Quantum enhanced magnetometer and squeezed state of light tunable filter

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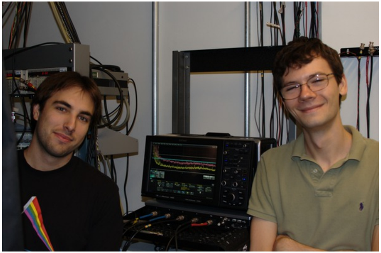
The College of William & Mary

August 13, 2013

People

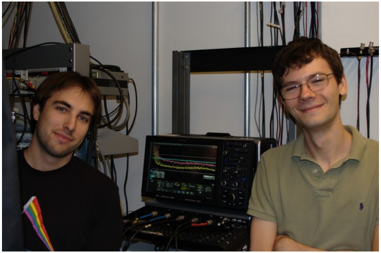
Travis Horrom and Gleb Romanov



Irina Novikova

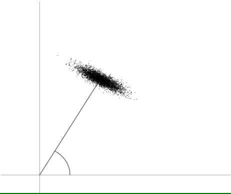
People

Travis Horrom and Gleb Romanov



Irina Novikova

Squeezed state

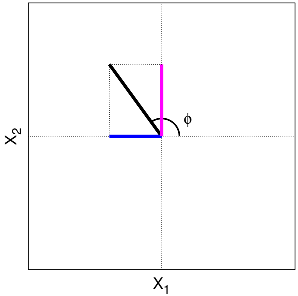


Transition from classical to quantum field

Classical analog

- Field amplitude a
- Field real part
  $X_1 = (a^* + a)/2$
- Field imaginary part
  $X_2 = i(a^* - a)/2$

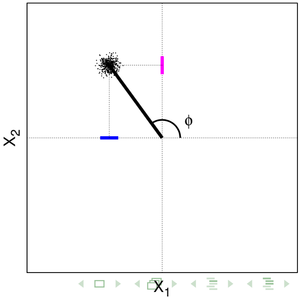
$$E(\phi) = |a|e^{-i\phi} = X_1 + iX_2$$



Quantum approach

- Field operator $\hat{a}$
- Amplitude quadrature
  $\hat{X}_1 = (\hat{a}^\dagger + \hat{a})/2$
- Phase quadrature
  $\hat{X}_2 = i(\hat{a}^\dagger - \hat{a})/2$

$$\hat{E}(\phi) = \hat{X}_1 + i\hat{X}_2$$



Heisenberg uncertainty principle and its optics equivalent

Heisenberg uncertainty principle

$\Delta p \Delta x \geq \hbar/2$

The more precisely the POSITION is determined, the less precisely the MOMENTUM is known, and vice versa

Optics equivalent

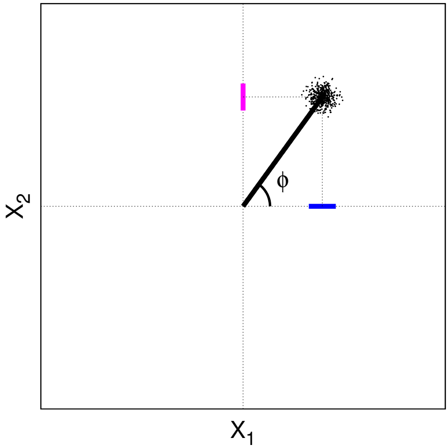
$\Delta \phi \Delta N \geq 1$

The more precisely the PHASE is determined, the less precisely the AMPLITUDE is known, and vice versa

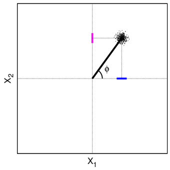
Optics equivalent strict definition

$\Delta X_1 \Delta X_2 \geq 1/4$

Squeezed quantum states zoo

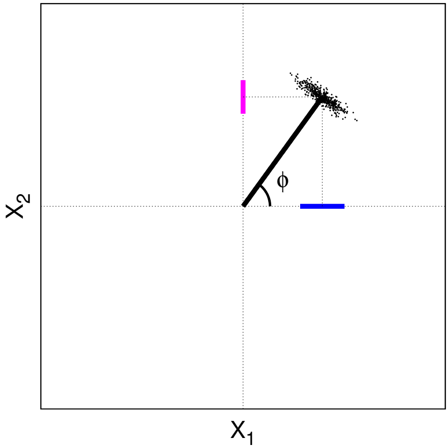


Unsqueezed coherent

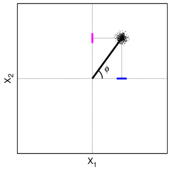


Notice $\Delta X_1 \Delta X_2 \geq \frac{1}{4}$

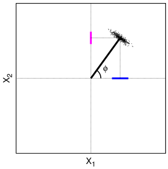
Squeezed quantum states zoo



Unsqueezed coherent



Amplitude squeezed



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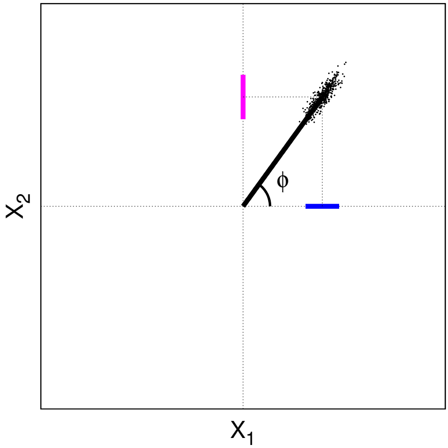
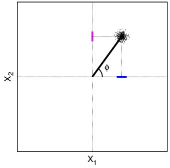
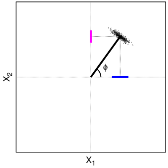
Squeezed quantum states zoo



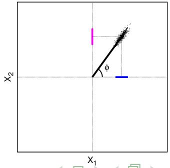
Unsqueezed coherent



Amplitude squeezed

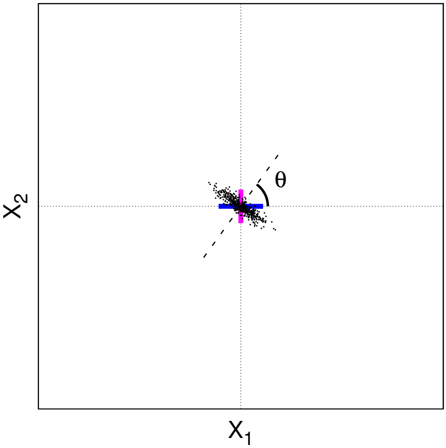


Phase squeezed



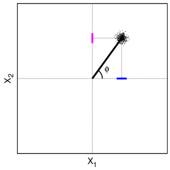
Notice $\Delta X_1 \Delta X_2 \geq \frac{1}{4}$

