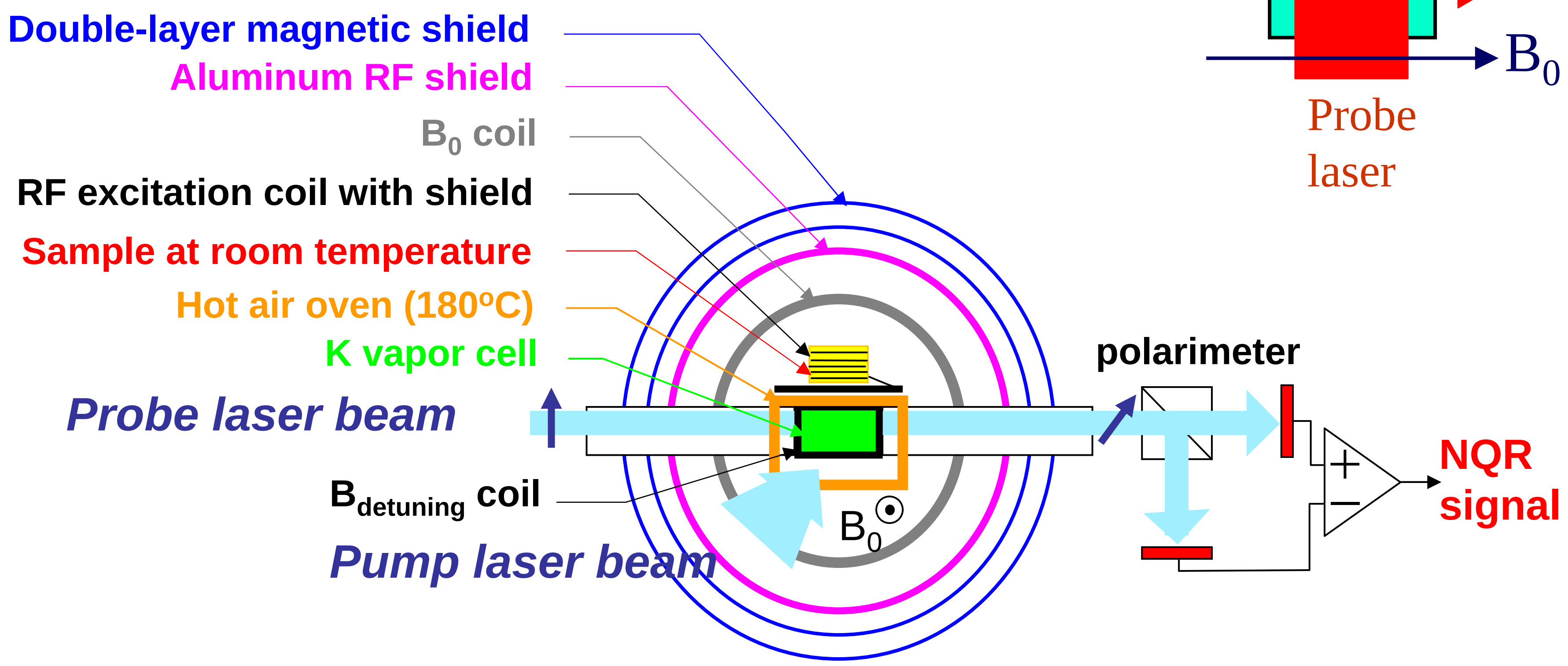
Under best conditions, SNR~ 0.5 with conventional RF detection

A.N. Garroway, et. al., IEE Transactions on Geoscience and Remote Sensing **39**, 1108 (2001)

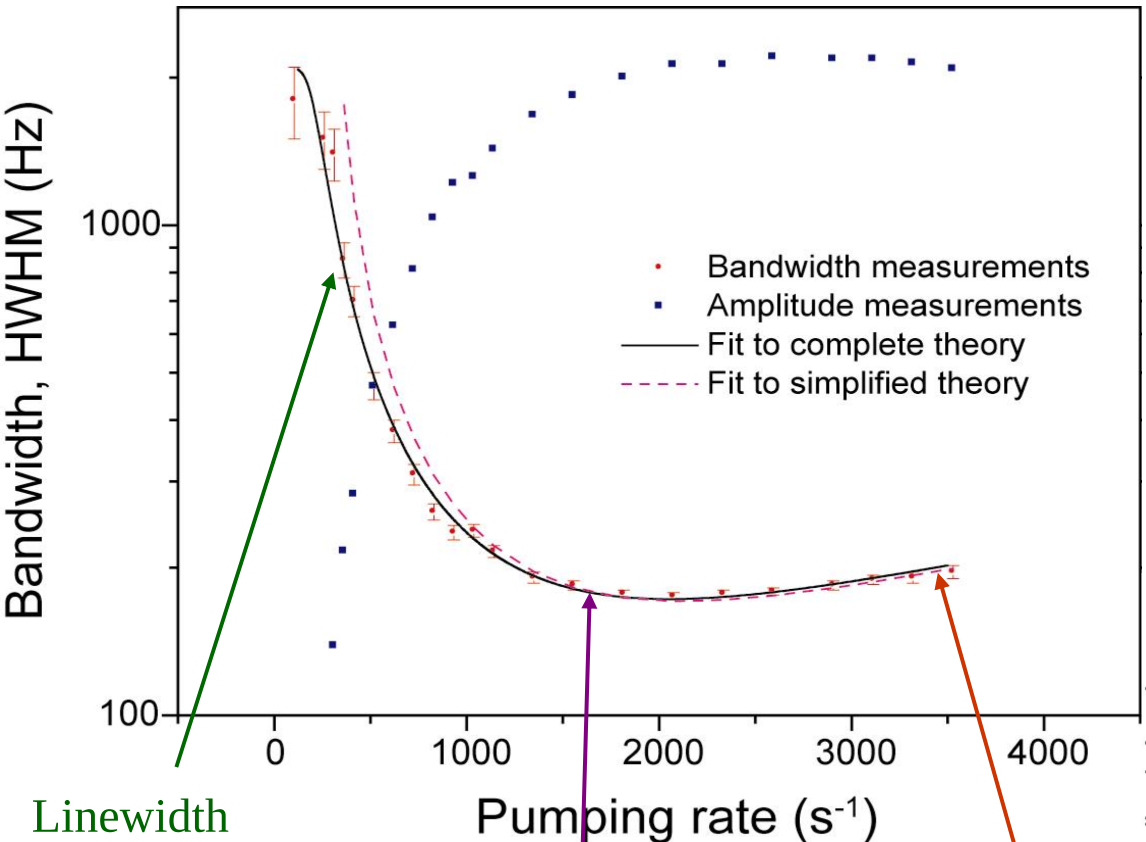
Tunable RF atomic magnetometer

- Tune B_0 field to the resonance condition $\omega_{rf} = \gamma B_0$
- Measure transverse spin precession induced by rf field $S_{\perp} = \gamma B_{rf} T_2$