Squeezed quantum states zoo

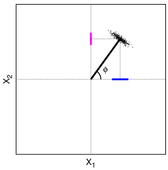


Notice $\Delta X_1 \Delta X_2 \geq \frac{1}{4}$

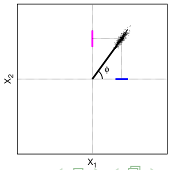
Unsqueezed coherent



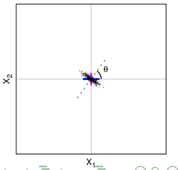
Amplitude squeezed



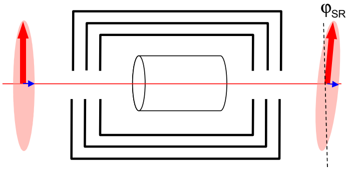
Phase squeezed

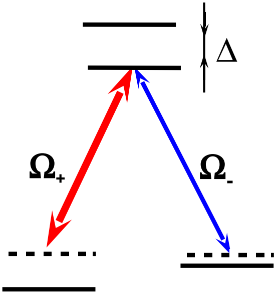


Vacuum squeezed



Self-rotation of elliptical polarization in atomic medium

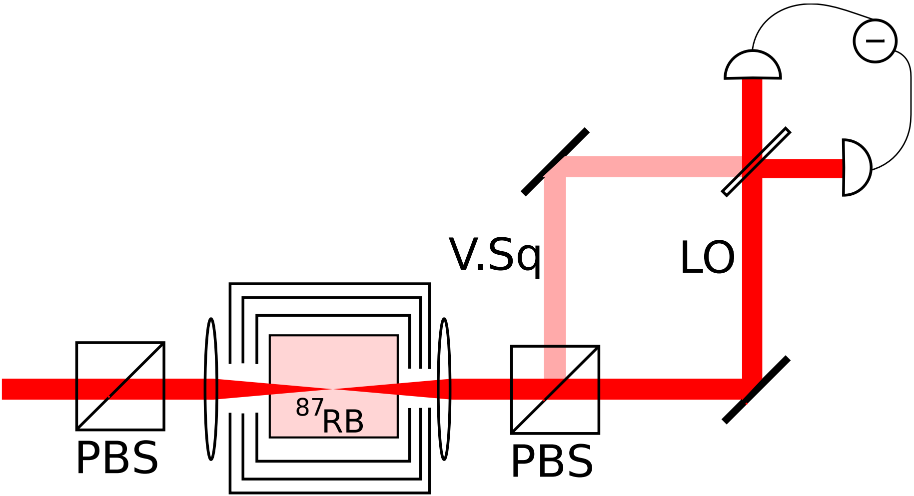




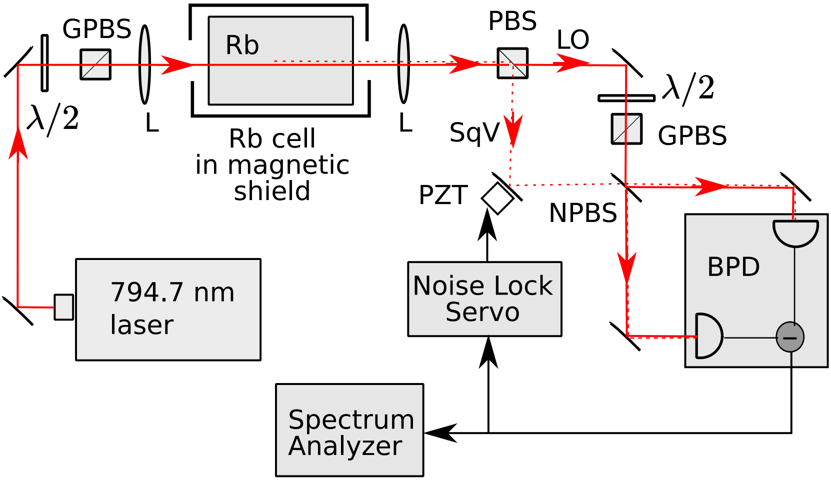
A.B. Matsko et al., PRA 66, 043815 (2002): theoretically prediction of 4-6 dB noise suppression

$$a_{out} = a_{in} + \frac{igL}{2}(a_{in}^{\dagger} - a_{in}) \quad (1)$$

Simplified setup

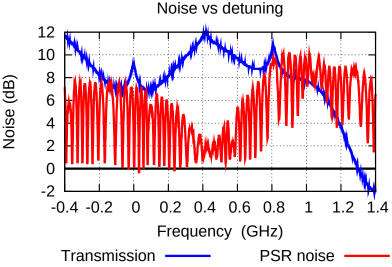


Setup

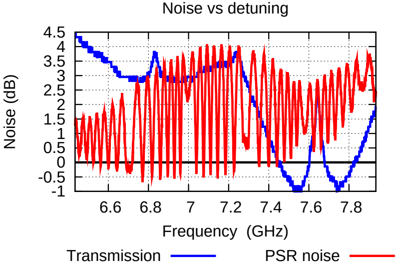


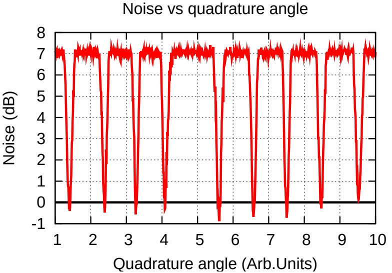
GPBS
Rb
PBS
LO
$\lambda/2$
L
Rb cell
in magnetic
shield
L
SqV
$\lambda/2$
GPBS
PZT
NPBS
BPD
794.7 nm
laser
Noise Lock
Servo
Spectrum
Analyzer

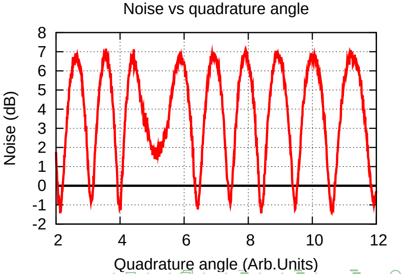
$F_g = 2 \rightarrow F_e = 1, 2$



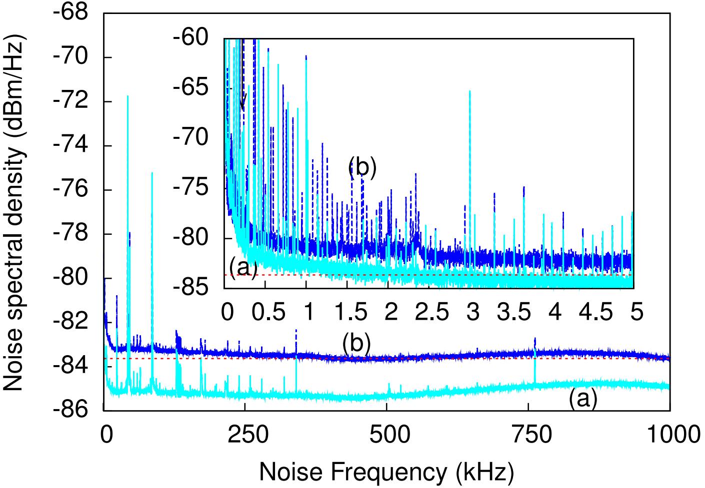
$F_g = 1 \rightarrow F_e = 1, 2$



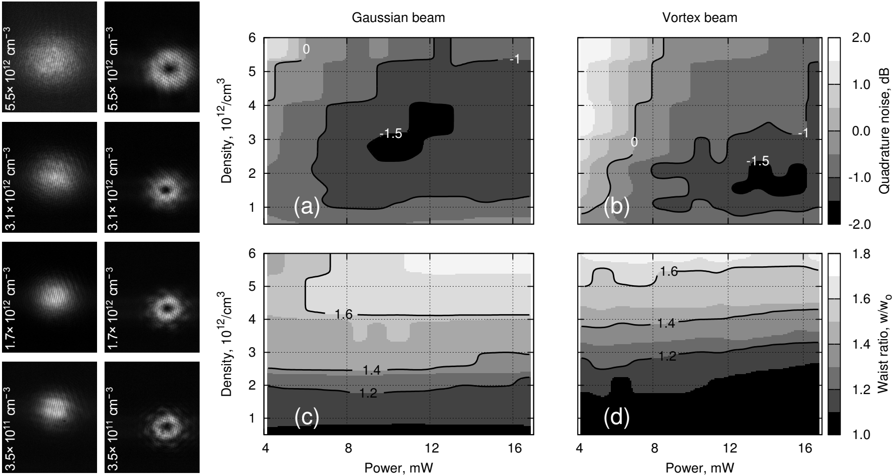




Atomic low frequency squeezing source

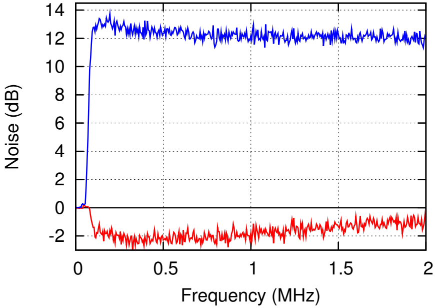


Squeezing and self-focusing

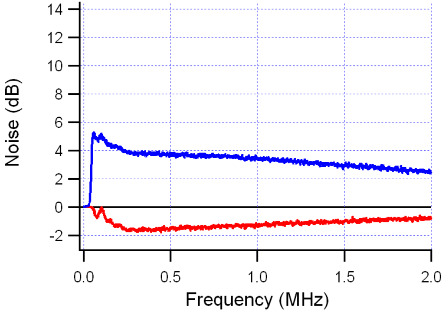


Vacuum cell vs coated cell

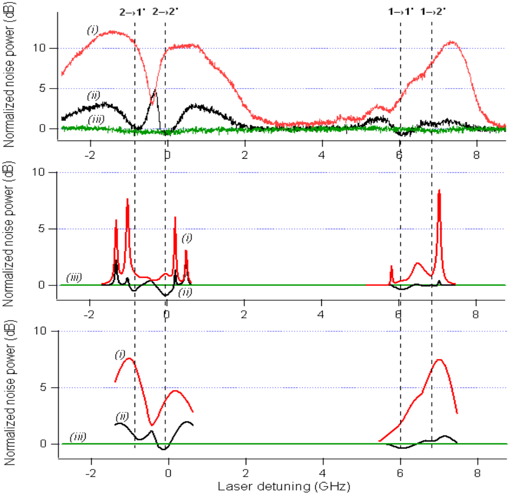
Vacuum cell



Coated cell



Squeezing theory and experiment

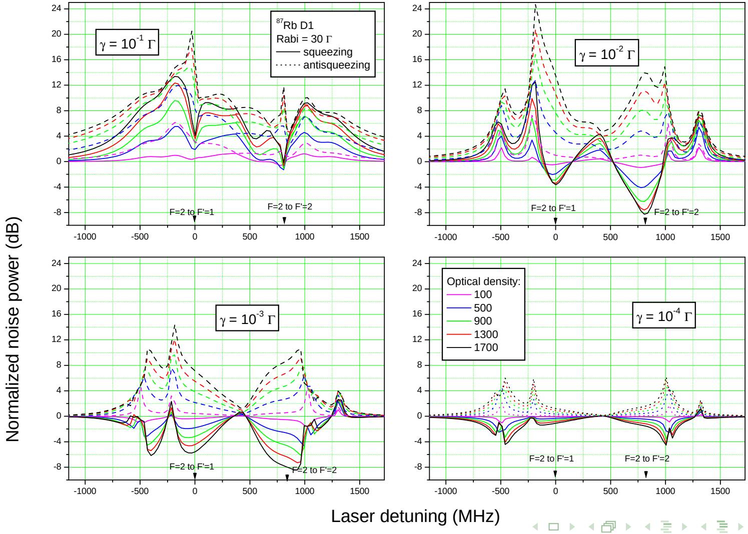


- ^{87}Rb cell
- no buffer gas
- density $2 \cdot 10^{11}$ cm^{-3}
- laser power 6 mW
- beam size 0.2 mm

E.E. Mikhailov, A. Lezama, T. Noel and I. Novikova, J. Mod. Opt. **56**, 1985 (2009).

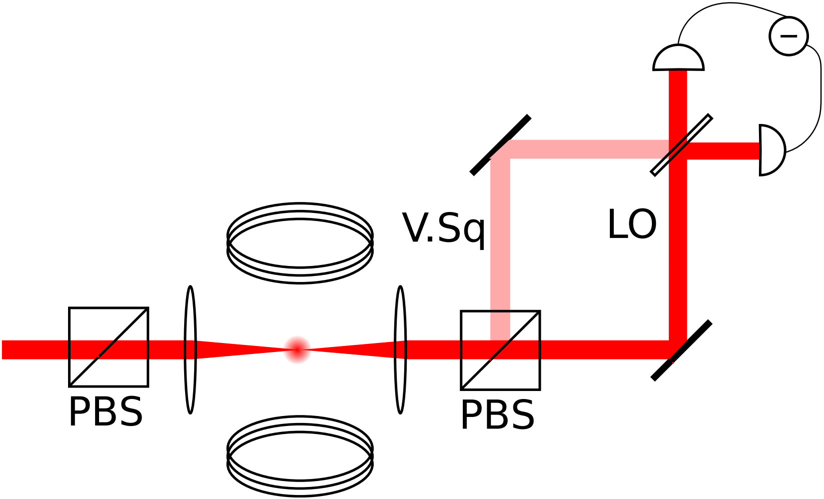
Theoretical prediction for MOT squeezing with ^{87}Rb

$F_g = 2 \rightarrow F_e = 1, 2$ high optical density is very important

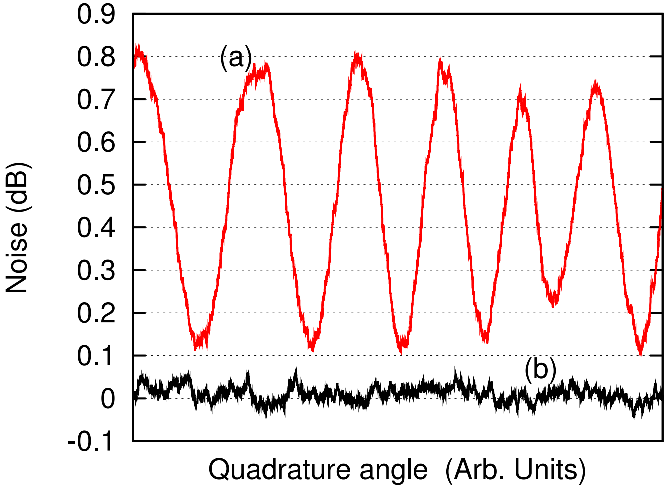


MOT squeezer

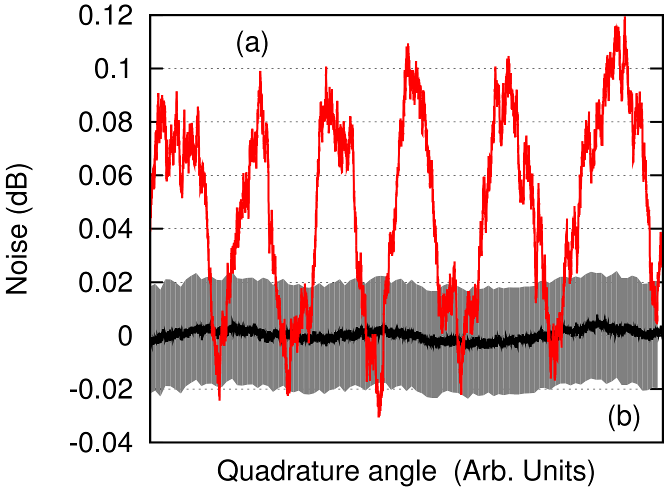
Cloud size =1 mm, T = 200 μK, N = 7 $\times$ 10^9 1/cm^3,
OD = 2, beam size = 0.1 mm, 10^5 interacting atoms



Noise contrast in MOT with ^{87}Rb $F_g = 2 \rightarrow F_e = 1$



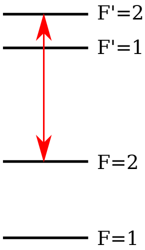
Squeezing in MOT with ^{87}Rb $F_g = 2 \rightarrow F_e = 1$

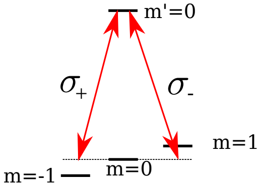


Travis Horrom, et al. Journal of Modern Optics, Issues 21, **58**, 1936-1941, (2011).

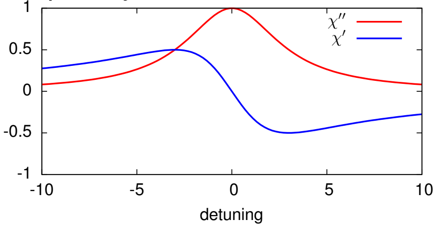
Optical magnetometer based on Faraday effect