Reduction of spin-exchange broadening in finite magnetic field

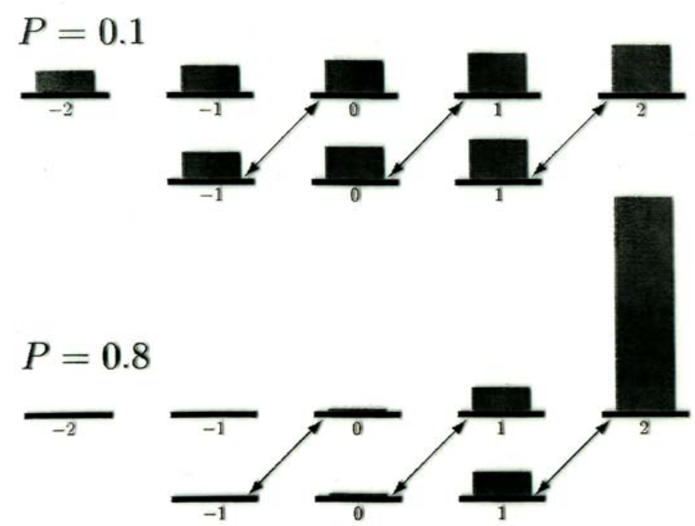


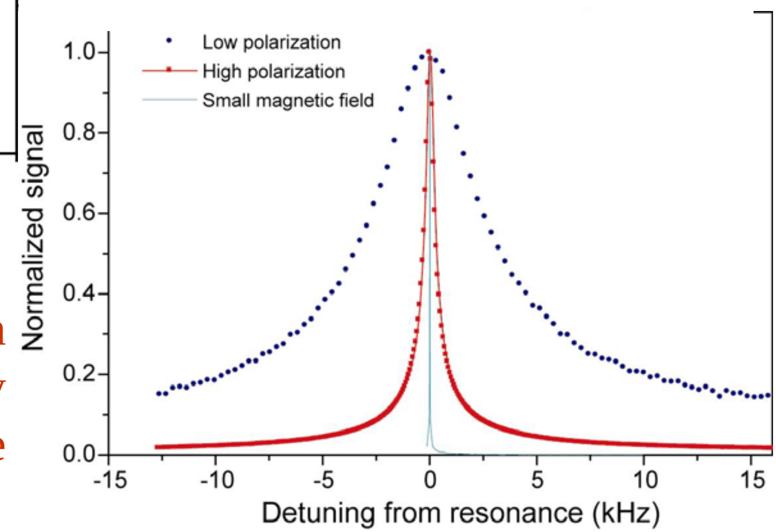
Linewidth dominated by spin-exchange broadening

Optimal pumping rate

$\Delta\nu = (R_{ex} R_{sd} /5)^{1/2}/2\pi$

Linewidth broadened by pumping rate

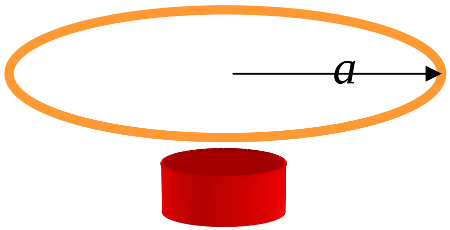




I.M. Savukov, S.J. Seltzer, MVR, K. Sauer, PRL **95**, 063005(2005)

RF detection limitations

- RF coil - Thermal Johnson Noise



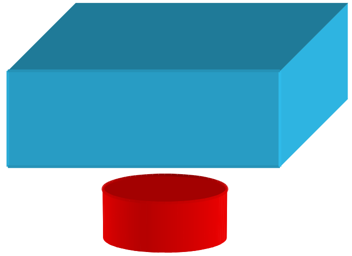
Resistivity of Copper

$$B_{rms} = \frac{4}{\omega a}\sqrt{\frac{kT\rho}{V_{wire}}}$$

$\Rightarrow$ V_{wire} limited by skin depth = 0.06 mm

$\Rightarrow$ For typical coils B = 0.8 fT/Hz$^{1/2}$

- Atomic magnetometer - Quantum Spin Fluctuations



Rate of alkali-metal collisions

$$B_{rms} = \frac{2}{\gamma}\sqrt{\frac{v[\sigma_{se}\sigma_{sd}/5]^{1/2}}{V_{cell}}}$$