^{87}Rb D_1 line

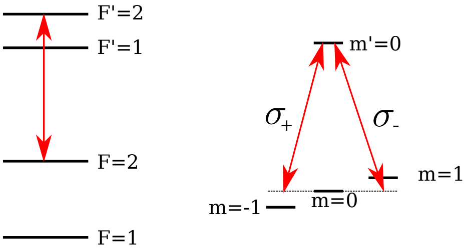




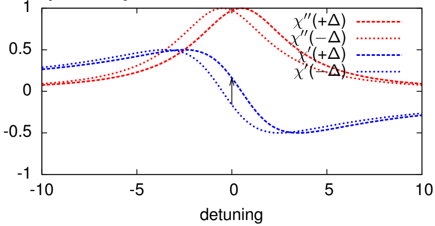
Susceptibility vs B



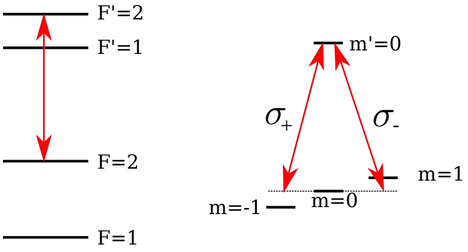
^{87}Rb D_1 line



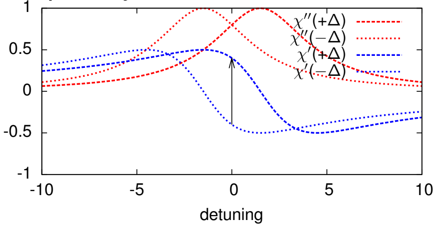
Susceptibility vs B



^{87}Rb D_1 line

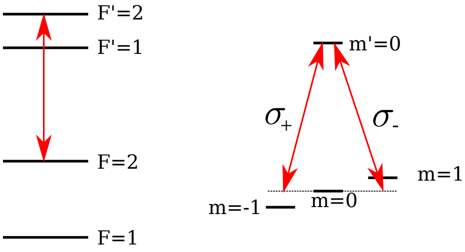


Susceptibility vs B

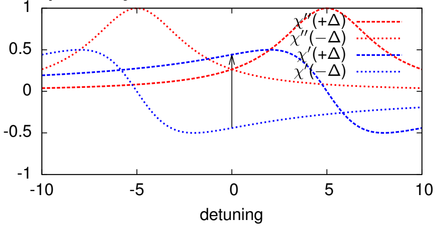


Optical magnetometer based on Faraday effect

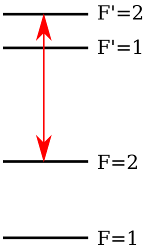
^{87}Rb D_1 line

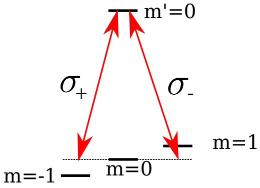


Susceptibility vs B

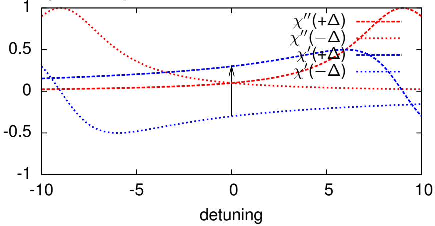


^{87}Rb D_1 line



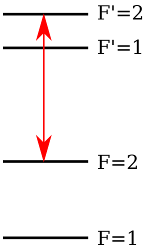


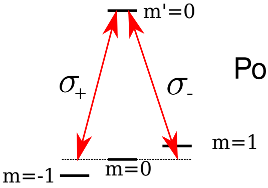
Susceptibility vs B



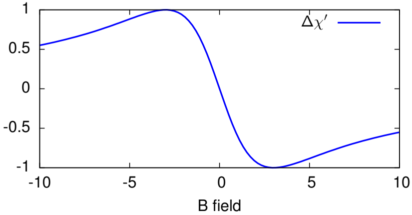
Optical magnetometer based on Faraday effect

^{87}Rb D_1 line

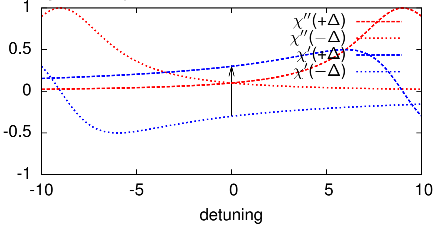




Polarization rotation vs B

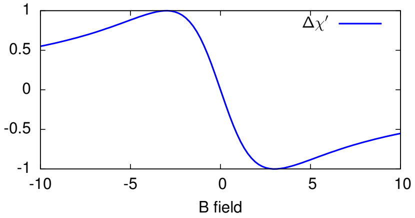


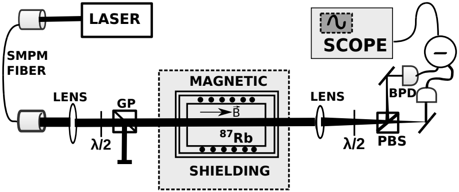
Susceptibility vs B



Optical magnetometer and non linear Faraday effect

Naive model of rotation

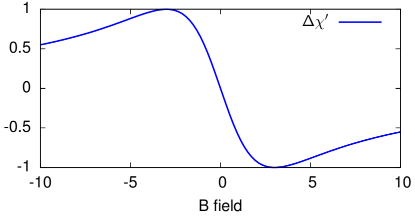


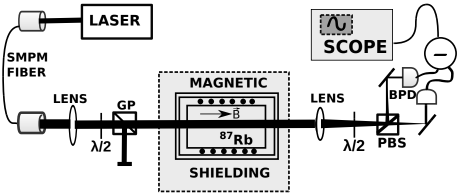


Experiment

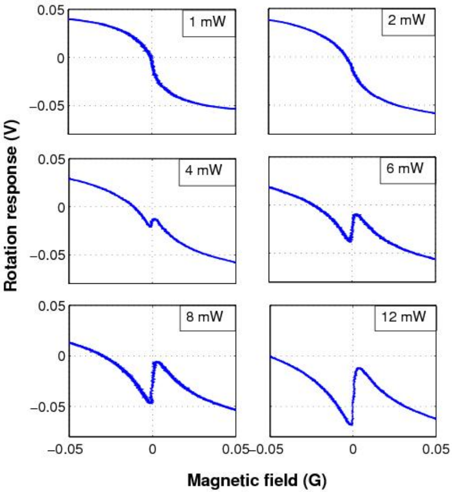
Optical magnetometer and non linear Faraday effect

Naive model of rotation

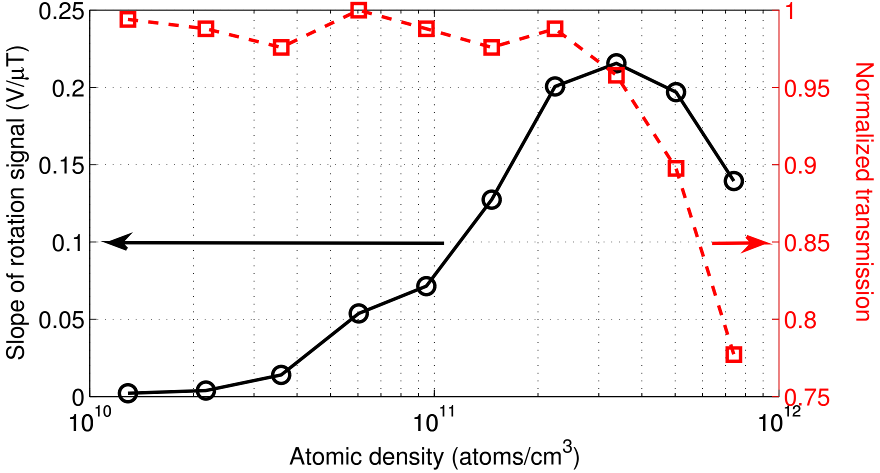




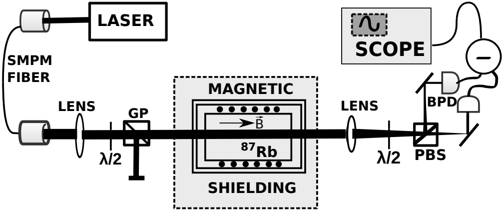
Experiment

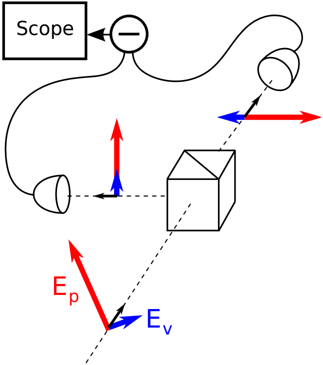


Magnetometer response vs atomic density



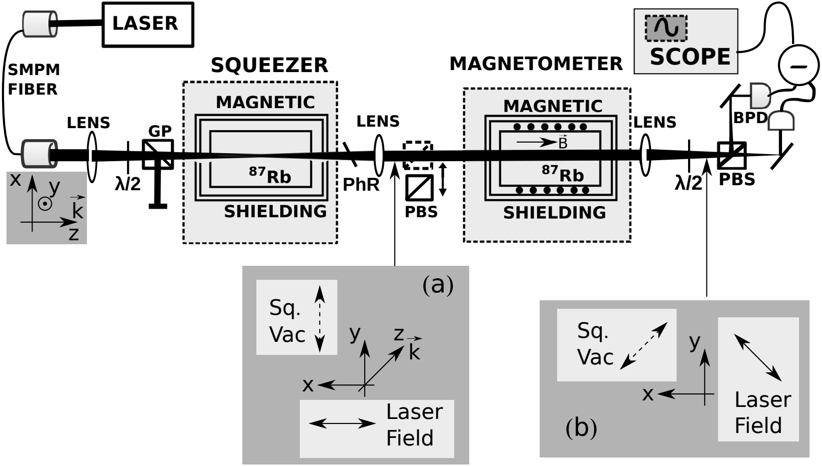
Shot noise limit of the magnetometer





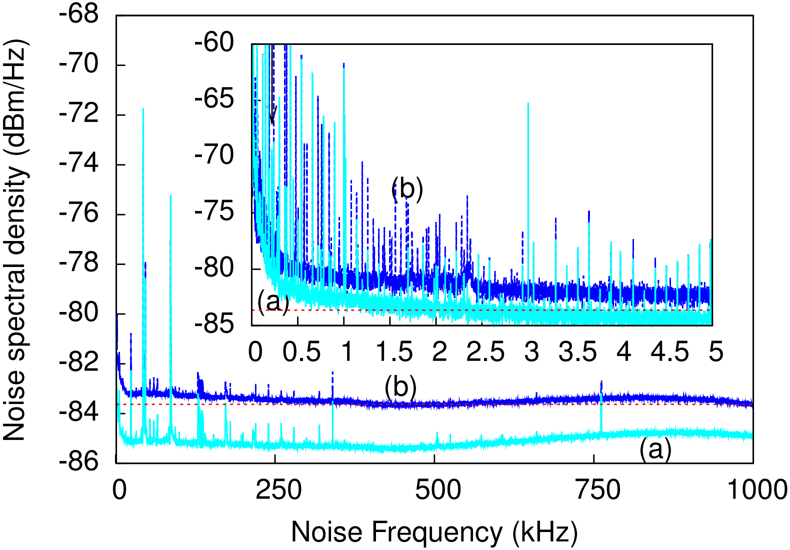
$$S = |E_p + E_v|^2 - |E_p - E_v|^2$$
$$S = 4E_pE_v$$
$$< \Delta S > \sim E_p < \Delta E_v >$$

Squeezed enhanced magnetometer setup

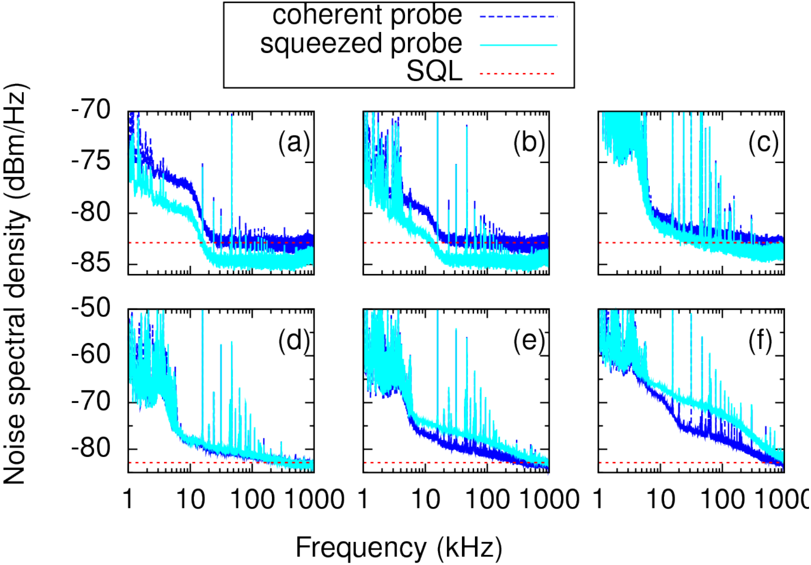


Note: Squeezed enhanced magnetometer was first demonstrated by Wolfgramm *et. al* Phys. Rev. Lett, **105**, 053601, 2010.