$\Rightarrow$ V_{cell} limited by distance to the target = 0.1-0.5 m

$\Rightarrow$ For typical magnetometer cells B = 0.01 fT/Hz$^{1/2}$

RF magnetometer setup

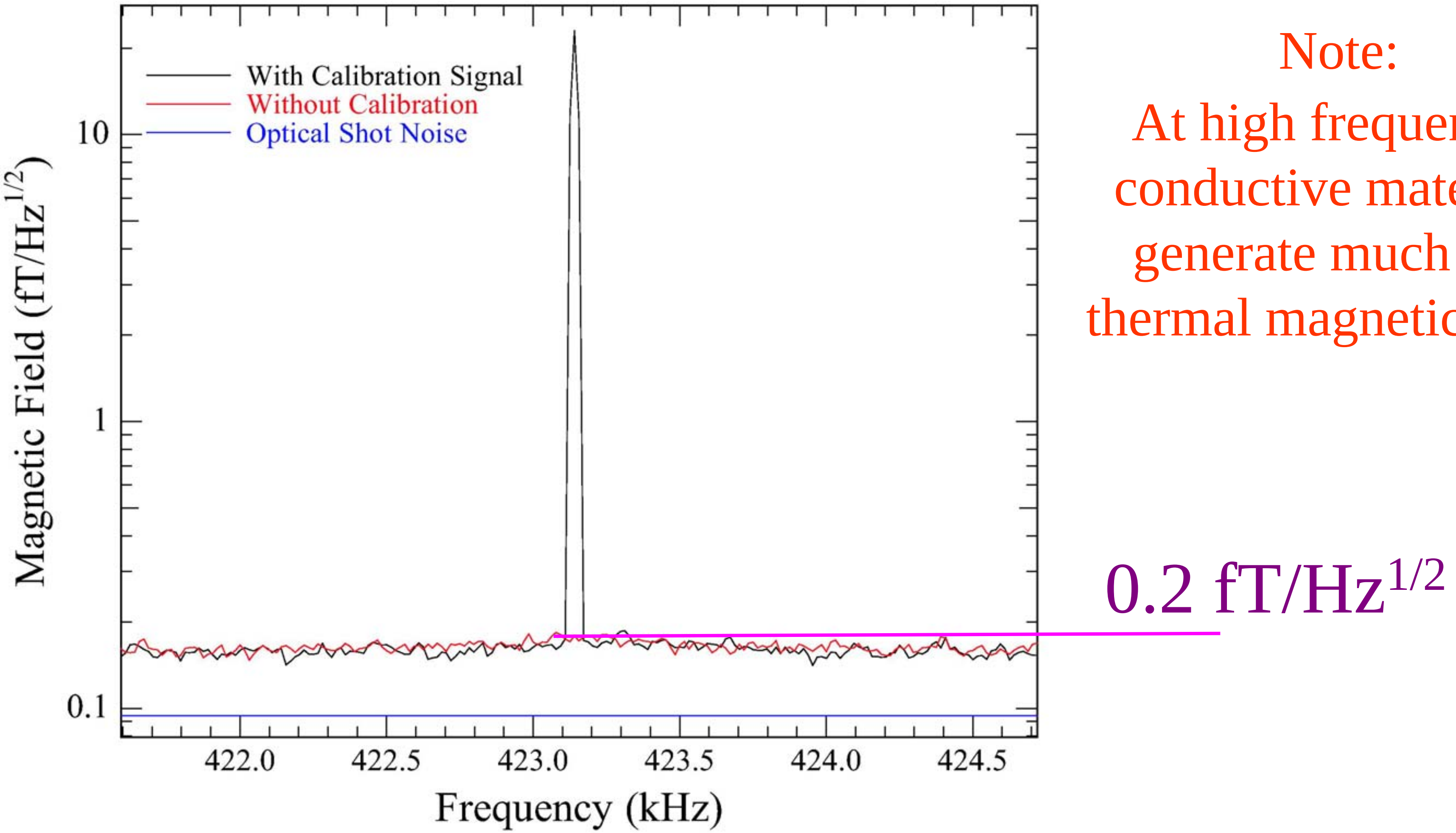
Simple balanced polarimeter

Rotation sensitivity: 4 nrad/Hz$^{1/2}$

↓

Optical detection of liquid-state NMR,
I.M. Savukov, S-K Lee, MVR, Nature (in press)