Magnetometer noise floor improvements

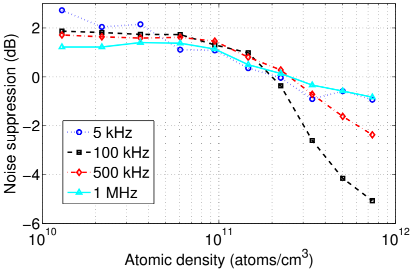


Magnetometer noise spectra

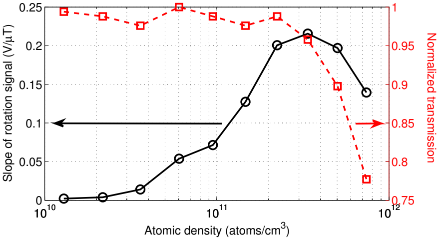


Noise suppression and response vs atomic density

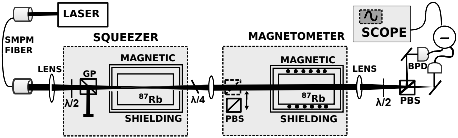
Noise suppression

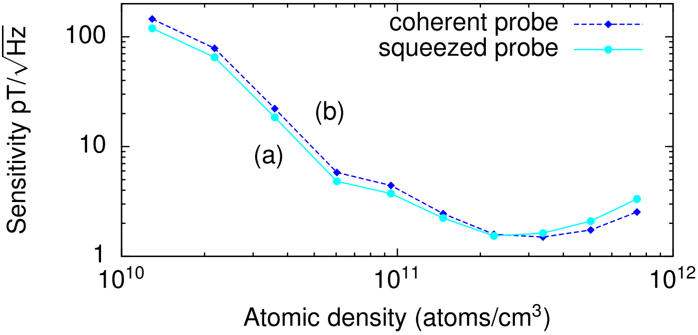


Response



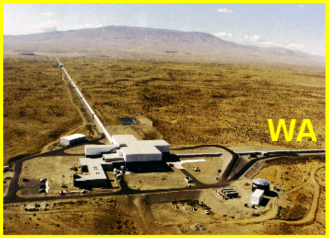
Magnetometer with squeezing enhancement



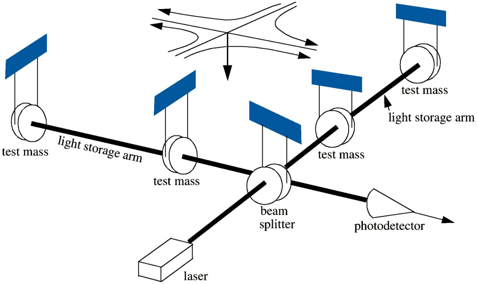


T. Horrom, et al. “Quantum Enhanced Magnetometer with Low Frequency Squeezing”, PRA, **86**, 023803, (2012).

Laser Interferometer Gravitational-wave Observatory

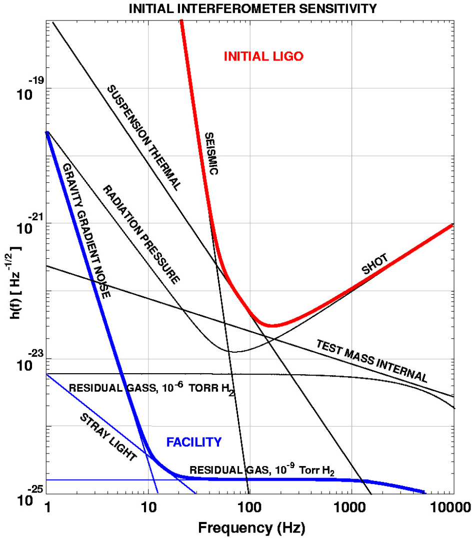


- $L = 4$ km
- $h \sim 2 \times 10^{-23}$
- $\Delta L \sim 10^{-20}$ m



World wide network of detectors

LIGO sensitivity goal and noise budget



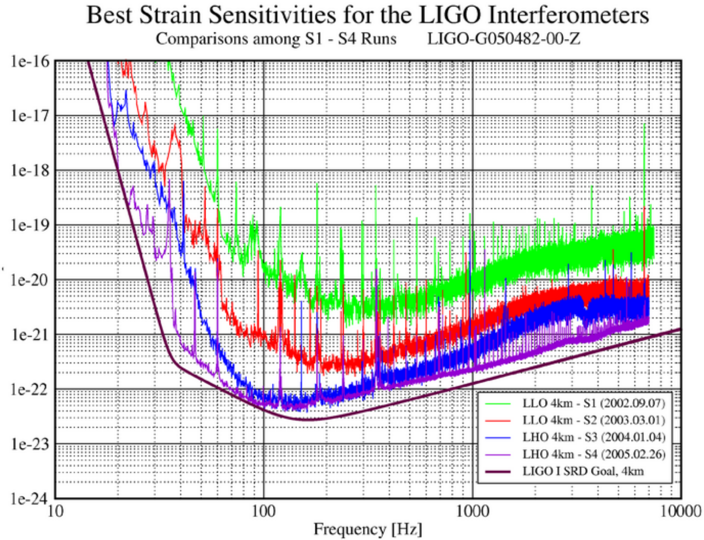
Displacement noise

- seismic
- thermal suspension
- thermal Brownian
- radiation pressure noise

Detection noise

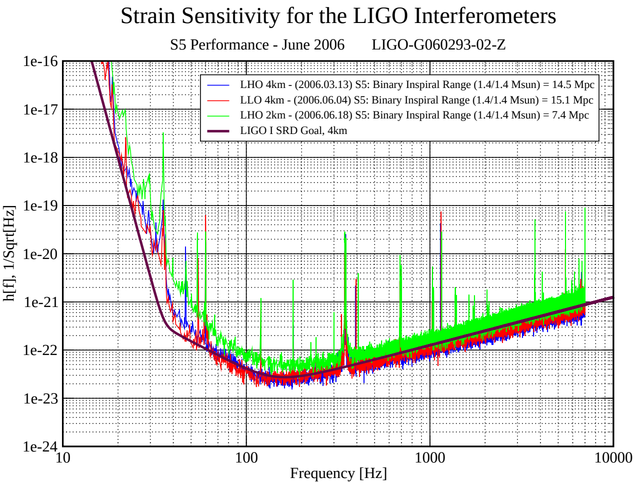
- electronics
- shot noise

LIGO sensitivity, S1-S4 runs



Inspiral search range during S4 was 8Mpc

LIGO sensitivity, S5 run, June 2006



Inspiral search range during S5 is 14Mpc

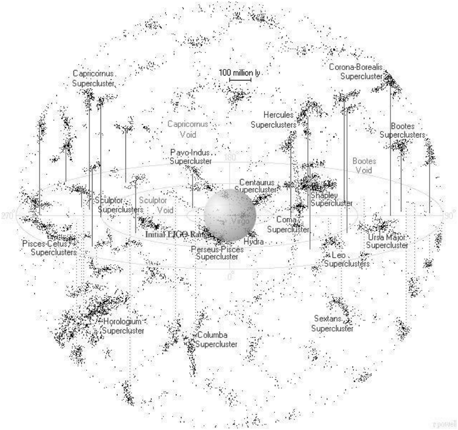
Upgrade

Goals

- Factor of 15 increase in sensitivity
- inspiral range from 20 Mpc to 350 Mpc
- Factor of 3000 in event rate
  One day > entire 2-year initial data run
- Quantum-noise-limited interferometer

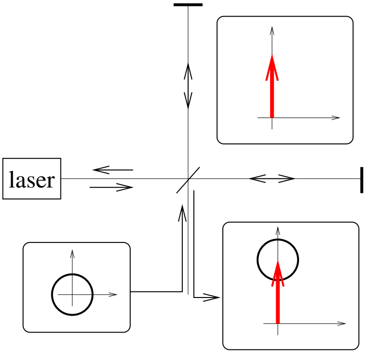
How

- better seismic isolation
- decreasing thermal noise
- higher laser power

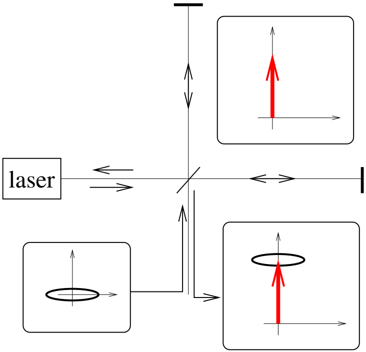


Quantum limited interferometers

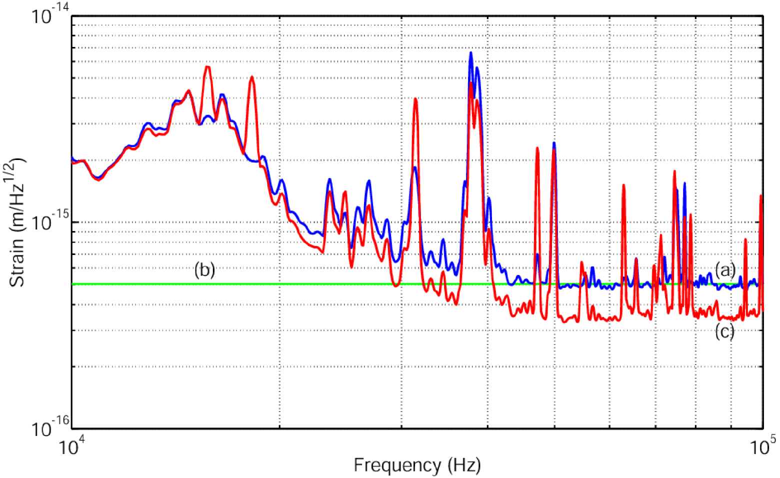
Vacuum input



Squeezed input



GW 40m detector with 4dB of squeezed vacuum



Signal to noise improvement by factor of 1.43
"A quantum-enhanced prototype gravitational-wave detector", Nature Physics, **4**, 472-476, (2008).

Limiting noise - Quantum Optical noise

Next generation of LIGO (advanced LIGO) will be quantum optical noise limited at almost all detection frequencies.

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shot noise

Uncertainty in number of photons

$$h \sim \sqrt{\frac{1}{P}} \qquad (2)$$

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radiation pressure noise

Photons impart momentum to mirrors

$$h \sim \sqrt{\frac{P}{M^2 f^4}} \tag{3}$$

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radiation pressure noise

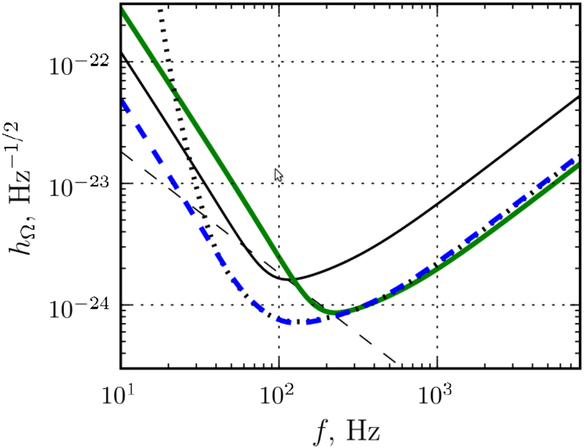
Photons impart momentum to mirrors

$$h \sim \sqrt{\frac{P}{M^2 f^4}} \tag{3}$$

There is no optimal light power to suit all detection frequency.
Optimal power depends on desired detection frequency.

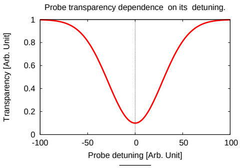
Interferometer sensitivity improvement with squeezing

Projected advanced LIGO sensitivity

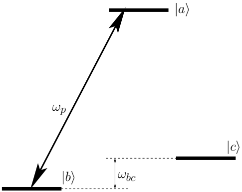


F. Ya. Khalili Phys. Rev. D 81, 122002 (2010)

EIT filter

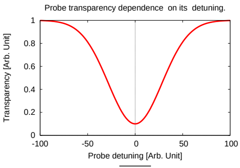


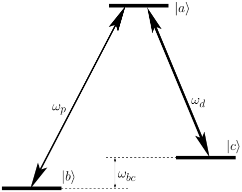
Probe transparency dependence on its detuning.
Transparency [Arb. Unit]
Probe detuning [Arb. Unit]
1
0.8
0.6
0.4
0.2
0
-100
-50
0
50
100

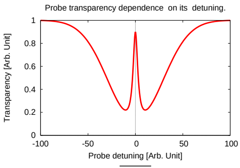


$|a\rangle$
ω_p
$|c\rangle$
$|b\rangle$
ω_{bc}

EIT filter


Probe transparency dependence on its detuning.
Transparency [Arb. Unit]
Probe detuning [Arb. Unit]
1
0.8
0.6
0.4
0.2
0
-100
-50
0
50
100


$|a\rangle$
ω_p
ω_d
$|c\rangle$
$|b\rangle$
ω_{bc}

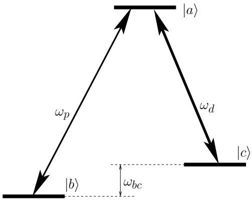

Probe transparency dependence on its detuning.
Transparency [Arb. Unit]
Probe detuning [Arb. Unit]
1
0.8
0.6
0.4
0.2
0
-100
-50
0
50
100

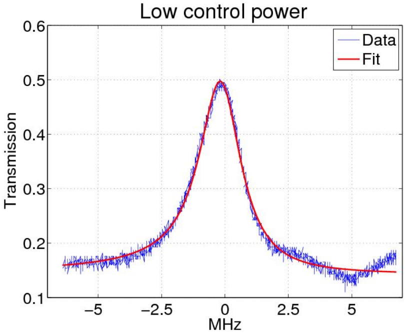
Squeezing and EIT filter

$$\begin{pmatrix} V_1^{out} \\ V_2^{out} \end{pmatrix} = \begin{pmatrix} A_+^2 & A_-^2 \\ A_-^2 & A_+^2 \end{pmatrix} \begin{pmatrix} V_1^{in} \\ V_2^{in} \end{pmatrix} + \left[1 - \left(A_+^2 + A_-^2\right)\right] \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

$$\varphi_\pm = \frac{1}{2}(\Theta_+ \pm \Theta_-)$$

$$A_\pm = \frac{1}{2}(T_+ \pm T_-)$$





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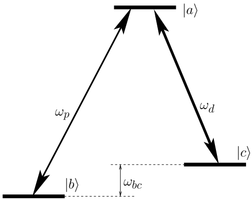
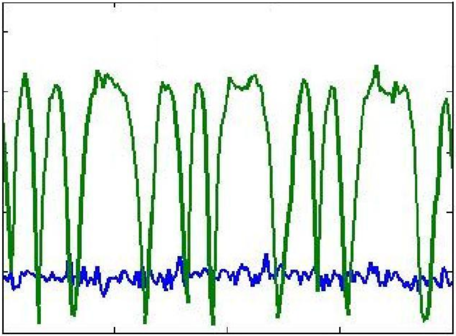


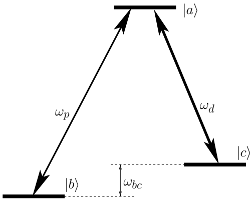


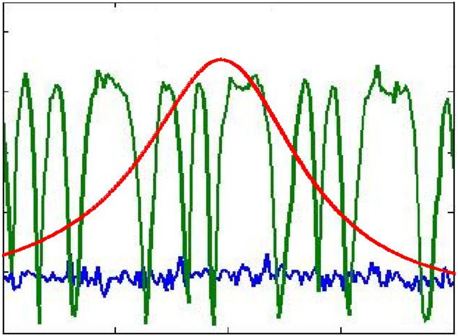
Squeezing and EIT filter

$$\begin{pmatrix} V_1^{out} \\ V_2^{out} \end{pmatrix} = \begin{pmatrix} A_+^2 & A_-^2 \\ A_-^2 & A_+^2 \end{pmatrix} \begin{pmatrix} V_1^{in} \\ V_2^{in} \end{pmatrix} + \left[1 - \left(A_+^2 + A_-^2\right)\right] \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

$$\varphi_\pm = \frac{1}{2}(\Theta_+ \pm \Theta_-)$$

$$A_\pm = \frac{1}{2}(T_+ \pm T_-)$$





Squeezing and EIT filter

$$\begin{pmatrix} V_1^{out} \\ V_2^{out} \end{pmatrix} = \begin{pmatrix} A_+^2 & A_-^2 \\ A_-^2 & A_+^2 \end{pmatrix} \begin{pmatrix} V_1^{in} \\ V_2^{in} \end{pmatrix} + \left[1 - \left(A_+^2 + A_-^2\right)\right] \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

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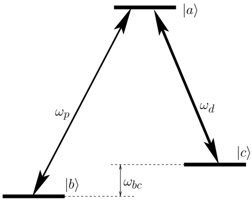
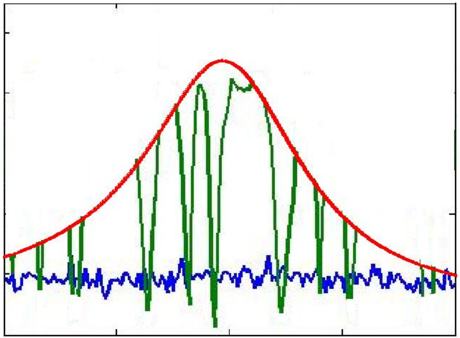
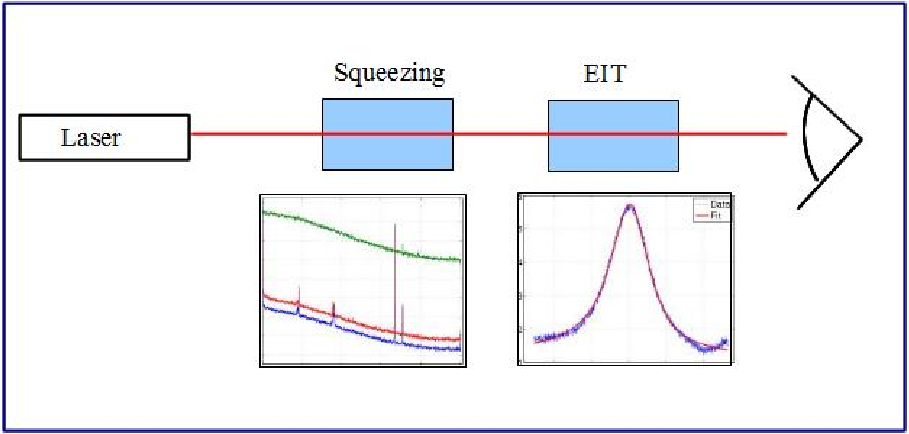
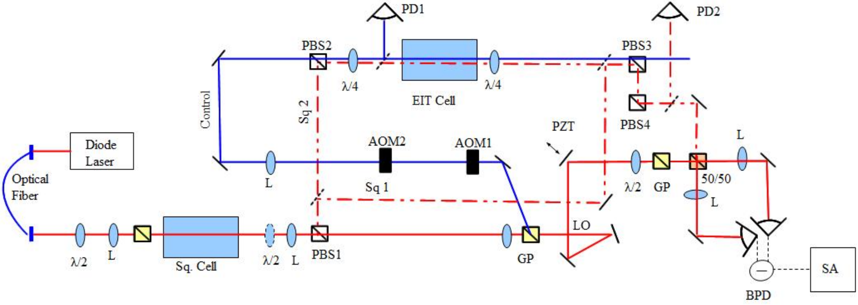




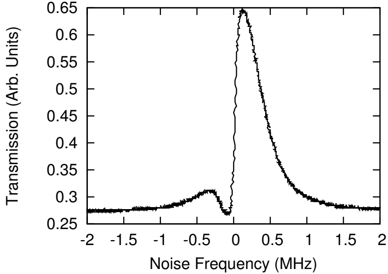
Squeezing and EIT filter setup



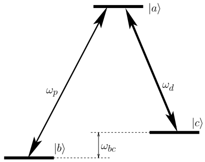
Squeezing and EIT filter setup



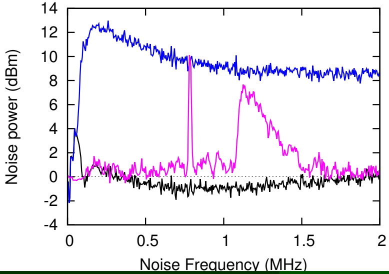
EIT filter and measurements without light