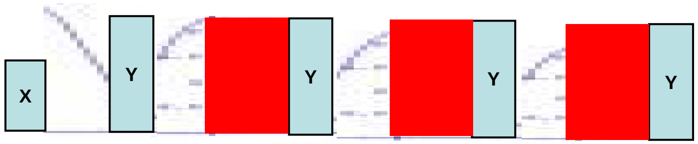
RF magnetometer sensitivity



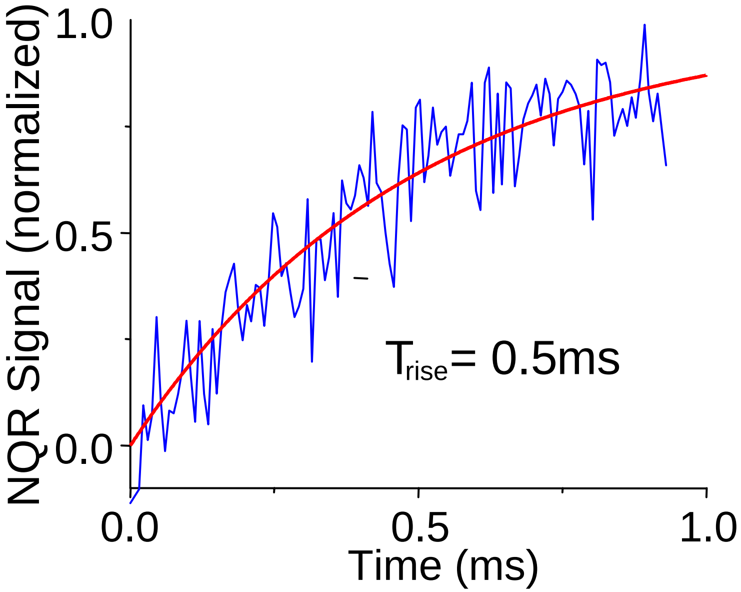
Note:
At high frequencies conductive materials generate much less thermal magnetic noise

First detection of NQR signals with atomic magnetometer

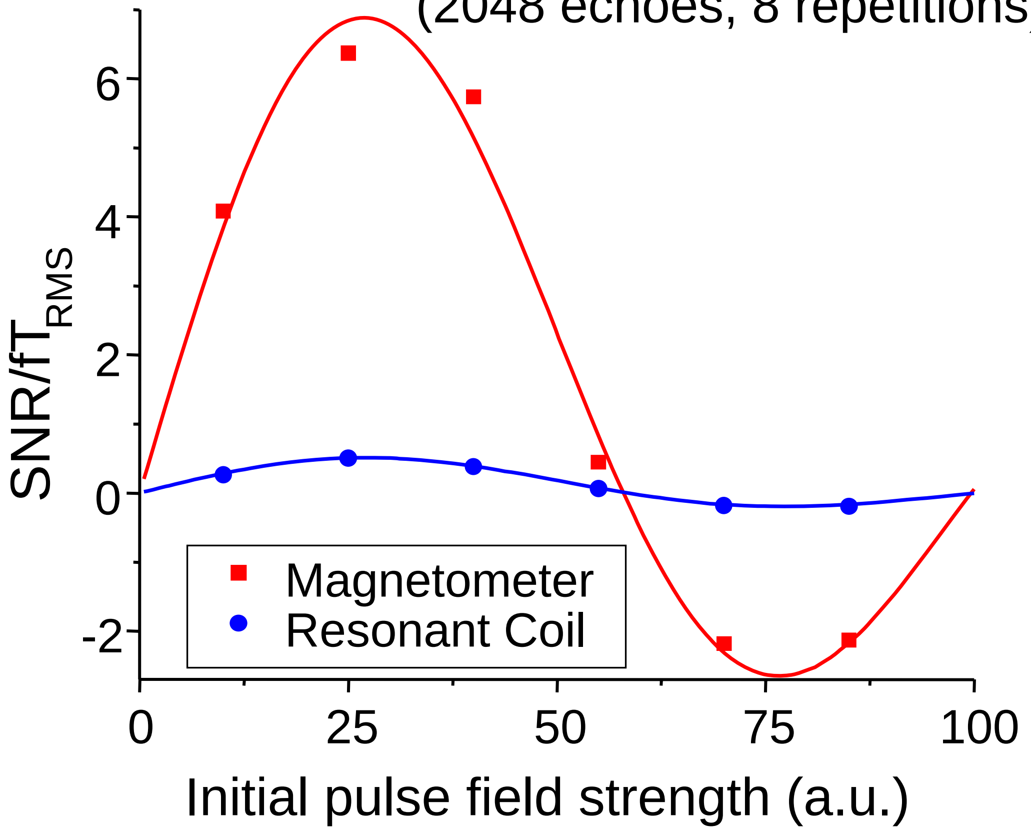
- Spin-echo sequence



Averaged echo signal



22 g of Ammonium Nitrate
4 minutes/point
(2048 echoes, 8 repetitions)



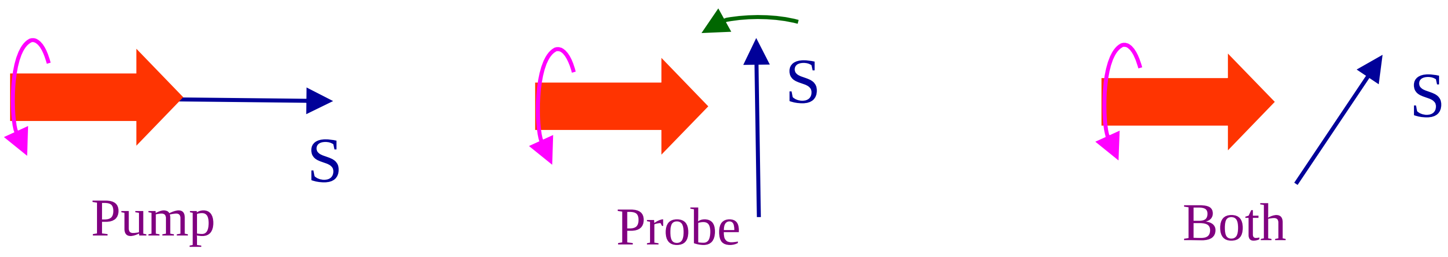
Signal/noise 12 times higher than for RF coil located equal distance away from the sample!

Resonance narrowing in optically dense samples

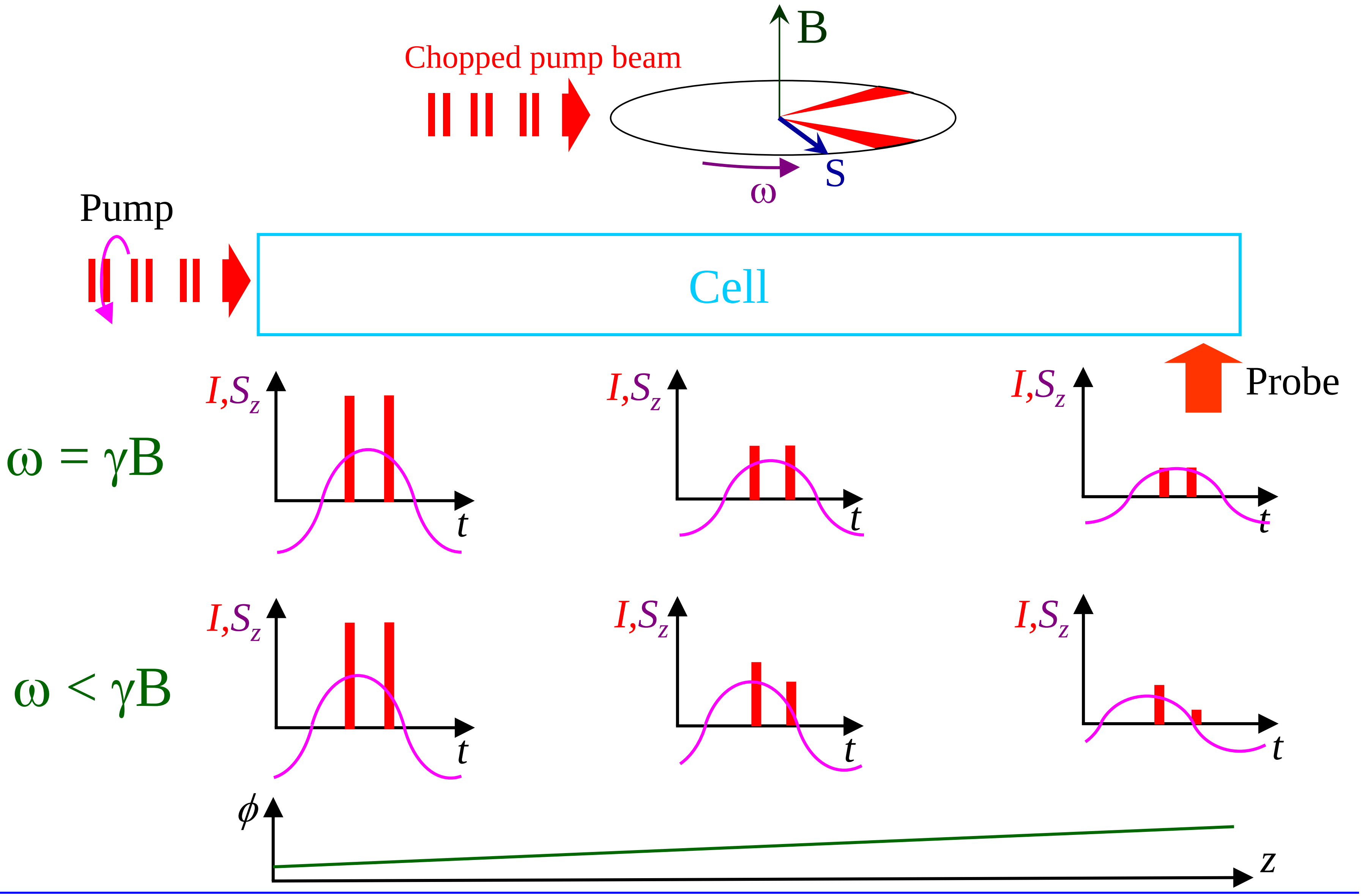
- Use large number of atoms $N = 10^{15}$-10^{17}
- Requires very low noise readout, e.g. $\delta\phi \sim 10^{-8}$–10^{-9} rad
- Affected by technical noise