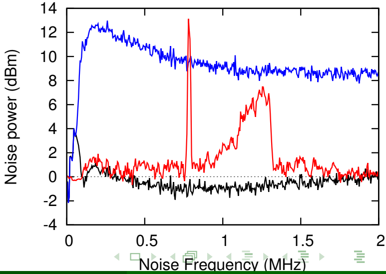


Coherent signal

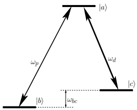


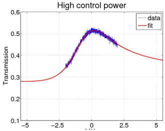
Signal in the noise quadratures



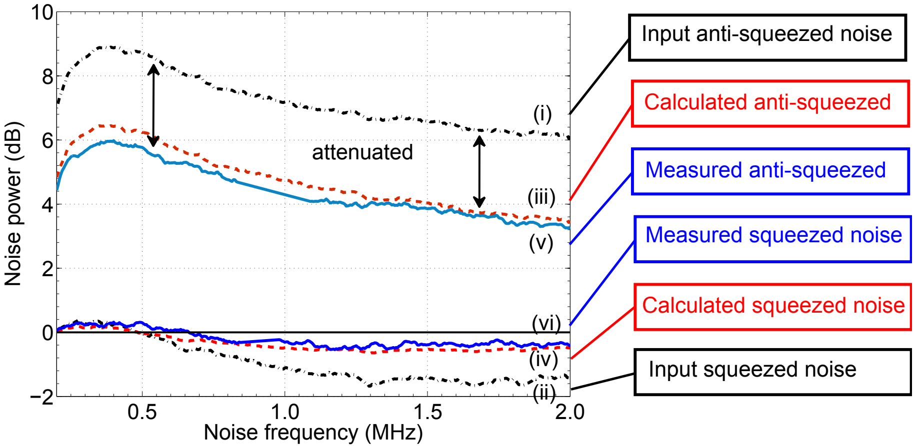


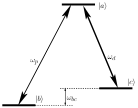
Wide EIT filter and squeezing

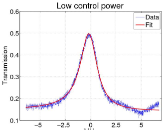




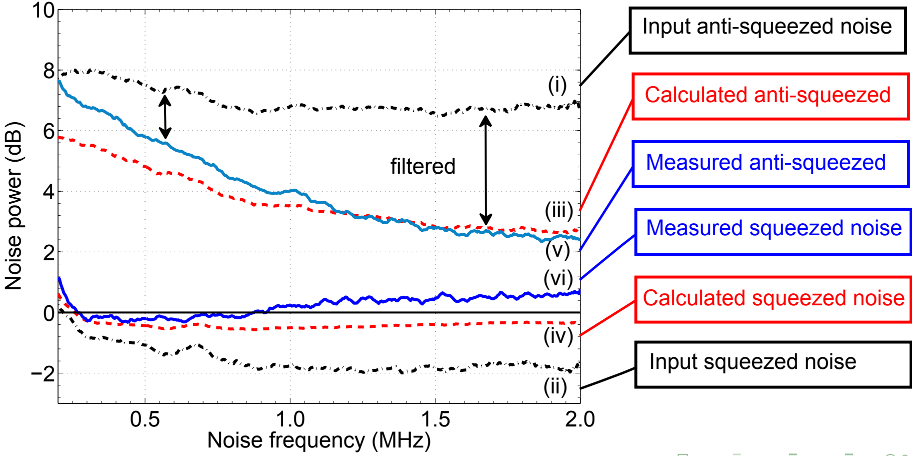
- Peak transmission = 52%
- FWHM= 4MHz







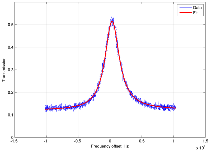
- Peak transmission = 50%
- FWHM= 2MHz

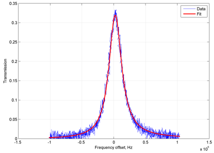


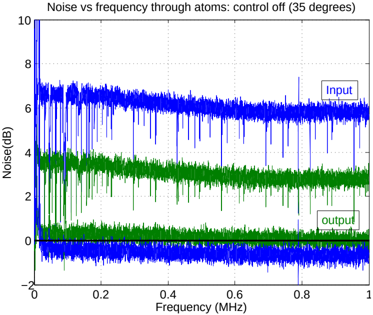
Narrower filter with control on/off

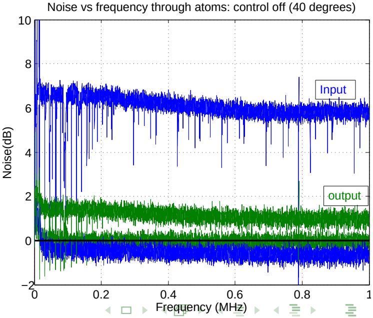
T=35°C, no control
transmission 42%

T=40°C, no control
transmission 17%



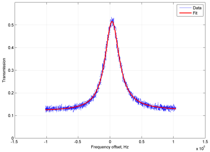


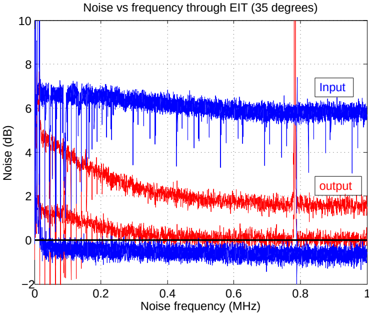




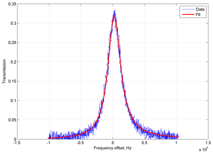
Narrower filter with control on/off

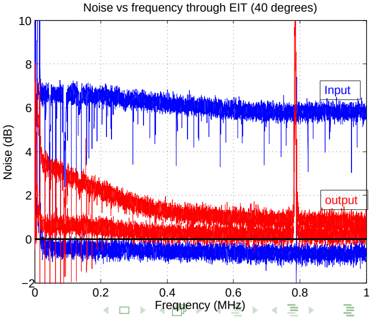
T=35°C, no control
transmission 42%



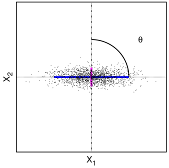


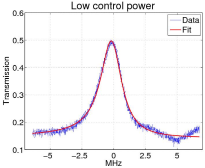
T=40°C, no control
transmission 17%

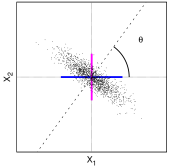




Squeezing angle rotation

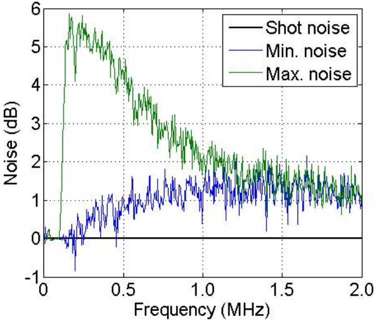




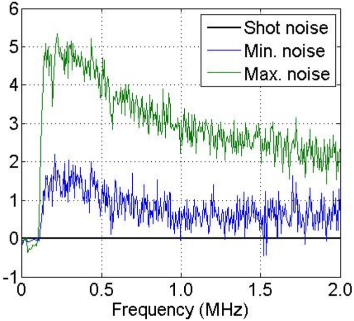


$$\begin{pmatrix} V_1^{out} \\ V_2^{out} \end{pmatrix} = \begin{pmatrix} \cos^2\varphi_+ & \sin^2\varphi_+ \\ \sin^2\varphi_+ & \cos^2\varphi_+ \end{pmatrix} \begin{pmatrix} A_+^2 & A_-^2 \\ A_-^2 & A_+^2 \end{pmatrix} \begin{pmatrix} V_1^{in} \\ V_2^{in} \end{pmatrix} + \left[1 - \left(A_+^2 + A_-^2\right)\right] \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

Locked at 300kHz



Locked at 1200kHz



Summary

- We demonstrate fully atomic squeezed enhanced magnetometer
- Magnetometer noise floor lowered in the range from several kHz to several MHz
- Demonstrated sensitivity as low as 1 pT/$\sqrt{\text{Hz}}$ in our particular setup
- Demonstration of amplitude squeezing filter with atoms

For more details:

- T. Horrom, et al. “Quantum Enhanced Magnetometer with Low Frequency Squeezing”, PRA, **86**, 023803, (2012).
- T. Horrom, et al. “All-atomic generation and noise-quadrature filtering of squeezed vacuum in hot Rb vapor”, Journal of Physics B: Atomic, Molecular and Optical Physics, Issue 12, **45**, 124015, (2012).