Would be nice to use atoms themselves to amplify detected signal

- Use laser absorption to arrange interaction between atoms
- Same laser acts as both pump and probe beam

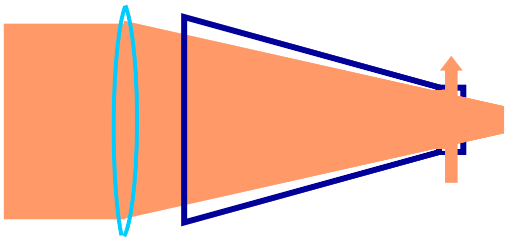


Phase amplification



Further Details

- Use convergent pump beam and a conical cell to compensate for pump absorption



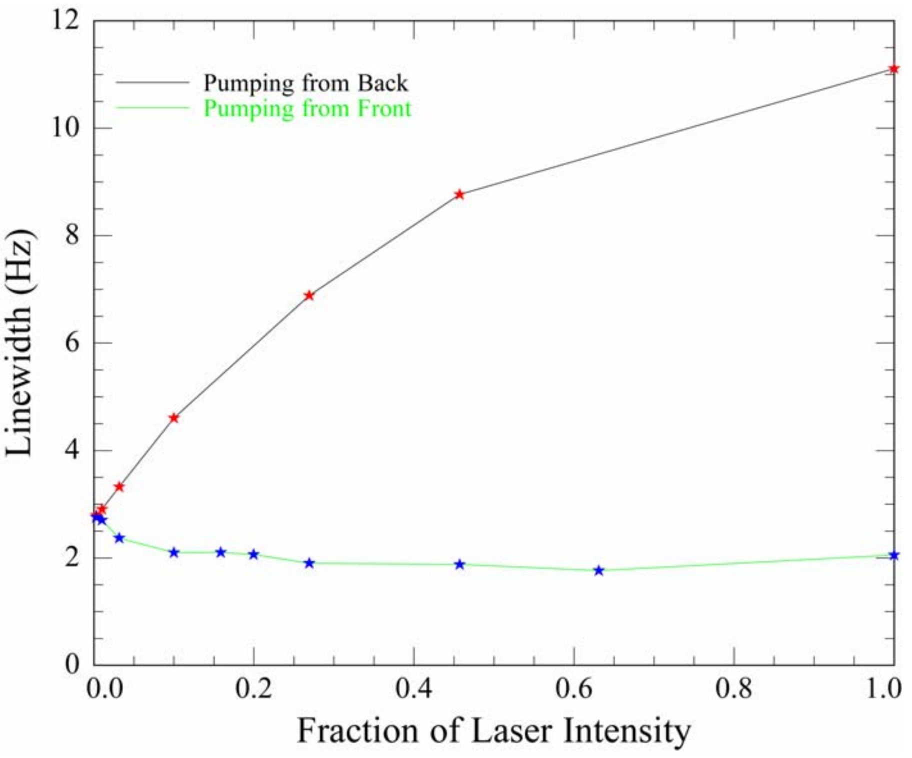
- He buffer gas to limit diffusion
- N_2 buffer gas for quenching of spontaneous emission

- Numerical light propagation model indicates phase gain ≃ OD under optimized conditions

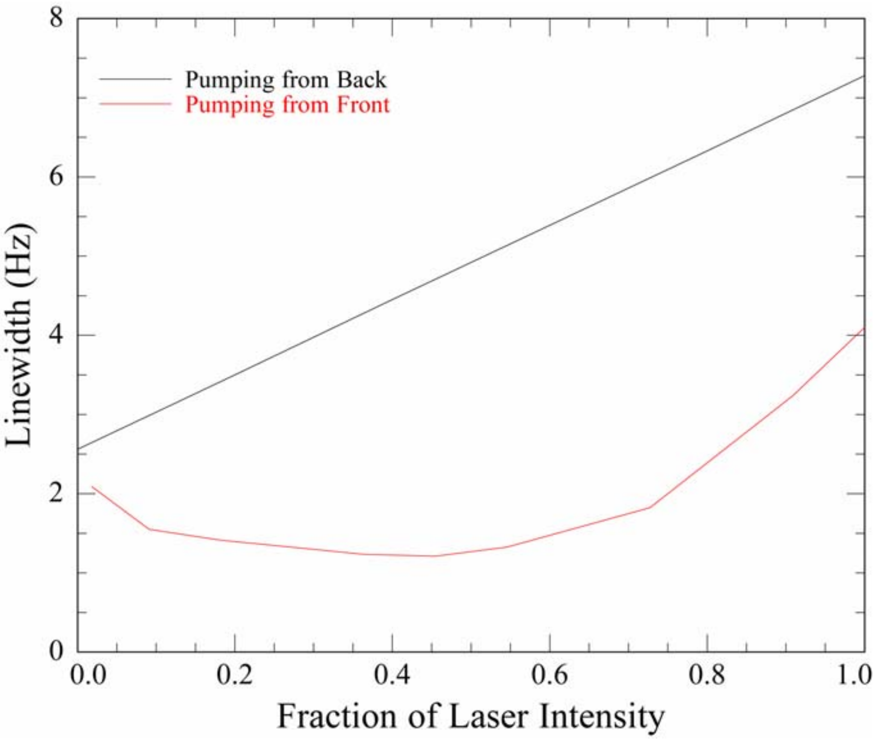
First experimental demonstration

- Compare resonance linewidth when pumping from the front and the back of the cell:

Experiment



Numerical model



- Observed resonance narrowing below intrinsic linewidth
- Need to optimize parameters to get a larger effect

- Collaborators
  - ⇒ Tom Kornack
  - ⇒ Iannis Kominis
  - ⇒ Hui Xia
  - ⇒ Andrei Baranga
  - ⇒ Dan Hoffman
  - ⇒ SeungKuyn Lee
  - ⇒ Scott Seltzer
  - ⇒ Karen Sauer
  - ⇒ Parker Meares
  - ⇒ Oleg Polyakov

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